MAINTAINING THE PORTFOLIO OF WETLAND FUNCTIONS ON LANDSCAPES: A RAPID EVALUATION TOOL FOR ESTIMATING WETLAND FUNCTIONS AND VALUES

Irena F. Creed, David A. Aldred, Jacqueline N. Serran, Francesco Accatino

ABSTRACT

Wetland loss in Alberta is ongoing despite a policy of no-net loss of wetland area that has been in place since 1993. The Government of Alberta (GOA) recently replaced the policy of no-net loss of wetland area (1993) with a policy of no-net loss of wetland function (2013). The GOA commissioned the development of an Alberta Wetland Relative Value Evaluation Tool (ABWRET) to implement the no-net-loss of wetland function policy. However, the assessment of the over one million wetlands in Alberta using the "on-the-ground" ABWRET-Actual is not reasonable or realistic, and so, a "from-the-sky" ABWRET-Estimator was developed. Together, these ABWRET tools provide planning and regulatory tools to reduce the risk of wetland loss in Alberta.

The ABWRET tools assess the following four wetland functions: hydrologic health (HH), water quality (WQ), ecologic health (EH), and human use (HU) for every wetland in Alberta. Sub-functions were identified for each function and include: water storage and stream flow support sub-functions for HH, water cooling, sediment retention, phosphorus retention, and nitrate removal sub-functions for WQ and organic nutrient export, fish habitat, invertebrate habitat, amphibian habitat, water bird nesting habitat, songbird, raptor and mammal habitat, and plant and pollinator habitat sub-functions for EH.

The ABWRET-Estimator divides the province into functional units called relative value assessment units (RVAUs) so that wetlands in similar landscapes could be assessed against each other to provide relative estimates of wetland function within that geographic region. Wetland function was assessed for each RVAU by the ABWRET-Estimator using 73 process-based indicators that were estimated using existing GIS and remote sensing data. Indicators were standardized from 0-1 and combined to establish sub-function scores using models derived from expert opinion and literature review. The sub-function scores were then combined into an overall function score by taking the highest sub-function score for a given function. The overall relative wetland value score for each wetland was then estimated using a weighted average approach of the function scores. Using this information, wetlands were then assigned an *a*, *b*, *c*, *d* score based on their relative wetland value score percentile, where a score of *a* indicated a high functioning wetland. The *a, b, c, d* score was then modified based on historic wetland loss within each RVAU. Function scores were raised by one letter in RVAUs where a high amount of wetland loss has historically occurred to increase wetland protection. Conversely, the relative wetland value score letters were lowered by one letter (not less than *d*) in RVAUs with the lowest loss of wetlands to reduce wetland protection.

The GOA has a powerful set of tools to implement their new wetland policy. Planners can use the ABWRET-Estimator tool to reduce risk of loss of wetland functions by supporting informed wetland planning and management decisions at both local and watershed scales. Regulators can use the ABWRET-Estimator tool to avoid the loss of high-functioning wetlands when evaluated proposed development activities. A commitment to continuous improvement of the ABWRET

tools together with a routine monitoring of potential changes in wetland functions will contribute to the reduction of further loss of wetland functions and their associated services for Albertans.

INTRODUCTION

Problem Statement

People value wetlands variously for the functions they provide, including flood control, improvement of downstream water quality, biodiversity, and aesthetic and recreational benefits. Despite a policy in existence for many years to prevent net wetland area loss in Alberta, Canada, wetlands continue to be lost due to non-compliance with existing laws simultaneous with replacement mechanisms that have been judged to be inadequate. This policy failure has led to the development of a new policy and innovative approaches that are expected to better support protection of both wetland area and function. The new policy features simple and accessible tools to address planning and regulatory requirements. This case study relates the building and uses of a tool for simultaneously estimating the functions and values for over one million wetlands in Alberta.

Background

Agricultural, industrial and natural resource extraction activities have caused substantial loss and degradation of wetlands in the Canadian province of Alberta since the late 1800s. The loss is extensive, with claims that two thirds of all wetlands in the southern and central settled areas of Alberta have been lost (Alberta Environment and Parks 2013a).

In response to continuing wetland losses, the Government of Alberta (GOA) introduced a wetland policy in 1993 to manage wetlands in developing areas to "sustain the social, economic and environmental benefits that functioning wetlands provide, now and in the future" (Alberta Water Resources Commission 1993). The policy's strategy was to achieve no net loss of total wetland area by conserving wetlands where possible or otherwise compensating for wetland degradation or removal. While Alberta was one of the first provinces to adopt a wetland policy, a mechanism to fully implement this policy was not developed until 1999 with the introduction of the Water Act, which created a legislative requirement to obtain a permit to conduct activities that negatively impact wetlands.

However, loss of wetland area has continued since 1999 (Clare and Creed 2014), indicating that the wetland policy has been ineffective at meeting its no net loss of area goal. Although the policy emphasized avoidance as the preferred mechanism of wetland conservation when development occurs, Clare et al. (2011) found that the policy was often overlooked by developers or agricultural property owners, in part because the economic benefits of wetland removal were assumed to outweigh an inherent perceived low value of wetlands. Other key challenges were found to be: (1) lack of agreement on what constituted avoidance; (2) failure to identify and prioritize wetlands in advance of development; (3) a "techno-arrogance" that assumes that construction of compensatory wetlands can fully replicate the quality of removed wetlands; and (4) inadequate enforcement of regulatory approval or compensation requirements (Clare et al. 2011).

With ongoing unpermitted wetland loss and emerging scientific literature regarding the importance of wetlands and their functions (e.g., Cohen et al. 2016), the GOA developed a new wetland policy in 2013 that shifts the focus of wetland protection from area to function. Instead of focusing on the no net loss of wetland area, the policy acknowledges that different wetlands function differently and that wetland areas are not all of equal value. Recognizing that land developers lack accessible information about the functions and values of wetlands that are being considered for development, the policy also requires the GOA to make assessments of individual wetland functions and values in advance for planning purposes and subsequent regulatory processes. The policy also strives for continuous improvement of assessment methods – as new science and technology emerges, this information will be incorporated into the policy.

As with the previous policy, the new policy emphasizes avoidance as the preferred action when developing. Where avoidance is not possible, the goal is to minimize impacts on cumulative wetland value over regional scales by enforcing replacement of wetland values within the same region. Replacement can take the form of restoring previously removed or degraded wetlands, constructing new wetlands, or contributing funds to help preserve, restore or change wetland functions through educational outreach or research that advances wetland science (Alberta Environment and Parks 2016). Replacement is based on the value of the removed wetland relative to those of other regional wetlands, with policy targets requiring a replacement of (1) a 1:1 area-for-area ratio for wetlands with low levels of functions and up to 8:1 area-for-area ratio for wetlands with high levels of functions, and (2) at a total ratio of 3:1 for all wetlands in the settled areas of Alberta (also known as the "White Area"). The policy has been in effect for the White Area since June, 2015.

Need for Landscape-level Assessment

The new wetland policy requires simultaneous development of rapid assessment tools to (1) provide estimates of wetland functions and values at broad regional scales for planning purposes, and (2) provide site-based assessments for regulatory approval. The GOA commissioned the Alberta Wetland Relative Value Evaluation Tool-Estimator (ABWRET-E) to deliver off-site estimates of relative value for all wetlands in the White Area of Alberta, and the ABWRET-Actual (-A) to estimate levels of wetland functions at the site level based on integrating field observations with existing spatial data. These tools are built from the same logical foundation and are intended to complement each other (Figure 1). The ABWRET-E is designed to facilitate avoidance at the beginning of the planning process by allowing planners and developers to understand the relative value of a particular wetland early in the development process. The ABWRET-A, on the other hand, is a regulatory tool that provides a standardized method for rapid on-the-ground assessment of wetland functions. Together, these tools enhance the potential for avoiding impacts to wetlands and, when wetlands must be removed, ensure that the relative levels of functions are known so that steps can be taken to make certain that value is replaced. We focus on ABWRET-E here; information on the ABWRET-A can be found in GOA (2015) and in Chapter # of this book.

Funding Source
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STUDY AREA

The province of Alberta has had one of the fastest growing economies in Canada since the 1990s. Resulting urban and agricultural development pressures have resided primarily in the southern and central areas of the province set aside in 1948 for settlement and agriculture as the White Area. Comprising 39 percent of Alberta's 660,000 square kilometers, more than 80 percent of the province's populations live in the urban centers of the White Area.

Over one million wetlands exist in the White Area, predominantly small shallow marsh wetlands in the Grassland and Parkland natural regions that correspond roughly to Alberta's portion of the Prairie Pothole Region. The Institute of Wetlands and Waterfowl Research has estimated that 80 to 90 percent of wetlands adjacent to urban centers have been lost in the White Area, with losses continuing at a rate of about 0.5 percent annually (Badiou 2013).

The ABWRET-E was developed and implemented for the White Area. The other major land designation in Alberta is the "Green Area", set aside for forest and resource production and wildlife protection. A version of the ABWRET-E for the Green Area has not been developed to date, although the GOA plans to extend the tool to this area. In the meantime, developers and regulators are expected to operate in accordance with wetland policy directives applied to the White Area.

METHODS

The ABWRET-E was designed to provide an efficient "desktop" mechanism for simultaneously estimating the functions of large numbers of wetlands at regional scales. The ABWRET-E differs from the ABWRET-A in that (1) it is a planning tool and not a regulatory tool, (2) it is completely automated and does not require a site visit, and (3) it can be continually improved as new data and models become available.

Relative Value Assessment Units

The relative value assessment approach required by Alberta's Wetland Policy uses spatial units (Relative Value Assessment Units or RVAUs) in which wetlands in similar landscapes are assessed against each other to provide relative estimates of their functions and values. RVAUs ensure that wetlands are assessed within common hydrological and ecological units in accordance with the spatial principles of water management frameworks (Creed et al. 2011). At the same time, the size of the RVAUs must be suitable to management purposes; the GOA recommended defining about 20 RVAUs for the province. We defined RVAUs by classifying minor sub-watersheds (Alberta Environment and Parks 2014) to a provincial classification of climate, soil, landform and vegetation (Alberta Parks 2005) and then merging same-classification minor sub-watersheds within the seven major river basins in Alberta.

Wetland Inventory

The basis of the ABWRET-E is the Alberta Merged Wetland Inventory (AMWI) (Alberta Environment and Parks 2013b), which is classified to Canadian Wetland Classification System (National Wetlands Working Group 1997) classes: Marsh, Swamp, Bog, Fen and Open Water classes. The AMWI is a mosaic of multiple wetland inventories captured using different source data types (minimum size of polygons ranges from 0.04 to 1 hectare) acquired between 1998 and 2009, and using different technologies under a variety of initiatives. The AMWI wetlands were assigned to RVAUs by clipping to RVAU boundaries as these boundaries represent topographic ridges. The AMWI wetlands were composed of adjacent fragmented wetlands that were merged into single wetland objects while preserving the original areas and perimeters of each wetland class within the resulting objects as tabular attributes. The methods used to merge adjacent wetlands are available upon request to the corresponding author.

Wetland Functions

The GOA's Wetlands Policy Intent identified four major function groups provided by wetlands to be assessed:

Hydrologic Health* (HH): the water storage and delay function provided by wetlands for impeding and desynchronizing the downslope movement of peak flows.

Water Quality (WQ): the retention or removal of sediment or nutrients provided by wetlands for purifying receiving waters.

Ecological Health* (EH): the habitats for aquatic and terrestrial plants and animals provided by wetlands for enhancing biodiversity.

Human Use (HU): the multiple human activities that are supported by wetlands including recreation and education as well as the importance of wetlands to historical and current culture (this is not a wetland function per se, but its inclusion as a function was to ensure that wetlands that are highly used by people would receive a relatively high value).

* The GOA's use of the term "health" is not necessarily synonymous with wetland integrity or condition, as is the practice in the United States, but rather refers to the level of functions within these defined.

Wetland functions were estimated from indicators that were identified from and combined using models derived from expert opinion and extensive literature review (Government of Alberta 2015). Wetland HH was derived from water storage and stream flow support sub-functions. Wetland WQ was derived water cooling, sediment retention, phosphorus retention, and nitrate removal sub-functions. Wetland EH was derived from organic nutrient export, fish habitat, invertebrate habitat, amphibian habitat, water bird nesting habitat, songbird, raptor and mammal habitat, and plant and pollinator habitat sub-functions. There were no sub-functions for HU. Sub-functions were combined into functions, and the functions were then aggregated into value scores (Figure 2). The modelling steps are outlined in Figure 3 and summarized in the subsequent sections. The GOA was prompted to take this function score approach as they realized that the relative functions and values of individual wetlands could not be reliably estimated based solely from the Canadian Wetland Classification System (National Wetlands Working Group 1997).

GIS Database

The ABWRET-E was executed in a vector geographical information system (GIS) environment because (1) vector geometry allows finer delineation of wetland and other landscape features, meaning that less information is lost, and (2) vector geometry allows for a tabular data structure that provides easy cross-referencing in desktop or web-based applications. Vector methods were developed and tested to automatically extract data useful for estimating wetland values in ArcGIS (ESRI 2011). These vector methods are available upon request to the corresponding author.

Potential GIS data that could be used in the ABWRET-E were identified by searching provincial, national and international databases. Where several different data layers for one indicator were identified, the layer that was of the highest quality was chosen, representing the "best in practice". The "best in practice" layer that provided complete spatial coverage of a given RVAU was used for that RVAU. From the "best in practice" layers, secondary GIS data layers were generated, where required, for indicator extraction using GIS reclassifications, feature selections or mergers, or digital terrain analyses.

A data confidence score of the "best in practice" data was determined to identify strengths and weaknesses in the ABWRET-E, and to set priorities for data acquisition to ensure continuous improvement of the tool. Spatial confidence scores from 1 (low) to 10 (high) were calculated by linear scaling of log-transformed minimum resolvable unit areas. The minimum resolvable unit area (the smallest area that can be detected on a map) was obtained from information published in metadata, or calculated as either the pixel resolution for a raster GIS data layer or the square of the minimum detectable size of a vector GIS data layer (i.e., the map scale divided by 1,000 (Tobler 1987)). Temporal confidence scores from 1 to 10 were assigned by placing the age of the data layers into a qualitative matrix of "temporal sensitivity" where the information contained in a given data layer is sensitive to changes over time (e.g., geology layers are not sensitive to changes over time, 30-year climate normal layers are moderately sensitive, and land use maps are highly sensitive). An overall data confidence score for each data layer was determined by averaging the spatial and temporal confidence scores.

Wetland Indicators

Indicators are measurable variables that can be used to quantify specific parameters contributing to a wetland's sub-function. The GOA intended that the ABWRET tools (-E and -A) use the smallest number and simplest characterization of indicators possible to estimate sub-functions. The initial list of 200+ GIS- and field-based indicators identified by wetland experts (Wetland Assessment Working Group 2011) was narrowed down to a final list of 73 indicators, each of which could be automatically extracted from GIS data layers (Tables 1-4). This final list of indicators captured wetland functions with a level of confidence acceptable to the GOA at the time of the ABWRET-E development.

Indicator values may be categorical or continuous integer or floating point numbers depending on the data layer type used. For each wetland, indicator values were extracted using vector GIS methods and standardized to 0 to 1 indicator scores (where 1 indicates the best indicator performance within an RVAU) using classification or linear scaling according to sub-function models. Standardization of indicator values by linear scaling used the following formula:

$$y_i = \frac{x_i - min_i}{max_i - min_i} \tag{1}$$

where *y* is the standardized score for indicator *i*, *x* is the observed score, and *min* and *max* are the minimum and maximum scores from all wetlands within the RVAU. This linear scaling technique assigns a value of 0 to the minimum observation and a value of 1 to the maximum observation and assigns scores to all other observations based on their position between the minimum and maximum.

Wetland Sub-Functions and Functions

Indicator scores were combined into sub-function scores from 0 to 1 (where 1 indicates the best sub-function performance within a RVAU) using a combination of scaling, weighted average and "if-else" statements according to the sub-function models (c.f. Government of Alberta 2015).

Sub-function scores were combined into function scores for each wetland by taking the highest of the sub-function scores associated with each function within a RVAU.

Function scores were then standardized to a 0 to 1 range within each RVAU using the same linear scaling method described for indicator scores.

Wetland Values

Relative wetland value scores describe the overall functioning of a wetland compared to all other wetlands in an RVAU. These overall scores were calculated by combining function scores into a single value between 0 and 1. Relative wetland value scores were calculated for each wetland by using a weighted average of the four standardized function scores, where weights were given as 0.3 for HH, WQ and EH and 0.1 for HU. Thresholds in the frequency distribution of relative wetland value scores for the entire White Area were then used to define relative wetland value categories ranging from *a* to *d*, where *a* is the highest value category and *d* the lowest.

Policy Lever to Ensure Maintenance of Wetland Area (*a*, *b*, *c*, *d* scores)

While the GOA moved from an area to a function based wetland policy, the GOA still wanted to maintain the 3: 1 replacement ratio target based on wetland area for the White Area (Alberta Water Resources Commission, 1993). Percentiles of relative wetland value categories were simulated to identify potential thresholds for *a*, *b*, *c* and *d* value scores that would result in a 3: 1 replacement ratio. To ensure that the highest functioning wetlands within the White Area are conserved, the top 5 percent of value scores were required to be assigned a relative wetland category of *a*. To ensure that options for compensation were maintained, the bottom 5 percent of value scores were required to be assigned the value category of *d*. These constraints are summarized in equation (2).

$$\begin{cases} a \times 8 + b \times 4 + c \times 2 + d \times 1 = 3{:}1 \\ a + b + c + d = 1 \\ 0.05 \leq a < 1, 0 < b < 1, 0 < c < 1, 0.05 \leq d < 1 \end{cases} \tag{2}$$

where *a*, *b*, *c* and *d* represent the thresholds in the percentiles (expressed as decimal fractions) that were used to define value categories *a*, *b*, *c* and *d* by wetland number only (not area).

All possible percentiles of *b* in intervals of 0.01 were solved for all percentiles of *a* in intervals of 0.01 from 0.05 to 0.29:

$$\begin{cases} 0 < a \leq 0.167, -3 \times a + 0.5 < b < -\frac{7}{3} \times a + \frac{2}{3} \\ OR \\ 0.167 < a < 0.29, 0 < b < -\frac{7}{3} \times a + \frac{2}{3} \end{cases} \tag{3}$$

Progressing through each combination of *a* and *b* percentiles, we then calculated the answers to *c* and *d* using equations (4) and (5):

$$c = -7 \times a - 3 \times b + 2 \tag{4}$$

$$d = 6a + 2b - 1 \tag{5}$$

For example, if *a* = 0.10, then *b* ranges from 0.21 to 0.43. If we let *b* = 0.30, then *c* = -7 × 0.10 − 3 × 0.30 + 2 = 0.40 and *d* = 6 × 0.10 + 2 × 0.30 − 1 = 0.20. All 438 possible combinations of *a*, *b*, *c* and *d* percentiles meeting the requirements of the 3:1 replacement ratio and the minimum 5 percent *a* and *d* assignments were calculated.

The GOA selected an option where the wetland value categories approximated but did not meet the 3:1 ratio in the White Area. The selected option was where 10% of wetlands were classified as *a*, 20% as *b*, 30% as *c*, and 40% as *d* (i.e., a 2.6:1 replacement ratio). The selected 2.6:1 ratio provided by the 10-20-30-40 option offered a conservative estimate of value that would avoid ratios higher than 3: 1 when the regulatory tool was applied. The GOA felt conservative estimates were appropriate for three reasons. First, ABWRET-E value scores included results from GIS-based indicators only; the GOA anticipated that field-based indicators in the ABWRET-A would raise maximum function scores by identifying features that cannot be detected in the GIS data layers alone. Second, the original 3:1 replacement ratio was based on the assumption that many replacement wetlands would fail, an assumption the GOA felt was no longer appropriate given increasing experience, research and technology in replacing wetlands. Finally, the GOA used the 10-20-30-40 option during policy development when they were calculating the potential effects of their policy on the economy, and given the preceding qualifications, it made sense to stay with the 10-20-30-40 option.

Policy Lever to Ensure Protection of High Risk Areas (A, B, C, D scores)

Some RVAUs have experienced high rates of wetland loss where others have experienced lower rates; therefore, RVAUs should be treated differently when assigning wetland value scores. Alberta's new wetland policy estimates wetland loss – both number and area – using an area-frequency power function that was applied to each RVAU wetland inventory. Estimating wetland loss depends on the assumptions that (1) a negative linear relationship exists between the number and area of wetlands plotted on log-log scales on undeveloped landscapes, and that (2) there is a preferential loss of wetlands from small to large. The linear relationship between number and area of wetlands can be expected to break at a point equivalent to the largest wetlands that have been lost. We extracted this break in the linear relationship for each RVAU using piecewise linear regression. Wetland loss (both number and area) were estimated from the difference between (1) the linear relationship below the break extrapolated to small wetland areas from observed data above the break, and (2) the observed linear relationship below the break. See Serran and Creed (2016) for further details of the method used.

The relative wetland value score letters (*a-b-c-d*) were raised by one letter (not higher than *a*) in RVAUs with the highest loss of wetlands to increase wetland protection. Conversely, the relative wetland value score letters were lowered by one letter (not less than *d*) in RVAUs with the lowest loss of wetlands to reduce wetland protection. Adjusted letters were indicated by changing the letters to upper case (A-B-C-D). Wetlands in the top 5 and bottom 5 percent of value scores within each RVAU were exempted from this wetland loss adjustment of value categories.

RESULTS

Twenty-one RVAUs were defined for the Province of Alberta. Eleven RVAUs had at least 10 percent White Area and were selected for development and application of the ABWRET-E. These 11 RVAUs ranged in area from 13,447 to 75,506 square kilometers, covering 95 percent of the White Area and featuring 1,326,194 wetlands covering a total of 5,619,934 ha. Wetland number per square kilometer ranged from 1.4 (RVAU #10) to 8.3 (RVAU #5) and wetland area in hectares per square kilometer ranged from 3.6 (RVAU #2) to 45.3 (RVAU #9). The lowest density of wetlands by area (but not by number) and the highest rates of wetland loss were found in the southern areas of the Province. Wetland density by number is actually lowest in the north, but that is because of large peat wetlands. A single wetland in the north can be hundreds or thousands of square kilometers in size, yielding low density by number values. (Table 5).

Wetland functions scores were not distributed evenly throughout the White Area. Higher HH and EH function scores were distributed in the southern areas of the province, and higher WQ and HU function scores were distributed in the northern areas.

The distributions of relative wetland value scores (*a-b-c-d*) by number and area for each RVAU are shown in Table 6 and Figure 4. The proportions of high functioning (i.e., *a* or *b*) wetlands were smaller by number in all RVAUs except two in the southern areas of the Province, and smaller by area in all RVAUs. After adjustment of relative wetland value scores to increase value in RVAUs with the highest historic loss of wetlands (and to decrease value in RVAUs with the lowest historic loss), the proportions of high functioning (i.e., A or B) wetlands were found to be generally larger by both number and area in southern RVAUs where wetland loss was generally higher (Table 6; Figure 5). The policy lever adjustment ensures that the costs of wetland removal will be higher in the southern areas of the province where historic wetland loss has been greatest. Distributions of wetland value categories were more highly skewed toward the bottom range of values than wetland value categories by number, both before and after policy lever adjustments, resulting in proportionally larger areas of low functioning (i.e., *c* or *d*, C or D wetlands). This indicates that there is no bias towards large wetlands as indicators of wetland function or value.

A complete digital database of primary and secondary GIS data layers, including metadata and data confidence assessments, was delivered to the GOA. A provincial map of combined data confidence (Figure 6) illustrates where shortcomings in data quality exist. Data confidence was found to be generally high in the White Area, but with lower confidence in the southern areas of the province where historic loss of wetlands has been highest.

CURRENT USE OF THE LANDSCAPE-LEVEL ASSESSMENT

The ABWRET-E is currently in use by the GOA as a planning tool. Due to the limitations of the AMWI (i.e., classification biases, variations in spatial resolution, errors in accuracy and precision), the GOA decided to summarize wetland value scores by township section. This was done to avoid the assumption by users that wetlands that do not exist in the AMWI do not exist on the landscape and therefore do not require permissions. For each township section, the summary provides the total estimated area in hectares for all wetlands and for A, B, C and D wetlands. The summaries are viewable online through the GOA's GeoDiscover portal (https://geodiscover.alberta.ca/geoportal/catalog/main/home.page). In the future, as data quality improves, summaries are expected to be provided in finer units or by wetland.

Use by Planners

The GOA plans to work with municipalities to explore how the ABWRET-E can support informed wetland planning and management decisions at the local scale. Relative wetland value categories can be used by planners to identify wetlands that should be prioritized for conservation under municipal legislation. In Alberta, the Municipal Government Act (2000) provides municipal governments control over bodies of water within their jurisdiction allowing them to designate them as a conservation easement (where land owners retain ownership of the land but are required to protect the water body) or an environmental reserve (where municipalities take ownership of the land and can implement a buffer around the water body to prevent pollution and conserve the wetland's natural state). The ABWRET-E can inform planners of areas that should be targeted for protection (e.g., areas with the highest densities of high value wetlands) or mitigation (e.g., areas with the lowest densities of high value wetlands where restored wetlands have greater potential for high value). Further, in the event of an incident (e.g., an oil spill), the ABWRET-E results can assist in making a quick assessment to examine wetlands at risk and coordinate responses accordingly.

The ABWRET-E outputs can be scaled from individual wetland to regional scales, allowing for management at watershed scales. At the regional scale, results from the ABWRET-E can be used to feed into other policies and frameworks such as Alberta's Land-use Framework (Government of Alberta 2008). Alberta's Land-use Framework strives to manage Alberta's land and natural resources sustainably allowing for the achievement of Alberta's long-term economic, environmental and social goals. The Land-use Framework has developed several strategies that involve wetlands to achieve "smart growth". These strategies include using cumulative effects management to manage impacts of development on water, developing policy instruments for conservation on private and public lands, and establishing data and knowledge systems so that sound decisions are made. The ABWRET-E can assist in developing these strategies as the ABWRET-E outputs (1) can be input into models to examine the cumulative effects of the loss of wetland functions at watershed scales, and (2) can help to prioritize areas for wetland protection or restoration to achieve watershed management targets.

Use by Regulatory Personnel

The ABWRET-E estimates of wetland value scores should not replace those of the ABWRET-A, which are required for regulatory purposes. However, the ABWRET-E can be used in the regulatory process to facilitate avoidance and to encourage, where appropriate, relocation of planned activity. To conduct work in and around a water body in Alberta, approval must be obtained under the Water Act (1999) and (if appropriate) the Public Lands Act (2000). The Water Act requires approval for any activity that may affect an aquatic environment. When deciding whether or not to grant approval, the ABWRET-E can estimate the loss of wetland area and function for proposed activities, and can offer alternative sites if the loss in proposed area is too high. The ABWRET-E can also identify priority areas for policy compliance inspections. Priority areas for inspection could include areas where the consequences of Water Act contraventions would have a severe impact on wetland value loss. Government officials can look at past and present development projects where there are a large number of high value wetlands to ensure that any wetland removal or degradation is permitted and the appropriate compensation is being conducted.

COMPARISONS WITH FIELD EVALUATIONS

It is crucial that rapid evaluation tools based on GIS data are representative of field data. Given the recent release of the ABWRET tools for implementation, only a small amount of the ABWRET-A field data is available for comparison. Once a larger repository of field data is collected, the GOA plans to assess the concordance between the ABWRET-E and –A tools on a regular basis, (i.e., every five years). Results from this concordance exercise will help GOA continuously improve the ABWRET tools.

For this case study, we assessed the concordance between the ABWRET-E data and the limited ABWRET-A data that were available. The ABWRET-E methods differ from those of the ABWRET-A in several important ways. First, ABWRET-E identifies the spatial attributes of wetlands through GIS processing of AMWI polygons, whereas ABWRET-A requires manual digitization of wetland boundaries from local aerial photography. Second, ABWRET-E is based on GIS data only, whereas ABWRET-A uses combined GIS and field data. We compared ABWRET-E and -A indicator values, sub-function, function and value scores, and value categories in 48 manually digitized wetland polygons that intersected the ABWRET-E wetland polygons. The ABWRET-E and -A tools were found to produce largely concordant results demonstrated by strong and significant correlations as measured by Spearman rank correlation coefficients between (1) all pairs of indicator values, (2) all pairs of sub-function and function scores except one WQ sub-function score (water cooling) and three EH sub-function scores (organic nutrient export, invertebrate habitat and amphibian habitat), and (3) EH function scores. These disagreements were reduced when function scores were combined into value scores; pairs of value scores were found to be concordant. However, this concordance did not result in strong agreements in *a-b-c-d* (37.5 percent) or adjusted A-B-C-D (51.1 percent) value categories.

Based on these concordance tests, the GOA introduced 10 modifications to the ABWRET-A in May, 2016 to improve concordance with the ABWRET-E, including the removal or addition of indicators, modification of sub-function combining models, standardization of function scores, and applying ABWRET-E thresholds for value score categorization. As data quality improvements are secured in the future from more accurate and recent data sources, concordance is expected to improve.

LESSONS LEARNED

Simplifying Indicators and Sub-Function Models

The GOA recommended defining a set 20 indicators for the quick assessment of wetlands. The final list of indicators that was used in the ABWRET-E consisted of 73 indicators. We used a mathematical technique known as global sensitivity analysis to investigate how variations in outputs are affected by variations in input parameters to target the most influential indicators of HH, WQ and EH sub-functions (Pianosi et al. 2016). Specifically, the conditional variance method of sensitivity analysis (Saltelli et al. 2008) calculates a sensitivity index for each indicator in a sub-function model, representing the variance obtained in sub-function scores using all different possible indicator values to identify the most influential indicators. Including the most influential indicators only would both reduce computational and data storage expense for the ABWRET-E and simplify the regulatory process for permit seekers who would be required to do field-based measurements of indicators for the ABWRET-A.

Not all indicators had the same degree of influence on the wetland sub-function scores. Of the original 73 indicators, 4 indicators were exclusive to HU and were not used in the global sensitivity analysis as we focused on wetland function only (and not wetland use). Of the remaining 69 indicators, six indicators were not measured in all RVAUs due to incomplete spatial coverage of the input data layers and therefore were excluded from the global sensitivity analysis. Of the remaining 63 indicators, we identified 23 indicators (31% of all indicators) that contributed at least 10 percent of the variance to at least one of the 13 sub-function models. The contributions of these 23 indicators totaled no less than 60 percent of the variance for 10 of the 13 sub-function models. The remaining 40 indicators may be considered as candidates for removal in simplified models, or the models could be re-configured to inflate the relative contributions of the indicators according to their relative importance based on expert knowledge.

The global sensitivity analysis revealed that data type (e.g., continuous versus binary) and data order in the sub-function models had strong influences on whether an indicator was important. Indicators with binary (0 or 1) scores were usually more influential in the sub-function score results. Further, the higher an indicator appeared in the rule hierarchy of a sub-function model formula, the higher the influence it had. For example, a binary indicator of connectivity to surface water networks was given the first priority in the hierarchies of HH and WQ sub-function models, meaning that if the indicator value met a defined condition, then no other indicators contributed information to the sub-function score. We suggest that the results of the sensitivity analysis be discussed with the same experts that provided the knowledge for the construction of the combining models. This would create a process where the mathematical technique and the experts are used iteratively to avoid unintended consequences (e.g., some indicators that have a low importance and should have more).

Synergies and Tradeoffs

Unintended consequences can occur in the aggregation of functions into overall value scores and categories. Synergies may be produced where protection of one function has positive feedbacks for the protection of other functions; alternatively tradeoffs may be produced where protection of one function comes at the cost of other functions.

Equal weights were given for HH, WQ and EH scores (0.3) and 0.1 for HU scores in the ABWRET-E. This equal weighting of functions removes consideration of whether one or more functions may be a priority in a given RVAU. However, aggregation techniques could be chosen to prioritize some functions over others; for example, different weights could be assigned to characterize different degrees of importance. The choice of aggregation techniques requires careful consideration. For example, if a higher weight is given to HH function scores, will this lead to a general improvement in HH function on the landscape? If equal weight is given to all function scores, will the same improvement be found for all functions? Simulations made by Accatino et al. (2016) showed that the outcomes of aggregation techniques can lead to counterintuitive and unintended consequences. Some techniques based on weighted average led to synergies; for example, when a higher weight was assigned to HH function scores, improvement in WQ function was also detected as the two functions are complementary. However, other techniques led to tradeoffs; for example, threshold-based schemes based on a minimum, where the aggregated score is equal to the worst performing function, promoted mono-functional wetlands but multifunctional landscapes.

Static versus Dynamic Assessments

Wetland function assessments and value assignments are currently made under the assumptions of static landscapes and human preferences. However, the implementation of the wetland policy will create feedbacks that must be considered. For example, indicators of wetland function are sensitive to changes in a surrounding landscape that evolve over time; indicators, functions and values will periodically need to be recalculated and value distributions refreshed to capture potential shifts that may affect the value categories. Similarly, values are sensitive to changes in human preferences that can change over time; aggregation rules for combining functions will need to be revisited to capture potential shifts in human preferences (Ostrom 2009). Agent-based models are recognized tools for simulating complex systems (Farmer and Foley 2009) including landscape and human dynamics (Matthews et al. 2007). The potential consequences of implementation of Alberta's wetland policy should be simulated over time to capture these feedbacks. We plan to use agent-based models to explore the potential consequences of feedbacks between the landscape and human components that arise from the implementation of a wetland protection and restoration strategies to meet the wetland policy objectives.

FUTURE USE OF THE LANDSCAPE LEVEL ASSESSMENT

Refining the currently available wetland inventory

The wetland inventory is the single most important data layer in the ABWRET-E, but confidence in wetland function estimates is negatively affected by its unreliability in many areas. The current AMWI contains numerous omission and commission errors as well as incorrect wetland boundaries, due in part to the contributions of different initiatives using different methods, specifications and data sources to create the merged inventory. Future work will require improving the AMWI by developing methods to standardize and automate wetland inventory creation using fine spatial resolution data acquired at regular repeat intervals. The integration of accurate and high spatial resolution Light Detection and Ranging (LiDAR) elevation data and color satellite or aerial photograph data obtainable at regular intervals will help to improve wetland identification, delineation and classification results (e.g., Serran and Creed 2016; Waz and Creed 2016). Standard automated methods will provide replicable results that can be compared across regions and will allow for rapid re-assessments in a changing landscape. Investment in the wetland inventory will also significantly improve confidence in wetland function estimates. All 73 indicators depend on the accurate identification of the presence or absence of wetlands, and 26 of the 73 indicators are obtained directly from attributes of the wetland inventory (e.g., wetland area, wetland type, wetland perimeter-to-area ratio).

Monitoring Extent and Recovery of Wetland Functions

Monitoring of existing wetland functions over time and the return of wetland functions post restoration can determine whether the ABWRET tools effectively capture the processes that affect wetland function. The ABWRET-E, in combination with other emerging technologies, can assess the functions of existing and restored wetlands on a regular basis using indicator data that is regularly refreshed. For example, new and cost-effective remote sensing techniques using drones could be used to acquire accurate and repeatable indicator data on demand to monitor functions over time and space (Koneko and Nohara 2014). This information will assist the GOA to determine if its policy of preserving wetland function through wetland restoration is effective.

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Table 1. Indicators of Hydrologic Health sub-functions (WS = Water Storage; SFS = Stream Flow Support).

Indicator	Units	WS	SFS
Aquifer Vulnerability Index	categorical	✓	
Channel Connection	yes/no	✓	✓
Class A or B (Alberta Water Act Codes of Practice Streams)	yes/no	✓	✓
Elevation Percentile In HUC8	percentile	✓	✓
Floodways or Riparian Area	yes/no	✓	✓
Hydrologic Detention Time (L/G Index)	m	✓	
Percent Fen	percent	✓	✓
Percent Open Water	percent	✓	✓
Percent Wooded (Forest and Swamp)	percent	✓	✓
Perimeter-Area Ratio	$m:m^2$	✓	✓
P-PET (1971-2000)	mm/yr	✓	✓
Soil Texture	categorical	✓	
Springs or Other Groundwater Discharge Area	yes/no	✓	✓
Subzero Days (1971-2000)	days/yr	✓	✓
Water Permanence Probability	percent	✓	✓
Wetland Area	m^2	✓	
Wetland Size Percentile In HUC8	percentile	✓	✓
Wetland Vegetated Area	m^2	✓	✓
Wind Intensity - Summer	W/m^2	✓	✓

Table 2. Indicators of Water Quality sub-functions (WC = Water Cooling; SR = Sediment Retention; PR = Phosphorus Retention; NR = Nitrate Removal).

Indicator	Units	WC	SR	PR	NR
Aspect of Wetland's 100 m Upslope Buffer	categorical				✓
Channel Connection	yes/no	✓	✓	✓	✓
Class A or B (Alberta Water Act Codes of Practice Streams)	yes/no	✓	✓	✓	✓
Clumpiness Index for Vegetation and Water	m^2		✓	✓	✓
Floodways or Riparian Area	yes/no	✓	✓	✓	✓
Growing Degree Days (1971-2000)	days/yr				✓
Hydrologic Detention Time (L/G Index)	m	✓	✓	✓	✓
Organic Soil Content	categorical			✓	✓
Percent Fen	percent	✓			
Percent Marsh or Swamp	percent				✓
Percent Open Water	percent	✓	✓	✓	
Percent Wooded (Forest and Swamp)	percent	✓			✓
Perimeter-Area Ratio	$m:m^2$				✓
Soil Texture	categorical			✓	✓
Springs or Other Groundwater Discharge Area	yes/no	✓			
Slope In 500 m Buffer	degrees		✓		
Subzero Days (1971-2000)	days/yr		✓	✓	✓
Water Permanence Probability	percent	✓		✓	✓
Wetland Vegetated Area	m^2		✓	✓	

Table 3. Indicators of Ecological Health sub-functions (OE = Organic Nutrient Export; FR = Fish Habitat; INV = Invertebrate Habitat; AM = Amphibian Habitat; WB = Waterbird Nesting Habitat; SRM = Songbird, Raptor and Mammal Habitat; PH+POL = Plant and Pollinator Habitat).

Indicator	Units	OE	FR	INV	AM	WB	SRM	PH+ POL
Bog/Fen/Marsh/Swamp Uniqueness for 1 km Buffer	percent			✓			✓	✓
Channel Connection	yes/no	✓	✓					
Class A or B (Alberta Water Act Codes of Practice Streams)	yes/no	✓	✓					
Clumpiness Index for Herbaceous and Woody Vegetation in the Wetland	m^2			✓			✓	✓
Clumpiness Index for Vegetation and Water	m^2	✓	✓	✓	✓	✓	✓	✓
Distance from Wetland to Nearest Developed Land or Annual Cropland	m			✓	✓	✓	✓	✓
Distance from Wetland to Nearest Road	m		✓		✓		✓	✓
Fen, Marsh, or Swamp Uniqueness in 1 km Buffer	percent				✓			
Fen or Marsh Uniqueness in 1 km Buffer	percent					✓		
Floodways or Riparian Area	yes/no	✓	✓			✓	✓	✓
Growing Degree Days (1971-2000)	days/yr	✓						
Habitat Connectivity to Other Wetlands within 1 km	yes/no				✓	✓	✓	
Important Bird Area	yes/no					✓		
Internal Wetland Type Richness	number (continuous)			✓			✓	✓
Key Wildlife Biodiversity Zone	yes/no						✓	
Nesting Bird Colony, Piping Plover Water Body or Trumpeter Swan Use Area	yes/no					✓		
Open Water Area	m^2		✓					

Indicator	Units	OE	FR	INV	AM	WB	SRM	PH+ POL
Organic Soil Content	categorical	✓						
Percent Bog, Fen or Marsh	percent	✓						
Percent Fen, Marsh or Swamp	percent						✓	✓
Percent Marsh	percent			✓	✓	✓		
Percent Natural Cover Within 1 km	percent			✓			✓	✓
Percent Open Water	percent		✓	✓	✓	✓	✓	✓
Percent Perimeter Adjoined By Natural Cover	percent		✓	✓	✓	✓		✓
Percent Undeveloped Openlands Within 1 km	percent				✓	✓		
Rare Plant Species Range	yes/no							✓
Road Density in 1 km Buffer			✓				✓	✓
Sensitive Amphibian Range	yes/no				✓			
Sensitive Raptor Nesting Area	yes/no						✓	
Shorebird Staging Wetland	yes/no					✓		
Soil Texture	categorical	✓						
Subzero Days (1971-2000)	days/yr		✓					
Trumpeter Swan Area	yes/no					✓		
Water Permanence Probability	percent		✓					
Waterfowl Breeding Density	number (continuous)					✓		
Waterfowl Staging Wetland	yes/no					✓		

Indicator	Units	OE	FR	INV	AM	WB	SRM	PH+ POL
Wetland Density (Open Water Only) Within 1 km	percent					✓		
Wetland Density within 1 km	percent						✓	✓
Wetland Density (No Bogs) within 1 km	percent			✓	✓			
Wetland Type Richness within 1 km	number (continuous)			✓			✓	✓
Wetland Vegetated Area	m^2	✓			✓	✓	✓	✓
Wind Intensity - Winter	W/m^2						✓	

Table 4. Indicators of Human Use function.

Indicator	**Units**
Access to Trail Network	yes/no
Alberta Culture Listing of Historical Resources	categorical
Distance from Wetland to Nearest Road	m
Distance to Nearest Well-Settled Area	m
Ecological Reserve or Natural Area	yes/no
Fringe Wetland	yes/no
Lacustrine Wetland	yes/no
Ownership	yes/no
Percent Open Water	percent
Road Density in 1 km Buffer	
Water Permanence Probability	percent
Wetland Area	m^2

Table 5. Current wetland number and area and estimated percent loss of wetlands by number and area for each RVAU. Loss estimates were used to develop policy lever adjustments to relative wetland value categories in each RVAU (-1 denotes lowering value categories by one letter, +1 denotes raising value categories by one letter, 0 denotes no adjustment).

RVAU	Area (km^2)	Current Wetland Number	Current Wetland Area (ha)	Lost Wetland Number (%)	Lost Wetland Area (%)	Policy Lever Adjustment
1	26359.82	76802	97662.32	82.50	40.11	**+1**
2	26567.35	57009	94526.69	83.55	38.10	**+1**
3	43397.48	130093	189115.86	84.89	40.42	**+1**
4	13447.24	57254	137060.42	83.62	30.93	**+1**
5	32316.84	268342	309229.13	70.08	28.26	**0**
6	25182.83	47042	299035.24	81.35	23.59	**0**
7	23161.47	181692	264544.74	43.54	10.18	**-1**
8	25020.79	134053	481478.90	69.46	30.86	**0**
9	45204.45	183071	2048024.09	63.07	15.85	**-1**
10	75506.06	108719	1095703.03	75.38	15.08	**0**
11	24174.32	82117	603553.29	85.06	30.22	**+1**

Table 6. Distributions of relative wetland value categories for each RVAU. Categories given in lower case letters describe the relative value of wetlands from *a* (high value) to *d* (low value). For each RVAU, policy lever adjustments were used to adjust relative wetland value category letters upward (+1), downward (-1) or no change (0); adjusted relative wetland value categories are given in upper case letters from A (high value) to D (low value).

RVAU	Policy Lever Adjustment	*a* Wetland Number (%)	*a* Wetland Area (%)	A Wetland Number (%)	A Wetland Area (%)	*b* Wetland Number (%)	*b* Wetland Area (%)	B Wetland Number (%)	B Wetland Area (%)
1	**+1**	16.99	14.08	60.36	43.67	43.38	29.60	18.60	9.14
2	**+1**	5.62	3.43	20.30	17.66	14.67	14.24	21.56	10.21
3	**+1**	2.33	2.76	41.56	36.16	39.23	33.40	13.51	8.53
4	**+1**	23.53	18.79	55.00	38.29	31.46	19.50	19.79	10.53
5	**0**	17.05	8.45	17.05	8.45	8.37	11.98	8.37	11.98
6	**0**	1.75	0.51	1.75	0.51	3.52	3.38	3.52	3.38
7	**-1**	21.55	8.85	5.00	4.40	12.74	13.94	16.55	4.45
8	**0**	3.42	0.77	3.42	0.77	2.95	2.49	2.95	2.49
9	**-1**	2.66	0.39	2.66	0.39	27.34	10.81	2.34	8.08
10	**0**	3.49	0.79	3.49	0.79	21.15	4.77	21.15	4.77
11	**+1**	1.05	0.40	37.87	10.42	36.82	10.02	31.04	5.96
RVAU	Policy Lever Adjustment	*c* Wetland Number (%)	*c* Wetland Area (%)	C Wetland Number (%)	C Wetland Area (%)	*d* Wetland Number (%)	*d* Wetland Area (%)	D Wetland Number (%)	D Wetland Area (%)
1	**+1**	18.60	9.14	16.03	40.10	21.04	47.18	5.00	7.08
2	**+1**	21.56	10.21	53.14	63.83	58.15	72.13	5.00	8.30

3	**+1**	13.51	8.53	39.92	44.63	44.92	55.31	5.00	10.68
4	**+1**	19.79	10.53	20.22	43.38	25.22	51.18	5.00	7.80
5	**0**	37.02	20.23	37.02	20.23	37.56	59.34	37.56	59.34
6	**0**	22.52	6.82	22.52	6.82	72.21	89.29	72.21	89.29
7	**-1**	44.76	16.75	12.74	13.94	20.94	60.46	65.70	77.21
8	**0**	19.32	5.24	19.32	5.24	74.31	91.51	74.31	91.51
9	**-1**	36.39	2.79	25.01	3.02	33.60	86.00	69.99	88.50
10	**0**	30.45	6.00	30.45	6.00	44.90	88.44	44.90	88.44
11	**+1**	31.04	5.96	26.09	78.82	31.09	83.61	5.00	4.79

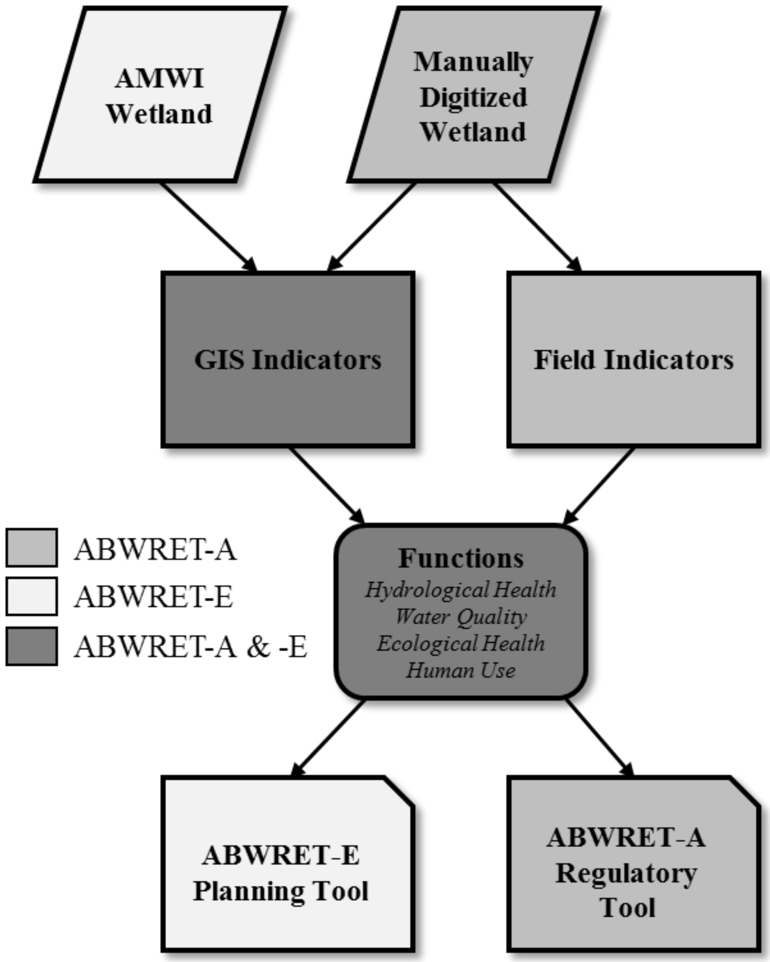

Figure 1. Relationship between ABWRET-E and -A

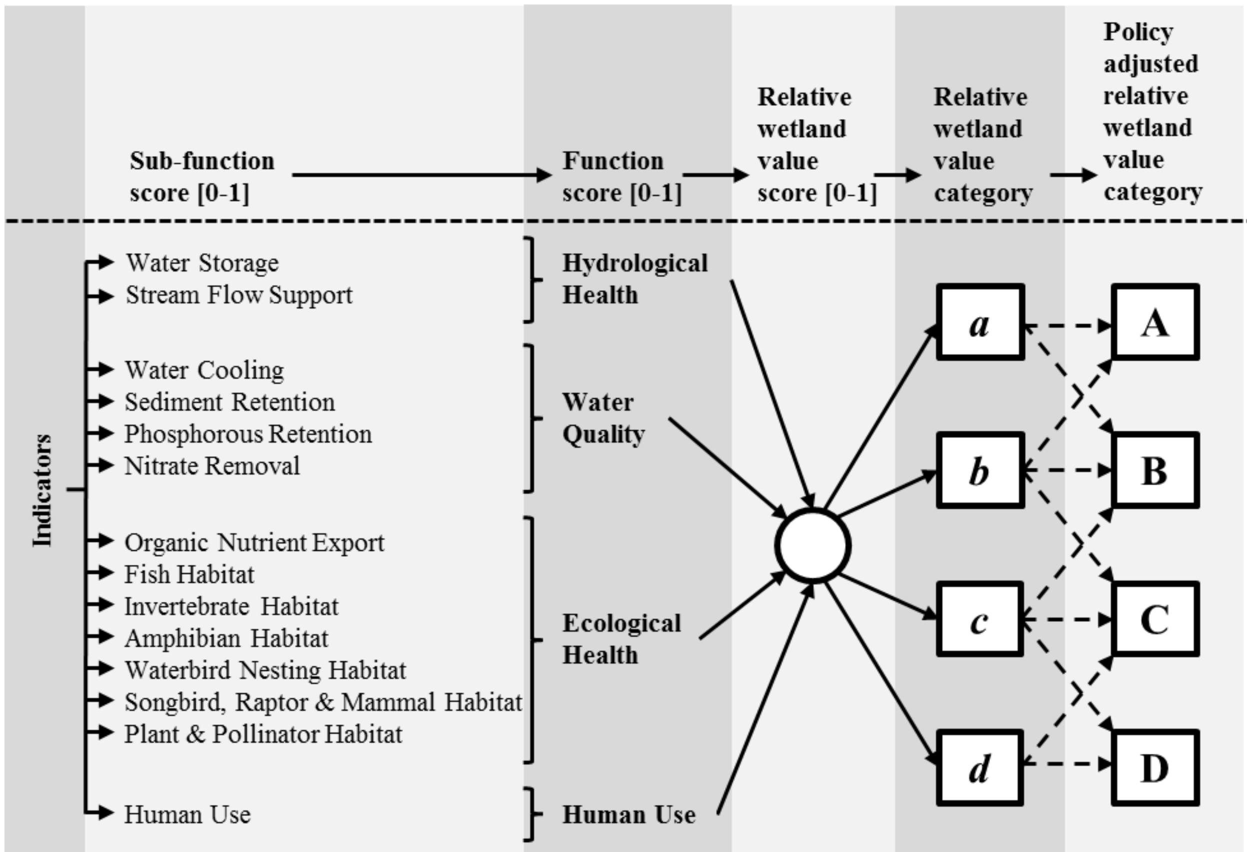

Figure 2. ABWRET-E and -A combine indicators to wetland sub-function and function scores and bundle function scores to produce wetland scores.

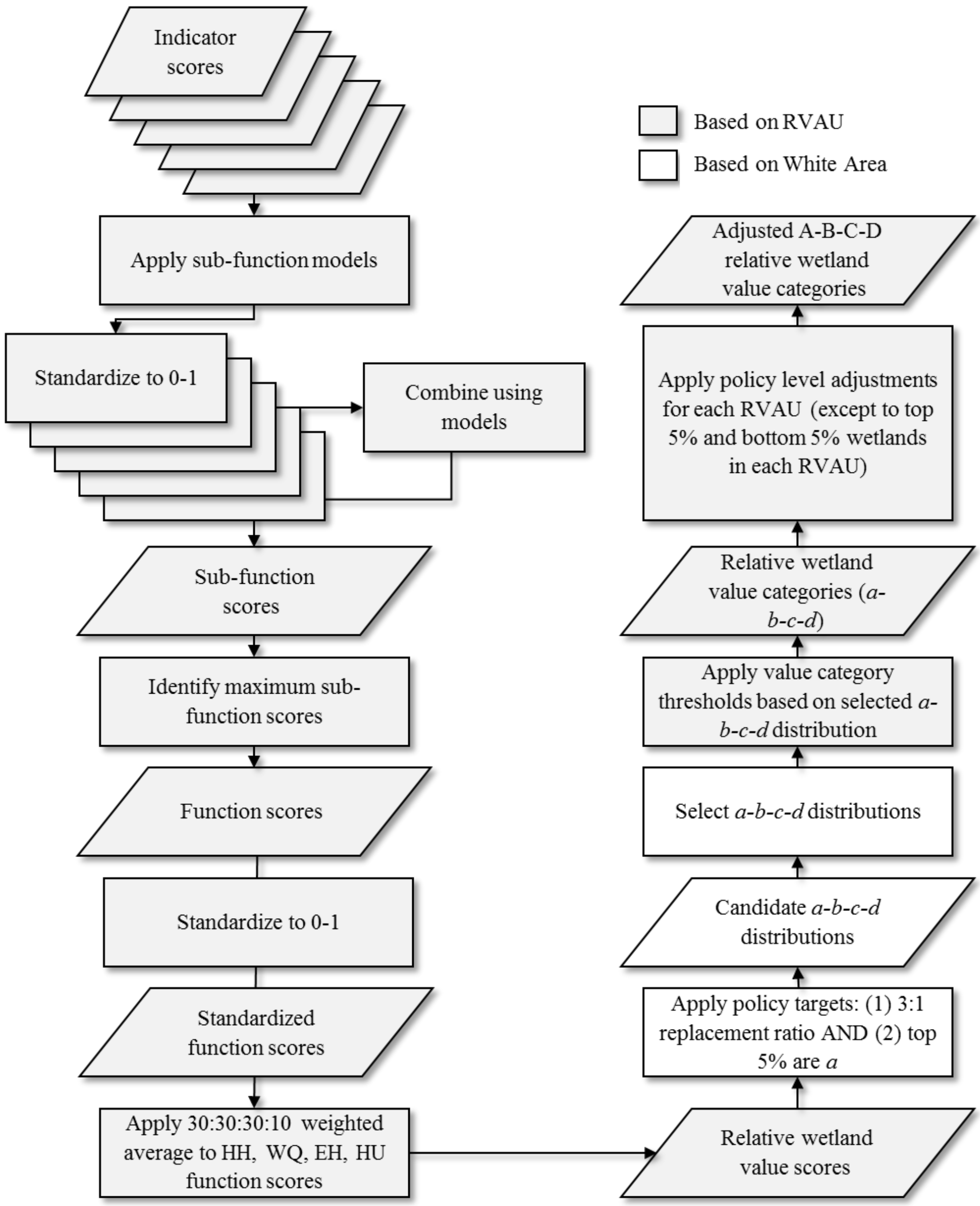

Figure 3. Flowchart of steps used to apply the ABWRET-E.

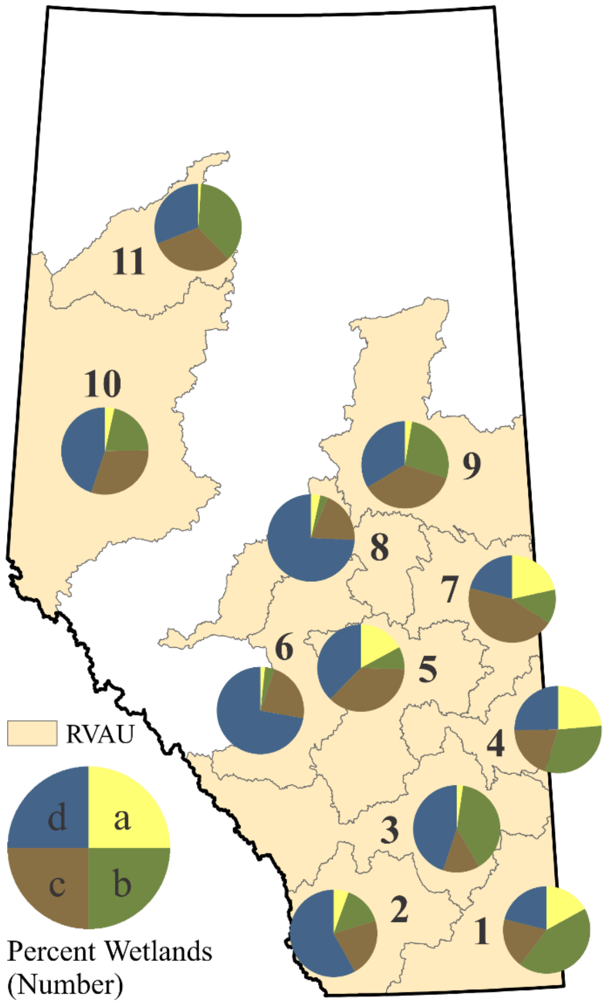

Figure 4. Distribution of relative wetland value categories by number (left) and area (right) for each RVAU (see Table 6 for numerical summaries). Categories *a*, *b*, *c* and *d* describe the relative value of wetlands from *a* (high value) to *d* (low value).

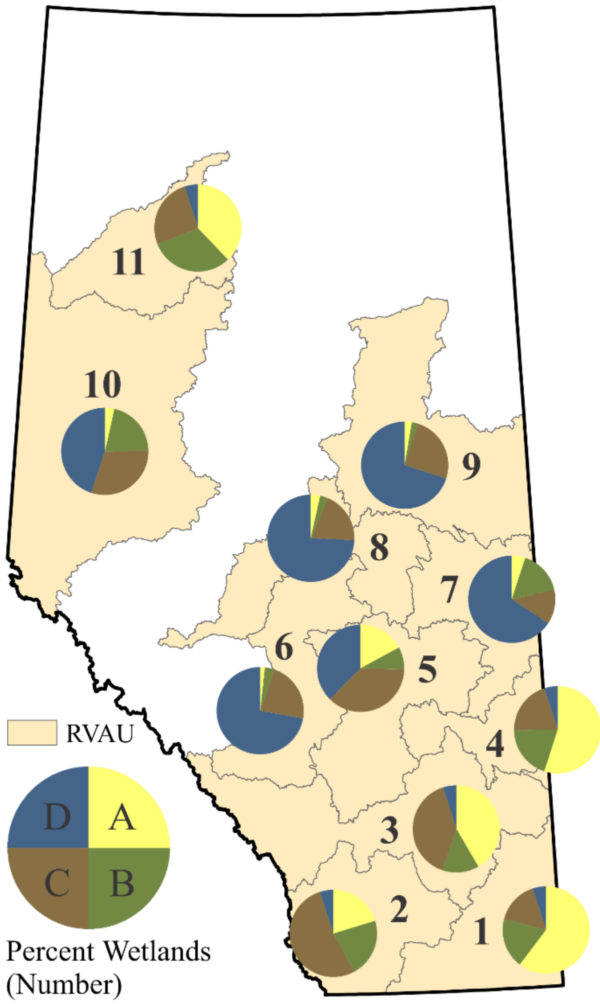

Figure 5. Distribution of adjusted relative wetland value categories by number (left) and area (right) for each RVAU (see Table 6 for numerical summaries). Categories A, B, C and D describe the relative value of wetlands from A (high value) to D (low value).

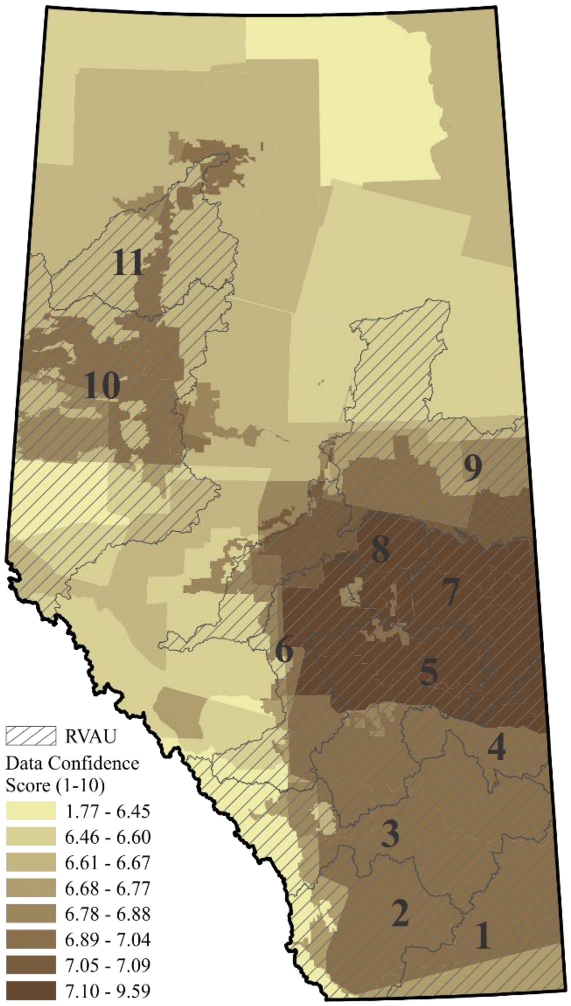

Figure 6. Confidence scores for data layers used in relative wetland value assessment. Data confidence scores from 1 (low confidence) to 10 (high confidence) were calculated as the average of spatial and temporal confidence scores assigned from metrics of spatial resolution and data layer age respectively.