State of Science Assessment of Remote Sensing of Great Lakes Coastal Wetlands

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Table of Contents

Executive Summary Great Lakes Project

1. Introduction: The Problem

During both the International Lake Ontario-St. Lawrence River Study (LOSLRS) and the International Upper Great Lakes Study (IUGLS), coastal wetland performance indicators were developed and used to help assess how changes in Great Lakes water level management strategies may impact wetland vegetation response along the shoreline of the lakes. Meadow marsh and changes in its area and borders were identified as the key variables to monitor.

This project was focused on developing a state of science assessment of remote sensing of Great Lakes coastal wetlands, particularly related to the optimum approach or approaches to monitor and separate six vegetation classes:

1. Transition to uplands;
2. Meadow marsh;
3. Typha (cattail);
4. Misc. Mixed Emergent (non-persistent emergent);
5. Mixed Emergent (defined here as cattail invaded sedge-grass meadow marsh)
6. Floating (or submerged aquatic vegetation).

It was suggested that changes in boundaries of two meters or more should be identifiable. It was further decided that the Minimum Mapping Unit would be either 2 m x 2 m or 4 m x 4 m. The required DEM accuracy in x and y was suggested to be 2 meters. The "ideal value for z" (i.e. for elevation) was 1 cm, but one stakeholder suggested that 5 cm would be acceptable. Accuracy required is often a difficult parameter to both specify and quantify. For example, what does 90% accuracy mean? Does it mean that 90% of all decisions for each MMU are correct? Or does it mean that 90% of the surface area has been put into the correct class? The accuracy required is assumed to be 90%: i.e. 90% of the MMU's and 90% of the area in each class are all properly identified.

2. Approach

To set the stage, detail on how the focus was arrived at is followed by a general commentary on the general constraints and benefits typically associated with the use of remote sensing.

The project activity began with a short reading list of key publications on remote sensing and wetlands relevant to the Great Lakes. The list and papers were provided by staff of the IJC as well as Canadian and US government scientists. The publications included ones by government scientists and staff from Canada and the US, academics, as well as scientists and remote sensing specialists in both provincial and state governments. As the work progressed many of those whose papers were reviewed were contacted. (See the list in Appendix B.) The cooperation received from scientists on both sides of the border under very tight deadlines was outstanding.

A list of remote sensors, platforms and data processing approaches was developed and approved to be assessed for their potential to meet the needs of the project. As the key papers were read, more results from other papers were identified as potentially relevant. In all the results from over 1000 documents were scanned (including several books, many book chapters and several summaries). One review suggested that there were over 5900 papers on remote sensing of wetlands. As more documents were scanned the breadth and depth of papers read in detail increased dramatically. Over 125 contributions were read in detail. Key points related to the detail of interest were recorded in over 50 pages of point form notes tied back to the documents.

As the material to meet the needs of this contract were assembled, it was apparent that a great deal more information was readily available on how newer remote sensing systems and processing tools as well as data handling tools might be used to monitor wetlands across the entire basin rather than for the information needed to monitor meadow marsh. While the focus of this report was only on the use of remote sensing for the limited range of detail noted above, it was decided, with the approval of the scientific authority, to provide a more general assessment of the use of remote sensing for broader monitoring.

3. Recommended Remote Sensing Approaches for the Project at Hand

The results given here require a number of suppositions and assumptions, including making the assumption that research results can be translated into operational applications. That is only done here where results and explanations (and the experience of this author) offer strong support for it being so. The goal here is to err on the side of caution. It has been assumed that the results must lead to the minimum mapping units of the sizes specified and the classes identified – monitoring change in meadow marsh and elevations or "z" values in test sites in the Great Lakes Basin.

The imagery types and resolutions that would appear to at least partially meet the stated needs focusing on monitoring changes in meadow marsh and five other wetland classes are the following with the caveats noted:

1. Advanced airborne "coastal" LiDAR with either a multispectral or hyperspectral sensor which would provide seamless data from uplands into the water;[1]
2. Colour infrared aerial photography (airplane) with (optimum) 8 cm resolution. The "z" or elevation information obtainable was not determined and CIR cannot be used to map submerged aquatic vegetation;
3. Colour infrared UAV photography with elevation determination rated at 10 cm at a cost of $35,000 to $40,000 for 16 test sites. CIR cannot be used to map submerged aquatic vegetation;
4. Colour infrared UAV photography with high accuracy elevation determination rated at 3-5 cm but at a considerably higher cost than #2. CIR cannot be used to map submerged aquatic vegetation;
5. Airborne hyperspectral imagery (which provides limited to no "z" value);
6. High resolution optical satellite data with better than 1 meter resolution may provide the information about meadow marsh, but will not provide the "z" value.

4. Findings Related to Basin-Wide Studies

The potential application of a number of sensors and platforms were examined in terms of what the literature seemed to say about how well they would provide wetland mapping with a MMU of 0.2 hectares and 1 hectare. More specifically they were assessed as to how well the literature suggested that they could identify shorelines, water, submerged aquatic vegetation, Phragmites, flooded vegetation and elevation data with a 10-15 cm contour.

The sensors and platforms assessed included satellite-based C-band and L-band synthetic aperture radar, optical satellite data at various spatial resolutions, airborne hyperspectral, airborne LiDAR plus either hyperspectral or multispectral, and aerial photography from either a UAV or airplane. In addition various

[1] The placement of this option as one that would meet the requirements was supported after the fact by Ms. Molly Reif in a personal communication to Lori White, March 9, 2018.

information extraction approaches were evaluated including visual interpretation, supervised and un-supervised image analysis, object based image analysis and learning systems.

The results are presented in an overview table. The responses recorded in each cell were a simple "yes," "no," and "maybe" or "low," "medium," and "high," with an occasional "?" where the literature seemed inconclusive. Again, this overview is meant to be a general guide or a jumping off point for discussion.

In addition to the overview there is a brief discussion on new approaches to storing, accessing and using remote sensing data, including an example drawn from recent work.

5. Some Recommendations on Promising Areas of Remote Sensing Wetlands Research

The rapid growth in the number and availability of remote sensing systems (both sensors and processing approaches) has created both opportunities and challenges for the wetlands community. Obviously the opportunities come from the range of new data types, the number of suppliers, and the potential to unlock new information in ways never thought possible just a few years ago. The challenges come from a dearth of experience with these new systems, the potential that some have been over-sold, and whether or not the new systems will be sustainable or available in the future.

With these challenges in mind a number of recommendations can be made:

Technical – Assessment of the Problem at Hand

1. The newer UAVs with the capability to obtain more accurate z values should be investigated to determine if they really will meet the needs for the application being investigated here;
2. WorldView imagery, Planet Doves/RapidEye/Skysat imagery and similar higher resolution satellite imagery should be evaluated for their potential to monitor changes in meadow marsh to determine what a workable MMU might be;
3. Research should be carried out to determine if there is some index or set of indices that could be derived from coarser resolution multi-date/multi-sensor data (such as Landsat or SPOT combined with SAR) that would indicate that change has occurred. Such a tool might be useful for large area monitoring;

Technical – Looking to Basin-Wide Assessments

4. Access to multi-date RCM and future L-band data should be ensured;
5. Research should continue focused on key wetland parameters in the Great Lakes with multi-date RCM C-Band data combined with higher resolution optical data;
6. Since object based image analysis (OBIA) approaches seem to yield better results than traditional classifiers and since they work using different data sets including non-remote sensing data, they should be further investigated with reference to the limitations identified by Dronova cited in Appendix C;
7. Learning classifiers such as random forest may lead to greater accuracies, especially with complex multi-sensor data types – but the question must be answered, how consistent are the results over a large area and has the approach followed recommended procedures for establishing importance values?;
8. Learning classifiers should be combined with known information on change to determine if a change assessment tool can be developed for wider application;
9. Data from the newer aquatic/terrestrial LiDAR systems combined with multi-spectral or hyperspectral data should be examined for information content on the land-water interface and wetland characterization; and

10. There appears to be several groups with somewhat different wetland inventory schemes in use in the Great Lakes Basin. These were developed based on the needs and technologies available when they were conceived. It would be useful to evaluate the extent to which they reflect current needs and remote sensing technologies' capabilities.

6. Lessons Learned

This section details lessons learned with respect to doing this sort of review of wetlands remote sensing in general, as well as some of the lessons learned from a more technical point of view.

General

1. It is important to focus ones attention on what truly matters in a review such as this. There is an amazing amount of research published on wetlands remote sensing – over 5500 papers by one reviewer's account. Jumping into such a sea of information without a clear target would have been disastrous.
2. This review began with a series of discussions on what the data needs were that were to be addressed. Such a discussion may be time consuming, but it leads to a better understanding of the problem and, consequently, a much clearer assessment.
3. The number of excellent and yet practical researchers associated with wetlands remote sensing research who are working together in the Great Lakes Basin is a valuable cross-border resource that might be better exploited.
4. Taking advantage of recent technology developments, data sharing has become important in other areas and other applications.
5. Data repositories can save money and broaden the use and usefulness of data.
6. The book edited by Tiner et al (2015) is a valuable and accessible resource, although there is scant material on high resolution satellite data and little mention of thermal data.

Technical

7. The use of higher resolution optical data to "sharpen" lower resolution data (even from other sensor types) can lead to deriving better information from remotely sensed data.
8. Multi-date Sentinel-2, Landsat and/or SPOT data can be used to map land use in areas surrounding wetlands.
9. A major consideration in determining what information remote sensing can and cannot provide about wetlands is the chosen minimum mapping unit and classification system used.
10. Research seems to indicate that better spectral resolution can lead to what seems to be better spatial resolution.
11. The user community should be aware that because of speckle, spatial resolution of SAR data does not equate to spatial resolution of optical data. Some suggest that the effective spatial resolution may be $^{1}/_{3}$ of the stated spatial resolution.
12. Radar data can generate elevation data that may be very useful in wetland studies and far more precise than those unfamiliar with the data may realize.

1. Introduction

1.1. The Problem

The problem is well stated in the Statement of Work given in Appendix D, Section D1.2 and which is repeated here for completeness and to provide context for the remainder of this report.
During both the International Lake Ontario-St. Lawrence River Study (LOSLRS) and the International Upper Great Lakes Study (IUGLS), coastal wetland performance indicators were developed and used to help assess how changes in Great Lakes water level management strategies may impact wetland vegetation response along the shoreline of the lakes. As part of the LOSLRS, the meadow marsh performance in particular was critical to the decision to support the newly adopted Plan 2014, although change in other wetland vegetation zones is also important to support habitat response. Going forward, the Great Lakes – St. Lawrence River Adaptive Management (GLAM) Committee is working to develop an appropriate strategy for tracking changes in Great Lakes coastal wetland vegetation and how those changes may be related to water level fluctuations. The information will be used to help verify the original performance evaluation model and also to provide information that supports reporting on change over time. To support the development of a longer-term strategy for tracking coastal wetland vegetation related to water levels, the GLAM Committee is looking for the contractor to develop a state-of-science synthesis of remote sensing options that can form the basis for future planning.

1.2. Objective

The objective of the project for which this is the report is given in the Statement of Work (SoW) (Appendix D, Section D1.4):
This project will focus on developing a state of science assessment of remote sensing of Great Lakes coastal wetlands, particularly related to:

1. *Improving topographic and bathymetric elevation estimates;*
2. *Defining wetland extent; and*
3. *Differentiating vegetation communities within wetlands.*

The primary activity to be completed under this Contract and reported on here then is to acquire "*a comprehensive summary of available scientific methods for wetland monitoring through a qualified Subject Matter Expert working in concert with experts identified by the Scientific Authority will provide the Great Lakes – St. Lawrence River Adaptive Management Committee with a detailed assessment of potential options to perform the necessary monitoring effort.*"

As we begin the report it is useful to outline the scope of the problem of conducting a review of the State of Science of Wetland Remote Sensing. We estimate that the contributors to Tiner et al (2015) list some 1400 citations. Demonstrating that wetlands are a world-wide concern Guo et al (2017) cross-referenced wetland and remote sensing using the Science Citation Index Extended (SCIE) database from Web of Science. Their project was sponsored by the National Natural Science Foundation of China National Key Research and Development Project. They identified 5719 papers for their review. They cited 283 of these. We did NOT review 5719 papers, or even 1400. We did read and review Tiner et al and Guo et al for this study.[2] We have also reviewed a number of papers provided by the contract authority and her colleagues, papers that these papers led to, as well as those that came up in a number of targeted searches associated with the Great Lakes, wetlands and what appeared to be relevant remote sensing technologies. Interestingly enough, many of the papers (including some older bench-mark papers) that we regard as important for this study were not cited in the Guo et al review (2017).

[2] Guo does provide an interesting history of the study of wetlands from imagery dating from 1964 to 2015.

In 1958 Evelyn Pruitt, a research geographer interested in coastal areas, coined the term remote sensing. Remote sensing included both photographic and non-photographic imaging sensors. Remote sensing can be defined as "the acquisition of information about an object or phenomenon without making physical contact with the object and thus in contrast to on-site observation." This definition from Wikipedia (Accessed February 16, 2018) is similar to that first used in the Manual of Remote Sensing in the 1980s.

The subject matter expert and author of this report is Dr. Robert Ryerson, a Certified Mapping Scientist (Remote Sensing) who has specialized in vegetation assessment with remote sensing data. He has worked on this project with the advice of a number of experts identified by the Scientific Authority and others identified through the literature review. Those consulted by e-mail, telephone or in person are listed in Appendix B.

1.3. Introduction to the Report

Section 2 details the data needs – the parameters underlying the review and how they were determined. Section 3 explains some of the intricacies of evaluating remote sensing tools and processes. While in discussions it was suggested that there was no need to "repeat high level context information that is already in the Annex 7 Report," some context information is included here in that it can be assumed that some of those reading this report will not have read all of the other background material. Section 4 presents some recommended remote sensing approaches to obtain the required information, drawing on Appendix C which provides an explanation of the literature review process. Section 5 provides more general suggestions for future consideration related to a broader monitoring than is required to meet the deliverables of this contract. Section 6 is intended to provide a summary of a workshop held to discuss the future potential of remote sensing for marsh meadow wetland monitoring in the Lake Ontario Basin and St. Lawrence region as well as the Great Lakes Basin as a whole. The final section presents some lessons learned that may be useful to guide future research and development related to this important topic.

2. Data Needs: Establishing the Parameters Underlying the Review

2.1. Introduction

Data needs as well as the parameters and guidance for conducting the review were outlined in two Tasks in the SoW. (See Appendix D, Section C2.1.) Task 1 was a "kick-off conference call to discuss project expectations." Task 2 called for the preparation of a "draft spreadsheet synthesis of key findings." The remainder of this section discusses the two tasks, how they have evolved over the course of the work and the agreed-upon response to them.

2.2. Task 1: Kick-off Conference Call

There were actually several conference calls convened by the Scientific Authority or others associated with the project that involved a variety of players and stakeholders from the IJC, Government of Canada, Province of Ontario, and both Government employees and academe in the USA. The discussions in these calls were to clarify both the expectations and parameters to be examined. Time and effort were expended on this step in that this forms the basis of both the expectations of the client and deliverables required of the contractor.

One of the lessons learned in performing scans and evaluations of the capabilities of remote sensing in the past is the need to clearly understand what information the client wants to extract from the remote sensing data. To establish what the required capabilities of remote sensing are with regard to the subject at hand the following questions were asked to set the parameters for the review:

1. What information is required and why is that information required (i.e. for what purpose)?
2. Are there any surrogates for the attribute of interest?
3. What is the Minimum Mapping Unit (size or ground area)[3];
4. What is the ideal accuracy required to identify and map the attribute of interest or its surrogate?
5. What is an acceptable accuracy required to identify and map the attribute of interest or its surrogate?

In studies involving vegetation the answer to the first two questions typically involves the use of specific and clearly definable classes. Through several e-mail exchanges culminating in Conference Calls on January 25th and February 1st involving a number of Stakeholders, the Contractor and Contract Authority, it was decided that the focus would be on assessing the potential of various remote sensing methods to identify the optimum approach or approaches to monitor and separate six vegetation classes:

1. Transition to uplands;
2. Meadow marsh;
3. Typha (cattail);
4. Misc. Mixed Emergent (non-persistent emergent);
5. Mixed Emergent (defined here as cattail invaded sedge-grass meadow marsh) [4]
6. Floating (or submerged aquatic vegetation).

Meadow marsh and changes in its area and borders were identified as the key variables to monitor. It was suggested that **changes in boundaries of two meters or more should be identifiable**. As is further explained in Section 3, identifying clearly defined classes with remote sensing is not always easily done.

It was decided that the **Minimum Mapping Unit would be either 2 m x 2 m or 4 m x 4 m**.

The required DEM accuracy in x and y was suggested to be 2 meters. **The "ideal value for z" (i.e. for elevation) was 1 cm, but one stakeholder suggested that 5 cm would be acceptable**.

Accuracy required is often a difficult parameter to both specify and quantify. For example, what does 90% accuracy mean? Does it mean that 90% of all decisions for each MMU are correct? Or does it mean that 90% of the surface area has been put into the correct class? **As of February 23rd as Section 4 is being written the accuracy required was not specified but is assumed to be 90%.**

The table on the following page has the details of sixteen wetlands used as an example of what one might wish to assess with respect to the parameters noted above.

The concept of "surrogate" for a feature of interest is common in remote sensing. A **surrogate is an easily recognizable indicator that the feature of interest is present**. Are there one or more surrogates for the classes of interest? Is there some unique spectral response or colour when one combines two images from two time periods that may indicate that there has been a change in meadow marsh? While surrogates are often found by trial and error, on occasion they are identified by subject matter experts who understand how the features of interest appear on imagery.

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[3] "The MMU is the specific size of the smallest feature that is being reliably mapped in your map. MMU is used in both data collection and in map production." (***ESRI Insider***. Accessed February 15, 2018. https://blogs.esri.com/esri/esri-insider/2015/05/21/a-question-of-scale-resolution-and-MMU/ :

[4] Dr. Doug Wilcox, one of the experts involved, noted that it will be a challenge to distinguish this zone because it has parts on both sides (cattail lower and meadow marsh above). It is not clear what the criteria would be to define this zone.

Table 1: Sizes of Sample Wetlands

Name	Site Code	Acres	Area SqM	xDim m	yDim m
Sodus Bay Wetland	PE-36	99.81	403924	450	1190
Maxwell Bay Wetland	BB-1	27.83	112609	518	491
Port Bay Wetland	DRM-17	428.71	1734940	1610	3984
Braddock Bay Wetland	OE-38	521.34	2109792	2656	2687
Sterling Creek Wetland	DRM-13	767.34	3105317	3505	3455
North Pond Area Wetland	BB-2	46.82	189461	468	758
Lakeview Pond-Sandy Creek-Colwell Ponds Marsh	BB-3	815.18	3298930	1704	4115
Muskalonge Bay Wetland #1	PE-28	219.81	889548	1474	1336
Perch River Wetland	OE-39	224.29	907653	2714	2023
Isthmus Marsh	OE-40	51.55	208623	820	690
North Buck Bay Wetland	DRM-16	15.56	62975	423	541
Rift Area Wetland	PE-30	20.51	83007	367	484
Flatiron Marsh Wetland	OE-37	58.20	235528	954	764
Grass Point Wetland	PE-34	7.00	28333	256	214
Round Pond	BB-100	239.65	969814	1471	1488
Brush Creek Wetland	DRM-100	182.41	738203	2245	1176

The name and site codes are identifiers of the specific wetlands. The area is given in acres and square meters. The dimensions in meters are estimates of the size of a rectangle to fully enclose the wetland – believed useful to assess the requirements for aircraft or satellite data coverage. Material provided by Tim Howard.

2.3. Task 2: Prepare Draft Spreadsheet to Synthesize the Key Findings

From the SoW: "*The contractor will develop a spreadsheet or table that will provide a summary of findings from a combination of discussions with experts identified by the Scientific Authority, sampling of the literature, and knowledge and experience of the contractor. Each column of the table will contain the specific information or attribute required. Obviously as the number of columns increases the level of detail obtainable may need to be adjusted. At the outset the number of rows is unknown. One might assume that there would be more than ten and less than fifteen to twenty.*"
With the clarification of the information required and the parameters of the literature review, the sixteen parameters and conclusions drawn in discussion with the Scientific Authority are presented here to set the stage for the review and the remainder of this report. The agreed upon response to each task is given in **Bold font**. "**Noted**" implies that the requirement was understood and will be met within the limitations of the remote sensing technology selected.

1. *Brief description of the information (or attribute or feature) required;* **Done - See above.**
2. *Outline of who needs the information (identify as many as possible);* **The Client is GLAM. Other clients or partners may include the agencies in the Government of Canada, the Province of Ontario, relevant US Federal and State agencies**
3. *Outline why the information is needed - the operational requirement that would be met;* **The data are needed to verify the models developed for changes in meadow marsh**
4. *Brief description of the probable surrounding features or context including associated vegetation;* **See above classes. Bare sediment is also of interest.**
5. *Outline when the feature of interest or information required is likely most readily separated from the surrounding features;* **Noted, should be possible.**

6. *Identify any surrogates or "markers" that may indicate the presence of the information attribute or feature of interest;* **Noted, we are not sure if this is be possible. Suggestions will be made on how to identify surrogates if none are identified in the literature.**
7. *Brief description of threats to the feature – especially those that might be identifiable from remote sensing (e.g. relative sensitivity to changes in water level, including what changes have a deleterious impact);* **Noted, should be possible.**
8. *The typical minimum mapping unit (area) at which the information is needed;* **See above.**
9. *A description of where the feature will be found (the distance from the shore, smaller lakes feeding into the Great Lakes, etc.);* **Noted**
10. *The likely total area of the information or feature of interest in the basin (if known);* **This question is now irrelevant to the project's stated requirements**
11. *The likely distribution of the information or feature of interest in the basin (if known);* **This question is now irrelevant to the project's stated requirements**
12. *How often the information is required (frequency);* **The Scientific Authority suggests yearly. Seasonal information may be useful in research. Both will be considered**
13. *Past experience with remote sensing (where known) on the successful use of the technology including accuracy;* **Noted**
14. *Past experience with remote sensing (where known) detailing the difficulties in using remote sensing imagery (cost, availability, accuracy, need for multiple image acquisitions, time of year, ability to separate the attribute of interest from surrounding features, need for ground data, etc.)* **A separate sub-section in the next section will begin to address this issue.**
15. *Likely applicable remote sensing technology including resolution and relative cost where cost information is readily available;* **Noted. It is expected that precise cost information will be difficult to impossible to obtain.**
16. *Identify relevant bibliographic sources (in cooperation with the Scientific Authority and Project experts)* **Noted. References are given in References.**

3. Evaluating Remote Sensing Tools and Processes

3.1. Introduction: Some Caveats

Of the over one hundred papers and book chapters read in detail for this review virtually every one began with a commentary on the difficulty of using remote sensing to monitor wetlands. This has been taken as both a warning and a challenge in the preparation of this report. Those difficulties were further enumerated in the summaries of the hundreds of articles scanned. At the same time most papers also noted the many benefits associated with using remote sensing for wetland monitoring, where it was feasible. This section provides an introduction to both the challenges and benefits associated with the use of remote sensing in general, beginning with a few caveats. Specifics on remote sensing of wetlands are further detailed in Sections 4 and 5 following the literature review introduced in Appendix C.

A review or state of science assessment such as being reported on here should always begin with a few caveats as to what is and is not part of this review or intended in this review. Here we have identified six.

- This is NOT a comprehensive review of all R&D in wetlands remote sensing. The total amount of time allocated to this work, including a workshop, is about 20 days. This report targets work on wetlands that is related to or seems in some way to meet the information needs of the stakeholders associated with the Great Lakes in general and Lake Ontario and the St. Lawrence in particular. The focus is therefore on North American wetlands work in general and the Great Lakes Basin in particular. It largely ignores tidal wetlands, salt-water wetlands, tropical wetlands, prairie pot-hole wetlands, wetlands in the far north and those in Mediterranean climates.

- The author has had commercial dealings with almost all of the companies involved in the field in Canada and many others elsewhere. Where we mention (or don't mention) a commercial entity, this is not necessarily an endorsement or criticism of that entity.
- While we have tried to be inclusive in selecting work for review, we may well have missed something. It is anticipated that the workshop will identify any significant gaps. (The workshop is discussed in brief in Section 7.)
- In the list of references and to simplify preparation of this document we have not identified any but the first author if there are three or more authors.
- An assessment of "users' needs" is always complex. It is made more complex by the range of opinions held by different users and stakeholders.
- There is often a distinction between what users want and what they need. Typically a user is willing to pay for what they want, but may not always recognize what they need: a dialogue is often required. The workshop that marked the end of this study provided an opportunity to begin that dialogue.

Reviews of remote sensing typically begin by extolling the benefits of remote sensing. Here we begin with a discussion of some of the constraints to provide a realistic setting for this review before we identify some of the benefits of using remote sensing. The list of benefits and constraints identified here is meant to be an indication of the issues associated with using remote sensing – it is by no means complete.

3.2. Some Constraints and Benefits Associated with the Use of Remote Sensing

Remote sensing is not a "silver bullet" that will solve all data problems, as some of its more exuberant proponents often claim. But used properly in the right circumstances it WILL solve many of the problems of those who need information about the surface of the Earth. For this project we have tried to select for review only that research where the researchers seem to be mindful of the constraints faced. Some of the many constraints or issues associated with the use of remote sensing (RS) data and technologies that must be kept in mind are the following:

- Hammer and nail syndrome: if the only tool you have is a hammer, then every problem looks like a nail. Some of those with access to only one or another of the RS data types will tend to use that data type to try to obtain good results – whether or not it is the best data type for the purpose. (We have tried to consider that sort of bias when reviewing the literature.);
- Calculating and evaluating accuracies can be problematic;
- The desire to obtain good results sometimes leads some researchers to generalize the data classes to an extent that may render them useless;
- Remote sensing almost always requires well-planned and well executed field work for training interpreters or for "training" computer image analysis systems, as well as for verification of results;
- The term "Ground Truth" is often used to refer to data collection in the field. The "Awful Truth about Ground Truth" is that sometimes the "true" information is collected by the remote sensor, not by those on the ground. This is especially so if the ground data are lacking, largely incomplete, located imprecisely, collected by inexperienced individuals, or not collected at the same time as the remote sensing data;
- Accuracies can vary greatly depending upon the interpreter's skill and understanding of what is being interpreted. For example, wetland experts, not urban planners, should be interpreting imagery over wetlands;
- Success in small R&D test sites does not always translate into fully operational applications over much larger areas;
- Costs for operational programs are often difficult to estimate without soliciting information through a formal "Request for Information" or "Request for Quote;"

- Access to large amounts of RS data and advanced algorithms and powerful processing systems may, or may not, generate useful results;
- Some users are more important than others when it comes to accessing certain data types – this may lead to problems getting appropriate data at the right time if wetlands are considered to be unimportant;
- Cloud cover can prevent the acquisition of optical RS data;
- It is often difficult to acquire multi-sensor RS data on the same (or even similar) dates;
- It is often difficult to coordinate remote sensing data acquisition with ground data collection;
- Some vegetation types cannot be distinguished from surrounding but different vegetation types;
- Some RS data available for research purposes today or in the past may not be available for operational use in the future; and
- The fact that many researchers are assessing the same approach does not necessarily mean that the approach is a valid one. There is sometimes a herd instinct when it comes to assessing new approaches to image analysis – one researcher will attempt a new approach, obtain interesting results and many others will soon follow.

As there are many constraints on the effective use of remote sensing, there are also many potential (but not always realized) benefits of using the technology. The use of remote sensing may lead to:

- Reduction of field work;
- Mapping larger areas and do so faster and at lower costs;
- Effective monitoring of change over time;
- Quantitative measures of past and current conditions;
- The creation of data to test models; and
- A better understanding of the local environment or geography of an area.

4. Recommended Remote Sensing Approaches

4.1. Introduction

This section recommends how to obtain the required information asked in the SoW and elaborated upon above. It suggests two recommended approaches to obtain the data required and potential alternatives that might be explored. It is based on what came out of the literature review (described in Appendix C) of documents listed in the References and discussions with a number of experts listed in Appendix B.[5]

The objective is to identify appropriate remote sensing tools to:

1. **Monitor and separate six vegetation classes in sample wetlands[6]:**
    a. **Transition to uplands;**
    b. **Meadow marsh;**
    c. **Typha (cattail);**
    d. **Misc. Mixed Emergent (non-persistent emergent);**
    e. **Mixed Emergent (defined here as cattail invaded sedge-grass meadow marsh)**
    f. **Floating (or submerged aquatic vegetation).**
    g. **Bare sediment is also of potential interest**

[5] We are deeply appreciative of those who shared pre-publication or unpublished manuscripts detailing their latest work and relevant findings. These include Drs. Doug Wilcox, Koreen Millard, Brian Brisco, Adam Hogg and Brian Huberty.

[6] It is assumed here that the project aimed at validating a model on the impact of water level changes at the detail requested is economically feasible only in sample or test areas such as the 16 sites described by Wilcox and Bateman (Prepublication Manuscript) and Howard et al (2016).

2. **Provide information with a minimum mapping unit of 2 x 2 meters or 4 x 4 meters;**
3. **Obtain an accuracy of 90% (90% of the meadow marsh area classified correctly)**
4. **Acquire Digital Elevation Model accuracy in x and y of 2 meters and 5 cm in z (elevation.)**

In addition we are to identify:

1. **When the classes are likely most easily separated from surrounding features;**
2. **Detail past experience with remote sensing (where known) including specific difficulties in using remote sensing imagery. (Factors to be considered include cost, availability, accuracy, need for multiple image acquisitions, time of year, ability to separate the attribute of interest from surrounding features, need for ground data, etc.): and**
3. **Identify costs where obtainable.**

Lastly we would like to identify any surrogates or "markers" that may indicate the presence of the information attribute or feature of interest, noting that none have been identified in the literature reviewed.

Also of interest are the following questions which were addressed at the workshop:

1. **Where are the features of interest located;**
2. **How often information is required; and**
3. **Threats to the feature – especially those that might be identifiable from remote sensing (e.g. Relative sensitivity to changes in water level, including what changes have a deleterious impact).**

4.2. Recommended Sensors, Platforms and Processing Approaches

The state of science of remote sensing for determining the information required here about meadow marsh is reviewed in Appendix C. The concentration of the review has been on research on remote sensing of wetlands of the type found in the Great Lakes Basin. Over 100 papers and book chapters have been cited out of over 1000 whose results have been scanned.

The results given here require a number of suppositions and assumptions. Making the assumption that research results can be translated into operational applications is only done here where results and explanations (and the experience of this author) offer strong support for it being so. The goal here is to err on the side of caution. It has been assumed that the results must lead to the minimum mapping units of the sizes specified and the classes identified. Table 2 on the following page summarizes the findings of the state of science review in Appendix C for the problem at hand – monitoring change in meadow marsh and elevations in test sites in the Great Lakes Basin.

Section 5 takes a broader view of the use of remote sensing and related technologies in the Great Lakes basin.

Table2: Systems and Sensors to Meet the Requirements

The following table summarizes the literature scan carried out in Appendix C to meet the requirements specified by the IJC. The scan is organized based on the sensors and platforms and processing approaches reviewed in Appendix C which are listed in Column 1. The second column indicates the expected success with which the main classes can be mapped with the tool listed at the minimum mapping unit specified. The third column identifies the success with which meadow marsh changes might be identified. Success expected for each minimum mapping unit (MMU) is estimated in three general ranges: high accuracy (estimated over 90%), limited (some useful information about the factor may be available) and nil (meaning that the tool will be unlikely to deliver the required accuracy given the MMU). In some cases two of the tools must be used together to achieve success and where this is the case that is indicated. The “z value” column indicates the elevation value than can be determined. If below 10-15 cm – nil is given as the response. In some cases the elevation will depend on time of year, sophistication of the system, flying height and other factors. The potential surrogate column provides an indication as to whether or not the sensor, platform or processing approach might be able to deliver a surrogate for the specified meadow marsh classes or changes in them. In most cases a “yes?” indicates that the author believes that such a surrogate might be determined. Cost is a very general estimate. Commercial costs are difficult to obtain, although some costs have been determined for the technologies that look most promising. Under costs it should also be noted that the Government of Canada has supply arrangements with which one may calculate the expected costs. Literature provides an indication as to whether or not there is literature that supports the prognosis for success. Difficulties and comments offer additional relevant information.

Sensors, Platforms and Processing Approaches	**Meadow Marsh Classes**		**Meadow Marsh Changes**		**Z value in cm**	**Potential Surrogates**	**Cost of data &/or analysis**	**Literature Available to Support Claim**	**Difficulties and Comments**
	2 x 2 m MMU	**4 x 4 m MMU**	**2 x 2 m MMU**	**4 x 4 m MMU**					
Sensors and Platforms									
Synthetic Aperture Radar	nil	nil	nil	nil	3-10	Yes?, L-Band	High/high	Yes	Resolution insufficient for MMU
Optical satellite 10-30 m resolution	nil	nil	nil	nil	nil	no	Free/Low	Yes	Resolution insufficient for MMU
Optical satellite 3-9 m resolution	nil	nil	nil	nil	nil	Yes?	Free/Low	Yes	Indices and special processing may lead to a surrogate
Optical satellite resolution under 1m multispectral	Limited	Yes?	Limited	Yes?	nil	Yes?	Free to high	Limited	
Airborne Lidar + multispectral or hyperspectral	Yes	Yes	Yes	Yes	5-10	NA	High/high	Yes	Flying height and time of year will determine success in “z.”
Airborne Hyperspectral	Yes	Yes	Yes	Yes	nil	NA	High/high	Limited	Data is not easy to process
Aerial Photography (By Airplane) 8-12 cm resolution colour IR	Yes	Yes	Yes	Yes	?	NA	High/medium	Yes	Well-tested approach
Aerial Photography (by UAV) 3-10 cm	Yes	Yes	Yes	Yes	5-10	NA	Medium?	Limited	z<10 cm requires special drone
Processing Approaches									
Visual interpretation (airborne images)	Yes	Yes	Yes	Yes	nil	NA	Medium/Low	Yes	Well-tested approach
Supervised and Un-Supervised Image Analysis with medium to high resolution data	Limited	Limited	Limited	Limited	nil	No	Medium/low	Yes	Not recommended for fine detail
Object-based Image Analysis (OBIA) for use with high res satellite data	Limited	Yes?	Limited	Yes?	nil	Yes	Medium/low	Limited	This tool may lead to a surrogate for wider application
Learning analysis multi-sensor systems	Limited	Limited	Limited	Limited	nil		Medium/?	Limited	

There are six imagery types and resolutions that would appear to meet or partially meet the stated needs (see notes below) to monitor changes in meadow marsh and five other wetland classes. In fact, given the elevation criterion of 5 cm and the need to monitor submerged aquatic vegetation, the list is actually more limited. The six potential options would appear to be the following:

- Airborne LiDAR with either multispectral or hyperspectral sensor;[1]
- Colour infrared aerial photography (CIR) (airplane) with (optimum) 8 cm resolution;[2]
- Colour infrared UAV photography with elevation determination rated at 10 cm;[3]
- Colour infrared UAV photography with high accuracy elevation determination rated at 3-5 cm;[4]
- Airborne hyperspectral imagery;[5]
- and
- High resolution optical satellite data with better than 1 meter resolution.[6]

Notes:
[1]This would appear to be the most expensive option. It does provide the potential to acquire seamless information into the water, including bathymetry.

[2] It is not clear how accurate the z value, or elevation would be. Submerged aquatic vegetation would not be identified with CIR.

[3]A contractor has advised that the less accurate UAV imaging system is easier to use and provides image data that are acceptable. Submerged aquatic vegetation would not be identified with CIR.

[4]While elevation data meet the needs, the data take longer to acquire and result in more complex stitching together of imagery. Submerged aquatic vegetation would not be identified with CIR.

[5] Hyperspectral imagery is expensive. Furthermore, if hyperspectral imagery is used on its own, the system cannot deliver z values of the detail required.

[6]These data have not been directly assessed for this application. The assessment is based on comparative studies and assessment of sample imagery by the author taken with the normal relationships between minimum mapping units and pixel sizes.

The following questions were addressed at the workshop with the results noted:

1. **Where are the features of interest located?**

The features of interest for the initial discussion and evaluation of results from different systems are the already-established 32 wetland test sites around Lake Ontario mentioned elsewhere in this report. Specific wetlands for joint work and/or sharing of results include those in the Bay of Quinte area and the sites used by Drs. Wilcox and Howard and Mr. Grabas.

2. **How often is the information required?**

Accurate elevation data need only be acquired once. At the outset it is believed that the information on wetland types (i.e. vegetation type) would be required every five years unless there was an extreme event such as extremely low water levels or perhaps flooding, then the wetland site should be monitored for several years thereafter;

3. **Are there threats to the feature that might be identifiable from remote sensing?**

There are many potential threats to wetlands in the Great Lakes that can be monitored or identified from remote sensing data ranging from changes in water level to invasive species, increased (or decreased) sediment loads, movement or lack of movement of sand, etc. The first priority is to establish what information can be reliably obtained from which sensor at what relative cost.

5. Findings Related to Basin-Wide Studies

5.1. Introduction

This section will summarize useful information from Appendix C that was discovered through the literature review that may be useful to the IJC or those monitoring wetlands in the Great Lakes Basin. As well it contains some conclusions drawn through a combination of previous experience and recent discussions with a number of people involved in remote sensing and wetlands in the Great Lakes as well as with others on the periphery of the remote sensing community. It is not an expected part of the project, but with the information and ideas being available, it seemed reasonable to spend a few extra hours to provide additional value to the client.

The first subsection below provides some commentary on what are called organizational considerations including data sharing. The next subsection addresses what remote sensing tools might be of use in broader studies of wetlands in the Great Lakes Basin. A summary table is included. Looking at the more general case in Table 3 some of the sensors and processing approaches are clearly at the operational stage, others are between research and operational and others are still clearly at the research stage.

5.2. Some Organizational Considerations: Data Sharing

Data sharing has been an important part of the work done in the Great Lakes for some decades. One can cite just a few examples that have been encountered in the preparation of this work:

- The materials for this review have been provided by people in several agencies of the Government of Canada, staff in the Government of Ontario, faculty members of several universities in Canada and the US, staff in the US Government, and staff in the State of New York. The cooperation has been exemplary;
- The work by Bourgeau-Chavez et al (2015) resulted in a Basin-wide data base (or map) of wetlands and surrounding lands. That data has been shared with the Government of Ontario;
- The Government of Ontario has shared data and information with the Government of Canada – and vice versa;
- Agencies of the US government have shared data with counterparts on both sides of the international boundary;
- Many joint papers have been written by people on both side of the international boundary; and
- It has been learned that there are formal groups involved in remote sensing on both sides of the border. (This author gave an invited presentation to one of the US groups in 2017.[7])

As we looked at this interest in data sharing and cross border research collaboration, several questions, ideas and concepts came to mind.

Given the already fine cross-border linkages in remote sensing R&D and the importance of remote sensing to the understanding, monitoring and management of the Great Lakes Basin why is there not a remote sensing advisory committee associated with the IJC?

[7] The presentation was titled "The View from the North: An Historical Perspective on Remote Sensing in Canada…and a Look to the Future")

So-called “Big Data” and data sharing have become popular topics in the geospatial realm with considerable technological advancements in the field over the last few years. We have also seen rapid change in the quantity and quality imagery and other data that is being handled. A company based in the National Capital Region, CUBEWERX, has been doing both demonstration and operational projects in this area of data sharing/distribution for some time. In Canada, the initial development leading to a “Thematic Exploitation Platform” concept was done through the GeoConnections program. Today CUBEWERX hosts a few operational services for public and private organisations. For example, they operate a web based host-managed service for the Government of Saskatchewan to provide images and other geospatial data. When they began operating the service three years ago there were 2,500 users a month accessing the system. Today this system serves more than 400,000 users per month. This sort of platform may be of interest and use to the IJC and its partners. (See text box on the following page.) As a follow-up to this idea, White (Personal Communication, March 11, 2018) has suggested that it might also be useful to have an online wetland web-map connecting various Federal/Provincial/State government agencies from both sides of the border where members could upload field data collections, UAV imagery, remote sensing products etc. It would also allow for users to be involved with imagery interpretation and validation.

Thematic Exploitation Platform - Executive Summary[8]
The concept demonstrates the use of an innovative computerized Exploitation Platform for large volumes of Earth Observation (EO) Data. In the traditional workflow for the analysis of EO data, users download the data to their local site and then process it locally using available software and other computing resources. With the increasing volume of data available from current and upcoming satellites, and the need for more powerful and scalable computing resources for processing EO data, existing methods of working are inefficient and restrict the use and exploitation of EO data. We suggest a working environment where users can package their applications and upload them to a Cloud environment that supports the processing of users algorithms at scale - avoiding the need to download and store large volumes of images locally. The approach encourages wider exploitation and more efficient use of EO data. The idea is simple, move the applications near the platform rather than download an ever-growing volume of images to a larger and ever-growing audience. Resolving the EO data replication problem, reducing the overall processing time as well as augmenting the processing capability using a scalable Cloud infrastructure will avoid costly capital expenditures for processing equipment and bandwidth for user communities and support timely decision-making for all users of EO data.
Source: Edric Keighan, CEO, CUBEWERX, personal communication March 9, 2018.

5.3. Large Area Lower Resolution Applications

The pool of wetland remote sensing knowledge and experience available in the Great Lakes Basin is unsurpassed. The review confirms that the research, development and operational programs are first rate. What this section does is try to capture the knowledge available from that deep pool of knowledge to identify what remote sensing tools and platforms could contribute to a broader study of wetlands in the Great Lakes basin with a less constrained set of parameters. Given the interest of the IJC in remote sensing of wetlands, it seemed that bringing together a summary of more general approaches may well be useful. This short section attempts to do that.

[8] This information was obtained following a conversation with Mr. Keighan on another matter. At this time the author has no business relationship with CUBEWERX.

Building a general summary is not without its limitations. As noted in Appendix C, the most useful approaches often apply more than one type of sensing. Lang and McCarty (2008) noted that researchers have debated as to “whether spatial or spectral resolution is more important to the mapping of wetlands. It appears from available research that a combination of spatial and spectral resolutions is needed to map wetlands with remotely sensed data. The necessary spatial resolution, of course, depends upon the size of the wetland patch that is being mapped.” Another truism is that “the specifications of a good wetland map depend heavily on what that map is being used for” (Land and McCarty, 2008). It is within these limitations that the following table is offered as an initial assessment of what might be “doable.”

The following table summarizes some of the conclusions one might draw from the scan in Appendix C about the use of remote sensing to meet more general requirements for wetland-related information related to the Great Lakes. The summary is an additional deliverable that is NOT called for in the contract carried out by Kim Geomatics Corporation.

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Table 3: Systems and Sensors to Provide General Wetland-Related Information Over a Large Area

Sensors, Platforms and Processing Approaches	Wetland Classes[1] 0.2 hect.	Wetland Classes[1] 1 hect	Shore[2]	Water[3]	SAV[4,5]	Phrag-mites[5]	Flooded Vegetation[5]	Z value 10-15 cm	Cost of data &/or analysis	Literature Available to Support Claim
Sensors and Platforms										
Synthetic Aperture Radar – multi-look C-Band RCM[7] data[8]	maybe	yes	yes	yes	no	?	yes	?	L?/H	yes
Synthetic Aperture Radar – L-Band[8]	yes	yes	yes	yes	no	yes	yes	yes?	L?/H	yes
Optical satellite 10-30 m resolution	maybe	yes	Yes? – success depends on bands used, time of year, and resolution (spatial and spectral)				no	no	L/M	yes
Optical satellite 3-9 m resolution	maybe	yes					no	no	M/M	yes
Optical satellite 1 meter multispectral	yes	yes					no	no	M/M	yes
Airborne Lidar + multispectral or hyperspectral	yes	yes	yes	yes	yes	yes	maybe	yes	H/M	yes
Airborne Hyperspectral	yes	yes	yes	yes	yes	yes	no	no	H/H	limited
Aerial Photography (By Airplane) 8-12 cm resolution colour IR	yes	yes	yes	yes	no	yes?	no	yes?	M/H	yes
Aerial Photography (By Airplane) 8-12 cm resolution normal colour	yes	yes	maybe	maybe	yes	yes?	no	yes?	M/H	yes
Aerial Photography (by UAV) 3-10 cm colour IR	yes	yes	yes	yes	no	Yes	no	yes	H/H	No
Processing Approaches										
Visual interpretation (airborne images)	yes	yes	yes	yes	?[6]	Yes	no	NA	M/H	yes
Supervised and Un-Supervised Image Analysis with medium to high resolution data	maybe	maybe			no	No	no	NA	L/M	yes
Object-based Image Analysis for use with high res satellite data	yes	yes	?[6]	?[6]	?[6]	May	no	NA	H/M?	limited
Learning analysis multi-sensor systems	yes	yes	?[6]	?[6]	?[6]	May	no	NA	H/M?	limited

READER PLEASE NOTE: This table is not part of the required deliverables for this contract. This table on capabilities provided here is meant to be but a general indication or guide based on a first pass over the literature reviewed. All should be regarded as open to further discussion and modification.

The responses in each cell are given as "yes"(meaning the sensor or process is expected to deliver the information assuming the correct time of year); no (not expected to deliver); may (it may or may not deliver); or "?" meaning that there is not enough evidence to make a statement.

[1]It is expected that the classes at a minimum would be: water, submerged aquatic vegetation, cattails, grasses, upland shrub/herbaceous, forest, cropland, urban/built with MMU given. [2]Shoreline; [3]Open water; [4]Submerged aquatic vegetation. [5]MMU will be a function of the sensor's spatial and spectral resolution and bands; [6]Will depend whether Colour IR or true colour imagery is used. [7] RCM data will be free to the Govt of Canada – but others? Best if data is combined with optical [8]Best if combined with optical. Data may be free?

6. Some Recommendations on Promising Areas of Remote Sensing Wetlands Research

The rapid growth in the number and availability of remote sensing systems (both sensors and processing approaches) has created both opportunities and challenges for the wetlands community. Obviously the opportunities come from the range of new data types, the number of suppliers, and the potential to unlock new information in ways never thought possible just a few years ago. The challenges come from a dearth of experience with these new systems, the potential that some have been over-sold, and whether or not the new systems will be sustainable or available in the future.

With these challenges in mind a number of recommendations can be made:

Technical – Assessment of the Problem at Hand

1. The newer UAVs with the capability to obtain more accurate z values should be investigated to determine if they really will meet the needs for the application being investigated here;
2. WorldView imagery, Planet Labs Dove imagery and similar higher resolution satellite imagery should be evaluated for their potential to monitor changes in meadow marsh to determine what a workable MMU might be;
3. Research should be carried out to determine if there is some index or set of indices that could be derived from coarser resolution multi-date/multi-sensor data (such as Landsat or SPOT combined with SAR) that would indicate that change has occurred. Such a tool might be useful for large area monitoring;

4. Technical – Looking to Basin-Wide Assessments

4. Access to multi-date RCM and future L-band data should be ensured;
5. Research should continue focused on key wetland parameters in the Great Lakes with multi-date RCM C-Band data combined with higher resolution optical data;
6. Since object based image analysis (OBIA) approaches seem to yield better results than traditional classifiers and since they work using different data sets including non-remote sensing data, they should be further investigated with reference to the limitations identified by Dronova cited in Appendix C;
7. Learning classifiers such as random forest may lead to greater accuracies, especially with complex multi-sensor data types – but the question must be answered, how consistent are the results over a large area and has the approach followed recommended procedures for establishing importance values?;
8. Learning classifiers should be combined with known information on change to determine if a change assessment tool can be developed for wider application;
9. Data from the newer aquatic/terrestrial LiDAR systems combined with multi-spectral or hyperspectral data should be examined for information content on the land-water interface and wetland characterization;
10. There appear to be several groups with somewhat different wetland inventory schemes in use in the Great Lakes Basin. These were developed based on the needs and technologies available when they were conceived. It would be useful to evaluate the extent to which they reflect current needs and remote sensing technologies capabilities;

7. Outcomes of a Workshop

7.1. Introduction

The expert recommendations from this review were to be combined with inputs from a broader workshop of experts from both remote sensing and wetlands. The aim was to increase transparency in the process and ensure that a range of perspectives are captured in the final information and recommendations provided back to the GLAM Committee. The open and far ranging discussions did manage to help the remote sensing and wetland communities better understand the needs of one and the capabilities of the other. The workshop was held on March 26 to March 27, with a number of individual informal discussions taking place during the evening of March 26. This brief summary is meant to capture the essence of the workshop related to this report. It is not meant to be a summary of the workshop. Such a summary is being prepared by Ms. White.

7.2. Participants

There were 26 participants on the first day, of which 15 were in person and 11 on the Webinar. There were 22 participants on the second day – half of whom were in person.

The full list of participants is given in Appendix B.

7.3. Workshop Presentations

The formal presentations included an introduction to the activity and workshop, an overview of the GLAM activity, a summary of the report by Ryerson, and presentations on wetlands research and remote sensing work as described in the agenda. These were given by Dr. Bourgeau-Chavez, Greg Grabas and Tim Howard and Mike Shantz, and by Johanna Linnarz and Adam Hogg. A final presentation was given by Wayne Szameitat, TeledyneOptech on LiDAR technology. Throughout the workshop other participants brought up imagery and examples of their work either in wetlands or remote sensing of wetlands as informal presentations that provided additional richness to the discussions. The discussions were allowed to explore ideas and questions as they arose, leading to a thorough consideration of a range of opinions and experience related to the presentations given.

7.4. Workshop Comments and Relevant Discussion

In general those attending were of the opinion that the key technologies and approaches were covered in the draft report related to the information that served as the focus of this report. There were no disagreements with the general findings and recommendations. Ryerson suggested that the only sensor system that perhaps might have been added was thermal imaging, although the resolution of thermal data tends to be lower than the Minimum Mapping Unit that served as the target. The new UAV system being procured by ECCC will include a thermal system and a quick evaluation of that system may be useful.

Following (and in some cases during) the presentations there was a lengthy discussion that took place on topics as diverse as the Minimum Mapping Unit, frequency of coverage required, requirements for elevation data, as well as information on submerged aquatic vegetation and capabilities of various sensors. These discussions, which will be reported in a separate document, led to the framing of a number of operational considerations and research questions. These in turn led to the discussion of potential cross-border collaboration and assessments that would appear to be of value to the GLAM Committee specifically and the IJC in general.

Several findings came out of the workshop that would appear to modify the potential usefulness of various approaches suggested to derive the necessary information.

- As noted above, it appears that how to obtain elevation data of sufficient accuracy is a question that has not yet been completely answered;

- It was also clearly stated that elevation data (topographic and elevation) only need be obtained once or at least less frequently then vegetation data – this has a potentially significant impact on what methods might be used to assess vegetation;

- It was also clearly stated by some that submerged aquatic vegetation is not as important to accurately monitor as on-shore vegetation[9] – this too has a potentially significant impact on what methods might be used to assess vegetation and monitor change;

- The features of interest for the initial discussion and evaluation of results from different systems are the already-established 32 wetland test sites around Lake Ontario mentioned elsewhere in this report – it is too early to discuss a basin-wide monitoring program;

- The definition of a minimum mapping unit (MMU) will depend on what the data are used for. The suggested MMU of 2 x 2 meters without the need to determine elevation data at the same time brings data such as Worldview's higher resolution data into play;

- It is believed that the information on wetland types (i.e. vegetation type) would be required every five years unless there was an extreme event such as extremely low water levels or perhaps flooding, then the wetland site should be monitored for as many as four to five years thereafter;

- The best approach to do the interpretation (e.g. visual vs some form of machine-aided interpretation) is open to discussion – an evaluation of the relevant methods might be useful;

- There are many potential threats to wetlands in the Great Lakes that can be monitored or identified from remote sensing data ranging from changes in water level to invasive species, increased (or decreased) sediment loads, movement or lack of movement of sand, etc. The first priority is to establish what information can be reliably obtained from which sensor at what relative cost;

- Side discussions led by Dr. Howard began to address the idea of surrogates for the changes that are of interest to the GLAM Committee;

- The idea of a remote sensing advisory committee for GLAM was broached and briefly discussed; and

- Virtually all of the experts attending offered data, advice and/or expressed a willingness to collaborate in research, assessing data, and field work.

[9] It should be noted that those involved in fishery research were not present and they would likely have spoken to the value of submerged and aquatic vegetation.

Before the workshop was adjourned Ms. Leger framed a collaborative approach involving teams on both sides of the border to examine the usefulness of the UAV data for assessing and monitoring wetland classes, the accuracy of various tools for determining elevation information, and the usefulness of high resolution satellite data for monitoring. Finally she recommended that the LiDAR data being collected by the US Army Corps of Engineers and the CHS be evaluated for elevation data as well as for meeting other potential needs. Other factors that should be studied would appear to include assessing how different resolutions of UAV data might serve to reduce or better plan field work. Specific wetlands for joint work and/or sharing of results include those in the Bay of Quinte area and the sites used by Drs. Wilcox and Howard and Mr. Grabas. Following the meeting Dr. Wilcox submitted his suggestion of a way forward that appears to mesh with the suggestions of Ms. Leger.

The meeting ended with considerable enthusiasm for what the next steps might bring.

8. Lessons Learned

8.1 Introduction

This section details lessons learned with respect to doing this sort of review of wetlands remote sensing in general, as well as some of the lessons learned from a more technical point of view.

8.2. General

1. It is important to focus ones attention on what truly matters in a review such as this. There is an amazing amount of research published on wetlands remote sensing – over 5500 papers by one reviewer's account. Jumping into such a sea of information without a clear target would have been disastrous.
2. This review began with a series of discussions on what the data needs were that were to be addressed. Such a discussion may be time consuming, but it leads to a better understanding of the problem and, consequently, a much clearer assessment.
3. The number of excellent and yet practical researchers associated with wetlands remote sensing research who are working together in the Great Lakes Basin is a valuable cross-border resource that might be better exploited.
4. Taking advantage of recent technology developments, data sharing has become important in other areas and other applications.
5. Data repositories and collaboration can save money and broaden the use and usefulness of data.
6. The book edited by Tiner et al (2015) is a valuable and accessible resource, although there is scant material on high resolution satellite data and little mention of thermal data.

8.3. Technical

7. The use of higher resolution optical data to "sharpen" lower resolution data (even from other sensor types) can lead to deriving better information from remotely sensed data.
8. Multi-date Landsat and SPOT data can be used to map land use in areas surrounding wetlands.
9. A major consideration in determining what information remote sensing can and cannot provide about wetlands is the chosen minimum mapping unit and classification system used.
10. Research seems to indicate that better spectral resolution can lead to what seems to be better spatial resolution.

11. The user community should be aware that because of speckle, spatial resolution of SAR data does not equate to spatial resolution of optical data. Some suggest that the effective spatial resolution may be $^{1}/_{3}$ of the stated spatial resolution.
12. Radar data can generate elevation data that may be very useful in wetland studies and far more precise than those unfamiliar with the data may realize.

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Not all material consulted is referenced: material judged to have no relevance has been omitted.

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    b. Brisco, B. Mapping and Monitoring Surface Water and Wetlands with Synthetic Aperture Radar Chapter 6
    c. Clewley, D. et al Mapping the State and Dynamics of Boreal Wetlands Using Synthetic Aperture Radar Chapter 17

d. Difebo, A. et al Fusion of Mulispectral Imagery and LiDAR Digital Terrain Derivatives for Ecosystem Mapping and Morphological Characterization of a Northern Peatland Complex. Chapter 18
e. Johnson C. Mapping Invasive Wetland Plants Chapter 23
f. Knight, J.F. et al Theory and Applications of Object-Based Image Analysis and Emerging Methods in Wetland Mapping Chapter 9
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h. Madden, M. et al Unmanned Aerial Systems and Structure from Motion Revolutionize Wetlands Mapping Chapter 10.
i. Paine et al "Airborne LiDAR-Based Wetland Mapping on an Arctic Coastal Plain, North Slope, Alaska Chapter 19
j. Ramsey, E. and A. Rangoonwala Radar and Optical Imager Fusion and Mapping of Wetland Resources Chapter 8
k. Tiner, R.W. Classification of Wetland types for Mapping and Large Scale Inventories Chapter 2
l. Tiner, R.W. Introduction to Wetland Mapping and its Challenges Chapter 3
m. Tiner, R.W. Early Applications of Remote Sensing for Mapping Wetlands Chapter 4

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Appendix A: Wetland Mapping Websites

Canadian Wetland Inventory – Ducks Unlimited Canada
http://www.ducks.ca/initiatives/canadian-wetland-inventory/

Ducks Unlimited – Great Lakes Region
https://www.ducks.org/media/Conservation/GLARO/_documents/_library/_gis/NWI_Workplan.pdf

Minnesota National Wetland Inventory Program

https://www.dnr.state.mn.us/eco/wetlands/nwi_proj.html

MTRI Great Lakes Coastal Wetland Mapping

http://www.mtri.org/coastal_wetland_mapping.html

Ontario Ministry of Natural Resources and Forestry

https://www.ontario.ca/page/make-natural-heritage-area-map

Appendix B: Individuals Contacted and Workshop Participants

B.1. Individuals Contacted

Acronyms Used in Appendix B	
ECCC	Environment and Climate Change Canada
DFO	Fisheries and Oceans Canada
GLAM	Great Lakes - St. Lawrence River Adaptive Management Committee
IJC	International Joint Commission
MDDECC	Ministère du Développement durable de l'Environnement et de la Lutte contre les changement climatiques / Ministry of Sustainable Development, Environment and the Fight against Climate Change
NYDEC	New York Department of Environmental Conservation
OMNRF	Ontario Ministry of Natural Resources and Forestry
S&T	Science and Technology (ECCC Branch)
SUNY - ESF	State University of New York - College of Environmental Science and Forestry
USACE	United States Army Corps of Engineers
USEPA	United States Environmental Protection Agency
USFWS	United States Fish and Wildlife Service

Several individuals participated in various conference calls, provided papers and other materials and had input:

Dr. Laura Bourgeau-Chavez, Michigan Tech University, MTRI
Dr. Brian Brisco, CCMEO, Government of Canada
Jim Greene, TeledyneOptech
Mike Hall, Automated Engineering Technologies Ltd., Guelph
Adam Hogg, OMNRF, Government of Ontario
Dr. Tim Howard, SUNY-ESF NY Natural Heritage Program
Mr. Brian Huberty, U.S. Fish &Wildlife Service, US Government
Dr. Brigitte LeBlon, UNB
Johanna, Linnarz, OMNRF, Government of Ontario
Dr. Koreen Millard, DRDC, Government of Canada
Molly Reif, US Army Engineer Research and Development Center Environmental Laboratory
Dr. Bahram Salehi, Memorial University/C-CORE
Mike Shantz, ECCC, Government of Canada
Jonathan Staples, OMNRF, Government of Ontario
Lori White, Scientific Authority, ECCC, Government of Canada
Dr. Doug Wilcox, SUNY Brockport

B.2. Workshop Participants

The following table summarizes the participants both in person and on the Webinar. The second table identifies the affiliations of the participants. Material provided by Mike Shantz.

Final Summary		
	26th	**27th**
In Person (IP)	15	11
Webinar (Web)	11	11
No	2	6

	FINAL WETLAND EXPERTS WORKSHOP PARTICIPANT LIST			
		Mar. 26-27, 2018 - Burlington, ON		
Invited Experts and Associates			**Participation**	
	Name	**Organization**	**26**	**27**
1	Dr. Robert Ryerson	Contractor	IP	IP
2	Lori White	ECCC - Ottawa (S&T)	IP	IP
3	Jason Duffe	ECCC - Ottawa (S&T)	IP	IP
4	Sarah Banks	ECCC - Ottawa (S&T)	Web	Web
5	Amir Behnamian	ECCC - Ottawa (S&T)	Web	Web
6	Adam Hogg	OMNRF	Web	NO
7	Johanna Linnarz	OMNRF	Web	NO
8	Brian Huberty	USFWS	Web	Web
9	Laura Bourgeau-Chavez	Michigan Tech Research Institute	IP	IP
10	Michael Battaglia	Michigan Tech Research Institute	IP	IP
11	Jennifer Dunn	NYDEC	NO	Web
12	Marianne Bachand	ECCC - Quebec City / GLAM Assoc.	NO	Web
13	Mathieu Roy	ECCC - Quebec City	Web	Web
14	Daniel RokitnickiWojcik	ECCC - Downsview	IP	NO
15	Fred Luckey	US EPA / GLAM	Web	Web
16	Greg Mayne	ECCC - Downsview	IP	NO
17	Wayne Szameitat	Optech	IP	NO
GLAM Project Team, Committee members, and associates				
18	Daniel Ferreira	ECCC-Burlington / GLAM support	IP	IP
19	Greg Grabas	ECCC - Downsview	IP	Web
20	Dr. Tim Howard	SUNY-ESF NY Natural Heritage Program	IP	IP
21	Mike Shantz	ECCC- Burlington / GLAM	IP	IP
22	Bill Werick	GLAM	Web	NO
23	Dr. Doug Wilcox	SUNY - Brockport	Web	Web
24	Wendy Leger	ECCC- Burlington / GLAM	IP	IP
25	Bryce Carmichael	USACE - Cincinnati / GLAM support	Web	Web
26	Jade Zavarella	ECCC - Burlington/Student	IP	IP
27	David Fay	IJC - Ottawa / IJC Advisor	IP	IP
28	Arun Heer	USACE - Cincinnati / GLAM	Web	Web

Appendix C: Literature and Technology Review

C.1. Introduction

The literature review began with some ten to fifteen papers suggested by the contract authority and her colleagues. As papers were read and more experts were consulted the list of papers expanded dramatically, even with the limited topic eventually arrived at. Over 50 pages of summary notes were made from over 100 papers and relevant book chapters. Of these some 25 publications were themselves reviews which in turn referenced well over 1000 additional papers. A number of the reviews, as well as guidance provided in some of the as yet unpublished papers provided, were useful in limiting the effort directed to "dead ends" for the project at hand.

As a result of timing a more general literature review began before the final requirements were identified. This has led to an additional deliverable – a commentary on other potential applications and opportunities drawn from notes on promising research, the potential to share data, etc. What are believed to be the more useful conclusions from our review on various sensors, approaches to interpretation, and projects are noted here and summarized in the main report in Section 5.

Several points have been made by others when reviewing the use of remote sensing of wetlands. Lang and McCarty (2008) have noted that different authors have come up with far different minimum mapping units for the same data. The Federal Geographic Data Committee (1992) quoted by Lang and McCarty stated that "as a general rule, it takes an area three by three pixels wide to identify an object on the ground. The more similar a cover type is to adjacent cover types, the larger the area that will be needed." While written over a quarter of a century ago, this rule of thumb is still useful for optical data.

C.2. Leading to the Recommended Remote Sensing Tools

C.2.1. Introduction: Sensors and Platforms and Processing Approaches

The basic requirements that combined the identification of both marsh meadow and changes in the extent of marsh meadow and several other wetland types as well as a minimum mapping unit of either 4 square meters or 16 square meters, quickly eliminated most of the remote sensing tools examined. And the elimination usually occurred even without the 90% accuracy requirement.

The remote sensing tools examined include both sensors and processing approaches.

The sensors include the following:

- Synthetic Aperture Radar (SAR) (which comes with its own specialized processing tools – discussed here with the sensor);
- Optical satellite data of three types (low-medium resolution imagery at 10-30 meters; medium to high resolution imagery at 3-5 meters; and high resolution imagery at better than 1 meter);
- Airborne LiDAR;
- Airborne hyperspectral (space borne hyperspectral data are not routinely available);
- Aerial photography (by airplane); and
- Aerial photography (by UAV or drone).

The processing approaches include:

- Visual interpretation;
- Supervised and un-supervised image analysis;
- Object-based analysis;
- Learning analysis multi-sensor systems; and

- Specialized radar processing tools.

These sensors, platforms, and processing approaches are discussed here in terms of why they can or cannot meet the requirements laid out as the main deliverable, as well as what they might contribute in a more general sense to wetland studies in the Great Lakes Basin.

C.2.2. Sensors and Platforms

C.2.2.1. Introduction

The fact that each sensor and platform is discussed here separately mirrors one of the problems in the field. All too often researchers (and reviewers) tend to focus on one or another of the sensors available or one or other of the platforms available. In fact, recent research, including some reviewed here, has found that combinations of two or more data types and approaches may lead to a better solution. Indeed, this multi-sensor approach is mirrored in some recent commercial offerings of direct relevance to this study. Teledyne Optech, for example, has combined the value of their LiDAR sensor with a CASI hyperspectral sensor.

C.2.2.2. Synthetic Aperture Radar

We begin by assessing synthetic aperture radar (SAR), an active sensor that sends out a pulse of microwave energy and records the return. SAR systems, SAR data processing and interpretation are complex: to effectively set up a SAR monitoring system one must understand the physics of the entire process and how the SAR signal interacts with the features being studied.[11] SAR is one of the sensors often mentioned and recommended for wetlands mapping (White et al, 2015). SAR data have been examined for wetland and related mapping for some time. Long before SAR data from satellite were routinely available, airborne SAR was being studied for wetlands and related work in Asia, Africa and Canada in the early-mid 1990s (Campbell et al, 1995). In the first major manual on imaging radar applications, work on wetlands was well represented (Henderson and Lewis, 1998).

Research with airborne data in preparatory studies for more advanced satellite SAR systems continued through into the early 2000s. One example was the evaluation of the "use of single polarization, dual polarization, multipolarization, and polarimetric combinations … for wetland classification as input to decision making and methodology development in the Canadian Wetlands Inventory." (Brisco et al, 2011) Brisco et al (2011) also found that C-band airborne SAR data were better for herbaceous wetland identification.

Radar comes in several wavelengths with significant differences between them for wetlands applications.[12] These differences are discussed in the following paragraphs.

The book edited (and partly written) by Tiner et al (2015) provides an excellent review of wetlands remote sensing with over 500 pages of well written and informative material and an estimated 1400 references cited. A much shorter but still useful review of wetlands remote sensing was provided more recently by Mahdianpari et al (2017b). They provide a good summary of both optical and SAR work (including 200 references) and the value of polarized SAR data in particular. They note that radar data are useful in that SAR can penetrate cloud cover – a distinct advantage over optical data, all other factors being equal. However, they also point out that SAR data often requires more time-consuming pre-processing of the data and this requires more advanced understanding of SAR processing and the physics

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[11] A variety of on-line tutorials and educational materials are available for the neophyte. One relatively simple tutorial is given at https://www.asf.alaska.edu/asf-tutorials/tutorial-overview/

[12] The three most common SAR bands used in remote sensing are X-band at 3.75-7.5 cm; C-band at 7.5-15 cm; and L-band with a wavelength of 15-30 cm.

of the interactions between the sensor and the feature of interest. In wetlands these relationships are complex, as has been noted by other authors whose work involved SAR data and wetlands, including Brisco et al (2011), Dubeau et al (2012), White et al (2015), Amani et al (2017a), and White et al (2017).

To reduce the inherent complexities in SAR different authors have developed different approaches. For example Brisco (in Tiner et al, 2015, p. 123) uses a simple but effective diagram to explain the six types of backscattering necessary to understand SAR data. Bourgeau-Chavez has also used a graphic to explain the differences in scattering of L-band and C-band in flooded and non-flooded forest and grassland. Another approach to simplifying SAR was reported by Ball (2002). That work showed how a simple user-oriented product could be created from SAR data for monitoring by non-specialists monitoring for the Ramsar Convention. Brisco et al (2017) used a similar approach to develop a unique colour image product and interpretation key to enable wetland managers to use the product without knowledge of the intricacies of SAR and interferometry. Such easily understandable graphics should be used when attempting to explain and introduce SAR data to the wetlands user community. While user products are to be encouraged, they should be developed with the user's input and understanding if they are to be trusted by the decision makers relying on them.

Addressing one of the areas important here, water level, research by Brisco et al (2015) has "clearly shown that water level changes on the order of 4 cm (or possibly better) can be monitored in wetlands with suitable coherence which generally includes both marsh and swamp wetland classes." With the launch of several SAR constellations in the next few years allowing for higher exact revisit times, coherence should be able to be maintained throughout the growing season in marshes and swamps, allowing for more accurate monitoring of water levels. While Brisco et al (2015) did have promising results, the current InSAR research by White and her colleagues looking at coherence at Long Point and Bay of Quinte show results that are not as good. Coherence was only maintained at certain periods throughout the year. L-band imagery was much better. But if one could obtain consistent RCM data with a much higher exact revisit times than Radarsat-2, one might be able to get much more consistent coherence and measure the water level changes more accurately. The key with C-band appears to be a more frequent revisit time…but more research is needed to verify this (White, personal communication, March 11, 2018). L-band is preferred over C-band for InSAR applications because the longer wavelength allows for greater penetration of the vegetation canopy. The use of SAR data over a season may offer a solution to monitoring seasonal flooding of wetlands and the response of general wetland classes to controlled water levels in the Great Lakes.

One issue in acquiring multi-date imagery for the Great Lakes is accessibility to SAR data. More specifically, our understanding is that it is sometimes difficult to get RADARSAT data for specific dates in the summer months because of prior commitments to acquire data in the north for ice monitoring, pollution monitoring (the ISTOP program), national security and crop monitoring. With the launch of the upcoming follow on mission to RADARSAT-2, the Radarsat Constellation Mission (RCM), there is the possibility of acquiring more frequent SAR data for wetland monitoring. With the potential for more frequent and more timely data, the potential for C-Band SAR for wetland mapping improves. It is suggested that this need for data should be explored with the appropriate agencies responsible for access to RCM data.

In addition to the complexities of SAR data there are other limiting factors in its application to meadow marsh monitoring. Mahdianpari et al (2017b) explain that because of the inherent "speckle" in SAR data one needs larger areas for training for the analysis, a factor that further reduces the resolution and the effective minimum mapping unit that is possible with SAR data.

Most of the SAR data referred to here has been C-band, which has shown to be useful for mapping surface water and deciduous swamps during leaf-off season (White et al, 2014; Behnamian et al, 2017). Flooded vegetation has been mapped by White et al (2014) while deciduous swamps have been mapped by Gosselin et al (2014). Mahdianpari et al (2017b) note the importance of longer wavelengths such as L-band for penetration of the vegetation canopy compared to both C-band and X-band data. Others have come to the same conclusion about the potential for L-band, including Corcoran et al (2012).

Longer wavelength L-band radar data such as that provided by the Japanese ALOS PALSAR (JAXA, 1997), have the ability to penetrate the vegetation canopy better than X or C-band data. Bourgeau-Chavez et al (2015) used ALOS PALSAR data for “mapping wetland ecosystem types, such as emergent wetland and forested wetland, as well as to delineate wetland monocultures (Typha, Phragmites, Schoenoplectus) and differentiate peatlands (fens and bogs) from other wetland types. The overall accuracy for the coastal Great Lakes map of all five lake basins was 94%, with a range of 86% to 96% by individual lake basin (Huron, Ontario, Michigan, Erie and Superior). Accuracies ranged from 86 to 96% across the Great Lakes.” These accuracies appear to be much better than those obtained with C-band or X-band SAR. Of particular interest is the fact that multi-date PALSAR was found to be useful for mapping invasive Phragmites australis, which is taller than native species L-HH (Bourgeau-Chavez et al ,2009). Similar high accuracies were noted in the use of multi-date PALSAR and Landsat data by Dubeau et al (2012) in Ethiopia. In the latter case topographic data were found to be useful in improving the results – a factor noted in the requirement here to include topographic information. It has been noted that while the PALSAR data yields excellent results these results may be improved through the use of a learning classification system such as Random Forest (Dubeau et al, 2012; LaRoque et al, 2014). These tools are further discussed under processing approaches.

There are three issues with L-band PALSAR data: the system is not a continuing program; the data are expensive ($2100 for one scene), and at a nominal 10 meters resolution products derived from interpretation of these data will not meet the stated minimum mapping unit for this assessment. On the first issue there are early indications (Motohka, et al, 2017) that Japan plans to launch a follow-on L-band system in Fiscal Year 2020. On the second issue the data costs may be reduced by 40% for a volume order.[13] When considering the high accuracies given by Bourgeau-Chavez et al (2015), it should be noted that the minimum mapping unit in their work was 0.2 hectares – or as much as 125 to 500 times larger than the area of the MMU being investigated here. Nevertheless, L-band SAR imagery is an excellent tool for broader spatial scale and broader wetland class mapping.

To date research in the use of SAR provides two somewhat different answers to the question at hand – is SAR data alone useful for monitoring changes in meadow marsh?:

- Research in the application of C-band SAR of the sort that will be provided by the Radarsat Constellation Mission suggests that there may be some applications associated with some elements of wetland monitoring including delimiting water boundaries. However, at this stage, C-band and X-band SAR would appear to be of limited use for the issue at hand, monitoring changes in meadow marsh extent.

- L-band SAR appears to have some potential to monitor meadow marsh, albeit with a maximum resolution of 7-10 m (depending on polarisation and looks) (JAXA, 1997), not at the resolution or minimum mapping unit required for the application being investigated here. With its already demonstrated value in wetland monitoring (Bourgeau-Chavez, 2015) it is therefore suggested that the IJC or other stakeholders encourage the Governments involved to seek access to data from the system when it does come on line in 2020 and that the tools be considered as part of a package to monitor the basin wetlands as a whole. In addition two other L-band SAR satellites with similar nominal resolutions to PALSAR are planned to be launched in the near future, SAOCOM (2018) and NISAR (2021). It is expected that the data from these satellites will be freely available, therefore should be considered for a basin-wide wetland monitoring system.

[13] Personal communication: Laura Bourgeau-Chavez, February 26, 2018

While C-band and X-band SAR on their own may have no direct use for the application being investigated here, C- and X-band SAR data are often seen as complimentary to optical data for shoreline mapping, among other wetland applications (Banks et al 2017). In the research by Banks et al, SAR data were required for "accurate discrimination of substrate types, while optical data were required for accurate discrimination of some vegetated and non-vegetated classes." The work by Bourgeau-Chavez et al (2015) also saw a complementary role for L-band SAR and Landsat data to provide a repeatable process, albeit at 20-30 meter resolution.

The complementary role for C-band SAR is one that should be further researched, while it would appear that the potential for L-band used in conjunction with other remote sensing data may lead to more immediate results, assuming that the L-band data are available in the future.

C.2.2.3. Optical Satellite Data

C.2.2.3.1. Introduction

Typically optical satellite imagery includes data from those sensors that image in a panchromatic band (simply explained as blue, green and red displayed together in grey tones), and/or the blue, green, red, near-infrared and occasionally the short-wave infrared bands such as those in Landsat 8 (NASA 2013). These in turn are usually classified by the size of the pixel for which reflectance values are recorded. Here we arbitrarily consider low to medium resolution imagery at 10-30 meters; medium resolution imagery at 3-9 meters; and high resolution imagery at better than 2 meters. The rational for the resolution groupings used here is the specific MMU being investigated – i.e. 2 x 2 m and 4 x 4 m.

In conducting this review of optical satellite data several observations can be made at the outset. First, there appears to have been far more research published on the use of Landsat than on finer resolution SPOT data or even finer Worldview data for wetland assessments. Several reasons may be the cause of this apparent discrepancy. While one would think that there would be more attention paid to the higher resolution data for assessing complex wetland environments, it may be that the higher cost of SPOT and Worldview-like data and the ease of access to Landsat data have led to researchers attempting to extract the maximum out of the more available (and less expensive) Landsat data. On the other hand there may be less scientific work with SPOT data simply because it is already being used in operational wetland mapping programs and researchers rarely publish about the science behind operational work. Another point germane to this study is that previous research has demonstrated that higher spectral resolution can lead to an apparently higher spatial resolution (Harvey and Hill, 2001). Lastly, for data to be truly comparable from one date to another the sensors should be calibrated and consistent in how reflectance values are recorded by the sensor (Klemas, 2011).

Some of those offering high resolution sensors note in the material about their systems that the data are not calibrated.[14] One must therefore be mindful of this fact when designing monitoring approaches with such imagery. Lastly there are often questions about the geometry of satellite imagery. The precision with which one can tie an image to the ground to assess changes from one year to the next, for example, is an important and often overlooked characteristic of imagery. Geometry becomes even more important in mapping changes in wetland communities since they tend to have few points that can be used for ground control to allow precise registration of imagery.

C.2.2.3.2. Low-Medium Resolution Data: 10-30 Meters

It is assumed that 10-30 meter data – such as Landsat TM will not be useful if used alone for monitoring change of the type required here – the six classes with a MMU of 4 m^2 to 16 m^2. At best it is believed that such imagery would only be useful for monitoring gross trends or if used in concert with other data.

[14] See for example the information on Planet's Skysat imagery – there is no radiometric correction. https://www.planet.com/products/hi-res-monitoring/

A number of authors have reached the conclusion that Landsat data are often best combined with SAR data for monitoring wetlands. However, even in the best cases the research reviewed did not lead to accuracies at the detail required for this assessment. With that stated, there have been studies that demonstrate the usefulness of combining Landsat or other relatively coarse data with SAR or in pan-sharpened[15] mode to carry out monitoring. This is much as Amani et al (2017a) did using pan-sharpened Landsat 8 data for segmentation along with SAR data, or where complementary Landsat 5 was used with RADARSAT-2 data for monitoring in remote areas such as the Arctic where less detail is required (Banks et al (2017).

Multi-date Landsat data have been used with some effect by Bourgeau-Chavez (2015) who mapped details within wetlands as well as surrounding land uses. When comparing PALSAR and Landsat they concluded that “Landsat TM bands are most useful for distinguishing upland cover types.” Gallant et al (2014) also used Landsat data with SAR data to help “remove confusion of wetland features with upland grasslands. These results suggest SAR data can provide useful monitoring information on the statuses of wetlands over time.” They found that they could “extract features of wetland vegetation stands as small as 30 m in width with consistency across years.” Grenier et al (2014) used Landsat-7 and Radarsat-1 data to map five wetland classes (Bog, fen, swamp, marsh and shallow water) with a MMU of 1 hectare – a far greater MMU than we are concerned with here – and five times that of Bourgeau-Chavez et al (2015).

Several authors have summarized the problems with using Landsat TM data for wetlands monitoring. Gallant et al (2014) noted that wetlands have proven “challenging to map remotely with high accuracy and consistency because the presence of water is highly dynamic and overstory vegetation can obscure wetlands viewed from above. Furthermore, the spatial extent of many wetlands is smaller than the resolvable capacity of most civilian satellite sensors, resulting in pixels where wetland components are eclipsed by upland components.” Amani et al (2017a) noted that when considering optical data, even when used with radar: “wetland classification is a challenging issue in remote sensing because different wetland types are spectrally and texturally similar. Klemas (2011) concludes that Landsat TM was acceptable to monitor changes in large watersheds, but “freshwater wetlands are small, patchy, and spectrally impure. Medium-resolution sensors, such as Landsat TM, miss some of these patchy wetlands and produce too many mixed pixels, increasing errors. Therefore, to map upstream, freshwater wetlands, managers needs high spatial resolution and, in some cases, hyperspectral imagery.” For the application here, lower resolution data is not useful.

There is one potential application for low to medium resolution satellite data. Providing background to the idea is the approach by Dubeau et al (2012) who used wet and dry season Landsat data and derived vegetation and wetness indices. In all 19 vegetation, soil, and water indices were derived from the Landsat 5 TM surface reflectance data. With these indices and other data they mapped eight wetland types and three terrestrial/upland classes. It may well be that somewhat more general data may, when used either singly or with another data set, be converted to a specific index or set of indices that would indicate the presence of the type of change seen as important.

C.2.2.3.3. Medium Resolution Data: 3-9 Meters

The data that fall into the category of medium resolution are exemplified by much of the SPOT satellite data (Satellite Imaging Corporation, 2017a[16]) and Rapideye, both with resolution on the order of 5 meters. Both data sets have been used extensively in the study of wetlands – primarily for mapping. In their review Ozesmi and Bauer (2002) list SPOT data along with Landsat as one of the most-used systems in wetlands mapping.

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[15] Pan-sharpened data use a higher resolution panchromatic band to add better spatial detail to a coarser image data set – usually a normal colour or colour infrared rendition.

[16] We use Satellite Imaging Corporation’s web site as a source of characteristics for many of the optical satellites. This allows them to be compared in the same format. https://www.satimagingcorp.com/

With higher spatial resolution compared to Landsat it is not surprising that SPOT data have been used in operational wetland mapping by Ducks Unlimited, for example[17] as well as others (Alberta Environment and Parks, 2017.) A broad range of wetland classes have been derived from SPOT data – both from one image date during the height of the growing season or by using multiple dates. However, even with its broad use in wetland mapping, given the spatial resolution of this type of data their application to the requirement being assessed is regarded as limited.

The higher resolution data in this group, such as imagery from Planet's Dove constellation (Satellite Imaging Corporation, 2017b), may warrant an evaluation for monitoring the changes that are of interest to this study. While the data have apparently been used for agricultural crop assessments, it is not clear if they have been used for wetlands assessments. Unfortunately the sample imagery of Key West and Peru[18] does not appear to be at full resolution and cannot, therefore, be assessed in even a general way as to its potential with the resources available for this project.

In the previous section it was noted that one might be able to use the lower resolution data to develop some form of surrogate for the changes that are of interest. There is a likely a greater opportunity to use data such as provided by SPOT rather than Landsat to develop useful indices that would indicate the presence of the type of change seen as important. It is not clear that the Planet sensors have the necessary calibration to be used in a rigorous quantitative fashion.

C.2.2.3.4. High Resolution Data: < 3 Meters

Imagery in this class ranges from 2.5 meter multispectral ALOS to 0.82 meter IKONOS imagery down to WorldView-4 at 0.31 meters. Like the better resolution data discussed in the previous subsection, a review of the literature application in wetlands shows but a few relevant examples of the data's use. Work on IKONOS data has been cited in Knight et al (2015, in Tiner et al, p. 179). The IKONOS data was used with Object Based Image Analysis but results reported (76% accuracy) would suggest that the data may not be useful for the application being assessed here. IKONOS data has also been used in an assessment reported in Difebo et al (in Tiner et al, 2015). They used 0.82 panchromatic and four 3.2 m multispectral bands (blue, green, red near IR) IKONOS data to map seven wetland classes. These were: mat around pools, bog-lichen, bog-lichen/conifer, bog-dense conifer, fen-dense conifer, fen-riparian fen/sedges, and fen-poor fen. While the point of the exercise was to assess the contribution of LiDAR data-derived terrain derivatives on improving the result, the result with just the IKONOS had an overall accuracy of 71.8%, and only marginally better with the terrain information. Given the low accuracy and larger MMU, these results also call into question the use of IKONOS data. The sample ALOS optical imagery[19] available to this author is inconclusive as to whether or not the data may be useful for the purposes here. There may be some potential application to monitoring wetland changes, but not likely at the MMU required here.

One of the issues found with using high-resolution imagery is that it is "more sensitive to within-class spectral variance, making separation of spectrally mixed land cover types more difficult than when using medium-resolution imagery (Klemas, 2011).

The WorldView data (or similar data 0.5 m resolution or better) would appear to be worth assessing at least as an indicator of change, although the use in this case may not be cost effective.

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[17] Also see the Ducks Unlimited web site at http://www.ducks.org/conservation/geographic-information-systems

[18] The sample imagery was accessed February 26, 2018 at http://content.satimagingcorp.com.s3.amazonaws.com/static/galleryimages/satellite-image-illegal-mining-peru.jpg and http://content.satimagingcorp.com.s3.amazonaws.com/static/galleryimages/satellite-image-key-west.jpg

[19] See image of a wetland area in Brazil accessed February 26, 2018 at https://www.satimagingcorp.com/gallery/more-imagery/alos/alos-tatui/

C.2.2.4. Airborne LiDAR

Airborne **<u>Li</u>**ght **<u>D</u>**etection **<u>a</u>**nd **<u>R</u>**anging data are products of active sensors that produce an output much more complex to process (and understand) than the optical satellite data in the previous section. Like SAR, LiDARs rely on sending a pulse (of light instead of microwave) and measuring the return. However, since the pulses sent are in the green band (for bathymetric applications), near-infrared band (for topographic applications) or blue-green for coastal areas in the newer sensors, LiDARS cannot penetrate cloud. They can be used at night. Furthermore there are many complexities that are introduced by the type of vegetation, the presence of water, the pulse frequency and other factors. These factors must be understood and kept in mind when using or planning to use LiDAR data, as has been well described in the literature (Hopkinson et al, 2005; Hopkinson et al, 2006; Hogg and Holland, 2008; Lang et al, 2015; Madden et al, 2015; Natural Resources Canada, 2017). As with SAR, there are scientists who tend to specialize in the processing and understanding of LiDAR data.[20]

One of the factors of interest in this assessment is elevation. LiDAR has long been seen as a tool that can yield much more accurate elevation data than available Digital Elevation Models (DEMs) provided by governments. Information available from suppliers suggests that elevation measurements acquired by LiDAR can now be mapped with optimum accuracies on the order of 3-10 cm assuming certain parameters for the flight, type of vegetation, presence of water and processing (See TeledyneOptech 2015 and 2017). The rapid advances in LiDAR technology can be seen in the elevation accuracy of up to 3 cm vertical cited in 2015-2017 compared to accuracies cited of 10-15 cm in a 2011 literature review (Klemas, 2011a).

Research has demonstrated that elevation information provided by LiDAR, when combined with other information such as aerial photographic interpretation, has led to improved mapping of wetlands (Hogg and Holland, 2008). Bare earth LiDAR-derived DEMs were proven to be useful in better understanding variations in treed and non-treed wetlands including, one might infer, meadow marsh environments. Accuracy was improved by 8% over aerial photography alone. At the same time, use of LiDAR data alone proved to be insufficient at that time to meet the accuracy requirements for the assessment here (Hogg and Holland, 2008). Improvements associated with the use of LiDAR in mapping in a low canopy environment on the Belgian coast were also demonstrated by Kempeneers, et al (2009). Accuracy in the fourteen class map went from 55% to 71% with the fusion. These accuracies do not meet the standards set for this assessment. Other uses for LiDAR that have been cited include mapping invasive species such as *Phragmites australis* from low marsh plants (Klemas, 2011).

While the early LiDAR systems were limited in their ability to contribute to wetland mapping except in a complementary fashion, more recent LiDAR system developments have seen multispectral[21] LiDARs such as TeledyneOptech's Titan system which can provide data from shallow-water on to the land, providing an integrated coastal mapping system (TeledyneOptech 2017). Morsy (2017) has developed an automated approach to use such data to accurately identify the shoreline, something that was not easily done with previous LiDAR systems. He has also provided an excellent review of the LiDAR literature on shoreline discrimination and the problems inherent in the use of this technology. Other relatively recent

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[20] For those with a limited understanding of LiDAR and who may wish to learn more about the technology there is a simple introductory on-line tutorial on LiDAR produced by the US National Oceanographic and Atmosphere Administration. See https://coast.noaa.gov/digitalcoast/training/intro-lidar.html. The tutorial is said to take 80 minutes to complete and is focused on mapping in coastal areas.

[21] The reader should note that Multispectral refers to the use of three different areas of the spectrum for the laser beam used, not the creation of a multispectral image such as is made with data from an optical satellite or airborne imaging system such as Landsat.

advances have seen LiDARs combined with hyperspectral scanners and aerial cameras in one integrated data collection system.[22]

In 2018 we have been told that the "US Army Engineer Research and Development Center Environmental Laboratory Joint Airborne Lidar Bathymetry Technical Center of Expertise will be collecting coastal lidar and hyperspectral imagery along Lakes Erie and Ontario this FY (exact timing is unknown) along the standard National Coastal Mapping Program footprint (~500 meters onshore and about ~1km offshore or until laser extinction due to water clarity). There is a possibility (should additional funds become available) that priority (GLAM) embayment areas may also be surveyed along Lake Ontario. … The airborne hyperspectral imagery has 1 meter spatial resolution with 48 spectral bands. The lidar data has point clouds which range between 0.7 to 2 meter spot spacing and digital elevation bare earth and first return grids with 1 and 5 meter spatial resolution." (Personal Communication: Molly Rief to Lori White, March 9, 2018)

The integration of LiDAR with hyperspectral or an aerial camera in one package leads to a whole new potential approach to both wetland mapping and understanding. This has been noted in Richardson and Millard (accepted, in press) who provide a useful "summary table of typical airborne LiDAR data types and derivatives used for wetland-related applications." This table describes the data format or derivative and a description of the wetland-related application and they cite a reference for the material. They also note that more complex analysis of the LiDAR returns may yield further information. However, LiDARs fully integrated with hyperspectral or aerial cameras systems are said to cost more (Rapinel et al, 2015). In 2015 Madden et al noted that LiDARs would be used on UAV platforms. The use of small robust LiDARs has been given a push by the need for lased-based systems for guidance in autonomous vehicles. Today there are said to be 12 LiDAR sensors made for use on UAVs (Corrigan, 2018). Most of the systems are so new that the accuracies stated do not appear to have been verified for the sort of application being assessed here.

One of the conclusions of Richardson and Millard (Accepted, in press) is that "there are still many limiting factors and uncertainties related to LiDAR system settings and methods used to measure vegetation parameters (Hopkinson et al. 2005), and this information is not often published in studies and sometimes not provided by the data provider. In addition to limited penetration into dense vegetation, wetland environments present a unique challenge in the measurement of vegetation parameters with LiDAR: the wetness of the environment may influence the sensor's ability to measure pulses."

So while LiDAR has had an obvious and well-researched potential role to play in wetland monitoring by introducing more precise elevation information, the future is somewhat less clear given the projected use of UAV-based LiDARs for elevation and one-stop integrated laser/camera or laser/hyperspectral systems. It is worth noting that Ms. Reif, cited above, expressed the opinion that while the accuracy cannot be guaranteed, this data set should meet the requirements laid out here, independently and after the fact confirming the evaluation made here.

C.2.2.5. Airborne Hyperspectral

Hyperspectral imaging, sometimes referred to as imaging spectroscopy, generates very fine ($\approx$ 10 nm spectral range) data for up to several hundred spectral bands. The interest in hyperspectral data comes from the detailed spectral information one can obtain that may help identify subtle differences that may exist between the different vegetation types found in complex wetland environments.
While aircraft are the primary platforms to obtain hyperspectral information, there has been a satellite system with long term plans to have another. The US Hyperion satellite hyperspectral system, which was shut down in 2017 after 17 years of operation, had 220 unique spectral channels with 30 m spatial

[22] See for example the options offered by TeledyneOptech at http://www.teledyneoptech.com/index.php/products/airborne-survey/lidar-systems/

resolution and a 7.5 km swath. Hyperion data have been reported by several authors cited by Guo et al (2017) to achieve good results consistent with the spatial resolution of the system – which is significantly less detailed than what is called for here. Mapping results with Hyperion were better for wetland mapping than the results obtained with Quickbird. This may be yet another indication that better spectral data makes up for poorer spatial resolution.

Several hyperspectral airborne sensors are available. Itres Research Limited of Canada has been producing their *casi* systems for over thirty years.[23] The *casi* system has been selected by TeledyneOptech for integration into their LiDAR system. A considerable amount of work has been done on coastal wetlands with these systems including much of the UK coast, large areas of British Columbia, some in the Great Lakes and elsewhere. Other hyperspectral systems include the US AVIRIS research system, the Australian Hymap System and Finland's AISA.

Klemas (2013) noted that "using a fusion of LIDAR, hyperspectral, and radar data with narrow-band vegetation indices, researchers have been able not only to discriminate some wetland species but also to make progress on estimating biochemical and biophysical parameters of wetland vegetation, such as water content, biomass, and leaf area index." Airborne LIDARs have also been applied with hyperspectral imagers to map wetlands, beaches, coral reefs, and submerged aquatic vegetation. Guo et al (2017) cite several authors who successfully mapped invasive species of different types and changes in vegetation with accuracies that ranged from poor to 90%. Another interesting application is the use of hyperspectral data to map nutrients in the water and attributes of the vegetation. Kalacska et al (2015) of McGill used *casi* data to examine foliar chlorophyll and nitrogen content in 19 species in Mer Bleu near Ottawa.

Research to date and studying the hyperspectral imagery available seems to suggest that with fine enough spatial resolution airborne hyperspectral data would be able to monitor the changes of interest here. One interesting observation made by Klemas (2011) was that "aerial hyperspectral image analysis is too complicated for typical National Estuarine Research Reserve System (NERRS) site personnel and the imagery is too expensive for large NERRS sites or entire watersheds." It is not clear what elevation information could be obtained with hyperspectral sensors.

C.2.2.6. Aerial Photography (By Airplane)

Relatively low altitude orthorectified colour infrared (CIR) aerial photography with a resolution of 0.3 m has been widely used to characterize the wetland classes of interest in this assessment (with the exception of submerged aquatic vegetation, of course) and recent changes in them (Wilcox and Bateman, undated; Howard et al, 2016). It should be noted, however, that colour infrared imagery cannot penetrate water, meaning that sub-aquatic vegetation cannot be identified or mapped. Optimal time of year appears to be mid-summer. It has been noted that stereo imagery and elevation information adds to the ease with which the required information is extracted and it is expected that field work is coincident with the image acquisition. Other researchers working in the Great Lakes Basin have effectively used visual interpretation of aerial photography (Hogg et al, undated).

Historical changes in meadow marsh have been monitored over a period of decades (Wilcox et al, 2008) using a variety of aerial photography, including panchromatic imagery from the 1950s as well as more recent digital aerial photography. Scales ranged from 1:4800 to 1:40,000 (Hudon et al, 2006). Ground data sampling was done along randomly selected transects and a topographic cross-section was surveyed using a laser transit. In Wilcox and Bateman (undated) the 16 wetlands included in the Wilcox et al. (2008) study were "reassessed through an aerial photointerpretation study, thus providing a new baseline

[23] http://www.itres.com/why-itres/

for future evaluations." Howard et al (2016) also developed an approach to using aerial photography. Both of these approaches described in the following text box appear to be consistent with how photographic interpretation should be carried out as described in some detail in the Manual of Photographic Interpretation (various chapters on the process of interpretation, especially Tiner in Philipson, 1997).

Approaches to Photographic Interpretation of Meadow Grass Changes in the Great Lakes Basin
Color infrared vertical orthophotos from 2014 were acquired from the New York Natural Heritage Program, and natural color vertical orthophotos from 2015 were acquired from USDA NAIP. A scale of 1:1500 or better was used when drawing polygons. The border extent used in Wilcox et al (2008) was overlaid on each orthorectified photo to ensure that the proper extent of each wetland was delineated. For each wetland, we quantified four vegetation types (Cattail, sedge/grass Meadow Marsh, Mixed Emergent, and Floating leaf) by areal extent for comparison to the Wilcox et al (2008) study. When two or more emergent vegetation types were observed within the same polygon, the following rules applied: 1) if one vegetation type composed 90% or more of the stand, it was considered purely that type, and 2) if more than one type of vegetation composed more than 10% of the stand, then the polygon was labeled as Mixed Emergent. The location of existing community boundaries, as well the spectral signature, helped identify the extent to which borders had expanded or contracted in the newer photos. Area of Meadow Marsh decreased from 2001 to 2014/2015 in all wetlands, except for very minor increases in Maxwell Bay and Braddock Bay. In some cases, losses were due to increases in Cattail (Kents Creek, Black River Bay South, North Pond) and in others to Mixed Emergent (Lakeview Pond, South Colwell Pond, Eel Bay, Point Vivian Bay) or both (Round Pond). Again, lack of major changes is in agreement with conclusions drawn by Wilcox et al (2008). Source: Wilcox and Bateman, Undated
In this work the primary goal of photo-interpretation was to delineate the extent of meadow marsh and cattail stands. Previous work has shown a substantial response of these community types to LOSLR regulation (Wilcox et al. 2008). The process was described as follows: "we examined the imagery and delineations for any significant changes and delineated vegetation types anew/again. For each wetland, our approach was to pan through the delineation at a scale of 1:2000, with the delineations based on 2012 overlaying the 2014 imagery. We looked for any vegetation edge deviations of 6 m or more, when these were encountered, we modified the delineations at 1:1000 scale. This 6-meter threshold made it more likely that the changes were not artifacts of imagery alignment or variation in photo interpretation. For each wetland, we also checked for and corrected any topological errors, such as polygon overlaps or gaps." Source: Howard et al, 2016

Clearly, colour infrared airborne imagery would appear to meet the requirements except for submerged aquatic vegetation, as it was this imagery that was used to establish the baseline referred to in Wilcox and Bateman (Undated). The precision of elevation information that is obtainable depends on the flying height, type of camera, and overlap of the imagery obtained.

C.2.2.7. Aerial Photography (by UAV or Drone)

Ten years ago imagery from an unmanned aerial vehicle or UAV would not have been considered for the sort of project being assessed here. Even five years ago the technology would not have been able to produce the elevation accuracy demanded, or the quality of colour infrared imagery. Today things have changed.

According to product specifications the more advanced UAVs such as Trimble's UX5 HP (Trimble, 2015 and 2016) or the eBee RTK (Sensefly, 2018) can produce colour infrared imagery, elevation information with accuracy of a few cm, and be pre-programmed to cover a specific area – even if odd-shaped. They can cover up to 80 hectares in one flight of 50 minutes duration with 2 cm pixels. According to the product sheets nine of the sixteen test sites identified by Howard et al (2016) could be covered in one flight of 50 minutes. Three more would require two flights, while two more would require three flights and the two largest five flights. A supplier of UAV mapping has reported that while the more advanced systems offer elevation accuracies of a few cm, they tend to be slower, cover less area on one flight and, for their engineering purposes they have found 10 cm data from the less accurate system sufficient.[24]

An added advantage to the use of UAVs is that field work can easily be conducted at the precisely the same time as the flights – the UAV operator and field worker may be the same person and, worst case, may travel to the site in the same vehicle.

Aerial photography by an RTK compatible drone with a colour infrared camera would appear capable of delivering the imagery with positional detail necessary to track changes in marsh meadow wetlands (with the proviso that submerged aquatic vegetation could not be mapped) as well as provide sufficiently accurate elevation details.

C.2.3. Processing Approaches

C.2.3.1. Introduction

Obtaining the imagery from which to extract the required information is but the first, albeit important, step. As mentioned elsewhere in this report field data collection is virtually always required and must be coordinated with the remote sensing data acquisition. The level of detail and type of field data required will vary with the processing approach and data types used. An interesting summary of what tools have been used in remote sensing of wetlands was given in Dronova's (2015) Figure 3, Applications of classification approaches by general method type and publication year.[25] In the more recent years the number of papers using maximum likelihood and supervised classification has diminished while machine learning and Object Based Image Analysis have increased.

Depending upon the processing approach decided upon there may be pre-processing, merging of data sets using a common spatial reference, and obviously the processing approach will dictate the supporting hardware, software and skill sets required of those extracting the information. The remainder of this section discusses the pros and cons of the various approaches in general terms. Much more detail than what is given here would be needed to plan and apply any of the approaches.

C.2.3.2. Visual Interpretation

The interpretation process depends on having appropriately trained people to do the interpretation. In this case one would assume that these are wetland specialists. Given that what is required is monitoring changes in an existing baseline set of information, it may be possible to have a set of dichotomous keys or guides that a less experienced individual might then apply.

[24] Personal Communication March 2, 2018: Mike Hall, Senior Technologist, UAV Flight Operations Manager, Automated Engineering Technologies, Guelph, Ontario.
[25] The figure is inserted in Appendix E.

Visual interpretation by experts tends to be able to identify subtle changes, in more detail, and with less error than machine based methods. Simply stated, machine-based methods cannot yet take in all of the factors that the human brain does when interpreting an image.[26] In addition to colour the human interpreter uses the shape of the feature, context (what is around or near the feature), pattern (man-made or natural) and texture (smooth or rough). However, visual interpretation approaches are often criticized for taking more time for large areas, being less rigorous, and less repeatable. Given that a relatively small number of sample plots are assumed to be the targets of this assessment, and the success of past efforts using visual interpretation of the imagery being suggested, the negative factors do not outweigh the positive factors.

C.2.3.3. Supervised and Un-Supervised Image Analysis

The traditional image processing procedures are pixel classifiers which have been in routine use since the early to mid-1970s. While many papers have been published using these tools for wetlands mapping (Guo et al, 2017), results are not typically reported to be at the level required here The two types of pixel classifiers are usually referred to as supervised and un-supervised image analysis. They are based on the assumption that different objects (in this case wetland vegetation) have unique spectral "signatures." Using this approach there are various methods to identify changes from one date to another in imagery of the same type. One of the factors to keep in mind is that errors are cumulative. If there is a 90% error in the first classification and a 90% error in the second, when they are overlaid, the expected combined accuracy over time is NOT 90%, but rather closer to 81%.

For a supervised classification the analyst chooses areas representative of the feature of interest and uses these to "train" the computer to recognize these features throughout the image. Where there are unique "signatures" for the features of interest in the imagery of the required resolution to meet the minimum mapping unit specification, the approach can work very well. Of course success depends on several factors, including the representativeness of the training samples and homogeneity of the feature of interest. Such approaches have long been used to map crop types using Landsat data: agricultural regions in Canada and the US typically have large homogeneous areas of relatively similar signatures suitable for the scale of the data. As noted elsewhere in this report, wetlands rarely exhibit unique uniform homogeneous signatures over small areas, never mind large ones.

Un-supervised classification depends on the same assumption: different objects (in this case wetland vegetation) have a unique spectral "signature." This approach allows the computer to select unique classes and then either the computer or the analyst brings the various classes together in a fashion that groups the classes to match the requirements of the project. This approach can be faster, but in the end depends on the same basic assumptions about unique spectral signatures.

With higher resolution data the appearance of objects in the imagery has become more complex and there is less homogeneity. With the increased resolution also comes more information such as patterns, shapes, and textures. Neither of these approaches makes use of these important attributes that make visual interpretation so powerful. Furthermore, these methods cannot be used to bring together imagery of different types – such as LiDAR and hyperspectral or SAR and high resolution satellite data. It is therefore doubtful if these methods will play any role in the monitoring of marsh meadows, although they may play a future role in mapping of large areas.

C.2.3.4. Object-based Image Analysis (OBIA)

Object-based classification is a relatively new approach to image analysis developed for high spatial resolution images. Applications to wetlands started appearing in the literature with some regularity in the

[26] For a more complete discussion of the issue of machine vs human interpretation see Haack and Ryerson, 2017.

early to mid-2000s (Dronova, 2015). OBIA can integrate multi-source remote sensing data or remote sensing and GIS data. The principle of object-based classification is to group objects (groups of pixels or data points tied to a specific location) that have similar features, such as a similar pixel shape, color, pattern or texture, and classify them based on the object features (Guo et al, 2017). In other words, it uses some of the same interpretation parameters that are so valuable in visual image interpretation.

Some researchers have used OBIA to bring together data from different sensors: that is not possible with pixel classifiers. Grenier et al (2014) brought together data from Landsat ETM data and RADARSAT, while Amani et al (2017a) used SAR and optical data. Mahdavi et al (2017b), citing other authors, contended that the result of object-based classification has a “more ecologically meaningful interpretation compared to that of pixel-based classification.” They also suggest that “OBIA can facilitate the processing of a large volume of multisource data and can be efficiently combined with supplementary data sets without a complicated data fusion process.” Guo et al (2017) cite a number of uses of OBIA as well as some modifications to the approach. Dronova (2015) has reviewed 73 papers on Object Based Image Analysis applied to wetlands that were published up to December 31, 2014. The process to arrive at wetland classes using OBIA is detailed by several authors cited previously including Amani et al (2017a) and Knight et al (2015, p. 175-176).

While results are often said to be more accurate than pixel classifiers – as much as 31% more accurate in one paper cited by Dronova (2015), she maintains that there are still a number of concerns. Like many engaged in applying remote sensing to wetlands she mentions the complexity of the surface of wetlands. “Progress in applications and further improvement of delineation and classification accuracies are currently hampered by wetland surface complexity, dynamics and by the shortcomings in OBIA implementation.” She concludes[27] that:

1. OBIA is useful for alleviating local spatial heterogeneity of wetlands – as a smart filter to remove noise and work with fine scales of data;
2. OBIA can map isolated wetlands;
3. OBIA framework facilitates hierarchical approaches to detection and classification of wetland ecosystems and their components as well as controlling for the effects of outlying pixels;
4. Flexibility of the OBIA process is coupled with the risk of overly subjective algorithms that may be difficult to validate, reproduce or generalize.
5. The capacity to use OBIA to monitor wetland change and long-term dynamics is still under-developed compared to strategies for single-date or same-year seasonal analyses;
6. A number of wetland-specific challenges to remote sensing-based landscape inference remain important concerns in OBIA, despite its ability to alleviate local surface heterogeneity and reduce “salt-and-pepper” speckle. Spectral similarity of diverse classes due to homogenizing effects of moisture or dead vegetation signals may reduce classification accuracy and the effectiveness of class discrimination.

Further details are not included here inasmuch as it is not expected that the process would be used in the meadow marsh change mapping at which this assessment is directed.

C.2.3.5. Learning analysis multi-sensor systems

Most of the more traditional image analysis approaches assume that the data follow a normal curve. Learning analysis systems such as Random Forest make no such assumptions – they can work with non-parametric data and data of many types. The Random Forest algorithm is similar to a decision tree algorithm, though it is constructed based on a series of trees. Random Forest and other learning systems

[27] Parts of the following points are taken verbatim, while others are a summary of the 1.5 pages devoted to her concluding remarks.

have been used by a number of authors looking at the complexity of wetlands with multiple data sets – not all of which are image data (Dubeau et al, 2012; Corcoran et al, 2013; Bourgeau-Chavez et al, 2015; LaRoque et al, 2014; Mahdianpariet al, 2017). A variety of open source Random Forest classifiers are available including imageRF, which is "platform and license independent and uses generic image file formats. It … is implemented as an add-on in the free EnMAP-Box and may be used in the commercial IDL/ENVI software." (Waske, 2012) A key point when using such learning classifiers is to ensure that the proper approach has been followed to ensure that the importance values are both stable and meaningful, otherwise classifications will be inconsistent and results unreliable. Specifically "random forests must be run more than once and the variability of values must be assessed" as described in Behnamian et al (2017b).

Mahdianpariet al (2017) summarizes the benefits of the Random Forest algorithm as:

1. It is less affected by outliers and noisier datasets;
2. It has a great capability to deal with a high dimensional, multi-source dataset;
3. It has represented a higher classification accuracy compared to other well-known classifiers, such as support vector machines (svm) and maximum likelihood;
4. It assesses the variable importance of input features; and
5. It is an easy to handle classifier, since only two input parameters need be determined by the user: the number of trees and the number of split variables.

It would certainly appear that for mapping large areas of complex wetland environments the learning systems approach in general and Random Forests in particular offer some potential.

One of the issues in this assessment is the potential future need to map subtle changes in meadow marsh across a larger area than sample test sites. While the way in which to do this is clear with aerial photography, the cost would be enormous. The question posed elsewhere in this report was is there a surrogate using, for example, high resolution satellite data to track changes in meadow marshes over a wider area? The Wiki definition of learning systems[28] tells us that learning systems can be supervised. A supervised learning algorithm analyzes the training data and produces an inferred function, which can be used for mapping new examples. Might such a supervised learning system be developed to identify a surrogate for meadow marsh change using, for example, some combination of high resolution satellite data and other available products or data sets?

C.2.3.6. Specialized Radar Processing Tools

Radar data are complex as are the tools used to process them. It has been noted previously that a number of authors have developed special products and graphics to make the products more understandable by those without a background in radar. These are to be encouraged.

The term decomposition appears in the literature and different decompositions appear to work better than others with different data sets. Those that have been cited and applied to wetlands include the Freeman-Durden Decomposition and the Cloude Pottier polarimetric decomposition (Brisco et al, 2011), the Touzi incoherent decomposition (Touzi et al, 2007). Interestingly the only one cited by Guo is that of Touzi, a Senior Scientist in the Government of Canada.

One of the problems with many of these terms, including decomposition, is that they are not well explained for the non-specialist. The text box below provides the clearest explanation found to date. This may be better understood by reference to the diagrams provided in Bourgeau –Chavez et al and Brisco et al (in Tiner et al, 2015).

[28] Source Accessed March 1,: https://en.wikipedia.org/wiki/Supervised_learning

Decomposition Explained
In a single-channel SAR system both the transmitted and received energy from the satellite are either horizontally (H) or vertically (V) polarized. In dual-channel SAR systems the signal can be both co-polarized (transmitted and received energy as HH or VV) and cross-polarized (transmitted and received as HV or VH). With the advancement of fully polarimetric satellite systems such as RADARSAT-2 the satellite can transmit and receive energy in all four planes (HH, VV, HV and VH), maintaining the phase and allowing for mapping of the different scattering mechanisms within a wetland, rather than just the difference between low and high backscatter values. The phase measures the time it takes for the radar signal sent from the satellite to interact with the target on the ground and return to the satellite. This allows the user to decompose the SAR backscatter being returned from the objects being sensed into four common scattering types: (1) specular scattering (no return to the SAR), which occurs from smoother surfaces such as calm water or bare soil; (2) rough scattering, which results when there is a single bounce return to the SAR from surfaces such as small shrubs or rough water; (3) volume scattering, which is when the signal is backscattered in multiple directions from features such as vegetation canopies; and (4) double-bounce or dihedral scattering, which results when two smooth surfaces create a right angle that deflects the incoming radar signal off both surfaces such that most of the energy is returned to the sensor. This latter scattering case typically occurs when vertical emergent vegetation is surrounded by a visible, smooth water surface. Flooded vegetation can also have a combination of double-bounce and volume backscattering. When fully polarimetric SAR images are acquired throughout the growing season, the user can analyze the backscatter response from each stage of the hydrologic and vegetation development (leaf-on and leaf-off) to better understand responses during wetter and dryer periods.
Source: White et al, 2015.

For the current work on meadow marsh change monitoring it is anticipated that SAR data would not likely be used except as a possible data set to develop a surrogate for change detection. Further explanation of SAR processing tools is not necessary

Appendix D: Statement of Work

The Following material is extracted as given in the statement of work, except the contract value has been removed. In the contract the statement of work was in Appendix D. Here it is in Appendix C.

D1.0 Scope

D1. 1 Title

State of Science Assessment of Remote Sensing for Great Lakes Coastal Wetlands

D1.2 Introduction

The Great Lakes Basin contains roughly 18% of the world supply of fresh surface water, and 84% of North America's supply. The Basin is home to approximately 8.5 million Canadians and 30.7 million Americans – one third of the population of Canada and one tenth of the population of the United States. These people depend on the Great Lakes watershed for much of their water supply. Furthermore, the basin produces 25% of Canada's agricultural output and 7% of the US's agricultural output. Coastal wetlands are critical to maintaining the overall health of this unique ecosystem including water quality, wildlife, and recreational activities. As such Coastal wetlands represent a critical habitat throughout the Great Lakes basin.

During both the International Lake Ontario-St. Lawrence River Study (LOSLRS) and the International Upper Great Lakes Study (IUGLS), coastal wetland performance indicators were developed and used to help assess how changes in Great Lakes water level management strategies may impact wetland vegetation response along the shoreline of the lakes. As part of the LOSLRS, the meadow marsh performance in particular was critical to the decision to support the newly adopted Plan 2014, although change in other wetland vegetation zones is also important to support habitat response. Going forward, the Great Lakes – St. Lawrence River Adaptive Management (GLAM) Committee is working to develop an appropriate strategy for tracking changes in Great Lakes coastal wetland vegetation and how those changes may be related to water level fluctuations. The information will be used to help verify the original performance evaluation model and also to provide information that supports reporting on change over time. To support the development of a longer-term strategy for tracking coastal wetland vegetation related to water levels, the GLAM Committee is looking for the contractor to develop a state-of-science synthesis of remote sensing options that can form the basis for future planning.

In completing the work outlined in this Contract, the Contractor will, as outlined below, work with the Scientific Authority – Ms. Lori White of Environment and Climate Change Canada. The scientific authority, though not a party to this Contract and not bound by the terms of this Contract, will endeavor to provide the support described below and work with the Contractor as described in this Contract.

D1.3 Estimated Value

Removed.

D1.4 Objective

This project will focus on developing a state of science assessment of remote sensing of Great Lakes coastal wetlands, particularly related to:

- Improving topographic and bathymetric elevation estimates;
- Defining wetland extent; and
- Differentiating vegetation communities within wetlands.

Acquiring a comprehensive summary of available scientific methods for wetland monitoring through a qualified Subject Matter Expert working in concert with experts identified by the Scientific Authority will provide the Great Lakes – St. Lawrence River Adaptive Management Committee with a detailed assessment of potential options to perform the necessary monitoring effort.

The plan is to combine the expert recommendations from this review with a broader workshop of experts to increase transparency in the process and ensure a range of perspectives are captured in the final information and recommendations provided back to the GLAM Committee.

D1.5 Background, Assumptions and Specific Scope of the Requirement

The GLAM Committee is very interested in how changing Great Lakes water levels impact coastal wetlands, particularly the vegetation composition. In past studies, predictive models have been developed to assess vegetation changes resulting from fluctuating water levels and efforts are now underway to look at verifying model results under observed water level conditions. To date, the GLAM Committee has focused on site-scale field sampling to look at wetland vegetation response to changing water levels. While this approach provides very detailed vegetation information, it can be resource intensive and there are difficulties in scaling to other coastal wetlands. At a coastal wetlands expert meeting in Burlington Ontario on April 3rd and 4th, 2017, one of the recommendations was to look at remote sensing options to improve spatial coverage of the monitoring and support change detection and to build that into a longer-term strategy for tracking wetland response to changing water levels. There has been a long history of study of the Great Lakes Basin with remote sensing dating from the mid-1970s Pollution from Land Use Activities Reference Group of the IJC and continuing with work done more specifically on Ramsar Convention wetlands in 2002 for an ESA sponsored study won in an open competition by Canadian industry. At the 2017 meeting it was noted that data acquisition and processing technologies continue to evolve rapidly and GLAM would benefit from a synthesis of the state of science in the area of remote sensing of wetlands before developing a longer-term monitoring strategy.

Development of the draft synthesis report from this project will benefit from a wide variety of recent and existing efforts in this area including work to support the nearshore framework of the Great Lakes Water Quality Agreement as well as other discussions that have taken place within the IJC and supporting agencies. The intent is not to start from scratch but instead to connect with those that are leading efforts in the above mentioned areas and to pull that information together and synthesize critical aspects to allow a comparison of methodologies and approaches to support GLAM efforts moving forward. GLAM Committee members and technical experts involved in the specific wetlands efforts will support the project by serving as data transfer facilitators between the contractor and activities and expertise within individual agencies. The report shall include a clear, detailed statement of the path for implementation of the various remote monitoring methods proposed and consider potential cost savings that each method may provide over the field monitoring method currently being employed by the Committee.

Background materials to support the effort will be provided by the scientific authority and will include:

1. Key background documents including scientific and related policy papers including but not limited to:
   a. Papers already provided
   b. Papers that detail recent and existing efforts in the area of wetlands and remote sensing including work prepared to support the nearshore framework of the Great Lakes Water Quality Agreement as well as other discussions that have taken place within the IJC and supporting agencies;
   c. National Agriculture Imagery Program (NAIP) https://www.fsa.usda.gov/programs-and-services/aerial-photography/imagery-programs/naip-imagery/
   d. Thogmartin, W.E. et al in (2004) Commentary: A cautionary tale regarding the use of national Land Cover Data Set Wildlife Society Bulletin 32 (3) 970-978;
   e. Ball, D., et al (2002) Treaty Enforcement Services Using Earth Observation: Wetlands Monitoring ESA Final Report for ESA ESRIN Contract No. 15471/01/I-LG;
   f. Gierman, D.M. and R.A. Ryerson (1976) Land Use Information in the Great Lakes Basin, Final Report, Task B1, Pollution from Land Use Activities Reference Group, International Joint Commission, Windsor, Ontario. 23 pp + 568 pp tables.
2. IJC decisions and policy statements related to the subject of wetlands and their importance in the Great Lakes Basin;
3. Government of Canada decisions and policy statements related to the subject of wetlands and their importance in the Great Lakes Basin (or elsewhere);
4. Government of the United States decisions and policy statements related to the subject of wetlands and their importance in the Great Lakes Basin;

5. Relevant State or provincial Government decisions and policy statements related to the subject of wetlands and their importance in the Great Lakes Basin;

As well, the scientific authority from ECCC will support the effort by facilitating access to twelve to fifteen experts who will provide in a timely fashion (within two weeks of Contract being signed) the following information or that agreed to by the Scientific Authority and Contractor:

a. Details of information that is required and why that information is required (i.e. for what purpose);
b. Ideal accuracy required in identifying and mapping the attribute of interest;
c. Acceptable accuracy required in identifying and mapping the attribute of interest;
d. Identification of any surrogate for the attribute of interest;
e. Recent experience including scientific papers dealing with remote sensing of wetlands in the Great Lakes basin or similar regions;
f. Recent experience including scientific papers and/or guidelines dealing with operational wetland management in the Great Lakes basin or similar regions;
g. Opinions, concerns and other information or suggestions that may be related to remote sensing of wetlands.

Geographic Scope:
The state of science report is related to coastal wetlands within the Great Lakes Basin, with particular focus on the Lake Ontario – St. Lawrence River shoreline.

D2.0 Requirements

D2.1 Tasks, Activities, Deliverables and Milestones

Task 1: Kick-off conference call to discuss project expectations
The contractor will review the existing background material provided by the scientific authority regarding the existing wetlands performance indicators associated with water level fluctuations as well as the longer-term monitoring needs *(see section D1.5 – Background and assumptions).* The contractor will then work with the scientific authority as well as representatives from the IJC and GLAM Committee to schedule an initial conference call to discuss relevant background regarding the project and expectations as they relate to developing the wetlands remote sensing state of science report for use by the GLAM Committee.

Task 2: Prepare draft spreadsheet synthesis of key findings
The contractor will develop a spreadsheet or table that will provide a summary of findings from a combination of discussions with experts identified by the Scientific Authority, sampling of the literature, and knowledge and experience of the contractor.

Each column of the table will contain the specific information or attribute required. Obviously as the number of columns increases the level of detail obtainable may need to be adjusted. At the outset the number of rows is unknown. One might assume that there would be more than ten and less than fifteen to twenty. For each column the rows will consider and may detail the following:

1. Brief description of the information (or attribute or feature) required;
2. Outline of who needs the information (identify as many as possible);
3. Outline why the information is needed - the operational requirement that would be met;
4. Brief description of the probable surrounding features or context including associated vegetation;
5. Outline when the feature of interest or information required is likely most readily separated from the surrounding features;
6. Identify any surrogates or "markers" that may indicate the presence of the information attribute or feature of interest;
7. Brief description of threats to the feature – especially those that might be identifiable from remote sensing (e.g. relative sensitivity to changes in water level, including what changes have a deleterious impact);
8. The typical minimum mapping unit (area) at which the information is needed;

9. A description of where the feature will be found (the distance from the shore, smaller lakes feeding into the Great Lakes, etc.);
10. The likely total area of the information or feature of interest in the basin (if known);
11. The likely distribution of the information or feature of interest in the basin (if known);
12. How often the information is required (frequency);
13. Past experience with remote sensing (where known) on the successful use of the technology including accuracy;
14. Past experience with remote sensing (where known) detailing the difficulties in using remote sensing imagery (cost, availability, accuracy, need for multiple image acquisitions, time of year, ability to separate the attribute of interest from surrounding features, need for ground data, etc.)
15. Likely applicable remote sensing technology including resolution and relative cost where cost information is readily available;
16. Identify relevant bibliographic sources (in cooperation with the Scientific Authority and Project experts)

Three specific information needs are highlighted that must be considered:

1. Acquisition of topographic/bathymetric data in coastal wetlands: Information will be provided on existing, new and emerging technologies for acquiring elevation information in Great Lakes coastal wetlands. This may include topographic and bathymetric LiDAR, stereoscopic air photo interpretation, or other strategies. The GLAM Committee is particularly interested in getting comparable information on the identified technologies/approaches related to cost per unit area where available, resolution, uncertainty or difficulties in acquiring imagery, coverage area, timing of acquisition, and other pros and cons of each technology/approach.
2. Acquisition and processing of imagery and remote sensing products to support delineation of wetland extent and distinguishing vegetation communities within wetlands. Information will be provided on existing, new and emerging technologies and approaches for delineating wetland extent and distinguishing vegetation communities within wetlands. This will be based on: a scan of relevant literature identified by the Scientific Authority and the experts being consulted, documents obtained by the contractor, as well the contractor's experience. At a minimum the contractor will consider information on satellite based data acquisition and airborne based options including drones. Of particular interest is comparable information on the identified approaches related to the timing and frequency of acquisition, resolution/scale, cost, coverage area, the role of ground control data, the confidence level and which vegetation communities can be identified, the characteristics of the vegetation community identification, repeatability and sensitivity, and other pros and cons for each approach.
3. Identification of existing estimates of wetland extent for Great Lakes coastal wetlands. Further information is required on new and available mapping datasets representing Great Lakes coastal wetland extent. Comparable information on available as well as emerging datasets including coverage, extent, wetland classification approaches, cost, availability are to be detailed insofar as possible.

Task 3: Develop draft synthesis report capturing the state of science regarding remote sensing of coastal wetlands in the Great Lakes Basin
The contractor will prepare a summary report outlining the findings and results. The report will open with an executive summary of not more than two pages, a Table of Contents, description of the methodology used to obtain the information, the table, and will close with a summary of not more than ten pages of major considerations including areas of possible contention, lessons learned with no more than two pages detailing possible decisions or topics of discussion for a workshop. A full list of the literature and web pages consulted will be provided in an appendix.

Task 4: Participate in experts workshop to present findings and results
The contractor will participate in an Experts Workshop in the last two weeks of March 2018 to review and discuss the Contract Report. The contractor will support the ECCC scientific authority in the preparation of the draft workshop outline. The small and highly focused experts' workshop will include selected technical experts as well as IJC staff as appropriate. The Contractor will participate in the one-day workshop, expected to be held in Southern Ontario as part of the contract.

Primary Deliverables:
Task 1: A conference call with representatives from the IJC and GLAM Committee to discuss project background and expectations for the project.

Task 2: Draft spreadsheet synthesis of key findings.

Task 3: Complete draft report and appendices.

Task 4: Participation in experts workshop, to be held in the last two weeks of March 2018.

Schedule:
Task 1: A conference call scheduled by January 27, 2018.
Task 2: Draft spreadsheet synthesis of key findings by no later than March 10th, 2018.
Task 3: Complete draft report and appendices by no later than March 10th, 2018.
Task 4: Participation in Experts workshop by March 31st, 2018.

Appendix E: Additional Material

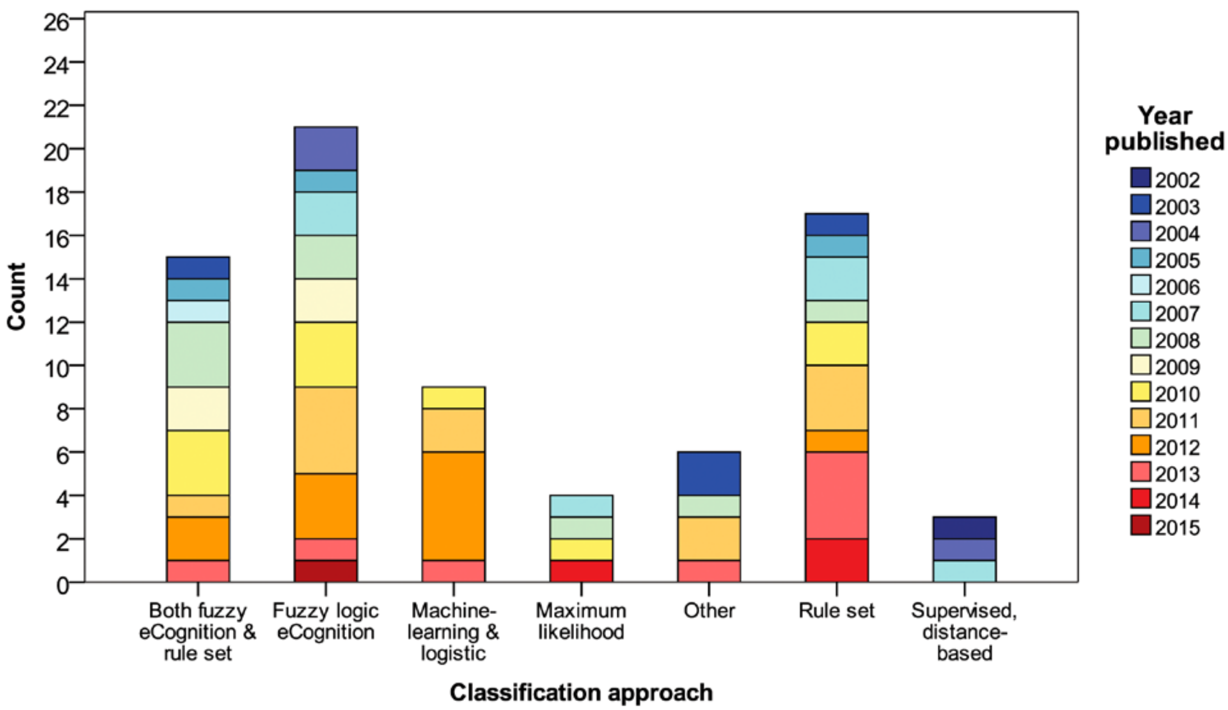

Figure 3. Applications of classification approaches by general method type and publication year (Dronova, 2015).

Appendix F: Cost Calculations

As with most other endeavours, there are trade-offs between information content and cost. A common refrain in remote sensing is you can have it fast, accurate or cheap – pick two. This is no different. The first example with a UAV is much lower cost but does not deliver the elevation information required, nor does the processing involve any interpretation. The second is much more expensive, but it does delveiur the information required.

Mr. Mike Hall, Automated Engineering Technologies Ltd., Guelph has 500 hours flying time with advanced UAVs such as the UX-5 and the more advanced UX5-HP. He has flown in the vicinity of 700 flights over five years. He kindly provided the cost of flying wetlands from under 200 acres to 800 acres and the per diem costs of doing so in areas of our fictitious wetlands listed below. The costs are for a UX5 with a 5 cm pixel flown at 100 meters with 10 cm vertical contour. (He suggested that the more advanced system with 5 cm vertical was slower, far more costly to process the data and for their engineering work did not yield results that were that much better.) The product would be a processed orthophoto tied to a UTM grid with contours. As per the agreement with Mr. Hall, we are not releasing the costs for each item, only the cost for the whole area. The cost of covering the 16 wetlands in the following table would be between $35,000 and $40,000.

Wayne Szameitat of TeledyneOptech in Vaughn provided an approximate cost estimate to cover the fictitious test sites listed in the following table using their CZMIL LiDAR with a casi Hyperspectral system. The system would deliver elevation information with better than 5 cm accuracy with a 2 x 2 meter minimum mapping unit. It was estimated that it would take 4 flights over 8 days – allowing a 25% contingency for bad weather. It was estimated that the aircraft would cost $30,000, equipment rental (with operator) would cost $99,000 and data analysis would cost $8000. The total would then be $137,000. It might be as low as $105,000 if the contingency is not used.