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An Identification and Evaluation of Strategic Priorities for Conservation and Restoration to Improve Watershed Resiliency in the Sturgeon River Watershed

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1 Introduction

1.1 Project objectives

Over the past two decades, the North Saskatchewan Watershed Alliance (NSWA) has been leading efforts to recognize and address watershed management issues in the North Saskatchewan River watershed of Alberta. The North Saskatchewan River watershed is composed of smaller sub-watershed units, some of which are represented by local watershed groups. The Sturgeon River Watershed Alliance (SRWA) is one such stewardship group operating in the Sturgeon River watershed – a sub-watershed of the North Saskatchewan River watershed. The SRWA is comprised of representatives from the NSWA, municipalities, and stakeholders located within the Sturgeon River watershed; project work is guided by overarching goals of the *Integrated Watershed Management Plan for the North Saskatchewan River in Alberta* (IWMP).

As a result of recent assessments done in the Sturgeon River Watershed, such as the *State of the North Saskatchewan Watershed Report* (NSWA, 2005), the *Sturgeon River Watershed State of the Environment Report (*City of St. Albert, 2012) and the *Influence of Climate, Landscape Change and Licenced Water Removal on Flows in the Sturgeon River Basin* (NSWA, 2017a), knowledge areas were identified that, if explored would provide valuable insight for the overall management of the Sturgeon River watershed. Of particular importance for watershed management and restoration planning is a means to assess overlapping impacts across the watershed. Significant urban developments, agricultural expansion, and linear disturbances in the Sturgeon River watershed coupled with impacts of a changing climate result in increased variability in stream flow and the frequency of floods and drought.

The focus of this project was to take a cumulative effects modelling approach to identify strategic conservation and restoration priorities aimed at building watershed resilience through conservation and restoration strategies in the Sturgeon River watershed. Landscape, anthropogenic and hydroclimatic attributes of the Sturgeon River watershed were integrated in the model, which allows users to simulate how various indicators of hydrologic change might respond to changes in land use and climate.

The objectives of the project were to:

- Develop a standardized set of indicators for assessing watershed resilience in the Sturgeon River watershed,
- Develop custom hydrologic and land use models for the Sturgeon River watershed,
- Perform model scenario simulations of the relative impact of climate and land use changes on hydrologic indicators,
- Provide recommendations for conservation and restoration areas within the Sturgeon River watershed, and
- Create a user-friendly web-based tool to view results of the model simulation scenarios.

Consultation and cooperation with the Sturgeon River Watershed Alliance Technical Advisory Committee (TAC) was upheld throughout all phases of the project. The TAC consists of technical staff from municipal and provincial governments as well as NGOs,, and functioned to ensure the approach met the needs of the watershed.

1.2 Study area

The spatial scope of the project is defined as the entire Sturgeon River watershed in Central Alberta (Figure 1). The Sturgeon River drains a land area of approximately 3,301 km^2, flowing from its headwaters through three lakes, Isle Lake, Lac Ste. Anne, and Big Lake, before reaching the confluence with the North Saskatchewan River.

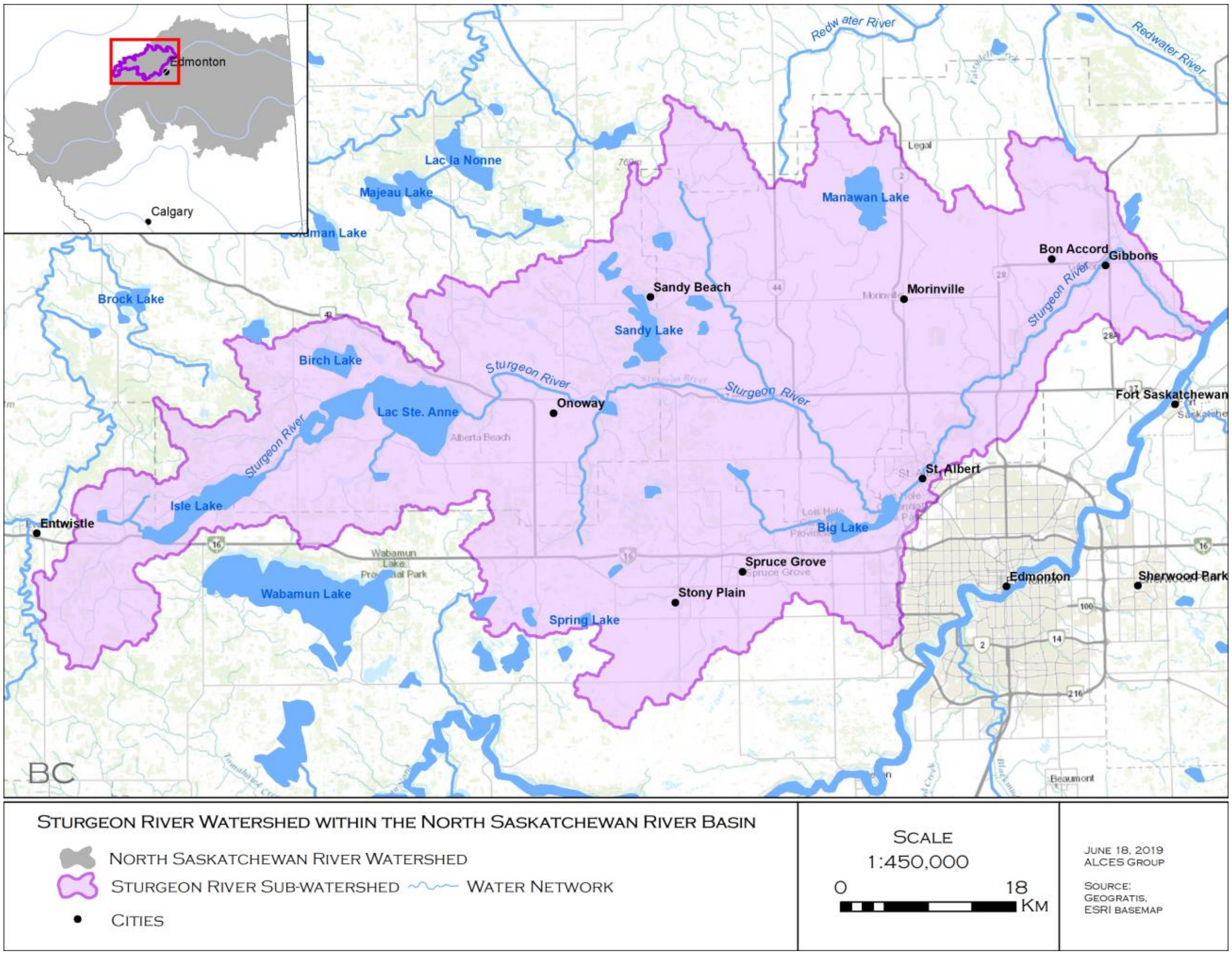

Figure 1. The Sturgeon River watershed study area

The Sturgeon River watershed is characterized by a continental climate with cold winters and warm summers and relatively low precipitation (Figure 2). Climate data from Edmonton show that the majority of precipitation is received during June and July, which does not correspond to timing of the highest stream flows which are typically seen in April and May (NSWA, 2017b; Figure 2 and Figure 3). Periods of highest stream flows are associated with the melting snowpack, and snow accumulation has been decreasing over time (NWSA, 2017). Melting snow also provides important groundwater recharge that contributes to the very low late-season base flow in the Sturgeon River (NSWA, 2017b).

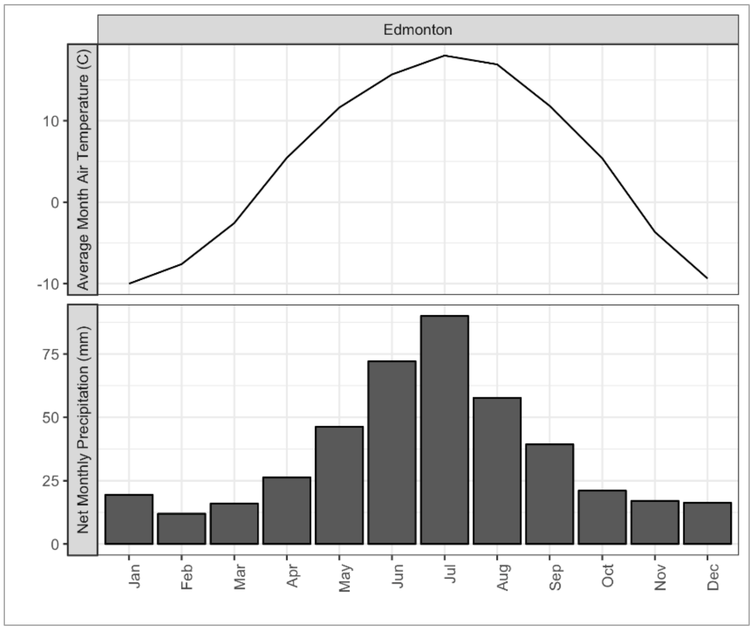

Figure 2. Average monthly air temperature and net monthly precipitation for the Edmonton climate station over the period from 1980-2016

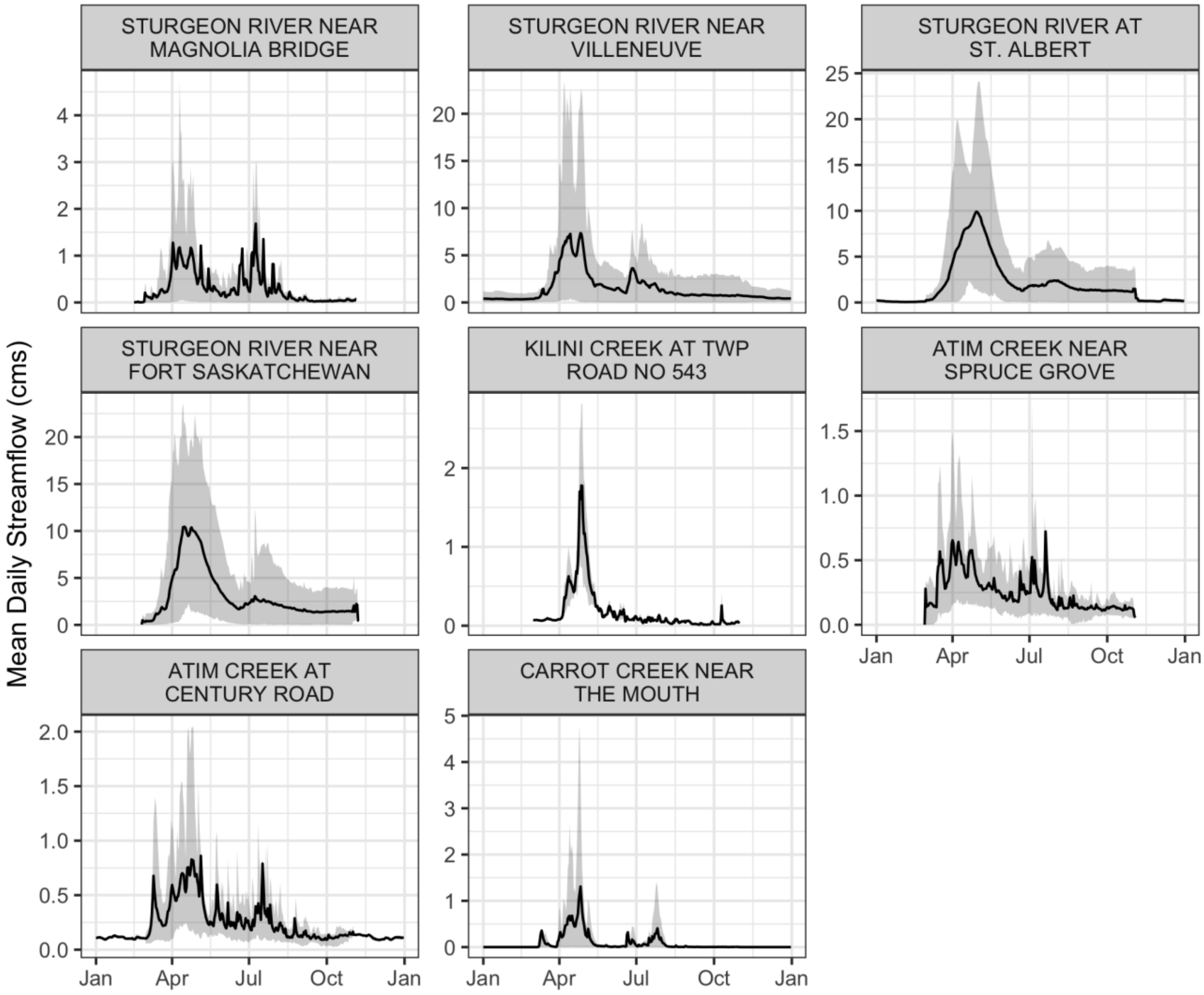

Figure 3. Daily average streamflow for Water Survey of Canada hydrometric stations in the Sturgeon River watershed for the period from 1913 - 2017, with varied dates for each station

The distinct landscape of the Sturgeon River watershed can be attributed to a transition in the Natural Regions from Boreal to Parkland. Agricultural crops are the dominant land cover in the Sturgeon River watershed, covering 37% of the area. Pasture (17%) is the second largest land cover, followed by forest (12%), wetland (11%), and shrubland (6%). Areas of human settlement consisting of urban and rural residential occupy a substantial proportion of the Sturgeon River watershed and have increased substantially in recent decades (NSWA, 2017b; Figure 4).

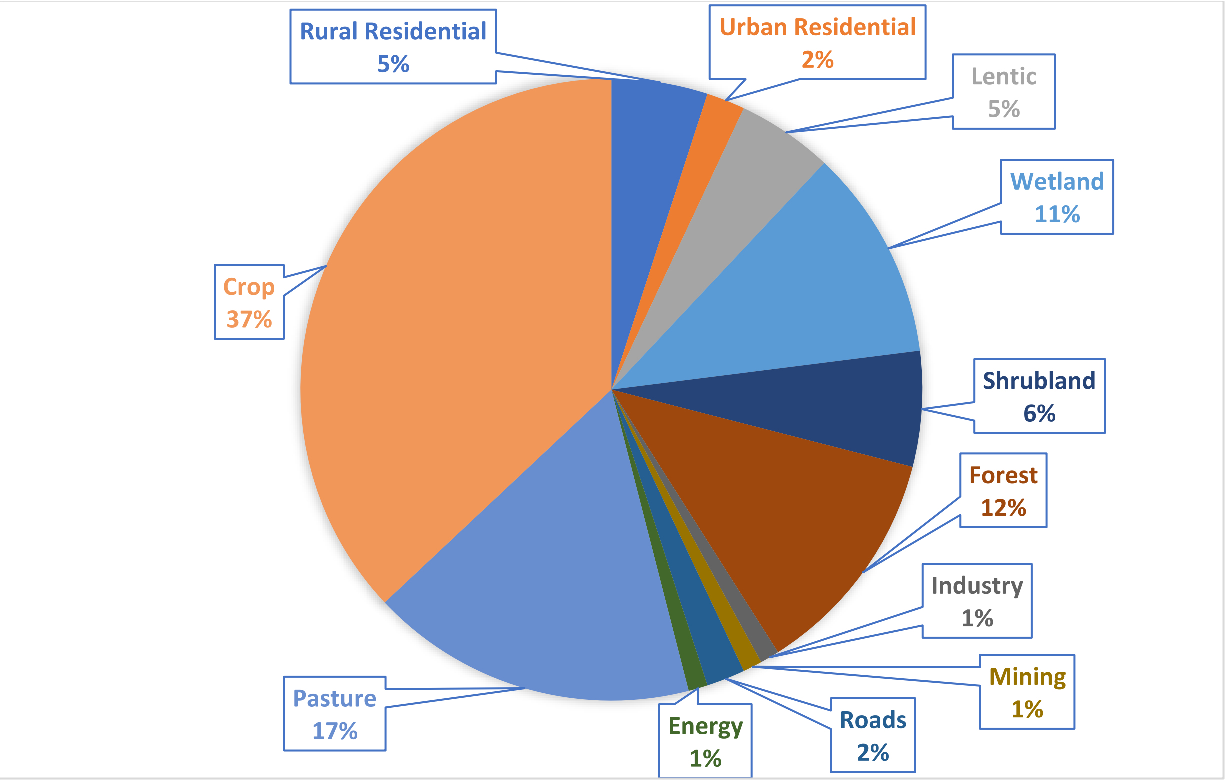

Figure 4. Proportion of land cover type across the Sturgeon River watershed

1.3 Watershed resilience

A number of preliminary steps were taken to customize the modelling tools according to the project objectives and the unique attributes of the Sturgeon River watershed. The first involved participation with the TAC to define *watershed resilience* and outline the standardized set of indicators used to assess change in watershed resilience based on landscape composition and climate.

1.3.1 Watershed resilience definition

Resilience is a complex term with multiple specified meanings. The engineering term is defined as the time required for a system to return to an equilibrium or steady-state following a perturbation (Gunderson, 2000). The ecological definition acknowledges alternative stable regimes, and measures resilience by the magnitude of disturbance that can be absorbed before the system reorganizes its structure and switches regimes (Gunderson, 2000).

1) For this project, we examine hydrologic resilience within the context of the ecological definition, and consider three aspects in this approach: the magnitude of change a system can undergo while remaining within the same stable regime,
2) the degree to which the system is self-organizing, and
3) the degree to which the system can learn and adapt.

Figure 5 portrays a schematic of system stability, where the valleys represent domains of attraction (or stable states), balls represent the system, and arrows represent the acting perturbation. In this schematic hydrologic and ecological resilience would be described as the amount of perturbation required to send a ball into an adjacent valley.

When considering hydrologic resilience, it is important to describe the system in question as well as the disturbance regime (Carpenter et al., 2001). For example, hydrologic conditions change naturally as a function of climate. Therefore, it is important to consider this relatively high natural variability.

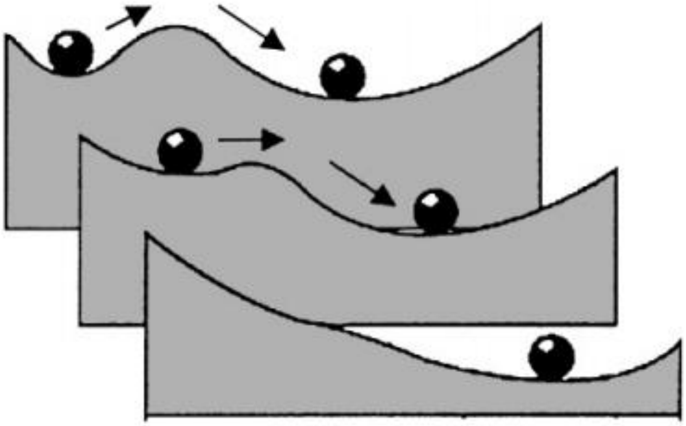

Figure 5. Ball and cup schematic of system stability. Valleys represent domains of attraction (or stable states), balls represent the system, and arrows represent the acting perturbation

Within the context of hydrology, a variable system is generally more resilient. A system that experiences relatively regular extremes in environment or external forces is able to adapt and evolve to those circumstances. A system that undergoes little change will not be able to adapt when faced with extreme circumstances even though it is perhaps more stable.

The working definition of *watershed resilience* was developed for the Sturgeon River watershed by participants at the Working Group meeting in July 2017. For this project, the definition of a resilient watershed is:

"A watershed that maintains key hydrological features able to perform diverse functions (recharge, storage, and discharge), and absorbs disturbance without shifting regimes".

Resilience was assessed within the context of the range of natural variability instead of referring to a specific period in time. The range of natural variability accounts for the range of natural disturbance (wildfire and pests), climate change, as well as hydrologic change. Against this backdrop of naturally occurring variability, one can assess how human activities can improve or worsen a watershed's response to extreme events like floods or droughts. A subsequent evaluation of whether a system has shifted outside the bounds of normalcy can also be conducted, forming the basis for defining watershed resilience.

1.3.2 Watershed resilience indicators

Indicators of watershed resilience are a means of evaluating the performance of watershed values and providing an objective assessment of how different scenarios will affect the resiliency of the Sturgeon River watershed.

If the status of an indicator is 'good', then one would conclude that the hydrology of the Sturgeon River watershed is resilient. In terms of 'good' relative to hydrologic resilience, we assume that no change relative to the range of natural variability is good performance. Shifts outside of this natural range are deemed as less resilient. The watershed resilience indicators that were used in this project are listed in Table 1, and described below.

Table 1. Watershed resilience indicators

Indicators
Change in peak streamflow
Low flow index
Flashiness index
Timing of low flow conditions
Timing of peak flow events
Frequency of low flow conditions
Frequency of peak flow events
Change in annual water yield

<u>Change in peak streamflow</u>

The "change in peak streamflow" indicator provides a means of assessing the influence of land cover and climate change and the watershed's ability to naturally absorb runoff. This indicator was assessed at the scale of the sub-basin, as series of smaller drainage units within the greater Sturgeon River watershed.

Change in peak streamflow was evaluated as the percent difference in peak flow between two points in time or two different scenarios (units = %), assessed at Water Survey of Canada sites within the Sturgeon River watershed.

<u>Low flow index</u>

The low flow index was used to assess hydrologic alteration in terms of potential threats to aquatic ecosystems and as a surrogate for water availability.

Low flows were assessed by dividing the average of the lowest annual daily streamflow by the average daily streamflow over all years (Poff and Ward, 1989) recorded at the Water Survey of Canada sites within the Sturgeon River watershed. There are no units for this indicator.

Flashiness Index

Flashiness is a reflection of the frequency and rate of short-term changes in streamflow (no units). The R-B index (Baker et al., 2004) was used to assess hydrologic alteration at Water Survey of Canada sites within the Sturgeon River watershed, in terms of how flashy the particular sub-basin is and how the index changes over time in response to land use activities.

Timing of low flow conditions

Timing of low flow conditions is an important indicator of when drought may be occurring, when the aquatic ecosystem may be experiencing stress, and when the availability of water for human consumption may be stressed. The timing of low flow conditions is determined as the Julian date of annual minimum streamflow assessed at Water Survey of Canada sites within the Sturgeon River watershed.

Timing of peak flow events

The timing of peak flow events is significant because it provides an opportunity to evaluate periods when flood potential is high. The timing of peak flow events is determined as the Julian date of annual maximum streamflow at Water Survey of Canada sites within the Sturgeon River watershed.

Frequency of low flow conditions

Frequency of low flow conditions is important given that it provides an indication of how flashy the system is in terms of hydrologic extremes and provides an indicator of how often water supply stress may occur. The frequency of low flow conditions is determined as how often low flow conditions occur over the simulation period at Water Survey of Canada sites within the Sturgeon River watershed.

Frequency of peak flow events

The frequency of peak flow events provides an indication of flashiness in terms of hydrologic extremes and information on how vulnerable a system may be in terms of flood hazard. The frequency of peak flow events is determined as the number of times a 1:100 flow is reached or achieved over the simulations period at Water Survey of Canada sites within the Sturgeon River watershed.

Change in annual water yield

This is an indicator of how much water the landscape (watershed) is producing annually and provides an understanding of changes in water availability. Annual water yield is an annual sum of water volume across the watershed (units $=m^3$) within sub-basins of the Sturgeon River watershed.

2 Methods

Two modelling tools were used to run simulations for this project - the Raven hydrological modelling platform and ALCES Online:

- Raven: a flexible, open sourced modelling framework that can be customized to understand the hydrological behaviour of a watershed and assess the potential effects of land use, climate, and other environmental change on streamflow. Raven is unique in that it provides access to a number of different methods for interpolating meteorological data, routing water, and representing hydrological processes (Craig et al., 2016).
- ALCES Online: a fully integrated web-based simulator that allows users to visualize historical, current, and future landscapes on a range of spatial and temporal scales.

A core component of the assessment involved application of Raven to derive relationships describing the effect of landscape composition and climate on streamflow indicators. ALCES Online was then applied to explore the implications of current and future land use and climate to watershed resilience and to assess the effectiveness of conservation and restoration strategies.

The spatial scale was previously defined as the entire Sturgeon River watershed, and smaller sub-basin units were delineated within this watershed (Figure 6). The temporal scale of the project was chosen to range from the year 1900 to 2065.

Existing datasets were utilized in ALCES Online, in addition to new datasets that were introduced into the tool. Hydroclimatic variables specific to the Sturgeon River watershed were compiled and entered into the Raven modelling platform. To ensure accurate representation of the Sturgeon River watershed characteristics by the Raven model, the model was verified by comparing historical data with model simulations for variables including snowpack and streamflow.

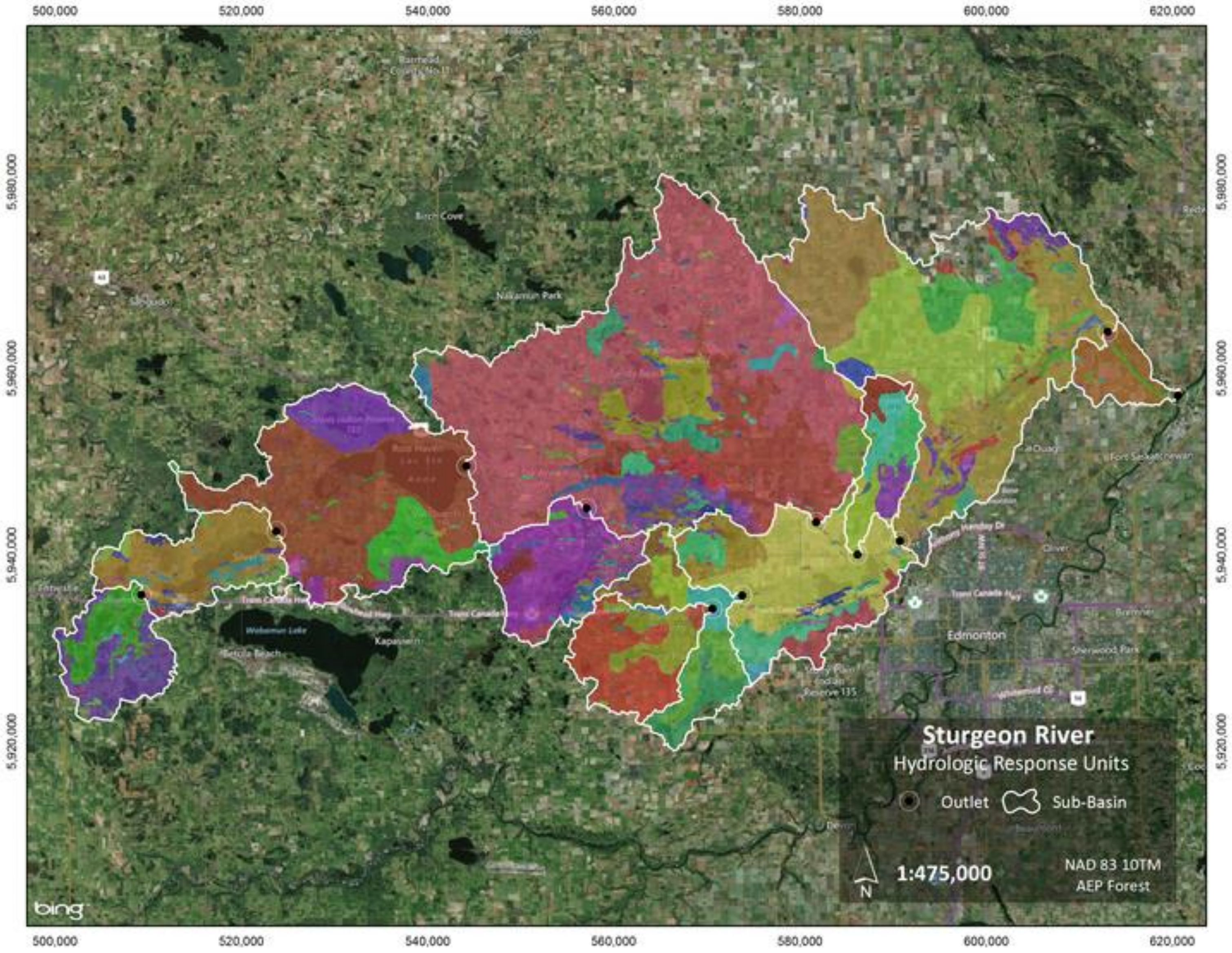

Figure 6. Sub-basins defined in the Sturgeon River watershed project area for hydrologic modelling.

2.1 Hydrological modelling

The hydrological model developed for the Sturgeon River watershed incorporates land use and climate in the Raven modelling platform to simulate streamflow using the current scientific state of knowledge.

Maps generated as part of the provincial government's Watershed Resiliency and Restoration Program (2015) identify the Sturgeon River watershed as being high priority for the mitigation of floods, drought, and water quality degradation. This model provides stakeholders with a tool that:

1. Accurately simulates the hydrological processes governing each watershed.
2. Offers flexibility to accommodate a range of climate and land-cover scenarios.
3. Provides accurate simulations of streamflow in the Sturgeon River and tributaries.

The model was customized with hydrological processes relevant to the region so watershed response was physically meaningful and well understood. The model can be used to evaluate single storm events or to develop long-term water balances for resource management.

Raven was calibrated and verified as per methods described in Chernos et al. (2017). Once streamflow and watershed processes were deemed suitable for the historic period between 1985 to 2016, simulation experiments were conducted to evaluate effects of land use on streamflow. Outputs from the simulation experiment were incorporated into ALCES Online as hydrologic indicators.

2.1.1 Hydrological modelling data

Previously reported scientific knowledge was incorporated into the custom hydrological model for the Sturgeon River watershed. These data were obtained from:

- Big Lake Stormwater Management Plan (Associated Engineering, 2004)
- Wetland Depression Storage (Pomeroy et al., 2010)
- Prairie Potholes and Non-Contributing Areas (Pomeroy et al., 2012; Shook, 2013)
- Isle Lake and Lac Ste. Anne Water Balances (NSWA, 2016)
- Urban Expansion, Climate Change in the Sturgeon River (Buendia, 2017)

Daily streamflow measurements were obtained from eight Water Survey of Canada (WSC) (2018) hydrometric stations in the Sturgeon River watershed (Table 2). Three hydrometric gauges had daily average streamflow (m^3/s) observations for the entirety of the 1985-2016 period: Sturgeon River Near Villeneuve, Sturgeon River at St Albert, and Sturgeon River near Fort Sakatchewan. In addition, partial records were available on the tributaries Atim Creek, Kilini Creek, and Carrot Creek, as well as Sturgeon River near Magnolia Bridge, located in the Sturgeon River headwaters.

Water levels were available from WSC gauges on two lakes: Isle Lake at Eureka Beach (05EA008) and Lac Ste Anne at Alberta Beach (05EA006). Lake storage curves were derived for Ilse Lake, Lac Ste Anne and Big Lake using storage curves obtained from Alberta Environment and Parks (*pers.*

coms.). Elevation outflow curves were obtained using rating equations, derived using non-linear regression analysis by North Saskatchewan Watershed Alliance (NSWA, 2016).

Historical water usage data was obtained for the region from Alberta Environment and Parks (AEP). For each sub-basin in the hydrological model, all surface water allocations were aggregated for each month of each year and were applied in the model as a negative inflow. In this case, all allocations were assumed to be used and to not be returned to the stream, providing a conservative (i.e. upper bound) water use estimate for the watershed.

Table 2. Water Survey of Canada hydrometric stations used in this study

Station Name	Station ID	Record Start	Record End	Drainage Area (km^2)
STURGEON RIVER NEAR MAGNOLIA BRIDGE	05EA010	1981	2013	121.2
STURGEON RIVER NEAR VILLENEUVE	05EA005	1917	2017	1889.5
STURGEON RIVER AT ST. ALBERT	05EA002	1913	2017	2590.9
STURGEON RIVER NEAR FORT SASKATCHEWAN	05EA001	1913	2017	3247.1
KILINI CREEK AT TWP ROAD NO 543	05EA013	2013	2017	168.0
ATIM CREEK NEAR SPRUCE GROVE	05EA009	1979	1996	315.0
ATIM CREEK AT CENTURY ROAD	05EA012	2005	2013	287.8
CARROT CREEK NEAR THE MOUTH	05EA011	2012	2014	97.1

Daily maximum and minimum air temperature (°C) and precipitation (mm) data were obtained from the Alberta Climate Information Service (ACIS, 2018) for six townships distributed evenly across the study area (Table 3). In order to verify meteorological processes in the model, snow water equivalent (SWE, mm w.e.) was collected from three monthly snow survey sites: Onoway (05EA803), Morinville (05EA802), and Westlock (07BC801) from AEP (*pers. comm.*).

Table 3. Six climate stations used in this study

Name	ID	Latitude	Longitude	Elevation (m)
Entwistle	T053R07W5	53.600	-114.980	780
AlbertaBeach	T054R03W5	53.679	-114.351	731
Morinville	T055R25W4	53.792	-113.649	701
SandyBeach	T055R01W5	53.811	-114.040	712
Gibbons	T056R23W4	53.827	-113.328	659
Sangudo	T056R06W5	53.889	-114.901	679

In order to reduce computation time, we grouped areas of similar elevation and land cover together into Hydrological Response Units (HRUs), which were each assumed to have shared hydrological characteristics. We delineated HRUs by finding the unique spatial overlay of 100 m elevation bands, land cover type, and contributing area. We derived elevation bands using the Canadian Digital Elevation Data digital elevation model (DEM), which was resampled from 18 m resolution to 200 m using cubic interpolation (NRCAN, 1995). We obtained land cover from ALCES Online Unity dataset (ALCES, 2016) and reclassified it into 7 classes: Agriculture, Coniferous Forest, Deciduous Forest, Disturbed (urban), Grassland, Lake, and Wetland. In addition, the landscape was divided into two hydrological types: Contributing, where runoff reaches surface water and stream channels and wetlands are connected to the channel network; and Non-Contributing, where runoff only contributes to streamflow during very large storm events and wetlands are isolated from the channel network. In total the hydrological model contained 223 HRUs.

2.1.2 Hydrological model formulation

The hydrological model employed in this study was a customized version of the HBV-EC model (Bergström et al., 1995; Canadian Hydraulics Centre, 2010) emulated within the Raven Hydrological Modelling Framework version 2.7 (Craig et al., 2018). The model simulates streamflow and other hydro-climatic variables (i.e. snowmelt, evaporation, etc.) at a daily timestep from 1985 – 2016.

The model spatially distributes daily minimum and maximum air temperature and precipitation from all climate stations across the catchment using inverse-distance weighting. Initially, water is delivered as precipitation that is passed through the forest canopy. Precipitation that is not intercepted by the canopy reaches the surface as rain or snow (see Figure 7). Snowmelt is calculated using a temperature index model corrected for aspect, slope, and vegetation type (see Jost et al., 2012 for further details). Rain and snowmelt then infiltrate the three-layer soil model, where it moves upward by capillary rise and downwards by percolation. Water returns to the surface (in the stream channel) from the middle soil layer which had a faster response and from the deepest soil layer, which had much slower response.

To account for wetland processes, which have been demonstrated to be particularly important in this region (Golder, 2009; Pomeroy et al., 2010; Pomeroy et al., 2012; Shook, 2013; Buendia, 2017), a custom wetland/depression storage model was implemented for the watershed. The landscape was divided into two types:

- Contributing: Runoff reaches surface water and stream channels; wetlands are connected to the stream network.
- Non-Contributing: Runoff only contributes to streamflow during very large storm events; wetlands are isolated from the stream network.

Runoff from Contributing Areas is routed through connected wetlands (i.e. wetlands located in contributing areas), where water can be temporarily stored, overflow, and seep into groundwater. Conversely, runoff from Non-Contributing Areas is routed to isolated wetlands (i.e. wetlands located in non-contributing areas), where water primarily evaporates, percolates downwards, or can flow overland during extreme rainfall events.

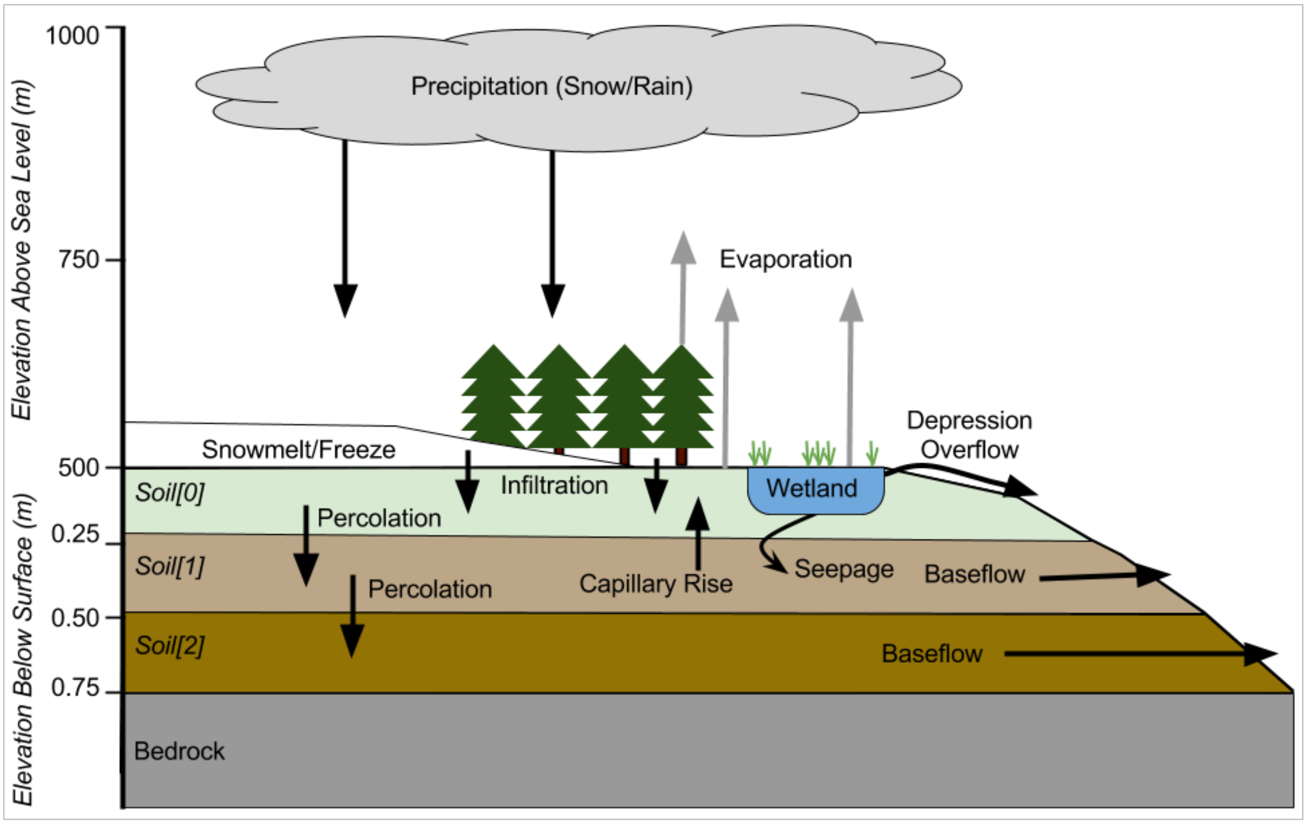

Figure 7. Schematic of driving processes and water pathways in the HBV-EC hydrological model emulation within Raven

The model algorithms are listed in Table 4 and descriptions of individual algorithms are described in further detail in Stahl et al. (2008) and Canadian Hydraulics Centre (2010).

Table 4. Algorithms used to represent hydrologic processes in the model. All algorithms are documented in the Raven User's Manual (Craig et al., 2018)

Process	**Model Algorithm**
Potential Melt	HBV
Rain-Snow Partitioning	HBV
Evaporation	Priestley-Taylor
Orthographic Corrections	HBV, Simple Lapse
Snow and Rain Interception	Hedstrom and Pomeroy (1998), Exponential LAI
Canopy Evaporation	Maximum
Snow Refreeze	Degree Day
Snow Balance	HBV (Snowbal Simple Melt)
Glacier Melt	HBV
Infiltration	HBV

Process	Model Algorithm
Soil Evaporation	HBV
Capillary Rise	HBV
Percolation	Constant
Baseflow (Soil Layer 1)	Power Law
Baseflow (Soil Layer 2)	Variable Infiltration Capacity
Depression Overflow	Linear
Seepage	Linear

2.1.3 Hydrological model calibration and verification

To ensure the best fit between simulated and observed streamflow values, 17 model parameters were calibrated using the Ostrich tool (Matott, 2005). The calibration procedure involved first identifying sensitive parameters (i.e. parameters that measurably affect model output) and then grouping and calibrating process-related parameters in a step-like fashion, broadly following Stahl et al. (2008), all while ensuring proper representation of key hydrological processes (i.e. snowmelt and meteorology). This approach is summarised in Table 5.

An initial parameter was set as a guided "first estimate" following physically realistic and published regional values (when available). Subsequent parameters were manually adjusted to emulate the shape and structure of the annual hydrograph. Sensitive parameters were identified by calibrating all model parameters to the Sturgeon River at Villeneuve hydrometric gauge for the 10-year 2000-2010 period using the Levenberg-Marqhart algorithm and calculating Composite Scaled Sensitivities (CSS) (Hill, 1998; Matott and Rabideau, 2008) within Ostrich. Parameters with a low CSS (< 1) were omitted from further calibration steps.

Table 5. Framework for parameter calibration, adapted from Chernos et al. (2017)

Guiding principle	Parameters	Criteria/objective
1) Isolate and exclude insensitive parameters	All	*CSS* < 1
2) Ensure correct air temperature and precipitation	T, P lapse rates	Maximize r^2, minimize *PBIAS* for T, P and SWE at independent climate stations
3) Ensure correct snowpack dynamics	melt factors	
4) Ensure no bias in water yield	Vegetation interception, vegetation snowmelt	Maximize NSE_{Q}, maximize NSE_{QMAF}
5) Emulate daily hydrograph shape and variability	Soil routing parameters	

Note: NSE is the Nash-Sutcliffe Efficiency coefficient, CSS is the composite scaled sensitivity, and PBIAS is the percent bias, while the subscript Q represents daily streamflow and subscript MAF represents mean annual flow. T, P, and SWE correspond to air temperature, precipitation, and snow water equivalent.

Further steps were executed in model calibration by adjusting parameters in process-based groups using multiple independent data sources (i.e. those not used in model forcing). First, the simulated SWE was compared with observed values from three snow survey sites, and snowmelt parameters were adjusted to ensure snowmelt timing and annual amounts were well emulated. Once meteorological and snowmelt observations were well reproduced, vegetation interception parameters were adjusted to ensure consistent annual water yield between simulations and observed streamflow records. Finally, the model was refined to fully reproduce the character of streamflow (i.e. daily variability and annual hydrograph shape) by calibrating sensitive soil routing, baseflow, and vegetation-specific melt parameters. This step of model calibration was automated, and the Dynamical Dimensioned Search (DDS) algorithm within Ostrich was used. The objective function of this automated run was to minimize combined Nash-Sutcliffe Efficiency coefficient NSE (Nash and Sutcliffe, 1970) of two hydrometric stations (Sturgeon River at Villeneuve and Sturgeon River at St Albert) for the 2000 – 2010 period. Given that several land cover specific parameters were relatively insensitive to automated calibration steps, final values were checked to ensure they were physically realistic and fell within the range of literature values.

The model was verified by using streamflow observations from all hydrometric sites outside the calibration period and for sites not used in calibration procedures during the entire study period. In addition, simulated SWE was compared with observations at several locations across elevations and locations within the study area. Although this check is not a "true" verification step, since these data were used to calibrate model parameters, they provide an estimate of the uncertainty in meteorological forcing and snowpack dynamics in the model.

2.2 Land use modelling

ALCES Online is a land-use simulation tool that is designed for comprehensive assessment of the cumulative effects of multiple land uses and natural disturbances to ecosystems (Carlson et al., 2014). The model operates by exposing a cell-based representation of today's landscape to user-defined scenarios that differ with respect to the rate and spatial pattern of future development and natural disturbance. Changes in the abundance, location, and age of natural and anthropogenic land cover types are tracked and applied to create maps of future landscape composition and indicators of interest.

2.2.1 Current landscape composition

The current composition of the study area, including natural and anthropogenic land cover types, was based on the integration of multiple land cover products including:

- the ABMI Wall-to-Wall Land Cover Inventory and the ABMI Wall-to-Wall Human Footprint Data (ABMI, 2010a; ABMI, 2010b),
- Grassland Vegetation Inventory (Alberta Environment and Parks, 2016),
- Wetland Classifications from Agriculture and Agri-Food Canada (AAFC, 2015),
- AltaLis Hydrography (AltaLIS, 2018),
- and numerous additional footprint inventories from:
    - Open Street Map,
    - AltaLIS,
    - CanVec,
    - Alberta Energy Regulator,

  - Alberta Environment and Parks,
  - National Rail Network,
  - ESRI Basemap,
  - Trans Canada Trail,
  - QuadSquad,
  - HikeAlberta, and
  - Municipalities (e.g., City of Edmonton, City of Calgary, City of Grande Prairie).

2.2.2 Pre-settlement Landscape Scenario

A land cover dataset was prepared at the provincial scale from which all anthropogenic features were removed to estimate landscape composition prior to industrialization and development of the region. The resulting simulation acts as a "pre-European Settlement" benchmark from which to assess subsequent land use changes.

The elimination of anthropogenic features from the landscape resulted in some areas where natural land cover was not classified; in these cases, classifications were assigned by referencing existing datasets, such as the base layer developed by the Alberta Tomorrow Foundation (ALCES Group, 2014). This base layer uses landcover and soils data to classify areas of the province into one of three pre-settlement land cover types: forest, wetland, or grassland.

The following are the major assumptions that were made to create the pre-settlement land cover dataset:

- Landcover types that make up the pre-settlement landscape are grassland, deciduous forest, wetlands, lotic waters, and lentic waters.
- Wetland coverage is assumed to equal the pre-settlement wetland from the Ducks Unlimited Canada Combined Wetland Inventory, plus current wetland coverage in the watershed.
- Areal coverage of lentic and lotic waters are assumed to remain constant, between current and pre-settlement landscapes.
- Forest only occurs within 100 m of permanent lakes, streams, and major rivers on aspects between 70 and 90 degrees.
- Everywhere else, the landscape is assumed to consist of grassland coverage.

2.2.3 Business-as-usual Scenario

The business-as-usual future land use simulation provides a base scenario that can be used to compare the land cover composition of the Sturgeon River watershed under different conservation and restoration strategies. The business-as-usual simulation is not intended to be a prediction, rather it provides context based on reasonable assumptions.

2.2.3.1 Assumptions

Oil Wells

Oil wells were estimated based on the areal proportion of oil hydrocarbon region (Mossop and Shetsen, 1994) within the watershed, relative to that within Petroleum Services Association of Canada (PSAC) regions.

The Sturgeon River watershed falls completely within PSAC boundary 5 and this proportion of PSAC 5 oil deposit equals 5.3%. The Alberta Energy Regulator (AER) publishes projections for future oil production (number of wells) by PSAC region until 2027 (AER, 2018). These projections were used for PSAC region 5, extrapolated out until 2060 at a constant rate, and multiplied by 5.3%. Decadal sums of number of wells were then tallied and converted to total well area, assuming each oil well is 1 ha in size (Table 6).

Table 6. Additional hectares of conventional crude oil wells placed on production in PSAC region 5 by decade

Decade	Additional Well Area (ha)
2010	185
2020	207
2030	118
2040	117
2050	117
2060	117

To simulate future increase of oil wells, existing land cover types were converted to oil well footprint and well age was set to 1 year, in order to easily identify new wells. Future well locations were simulated within the oil hydrocarbon region. Oil well development was specifically constrained to the oil hydrocarbon region, as defined by PSAC, and protected areas were excluded. The following land cover types were eligible to be converted to oil well:

- Agricultural crops
- Agricultural pastures
- Exposed land
- Coniferous forest
- Deciduous forest
- Mixed forest
- Grasslands
- Shrublands
- Snow and ice
- Wetlands

Natural Gas Wells

An approach similar to oil well development was applied for simulating the expansion of natural gas wells within the Sturgeon River watershed. The natural gas hydrocarbon region within the

Sturgeon River watershed comprised 1.9% of the area that fell within the greater PSAC region 5 boundaries. An area of 0.1 ha was assumed for each natural gas well, and vertical and horizontal wells were treated equally (Table 7). The natural gas hydrocarbon region that was used to focus development was also derived from Mossop and Shetsen (1994).

Table 7. Additional hectares of natural gas wells placed on production in PSAC region 5, by decade

Decade	Additional Well Area (ha)
2010	21.01
2020	2.10
2030	2.98
2040	2.85
2050	2.85
2060	2.85

Eligible land cover types (same as used in oil well development) were converted to gas well footprint, and well age was set 1 year. Natural gas development was excluded from protected areas, constrained within the natural gas hydrocarbon region, and allocated in a clustered manner.

Shale Gas Wells

For shale gas wells, projections are not given by PSAC region, but rather by the whole province. 0.25% of these projections were considered, because it was calculated that the Sturgeon River watershed comprises only 0.25% of the shale gas mask for the province. An area of 0.1 ha was assumed for each shale gas well (Table 8).

Table 8. Additional hectares of natural gas wells placed on production in PSAC region 5, by decade.

Decade	Additional Well Area (ha)
2010	0.022
2020	0.216
2030	0.321
2040	0.312
2050	0.312
2060	0.312

The shale gas hydrocarbon region that was used to focus development was derived from the Alberta Geological Survey, specifically the Summary of Alberta's Shale- and Siltstone-Hosted Hydrocarbon Resource Potential (Rokosh et al., 2012).

Eligible land cover types (same as used in oil and natural gas development) were converted to shale gas well footprint, and well age was set 1 year. Shale gas development was excluded from protected areas, constrained within the shale gas hydrocarbon region, and allocated in a clustered manner.

Access Roads

Access roads to oil, natural gas, and shale gas wells were simulated by growing out the least cost path between newly built well pads and the nearest section of road in the road network. The same landscape features as used in the oil and gas development were considered eligible indicators and were converted to minor roads. A road width of 17 metres (m) was assumed.

Aggregate Mines and Reclamation

The Sturgeon River watershed has a current mine pit footprint of 18.7 km^2. Aggregate mine growth was simulated based on estimates provided by the NSWA (G. Thompson, pers. comm., May 22, 2018). These estimates projected that16.2 km^2 of new aggregate pits and 24.3 km^2 of reclaimed pits will be created within the next two decades in the Sturgeon River watershed

Aggregate mine development was excluded from all parks and protected areas as well as 200 m from all minor roads. New development was constrained to regions showing aggregate potential, as derived from Edwards and Budney (2009). All eligible indicators (same as previous actions) were converted to mine pit footprint, through a clustered growth type.

For aggregate mine reclamation, it is estimated that 24.3 km^2 of the future mine footprint will be reclaimed by the year 2040. When simulating aggregate reclamation, mine pits were converted to exposed land.

Urban and Rural Settlement

City and town growth was estimated by projecting Statistics Canada historic (2011-2016) growth rates to the year 2060 and constraining this expansion within future municipal development limits derived from Municipal Development Plan reports (Town of Morinville, 2017; City of Spruce Grove, 2010; City of St. Albert, 2017; Town of Bon Accord, 2016; Town of Entwistle, 2013).

Major cities and towns considered were: Morinville, Bon Accord, Spruce Grove, City of St. Albert, Onoway, and Entwistle. Stats Canada population growth rates were 2.98%/year, 0.56%/year, 6.04%/year, 1.34%/year, -0.2%/year, and 1.68%/year respectively. The current total settlement footprint was calculated within these municipal regions, and then extrapolated out using the growth rates as listed above. Of note, the town of Onoway has a negative growth rate, so this town was excluded from the simulation, under the assumption that there would be no growth, but no reclamation of footprint either.

Protected areas were excluded from development, and all eligible indicators (same as listed in oil well development) were converted to total settlement footprint. Growth was carried out in a clustered fashion within the delineated future municipal development limits.

For rural growth, Census Divisions (CDs) were used. CDs are established by Statistics Canada and represent groups of neighbouring municipalities joined together for the purposes of regional planning and managing common services. The Sturgeon River watershed consists of 14.5% of Census Division 11 and 4.25% of CD 13. According to Stats Canada, CD 11 population grew by an average of 2.7% per year between 2011 and 2016, and CD 13 population grew by 0.6% per year. Considering that the Sturgeon River watershed is made up of 68.6% CD 11 and 31.4% CD 13, this results in a 0.284% growth rate per year. The current Rural Settlement footprint within the

Sturgeon River watershed is 184,000,000 m^2. 0.284% of 184,000,000m^2 is 522,192 m^2 per year, or 5,221,920 m^2 per decade.

Protected areas, First Nations reserves, and wilderness areas were excluded from rural development, and growth was constrained within 400 m of all existing roads. All eligible indicators (as listed in the oil development section) were converted to total settlement footprint. Development followed a clustered growth type.

Recreation

Assumptions for the simulation of recreation footprint was based on golf course growth within the province, since golf courses account for 62% of the provincial recreation footprint[1]. The simulated expansion of recreation footprint was based on the current ratio between recreation footprint and rural settlement footprint in the Sturgeon River watershed. Recreation footprint was simulated in patches of either 0.5 km^2 (54%) or 1 km^2 (46%), based on the current size class distribution of golf courses in the province[2]. Patches were located within 30 km of cities and towns, a buffer that accounts for 92% of current golf course footprint in Alberta.

The recreation to total settlement ratio within the Sturgeon River watershed is 10.5:256 or 0.04. Applying that ratio to the rural settlement growth rate results in a rate of 0.011352%. We can then apply this rate to the current recreation footprint of 10.499km^2. This results in a yearly projection of 1,191.85 m^2 of new recreation footprint each year, or 11,918.5 m^2 each decade.

This growth in recreation footprint was constrained to occur within 30 km of communities. All eligible indicators (same as used in other actions) were converted to recreation footprint, which can represent recreational land use types such as:

- Campgrounds
- Golf courses
- Golf driving ranges
- Mini Golf
- Indoor Other
- Outdoor Other
- Picnic
- Playground
- Ski Hill
- Sport Center
- Sport Field
- Sport Rink
- Sport Stadium
- Sport Track

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[1] Calculated with ALCES Online. ALCES Online was initialized using on a compilation of anthropogenic footprint inventories. Sources of inventories include Alberta Environment and Parks, ABMI, AltaLIS, CanVec, and GVI.

[2] Calculated with ALCES Online. ALCES Online was initialized using on a compilation of anthropogenic footprint inventories. Sources of inventories include AEP, ABMI, AltaLIS, CanVec, and GVI.

Wetland Loss

Based on pre-settlement simulations, wetland coverage in the Sturgeon River watershed has decreased from 492 km^2 in pre-settlement times to 137 km^2 currently. This represents a 72.2% decrease over 100 years. Applying this percent decrease to a future scenario would result in a further 9.9 km^2 of wetland loss per decade.

Wetland landscape types were converted to agricultural crop footprint in a clustered fashion with size classes split evenly between 5,000 m^2 and 10,000 m^2. Any wetlands within protected areas were excluded from this conversion, and loss was concentrated within a 500 m buffer around existing cropland.

2.3 Conservation and restoration strategies

Potential conservation and restoration strategies for improving the performance of the resilience indicators were identified by the TAC. Mitigation opportunities focused on restoring natural land cover (wetland, grassland and forest restoration), protecting existing wetlands and exploring the conversion of crop types (crop alternatives).

Using ALCES Online, a 50-year scenario was simulated for each strategy to assess capacity to improve resilience indicator performance. Strategies were simulated across the entire watershed and improvement in indicator performance was mapped at the scale of the sub-basin in order to identify where strategies can be implemented for maximum effectiveness.

2.3.1 Wetland protection

Wetland protection was simulated using the assumption that no further wetlands would be lost. This was done by removing the wetland loss action from the business-as-usual land use scenario. Wetlands were also protected from other development or land conversions in the simulation. This strategy allowed for wetlands to remain constant through time (Figure 8).

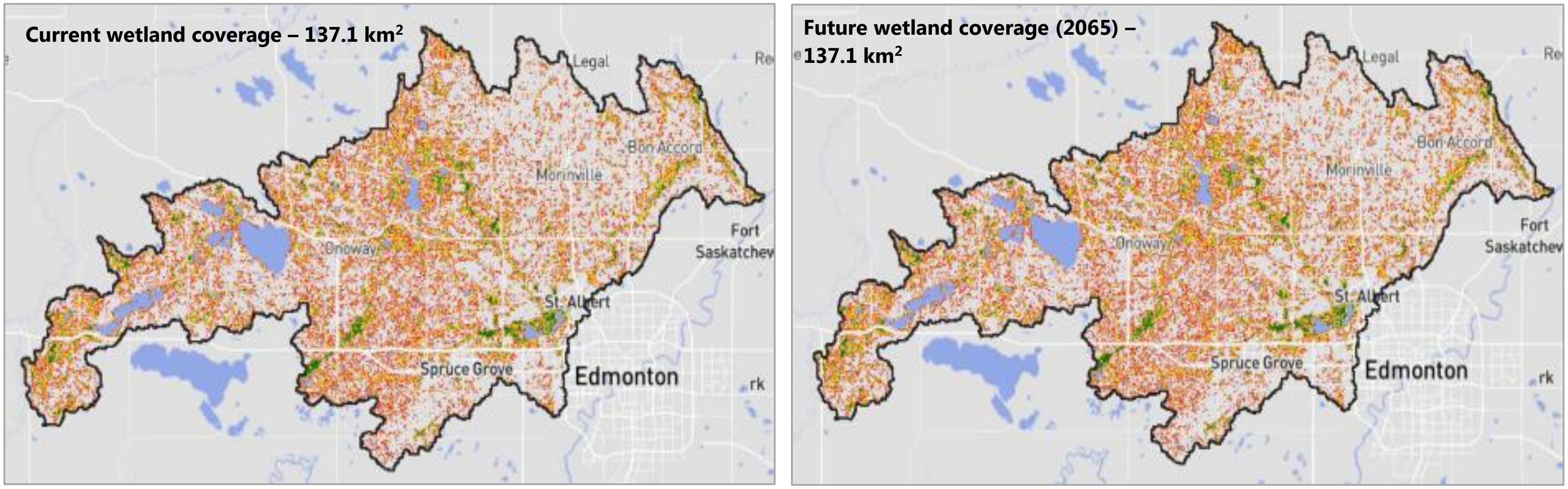


Figure 8. Current and future wetland coverage simulated using the wetland protection strategy.

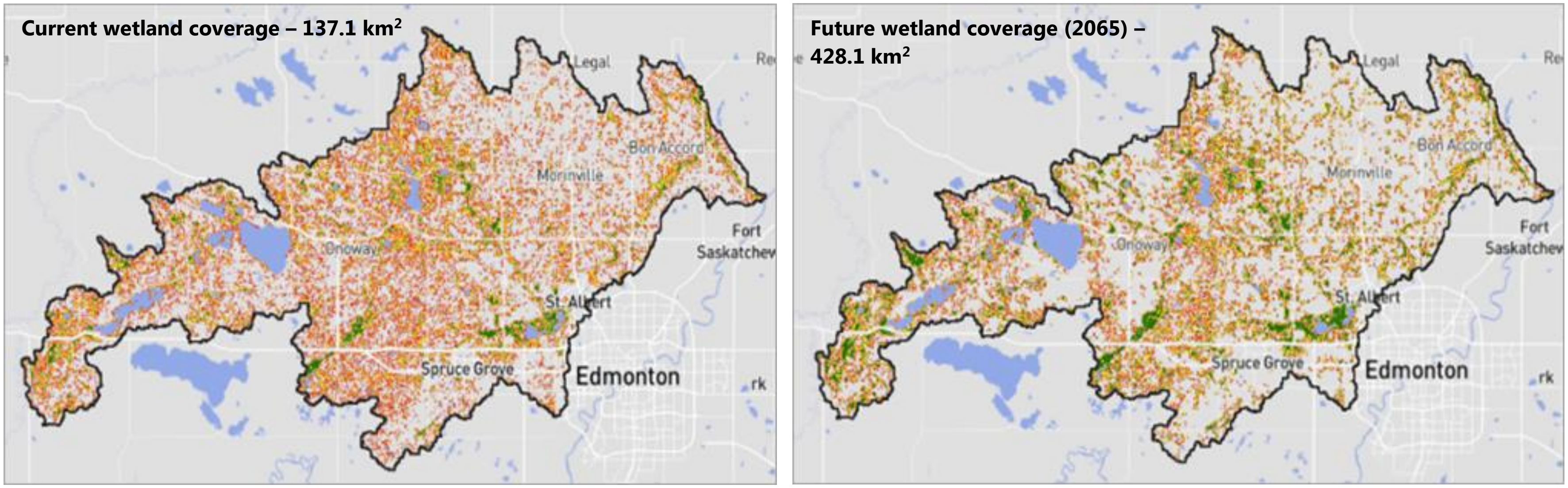


Figure 9. Current and future wetland coverage simulated using the wetland restoration strategy.

2.3.2 Wetland restoration

Restoration of historic wetlands was simulated by converting all eligible indicators to wetland type for areas classified as wetlands in the pre-settlement land use scenario. To meet pre-settlement wetland coverage, an additional 290.8 km^2 of wetland over 5 decades is required. This equates to 58.2 km^2 per decade (Figure 9).

The list of eligible indicators includes:

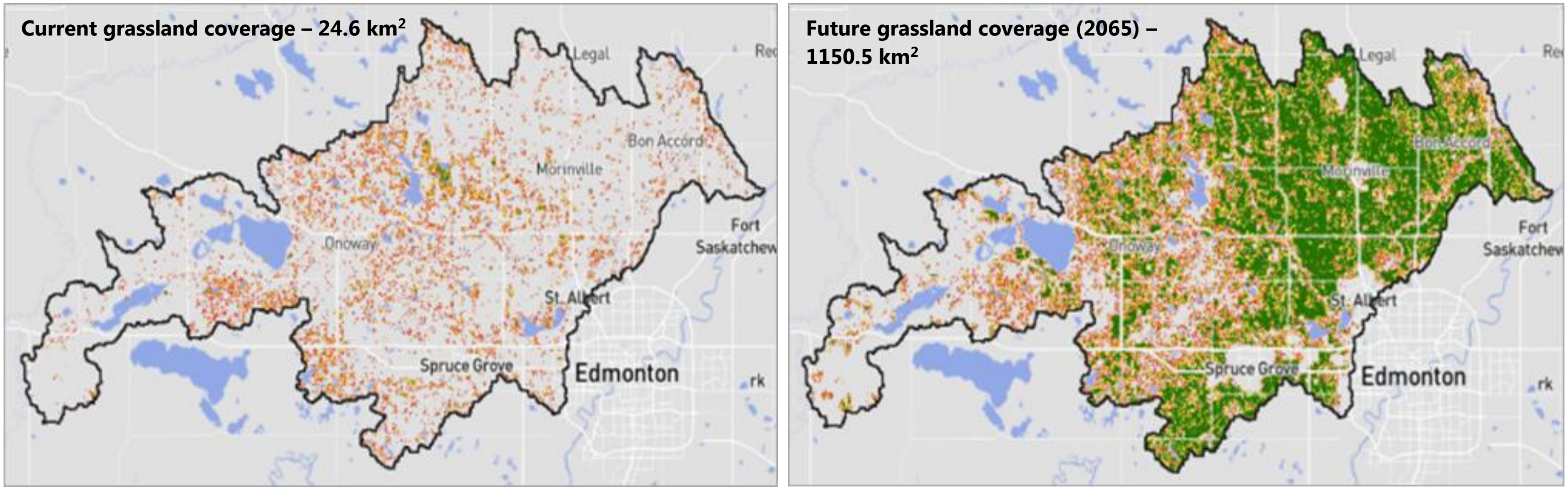
- Agricultural Crops
- Agricultural Pasture
- Exposed Land
- Coniferous Forest
- Deciduous Forest
- Mixed Forest
- Grassland
- Shrubland

2.3.3 Grassland restoration

Grassland restoration was simulated by converting existing cropland back to grassland coverage at rates required to reverse historic grassland to cropland conversion. Current cropland covers and area of 4,526.8 km^2 within the Sturgeon River watershed, therefore to restore this amount back to grassland within five decades would require 905 km^2 of grassland restoration each decade (Figure 10).

2.3.4 Forest restoration

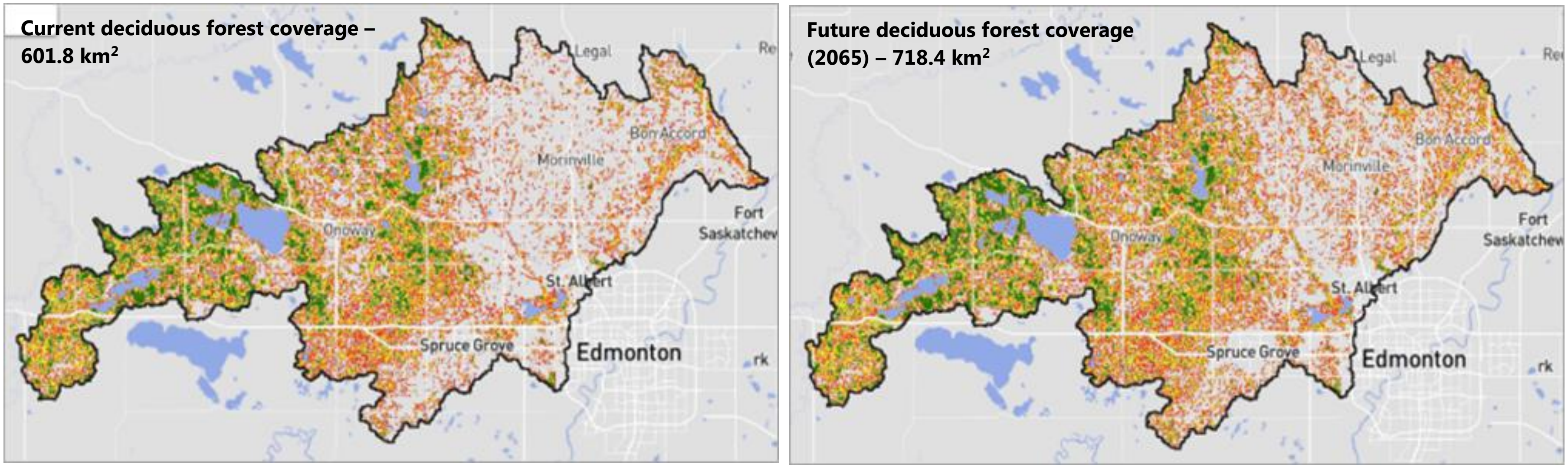
All grassland was converted to deciduous forest within each decade. This conversion was constrained to all north facing slopes and all areas within 100 m of permanent lakes, streams, or rivers (Figure 11).



Current grassland coverage – 24.6 km²

Future grassland coverage (2065) – 1150.5 km²

Figure 10. Current and future grassland coverage simulated using the grassland restoration strategy.



Current deciduous forest coverage – 601.8 km²

Future deciduous forest coverage (2065) – 718.4 km²

Figure 11. Current and future deciduous forest coverage simulated using the forest restoration strategy.

2.4 Evaluating effectiveness

Rather than simply showing absolute or relative values, an effectiveness index was calculated from zero to one, where zero indicates low effectiveness of the strategy, and one indicates high effectiveness.

This index was calculated using the change in watershed resilience indicator and the potential for strategy implementation. For example: An area with substantial wetland loss (high potential to restore) and where change in the watershed resilience indicator is high as a function of wetland restoration, would be assigned a high effectiveness

3 Results

3.1 Land use model

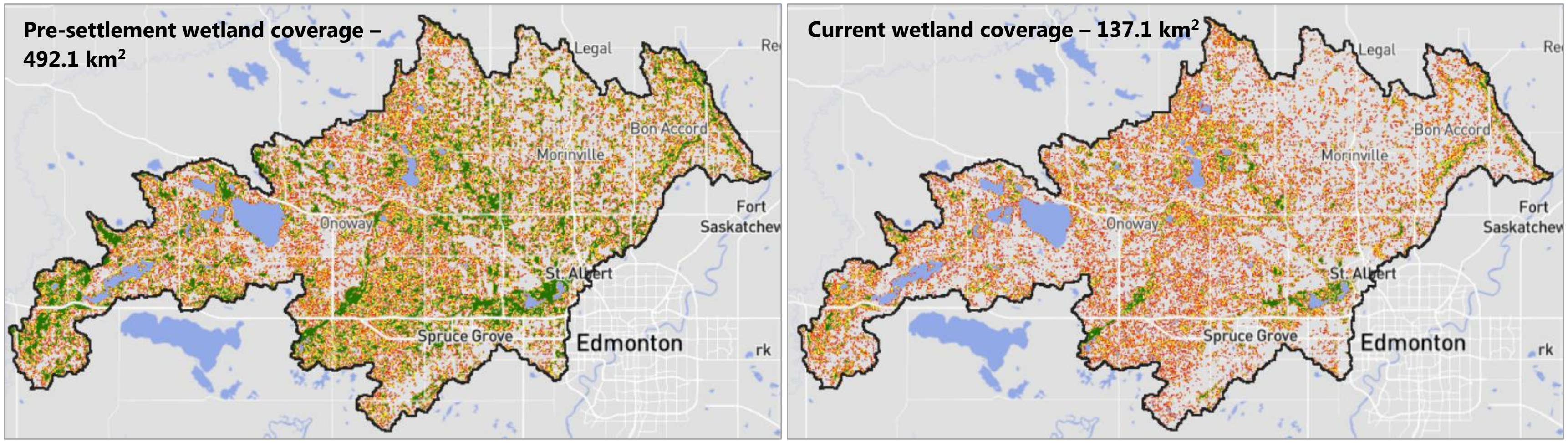
3.1.1 Pre-settlement

The pre-settlement scenario represents the watershed's landcover as it would have been prior to western industrialization. As such wetland coverage would be substantially higher under pre-settlement conditions (492.1 km^2; Figure 12), due to the lack of wetland loss from agricultural expansion.

Similarly, the total cropland coverage under pre-settlement conditions would equate to zero, representing no western agricultural influence on the landscape (Figure 13).

Interestingly, forest coverage would be lower as well, as the natural landcover for this area is best represented by grasslands and not forested areas (Figure 14).

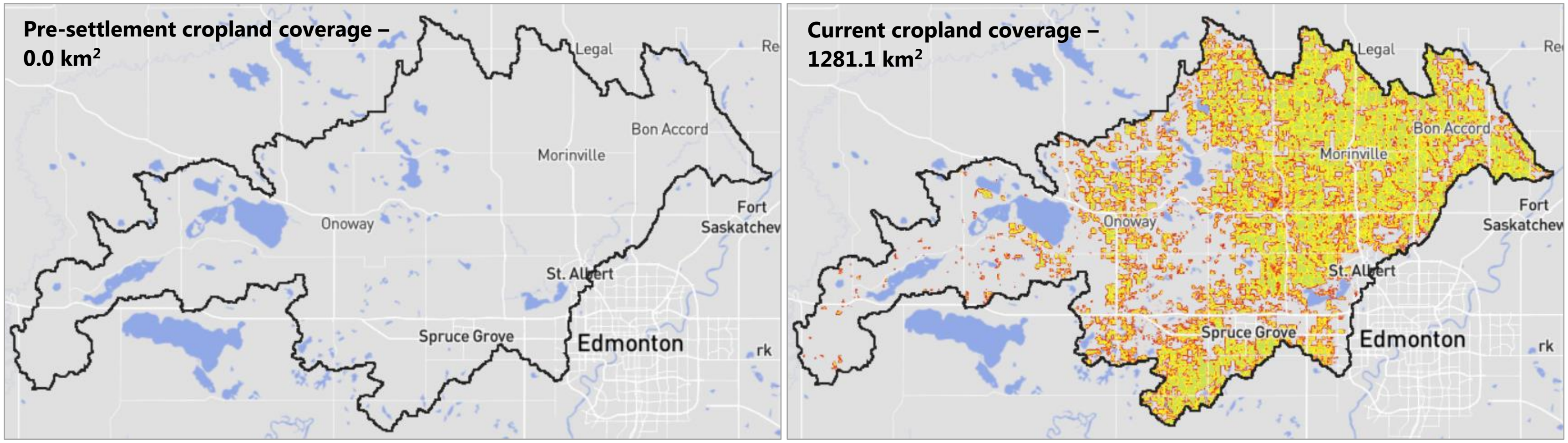
Finally, the total human footprint would equate to zero under pre-settlement conditions, representing no anthropogenic impacts on the landscape (Figure 15).



Pre-settlement wetland coverage – 492.1 km^2

Current wetland coverage – 137.1 km^2

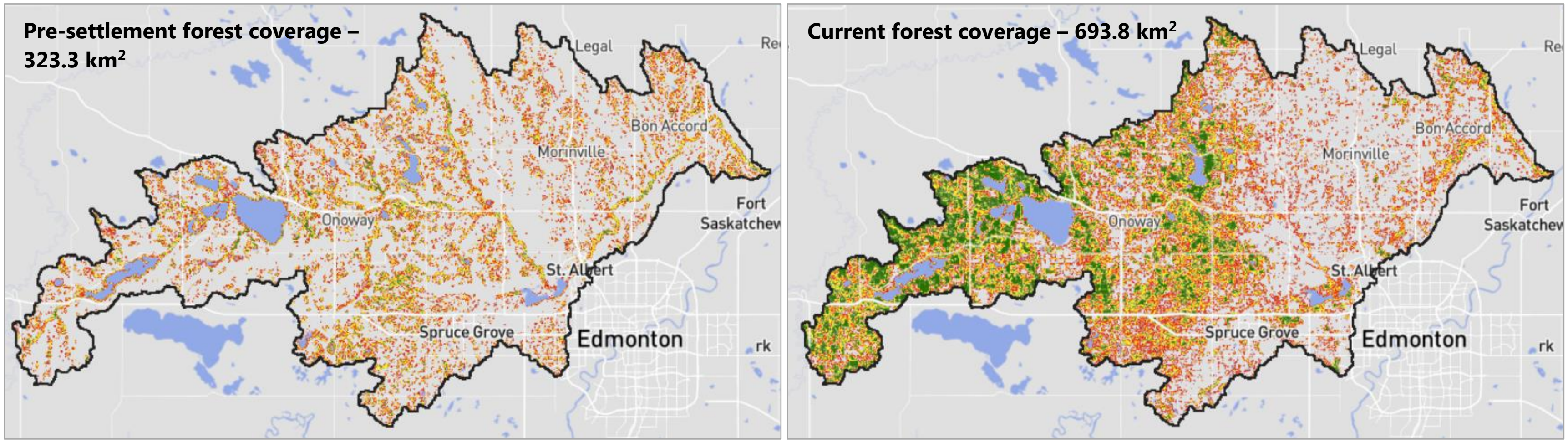
Figure 12. Pre-settlement wetland coverage relative to total current wetland coverage.



Pre-settlement cropland coverage – 0.0 km^2

Current cropland coverage – 1281.1 km^2

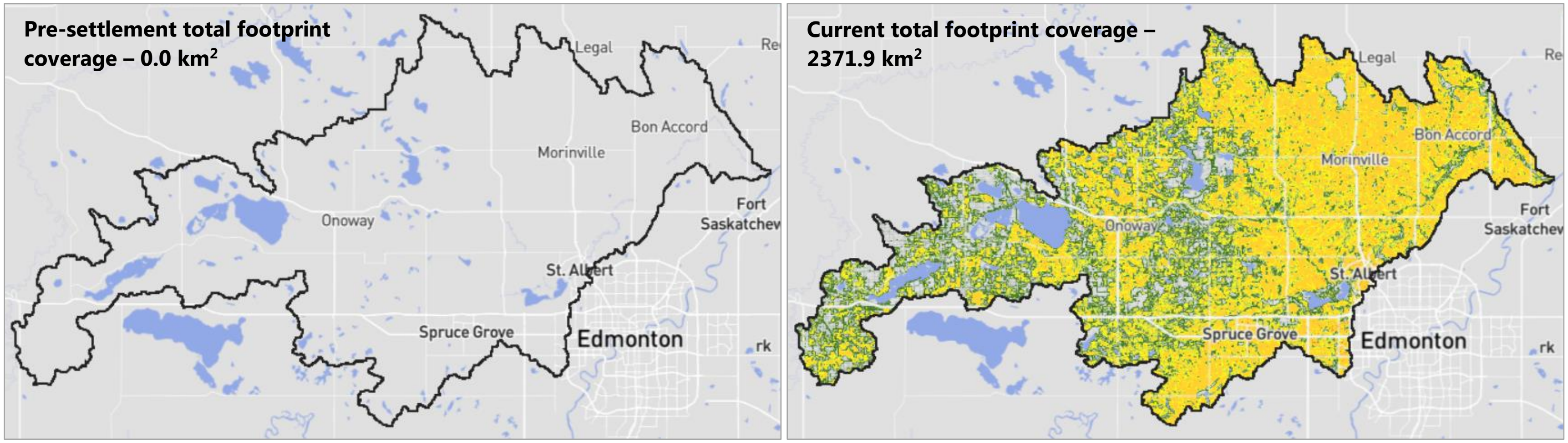
Figure 13. Pre-settlement cropland coverage relative to total current cropland coverage.



Pre-settlement forest coverage – 323.3 km^2

Current forest coverage – 693.8 km^2

Figure 14. Pre-settlement forest coverage relative to total current forest coverage.



Pre-settlement total footprint coverage – 0.0 km^2

Current total footprint coverage – 2371.9 km^2

Figure 15. Pre-settlement total footprint coverage relative to current total footprint coverage.

3.1.2 Business-as-usual

The Business-As-Usual (BAU) future scenario saw substantial wetland loss throughout the watershed, with coverage dropping from 137.1 km^2 to 82.9 km^2 in 2065 (Figure 16). This was primarily driven by the expansion of other footprints into wetland areas.

Although wetlands were mostly drained for crop expansion, other development actions within the BAU invaded croplands, resulting in a decreasing trend in agricultural crop coverage (Figure 17).

Forest coverage remained relatively stable throughout the BAU scenario, only decreasing by approximately 2.5% (Figure 18). This was largely due to the exclusion of protected areas and parks from development actions.

Overall, the total human footprint in the Sturgeon River watershed increased from 2371.9 km^2 to 2438.2 km^2, representing a 2.7% increase in coverage (Figure 19).

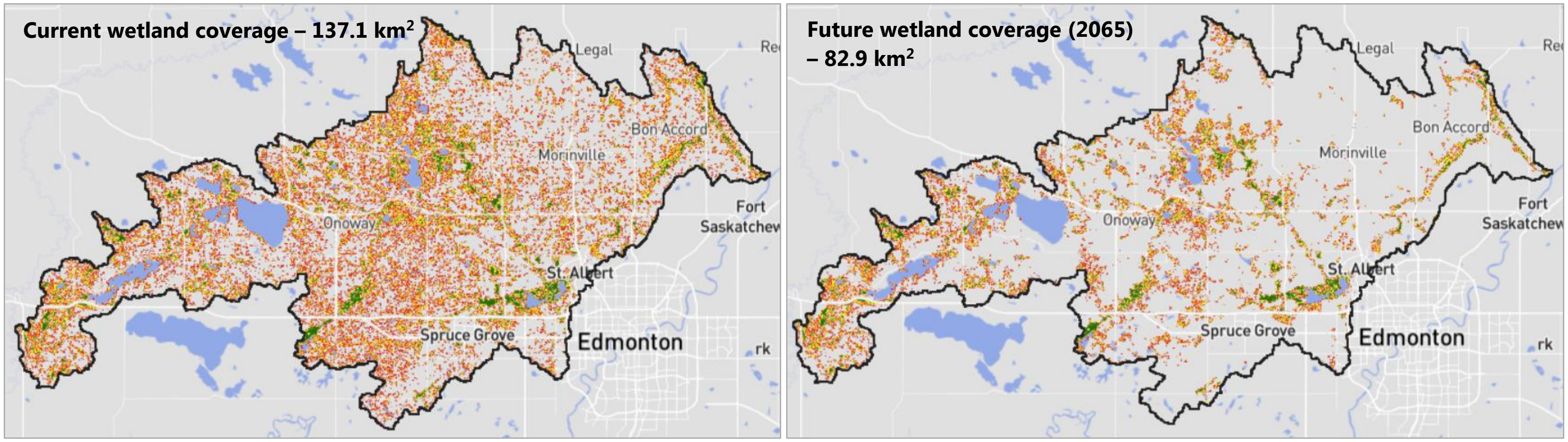


Figure 16. Total current wetland coverage relative to projected wetland coverage in 2065 under BAU.

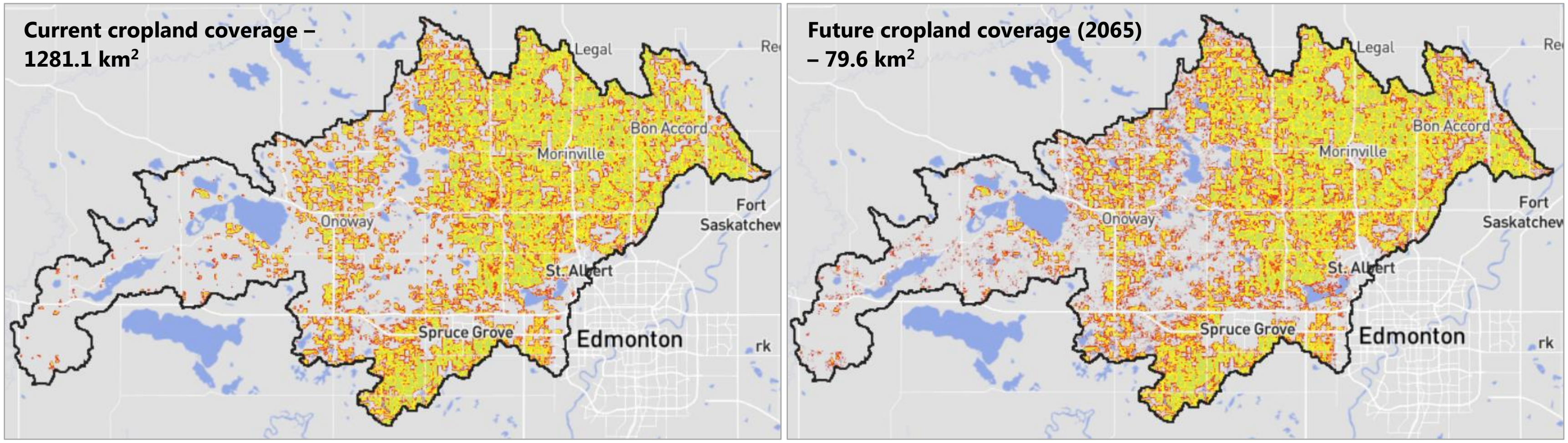
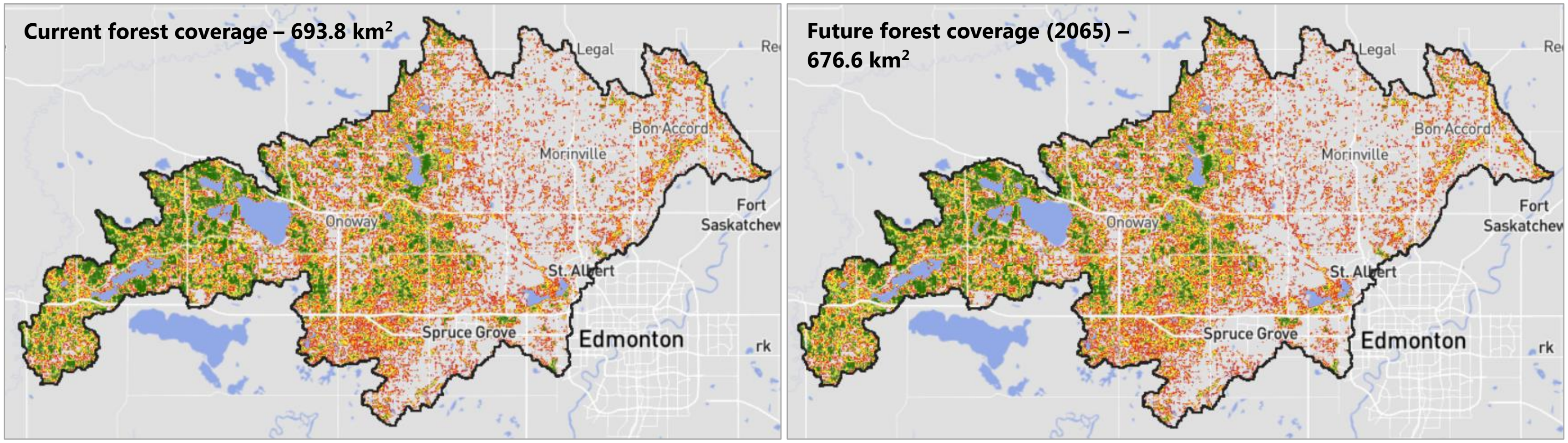


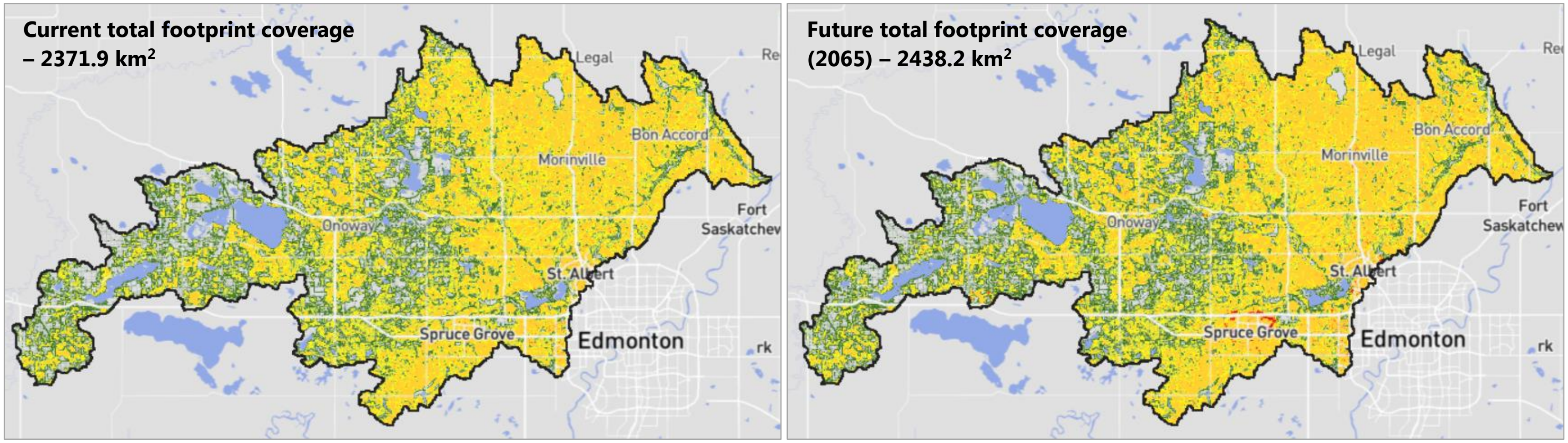
Figure 17. Total current cropland coverage relative to projected cropland coverage in 2065 under BAU.



Current forest coverage – 693.8 km^2

Future forest coverage (2065) – 676.6 km^2

Figure 18. Total current forest coverage relative to projected total forest coverage in 2065 under BAU.



Current total footprint coverage – 2371.9 km^2

Future total footprint coverage (2065) – 2438.2 km^2

Figure 19. Total current footprint coverage relative to projected total footprint coverage in 2065 under BAU.

3.2 Hydrological model

3.2.1 Model Performance

3.2.1.1 Parameter Sensitivity

To better understand the parameters (Table 9) and processes that drive streamflow in the watershed, model sensitivity to parameters were evaluated by deriving Composite Scaled Sensitivities (CSS, Figure 20). The model was most sensitive to parameters that control Agriculture precipitation interception (Agri_Cov, LAI), soil water routing, and wetland storage. Conversely, insensitive parameters included precipitation and temperature lapse rates and snowmelt factors. This suggests that given the low-relief and lack of a large winter snowpack, streamflow is driven primarily by rainfall events and soil water and wetland routing processes.

Table 9. Parameter description used in Composite Scaled Sensitivities analysis.

Parameter	Description	Value	Unit
	Calibrated Parameters		
Agri_Cov	Vegetation cover for Agriculture type	0.8	fraction
satwilt	saturation wilting point of soil	0.2	fraction
fldcap	field capacity of soil	0.3	fraction
HBV_BO	Infiltration coefficient	0.1	none
Wet_SeepK	Wetland depression seep coefficient	0.002	mm/d
Perc0	Percolation of top soil layer	1	mm/d
Wet_DepK	Wetland depression overflow rate	5	mm/d
Agri_LAI	Leaf Area Index for Agriculture vegetation	7	none
Wet_DepT	Wetland depression threshold for overflow	5000	mm
For_Cov	Vegetation cover for Forest type	0.6	fraction
pors	soil porosity	0.4	fraction
Base_N1	Shallow soil baseflow coefficient	2.2	none
Decid_corr	Deciduous forest snowmelt correction	0.75	fraction
Perc1	percolation of middle soil layer	1	mm/d
Decid_LAI	Leaf Area Index for Deciduous vegetation	8	none
Wetl_Cov	Vegetation cover for Wetland type	0.2	fraction
Base_K1	Shallow soil baseflow coefficient	1.2	none
Wetl_LAI	Leaf Area Index for Wetland vegetation	4	none
Wet_corr	Wetland snowmelt correction	0.8	fraction
	Non-Calibrated Parameters		
Alapse	Air temperature lapse rate	7	C/km

Parameter	Description	Value	Unit
Plapse	Precipitation lapse rate	1	mm/100m
K_melt	Global snowmelt factor	1	C/mm/d

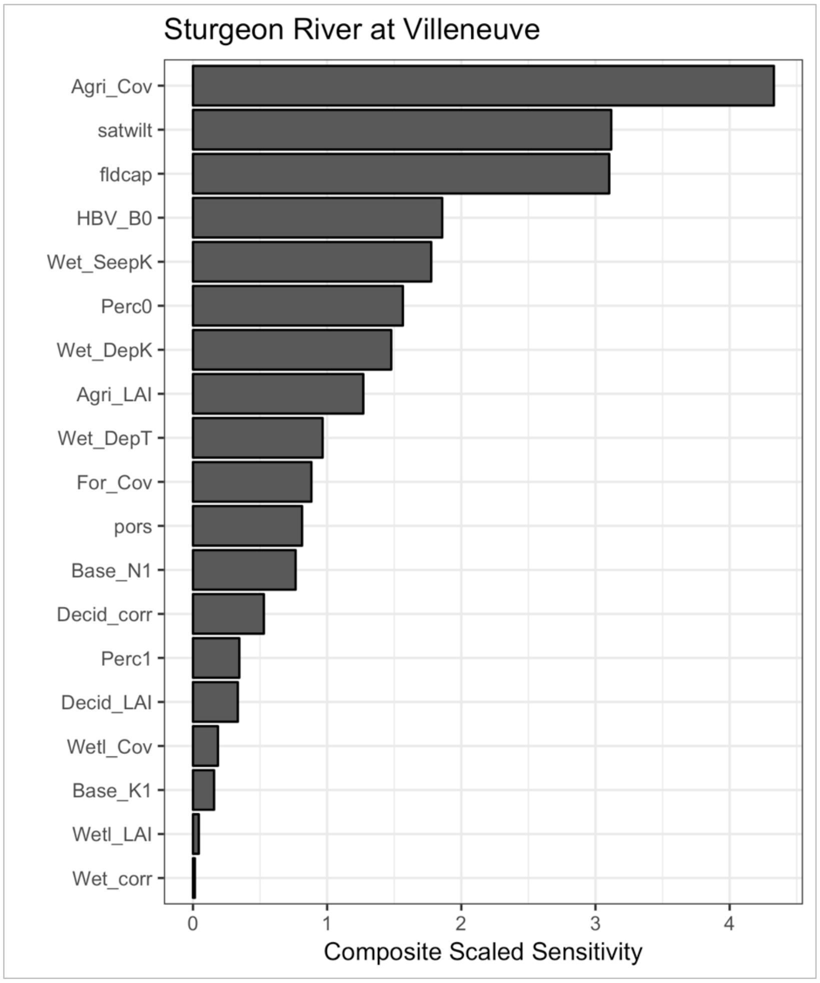


Figure 20. Parameter sensitivity for Sturgeon River watershed hydrological model.

3.2.1.2 Meteorology

Simulated monthly snow water equivalent closely followed observed values from three independent verification sites throughout the study region (Figure 21). For the entire study period (1985-2016), r^2 values displayed good results for the periodic snow survey sites (0.53 – 0.66). In general, this suggests that precipitation and air temperatures during the winter and spring were well emulated in the hydrological model. We note, however; that additional uncertainty exists in precipitation events, particularly during the summer when the region experiences isolated convective storms that may not have been detected by regional climate stations and are not captured by these snow survey sites.

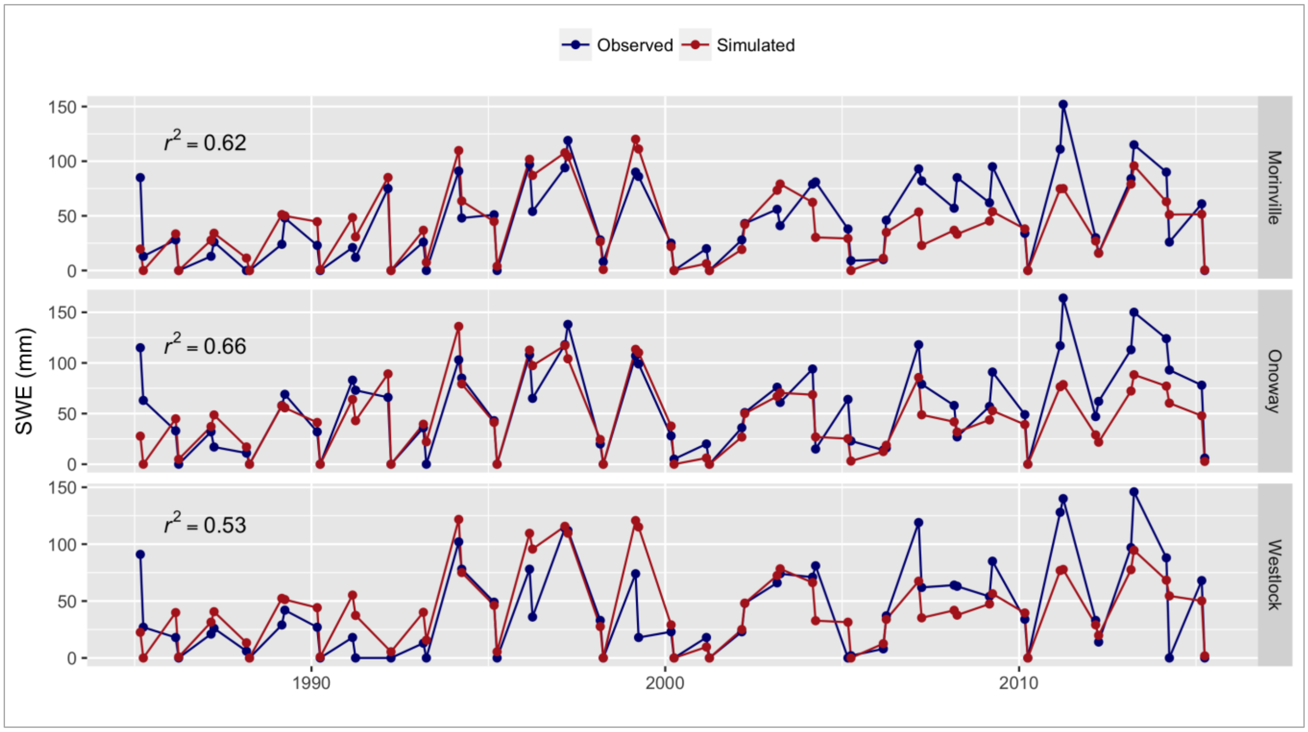


Figure 21. Simulated and observed monthly snow water equivalent (SWE) for the entire simulation period.

3.2.1.3 Streamflow

The model demonstrated moderate performance, with comparable statistics over the calibration and verification period for monthly streamflow (Table 10). In general, streamflow showed variable bias, with low PBIAS values for lower hydrometric stations on the Sturgeon River (near Fort Saksatchewan, at St Albert, and near Villeneuve), with higher bias in smaller tributaries (Kilini and Atim creeks). NSE values generally follow this pattern as well, where larger drainage area stations have better model performance. In particular, we note that performance is best below the three major lakes emulated in the model which gives confidence that storage and evaporation is well emulated in these lakes (Figure 22). Given that there was minimal bias in winter SWE, it is likely that the model is not well representing spatially isolated and variable summer convective precipitation events. As an alternative, or in addition, it is possible that contributing/non-contributing area delineation was inaccurate. Both of these factors are likely to be more important in smaller sub-basins, where contributing area could make up a relatively large fraction of the sub-basin area.

Table 10. Model performance statistics for the hydrological model. NSE is the Nash-Sutcliffe Efficiency and PBIAS is the percent bias.

Site	**Calibration**		**Verification**	
	NSE	PBIAS (%)	NSE	PBIAS (%)
KILINI CREEK AT TWP ROAD NO 543	-	-	0.16	41.9
ATIM CREEK AT CENTURY ROAD	-0.67	75.6	-0.14	47.1

Site	Calibration		Verification	
	NSE	PBIAS (%)	NSE	PBIAS (%)
STURGEON RIVER NEAR MAGNOLIA BRIDGE	0.01	90.3	0.38	-10.2
STURGEON RIVER NEAR VILLENEUVE	-	-	0.52	14.6
STURGEON RIVER AT ST. ALBERT	0.63	78.8	0.62	-26.4
STURGEON RIVER NEAR FORT SASKATCHEWAN	0.42	76.2	0.58	4.4

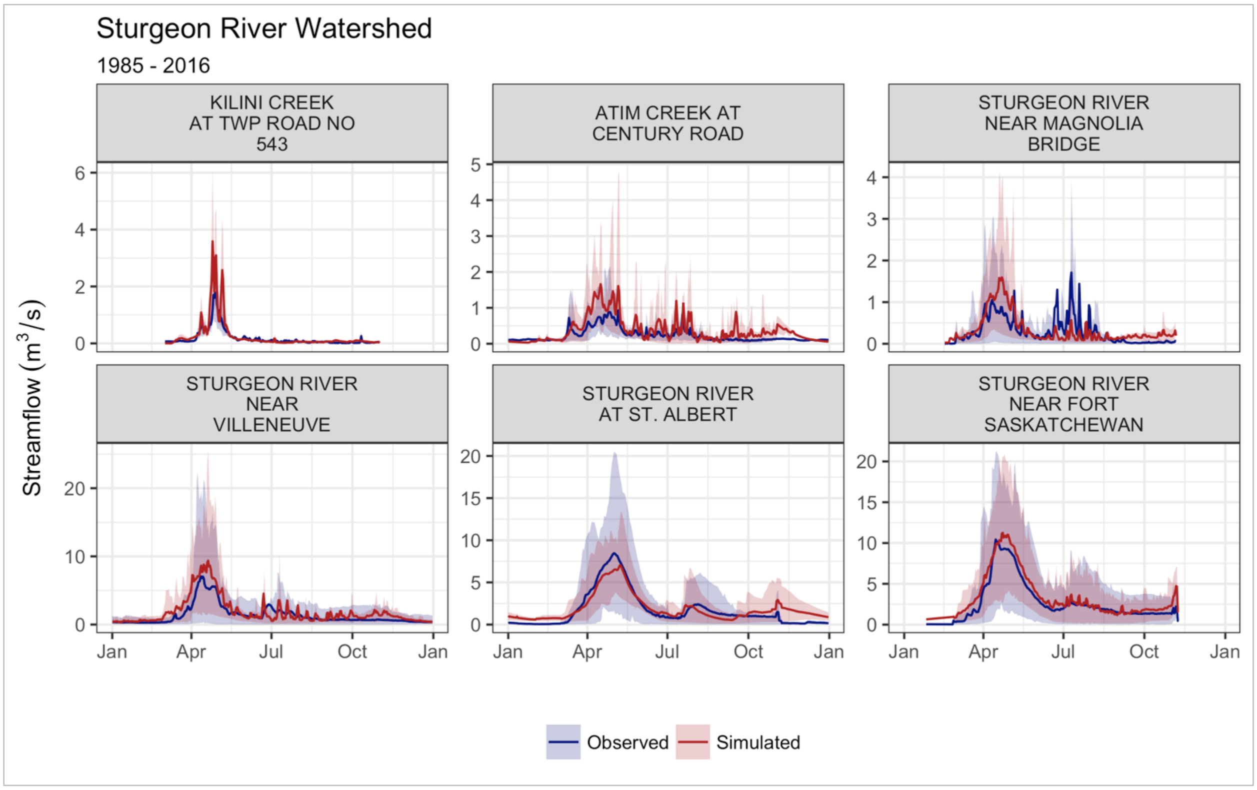


Figure 22. Observed and simulated streamflow for two hydrometric sites in the model domain. Shaded areas correspond to 10% and 90% quantiles.

Despite incomplete observational data, simulated water levels in Isle Lake and Lac St Anne were moderately well simulated (Figure 23). This suggests that water balance processes were relatively well constrained within the model over seasonal timescales, and that the storage and discharge curves were relatively accurate. Water levels appear to drop around approximately 2008, suggesting either an overestimate of water release/outflow, or evaporation in the lake. It is also possible that groundwater or human interactions not captured in the model may have affected observed lake levels. We additionally note that this drop in simulated water levels did not occur in the upstream Isle Lake, which suggests the discrepancy is not due to meteorological forcing data, and rather geographic groundwater or human interactions.

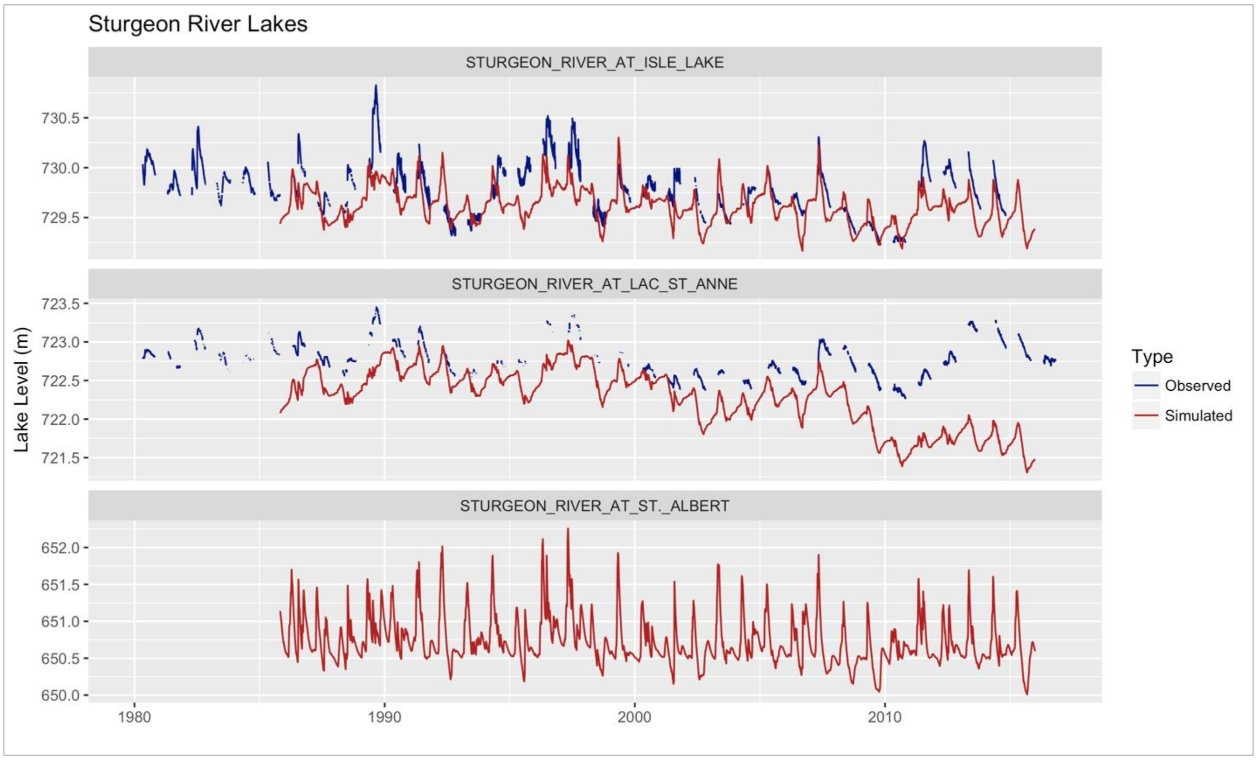


Figure 23. Simulated and observed water levels in three lakes modelled.

3.2.2 Hydrologic Findings

Water allocations for the Sturgeon River watershed increased substantially since 1960 and represents approximately 0.4 m3/s during ice-free months (Figure 24). Over half of the water allocations are located within the Sturgeon River near Fort Saskatchewan sub-basin, meaning they originate most likely in urban areas like St. Albert. Since 1960, there has been a strongly seasonal pattern in the data, with water allocations more than doubling during the summer months (June – October).

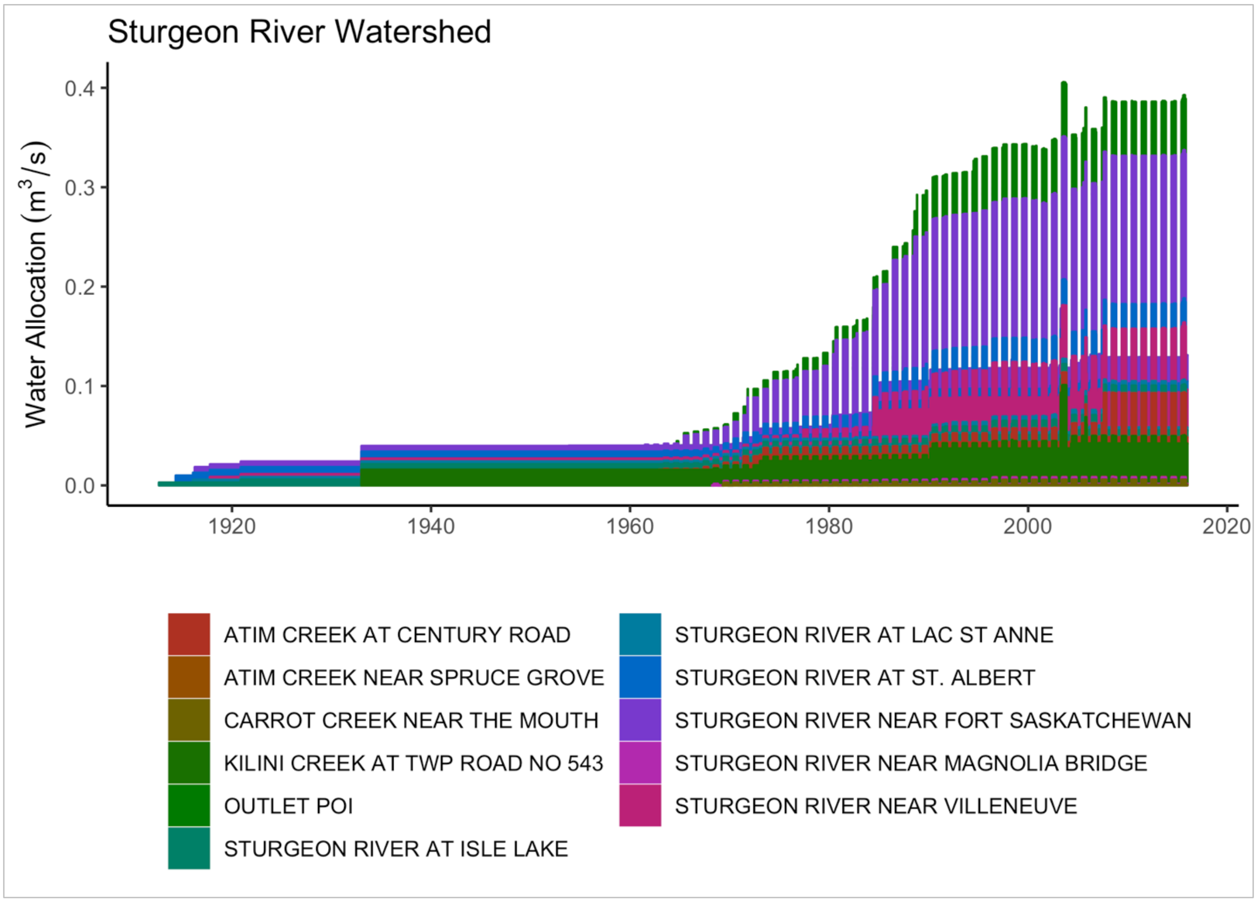


Figure 24. Water allocations in the Sturgeon River watershed, separated by sub-basin.

The model was able to quantitatively determine the most impactful processes controlling of the water balance for the Sturgeon River watershed (Figure 25). Precipitation is relatively low in the watershed, providing approximately 438 mm per year on average, of which 40 mm becomes snowmelt. Of the precipitation input to the watershed, 378 mm evaporates, 4 mm is removed for water use, and 3 mm is stored in deep groundwater; leaving only 54 mm to become runoff. This emphasized that evaporation is a dominant factor driving the water balance in the watershed. Given that the winter is very dry, most precipitation occurs during the summer, when air temperatures are warmest, and evaporation is subsequently high. In addition, surface water is stored throughout the landscape in both connected and non-connected wetlands as well as several large lakes which provide constant surface water availability, allowing much higher evaporation rates than would be possible in soils where water quickly percolates into deeper soil layers.

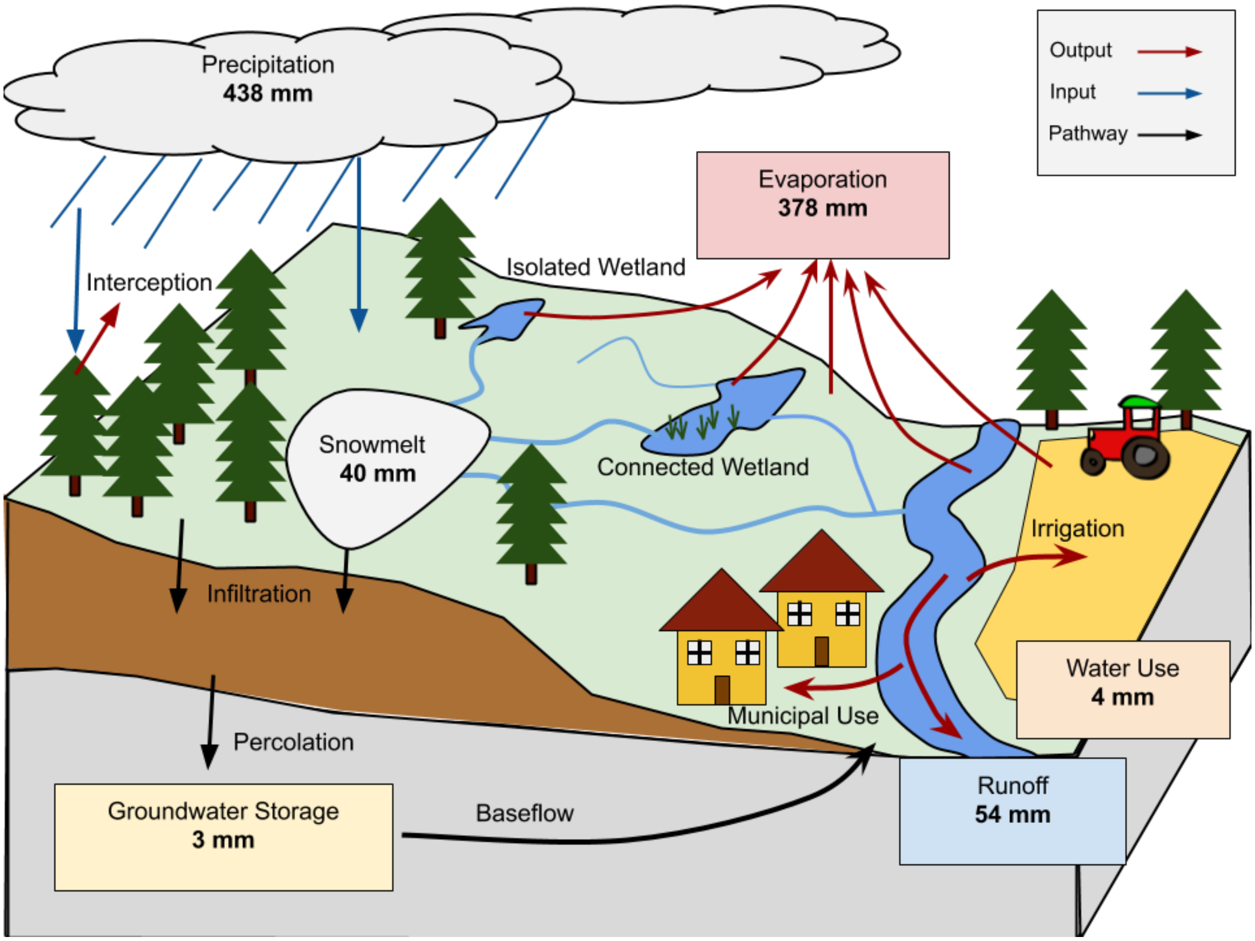


Figure 25. Full water balance for the Sturgeon River watershed.

3.2.3 Sources of Uncertainty

Although the model had modest performance and appears to adequately emulate the driving hydrologic processes governing runoff in the watershed, several sources of uncertainty exist in the hydrological model that should be noted. First, there is uncertainty in measurements that were used both in model forcing, calibration, and verification. Notably, precipitation data is limited to five regional sites and spatial interpolation is required to distribute these values across the model domain. Given the nature of summer precipitation events as primarily geographically small and isolated convective storms, it is likely that this dynamic is not fully captured in the model. In particular, the intensities are likely to be dampened, while some areas that did not receive the precipitation will receive simulated precipitation.

Lake storage and discharge dynamics are an additional source of uncertainty. Water level records for Lac St Anne are incomplete, containing no data over many spring and fall periods, as well as no winter values. In addition, it is unclear how representative and up-to-date the storage curves for the lakes are. Human influence, lake management or engineering, and lake sedimentation have likely impacted storage in the lake over time, and these factors are not captured in the current model configuration.

Finally, this model has built custom routines to attempt to emulate complicated wetland and prairie pothole dynamics, coupled with non-contributing areas. These hydrological dynamics are not well understood in the scientific community, and as such remain active avenues of research. While we believe this model offers an improvement over neglecting these processes entirely, significant uncertainty exists in delineating the precise boundaries between contributing and non-contributing areas as well as the size and rate of water storage and seep within prairie potholes and wetlands. While this is partly offset by our flexible workflow allowing these processes to be calibrated, independent verification data precisely focusing these wetland features is not available, and these processes can only be verified with our current dataset using streamflow observations at sub-basin outlets. As research continues into the dynamics of these hydrologic features and hydrological processes, more accurate algorithms, process representation, and subsequently hydrological models will be possible.

3.3 Conservation and Restoration Strategies

The development of what a future land use may look like in the Sturgeon River watershed under a series of conservation and restoration management plans allows for investigation into the different hydrologic regimes that may occur under different land management practices, thereby identifying the effects of land use strategies on hydrology in the watershed. Simulating conservation and restoration strategies within the Sturgeon River watershed can provide stakeholders with an understanding of the potential future land uses that may occur after applying these strategies, as well as a better understanding of how these future land uses can affect the hydrologic conditions in the watershed.

After consultation with the TAC, priority areas of focus for conservation and restoration strategies primarily involved wetland restoration and protection, conversion of cropland back to grassland, and pre-settlement forest cover restoration.

The following eight watershed resilience indicators were assessed relative to the conservation and restoration land use strategies:

1. Change in peak streamflow – desired outcome is reduced peak flow
2. Change in annual water yield – desired outcome is increased water yield
3. Change in flashiness index – desired outcome is reduced flashiness
4. Change in high flow frequency – desired outcome is no change in high flow frequency
5. Change in low flow frequency – desired outcome is no change in the frequency of low flow events
6. Change in peak streamflow timing – desired outcome is no change in peak flow timing
7. Change in low flow index – desired outcome is reduction in low flow index
8. Change in low flow timing – desired outcome is later onset of very low flows

These indicators were chosen after consultation with the TAC, and best represent functions of a healthy watershed that is resilient to shifting hydrologic states after a disturbance.

3.3.1 Forest restoration

Forest restoration had a relatively little effect at the scale of the watershed in terms of reducing peak streamflow. This is primarily due to the fact that forest restoration only occurred in portions of the watershed where forest occurred in the pre-settlement condition. The largest effect of this strategy was noticed downstream of Big Lake, where there is substantial development, resulting in higher rates of runoff. Restoring forest in this area would have a relatively high effect on peak flow reduction. Similarly, the effects of forest restoration on annual water yield, the timing of peak streamflow, flashiness, and high flow frequency were most pronounced around more urbanized areas (Figure 26 and Figure 27). These results suggest that increasing interception and infiltration can have desired effects on watershed processes, resulting in a more regulated streamflow regime.

The effects of forest restoration on low flow indicators like the frequency of low flow periods, low flow index, and timing were more distributed across the watershed. In particular, the middle portion of the watershed showed the greatest effect in terms of reducing the frequency of low flow events and the low flow index. The timing of low flow events was mostly affected in the eastern portion of the watershed (Figure 27).

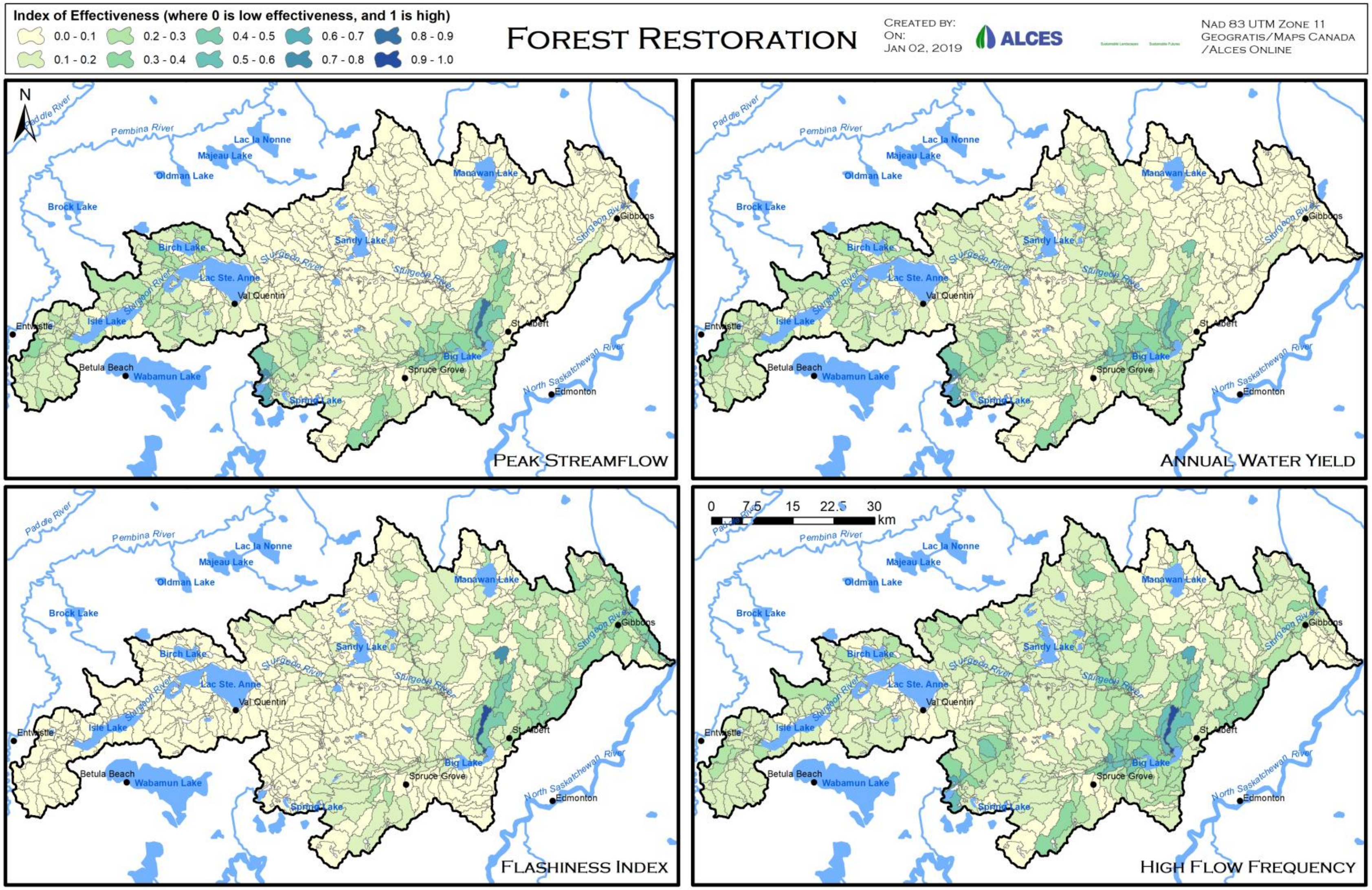


Figure 26. Response of peak streamflow, annual water yield, flashiness index, and high flow frequency to the forest restoration strategy.

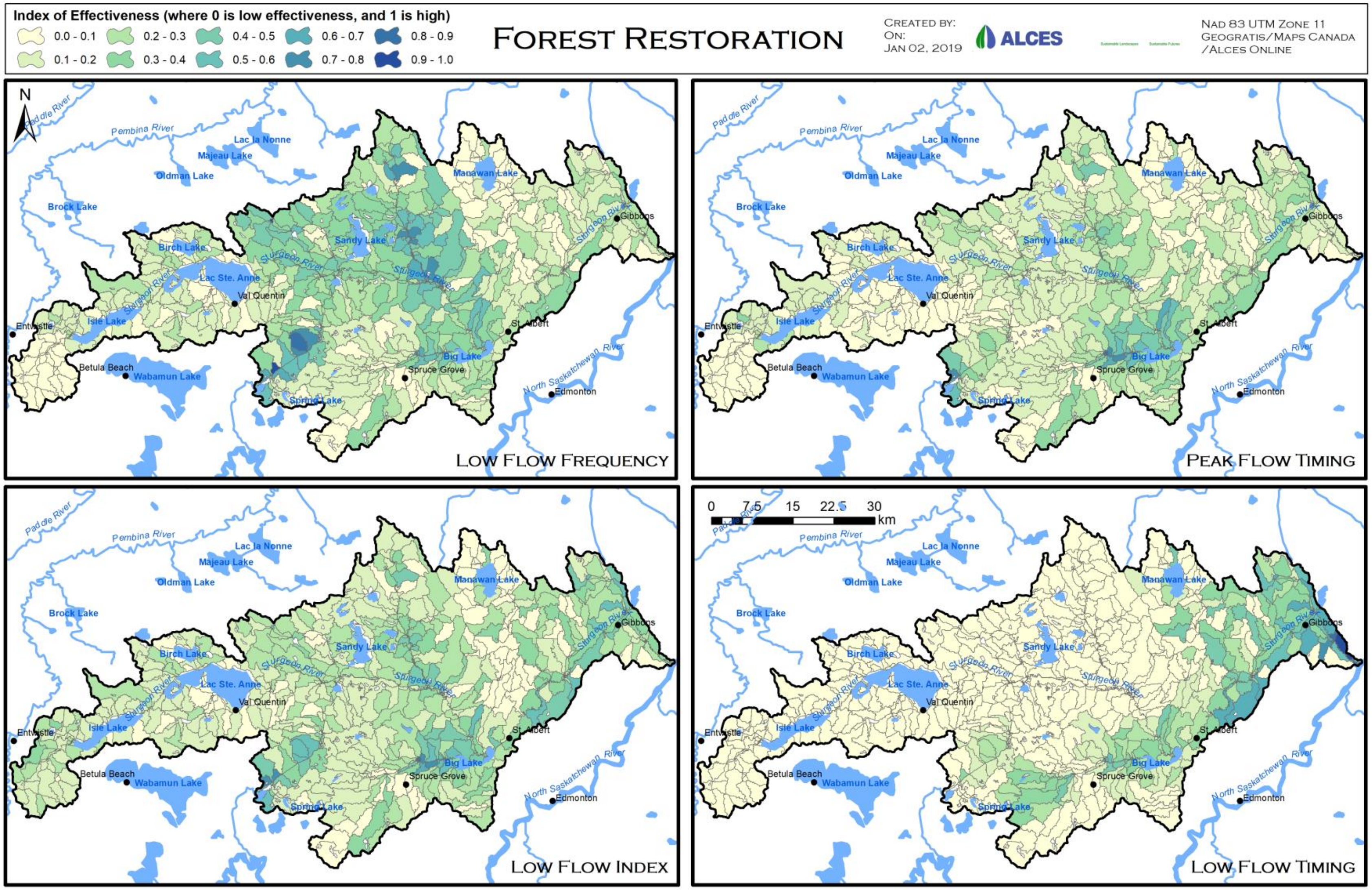


Figure 27. Response of flow flow frequency, peak flow timing, low flow index, and low flow timing to the forest restoration strategy.

3.3.2 Grassland restoration

Grassland restoration had the greatest effect on peak streamflow reduction and the frequency of high flow events along the eastern portion of the watershed. Substantial reductions in peak streamflow were obtained for several sub-basins. This was largely a factor where small communities like Morinville were converted from urban to grassland. This type of strategy would not likely occur in reality; however, demonstrates the effectiveness of implementing management practices that reduce runoff and improve infiltration. The effect of this strategy on annual water yield and flashiness was similar to forest restoration, where downstream of Big Lake showed the greatest potential for change. Changes in the timing of peak flow were mostly noticed along the eastern portion of the watershed, again with the largest effect near Big Lake (Figure 28).

Low flow indicator effects were more homogeneously distributed, with the largest effects again occurring in the middle of the watershed (Figure 29). This demonstrates the effect of holding more water on the landscape, resulting in a greater release later in the season. Although these changes are not dramatic, they again support the use of management practices that aim to increase infiltration through naturalization of the landscape.

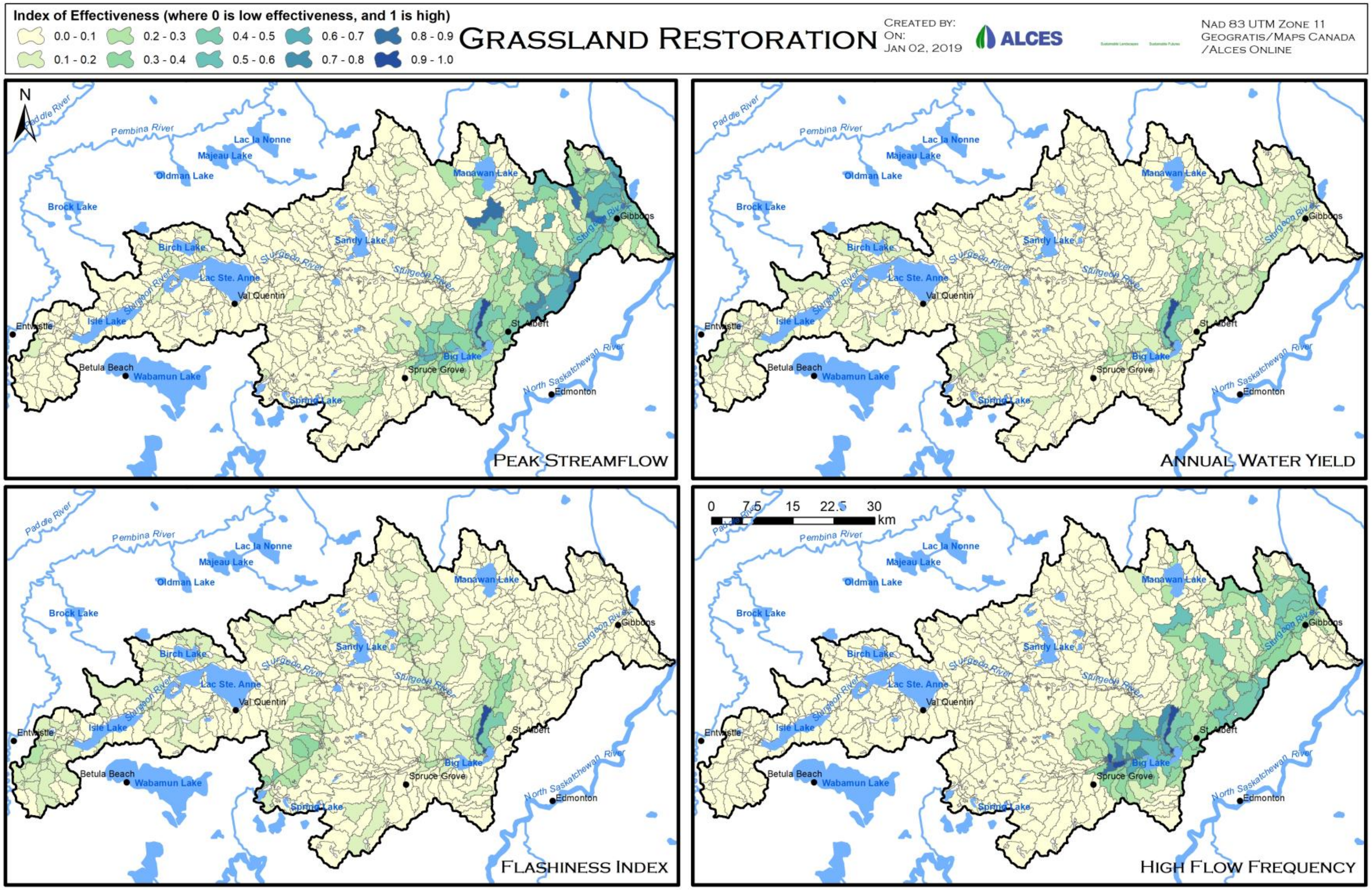


Figure 28. Response of peak streamflow, annual water yield, flashiness index, and high flow frequency to the grassland restoration strategy.

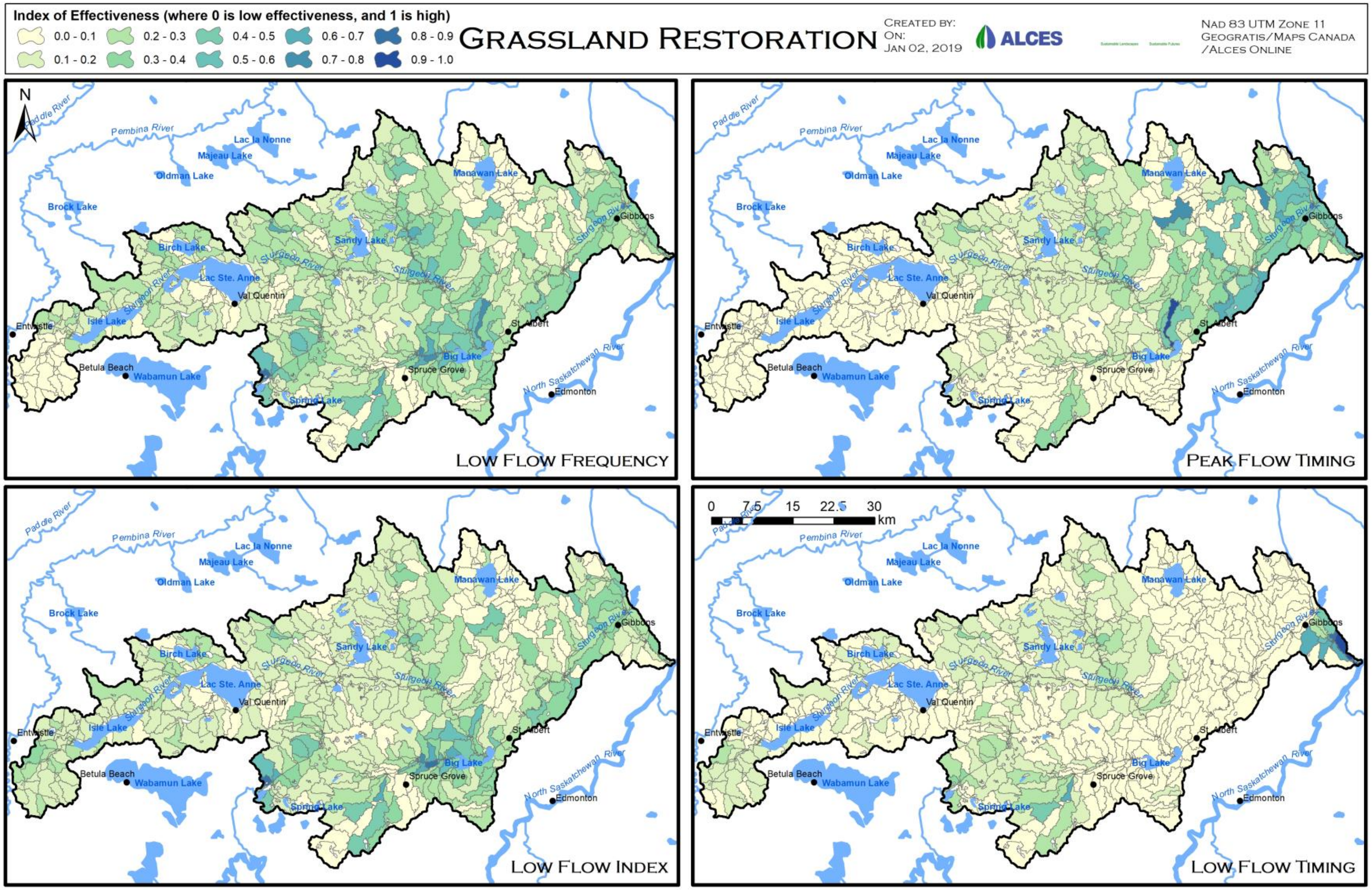


Figure 29. Response of flow flow frequency, peak flow timing, low flow index, and low flow timing to the grassland restoration strategy.

3.3.3 Wetland protection

Wetland protection was an effective strategy for reducing peak streamflow, flashiness, and the frequency and timing of high flow events in the heavily urbanized portion of the watershed. This implies that wetlands in this portion of the watershed are serving a hydrologic role in terms of damping streamflow response to runoff events. Likewise, wetlands are playing a role in providing reliable water yields in these portions of the watershed (Figure 30). The fact that wetland protection is not as effective in the remainder of the watershed suggests the wetland loss that has occurred does not dramatically differ from the wetland loss projected to occur under the BAU land use scenario. This does not suggest these wetlands are not playing a role hydrologically, rather wetland restoration in these areas may be a more effective strategy.

Low flow indicators did not meaningfully respond to this strategy, with again the greatest concentration of response around areas that are urbanized and in the headwaters of the watershed (Figure 31). Although there was no dramatic effect demonstrated through modelling, protecting wetlands in the headwaters does indicate potential to improve low flow indicators. This suggests these existing wetlands play a role hydrologically and should be protected, as they increase resilience in the watershed.

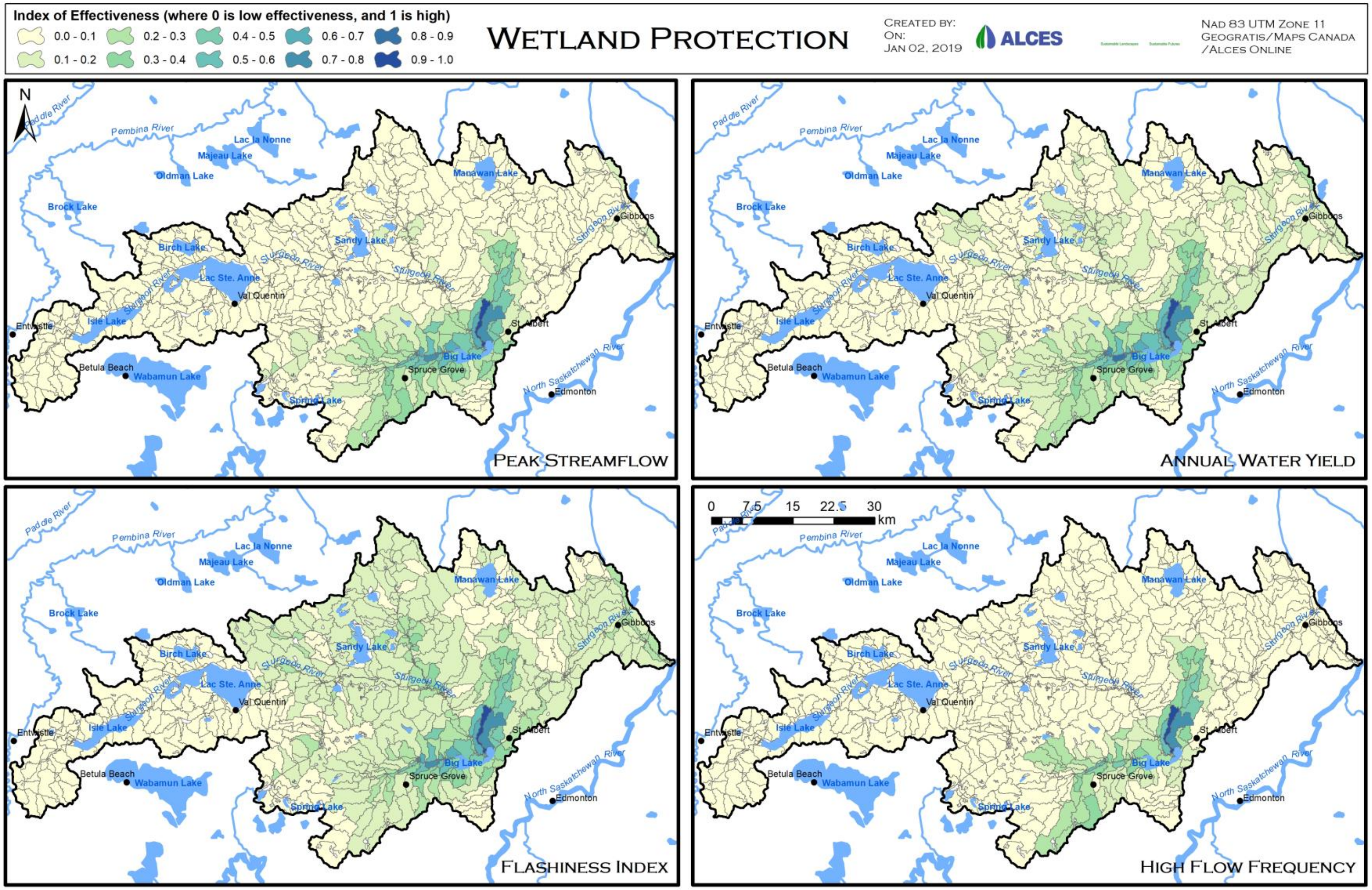


Figure 30. Response of peak streamflow, annual water yield, flashiness index, and high flow frequency to the wetland protection strategy

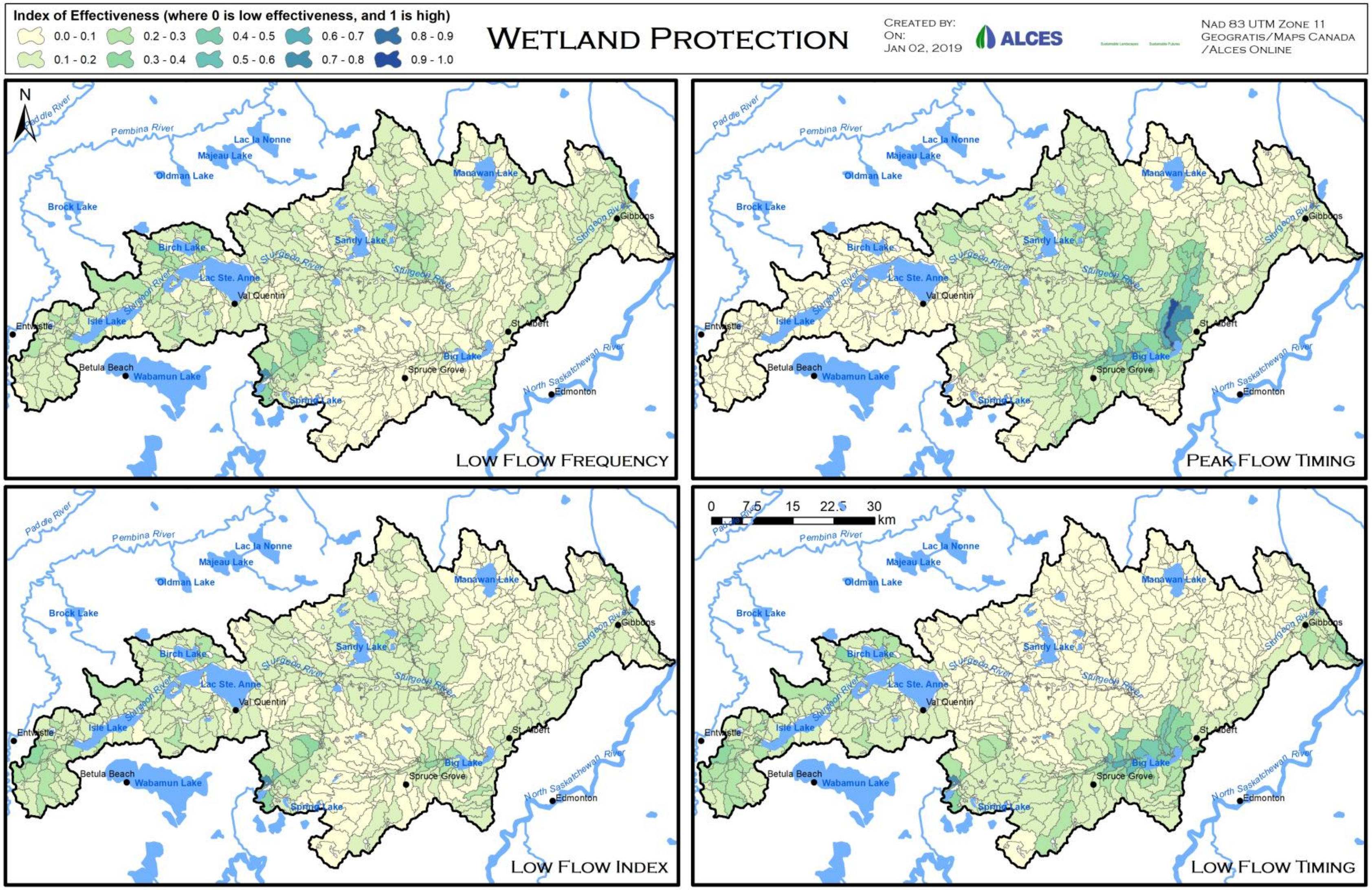


Figure 31. Response of flow flow frequency, peak flow timing, low flow index, and low flow timing to the wetland protection strategy

3.3.4 Wetland restoration

Wetland restoration was by far the most effective strategy in lowering peak streamflow, providing annual water supply, reducing flashiness, and ensuring reliable timing of peak flow (Figure 32 and Figure 33). This suggests that wetland loss throughout the watershed has been substantial and the hydrologic role of those wetlands is high. The eastern portion of the watershed showed the greatest effect overall, with the highest effects in sub-basins that are urbanized. Like wetland protection, this suggests improving or implementing wetland restoration strategies in areas with high runoff potential can have a large hydrologic effect at the scale of the sub-basin. Interestingly, the effect on the frequency of high flow events was most concentrated in the urbanized portion of the watershed – suggesting the number of times high flow events occurs is most likely driven by very wet conditions where wetland areas are already saturated, so it would take very large changes relative to current conditions to actually change how frequently those types of events occurs.

The low flow index was not meaningfully affected by wetland restoration – suggesting this is a meteorologically/climatologically driven indicator. The frequency of low flow events was shown to respond across most of the watershed, while the timing of low flow events was mostly affected in the headwaters and in areas with urban development. The areas between Lac St. Anne and Wabamun Lake also showed relatively substantive response to wetland restoration (Figure 33); this suggests this is an area that is hydrologically important and that has received relatively high wetland loss relative to pre-settlement conditions.

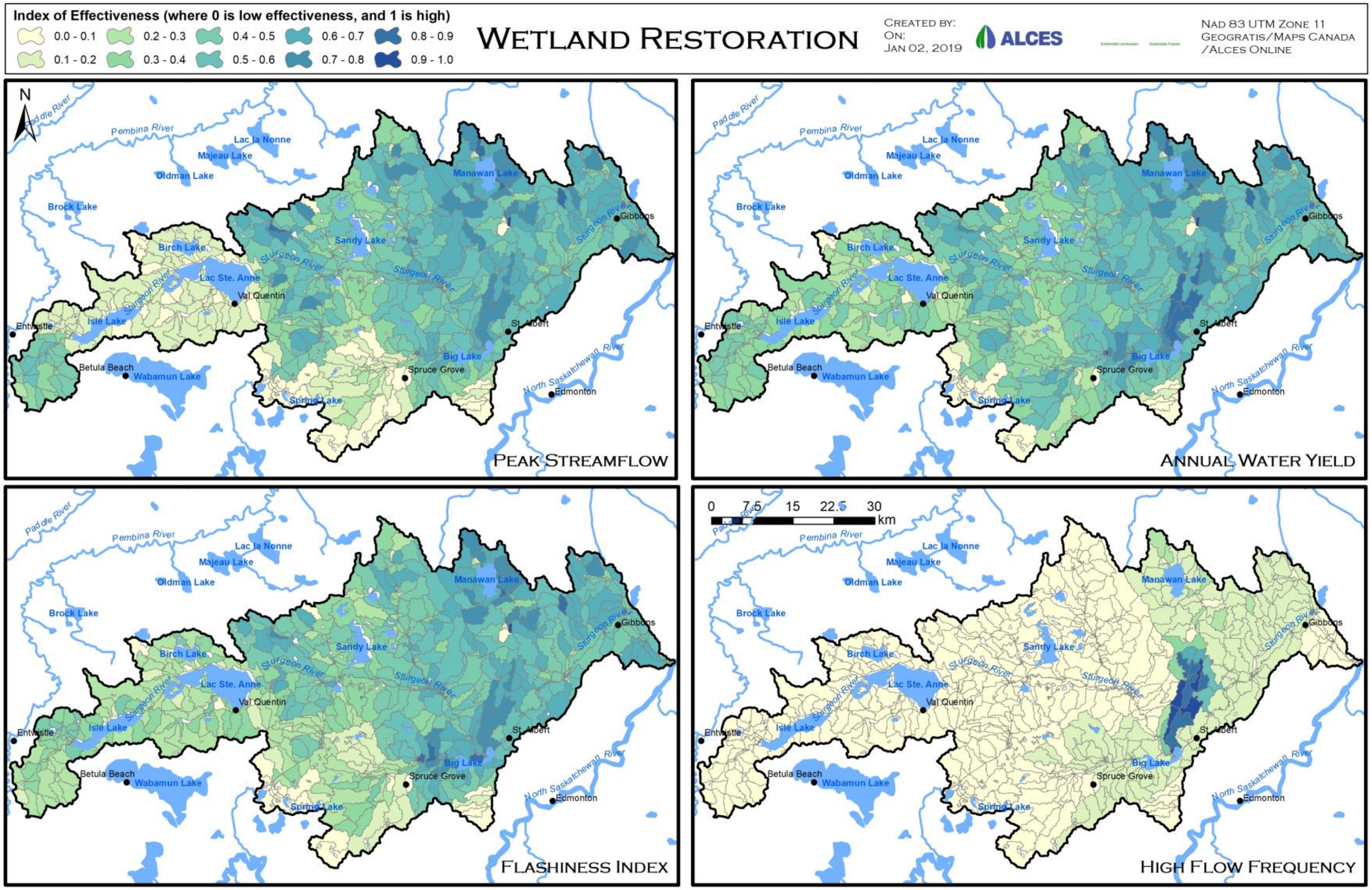


Figure 32. Response of peak streamflow, annual water yield, flashiness index, and high flow frequency to the wetland protection strategy

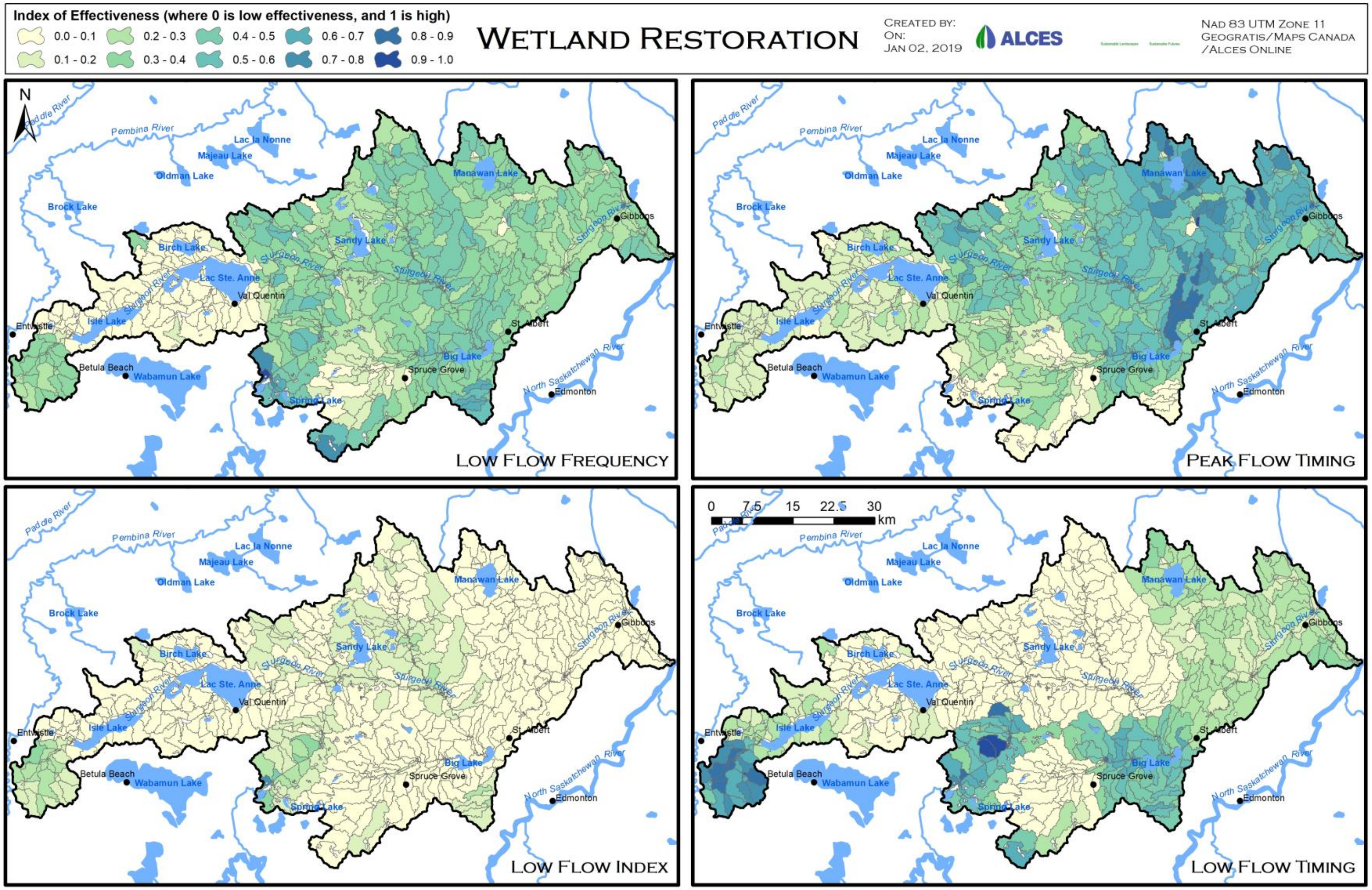


Figure 33. Response of flow flow frequency, peak flow timing, low flow index, and low flow timing to the wetland protection strategy

4 Conclusions and Recommendations

This study has demonstrated the relative benefits of implementing conservation and restoration strategies in terms of watershed resilience indicators focused on streamflow in the Sturgeon River watershed. This was achieved using a hydrologic model coupled with land use simulation in a modelling framework that allows for multiple scenarios to be tested. The hydrologic model was built using a customized version of the Raven hydrologic modelling framework, while land use simulation was conducted using ALCES Online. These models are both available to the NSWA and their membership for ongoing use. In addition, a publicly available web-based application is being developed to demonstrate results in a user-friendly manner.

Simulation results suggest the Sturgeon River watershed has experienced substantial land use change, with conversion of natural area to agricultural, industrial, and urban land use. As suggested by Buendia (2017), this change has resulted in altered hydrologic behaviour. This study confirms this assertion, demonstrating that conservation and restoration activities can have an influence on hydrologic function as assessed through resilience indicators.

These findings are important to consider relative to watershed resiliency, as activities that improve watershed function also are likely to provide benefit for increased watershed resilience. The model that has been developed can be used to prioritize locations for conservation or restoration opportunities, while site-specific fieldwork within priority areas can determine how best to capitalize on these opportunities.

Implementing conservation and restoration strategies is a substantial challenge, particularly given that current land use activities often offer some economic benefit. Therefore, a strategic approach to implementation is required, where costs and benefits are fully assessed. This project has identified the potential for benefit to watershed resilience with a specific focus on hydrology. This information can be used in combination with other values like wildlife habitat, recreation, and economic activity to further develop a strategic plan for implementation. Within this context, the conservation and restoration strategy that shows the most promise for improving watershed resilience related to hydrology is wetland restoration. Grassland and forest restoration also show promise but are likely to provide more local benefits.

It is recommended that this work be carried forward, as this, along with the SRWA's Water Management Plan, is ultimately an initial step in long-term conservation and restoration planning in the Sturgeon River watershed. To further this work, it is recommended that:

- The hydrologic model continues to be refined as process understanding and algorithms become available
- Individual sub-basins be selected by the TAC for further assessment in terms of potential to implement conservation or restoration strategies
- Additional scenarios be evaluated in the modelling framework to test the combination of conservation and restoration strategies
- Field assessment be completed for those sub-basins that demonstrate highest effectiveness, as per model results

- An implementation plan be developed based on further scenario analysis coupled with detailed field assessments to verify where opportunities for conservation or restoration exist
- Ongoing engagement and outreach be conducted with stakeholders and potential funders, enabling buy-in to implementation over the long-term

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