Wetlands and their Benefits:
Review and Synthesis of Tools and Models Assessing Wetland Function and Ecosystem Services

A report submitted to the

Alberta Biodiversity Monitoring Institute & Alberta NAWMP

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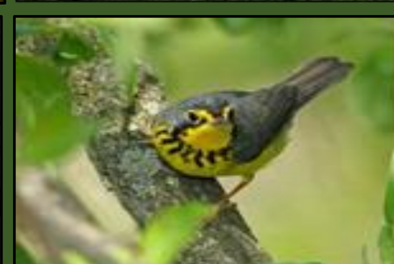

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EXECUTIVE SUMMARY

An initiative is underway in Alberta to explore an ecosystem services approach to land planning, wetland restoration, and wetland management based on the benefits wetlands provide to human well-being. As part of this process, Native Plant Solutions and Ducks Unlimited Canada were commissioned by the Alberta Biodiversity Monitoring Institute (ABMI) and the Alberta North American Waterfowl Management Plan (ABNAWMP) Partnership to conduct a literature review to synthesize the potential tools and models available for wetland ecosystem service assessment in Alberta.

Eight regulating, cultural, and supporting ecosystem services for wetlands were prioritized for review of potential tools and models for application. These included flood control, water purification, water supply and storage, climate regulation, recreation and tourism, science and education, aesthetic, and biodiversity. Following an initial literature review, thirteen tools and models were selected for further review in terms of their potential for application in Alberta. The initial selection criteria required that wetlands be represented in the tool/model, the tool/model could be applied in Alberta, and one or more of the ecosystem services being measured included the eight services identified as priorities.

Of the thirteen tools and models investigated, each had varying degrees of skill-level requirements, documentation, data input requirements, scale, applicability to wetlands, and applicability to Alberta. There were generally three types of tools and models reviewed: ecosystem function models, area-based ecosystem service models, and ecosystem service planning tools. The ecosystem function models (e.g., CRHM, HydroGeoSphere) are generally more data intensive, producing an output that summarizes an ecosystem function that requires an extra step to translate the output to an ecosystem service. The output of area-based ecosystem service models (e.g., GoA, CEAP) more easily envisions the potential effect of changes on the landscape (e.g., wetland drainage or restoration). For ecosystem service planning tools (e.g., Minnesota Wetland Tool, InVEST), the changes to the landscape and management scenarios are inherent to the model and they consider human beneficiaries which facilitates a translation to ecosystem service.

Potential opportunities and limitations for application in Alberta were presented for the tools and models reviewed for each ecosystem service. For water quantity (e.g., flood control, water supply and storage), a number of options were identified as potentially suitable for application in Alberta, ranging from more data intensive ecosystem function models (i.e., CRHM), to simpler area-based tools (i.e., CEAP). Although many tools and models were reviewed that have the potential to evaluate water purification as a wetland ecosystem service, limited options were available, with the model that has the most potential (i.e., IMWEBs) currently in development. With respect to climate regulation, there were limited options for tools and models evaluating carbon storage in wetlands. Although it is known that carbon sequestration is more than just a function of wetland area, this knowledge hasn’t been converted into a usable model from which ecosystem services could be obtained. Therefore, the carbon storage model developed in the GoA approach is considered to be the best option at this time. Of the cultural ecosystem services evaluated (i.e., recreation and tourism, science and education, and aesthetics), three tools had the potential for assessment in Alberta: InVEST, ARIES, and SolVES. Selection of one tool over another will depend on the preferred approach for assessment: survey-based or data-intensive. However,

consideration of survey biases, and incorporation of methodology to improve data credibility should be reviewed prior to proceeding with a survey-based tool (i.e., SolVES). Rather, depending on the priority of cultural ecosystem service assessment to Alberta stakeholders, the simplicity of a qualitative score for 'social value' (i.e., Alberta Industrial Heartland tool) may be more appropriate. Finally, the major strength of ABMI's biodiversity model is its extensive dataset, making it the recommended biodiversity assessment approach for assessing wetland biodiversity.

As part of this process, a jurisdictional review was also conducted investigating jurisdictions where a wetland ecosystem service assessment has been developed as a tool, or applied on the landscape in association with planning or policy. This allowed for insights into the successes and barriers experienced in other regions related to the application and implementation. Four jurisdictions were contacted: Minnesota (Minnesota Restorable Wetland Prioritization Tool), Credit Valley (economic valuation of wetland ecosystem services), North Dakota (CEAP/ILM), and Delaware (statewide wetland valuation using InVEST). The key recommendation for the successful application across all jurisdictions was to pair ecosystem service assessment with strong wetland policies that encourage wetland restoration and/or protection.

Based on the model and tool review process, seven guiding principles for recommendations on assessment were identified:

1. Identify the key wetland ecosystem services for assessment.
2. No one tool will be capable of assessing all wetland ecosystem services.
3. Favour tools/models that include wetlands.
4. Identify the resolution required and the data available.
5. Consider the user of the tool and their skillsets.
6. Consider the output.
7. Weigh biophysical assessment versus economic valuation.

Eight indicators were identified as priorities for data requirements, many of which were common across the tools and models evaluated:

1. A wetland inventory.
2. A land use map.
3. Topography/elevation/LiDAR/DEM.
4. Watershed/subwatershed boundaries.
5. Soils data.
6. Climate data.
7. Population data.
8. Infrastructure data.

The jurisdictional review provided insight into key considerations for successful ecosystem service application for land management:

1. Pair ecosystem service assessment with strong policy and regulatory requirements.
2. Proceed with both internal and external reviews.
3. Track usage.
4. Weigh the opportunities versus limitations of economic valuation.
5. Ensure that the tool can be used by the intended audience.
6. Create a well vetted process for establishing a list of prioritized ecosystem services.

Tool/model	Model/ Tool Type	Analysis scale	Analysis type	Data input	Supporting documentation	Skill-level	Previously applied in AB	Freely available	Wetland specific	Flood control	Water purification	Water supply	Climate regulation	Recreation and tourism	Science and education	Aesthetic	Biodiversity
CRHM	Ecosystem function	Local	Quantitative	High	High	High	Yes	Yes	Adaptable	■	■	■					
SWAT	Ecosystem function	Local	Quantitative	High	High	High	Yes	Yes	Adaptable	■	■	■					
IMWEBs	Ecosystem function	Local	Quantitative	High	In Development	Moderate to High	No	Yes	Adaptable	■	■	■					
2011 GoA	Area-based/ES planning tool	Local	Quantitative, Qualitative	High	High	High	Yes	Yes	Yes	■	■	■	■				
ABMI	ES planning tool	Regional	Quantitative, Qualitative	Moderate	High	Moderate to High	Yes	Yes	Adaptable		■						■
Industrial Heartland	Area-based/ES planning tool	Local	Qualitative	High	High	High	Yes	Yes	Yes	■	■						■
CEAP	Area-based	Local	Quantitative	Moderate	High	Moderate to High	No	Yes	Adaptable	■	■	■	■				■
InVEST	ES planning tool	Local to Regional	Quantitative, Qualitative	Low to High	High	Moderate to High	No	Yes	Adaptable		■	■	■	■		■	■
ARIES	ES planning tool	Local to Regional	Quantitative, Qualitative	Low to High	Moderate	Moderate to High	No	Yes	Adaptable	■	■	■	■	■		■	
SolVES	ES planning tool	Local to Regional	Qualitative	Low to High	High	Moderate to High	No	Yes	Adaptable					■	■	■	
MN Wetland Tool	ES planning tool	Regional	Qualitative	Moderate	High	Moderate to High	No	Yes	Yes		■						■
HydroGeoSphere	Ecosystem function	Local to Regional	Quantitative	High	High	High	No	No	Adaptable	■	■	■					
DNDC	Ecosystem function	Local to Regional	Quantitative	High	High	High	No	Yes	Adaptable				■				

* ES = ecosystem service

1.0 INTRODUCTION

The Millennium Ecosystem Assessment (2005a) defines ecosystem services as "...the benefits people obtain from ecosystems." Ecosystem services are essential to human well-being and survival, providing provisioning (e.g., food, water, fiber), regulating (e.g., water quality, climate), cultural (e.g., recreational, aesthetic), and supporting services (e.g., photosynthesis, soil formation). Many of these services, such as water quality improvement, are difficult to represent (Keeler et al. 2012) and are therefore underestimated or overlooked in development decisions (Government of Alberta 2011a). However, decision makers are increasingly recognizing the importance of accounting for the value of ecosystem services, particularly when considering land use changes and wetland conservation, restoration, and enhancement (Delaware Department of Natural Resources and Environmental Control 2011). Wetlands provide many benefits to human well-being, such as water filtration prior to discharge to downstream waterbodies, or recreation and tourism, whereas the biodiversity a wetland ecosystem supports activities such as birdwatching, fishing, and hunting. In Alberta, assessing the ecosystem service values of wetlands will help decision makers consider priorities for wetland restoration when land use changes are considered.

One of the main challenges of incorporating ecosystem services into decision making involves the challenge of connecting ecosystem processes with changes in human well-being (Bateman et al. 2011). The term 'ecosystem service' is often used interchangeably with 'ecosystem function' (Ayanu et al. 2012; Brown et al. 2014; Delaware Department of Natural Resources and Environmental Control 2011); however, ecosystem services are directly linked to human well-being, whereas ecosystem functions are the physical, chemical, and biological activities within an ecosystem (USEPA 2009). Thus, ecosystem services are provided by ecosystem functions (Brown et al. 2014). Wetland ecosystem functions are dependent on the wetland type, condition, and location within a landscape (Delaware Department of Natural Resources and Environmental Control 2011). By identifying the physical, chemical, and biological processes that support these functions, the link to ecosystem service, as well as the benefits to human well-being and value, can be made (deGroot et al. 2010; Brown et al. 2014). Ecosystem functions that support wetland ecosystem services are generally better understood. Although the value for some ecosystem products, such as timber obtained from forests, can be obtained where market values exist, more often than not ecosystem service values are less well-established. This is particularly true for wetlands, including the value of regulating (e.g., global climate regulation, flood control, water treatment) and cultural (e.g., aesthetics, education) ecosystem services. By describing and valuing, whether in biophysical or economic terms wetland ecosystem services, decision makers can better understand and deliver wetland restoration projects on the landscape (Government of Alberta 2011a).

Limited information exists on the status of ecosystem services, including their economic value (Millenium Ecosystem Assessment 2005a). In terms of measuring the various ecosystem services provided by an area, there is no standard approach and most assessment tools have not yet met their expectations to support policy and decision makers with respect to a direct link to human well-being (Reyers et al. 2014). To measure the complex ecosystem services provided by an area, there are generally three types of data used to develop indicators: national statistics, remote sensing, and field estimates (Reyers et al. 2014). Each of these data types have advantages and disadvantages for use (see Brown et al. 2014), including availability, cost, effort, and the required expertise. With respect to ecosystem service assessments, the terms 'model' and 'tool' are often used interchangeably. For the purposes of this report, they are treated as two different approaches to an ecosystem service assessment, and are defined as follows. A model builds a simplified representation of wetland processes and is useful for its explanatory, predictive, and informative power. For example, a hydrology model may be designed to estimate the potential water storage loss, or gain, when a wetland is destroyed or restored. Models are often data intensive and require biophysical information, such as climate and soil data, landscape position, and land use, in order to populate the model's structure. For models, once key data requirements in the model structure are identified, suitable data sources may be lacking; however, stakeholders with common interests and goals, such as government regulators, university researchers, and non-governmental organizations, may work together to fill in data source gaps that help models to better replicate reality. In comparison, in this report a tool refers to a package of numerous models (e.g., for water quantity, water quality, carbon storage, etc.) to inform ecosystem service assessment for wetland protection or restoration within a watershed or region.

The endpoint for ecosystem service assessment, whether biophysical or economic, is a subject of debate. By obtaining economic valuation, a total understanding of natural capital (i.e., the yield of goods and services over time by natural, environmental, and ecosystem resources and land) within a region can be determined and assessed (Olewiler 2004). Economic value is the most common way to evaluate change to human well-being of ecosystem services (Brown et al. 2014); however, where the ecosystem service links to a measurable market value endpoint, as is the case with most wetland ecosystem services, valuation is complex and often specific to a region (Olewiler 2004). An economic valuation is often affected by a monetary expiration date and thus must be recalculated on a regular basis. In addition, few studies on natural capital value have been done in Canada; therefore, data on the economic links to wetland ecosystem services for many regions is limited. On the other hand, biophysical ecosystem service assessment may be more useful to land managers (Delaware Department of Natural Resources and Environmental Control 2011), and allows for assessment without having to consider economic principles for applying value. Where possible, the Millennium Ecosystem Assessment (2005a) identifies the need for ecologists and economists to work together to incorporate both biophysical and economic data, at a regional level, for optimal ecosystem service assessment.

The scale at which an ecosystem service assessment is applied also requires consideration, as assessment requires some amount of commonality across the selected spatial scale. Costanza et al. (1997) conducted an early estimate of the value of ecosystem services, at the biome-level, by compiling results from over 100 ecosystem service economic valuation studies. Although Constanza et al. (1997) judged that the risks of valuation at such a scale were outweighed by the exercise of this estimate, many have argued against utilizing values for ecosystem services generated at site-specific scales from other regions and applying them across a large scale (Bockstael et al. 2000). Ecosystem service information is site-specific, as service supply and demand applies to what is available in a given area (Brown et al. 2014). When considering the ecosystem service assessment, the scale at which to apply the assessment should consider data availability and relevance to decision-making. For example, although finer scale resolution is typically desirable for decision-making, data gaps and inconsistencies may restrict the level at which assessment can be applied. The spatial scale that is selected must also be relevant to the ecosystem services being evaluated (de Groot et al. 2010). For example, for hydrological services (i.e., water flow regulation, water purification, etc.), a watershed or sub-watershed scale may be most appropriate for land planning purposes, as it is at this level that the physical, chemical, and biological processes that support this service operate. Ecosystem service assessment is ultimately context-specific, relating the use of ecosystem services for human well-being in a particular region (Government of Alberta 2011a). The approach, endpoint, and scale for ecosystem service assessment must be scientifically credible, relevant to decision makers, user friendly, and accepted by all stakeholders.

In order for the Province of Alberta to consider an ecosystem service approach to support wetland management, models and tools that provide the best assessment of wetland ecosystem services must be selected. As part of this process, Native Plant Solutions and Ducks Unlimited Canada worked with the Alberta Biodiversity Monitoring Institute (ABMI) and the Alberta North American Waterfowl Management Plan (ABNAWMP) Partnership to find agreement on priority wetland ecosystem services for which to review and to synthesize the tools and models that may exist to evaluate wetland value. In total, eight ecosystem services were identified as priority for wetland management in Alberta (Table 1). These were partly based on the services identified in the Government of Alberta (2011a) report and adapted from the full list of ecosystem services for inland wetlands identified by the Millennium Ecosystem Assessment as part of the 'Wetlands and Water' focus (Millennium Ecosystem Assessment 2005b). Appendix A contains the descriptions of each of the ecosystem services considered (Government of Alberta 2011a; Millennium Ecosystem Assessment 2005a; Millennium Ecosystem Assessment 2005b; Delaware Department of Natural Resources and Environmental Control 2011).

As part of an Alberta initiative to explore an ecosystem service approach to land management, this report outlines a literature review conducted to synthesize tools and models available to evaluate wetland ecosystem functions and/or wetland ecosystem services. Section 2 summarizes the overall literature review process, including the tool selection criteria used to refine the list of tools/models assessed into those that are more wetland-specific, and also appropriate for application in Alberta (Section 2.1). A summary is provided for each tool/model, outlining the methodology, data requirements, and outputs in Appendix B. Where wetland ecosystem function models are reviewed, their linkage to ecosystem services is presented. Of the 13 tools and models selected for further review, Section 3 provides recommendations for tools most appropriate to wetland ecosystem service assessment in Alberta for each of the wetland ecosystem services identified in Table 1. In jurisdictions where wetland ecosystem service assessments have been developed as a tool, or applied on the landscape in association with planning or policy, an investigation was conducted to gain input on successes and barriers experienced in application and implementation (Section 4). Finally, based on the results of the review process, guiding principles for successful implementation are presented, as well as potential information gaps and next steps prior to implementation.

Table 1. Ecosystem services and wetland functions identified for review (modified from Delaware Department of Natural Resources and Environmental Control 2011 and Millennium Ecosystem Assessment 2005b).

Wetland Ecosystem Service	Ecosystem Function
Flood control	Water storage, flow moderation, stabilization of hydrological flows and regimes
Water purification	Nutrient transformation and retention, sediment retention
Water supply and storage	Surface water detention, flow moderation, stabilization of hydrological flows and regimes, groundwater recharge/discharge
Climate regulation	Carbon storage, greenhouse gas production
Recreation and tourism	Provision of wildlife and plant habitat
Science and education	Provision of wildlife and plant habitat
Aesthetic	Provision of wildlife and plant habitat
Biodiversity	Maintenance/support of hydrological, biological, physical and ecological characteristics, provision of wildlife and plant habitat

2.0 Literature Review

2.1 Tools/Models Reviewed and Selection Criteria

Approaches to measuring ecosystem services show strong promise for linking wetland conservation with human well-being (Vigerstol and Aukema 2011). This provides additional promise for invoking the well-being of people as a rationale for conservation (Tallis et al. 2008). For the purpose of this investigation, an ecosystem service is considered as goods and services that are used, or can potentially be used, to measure, prevent, limit or correct environmental damage either through wetland avoidance, protection or restoration (Statistics Canada 2007). Based on a literature review, and interviews with a number of the developers of the tools/models presented in Table 2, several ecosystem services tools and models and their applicability to practitioners in Alberta were further explored. In this initial review it was important to consider what each tool and model was designed for and how well it fit with its intended application. It was also important that the products investigated were free, publically available, and actively supported and applied. Certain tools reviewed here are in the development stage. Very few tools are being applied successfully at this time for ecosystem service assessments in the regions in which they were developed. Section 4 consists of a summary of jurisdictions using ecosystem services assessment tools to understand how to successfully apply these tools.

While reviewing the array of tools and models summarized in Table 2, a number of criteria were considered in this initial review. If, after this initial investigation, a tool or model fit the selection criteria presented in points 1 through 3 listed below, further investigation into the model and its applicability in Alberta was explored in Section 3. The criteria established for further tool/model investigation included:

1. Do wetlands have the potential to be represented in the tool/model?
2. Is the tool/model applicable to wetlands in Alberta?
3. Are there ecosystem services being measured that are of interest to Albertans?
4. Is the documentation regarding model structure available?
5. Is the tool/model free and open-access?
6. What are the data requirements?
7. Is the tool/model data intensive?
8. Does the tool/model have a spatial component?
9. What scale can the tool/model be applied at?
10. What are the assessment units?
11. Are the tool/model outputs quantitative, qualitative or both?
12. What is the overall quality of the output?
13. What are the data assumptions?
14. Are the models semi-distributed or fully distributed?
15. What level of expertise is required to run and operate the tool/model?
16. Does the tool/model have a user friendly interface?

Table 2. Ecosystem service tools and models identified during the literature review. Those that fit key selection criteria were chosen for further review for application in Alberta (see Table 3).

Tool/Model	Brief description	References	Chosen for further review?	Rationale for further review
Cold Regions Hydrological Model (CRHM)	Simulates hydrological processes in the western Canada Prairie Pothole Region (PPR) considering hydrological cycle, including wetland storage and runoff generation	Pomeroy et al. 2007; Pomeroy et al. 2010; Pomeroy et al. 2012; Pomeroy et al. 2014	Yes	Designed specifically for cold regions including Alberta; has been applied on prairie wetlands; fully distributed
Soil and Water Assessment Tool (SWAT)	A tool that predicts the impact of land management practices on water storage/flow, sediment and agricultural chemical yields in watersheds, land use and management conditions over time	Neitsch et al. 2011; Yang et al. 2008; Yang et al. 2016a; Wang et al. 2008	Yes	Well documented; models water quality and quantity; widely applied; has been applied on prairie wetlands
Integrated Modelling for Watershed Evaluation of BMPs (IMWEBs)	Continuous time series tool that assesses the effects of BMPs on both water quality and quantity in a watershed	Yang et al. 2016c	Yes	Fully distributed; models water quality/ quantity for individual wetlands; has been applied on prairie wetlands; allows for assessment of BMPs
2011 Government of Alberta Ecosystem Service Pilot	Case study near Calgary to assess water supply, flood control, water purification, and carbon storage of wetlands	Government of Alberta 2011a,b,c,d	Yes	Well documented; developed for Alberta wetlands; this tool models multiple ecosystems services
Alberta Industrial Heartland	Conducts a value assessment of wetlands in the Industrial Heartland region near Edmonton using GIS metrics to evaluate biodiversity, flood flow reduction, water quality improvement, and social value	Cobbaert et al. 2011	Yes	Developed specifically for Alberta wetlands; captures multiple services

Tool/Model	Brief description	References	Chosen for further review?	Rationale for further review
Alberta Biodiversity Monitoring Institute Water Purification	Simulates precipitation, overland flow, and surface water flow to identify areas contributing to export of nutrients and eroded sediment as well as areas for removing these substances	Habib et al. 2016	Yes	Well documented; developed for Alberta; goes beyond measuring function to assess impacts on population
Alberta Biodiversity Monitoring Institute Biodiversity	Uses ABMI's Biodiversity Intactness Index which is based on data collected through ABMI's biodiversity monitoring program	ABMI 2015; Habib et al. 2016	Yes	Well documented; developed for Alberta; based on long-term data collection in Alberta
Wetlands Component of the Conservation Effects Assessment Project (CEAP)	Developed approaches to quantify changes in ecosystem services (flood control, water purification, and carbon storage) resulting from wetland restoration	Gleason et al. 2008	Yes	Developed for wetlands in the Prairie Pothole Region of the Great Plains; well documented; models developed from field data
Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST)	Suite of models (carbon storage, biodiversity, water yield, water purification, sediment reduction, recreation, and aesthetic value) used to map and value ecosystem services	Sharp et al. 2016	Yes	Well documented tool; widely applied for ecosystem service assessments; models multiple ecosystem services; has both biophysical and economic model components; applied in a number of regions and countries
Artificial Intelligence for Ecosystem Services (ARIES)	Assesses ecosystem services through mapping source, sink, flow and users of ecosystem services using probabilistic models.	Bagstad et al. 2011; Villa et al. 2014	Yes	Models multiple ecosystem services; probabilistic approach allows for conveying uncertainty about inputs and outputs; all models consider human beneficiaries; applied in a number of regions and countries

Tool/Model	Brief description	References	Chosen for further review?	Rationale for further review
Social Values for Ecosystem Services (SolVES)	Assesses the perceived social values of cultural ecosystem services	Sherrouse and Semmens 2015	Yes	Designed specifically for cultural services; flexible design allowing users to model only the social values of interest; well-documented
Minnesota Restorable Wetland Prioritization Tool	Online tool used to develop priorities for wetland restoration that will result in the greatest improvement in water and habitat quality	Erickson et al. 2013	Yes	Designed specifically for wetlands; intended for developing wetland restoration priorities
A Landscape Cumulative Effects Simulator (ALCES)	Model used to simulate and evaluate effects of land use changes over time	ALCES 2017; North Saskatchewan Watershed Alliance 2009	No	Proprietary software; wetlands are not modelled independently of surrounding land use
Multiscale Integrated Models of Ecosystem Services (MIMES)	Integrated set of models that assess the value of ecosystem services as well as quantify the effects of land use changes on ecosystem services	Boumans et al. 2015	No	Not well-documented; requires commercial modelling software; not widely applied
Ecosystem Valuation Toolkit (EVT)	Database of ecosystem service values based on location and land cover type	Earth Economics 2017	No	Proprietary software; uses benefit transfer method to estimate ecosystem service values based on previous studies; not spatially explicit
Ecosystem Service Valuation (ESV)	Spreadsheet based tool utilizing the benefit transfer method for estimating the value of a landscape using a land cover dataset, ecosystem health estimates, and land cover valuation	Affordable Futures 2017	No	Not spatially explicit; uses benefit transfer method to estimate ecosystem service values based on previous studies

Tool/Model	Brief description	References	Chosen for further review?	Rationale for further review
Advanced Terrestrial Ecosystem Analysis and Modelling (ATEAM)	Suite of ecosystem models used to assess the vulnerability of humans sectors that rely on ecosystem services with respect to global change	Schröter et al. 2004	No	Developed strictly for European case study
Costing Nature	Web application used to assess ecosystem services, identifying the beneficiaries, and assess human impacts on ecosystem services	Mulligan 2015	No	Intended to be non-technical; has not been widely applied
Wildlife Habitat Benefits Estimation Toolkit (WHBRET)	Spreadsheet based model used to estimate monetary value of cultural ecosystem services	Kroeger et al. 2008	No	Not spatially explicit; relies on benefit transfer; only monetary valuation -— no biophysical component
HydroGeoSphere	Computer program that simulates the terrestrial portion of the hydrological cycle. Can also simulate the surface and subsurface transport of solutes including heavy metals or hydrocarbons	Brunner and Simmons 2012	Yes	Fully distributed; has been applied on prairie wetlands; becoming widespread in use
DeNitrification-DeComposition (DNDC)	Process-based computer simulation model of carbon and nitrogen biogeochemistry in agricultural ecosystems	Li 2012	Yes	Models carbon and nitrogen in wetlands; widely applied for modelling carbon sequestration and GHG emissions
Toolkit for Ecosystem Service Site-based Assessment (TESSA)	Intended to provide guidance to non-technical users on low-cost methods of assessing ecosystem services at a site specific scale	Peh et al. 2013; Merriman and Murata 2016	No	Intended for non-technical users; can only be applied at a site specific scale
Agricultural Policy Environmental Extender (APEX)	Field-scale model used for simulated management practices in agricultural regions related to water quality and water quantity	Mushet and Scherff 2017	No	Intended for field scale application; PPR depressional wetlands not fully developed in model

Tool/Model	Brief description	References	Chosen for further review?	Rationale for further review
Wetland Ecosystem Services Model Prototype	Developed an approach intended for standardizing the sharing of geospatial ecosystem service models. To demonstrate this approach the authors developed models to measure the water storage and waterfowl breeding benefits provided by wetlands in the PPR	Feng et al. 2011	No	Not well documented; not widely applied
Alberta Wetland Rapid Evaluation Tool – Actual (ABWRET – A)	Rapid field assessment to assign regulatory value to a wetland, as part of the Alberta Wetland Mitigation Directive. Scores for 14 wetland functions are generated, to assign a wetland to a value category. Wetland is then categorized based on frequency distribution in the White Zone, and historical loss trends.	Government of Alberta 2015	No	Outputs are relative scores; calculated per wetland rather than landscape level; field assessment; not applicable for restoration planning

2.2 Summary of Applicable Tools/Models

Only those tools/models investigated that met the key tool selection criteria in Section 2.1 were investigated further for their applicability to assess wetland ecosystem services in Alberta. Table 3 presents the thirteen tools/models included in this detailed review, including the ecosystem service each tool/model evaluates, as well as characteristics for key tool/model selection criteria (e.g., scale, data input requirements, etc.). For analysis scale, tools/models ranged from local (i.e., subwatershed, watershed) to regional (i.e., province-wide/state-wide). For analysis type, tool/model output was either qualitative (i.e., relative scale) or quantitative (i.e., biophysical or economic value). For data input requirements, tools/models were characterized as high (i.e., requiring Light Detection and Ranging (LiDAR), detailed climate and hydrological data), moderate (i.e., land cover data with coefficients for each wetland processes) or low (i.e., requiring only a general land cover dataset). For documentation, tools/models with a high level of documentation (i.e., user guides or websites where a model code can be interpreted) allowed for critical review, as compared to moderate documentation level (i.e., where peer-reviewed publications reviewing the tools/models exist, but do not allow for model code evaluation). Tool/model skill-level requirements ranged from moderate (i.e., could be applied by non-technical decision makers) to high (i.e., requires specialized knowledge of geographic information systems (GIS) or hydrology). Some of the tools/models reviewed have previously been applied in Alberta, demonstrating its applicability in

Alberta. Most tools/models were mostly freely available (i.e., open source). Finally, although all tools/models were adaptable to valuing ecosystem services, only some were specifically designed for wetlands. See Appendix B for the complete descriptions of the thirteen tools and models chosen for an in-depth review.

Table 3. Thirteen tools and models selected for further review for potential application in Alberta, including the ecosystem service(s) each evaluates, as well as key characteristics for tool selection criteria. Note that IMWEBs and the water purification module of CRHM are currently in development.

Tool/model	Model/ Tool Type*	Analysis scale	Analysis type	Data input	Supporting documentation	Skill-level	Previously applied in AB	Freely available	Wetland specific	Flood control	Water purification	Water supply	Climate regulation	Recreation and tourism	Science and education	Aesthetic	Biodiversity
CRHM	Ecosystem function	Local	Quantitative	High	High	High	Yes	Yes	Adaptable	■	■	■					
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CEAP	Area-based	Local	Quantitative	Moderate	High	Moderate to High	No	Yes	Adaptable	■	■	■	■				■
InVEST	ES planning tool	Local to Regional	Quantitative, Qualitative	Low to High	High	Moderate to High	No	Yes	Adaptable		■	■	■	■		■	■
ARIES	ES planning tool	Local to Regional	Quantitative, Qualitative	Low to High	Moderate	Moderate to High	No	Yes	Adaptable	■	■	■	■	■		■	
SolVES	ES planning tool	Local to Regional	Qualitative	Low to High	High	Moderate to High	No	Yes	Adaptable					■	■	■	
MN Wetland Tool	ES planning tool	Regional	Qualitative	Moderate	High	Moderate to High	No	Yes	Yes		■						■
HydroGeoSphere	Ecosystem function	Local to Regional	Quantitative	High	High	High	No	No	Adaptable	■	■	■					
DNDC	Ecosystem function	Local to Regional	Quantitative	High	High	High	No	Yes	Adaptable				■				

* ES = ecosystem service

3.0 TOOLS/MODELS MOST APPROPRIATE FOR ALBERTA

Based on the tools and models identified for further review in Table 3 and the wetland ecosystem services of interest identified in Table 1, a service by service comparison of the opportunities and limitations of each tool and model is considered. Key considerations for Selection Criteria (Section 2.1) were reviewed, offering advantages or disadvantages, depending on the question to be answered and the level of detail required. For example:

- **Skill-level:** Of the models and tools reviewed, some require a steep learning curve, while others could be applied by non-technical users or decision makers. For example, the Industrial Heartland tool offers a straightforward, relatively simple approach, while still being able to incorporate meaningful information. In comparison, the Cold Regions Hydrological Model (CRHM) model is very specialized, requiring advanced knowledge of hydrology, but may be necessary should the ecosystem focus be hydrological function and scientific consensus (Vigerstol and Aukema 2011).
- **Documentation:** Applied and well-documented tools and models allows for peer-review of the model components and a comparison of how various tools and models may function in real-world examples (e.g., Vigerstol and Aukema 2011; Bagstad et al. 2013). For example, Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) is a well-documented tool that has a relatively transparent code should users wish to review or modify. In comparison, Artificial Intelligence for Ecosystem Services (ARIES) offers moderate documentation in terms of its model coding, making it difficult to determine the mechanics of each model and to revise the model, if needed.
- **Data requirements:** Utilizing local data where possible ensures that ecosystem service assessment is regionally applicable; however, data acquisition can be costly and time consuming. For example, both the Soil and Water Assessment Tool (SWAT) and Integrated Modelling for Watershed Evaluation of Best Management Practices (IMWEBs) are fairly data-intensive tools, but provide quantitative biophysical outputs. Alternatively, the ARIES tool uses Bayesian networks where insufficient local data exists.
- **Scale:** Depending on the desired scale of output, models and tools have the ability to provide information at a low (e.g., regionally) or high-resolution (e.g., per wetland). For example, IMWEBs, unlike SWAT, can map hydrological function as one wetland per sub-basin. Alternatively, the results from the Minnesota Wetlands tool are used to identify general areas of interest for restoration or protection, rather than field-scale actions.
- **Wetland-specific:** A wetland-specific tool or model ensures components of the model or metric directly reflect the ecosystem service being evaluated; however, this may be more detail than required, depending on the question being asked. For example, components of the Government of Alberta's (GoA) tool metrics are wetland-specific. Alternatively, InVEST is not a wetland-specific tool. In the case of climate regulation as an ecosystem service, much of InVEST's climate model components are not meaningful for wetlands.

- **Alberta applicable:** Some tools and models, when developed for other regions, have the potential to be updated or modified for application in Alberta should the model or tool show promise. Some ecosystem service tools and models have already been applied in the province. For example, the GoA tool combines four modelling components for ecosystem services, based on metrics appropriate for Alberta wetlands. In comparison, the Minnesota Wetlands tool has only been applied in Minnesota, and a comparable tool would need to be developed for Alberta should it be selected for application.

Each of the considerations listed above may offer an opportunity or limitation in applying the tool or model for an ecosystem service assessment, depending on the questions to be answered or the scale at which the tool or model is to be applied. However, the model or tool characteristics for one criterion is not a reason to exclude a model's application. Rather, based on knowledge of wetlands in the White Zone in Alberta, data availability in the Province and application potential of each of the models or tools, recommendations of select tools or models that may provide the best approach are presented.

Of the tools and models reviewed, there were generally three types: ecosystem function models, area-based ecosystem service models and ecosystem service planning tools. Ecosystem function models are generally more academic and data intensive, requiring specialized knowledge to produce an output that summarizes an ecosystem function. Examples of this type of model include CRHM and HydroGeoSphere. Although these biophysical models provide information on the link between changes on the landscape (e.g., wetland drainage) and the resultant change to ecosystem function, additional steps are required to translate this information into ecosystem services and the value they provide to human well-being (Keeler et al. 2012). The second type of model is an area-based ecosystem service model, such as select models in the GoA tool, as well as the Conservation Effects Assessment Project (CEAP) tool. For this type of model the potential effect of changes on the landscape (e.g., wetland drainage or restoration) and its effect on ecosystem service outputs is more easily envisioned. In the third type of model, ecosystem service planning tools such as the Minnesota Wetland Restoration Prioritization Tool and InVEST, the changes to the landscape and management scenarios are inherent to the model and they consider human beneficiaries which facilitates a translation to ecosystem service. Particularly for the water quantity ecosystem services (e.g., flood control, water storage and supply), where a selection of models and tools was reviewed from each of the three general types described above, the pathway to ecosystem service assessment may vary. Linking ecosystem functions to human well-being has been recognized as one of the key challenges when approaching an ecosystem service assessment (Keeler et al. 2012). However, the tools and models presented below each present promising pathways for translating wetland functions to ecosystem services.

A synthesis of the opportunities and limitations for applying the selected tools and models for ecosystem service assessment in Alberta is presented below. For each of the ecosystem services - water quantity (i.e., flood control, water supply and storage), water purification, climate regulation, cultural services (i.e., recreation and tourism, science and education, and aesthetics), and biodiversity – models and tools are reviewed and the potential advantages and disadvantages to their application in Alberta is summarized.

Table 4. Service by service summary of potential tools or models for application of ecosystem service assessment in Alberta.

Ecosystem Services	Tool/Model
Flood control	**CRHM:** Simulates hydrological processes in the western Canada PPR considering hydrological cycle, wetland storage, and runoff generation.
	SWAT: Watershed scale tool capable of predicting impacts of land use changes on water quantity by simulating the total discharge of water from a watershed.
	IMWEBs: Continuous time series model that assesses the effects of BMPs on both water quality and quantity in a watershed
	GoA Pilot: Uses a GIS-based indicator approach with seven predictor variables to model the peak flow reduction of wetlands in the study area.
	Industrial Heartland: Conducts a GIS based assessment of flood flow reduction using seven metrics to assess a relative score for each wetland in the study area.
	CEAP: Developed models to determine the relationship of wetland zone area to wetland volume for each physiographic region of the PPR to estimate water storage capacity of wetlands.
	ARIES: Investigates flood regulation along rivers at an annual time scale based on annual precipitation and floodwater storage in green or grey infrastructure.
	HydroGeoSphere: Simulates the terrestrial portion of the hydrological cycle. Can also simulate the surface and subsurface transport of solutes including heavy metals or hydrocarbons.
Water purification	**CRHM:** Water quality component is early in development but once complete will consider nutrient (e.g., nitrogen and phosphorous) transport in both snowmelt and summer runoff periods.
	SWAT: Watershed scale model capable of predicting impacts of land use changes on water quality through simulating the reductions of total phosphorous, nitrogen, and sediments discharged from the watershed outlet.
	IMWEBs: Continuous time series model that assesses the effects of BMPs on both water quality and quantity in a watershed.
	GoA Pilot: Assesses the potential of wetlands to remove nitrogen, phosphorous, and sediments from a water supply by calculating a wetland purification score which is derived from six metrics.

Ecosystem Services	Tool/Model
Water purification (cont.)	**ABMI:** Identifies areas contributing to a non-point source export of nutrients (e.g., nitrogen and phosphorous) and sediments (e.g., total suspended solids) as well as areas that remove these substances and the impacts to downstream water users.
	Industrial Heartland: Conducts a GIS based assessment of surface water quality improvement using six metrics to assess a score for each wetland in the study area.
	CEAP: Estimated the differences in soil erosion and nutrient (e.g., nitrogen and phosphorous) loading of wetland catchments that were either cropped or contained perennial cover.
	InVEST: Nutrient model maps nutrient sources from watersheds and their transport to the stream. Data requirements are DEM, land use, watersheds, multiple water quality parameters. Sediment model maps overland sediment generation and delivery to the stream. Requires data on DEM, land use, watersheds, and various erosion indices.
	ARIES: Uses a probabilistic approach to assess the sources and sinks of sediment, beneficiaries, and hydrological flow across the landscape.
	MN Wetland Tool: Prioritizes wetland restoration areas to maximize improvements to water quality (e.g., nitrogen or phosphorous removal) on multiple decision layers and a restorable wetland inventory.
Water supply and storage	**CRHM:** Simulates hydrological processes in the western Canada PPR considering hydrological cycle, wetland storage, and runoff generation.
	SWAT: Watershed scale model capable of predicting impacts of land use changes water quantity by simulating the total discharge of water from a watershed.
	IMWEBs: Continuous time series model that assesses the effects of BMPs on both water quality and quantity in a watershed.
	GoA Pilot: Determines total water storage capacity of each wetland by estimating the existing water volume in a wetland as well as the additional water storage capacity when the wetland is full.
	InVEST: Provides an estimate of total water yield for a catchment by commuting indices that quantify the relative contribution of a parcel of land to the total generation of base flow. Data requirements include a DEM, precipitation, land use, watersheds, and various hydrological parameters.
	ARIES: Utilizes flow models spatially linking users to water sources with probabilistic evapotranspiration and infiltration models.

Ecosystem Services	Tool/Model
Water supply and storage (cont.)	**HydroGeoSphere:** Simulates the terrestrial portion of the hydrological cycle. Can also simulate the surface and subsurface transport of solutes including heavy metals or hydrocarbons.
Climate regulation	**GoA Pilot:** Assesses the carbon storage associated with Class III, Class IV, and Class V wetlands. Estimates the stock of carbon contained in existing wetlands as well as the amount re-emitted to the atmosphere resulting from wetland loss.
	CEAP: Estimates the stock of carbon contained in existing wetlands as well as the amount re-emitted to the atmosphere resulting from wetland loss based on field data collected from a sampling program.
	InVEST: Uses land use data and stocks of carbon stored in aboveground biomass, belowground biomass, soil, and dead organic matter to estimate carbon stored or the amount sequestered over time.
	ARIES: Estimates carbon balance by comparing emissions to probabilistic modeling of carbon sequestration and potential stored carbon.
	DNDC: Process-based computer simulation model of carbon and nitrogen biogeochemistry in agricultural ecosystems.
Recreation and tourism	**InVEST:** Uses empirical data on recreation to predict the spread of recreation based on the locations of natural habitats. If no empirical data is available, geotagged photos posted to the website Flickr are used a proxy.
	ARIES: Uses land cover that either contributes or detracts from recreational use, infrastructure promoting access to recreation sites, and beneficiaries to generate a relative valuation unit of recreation services provided.
	SolVES: Uses public value and preference surveys to map the perceived social value. If primary surveys can't be conducted, survey data from a previous analysis with comparable geographic features can be used.
Science and education	**SolVES:** Uses public value and preference surveys to map the perceived social value. If primary surveys can't be conducted, survey data from a previous analysis with comparable geographic features can be used.
Aesthetic	**InVEST:** Generates viewshed maps for marine and coastal communities to determine the visual footprint of new offshore development.
	ARIES: Utilizes probabilistic models of high quality views, features that degrade views, users' location and line of sight to determine spatially explicit relative aesthetic values.

Ecosystem Services	Tool/Model
Aesthetic (cont.)	**SolVES:** Uses public value and preference surveys to map the perceived social value. If primary surveys can't be conducted, survey data from a previous analysis with comparable geographic features can be used.
Biodiversity	**ABMI:** Uses the ABMI's Biodiversity Intactness Index which is based on long term biodiversity monitoring data, to demonstrate the impact land-use development on biodiversity.
	Industrial Heartland: Conducts a GIS based assessment of wetland biodiversity using nine metrics to assess a relative score for each wetland in the study area.
	CEAP: A wildlife habitat suitability model comparing field data on select species of habitat requirements with published literature of habitat requirements. Also quantifies upland floristic quality and species richness for cropped and restored catchments.
	InVEST: Models habitat quality and rarity as a proxy for biodiversity through combining data on land cover and threats to biodiversity.
	MN Wetland Tool: Prioritizes wetland restoration areas to maximize habitat (by considering biodiversity, species of concern, and bird habitat) using a restorable wetland inventory.

Flood Control, Water Supply and Storage

Three types of tools/models were reviewed that address ecosystem services with respect to water quantity: hydrological models (e.g., CRHM, SWAT), area-based tools (e.g., GoA, CEAP), and planning tools (e.g., InVEST). The hydrological models are function-based rather than ecosystem service models, requiring an additional step to translate outputs into service values. Because the hydrological models evaluate wetlands at the function level, they do not distinguish between potential flood control or water supply and storage. Therefore, a single review for each of these models is given below. The GoA Pilot tool considers ecosystem service assessment separately for both flood control and water supply and storage; therefore a separate review for each tool component, and how it might be applied in Alberta, is given. In total, nine models were reviewed to potentially evaluate water quantity-related ecosystem services: CRHM, SWAT, IMWEBS, the GoA Pilot, Industrial Heartland, CEAP, InVEST, ARIES, and HydroGeoSphere.

The CRHM hydrological model has been specifically tested on prairie wetlands and is designed for cold-weather regions like Alberta. It is suitable for small to medium catchments and is freely available with open-source code. As a fully distributed model, it is better able to model spatial variation in elements of interest through the target watershed. In addition, CRHM is one of the only models capable of modelling "fill and spill" dynamics, a key characteristic of prairie wetlands, as well as changes to contributing area as a result of drainage, changes in land use, and climatic variability (e.g., see Pomeroy et al. 2010, 2012, 2014 for the application of CRHM in Vermillion River and Smith Creek for wetland restoration and loss scenarios). However, the model is not fully integrated, focusing on surface water processes. Although the modelling components lead to highly detailed hydrology, this makes the model more data intensive and may be more detail than required, depending on the questions to be answered. There is some flexibility to the model in terms of the complexity of modelling based on available data and scale; however the model requires fairly advanced skills at this time in order to apply it. As the model is used on small to medium catchments, it is not a model to simulate hydrology province-wide. Ultimately, CRHM is more of a hydrological (i.e., functional) model than an ecosystem services model, and requires additional work to translate the outputs from hydrological terms to services. This translation step may be a barrier to some users.

SWAT is a hydrological model that has been widely used and applied in practice and in research. Because of this, much documentation is available, including numerous tutorials as well as training opportunities. A moderate level of expertise and knowledge of hydrology is required. Similar to CRHM, SWAT is a hydrological (i.e., functional) model that will require translation of the output to an ecosystem service value. The main limitations of SWAT are that it is a semi-distributed model and does not integrate surface and groundwater interactions. SWAT lumps all wetlands within a sub-basin, limiting the ability to observe the effect of a single wetland. The IMWEBs cell-based modelling system has a wetland module currently in development that will bridge this shortcoming.

IMWEBs shares many of the same model advantages as SWAT. It is relatively user friendly, while still requiring moderate to high levels of expertise in hydrology to operate it most effectively. Although it has high data requirements with potentially substantial effort to prepare the data for incorporation into the model, this gives the model great flexibility. The main advantage of IMWEBs over SWAT is that it maps one wetland per sub-basin compared with the more general modelling approach of SWAT with a single hydrological response unit containing many undistributed wetlands. Water retention capacity on a wetland-by-wetland basis can be determined. It is one of the only models capable of simulating changes to effective and non-effective contributing areas as a result of wetland drainage and restoration. Because the model is still in development, there currently is not enough documentation to provide a full evaluation of this model and its potential application for assessment of ecosystem services in Alberta; however, initial reviews suggest that important features such as accounting for changes to contributing area with wetland drainage or restoration, and antecedent hydrological conditions are present (W. Yang, pers. comm.). Overall, there appears to be many exciting developments for IMWEBS, suggesting the model may be potentially suitable for application in Alberta.

The GoA Pilot tool consists of two separate water quantity-based models: a flood control model and a water storage capacity model. The flood control model is based off the Industrial Heartland approach. While the data requirements are substantial, the methods used are fairly straightforward and do not appear to require a high degree of technical expertise to run. The GoA Pilot tool presents a good approach to trying to simplify a complex process (e.g., flood attenuation), improving over-measuring water storage alone. However, applying qualitative scores has limitations. The water storage model used is very similar to CEAP, but uses the Wiens (2001) volume-area relationship. A comparison of the performance of three volume-area relationships (see Figure 4.6 in Minke 2009), including Wiens (2001) and CEAP, suggests that Wiens' equation may not perform as well as one of CEAP's. The simplicity of both the GoA Pilot water storage model and the CEAP is both a strength and weakness; however, the weakness of simplification is somewhat attenuated by combining the water supply output with the flood control score.

The Industrial Heartland tool contains a flood control model. Although Cobbaert et al. (2011) note that “the highest value wetlands were often the healthiest” and large wetlands often score higher, this appears to be partially an artifact of how the score was designed, including the metrics that go into the wetland value scores. As noted in the previous paragraph, the limitation of using the qualitative score approach for valuing ecosystem services is that model and tool may unintentionally influence results through the selection of components of the score.

Similar to the GoA Pilot tool and the Industrial Heartland tool, CEAP uses an area-based approach to determining floodwater storage capacity. Although the model component of the CEAP tool is termed floodwater storage capacity, CEAP estimates water storage capacity based on wetland area. Note that the area used to develop the volume-area relationships is based on the elevation at which a wetland would spill, so this wouldn’t correspond to wetland areas delineated based on vegetation for example. The floodwater storage capacity model in the CEAP tool uses a mean wetland area for calculating water storage estimates; however, the model would be more accurate if it used actual wetland areas. Overall, this method produces conservative estimates of wetland storage capacity as it doesn’t account for dynamic hydrological processes that may attenuate the rate at which individual wetlands “fill and spill”. Nor does it account for that additional landscape storage of water achieved when wetland catchments merge and result in storage volumes greater than their sum. Should the CEAP tool be explored for application in Alberta some work would need to be done to translate the three zone system (i.e., Missouri coteau, prairie coteau, Glaciated Plains). The three zone system is used to account for differences in the wetland volume-area relationship with topography. Thus, ideally an Alberta equivalent would use a similar approach (e.g., categorize AB landscapes as coteau or plains based on topography/slope and use corresponding volume-area equations). The CEAP approach is stronger when there is a consideration of interception areas (e.g., as by Gleason et al. 2008); when considering the total precipitation falling on an area, what amount falls on land that lies within a wetland basin’s catchment? However, modelling interception areas to this degree makes this process considerably more complicated.

The InVEST tool has a water yield model more appropriate to address water supply and storage than flood mitigation as an ecosystem service. As this model is a component of a broad-based tool, rather than a wetland-specific one, no further consideration was given to considering this model for flood control as an ecosystem service for wetlands in Alberta.

Although ARIES has both a flood regulation and water supply modelling component to the tool, its complex statistical approach (i.e., Bayesian networks), and opaque model documentation, makes it difficult to recommend this tool without a better understanding of the mechanics of the modelling. In addition, it is a broad ecosystem service tool, rather than a wetland-specific one; therefore, no further consideration was given to ARIES as a model appropriate for the assessment of water quantity in Alberta.

HydroGeoSphere is another fully-distributed hydrological model that models surface and subsurface flow for lakes and wetlands. Similar to CRHM, it has been designed to model hydrology, rather than management scenarios as with IMWEBs. The model has been used on prairie wetlands; however, it places less emphasis on cold region processes than CRHM. There has been substantial scientific uptake of this model. Like the other ecosystem function models, its application would require a period of data calibration and verification, and it may be difficult to apply province-wide. In addition, the model itself is less user-friendly (i.e., does not have a geographical user interface) and requires the purchasing of a license to use the product.

Flood Control and Water Supply/Storage Summary

Overall, water quantity ecosystem services have the best range and number of options for assessment. Numerous models could be suitable, depending on what is the ultimate goal for output. In terms of the best model of prairie hydrology, CRHM is recommended. In addition, CRHM also has the advantage of an expected nutrient retention model (see 'Water Purification' review section). However, CRHM is data intensive and, as noted earlier, is a hydrological (i.e., functional) model, requiring extra translation for an ecosystem service output. Although SWAT would not be recommended, the updates currently being developed for IMWEBs are promising. Until detailed supporting documentation becomes available, the same level of evaluation cannot be applied that has been synthesized for other models, including a recommendation for application in Alberta. However, by incorporating both water quality (see 'Water Purification' section) and quantity into a single model, in addition to being specifically designed for prairie wetlands at the basin level, IMWEBs presents a potentially powerful option, particularly where wetland restoration is an activity of interest.

The simplicity of the CEAP water storage model, relying almost solely on having a wetland inventory, and its volume-area relationships, could be suitable for application in Alberta. However, although water storage is one of the most important aspects of how wetlands control floods, it is not the entire picture. Using the CEAP approach, the magnitude of wetland services will simply be a function of wetland area. Finally, the water storage and flood mitigation scores produced by the GoA Pilot and Industrial Heartland tools mitigates one of the downsides of using just wetland storage by attempting to account for the other factors that influence flood mitigation. However, a qualitative score provides less information than the quantitative hydrological models.

Water Purification

Ten models were reviewed that provide the potential for an ecosystem service assessment of water purification for wetlands in Alberta: CRHM, SWAT, IMWEBs, the GoA Pilot tool, Industrial Heartland, the ABMI tool, CEAP, InVEST, ARIES, and the Minnesota Wetland tool.

Although the CRHM model does not currently have functionality with regards to water quality, this module is undergoing research and development in order to eventually include this. Future review should be conducted once the model is developed to determine its potential application in Alberta. The model at this time is investigating using a coefficient for water purification based on wetland class.

SWAT can be used to model water quality based services, however its main limitation for application to water quantity based services is the same for water quality (i.e., lumping all wetlands within a sub-basin). The IMWEBs model that is in development (see 'Flood Control and Water Supply and Storage' section above) is slated to have a water quality component. During an initial review, IMWEBs appears to allow for the determination of nutrient sequestration and water retention capacity on a wetland by wetland basis, if so desired, based on wetland type and surrounding land use. As noted above, great potential exists where water quality and quantity-based ecosystem functions and services can be estimated in the same tool. As with CRHM, future review should be conducted once the model is developed to determine its potential application in Alberta.

The GoA Pilot tool consists of a water purification model, and is based off of the Industrial Heartland model. Although agriculture was not included as part of the pollutant source score in this model it does exist in the original Industrial Heartland version and would be recommended to be used should the GoA Pilot water purification model be applied within the White Zone of Alberta. Although the data requirements are considerable the methodology for water quality is relatively simple and it does not require a high level of technical expertise for application.

The water quality improvement model in the Industrial Heartland tool captures a variety of factors that contribute to a wetland's potential to sequester nutrients, providing a metric that is based on more than just wetland area. However, this nutrient model demonstrates one of the pitfalls of using a qualitative score as it allows for value judgements to be inserted. For example, the "Potential Significance" value will give more weight for water quality improvements to riparian wetlands versus geographically isolated ones. While there's some merit to this, the case could also be made that this represents an outdated view of the role of geographically isolated wetlands on the landscape. In addition, the model's methodology describing how the categories associated with each score were delineated (e.g., how were the wetland area classes defined and why were those scores assigned to each size class) was often lacking.

To model water purification as an ecosystem service in the ABMI tool it "identified source areas of pollutants, important areas for removing pollutants, and impacts to downstream water users" (Habib et al. 2016), making a direct link to the effect on human well-being. Nutrient retention was modelled after the InVEST tool's nutrient delivery ratio model. However, there are no wetland-specific parameters in the model, including no nutrient removal rates (T. Habib, pers. comm.). Wetlands may be represented inconsistently in the model, as either open water or as grassland/shrubland/forest. In addition, a number of removal efficiency assumptions for P, N, and total suspended sediments (TSS) are limiting. Removal efficiencies are currently based on different land covers, as well as assuming the same removal efficiency for all three pollutants, and need to be calibrated. The model also does not account for freezing conditions. Finally, the model notes that when interpreting pollutant removal outputs they should not be used to inform decision making since the calculations are based on assumed removal efficiencies and is intended to be interpreted when aggregated to a watershed or sub-watershed scale (Wilson et al. 2013).

The CEAP tool contains a sediment and nutrient reduction model; however, the model is mainly a soil erosion model. This model would be suitable if sediment loads are of interest in water purification assessment, but it is not ideal for measuring nutrients. In this model, nutrient loadings are calculated based on the amount of sediment. However, data from Tiessen et al. (2010) suggest that the dissolved fraction is more important than the particulate fraction for nutrient loading in receiving water bodies. Thus, this module is not recommended for nutrients.

The InVEST tool contains a nutrient delivery model that could be applied as a water purification ecosystem service assessment for wetlands. However, the tool is not focused on wetlands. Rather, they are modelled as nutrient sources, albeit small, with relatively high retention efficiency. The model appears to allow for the flexibility to change the values for nutrient sources and retention efficiency. It also includes both dissolved and particulate nutrient fractions, but is parameterized so that dissolved nutrient fractions are delivered via groundwater, not surface flow. Nutrient retention in InVEST is a function of more than just wetland area. It also reflects position within the watershed and the spatial arrangement of wetlands. It is not designed to model nutrient delivery in a mode relevant to prairie wetlands (i.e., in prairie wetland most nutrients are delivered during spring runoff and most in their dissolved form). Although it is potentially possible to adjust the model to approximate appropriate representation (e.g., by not expressing a dissolved particulate ratio to force all nutrients to be delivered via surface flow), this would require the user have a fairly high in-depth knowledge of the model. This aspect of the InVEST nutrient delivery model may be helpful from a planning perspective. Should the model be considered for application it would need to be coupled with a study of literature to parameterize certain numbers (e.g., export coefficients) to be appropriate for Alberta wetlands.

Similar to CEAP, the ARIES tool has a sediment regulation model, but it does not have a modelling component for nutrients. As noted previously, due to the limited documentation available for this tool, as well as being a broad, rather than a wetland-specific ecosystem service tool, no further consideration was given to ARIES as a model appropriate for assessment of water quality ecosystem services in Alberta.

The Minnesota Wetland tool is set up to prioritize areas for restoration. It does not provide quantitative water quality value estimates. In addition, because the tool was designed for Minnesota it would need to be generated for application in Alberta. For example, the water quality benefits decision layer contains some Minnesota-specific data (i.e., Environmental Benefits Index) and an Alberta equivalent would need to be identified. While the Minnesota Wetland tool has a fine resolution, with the water quality benefits layer applied within 30 m cell pixels, the stream power index used in the water quality benefits layer (for estimating overland flow) can provide only a rough approximation of “fill and spill” hydrology.

Water Purification Summary

Although ten models were reviewed that have the potential for a water purification ecosystem service assessment of wetlands in Alberta, there are limited options for a quantitative model of nutrient sequestration at this time. Even though it is currently in development, IMWEBs may be the best option for a quantitative nutrient model, and will likely be released prior to the CRHM water quality model. The nutrient delivery model of the InVEST tool could be used, but it is not designed specifically for prairie wetlands. In addition, InVEST would likely have the same substantial data requirements as IMWEBs, but with less functionality.

The Minnesota Wetland, Industrial Heartland, and GoA Pilot tools all provide acceptable qualitative water quality models, however the Industrial Heartland and GoA tools’ models are fairly data intensive, given that they only provide a qualitative score.

Climate Regulation

Five tools/models were reviewed to potentially evaluate climate regulation as a wetland ecosystem service. These include the GoA Pilot, CEAP, InVEST, ARIES, and DeNitrification-DeComposition (DNDC).

Carbon storage modelling in the GoA Pilot tool is based solely on wetland area and requires knowledge of wetland class. The focus is on Class III-V wetlands; however, if using imagery, users should be able to distinguish Class I and II wetlands from Classes III-V. Although the approach was used to look at historical wetland/carbon losses, it can be used to assess existing carbon stocks and understand the effects of future drainage. Note that estimates from this model may be conservative because the carbon loss rate applies to grasslands, not lands in agricultural production.

For CEAP, carbon storage was estimated from soil organic carbon (SOC) and volatile organic compounds data. CEAP greatly resembles the GoA tool but has different carbon storage rates for different land uses. Although land use would be a valuable added dimension to area-based estimates of carbon storage, CEAP storage rates might not represent a major improvement over those used in the GoA Pilot approach as the GoA model is based on data from sites in the Canadian PPR (i.e., values from Badiou et al. 2011). In addition, CEAP only assessed carbon stocks down to 30 cm and a recent inventory of wetland carbon stocks in the US shows that substantial reduction in SOC has occurred below 30 cm (Nahlik and Fennessy 2016). Additionally, there was no mass equivalent correction applied to these cores and there were likely substantial differences in the time horizon represented by these cores across the different landscape elements.

For InVEST, carbon storage is represented as four pools: aboveground biomass, belowground biomass, soil and dead organic matter. This framework is not ideal for prairie wetlands, though the model can be run based on only one of the four pools. Addressed as an important note by the tool, although most landscape carbon storage and sequestration rates consider only mineral soils, SOC in organic soils must also be considered for wetlands (Sharp et al. 2016), including carbon releases with land use conversion in wetland areas (IPCC 2008). This model cannot parameterize carbon accumulation within a single land use type through time. Instead, it focuses on changes in carbon storage with land use conversion. Thus, a detailed land use inventory is essential for best results.

Although ARIES has a carbon sequestration and storage modelling component to the tool, due to the complexity in its use of Bayesian networks where insufficient local data exists, as well as opaque model documentation, it is difficult to recommend without a better understanding of the mechanics of the modelling. It is a broad ecosystem service tool, rather than a wetland-specific one; therefore, no further consideration was given to ARIES as a model appropriate for assessment of climate regulation in Alberta.

DNDC is a process-based model of carbon and nitrogen biogeochemistry in wetlands. Although it is not prairie-specific, it represents many processes (e.g. water table dynamics, growth of mosses and herbaceous plants, and soil biogeochemical processes under anaerobic conditions) that apply to prairie wetlands. Field validation of the model has not been completed on pothole wetlands. The model is very detailed and data-intensive, making the DNDC difficult to recommend for climate regulation ecosystem service assessment.

Climate Regulation Summary

Overall, there were limited options for wetland carbon storage models. Although carbon sequestration is a function of more than just wetland area, that knowledge hasn't necessarily been converted into a usable model from which an ecosystem service could be obtained. The best option for Alberta might be to consider carbon storage as a function of wetland class (i.e., III-V) area, as in the GoA approach. Note that this approach could be refined by combining information on land use from CEAP, but would not be recommended solely using estimates of carbon storage from the American PPR.

Cultural Ecosystem Services

Three models have been selected as potential tools appropriate in Alberta for the assessment of cultural ecosystem services: recreation and tourism, science and education, and aesthetics. Cultural ecosystem service assessment has different data requirements compared to provisioning, regulating, or supporting services. Of the three models reviewed, options for survey-based vs. data-intensive models are presented. No specific recommendations for tools to evaluate cultural ecosystem services in wetlands is given in this report, as an initial decision on the level of detail required for cultural services, and whether to utilize a survey-based or data-intensive model, must be confirmed. However, there are a number of considerations when using a survey-based approach to assess cultural ecosystem services (e.g., Social Values for Ecosystem Services (SolVES)). First, surveys are frequently hampered by a non-response bias. Where response rates are low, survey administrators receive no perspective as to whether nonresponse is random, or opinion-based. Second, use of the Likert scale (i.e., as in SolVES), a 5 to 7 point scale where responses range from strongly agree to strongly disagree, often results in neutral (i.e., mid-range) responses as participants hesitate to favour one extreme. Third, particularly for environmentally-targeted surveys, responses can be biased by what is considered to be the 'socially-acceptable' opinion (e.g., choosing to value wetlands for their provision of freshwater). Should users wish to use a survey-based cultural service assessment, two model considerations should be incorporated. First, be specific and realistic, helping respondents to take the assessment seriously. Giving survey participants a fixed hypothetical budget as part of a willingness-to-pay approach can elicit what wetland services and processes are most valued. Second, following survey completion, determine the validity and confidence in responses. Documentation of the methodology used to validate will allow for stakeholder confidence in the approach. At a high level, the simplicity of a qualitative score for 'social value', as applied in the Alberta Industrial Heartland tool, may be a good approach when considering the cultural ecosystem services of wetlands.

With respect to incorporation of cultural ecosystem services into an ecosystem service assessment for wetlands, a point of caution during the assessment phase is recommended. Often social values and ecological functions do not align. That is, depending on a wetland's position with respect to a metropolitan area, cultural ecosystem services may be valued more highly, while the ecological function of the wetland may not be more important. Therefore, the effect of population (e.g., density, hedonic value, etc.) on any model's output of ecosystem services must be considered, or at a minimum presented with a caveat to the effect on a wetland's ecosystem function and resulting ecosystem service. However, the importance of cultural ecosystem services should not be overlooked in a wetland ecosystem service assessment, as cultural services often rank higher than regulating services in surveys of perceived importance (e.g., aesthetic more highly valued than water quality regulation and flood control to individuals; Government of Alberta 2011a). Overall, priority should be given to the ecosystem services most important to a stakeholder group, including the appropriate model or tool to most accurately assess that service.

Recreation and Tourism

During the review process, three models were identified as tools appropriate to the assessment of recreation and tourism as an ecosystem service for Alberta: InVEST, ARIES, and SolVES.

InVEST (Sharp et al. 2016) considers recreation and tourism as an ecosystem service (hereafter referred to as recreation) in terms of location value and pattern of use. Similar to the ability of some of the tools to connect aesthetic as an ecosystem service to biophysical data (e.g., correlation of slope to use by motorized vehicle users in SolVES), InVEST can estimate the contribution of landscape features to recreation use. One limitation of models using biophysical information is that the ability to apply the tool can be limited by data availability (i.e., recreation use rates). In the absence of use rates InVEST allows for the use of geotagged photographs from flickr as a proxy for visitation (i.e., photo-user-day estimates). Limitations of the InVEST recreation and tourism model are that the model is not driven by predictor variables having an effect on tourism, but rather estimates the effect that these variables may be having on use.

ARIES (Bagstad et al. 2011) approaches recreation, as with the other service areas in this tool, on a source and sink basis, with sources being natural settings capable of supporting recreational activity and sinks being landscape features that may limit recreational activity. Similar to the aesthetic probabilistic model approach for ARIES, assumptions are made including consumption vs. distance rate (e.g., a user will travel more frequently to a closer recreational use area, less frequently to a further recreational use area). Similar to InVEST, by using biophysical information (e.g., user data such as population or housing density, ZIP/Postal code data for user origin, or alternate proxy for user data such as hunting licenses issued), ARIES application can be limited by data availability. Although the model allows for flexibility depending on the recreational use identified for focus, it does not allow for consideration of different communities preferring different recreational uses, as SolVES can allow for.

The approach used to consider recreation and tourism as an ecosystem service in the SolVES tool (Sherrouse and Semmens 2015) is to identify the perceived social value the public has for recreation in a particular area based on spatial and non-spatial survey responses. Limitations of the model include that survey results often cannot be transferred from one area to another since recreation preference can be region-specific. SolVES is currently in development of a value-transfer methodology where biophysical and socioeconomic context is similar. Modelling is not done on an ecosystem service by service basis. It is up to the user to distinguish services separately during the output phase because of the survey-based approach of SolVES. Therefore, the approach described above for recreation is the same, in terms of data requirements and model outputs for science and education, as well as aesthetic. Based on this review, the SolVES model output may not be easily interpretable or meaningful from a planning perspective. For example, the environmental gradients in relation to value index would have many relationships, depending on how many subgroups are selected. Statistically akin to 'analyzing everything', this may lead to the detection of spurious relationships.

Recreation and Tourism Summary

For both the ARIES and SolVES models for recreation, one limitation is that by categorizing recreational users by type (e.g., hunters, motorized vehicle users), risk exists of assuming similar user preferences within a recreational user category. For example, not all hunters (e.g., urban vs. rural) may exhibit similar recreational use patterns. Bagstad et al. (2011) noted that caution needs to be given for biophysical models such as ARIES, and assumptions made on recreation use, user choice and distance travelled, as little spatial information on recreational value exists in the literature. Finally, although InVEST provides the option of Flickr and photo-user-day estimates as a proxy for visitation, Brown et al. (2014) note that when evaluating cultural services, indicators using social media were found to be less useful to decision-makers as opposed to indicators using environmental spaces. Although consumption of cultural ecosystem services may be of interest for some stakeholders, evaluation of the supply, demand, accessibility, and quality of environmental spaces (i.e., as evaluated using ARIES) is preferable at a local level.

Science and Education

During the review process, only one model was identified as a tool appropriate to the assessment of science and education as an ecosystem service for Alberta: SolVES.

SolVES (Sherrouse and Semmens 2015) considers science and education (identified in the model as 'learning value') as an ecosystem service. Out of the tools reviewed as part of this process, it is the only one that models science and education. SolVES defines science and education as an ecosystem service, as the value that can be gained from an environment through scientific observation and experimentation. As noted above, as a survey-based tool the data requirements and outputs for SolVES are the same across all services evaluated. Therefore, for further information on the model requirements for science and education assessment, see the 'Recreation and Tourism' assessment for Tools Most Appropriate to Alberta.

Aesthetic

Three models were identified during the review process as tools appropriate to the assessment of aesthetics as an ecosystem service for Alberta: InVEST, ARIES, and SolVES.

InVEST (Sharp et al. 2016) considers landscape, aesthetic, amenity, and inspiration as an ecosystem service (hereafter referred to as aesthetic) in terms of the aesthetic value derived from viewsheds. The InVEST scenic quality provision model quantifies the impact a visual obstruction may have on a view, particularly for marine and shoreline environments. For example, the model can estimate the impact of offshore windfarms on marine coastal views. The impact is targeted on the negative effect a development may have on view, but can also be designed to estimate the positive impact a development may have on view. Although impact to viewshed of the potential development/obstruction is considered in three dimensions (i.e., footprint and height of the development, considering topography and bathymetry from the digital elevation model (DEM)), it currently does not take into account the potential impact of other obstructions (e.g., vegetation, skyline) to the viewshed value.

Similar to InVEST, ARIES (Bagstad et al. 2011) considers aesthetic as an ecosystem service in terms of aesthetic value derived from viewsheds, as well as aesthetic proximity. As a line of sight model, like InVEST, aesthetic viewshed attaches value (in abstract units for 'scenic beauty') based on potential views (i.e., source), potential users, and obstructions to view (i.e., sink). A portion of the value calculation is dependent on housing values, with the assumption that higher housing values are related to more valued viewsheds (Sander and Polasky 2009). Due to the probabilistic model design of the ARIES tool, in order to attach value to aesthetic as an ecosystem service, it requires expert opinion to make assumptions on the effect that landscape type and obstruction may have to viewshed value. For example, a probabilistic assumption that is made is that infrastructure between a user and an open space depletes value by 50%. Or, for example, that alpine views are more valuable than wetland views in a particular landscape. Outputs from the model include maps of aesthetic value for an area. Bagstad et al. (2011) note that aesthetic preference can be region-specific, and where possible, assumptions should be based on preferences demonstrated in the literature, or on expert opinion of how landscape is valued in a particular area. A limitation similar to InVEST is noted, that viewshed blocked by vegetation or skylines is not currently considered, but could be accounted for using LiDAR data.

The approach to measure aesthetic as an ecosystem service in the SolVES tool (Sherrouse and Semmens 2015) differs from InVEST and ARIES in both the definition of aesthetic and the data requirements. Rather than estimating aesthetic value from biophysical data, it relies on public value and preference surveys to map perceived social value, including public preference for scenery, sights, sounds, smells, etc. for a particular environment. Instead of considering viewshed, it considers the weight that respondents place to an area's aesthetic value, as well as identifies specific locations where aesthetic has high value. This information can then be compared, in the model, to various biophysical features, such as distance to water, or land cover type. As noted above, as a survey-based tool, the data requirements and outputs for SolVES are the same across all services evaluated; therefore, for further information on the model requirements for aesthetic assessment, see the 'Recreation and Tourism' assessment for Tools Most Appropriate to Alberta. Note that there are also a number of other services that are evaluated as part of the survey used in SolVES, including cultural value (e.g., the ability to pass down wisdom and knowledge, traditions, and way of life of my ancestors), intrinsic value (e.g., valuing an environment in and of itself, regardless if people are present or not), spiritual value (e.g., an environment as a sacred, religious, or spiritually special place, where reverence and respect for nature is felt), and therapeutic value (e.g., the ability of an environment to make someone feel better, whether physically or mentally).

Aesthetic Summary

InVEST and ARIES both provide similar approaches to aesthetic ecosystem service, in terms of viewshed; however, to provide a baseline understanding of the aesthetic value of a particular wetland type to Albertans, the way in which the viewshed models have been structured (e.g., determining the effect that an obstruction may have on value) may not be applicable. In addition, Bagstad et al. (2013)

noted that in ARIES, for example, because of how these models incorporate user information (e.g., location, density, etc.), rising demand for an ecosystem service with an increase in population can be linked to an increase in value, even as an ecosystem is degraded. Alternatively, the SolVES tool approach to modelling aesthetic as an ecosystem service can get at the specifics of value weight and location that Albertans place on wetlands, including for different stakeholders and user groups. However, surveys are an intensive method of data acquisition that may not easily be transferred from one area to another.

Biodiversity

Five models existed to potentially evaluate biodiversity as a supporting wetland ecosystem service: ABMI, Industrial Heartland, CEAP, InVEST, and the Minnesota Wetland Tool.

Two of ABMI's major strengths is that it has the most extensive data source for biodiversity in Alberta and modelling biodiversity is a focus rather than one model among many. The physical and chemical wetland parameters that are being measured include those that drive important biodiversity gradients (e.g., specific conductance/salinity) and thus are important to account for. The approach of modelling biodiversity as a function of human footprint, as well as ecosystem and spatial features, is a sound one, allowing users to potentially distinguish major ecological gradients from the disturbance effect. Evidence of careful, thorough consideration in data analysis is given and the methodology is generally clear about assumptions made (e.g., additive footprint effects) and articulates plans to test assumptions or improve the model whenever possible (e.g., move from a 250 m buffer to the more relevant wetland catchment area). Note that the vegetation and aquatic macroinvertebrate protocols are much stronger than the vertebrate sighting protocols for wetlands. In addition, a province-wide modelling effort will be hampered by lack of wetland inventory and the need to collect physical/chemical covariates from each wetland.

For Industrial Heartland, biodiversity is assessed using nine equally weighted metrics. Although the output only provides a qualitative score, the metrics that go into the score make sense for determining a biodiversity value for wetland area. However, the model does not value a diversity of wetland sizes over a specific wetland size. Incorporation of this understanding would be an improvement.

Biodiversity is assessed as two components in CEAP: plant community quality/richness and potential wildlife habitat suitability. The model uses floristic quality index for plant communities, but requires knowledge of the relationship between plant species and disturbance, in addition to detailed plant community data. For the wildlife habitat suitability component, CEAP is designed to be flexible and could be used for any species if enough data and information on habitat requirements exists. Note that CEAP was not designed to collect biodiversity data, but rather habitat suitability (e.g., use visual obstruction of nest sites and minimum area requirements as defined from literature to look at habitat suitability for 10 bird species; Gleason et al. 2008). Overall, the wildlife habitat approach to assess biodiversity is weak, although possibly defensible in the absence of any data and if not used for planning purposes. If the modelling target was a select species of concern, rather than all diversity, its potential for use may be greater.

Biodiversity is not modelled directly in InVEST, but is instead a function of habitat quality and rarity. Although wetland data inputs may not exist, they could be developed. Sharp et al. (2016) acknowledge that this model gives only a coarse view of biodiversity. In addition, although economic components in addition to biophysical value exist for other models in the InVEST tool, the potential to determine the economic value attached to biodiversity does not exist.

The Minnesota Wetland tool is set-up to prioritize areas for restoration. It does not output quantitative habitat value estimates. The biodiversity benefits layer in the Minnesota Wetland tool is actually a biodiversity-recreation hybrid in that it explicitly incorporates number of game species. In addition, the components of the habitat benefits layer seem to be based on available state-wide data rather than a priori decisions about what's most important to biodiversity. Therefore, due to the approach of this layer in the Minnesota Wetland tool, it is not a recommended option for estimating biodiversity ecosystem service in wetlands of Alberta.

Biodiversity Summary

Overall, the ABMI approach is by far the best model to represent biodiversity as a supporting wetland ecosystem service for Alberta. Although the qualitative score provided by the Industrial Heartland model is an average option for assessing biodiversity, its flaw lies in valuing large wetlands over other sizes. In addition, the InVEST biodiversity model would not be recommended as it makes large assumptions about what habitat characteristics are associated with biodiversity. Although this approach may be sufficient in areas where data is lacking, for Alberta this does not make sense to employ these major assumptions where actual biodiversity data exists. Finally, although the Minnesota Wetland Tool incorporates biodiversity components into its tool, this portion of the tool does not have the same complexity as other models reviewed, and is based on available data. Therefore, no further consideration was given to its use in Alberta.

4.0 Examples of Jurisdictional Application of Wetland Ecosystem Services

Despite the recognition of the value of services provided by wetland systems, existing tools for assessing and valuing ecosystem services often fall short of the needs and expectations of decision makers (Keeler et al. 2012). One challenge lies in connecting ecosystem service tools with benefits to human well-being (Bateman et al. 2011). Another challenge may include the lack of wetland policies that encourage and support the use of service tools for land planning and wetland protection. The inability to connect ecosystem service assessments to land planning, insufficient site data to support ecosystem service models, and an inability to apply working tools from other jurisdictions to new regions also challenge the use of ecosystem tools and models for wetland planning.

As part of this ecosystem service study the developers of wetland ecosystem service tools from four jurisdictions were interviewed. It was important to understand how successfully these wetland tools were being applied, if they were being used effectively for land planning purposes, and if the creators of the tools were experiencing any shortcomings with either tool application/uptake or modelling weaknesses. The four jurisdictions investigated were: Minnesota (Minnesota Restorable Wetland Prioritization Tool), Credit Valley (economic valuation of wetland ecosystem services), North Dakota (CEAP/Integrated Landscape Modeling), and Delaware (statewide wetland valuation with InVEST). The initial intention of the jurisdictional investigation was to identify three jurisdictions with priority given to those in the PPR or those that had conducted province wide or state wide assessments. Minnesota, North Dakota and Delaware were the initial three chosen and although the methods used by Credit Valley were not examined in detail in this report, it was deemed important to have a Canadian example in the review.

Minnesota

The Minnesota Restorable Wetland Prioritization Tool was developed for the state of Minnesota to identify strategic locations for wetland restoration that maximize water quality benefits or habitat improvement. The tool was developed by the Natural Resource Institute at the University of Minnesota in conjunction with the Minnesota Pollution Control Agency. The intention of tool was to develop an online system that local governments (i.e., cities, counties, or watershed districts) could use to target areas for restoration at an intermediate scale. The original intention of the project was to use the tool to qualitatively identify subregions within a watershed where wetlands could be restored followed by the application of a site specific modelling process once these larger subregions were identified. This detailed model would consist of a data intensive hydrological model to quantitatively estimate the water quality (e.g., nitrogen, phosphorous, sediments) and water quantity benefits provided by wetlands. The more detailed hydrological model was not developed at the time as resources were not available; however, there still remains interest in developing a site-specific quantitative model to complement the existing online tool. The intention of the tool was a qualitative measurement of water quality and habitat. After completing a literature review, the Minnesota team found no suitable methods for measuring these two services for Minnesota wetlands.

This led the tool developers to create their own models as opposed to using existing ones. The tool is made up of a Restorable Wetland Inventory (RWI) along with three decision layers: stress, benefit, and viability. The three decision layers can be examined individually or weighted by the end user which allows for examining only the services or stressors of interest. The weights of each of the variables within the decision layers were determined by a combination of a literature review and expert judgement. The RWI was relied upon to identify areas of potential restoration since the current wetland inventory for Minnesota does not include drained or altered wetlands. The tool is kept current through updating the background data as new data becomes available (i.e., higher resolution DEM, updated soils data, updated land cover data). The tool developers are more focused on keeping the background data current than developing any new benefit layers although there is interest in developing a flood control benefits layer in the future. Minnesota is currently updating a state-wide wetland inventory using the National Wetland Inventory Plus (NWI+) standards. This inventory includes attributes that are aligned with the Enhanced Classification for Landscape Position, Landform, Water Flow Path, and Waterbody Type (LLWW classification; Tiner 2014). The hydrogeomorphic attributes that the LLWW classification provides can be used to allow for the creation of an additional benefits layer associated with flood control.

The largest challenge associated with the development of the Minnesota Wetland tool was assigning weights to variables within the models. For example, determining the relative impact of different land cover types (e.g., human development, pasture, cropland, or barren land) on the stress decision layer. The method for assigning weights began with a literature review to determine a range of acceptable values. Once the range of values were determined a panel of experts were assembled who voted on the most suitable weight for each of the variables within the models. The tool developers found that in most cases the results of the voting process led to values right in the middle of the predetermined acceptable range. They attributed this to members of the panel choosing a value in the middle if they were unsure where the proper placement should be. As a result the developers were not confident in the results and in turn went to an external peer review process. Experts in each of the fields determined the acceptable weights of each of the model components to be more reflective of the mechanisms they were trying to capture. The tool developers were confident in the findings of the external peer review and subsequently used these values for the variables within the model. Another challenge has been determining the usage of the tool since its creation. The use of the tool is optional and not a requirement in any state regulations. The tool developers monitor the webpage visits as an indicator of its usage but have no way of knowing if the tool has been used to identify an area for restoration that consequently resulted in a restored wetland. They have expressed interest in developing a survey or some other form of tracker to build in additional data collection to gain a better understanding of how the tool is being used.

Delaware

The state of Delaware conducted a statewide assessment of the ecosystem services provided by wetlands (Delaware Department of Natural Resources and Environmental Control 2011). The initial driving force of the wetland valuation study was partly due to coastal storms that had produced major flood events in the state. Consequently, the state was interested in quantifying how land use decisions were impacting both natural resources in general. More specifically, they were interested in understanding the benefits provided by wetlands in terms of both biophysical change as well as the associated economic value. By placing an economic value on retaining wetlands, the results from the study could potentially be incorporated into the land use decision making process to minimize wetland loss. For example, it was intended that the results could highlight the cost savings associated with water treatment through keeping wetlands intact as opposed to draining wetlands and constructing a water treatment plant. Additionally, Delaware has the advantage of being a small state which makes it more feasible to conduct a state-wide analysis. The study used InVEST to value the change in ecosystem services associated with continued trends of wetland loss in the state. InVEST was chosen as it is a spatially explicit tool that is capable of modelling several ecosystem services and is able to assess the changes in terms of biophysical changes as well as the associated economic value resulting from continued wetland loss. The ecosystem services that were assessed included carbon storage, water purification, and flood control (i.e., both inland and coastal storm protection). There was interest in using InVEST to estimate changes in additional ecosystem services but with limited resources and data available the state prioritized the services that were seen as being the most important to residents.

Overall the study provided a good local valuation of the benefits of wetlands which was seen as being needed to fuel wetland conservation in the state, although it wasn't without its challenges. One of the greatest challenges associated with conducting the study was obtaining data on local values for the various data requirements in InVEST. For example, this included data on nitrogen and phosphorous uptake rates, or carbon storage for each of the wetland types in Delaware. Although this study provides a strong example of conducing a jurisdictional-wide valuation of wetlands using a well-known ecosystem service tool, the results have not been used for planning purposes related to retaining wetlands as was originally intended. The valuation was not related to any policy or regulation and thus far has not been used to guide land planning decision making.

Credit Valley Conservation

Credit Valley Conservation (CVC), located in southern Ontario, conducted an assessment of natural capital and ecosystem services in the Credit River Watershed to understand the value provided by natural land cover types (Kennedy and Wilson 2009). The intention of this initial valuation was to highlight the importance and determine the value of natural capital at a coarse scale which could then be used to build awareness of the value of ecosystem services. The study recognizes that the methods employed for the valuation study sacrifice precision in order to achieve a cost effective initial assessment. However, they still felt that this method would highlight the attention that ecosystem services should receive when making land-use decisions. The results from this study were used to inform future studies specific to wetlands that eventually lead to the development of programs to support wetland restoration (Kant 2016). The initial natural capital assessment approach used a benefit transfer method, which relies on monetary values of ecosystem services determined from studies in other regions that is then adjusted for exchange rates, inflation or difference in income levels and applied. This was then applied to the land cover types in the Credit River Watershed. This initial valuation study was conducted on seven land cover types that included upland forest, riparian forest, urban forest, wetland, meadows, agriculture, and water. Wetlands were found to provide the highest total and per capita value of all land cover types which was largely a result of the benefits provided in the form of waste treatment. The results of this initial valuation led to wetland specific studies to better understand the value of wetlands to residents in the watershed.

A contingent valuation method study was conducted with residents in the watershed to estimate the willingness-to-pay for various wetland services. The survey results indicated varying degrees of willingness but in general, respondents indicated they were willing to pay for wetland conservation. CVC recognizes the caveats that are involved in these types of studies. For example, “yea-sayers” (i.e., those that respond in a particular way without fully considering the impact of monetary considerations), may bias the results (Lantz et al. 2013). As well, future surveys are needed on a regular basis to keep the valuation current since market demand changes. An additional bias associated with using the contingent valuation method is the sequencing effect where the willingness to pay differs depending on the order of the questions (Lantz et al. 2013). Lantz et al. (2013) discusses the various biases inherent with the methodology from the CVC study. Even with these reservations the CVC study still allowed for a general understanding of the level of interest, an estimate of value, as well as an indication as to what residents are willing to contribute to wetland conservation. This willingness-to-pay study was complimented by an additional study of rural landowners of both farmers and non-farmers gathering their perspectives on wetland conservation (Trenholm et al. 2013). This study examined landowner’s preferences towards wetlands, the willingness of landowners to participate in wetland conservation activities, and evaluated compensation preferences for wetland conservation.

The findings from the initial valuation study along with the results of the willingness-to-pay and landowner preference surveys highlighted the importance of wetlands to residents in the Credit River Watershed which motivated CVC to develop a wetland environmental benefit index (EBI). The wetland EBI is based on biophysical (biological and hydrological) and social attributes created to measure the changes in ecosystem services resulting from restoration and was developed with the intention of being used in a reverse auction process (Kant 2016). This will assist CVC in decision making to prioritize potential restoration projects to maximize benefits provided by the restored wetlands. The EBI was only recently developed and has not been applied in a wetland restoration project yet. The CVC is intent on incorporating its use in comparing restoration options. While the original valuation study offered a coarse approach in estimating the benefits provided by wetlands it was an important first step in developing wetland restoration strategies for CVC.

North Dakota

The United States Geological Survey (USGS) conducted a study in collaboration with the United States Department of Agriculture Farm Service Agency and Natural Resources Conservation Service to both develop and apply methods to quantify changes in the ecosystem services provided by wetlands resulting from wetland conservation initiatives. The models developed in this study were published in Gleason et al. (2008) as part of the CEAP and are summarized in Appendix B. Currently, the USGS is using the field data collected and the initial models developed by the CEAP to further develop tools to assess the ecosystem services associated with changes in land use. This program is known as the Integrated Landscape Modeling (ILM) partnership (Mushet and Scherff 2017). The ILM partnership has two main components: one intended to measure broadscale regional trends and the other focused on more detailed processed based modelling at the wetland level. To measure broadscale trends in the changes of ecosystem services resulting from various scenarios of land cover change, the ILM partnership is using the InVEST tool. InVEST is being utilized to quantify changes in amphibian habitat, carbon storage, plant communities, pollination services, and waterfowl/grassland bird habitat. The Agricultural Policy/Environmental Extender (APEX) is used as the processed based hydrological modelling system for ecosystem service quantification. APEX operates at the field scale to quantify the water, sediment, and nutrient outputs. Although it was designed without specific capabilities for depressional wetland systems such as those in the PPR, ILM is working to develop APEX to reflect these types of systems. The combination of the broadscale ecosystem service capabilities of InVEST along with the fine scale modelling of APEX allow for the assessment of a broad suite of wetland functions and associated ecosystem services at varying spatial scales.

The quality testing to date of the ILM model has focused mainly on the PPR. Some of the challenges that exist in the application of the model is its requirement for locally or regionally collected data. Certain model parameters also require input by experts for valuation (i.e., FQI coefficients to run the plant communities model). The model is also better suited at this time to assess ecosystem services provided by habitat quality and biodiversity than for wetland services connected to water quality or quantity. While the tool would be beneficial for use by conservation organizations and Provincial/Federal regulatory agencies, it provides limited use at this time by those urban centers and municipalities interested in wetland services that provide for improved flood control or water purification.

Jurisdiction Summary

The jurisdiction investigation provided valuable insight into integrating ecosystem services into land management practices. Key considerations were determined not only for the ecosystem tools themselves but also for understanding the requirements for successful uptake and use of the tools. For example, the Minnesota Restorable Wetland Prioritization Tool is easily accessible online with a user friendly interface. However, without being able to track the use of the tool there is no way of determining whether the tool is being used as intended. Without a strong policy related to wetlands, the statewide study in Delaware has not been used to guide land use decisions. CVC used economic valuation as the foundation for their studies with both the initial valuation and public surveys. These methods allowed for the development of the wetland environmental benefit index (EBI). In addition to some of the challenges associated with public surveys (i.e., response rate or yea-sayers), surveys will have to be periodically updated in order to have an accurate measure of market value. The ILM partnership from the USGS demonstrated that no single tool can cover every ecosystem service and more than one spatial scale may be required. The ILM relied on InVEST for looking at broadscale trends in habitat and carbon sequestration and developed a fine-scale tool for water quality and quantity quantification. Common themes were found in all jurisdictions related to the ease of use of the tool and single stakeholder developments. For example, do people know the tool exists and is it easy to apply? Is the tool more likely to be used if multiple stakeholders are involved in development rather than one stakeholder? What was an important theme in all jurisdictions was the necessity to pair ecosystem service assessments with a strong wetland policy. Without a wetland policy in place there was little drive to apply the results of the ecosystem service assessment into land management decisions no matter how strong the assessment tools may be.

5.0 SUMMARY

For the tools and models reviewed for each ecosystem service, the potential opportunities and limitations for application in Alberta were presented. For water quantity (i.e., flood control, water supply and storage), a number of options were identified as potentially suitable for application in Alberta, from more data intensive ecosystem function models such as CRHM, to simpler area-based tools such as CEAP. Although many tools and models were reviewed that have the potential to evaluate water purification as a wetland ecosystem service, limited options were appropriate, with the model that has the most potential (i.e., IMWEBs) still in development (Table 5). With respect to climate regulation, there were limited options for tools and models evaluating carbon storage in wetlands. Although we know that carbon sequestration is a function of more than just wetland area that knowledge hasn't necessarily been converted into a usable model from which ecosystem service could be obtained. Therefore, the model for carbon storage assessment used in the GoA approach is considered to be the best option at this time (Table 5). Of the cultural ecosystem services evaluated (i.e., recreation and tourism, science and education, and aesthetics), three tools had the potential for assessment in Alberta. These include InVEST, ARIES, and SolVES. Selection of one tool over another will depend on the preferred approach for assessment: survey-based or data-intensive. However, consideration of survey biases and incorporation of methodology to improve data credibility should be considered carefully prior to proceeding with a survey-based tool (i.e., SolVES). Rather, depending on the priority of cultural ecosystem service assessment to Alberta stakeholders, the simplicity of a qualitative score for 'social value' (i.e., Alberta Industrial Heartland tool) may be more appropriate. Finally, the major strength of ABMI's biodiversity model is its extensive dataset, making it the recommended supporting ecosystem service assessment approach (Table 5).

Based on the model and tool review process for the assessment of wetland ecosystem services in Alberta, a number of guiding principles for recommendations on assessment can be summarized:

1. **Identify the key wetland ecosystem services for assessment.** Direct the main effort to quantifying those ecosystem services that are considered to be most important to Alberta stakeholders. Priority ecosystem services may vary by watershed or municipality, and an ecosystem service assessment should reflect this. For priority wetland ecosystem services, identifying the questions to be answered and the level of detail required will assist in model selection. For ecosystem services not identified as a priority for assessment by stakeholders, models that output qualitative scores could be used, requiring less input data but still allowing for an assessment to be made.
2. **No one tool should be considered for wetland ecosystem service assessment.** Selecting a single tool, such as InVEST, can quantitatively model many services but may do so sub-optimally. Select the model that provides the best representation of the ecosystem service to be evaluated.
3. **Favour tools/models that include wetlands.** General landscape planning tools, such as InVEST and ARIES, may require unnecessary time compiling information and parameterizing aspects unrelated to wetlands. Where possible, select a tool or model that can reflect wetland types specific to Alberta.

4. **Identify the resolution required and the data available.** More nuanced models will base ecosystem services on more than just wetland area; however, with some wetland ecosystem services, area-based models may be the only method of assessment, depending on the data available, or may produce the required output with fewer data requirements.
5. **Consider the user of the tool.** If models are too data intensive or the model is too difficult to run, it is unlikely the tool will be widely adopted.
6. **Consider the output.** Qualitative scores, in comparison to quantitative values, offer the opportunity to simplify assessments and may require less data but shouldn't be solely relied upon for assessing provisioning, regulating, or supporting services. Note that qualitative scores are often the only option for the assessment of cultural services.
7. **Weigh biophysical assessment versus economic valuation.** Economic quantifications can be more meaningful if they are based on high quality biophysical data. For this reason, a model should not be prioritized only because it directly incorporates economics, as this may involve rejecting the best biophysical model available for an ecosystem service assessment. Strong biophysical data sets can provide a longer shelf life than tools or models only based on economic valuations.

Having considered the seven guiding principles listed above, particularly #1, an assessment of the data requirements to operate the models of interest should be completed. Commonalities exist across all models, in terms of the indicators they require for ecosystem service assessment. Priorities for data requirements should target:

1. **A wetland inventory,** including class, type, size, landscape position, and impact (e.g., drained, farmed, etc.). A wetland inventory is necessary for every single model and should thus be a priority. Consider the type of wetland inventory to be used such as the Canadian Wetland Classification System (CWI; Adams et al. 1997), the Alberta Wetland Classification System (AWCS; AESRD 2015), or Stewart and Kantrud (1971).
2. **A land use map,** including habitat type, agriculture type, crop use, federally or provincially protected areas.
3. **Topography/elevation/LiDAR/DEM**
4. **Watershed/subwatershed boundaries**
5. **Soils data**
6. **Climate data**
7. **Population data,** including population density, housing density or housing prices.
8. **Infrastructure data,** including road networks, drainage infrastructure, and infrastructure in support of recreational activities (e.g., campgrounds, trails, etc.).

White Zone management plans will generally be based on landscape (i.e., GIS) assessments. For example, for the Industrial Heartland tool, management plans were based on landscape assessments, even though rapid field assessments were also conducted. It will be important to determine the likelihood of future data availability as technology and information availability is changing rapidly. For example, there is currently no complete, publicly available LiDAR coverage for Alberta, nor is there a complete wetland inventory. These will likely be available in the near future (i.e., 3-10 years) and model selection should reflect this. If not, stakeholders run the risk of promoting a model that will be obsolete and dated before it is even widely used/implemented.

As noted previously, cultural ecosystem services have been found to have greater variety in indicators to quantify their value, as compared to all other service types (Egoh et al. 2012). Unlike the provisioning, regulating or supporting ecosystem service tools and models, the cultural service tools and models reviewed often did not share similar indicators used for assessment. Therefore, in order to be most effective with data acquisition (e.g., population data, infrastructure data), select the priority approach for cultural ecosystem service assessment prior to proceeding.

Experience in other jurisdictions has also given some insight into key considerations for successful ecosystem services application for land management.

1. **Pair ecosystem service assessment with strong policy and regulatory requirements.** Each jurisdiction contacted recognized that there was no link or a poor link to wetland policy. Strong policies that relate to wetlands are the key to success.
2. **Proceed with both internal and external reviews.** Experience in Minnesota from internal stakeholder consultation found that when confidence was possibly lacking in assigning a weight to various model components a moderate weighting was selected. As a result, external expert opinion was sought to more accurately reflect the mechanisms being captured.
3. **Track usage.** Both CVC and Minnesota lacked the ability to track a tool's application following its development. Identifying usage can help determine if implementation has been successful, or if modifications are required.
4. **Weigh the opportunities versus limitations of economic valuation.** CVC utilized a 'willingness-to-pay' approach for various wetland services. Although the approach identified an interest in wetland conservation in the area, CVC recognized that this valuation will change over time with market demands.
5. **Ensure that the tool can be used by the intended audience.** A tool that is either too complicated to use or lacks the data required to run it successfully will not be successful in the long term.
6. **Create a well vetted process for establishing a list of prioritized ecosystem services.** Prioritizing the key ecosystem services allows for proper model development and the best use of available resources.

Table 5. Thirteen tools and models selected for further review for potential application in Alberta, including the ecosystem service(s) each evaluates. * indicates the tool(s) or model(s) best suited for the service. Note that IMWEBs and the water purification module of CRHM are currently in development. Cultural services tool selection will depend on the preferred method of approach.

Tool / Model	Flood control	Water purification	Water supply	Climate regulation	Recreation and tourism	Science and education	Aesthetic	Biodiversity
CRHM	*		*					
SWAT								
IMWEBs	*	*	*					
2011 GoA	*		*	*				
ABMI								*
Industrial Heartland	*							
CEAP	*							
InVEST								
ARIES								
SolVES								
MN Wetland Tool								
HydroGeoSphere								
DNDC								

6.0 CONCLUSION

At the start of this project it was anticipated that one tool may work for the assessment of ecosystem services for Alberta's wetlands in the White Zone. After an extensive literature search and a review of possible tools and models it is apparent that no one tool or model is capable of addressing all the ecosystem services Alberta's wetlands provide. While a number of promising tools and models exist for important services such as water storage, water quality, biodiversity, and carbon storage, few models make the connection between a wetland function and the benefits provided to human well-being. Even fewer of the tools reviewed provided a clear approach for assessing the cultural ecosystem services of wetlands.

What was evident from the jurisdictional investigations is that strong policy related to wetlands is very important for the successful uptake and application of any ecosystem service tool. User friendly and easily accessed tools were also important for uptake.

It is clear that resources may not exist to refine and test tools capable of measuring all wetland related ecosystem services reviewed in this report. As a result, it is recommended that an effort be given to quantifying those ecosystem services considered the most important to Alberta stakeholders. It is also important that consensus occur on what level of scale for service assessment is the most beneficial and practical. Is assessment to the sub-watershed acceptable, or does the tool need to assess ecosystem services at the basin level? Once consensus is arrived at on these outstanding questions, then movement towards a functional service tool for Alberta's wetlands will be much more efficient.

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APPENDIX A: ECOSYSTEM SERVICE DEFINITIONS

Flood control: Considered as one of the top three priorities by Alberta stakeholders (Government of Alberta 2011a), flood control as an ecosystem service is a wetland's ability to reduce or delay peaks in overflow, depending on its location in a watershed (connectivity), and its ability to protect development and infrastructure as a result. The ecosystem function that supports this service is a wetland's ability to slow down, store, and absorb surface runoff before it is released. Beneficiaries include individuals, communities, businesses, and governments, where the cost of associated flood damages, or incorporation of flood-prevention infrastructure, is avoided. As wetland loss occurs with increased development, so too does the demand for flood control as an ecosystem service (Millennium Ecosystem Assessment 2005b).

Water purification: Considered as one of the top three priorities by Alberta stakeholders (Government of Alberta 2011a), water filtration as an ecosystem service is a wetland's ability to remove excess pollutants, supporting other ecosystem services such as water supply and storage (i.e., for provisioning of freshwater, for example), and aesthetics (i.e., where clearer water is valued more highly). The most common pollutants of concern include excess nutrients (e.g., nitrogen (N) and phosphorus (P)) and sediments. The ecosystem function that supports this service is the physical, chemical, and biological components of a wetland that supports retention and recovery (e.g., physical ability of wetland vegetation to settle sediments, chemical ability of wetland sediments for nutrient storage, biological ability of wetland vegetation for nutrient uptake). The location of wetlands in a broader landscape context is also important. Beneficiaries include individuals, agriculture, and government (Government of Alberta 2011a), where the cost to infrastructure for water treatment is avoided. For example, land use changes can put pressure on the components of a wetland that support water quality improvement, and diversion of polluted waters to wetlands may be beyond the water filtration potential of a wetland.

Water supply and storage: As an ecosystem service, water supply and storage is a wetland's ability to retain water for use for domestic, industrial or municipal purposes, including the support of other ecosystem services, such as recreation. The ecosystem function that supports this service is the hydrological function, including water balance, flow regulation, and groundwater interactions (Millennium Ecosystem Assessment 2005b). Beneficiaries include individuals and agricultural use (Government of Alberta 2011a). Water supply and storage is of particular importance in southern Alberta where, due to high per capita use of available water resources, water availability and restrictions to water licenses.

Climate regulation: As an ecosystem service, climate regulation is a wetland's ability to store carbon, preventing its release to the atmosphere where it would contribute to climate change, and the associated effects to human health, the environment, and climatic processes. The ecosystem function that supports climate regulation as an ecosystem service is a wetland's ability to store carbon in its plants, detritus, and soils (Millennium Ecosystem Assessment 2005b). Beneficiaries can include individuals, businesses, and government. The GoA's 2011 Ecosystem Services Approach Pilot on Wetlands highlighted carbon storage as an important ecosystem service for assessment, as carbon storage was one of the three key goals highlighted in Alberta's 2008 Climate Change Strategy (Government of Alberta 2008).

Cultural ecosystem services: Cultural ecosystem services, such as recreational, spiritual, and aesthetic benefits, are identified as one of the four key service types (in addition to provisioning, regulating, and supporting services) outlined in the Millennium Ecosystem Assessment (2005a). Cultural ecosystem services, as in many other regions, have been a high priority for management in Alberta (Government of Alberta 2011a). However, cultural ecosystem services can be difficult to quantify, with strong assumptions or limitations depending on the methodology applied (Healy and Secchi 2016). For example, surveys to assign value to cultural services can be regionally applicable but are costly to administer and need to be repeated every 5 to 10 years. In comparison, data-intensive models to assign value to cultural services may require making broad assumptions about how users within a region value a particular environment. In addition, cultural ecosystem services have been found to have a greater variety in indicators to quantify their value, as compared to all other service types (Egoh et al. 2012). These limitations make it difficult for decision makers to incorporate cultural preferences into ecosystem service assessments. Of the potential wetland ecosystem services to be evaluated in Alberta, three have been selected for review: recreation and tourism; science and education; and aesthetics.

***Recreation and tourism*:** Recreation and tourism is one of the most easily grasped ecosystem services by the public (Bagstad et al. 2011). The public often spends recreational time based on the features of the natural environment in a particular area (Millennium Ecosystem Assessment 2005a). For example, a tourist preference for a particular park for birdwatching can be influenced by the bird species richness in the area (Naidoo and Adamowicz 2005). The economic value of recreation and tourism is growing in many areas, even as the economic importance of many ecosystem provisioning services (e.g., forestry, agriculture) declines (Millennium Ecosystem Assessment 2005a; Sharp et al. 2016). However, with this increase in demand, incorporation of infrastructure to support recreation and tourism in natural environments has put these areas at risk. Therefore, identifying a tool that evaluates a particular environment's potential value for recreation and tourism is important to identifying the tradeoffs between development and preservation of natural spaces.

***Science and education*:** Natural environments provide a space for both formal and informal education (Millennium Ecosystem Assessment 2005a), as well as an area for research into the physical, chemical, and biological components of ecosystems and their functions. Science and education as an ecosystem service is often assessed at a local scale, as the value that is placed on this service can be very area-specific. As the understanding of the importance of environmental education increases so too has the demand for placing a value on this service (Millennium Ecosystem Assessment 2005a). In Alberta in 2011 science and education opportunities were identified in surveys of various stakeholders as a 'high value' benefits provided by wetlands (Government of Alberta 2011a).

***Aesthetic*:** Aesthetics as an ecosystem service is the value that people find in the attraction to natural environments, often represented as the support for public parks, or the preferred location for housing (Millennium Ecosystem Assessment 2005a). In terms of economic benefits, higher property values may be obtained adjacent to areas with higher scenic quality or greater open spaces (Sander and Polasky 2009). The ability of quality scenic areas to attract users may also benefit local businesses (Sharp et al. 2016). As the demand for areas of high scenic quality increases with urbanization, there has been a decrease in the aesthetic value of these areas in order to meet demand (Millennium Ecosystem

Assessment 2005a). Aesthetics as an ecosystem service provides not only economic benefits, but benefits to human well-being as well. Thus, identifying a tool for aesthetic assessment becomes important to decision makers for identifying the tradeoffs of development versus maintaining natural spaces. Note that in Alberta in 2011, aesthetics was identified in surveys of various stakeholders as a 'high value' benefit provided by wetlands (Government of Alberta 2011a).

Biodiversity: Biodiversity supports the supply of all other ecosystem services, both directly and indirectly (Millennium Ecosystem Assessment 2005a). As a supporting service, species variety not only improves the stability of ecosystem functions, it also improves other ecosystem services such as recreation and tourism (Cardinale et al. 2012). Biodiversity was previously identified to Alberta stakeholders as high importance when considering wetland ecosystem services (Government of Alberta 2011a); therefore, review and evaluation of tools and models to assess a wetland's biodiversity value are included in this report.

APPENDIX B: TOOL/MODEL DESCRIPTIONS

Cold Regions Hydrological Model (CRHM)

CRHM can be used to assess the benefits provided by wetlands with respect to water quantity (i.e., flood control and water supply). CRHM was developed to simulate the hydrological processes for a basin by taking into consideration processes such as snow distribution by wind, snow and rain interception by wind, sublimation, snowmelt, infiltration into frozen and unfrozen soils, water movement along hillslopes, evaporation, evapotranspiration, radiation exchange, groundwater flow, and streamflow hydraulics (Pomeroy et al. 2007). The Prairie Hydrological Model (PHM) was developed from CRHM to be used specifically for hydrological process simulations in the PPR of Canada. It incorporates the prairie hydrological cycle, wetland storage, and runoff generation (Pomeroy et al. 2010). CRHM is a data intensive model that requires various inputs including GIS datasets (i.e., DEM, land cover, wetland inventory, surficial geology, hydrology), meteorological datasets (air temperature, relative humidity, wind speed, incoming solar radiation, and daily precipitation), hydrometric datasets, soil moisture datasets, and snow survey datasets (Pomeroy et al. 2012). CRHM has been successfully applied on prairie wetlands to estimate the water quantity benefits provided by wetlands in the Vermillion River Watershed (Pomeroy et al. 2012) and Smith Creek Watershed (Pomeroy et al. 2014). At present there is no water quality component within CRHM although this is currently in development (J. Pomeroy, pers. Comm.). A nutrient transport module within CRHM known as WINTRA, once developed, will consider nutrient (e.g., nitrogen and phosphorous) transport in both snowmelt and summer runoff periods. WINTRA has initially been applied at a field scale to calculate the nutrient runoff of fields as a function of crop or forage type with the intention of developing a wetland component in the near future (J. Pomeroy, pers. comm.).

Soil and Water Assessment Tool (SWAT)

SWAT can be used to predict the water quantity and quality benefits provided by wetlands (i.e., flood control, water supply and storage, and water purification). It can be applied in watersheds with varying soil types, land use, and management conditions over long periods of time. SWAT is a continuous, long-term, physically based model that requires data on weather, soil properties, topography, vegetation, and land management practices occurring in the watershed (Neitsch et al. 2011). SWAT can be used to model water quality, such as nitrogen, phosphorous, and sediment, and volume on a daily basis which can in turn be used to assess ecosystem services such as freshwater for municipal, industrial, and agricultural uses, instream flows that support fisheries and recreation, flood risk, and inflows for hydropower and other water resource infrastructure (Vigerstol and Aukema 2011). SWAT has been applied to examine the effect of wetland conservation and restoration on water quality and quantity benefits in watersheds across Canada and the US, including the PPR (Yang et al. 2010; Martinez-Martinez et al. 2014; Martinez-Martinez et al. 2015; Yang et al. 2016a; Yang et al. 2016b). The quantity and quality function of individual wetlands cannot be evaluated in SWAT as wetlands within a sub-basin are lumped into a single wetland (i.e., semi-distributed model) intended to reflect the aggregate effect of all the wetlands within the sub-basin.

Integrated Modelling for Watershed Evaluation of BMPs (IMWEBs)

The IMWEBs tool is a cell-based modelling system developed to inform the assessment of Best Management Practices (BMPs) at multiple scales. IMWEBs was developed based off the structure of SWAT and is a continuous time series model that assesses the effects of BMPs for both water quality and quantity in a watershed (i.e., flood control, water supply and storage, and water purification). The tool currently simulates BMPs related to crop management, fertilizer management, and tillage management with wetland and livestock BMP modules currently in development. IMWEBs requires GIS data (e.g., DEM, land use, soils, stream networks, watershed boundary, farm boundary, field boundary, and location of climate stations), hydroclimate data (e.g., precipitation, temperature, solar radiation, wind speed, relative air moisture, flow, sediment, and water quality), and data on the BMPs that are to be assessed by the model. The wetland module in IMWEBs simulates water balance, sediment, and water quality processes at varying spatial scales to examine different scenarios (i.e., wetlands lost, gained, or maintained at current level). The results of the models (e.g., runoff, nutrients, and sediment yield) can be examined at an individual wetland, sub-basin, and watershed scale depending on the needs of the user. In the model the watershed is divided into sub-basins and each sub-basin only contains one wetland (i.e., fully distributed model) (Yang et al. 2016c).

2011 Government of Alberta Ecosystem Service Pilot

The Ecosystem Service Approach Pilot on wetlands was conducted by the GoA to advance the use of ecosystem services information to support decision making in Alberta. The pilot tool was conducted in an area that included the Town of Chestermere, a portion of Rocky View County, as well as an eastern portion of the City of Calgary. Water supply, flood control, water purification, and carbon storage were the ecosystem services chosen for assessment. The approach uses a combination of remotely sensed (e.g., satellite imagery, orthophotographs, and LiDAR) and empirical (e.g., climate) data to quantify the benefits provided by wetland in terms of biophysical values (i.e., cubic meters of water stored) or indices (i.e., water purification score) (Government of Alberta 2011a).

Assessing the water storage capacity of wetlands consists of calculating both the existing water volume in the wetlands as well as the total wetland storage capacity if the wetlands were full. The existing water volume in the wetland was calculated by using the estimated area of the water surface in a volume-area relationship that was developed in the Upper Assiniboine River Basin Study (Manitoba Conservation et al. 2000). The additional wetland capacity was calculated using the mean elevation of the boundary of the wetland. The result is an empirical estimate of water storage (volume) that can be summarized by area of interest, permanency class, or size class (Government of Alberta 2011b).

Flood control was assessed through the use of a GIS modelling approach to estimate the peak flow reduction benefits provided by wetlands. A wetland index of flood control was used which consisted of seven predictor variables: water storage capacity of the wetland, amount of impervious surfaces in the wetland catchment, wetland catchment to wetland ratio, amount of wetland subwatershed comprised by upland wetlands, wetland position in the subwatershed (i.e., at multiple scales), whether the wetland is connected to surface waters through natural or artificial drainage systems, and subsurface storage potential based on groundwater vulnerability measures. The predictor variables were all equally weighted to come up with the final flood control indicator value (Government of Alberta 2011b).

The water purification assessment focused on the ability of wetlands to remove nitrogen, phosphorous, and sediments from the water supply. To calculate a wetland's water purification potential, a Wetland Purification Score, derived from six metrics, was used. These metrics were:

- Wetland area;
- Pollutant sources - based on the percent urban land use area in the wetland catchment;
- Pollutant removal opportunity - derived from the level of disturbed land use within the wetland contributing area, the ratio of wetland area to contributing area, and position of wetland in the stream catchment;
- Pollutant transport potential - derived from the average slope of a wetland's contributing area;
- Potential significance - calculated as the distance from the wetland to the nearest river or stream; and,
- Recharge potential - determined from the position of a wetland based on elevation in the watershed.

As with the flood control score, the predictor variables in the wetland purification score were all equally weighted. In addition to the wetland purification score using the six metrics, a more advanced model was developed that uses 39 metrics. However, time constraints prevented it from being used in the pilot project. This advanced model included metrics based on wetland vegetation, soils, and surrounding land uses, among others (Government of Alberta 2011c).

The carbon storage of wetlands in the pilot study site was estimated by applying estimates of SOC concentrations to the wetland inventory. The estimates of SOC were based on previous research done on wetlands in the Canadian prairies (Badiou et al. 2011). These SOC estimates were applied to Class III, Class IV, and Class V wetlands (Stewart and Kantrud 1971) in the study site to estimate the stock of carbon contained in existing wetlands as well as the amount of carbon lost from wetland loss based on a historical wetland inventory (Government of Alberta 2011d).

Alberta Industrial Heartland

Cobbaert et al. (2011) conducted an assessment of wetland health and value in Alberta's Industrial Heartland, an area northeast of Edmonton. The tool consisted of both a field-based rapid assessment method as well as a landscape GIS-based assessment to assess the ecosystem services provided by wetlands. The GIS-based assessment was conducted to assess the benefits provided by wetlands with relation to biodiversity, flood flow reduction, water quality improvement, and social values. Each benefit was assessed using several metrics based off land cover datasets, a DEM, a wetland inventory, groundwater vulnerability, and a database of rare and threatened species which result in an overall relative score for each wetland in the study site.

The biodiversity model uses nine metrics that are all equally weighted:

- Wetland size;
- Diversity of wetland subclasses within wetland;
- Wetland subclass rarity;
- Wetland has permanent open water or is connected to surface water network;
- Wetland is near a fish bearing waterbody;
- Undisturbed land cover buffering wetland;
- Wetland focal species in wetland;
- Wetland is a focal wetland habitat; and,
- Wetland contains rare/ threatened species, communities or landforms.

The flood flow reduction model uses seven metrics that are all equally weighted:

- Wetland size;
- Wetland's stream watershed comprised by upslope wetlands;
- Wetland area: local watershed area;
- Proportion of wetland's watershed with impervious surfaces;
- Wetland's position in stream watershed;
- Wetland connected to surface water network; and,
- Groundwater vulnerability of area.

The water quality improvement model uses six metrics that are all equally weighted:

- Wetland size;
- Potential pollutants in wetland's watershed;
- Ability of wetland to improve water quality;
- Steepness of wetland's watershed;
- Wetland is a riparian wetland; and,
- Wetland's watershed position.

The social value model uses three metrics that are all equally weighted:

- Proximity to settlement;
- Wetland's proximity to a park or protected area; and,
- Wetland has historic resource value.

Each wetland is assigned an overall value score which is weighted based on the number of metrics in each of the four models (e.g., biodiversity has the most impact on overall score, and social value the least). The flood control model used in the 2011 Ecosystem Service Wetland Pilot was based of the flood flow reduction model developed by Cobbaert et al. (2011) with modifications and improvements for the study site (Government of Alberta 2011a).

Alberta Biodiversity Monitoring Institute (ABMI)

ABMI developed a system to assess and map several ecosystem services across Alberta including water purification, biodiversity, rangeland forage and carbon, forest timber and carbon, and pollination. The models were developed using NetLogo, a spatially-explicit agent-based platform that consists of three main components: a uniform grid of cells representing the landscape, user-defined type of agents, and links that can be used to form networks among agents. The models used the ABMI wall-to-wall land cover dataset which was converted to a grid cell size of 800 m. Consequently, the spatial location of features within cells is lost although the impacts of each land cover type within each cell is maintained by using an area-weighted sum of the land cover types comprising the cell (Habib et al. 2016). The ABMI wall-to-wall land cover dataset does not have a wetland land cover class. Shallow open water wetlands with less than 20% vegetation cover would be included in the water class while any wetlands with more than 20% vegetation cover would be classified as either grassland, shrubland or forest (ABMI 2012).

The water purification model simulates precipitation, overland flow, and surface water flow over a single year based on land cover and climate data. The model is used to identify areas that contribute to non-point source export of nutrients such as nitrogen, phosphorous, TSS, and sediment, areas that remove nutrients and sediment, as well as impacts to water users. Runoff is calculated for each cell in the grid as a percentage of precipitation data which is derived from runoff coefficients for each land cover class. The runoff moves downslope until it intersects the river network at which point the water flow moves downstream. Nutrients are loaded into surface water flow using export coefficients for each of the major land cover and human footprint types. The values for the runoff and nutrient export coefficients from each of the land cover types are taken from Donahue (2013). Soil erosion is loaded into surface water flow using the Revised Universal Soil Loss Equation (RUSLE) which estimates erosion based on rainfall, soil characteristics, slope, and land management practices. Removal of nutrients occurs during overland flow where a portion of the sediment and nutrient load is removed as water flows across the landscape before it reaches the river network. The percentages for nutrient and sediment removal rate of each land cover type is based on expert opinion. Once the flow, loading, and removal is calculated, the model can be used to identify areas on the landscape that act as either sinks or sources of nutrients and sediments (Habib et al. 2016).

The biodiversity model uses the ABMI's species intactness index which compares the predicted species relative abundance under current conditions with the predicted species relative abundance under the reference condition, which consists of no human footprint in the same region. The intactness index is scaled between 0 and 100, where 100 represents the current relative abundance being equal to the relative abundance expected under the reference condition, and 0 represents the current relative abundance being as far from reference conditions as possible. The relative species abundance is based on data collected through ABMI's long-term biodiversity monitoring program. The monitoring data is used to develop statistical models predicting the relative abundance of a species as a function of human footprint types, ecosystem types, and geographic location within the province.

Wetlands Component of the Conservation Effects Assessment Project (CEAP)

The USGS conducted a study to quantify the ecosystem services benefits resulting from wetland restoration activities funded by the Wetland Reserve Program in the PPR (Gleason et al. 2008). This was accomplished by collecting comprehensive field data on a subset of wetlands on program lands and using this data to estimate the changes in ecosystem services provided by all wetlands on program lands. Data were collected to estimate the following ecosystem services: floodwater storage, sediment and nutrient reduction, carbon sequestration, plant community quality and richness, and potential wildlife habitat suitability. The models developed as part of the plant community quality and richness, as well as the potential wildlife habitat suitability were not intended to be direct measures of biodiversity but still offer components that can be assessed and compared to other biodiversity tools/models. Similarly, the sediment and nutrient reduction model was developed for the upland catchments surrounding wetlands and not the wetlands themselves but still had merit for further investigation.

The floodwater storage capacity of wetlands was assessed by collecting morphometry data to develop models that predicts the relationship between wetland surface area and wetland volume. These models can then be used to estimate the maximum storage capacity of wetlands for a larger area. First, a topographic survey was conducted on wetlands to determine the surface area and volume of the wetland. Second, a linear regression analysis was performed to determine the relationship between wetland surface area and volume. To improve water volume estimates, models were developed for each of the physiographic regions of the PRR (i.e., prairie coteau, Missouri coteau and glaciated plains) since each region varies in topographic relief. Using a wetland inventory, these models were then used to estimate the storage capacity of wetlands on all program lands (Gleason et al. 2008).

The potential of uplands to reduce sedimentation and nutrient loading into wetlands basins was assessed on conservation program lands. This approach estimated differences in soil erosion rates in the upland portion of wetland catchments between tilled catchments and catchments with perennial cover. This approach used the RUSLE which required data on land cover, land management techniques, a DEM, and soil erosion parameters to estimate the average annual soil loss. Field data of phosphorous and nitrogen concentrations in the soil was multiplied by the soil-loss estimates (from the RUSLE) to estimate the level of nutrient loading in wetlands associated with soil erosion. The results indicated that the conversion of cropland to perennial cover would greatly reduce soil erosion rates on program lands (Gleason et al. 2008).

Carbon sequestration is estimated based on field data measured on wetlands and surrounding uplands in the study sites. SOC was measured on restored, native, and cultivated wetlands and their surrounding catchment zone from across the PPR to allow for comparison of SOC between regions and land management. The results from the field data is then used to estimate the total potential carbon storage of wetlands on all program lands by using a wetland inventory and an estimate of SOC on a per-acre basis (Gleason et al. 2008).

Plant community quality and richness was assessed on programs lands to evaluate the impact of conservation measures on the vegetative community composition. While not an ecosystem service in itself, these measures were conducted as plant community quality and richness influence a number of ecosystem services, both directly and indirectly. To assess plant communities, a floristic quality index and species richness was measured and compared between land-use treatments (e.g., restored lands and native prairie lands) with cropped lands acting as the baseline for comparison. Generally, the floristic quality of wetland and upland zones in restored program lands was greater than that of cropland but still lower than native catchments (Gleason et al. 2008).

An approach to assess potential wildlife habitat suitability on conservation program lands in the PPR was also developed as part of the CEAP program. Similar to plant community quality and richness, wildlife suitability was acknowledged as not being an ecosystem service but the concurrent benefits of managing land for wildlife habitat would provide benefits for other ecosystem services (e.g., water quality, reduction in flood risk, and carbon sequestration). Potential wildlife habitat suitability of ten bird species was evaluated by comparing field data on nesting area and vegetation obstruction requirements on program lands to published data on the habitat requirements of those ten species. The results indicated that in general the restored catchments provided at least some of the necessary habitat requirements for the bird species of interest while the cropped catchments did not (Gleason et al. 2008).

Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST)

The Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) tool consists of a suite of models used to quantify and map ecosystem services provided by terrestrial, freshwater, and marine ecosystems. InVEST is a GIS-based mapping tool that can be utilized at multiple scales depending on the data inputted to the models. There are currently 18 different models as part of the InVEST suite with 7 being relevant to this report: nutrient delivery, sediment delivery, water yield, carbon storage and sequestration, recreation and tourism, aesthetics, and habitat quality (Sharp et al. 2016).

The nutrient delivery model maps nutrient sources and their transport to stream while considering the ability of vegetation and soils to retain nutrients as water moves through the landscape. This model requires data on land cover, a DEM, export coefficients of nutrients, and nutrient filtration efficiency. Nutrients loads are determined based on land cover data and the associated loading rates for each land cover type. The nutrient loads are then divided into sediment-bound and dissolved parts, and are then transported across the landscape through surface and subsurface flow, respectively. As water flows across the landscape, nutrients are retained on the land as determined by the slope of the land and retention efficiency of the land cover type. The final output of the model shows the spatial distribution of nutrient sinks and sources in either relative terms or quantitative terms and requires calibration. Optionally, this model can value the avoided treatment costs provided by the landscape if data on nutrient removal costs are available (Sharp et al. 2016).

The sediment delivery model maps overland sediment generation and delivery to stream as a function of geomorphology, land use, and land management practices. This model requires data on land cover, a DEM, rainfall erosivity, soil erodibility, sediment retention for each land cover type, as well as optional coefficients for agricultural land management practices. For each pixel in the DEM, this model calculates the amount of eroded sediment based on the RUSLE and then combines this information with the sediment retention efficiencies of the downslope land uses to determine the sediment transport and delivery to stream. Similar to the nutrient model, the output of the sediment model shows the spatial distribution of sediment sinks and sources on the landscape as well as the sediment load delivered to the stream at an annual time scale. The model can also be calibrated to provide quantitative estimates as opposed to just relative. Similarly, this model can estimate a value on either avoided treatment or dredge costs provided by the landscape if data on removal or dredging costs is available (Sharp et al. 2016).

The InVEST seasonal water yield model uses spatial indices to estimate the relative contribution of land parcels to the water supply. The contribution of a parcel to the water supply is determined by considering several environmental factors including slope, vegetation, soil, climate, and position in flow path. Water flows across the landscape as determined by topography data and is either evaporated, transpired, withdrawn via a well, or flows out the watershed as streamflow or groundwater flow. This model requires data on precipitation, evapotranspiration, a DEM, land cover, soils, and parameter estimates for flow and recharge parameters for each land cover type. The output of this model is a qualitative estimate of the contribution of a parcel of land to the generation of flow.

The carbon storage model uses land cover maps and stocks of carbon in aboveground biomass, belowground biomass, soil, and dead organic matter to estimate either the carbon stored in a landscape or to estimate changes in carbon sequestration over time. This model requires land cover maps as well as estimates of carbon density in at least one of the four carbon pools (i.e., aboveground biomass, belowground biomass, soil, dead organic matter) for each land cover type. Future land cover data can also be used to estimate the changes in carbon sequestration rates over time resulting from land use changes. The output of this model is expressed as a quantitative estimate of carbon sequestered in the land and if estimates on the value of sequestered carbon is available this model can output a monetary value of sequestered carbon (Sharp et al. 2016).

The InVEST recreation and tourism model uses the location of recreation activities, accessibility, and other features that factor into decision about where to recreate to predict the spread of person-days of recreation. The model requires data on the locations of recreation activities, location of infrastructure in support of recreation activities, distance between access points and activities, and visitation rates for each location or activity. If empirical data on visitation is not available, visitation rates are estimated using geotagged photos posted to the website Flickr. The final output of this model is a map showing the spatial distribution of recreation use (Sharp et al. 2016).

The InVEST aesthetic model assesses the scenic quality of a landscape based on the location of natural desired features and development or infrastructure that impacts visual quality. It was created to determine where nearshore or offshore development can be seen by creating viewshed maps. The model requires data on access points, location of public parks, and the location of private property to determine where features can be observed by viewers as well as locations of desired natural features and undesired infrastructure. Through using a DEM of the study site, viewshed maps are created to determine the visual impact a feature has.

InVEST models habitat quality and rarity as a proxy for biodiversity by combining information on land cover and threats to biodiversity. The model requires data on current land cover, biodiversity threat locations, sensitivity of the land cover to threats, and the location of protected areas. Habitat quality is a function of the relative impact of each threat, the distance between habitat and the threat source, the level of legal protection the land has from disturbance, and the relative sensitivity of each habitat type to each threat on the landscape. Unlike the other models in InVEST, the habitat quality models cannot be monetized. The final output shows only the spatial distribution of the relative estimate of habitat quality (Sharp et al. 2016).

Artificial Intelligence for Ecosystem Services (ARIES)

ARIES uses artificial intelligence techniques with a collection of probabilistic ecosystem service models to quantify ecosystem service flows and their uncertainty. The ARIES models are spatially explicit and are run in either a desktop or web-based environment. For each of the models, ARIES maps the location and quantity of the sources, sinks, and users of ecosystem services while mapping the flows between them. There are currently 8 different models as part of the ARIES suite with 6 being relevant to this report: flood regulation, water supply, sediment regulation, carbon sequestration and storage, recreation, and aesthetic viewsheds and proximity (Bagstad et al. 2011).

The ARIES flood regulation model investigates flood regulation along rivers by quantifying the sources, sinks, users, and flows. The model operates at an annual time step using annual precipitation as the source of floodwater while storage in green or grey infrastructure acts as the sinks. Green infrastructure storage is the sum of the capacity of vegetation, soils, and floodplain for infiltration, absorption, detention, or evapotranspiration of potential flood waters while green infrastructure storage is the storage of water in detention basins and reservoirs. These sources and sinks determine the physical quantity (mm/yr) of precipitation that falls on the landscape, and is either detained on the landscape or flows to a river. The users, or beneficiaries, of floodwater regulation in this model are the residents or public infrastructure located within the floodplain boundaries. The flow of water is modelled by using the topography of the land and then by the direction of the streambed once the floodwater reaches a stream. This data requirements for this model are specific to each of the four components: source (i.e., annual precipitation), sink (i.e., evapotranspiration, runoff, soils, impervious surface cover, slope, vegetation), users (i.e., spatial location of beneficiaries in floodplain), and flow (e.g., DEM, stream network). This model is designed to be run at the watershed level with the final output showing the spatial distribution of the quantity of water on the landscape (Bagstad et al. 2011).

The water supply model of ARIES simulates the sources, sinks, and flow of water as well as the connection to human beneficiaries. Different land management scenarios can be assessed to understand their effects on the spatial distribution of water supply. The model operates at an annual time scale and considers the flow of surface water while taking into consideration groundwater extraction from wells and the infiltration of surface water into groundwater. The source models estimate the physical quantity of water and is derived from spatial data or calibrated hydrological model outputs of either surface water (i.e., precipitation, snowmelt, springs, or baseflow) or groundwater (i.e., recharge and infiltration). The sink models determine the quantity of water moving between surface and groundwater. Surface water sinks are modelled through infiltration to groundwater or evapotranspiration while the groundwater sinks are modelled through either springs or baseflow contribution to surface water. Water supply flows are modelled using a water routing model which relies on elevation data. In this routing model, water moves across the landscape as determined by a flow direction layer until it encounters a stream while considering the sinks or users of water that occur prior to reaching the stream. The users of water supply are modelled using data on well locations or surface water diversions. The data requirements for the water supply model are specific to each of the four components: source (i.e., precipitation, snowmelt, baseflow, infiltration), sink (i.e., evapotranspiration, runoff, soils), users (i.e., well locations, other water extraction points), and flow (e.g., DEM, stream network). This model operates at the watershed level with the final output showing the quantity of water and spatial distribution on the landscape (Bagstad et al. 2011).

The ARIES sediment regulation model simulates the sources of waterborne sediment, sinks where deposition occurs, users who are impacted by sediment (i.e., either positively or negatively), and the flows between them. This model can be used to understand the spatial connection between the sources of sediment, areas of sediment deposition, and the users that either value or are harmed by sediment delivery. The sources of sediment are estimated in physical terms (i.e., tons of sediment) based on either deterministic models (USLE or RUSLE) or a probabilistic models of sedimentation depending on the landscape type. The sinks are areas where sediment is deposited as water flows through a landscape. In this model only the deposition of sediment in floodplains and reservoirs is considered as opposed to including any deposition via overland flow before water reaches a stream. The users are defined as those who are either harmed by or benefit from sediment delivery or excessively turbid waterways. The sediment flow models describe the amount of sediment carried in flowing water or the amount of sediment delivered using stream network data and a flow direction layer derived from elevation data. The data requirements for the water supply model are specific to each of the four components: source (i.e., precipitation, runoff, soils, slope, land cover), sink (i.e., floodplains, reservoirs), users (i.e., population density, farmland), and flow (e.g., DEM, stream network). The sediment regulation model operates at the watershed level with the final output showing the quantity of sediment and spatial distribution on the landscape (Bagstad et al. 2011).

The ARIES carbon model estimates regional carbon balance through modelling carbon sources and potentially carbon sinks probabilistically. The sources in this model are the sequestrated carbon in vegetation and soils while the sinks are the areas of stored carbon that have the potential to be released through vegetation or soil disturbances (i.e., deforestation, fire, land use change). The carbon available to offset anthropogenic carbon emissions is the difference between the estimated carbon sequestered and the estimated carbon released. Additionally, ARIES also maps anthropogenic carbon emitters as the beneficiaries of carbon sequestration and storage. This model requires data on carbon sequestration, soils, vegetation, climate, and anthropogenic greenhouse gas emissions. The final output consists of the spatial distribution of carbon sequestration and stored carbon release as well as the uncertainty associated with those values (Bagstad et al. 2011).

The ARIES recreation model considers the sources, sinks, flows, and users of recreation to assess an ecosystem's ability to support recreation. The sources are those areas in the landscape that are suitable for a given a recreational activity. The input data can include spatial data on animal species richness or presence of rare species, habitat maps of game species, or public lands. The sinks are those areas that reduce recreational value and which can include undesirable visual features that reduce the quality of views such as clearcuts or energy infrastructure. The flow of users to the recreation areas is modelled using a road network with speeds and travel capacity as well as maps of recreational trails. The users of recreation value are modelled based on population data and if available any data to indicate the percentage of population taking part in different recreational activities (i.e., number of hunting or fishing licenses relative to population). The data inputs for all components of the recreation model are variable and are at the discretion of the user based on data available for the study site and the final output is expressed in a relative recreational enjoyment unit (Bagstad et al. 2011).

ARIES considers the impact of both viewsheds and proximity to open space as measure of aesthetic value. Both of these components consist of mapping the source, sink, flow, and users of this service. The aesthetic viewshed component is measured by a relative “scenic beauty” value which considers the presence of housing units (users), user-defined source of aesthetic beauty such as mountains or water bodies (source), features contributing to visual blight such as mines or clearcuts (sink), and a line-of-sight model based on a DEM to identify locations where topography blocks views (flow). The aesthetic proximity component is measured by a relative “open space” value which considers the presence of housing units (users), a form of open space (source), obstructions to the open space (sink), and a proximity to open space value (flow). These models require data on the location of users, features that provide a potentially valuable view, features that may degrade views, and DEM (Bagstad et al. 2011).

Social Values for Ecosystem Services (SolVES)

SolVES is a GIS-based tool used to quantify and map social values of ecosystem services. These social values are the non-market values associated with cultural ecosystem services (i.e., aesthetic, recreation and tourism, science and education) and can be evaluated for various stakeholder groups. SolVES uses responses to public value and preference surveys to along with other environmental data to derive a relative social value index that is mapped across the study area. The user is able to define their own social values (i.e., ecosystem services of interest) and can model that along with any number of environmental data, such as distance to water or dominant land cover while also specifying weighting options for the survey data as well as the spatial scale of the analysis. SolVES has the option to use a value transfer method where the social value index can be drawn from previous analysis that was conducted in an area with similar geographic features. However, no analyses have been conducted specifically for wetlands so this feature can’t be used until appropriate studies are conducted. Therefore primary surveys specific to wetlands that fit the requirements of the model inputs would need to be conducted to fully realize the potential of SolVES (Sherrouse and Semmens 2015).

Minnesota Restorable Wetland Prioritization Tool

Minnesota Restorable Wetland Prioritization Tool is an online tool used to prioritize areas across the entire state for wetland restoration or protection that maximize water quality benefits or habitat improvement. It is designed to identify sub-regions in a watershed with suitable physical conditions for restoration as opposed to identifying individual wetlands. The tool is made up of a Restorable Wetland Inventory (RWI) along with three decision layers: stress, benefit, and viability. The RWI was developed to identify locations that have the necessary conditions to support a wetland. This layer was developed from a compound topographic index (CTI), which is an index that uses a DEM to predict soil moisture based on slope and runoff. Areas that have low slopes with a large catchment are rated highest on this index. Those areas that met the threshold score on the index were then compared with a soil dataset within only those areas identified as having very poor drainage being selected. Finally the remaining areas were compared to the National Wetland Inventory (NWI) with any areas mapped as existing wetlands being removed from the RWI. The stress decision layer consists of a weighted combination of factors that reflect anthropogenic stress levels on the landscape. These factors include the intensity of development, presence of row crops, pasture or barren land, distance to feedlots, distance to roads, and population. The viability layer is used to identify areas with a greater likelihood of remaining as a self-sustaining wetland following restoration. This is based on land ownership, position in overland flow network, soil type, as well as the CTI. The benefits decision layer predicts the potential habitat, water quality, and soil erosion benefits achieved through wetland restoration. An index is calculated for each of the three benefits and combined to achieve an overall benefit score. The soil erosion benefit index is calculated based on the potential risk soil erosion determined from components of the Universal Soil Loss Equation (USLE) (i.e., rainfall runoff factor, slope length slope gradient, and soil erodibility factor). The water quality benefit index is based on the risk to degrade water quality estimated from a site's likelihood of overland flow during a rain event as well as its proximity to water. The habitat index is based on sites of biodiversity significance, species of greatest conservation need, potential bird habitat, level of protection, and the type of habitat.

HydroGeoSphere

HydroGeoSphere simulates the terrestrial portion of the hydrological cycle, consisting of both the surface and subsurface flow of water as well as the transport of solutes including heavy metals or hydrocarbons. The model is designed to incorporate all key components of the hydrological cycle including net precipitation (e.g., actual precipitation – interception), surface water inflow and outflow, surface/subsurface water interactive flow, infiltration, surface flow evapotranspiration, overland water withdrawal, surface water storage over time, subsurface water inflow and outflow, subsurface flow evapotranspiration, subsurface water withdrawal, and subsurface water storage over time. Data requirements for HydroGeoSphere include a DEM, climate data (i.e., precipitation, evapotranspiration, temperature, snowmelt), and several model parameters. The output is in the form of a spatial and temporal characterization of water in the terrestrial portion of the hydrological cycle (Therrien et al. 2010). HydroGeoSphere has been successfully applied to simulate wetland hydrology in the PPR (Liu et al. 2016) but, similar to CRHM, is ultimately more of a hydrological model to measure wetland function and would need to be translated into an ecosystem service.

DeNitrification-DeComposition (DNDC)

DNDC is a model used to describe carbon and nitrogen biogeochemistry processes at either a site-specific or watershed scale. A wetland-specific version of DNDC was created and while it was originally constructed to be used for forested wetland systems, the wetland processes incorporated in the model (e.g., water table dynamics, growth of mosses and herbaceous plants, and soil biogeochemical processes under anaerobic conditions) still apply to prairie wetlands. The model has four components (i.e., hydrological conditions, soil temperature, plant growth, and soil carbon dynamics) and can be used for estimating ecosystem soil carbon dynamics as well as greenhouse gas emissions including carbon dioxide, methane, and nitrous oxide. DNDC requires data on land use, soil properties, climate data, hydrology data, and management measures. While DNDC is a powerful tool for estimating carbon and nitrogen biogeochemistry processes in wetlands, it is a very detailed, data-intensive processed based model that hasn’t has widespread use on prairie wetlands.