NSWA
NORTH SASKATCHEWAN WATERSHED ALLIANCE

ALCES

Sustainable Landscapes Sustainable Futures

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

July 8, 2019

Suggested Citation: MacDonald, R., Marcotte, D., Chernos, M., Carlson, M., and Adrain, C. 2019. Strategic Priorities for Conservation and Restoration to Improve Watershed Resiliency in the Vermilion River Watershed. Prepared for the North Saskatchewan Watershed Alliance. 62 pp.

Table of Contents

List of Figures

List of Tables

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 stewardship groups. The Vermilion River Watershed Alliance (VRWA) is a newly incorporated stewardship group operating in the Vermilion River watershed. The VRWA works cooperatively with and is supported by the NSWA, and consists of elected municipal officials, government and non-government members. Project initiatives are guided by overarching goals of the *Integrated Watershed Management Plan for the North Saskatchewan River in Alberta* (IWMP) and the *Vermilion River Watershed Management Plan (VRWMP)*.

As a result of recent assessments done in the Vermilion River watershed (VRW) including the *State of the North Saskatchewan Watershed Report* (NSWA, 2005), knowledge areas were identified that, if explored would provide valuable insight for the overall management of the Vermilion River watershed. Of particular importance for watershed management and restoration planning is a means to assess overlapping impacts across the watershed. Agricultural expansion and linear disturbances in the Vermilion 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 Vermilion River watershed. Landscape, anthropogenic and hydroclimatic attributes of the Vermilion River watershed were integrated in the model, which allows users to simulate how various indicators of hydrologic change could 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 Vermilion River watershed,
- Develop custom hydrologic and land use models for the Vermilion 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 Vermilion River watershed, and
- Create a user-friendly web-based tool to view results of the model simulation scenarios.

Consultation and cooperation with the project Working Group was upheld throughout all phases of the project. The Working Group consisted of the board of directors of the VRWA as well as additional technical advisors (Appendix # list of working group members), and functioned to ensure the approach met the needs of the watershed stakeholders.

1.2 Study area

The spatial scope of the project is defined as the entire Vermilion River watershed in Central Alberta (Figure 1). The Vermilion River drains a land area of approximately 7,860 km^2, flowing from its headwaters in the southwest of the watershed to the confluence with the North Saskatchewan River in the northeast of the watershed.

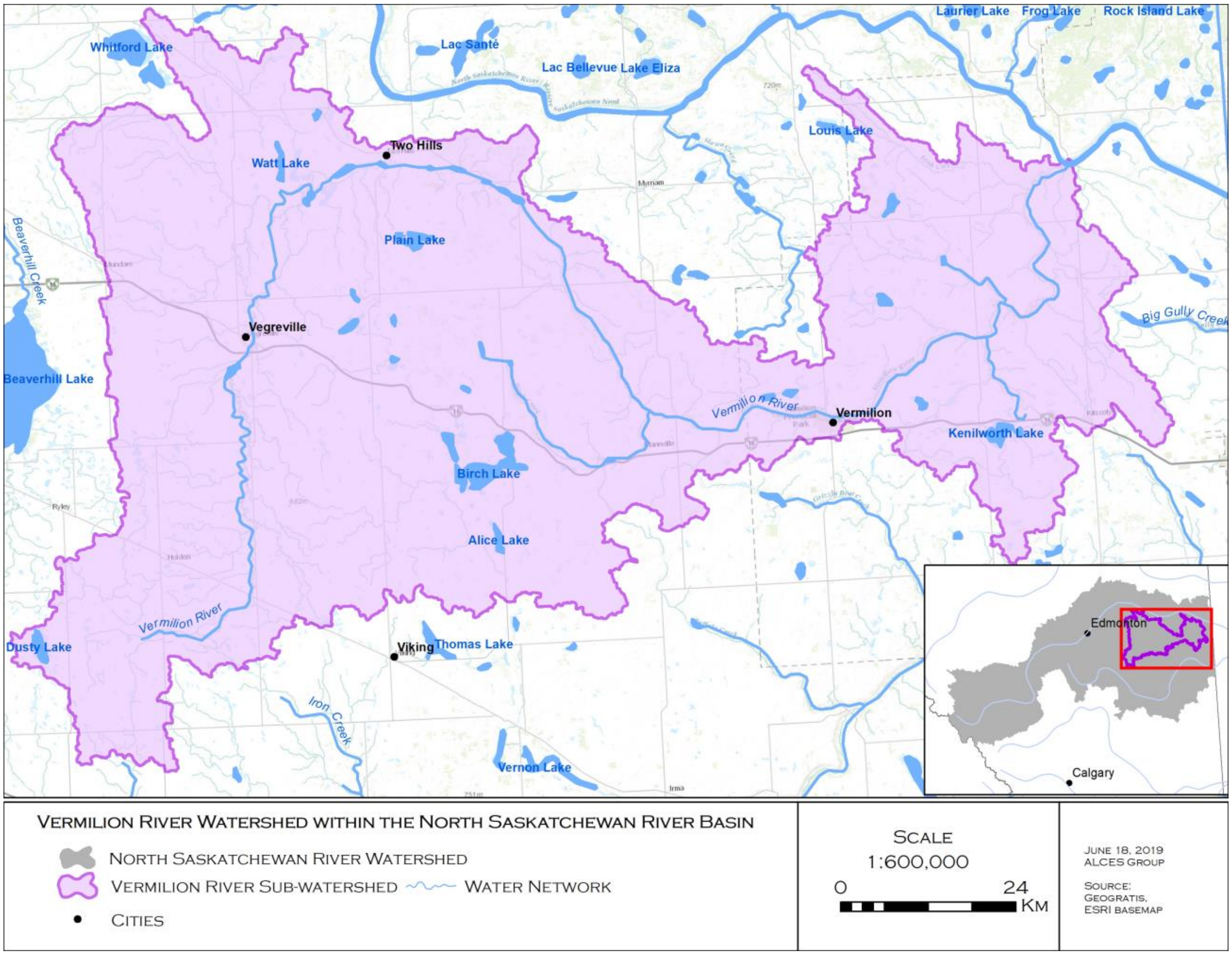

Figure 1. The Vermilion River watershed study area

The Vermilion River primarily flows through a Parkland Natural Region. There are relatively large portions of the Vermilion River watershed that do not contribute to streamflow in the Vermilion River on a regular basis. This is due to the physiographic setting, where internal drainage areas contribute to local features like sloughs or wetlands the majority of the time. It is only during wet conditions that larger portions of the watershed would contribute to streamflow in the Vermilion River. It is estimated that the effective drainage area of the Vermilion River watershed is approximately 2,360 km^2 (Golder, 2009).

The Vermilion River watershed is characterized by its continental climate, with cold winters and warm summers with relatively low precipitation amounts (Figure 2). Climate stations throughout the watershed demonstrate that the majority of precipitation is received during June and July, which does not actually correspond to the highest streamflow (Figure 3). This demonstrates the importance of winter snow accumulation and subsequent melt in providing substantial contributions to streamflow in the Vermilion River. Interestingly, June and July precipitation does result in substantial streamflow contribution to the Vermilion River near Holden, which is most likely a result of the artificially connected Holden drainage district. This highlights the influence of internal drainage in this system and demonstrates the effectiveness of draining water from the landscape.

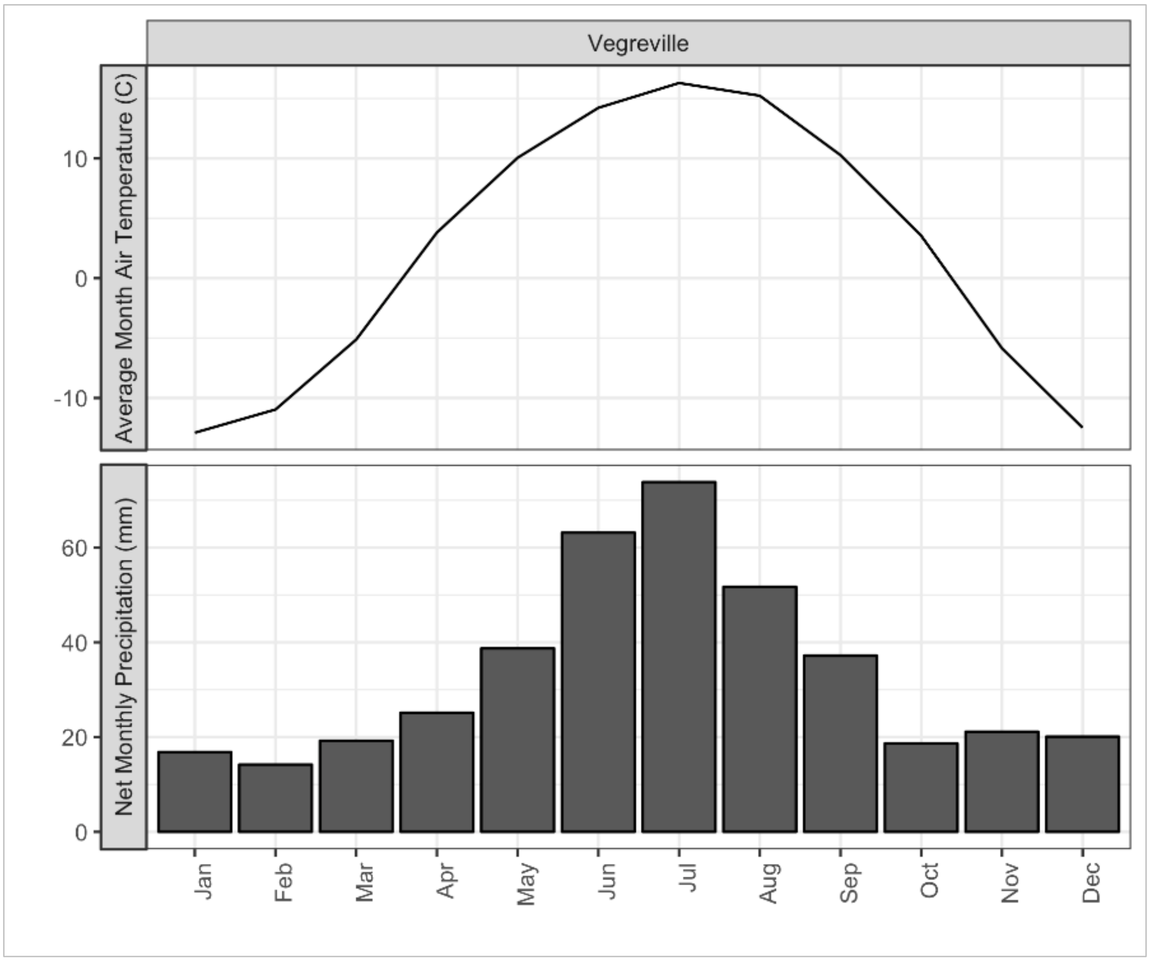

Figure 2. Average monthly air temperature and net monthly precipitation for the Vegreville climate station over the period from 1980-2016

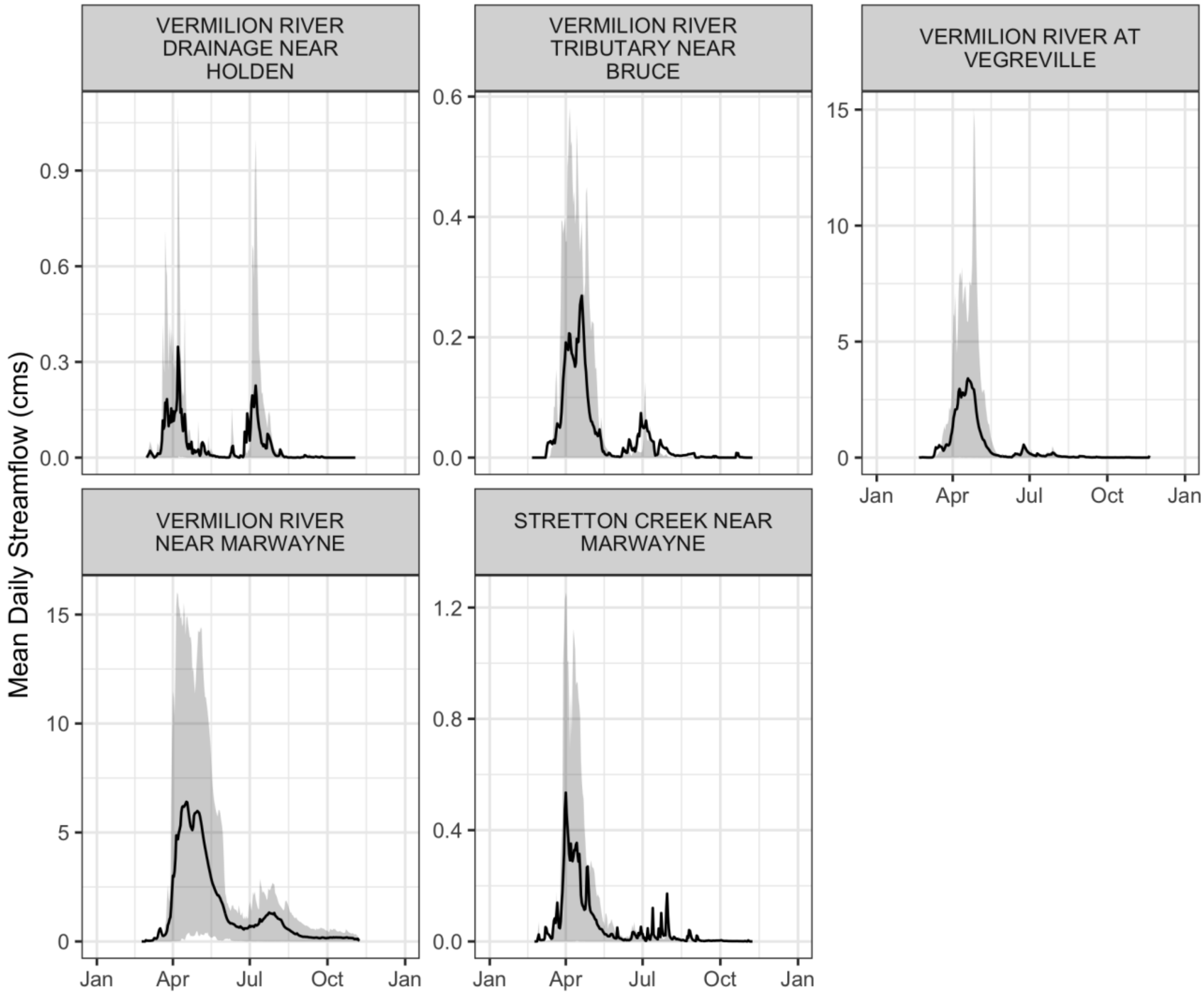

Figure 3. Daily average streamflow for Water Survey of Canada hydrometric stations in the Vermilion River watershed for the period from 1964 - 2017, with varied dates for each station

Land cover within the watershed is dominated by crops and pasture, making up 77% of the total study area, with natural land cover accounting for 20% of the total area and other human land use making up the remaining 3% of the area (Figure 4).

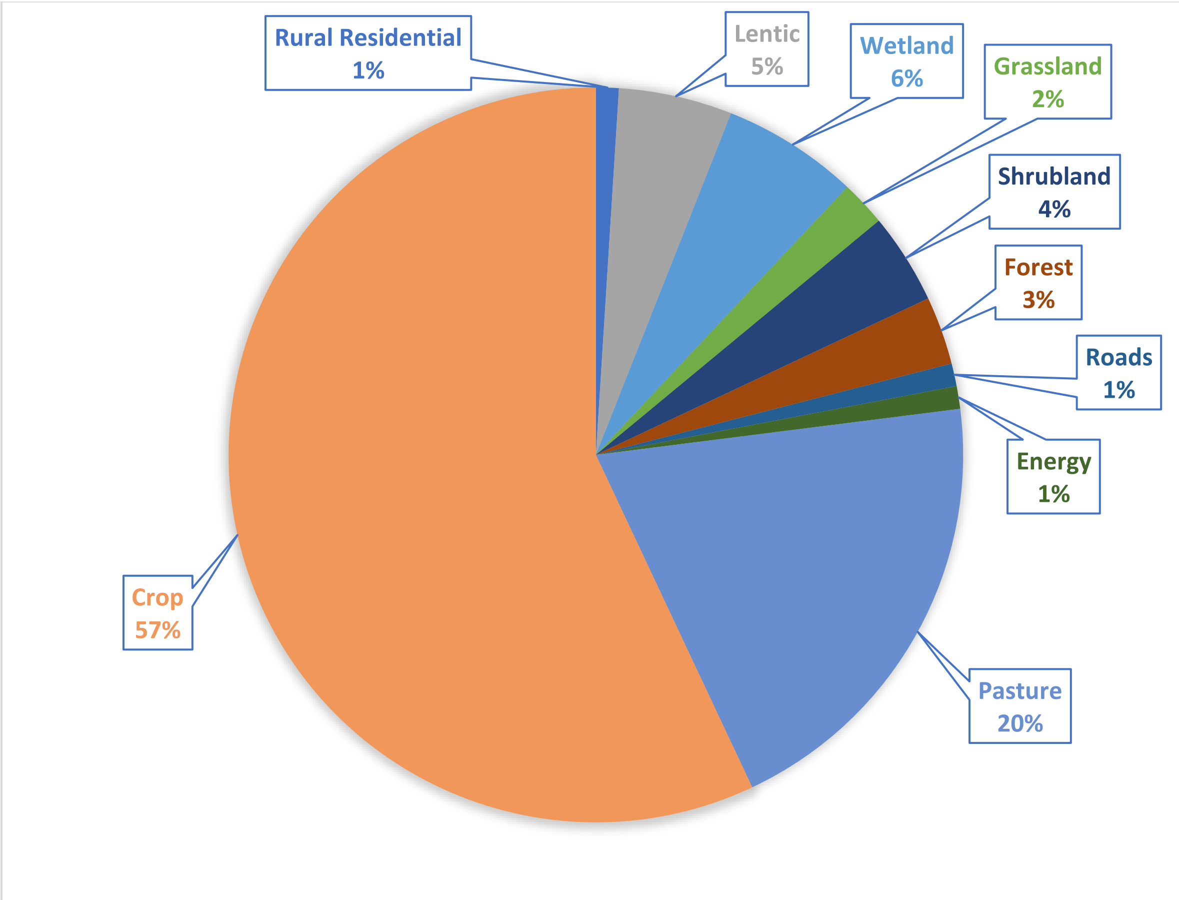

Figure 4. Proportion of land cover types across the Vermilion River watershed

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 Vermilion River watershed. The first involved participation with the Working Group 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).

For this project, we examine hydrologic resilience within the context of the ecological definition, and consider three aspects in this approach:

1) 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.

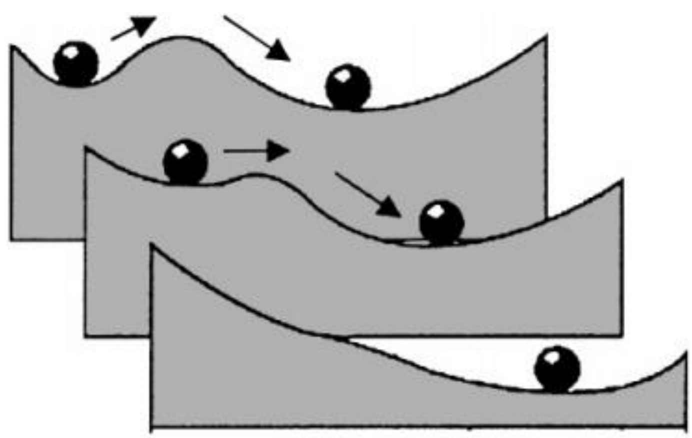

Figure 5. Ball and cup schematic of system stability. Valleys represent domains of attraction (or stable states), balls represent the system, and arrows represent the acting perturbation

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 Vermillon 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 Vermilion River watershed.

If the status of an indicator is 'good', then one would conclude that the hydrology of the Vermilion 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

Change in peak streamflow

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, smaller drainage units within the greater Vermilion 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 Vermilion River watershed.

Low flow index

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 Vermilion 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 Vermilion River watershed, in terms of how flashy a 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 Vermilion 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 Vermilion 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 Vermilion 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 Vermilion 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 Vermilion 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 Vermilion River watershed, and sub-basins were delineated within this watershed (Figure 6). The temporal scale of the project was chosen to range from the year 1900 to 2065.

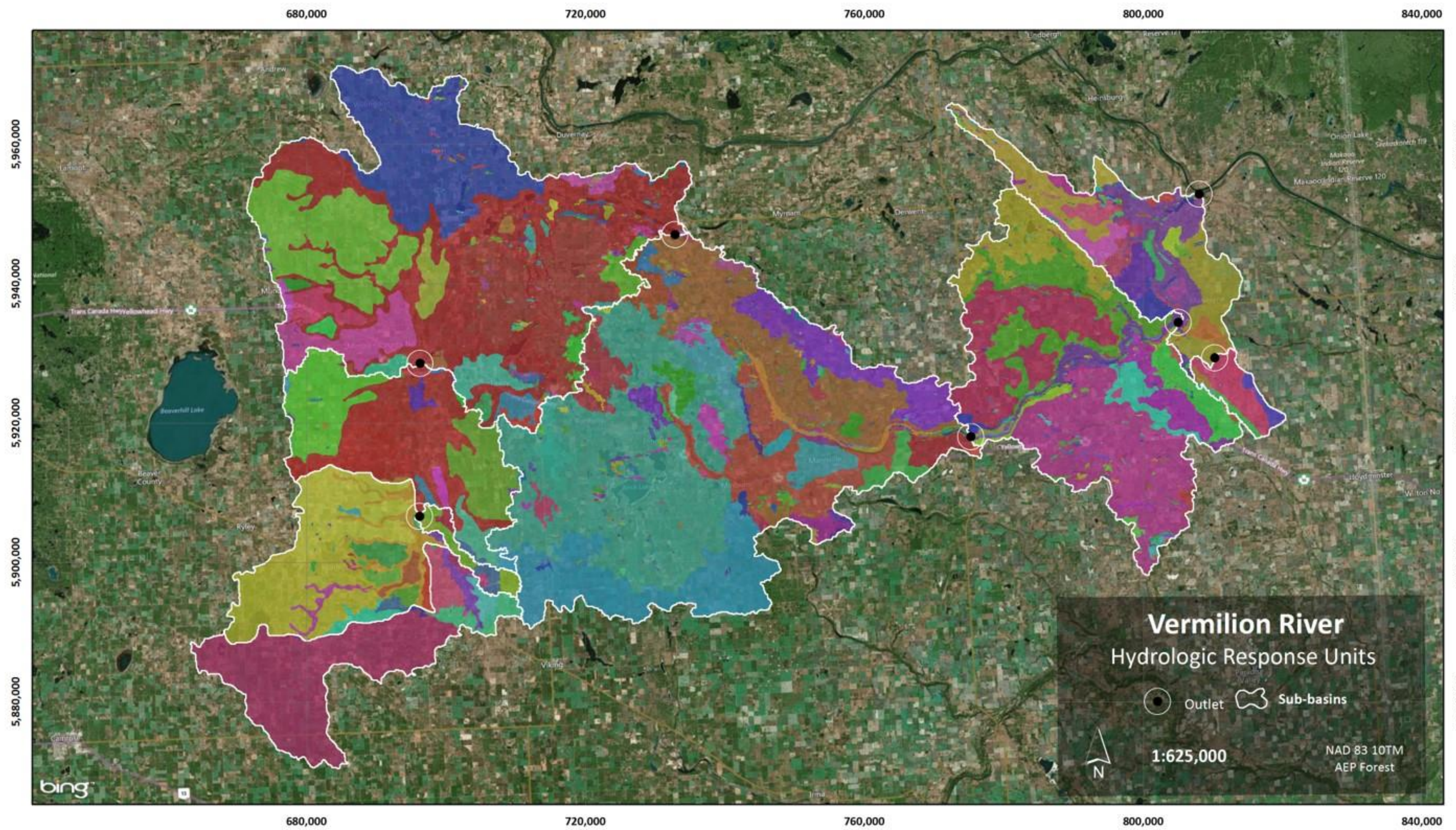

Figure 6. Sub-basins defined in the Vermilion River watershed project area for hydrologic modelling

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

2.1 Hydrological modelling

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

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 Vermilion 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 Vermilion River watershed. These data were obtained from:

- Ephemeral Flows, Non-Contributing Areas (Golder, 2009)
- Wetland Depression Storage (Pomeroy et al., 2010)
- Prairie Potholes and Non-Contributing Areas (Pomeroy et al., 2012; Shook, 2013)

Daily streamflow measurements were obtained from eight Water Survey of Canada (WSC) (2018) hydrometric stations in the Vermilion River watershed (Table 2). Hydrometric gauges with daily average streamflow (m^3/s) observations for the majority of the 1980-2017 period include Vermilion River Tributary Near Bruce, Stretton Creek Near Marwayne, Vermilion River at Vegreville, Vermilion Park Lake Near Vermilion, and Vermilion River Near Marwayne. Streamflow data were only available for one tributary in the watershed (Stretton Creek) and it is recognized that all hydrometric stations downstream of Vermilion Lakes Near Morecambe could have been affected by the Morecambe flood control structure, which is operational. In addition, all hydrometric records downstream of Vermilion Park Lake are additionally affected by a weir and lake structure. No lake storage curve was available for Vermilion Park Lake; therefore, we applied a generalized (trapezoidal) lake profile, with a measured area of 2.21 km^2 and a maximum depth of 50 m.

Historical water usage data were 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. *Indicates records do not coincide with the study period.*

Station Name	Station ID	Record Start	Record End	Drainage Area (km^2)
VERMILION RIVER TRIBUTARY NEAR BRUCE	05EE006	1987	2017	46
VERMILION RIVER DRAINAGE NEAR HOLDEN	05EE913	1981	1993	56
STRETTON CREEK NEAR MARWAYNE	05EE005	1978	2013	74
VERMILION RIVER AT VEGREVILLE	05EE009	1987	2017	1,615
VERMILION LAKES NEAR MORECAMBE	05EE011	2006	2017	3,810
VERMILION PARK LAKE NEAR VERMILION	05EE008	1983	2013	6,120
VERMILION RIVER NEAR MARWAYNE	05EE007	1983	2017	7,257
VERMILION RIVER AT LEA PARK*	05EE002	1964	1970	7,940

We obtained daily maximum and minimum air temperature (°C) and precipitation (mm) data from the Alberta Climate Information Service (ACIS, 2018) for five 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 four monthly snow survey sites: Two Hills (05EE801), Clandonald (05ED801), Bruce S.P. (05EE802), and Mannville (05FE801) from AEP.

Table 3. Five climate stations used in this study

Name	ID	Latitude	Longitude	Elevation (m)
Vegreville	T052R14W4	53.48	-112.05	634
Viking	T048R13W4	53.10	-111.78	691
Dewberry	T053R04W4	53.59	-110.52	600
Myrnam	T054R09W4	53.66	-111.23	607
Vermilion	T050R06W4	53.35	-110.86	619

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 hydrological response units (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 1980 – 2017.

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), 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.

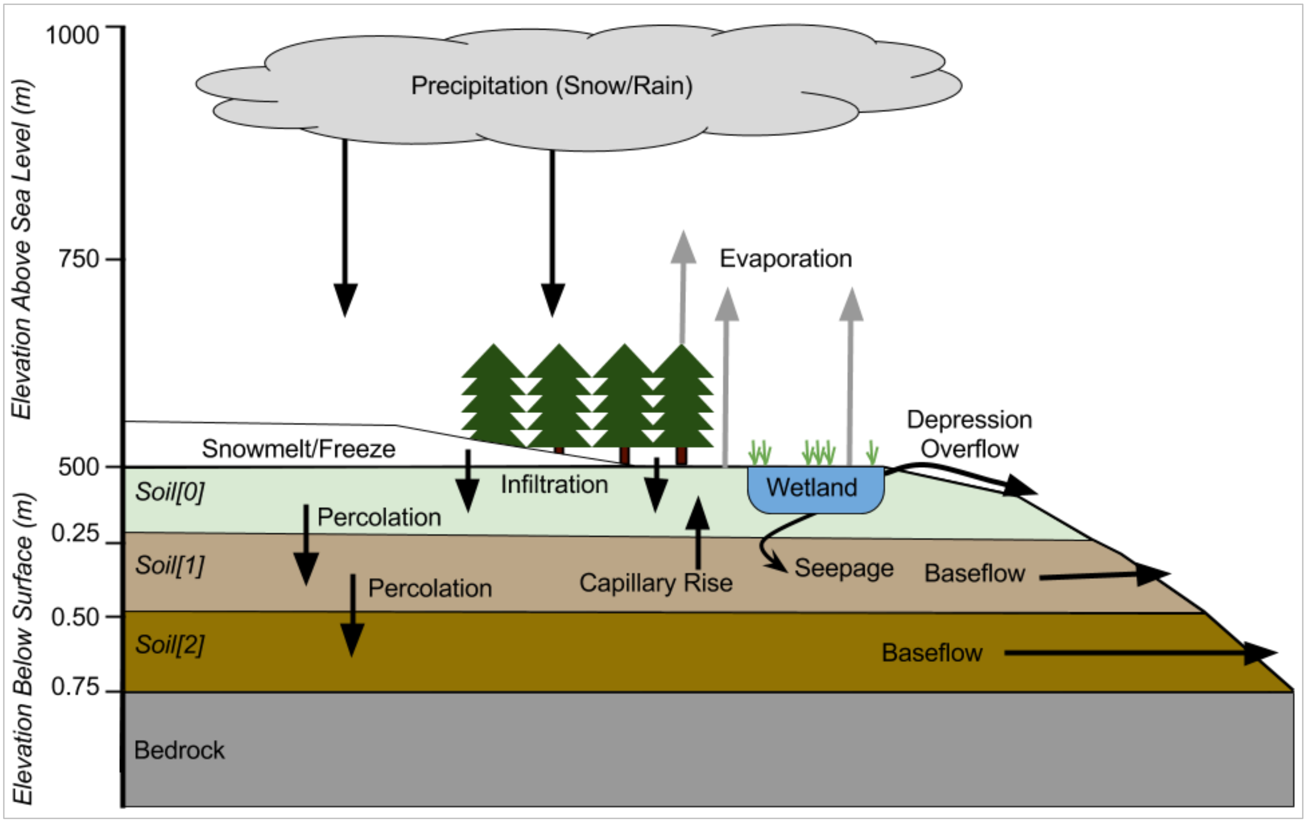

Figure 7. Schematic of driving processes and water pathways in the HBV-EC hydrological model emulation within Raven

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

Process	Model Algorithm
Snow Balance	HBV (Snowbal Simple Melt)
Glacier Melt	HBV
Infiltration	HBV
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 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 (Vermilion River at Vegreville and Stretton Creek near Marwayne) 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 Vermilion 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 Vermilion River watershed falls within PSAC boundaries 4 and 5 and the proportion of PSCA 4 and 5 oil deposit equals 2.1%. 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 4 and 5, extrapolated out until 2060 at a constant rate, and multiplied by 2.1%. 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	177.2
2020	173.5
2030	134.1
2040	134.4
2050	134.4
2060	134.4

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 Vermilion River watershed. The natural gas hydrocarbon region within the Vermilion River watershed comprised 9.3% of the area that fell within the greater PSAC region 4 and 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 regions 4 and 5, by decade

Decade	Additional Well Area (ha)
2010	152.1
2020	12.6
2030	22.8
2040	23.3
2050	23.3
2060	23.3

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

The shale gas hydrocarbon region (Rokosh et al., 2012) did not overlap with the Vermilion River watershed; therefore, there was no shale gas well development incorporated into this scenario.

Access Roads

Access roads to oil and natural 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 neighbouring 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 (reference). These estimates projected that 16.2 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. Applying a similar percent increase to the Vermilion River watershed would result in an additional 2.86 km^2 of new mine pits over two decades.

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 4.3 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 Vermilion, 2011).

Communities considered were Vermilion and Vegreville. Statistics Canada population growth rates were 0.78%/year and -0.04%/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 Vegreville has a negative population 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 (i.e. the town would stay the same size).

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 Vermilion River watershed consists primarily (99.3%) of Census Division 10 with a negligible portion (0.7%) of CD 12. According to Stats Canada, CD 10 population grew by an average of 0.94% per year between 2011 and 2016. The current Rural Settlement footprint within the Vermilion River watershed is 89.8 km^2 and this scenario assumed a growth rate of 8.4 km^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 Vermilion 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 Vermilion River watershed is 0.015. Applying that ratio to the rural settlement growth rate results in a rate of 0.014%. We can then apply this

[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.

rate to the current recreation footprint of 1.5 km^2. This results in a yearly projection of 0.002 km^2 of new recreation footprint 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

<u>Wetland Loss</u>

Based on pre-settlement simulations, wetland coverage in the Vermilion River watershed has decreased from 556 km^2 in pre-settlement times to 265 km^2 currently. This represents a 52.3% decrease over 100 years. Applying this percent decrease to a future scenario would result in a further 13.8 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 Working Group. 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 Vermilion River watershed and improvement in indicator performance was mapped at the scale of the sub-basins 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*).

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

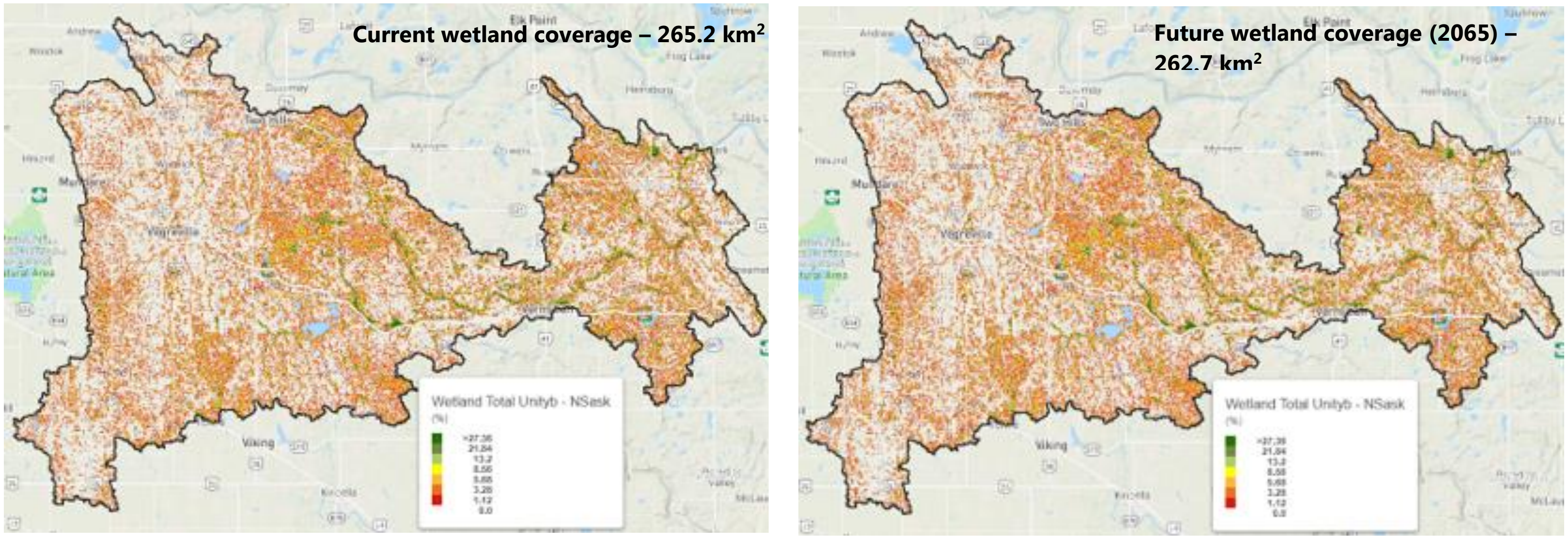

Figure 8. Current and future wetland coverage simulated using the wetland protection strategy.

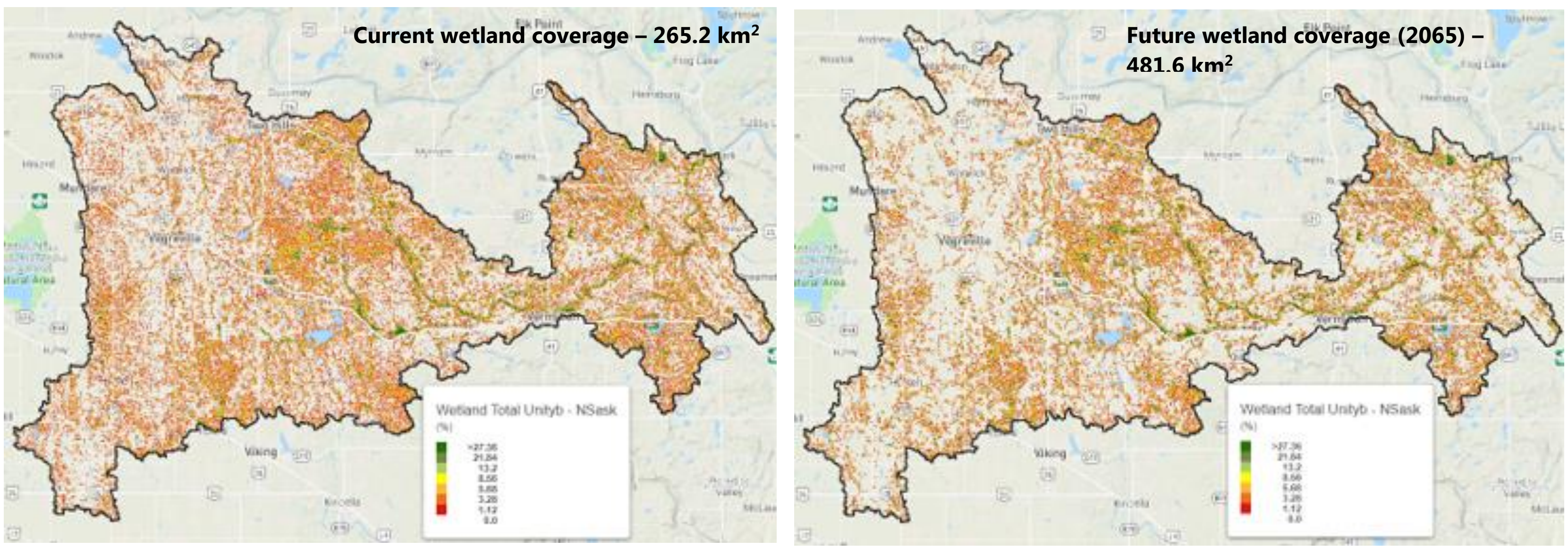

Figure 9. Current and future wetland coverage simulated using the wetland restoration strategy.

2.3.3 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 an area of 4,562 km^2 within the Vermilion River watershed, to restore this amount of crop back to grassland within five decades would require approximately 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).

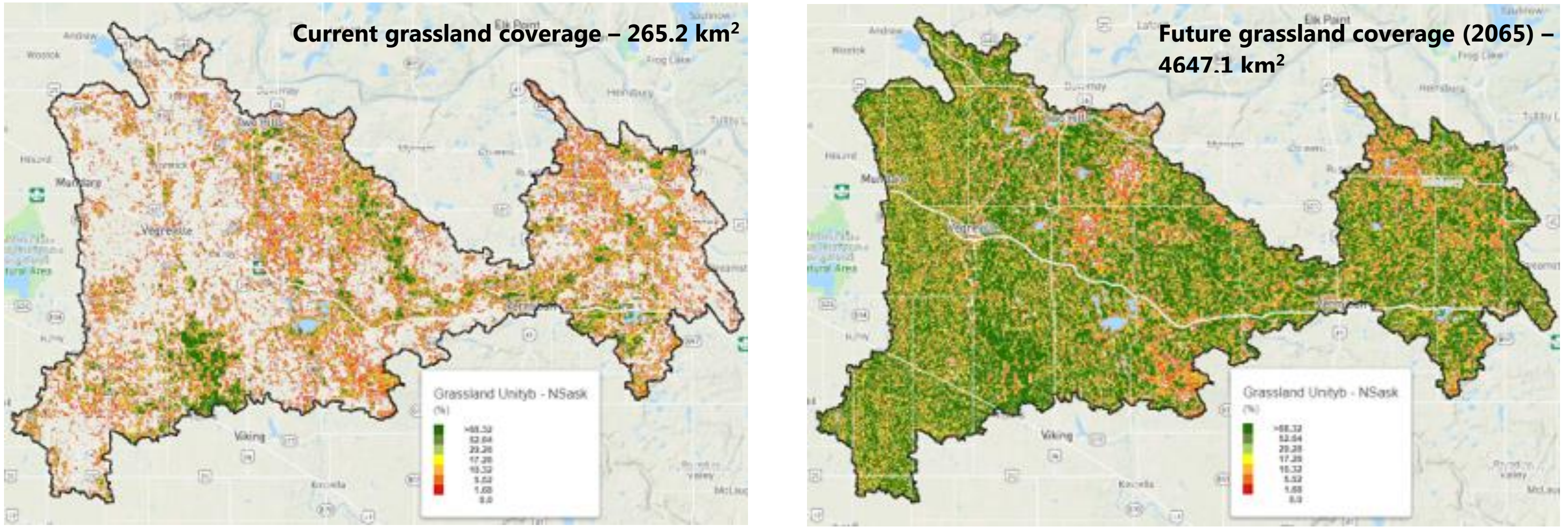

Figure 10. Current and future grassland coverage simulated using the grassland restoration strategy.

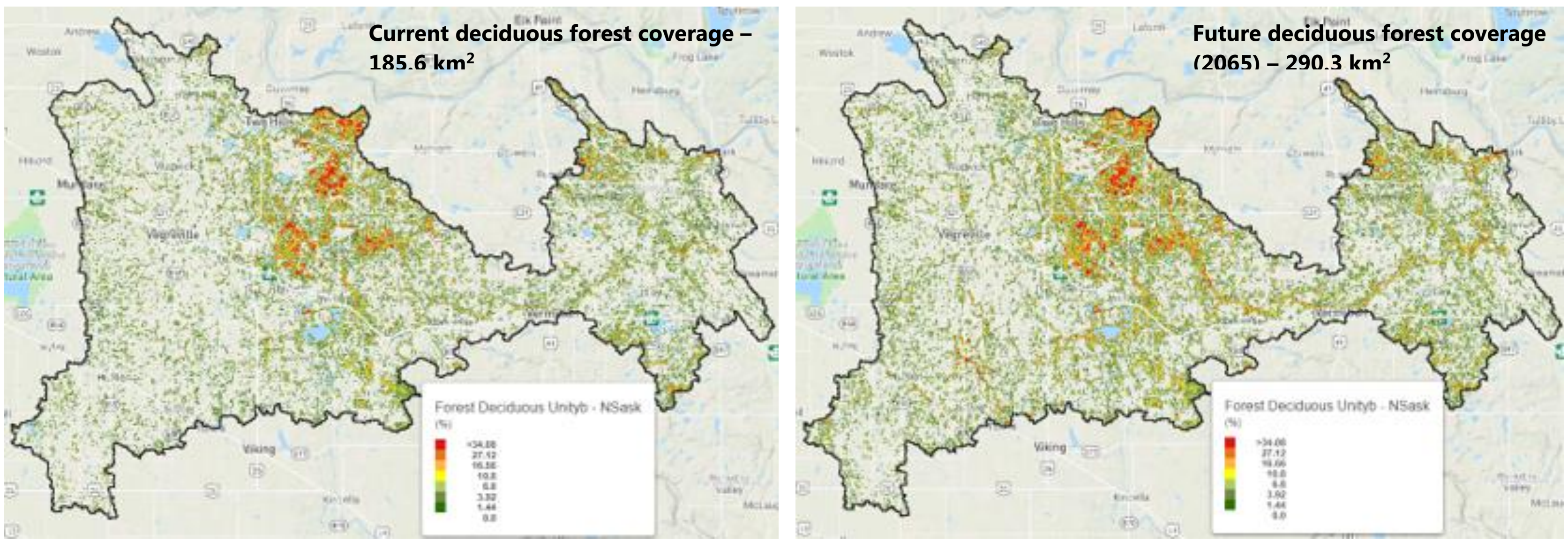

Figure 11. Current and future deciduous forest coverage simulated using the forest restoration strategy.

2.4 Evaluating effectiveness

Rather than simply showing absolute or relative values, an effectiveness index was calculated from zero to 1, where, zero indicates low effectiveness of the strategy to achieve the desired outcome for the indicator and 1 indicates high effectiveness.

This index was calculated using 1) the change in watershed resilience indicator and 2) the potential for strategy implementation. For example: A high effectiveness would be indicated by an area where change in the watershed resilience indicator is high as a function of wetland restoration, and where there has been substantial wetland loss (high potential to restore).

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 (556 km^2; Figure 12), due to the lack of wetland loss from anthropogenic footprint developments.

Similarly, there would be no cropland coverage under pre-settlement conditions, since this represents a western influence on the landscape (Figure 13).

Forest coverage would increase substantially around riparian areas and on cooler north facing slopes, yet decrease in other areas where the natural landscape is best represented by native grasslands (Figure 14). In total forest coverage increased by 278% in the pre-settlement scenario.

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

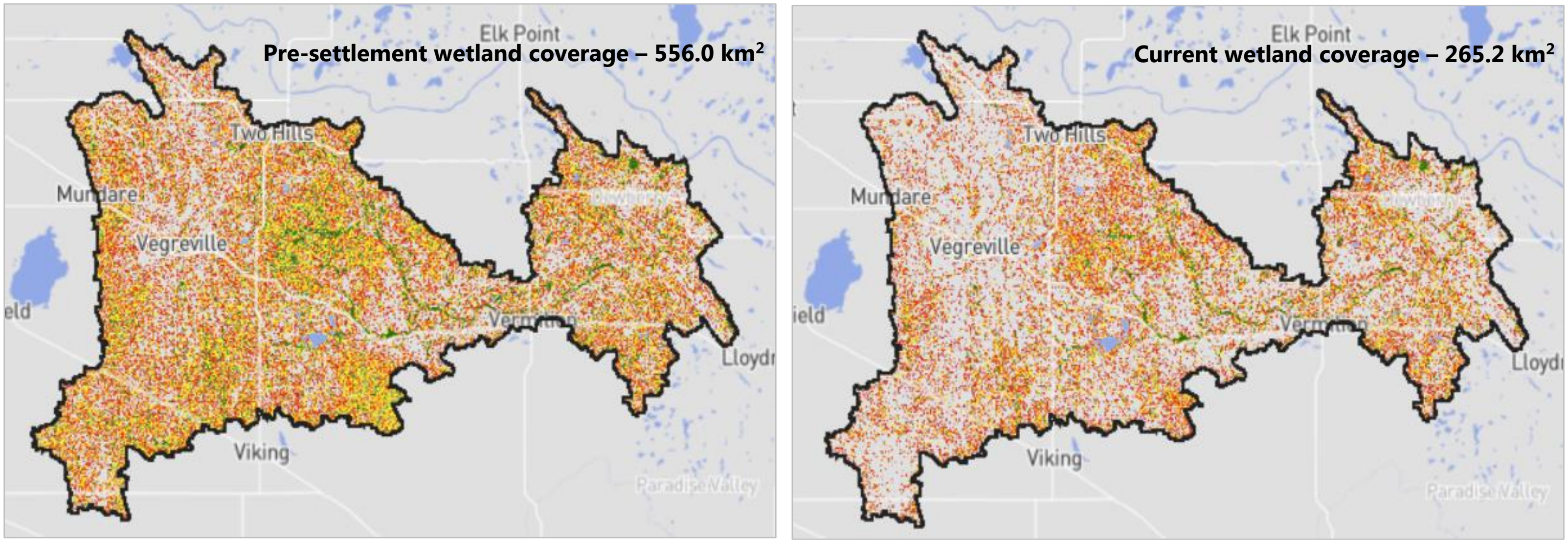

Figure 12. Pre-settlement wetland coverage relative to total current wetland coverage.

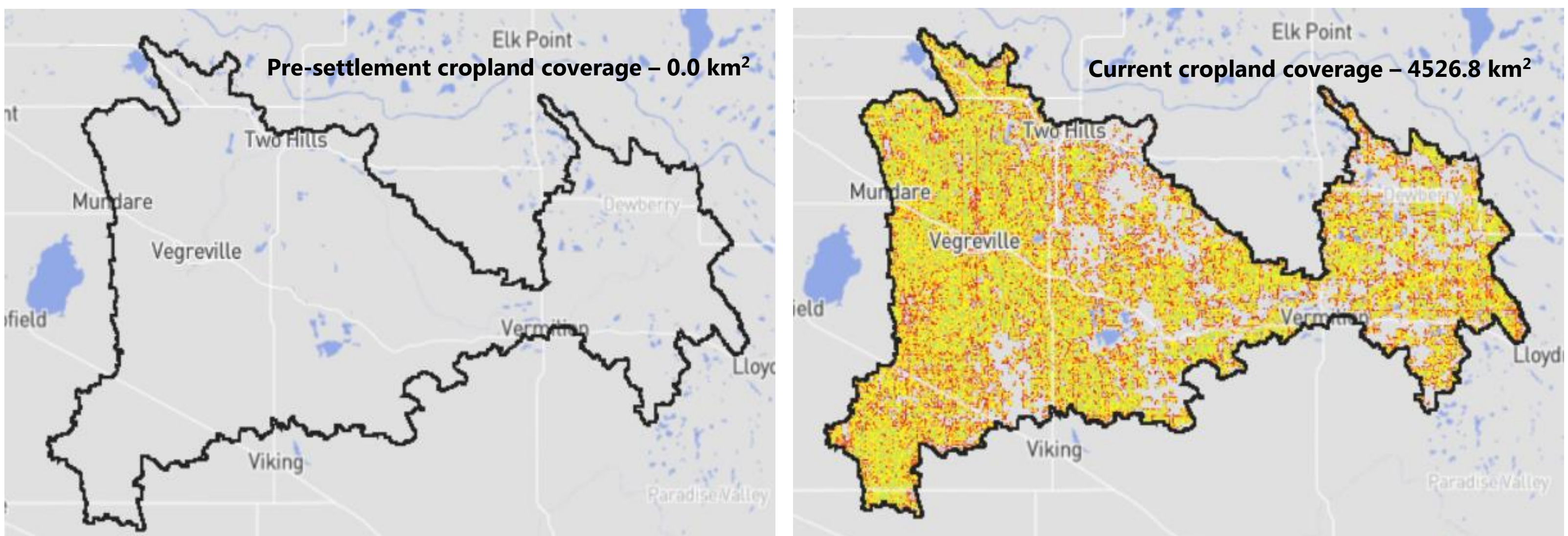

Figure 13. Pre-settlement cropland coverage relative to total current cropland coverage

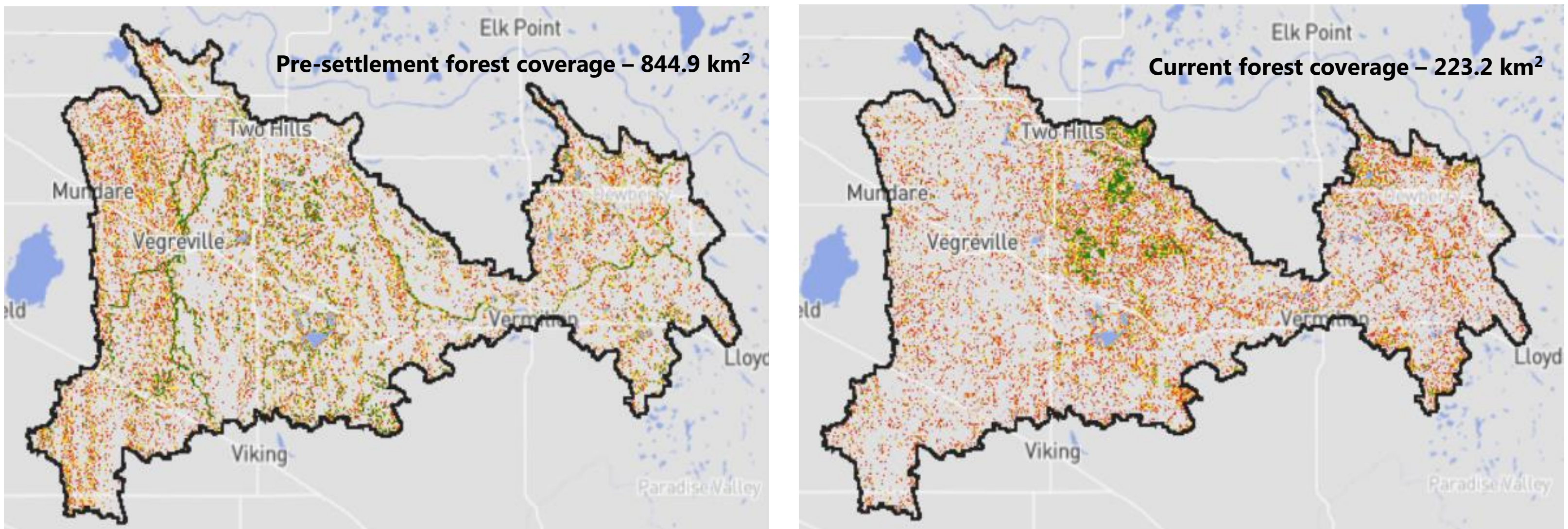

Figure 14. Pre-settlement forest coverage relative to total current forest coverage.

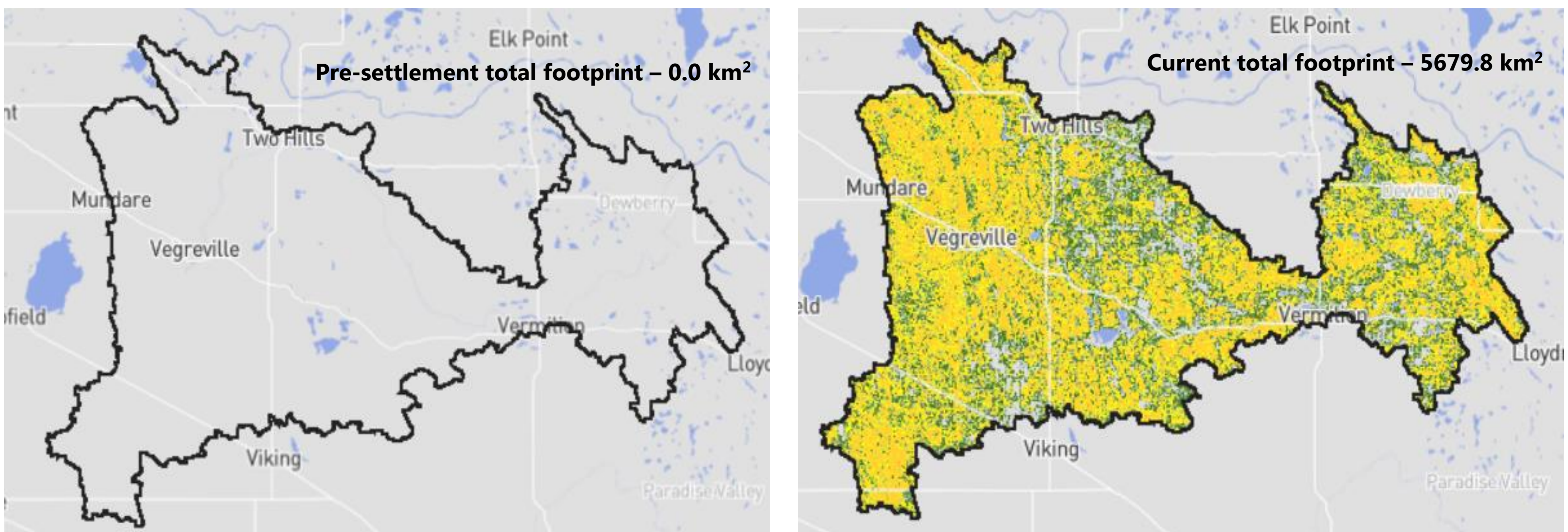

Figure 15. Pre-settlement total footprint relative to current total footprint.

3.1.2 Business-as-usual

The Business-As-Usual (BAU) future scenario saw substantial wetland loss throughout the watershed, with coverage dropping from 256.2 km^2 to 194.2 km^2 in 2065 (Figure 16). This was primarily driven by the expansion of other footprints into wetland areas.

Among other footprint expansions, wetlands were drained and converted to cropland in the BAU scenario, resulting in an increasing trend in agricultural crop coverage, from 4,526.8 km^2 to 4,561.5 km^2 (Figure 17).

Forest coverage remained relatively stable throughout the BAU scenario, only decreasing by approximately 0.9% (Figure 18). This was largely due to the exclusion of protected areas such as conservation easements from development actions.

Overall, the total human footprint in the Vermilion River watershed increased from 5,679.8 km^2 to 5,767.2 km^2, representing a 1.54% increase in coverage (Figure 19).

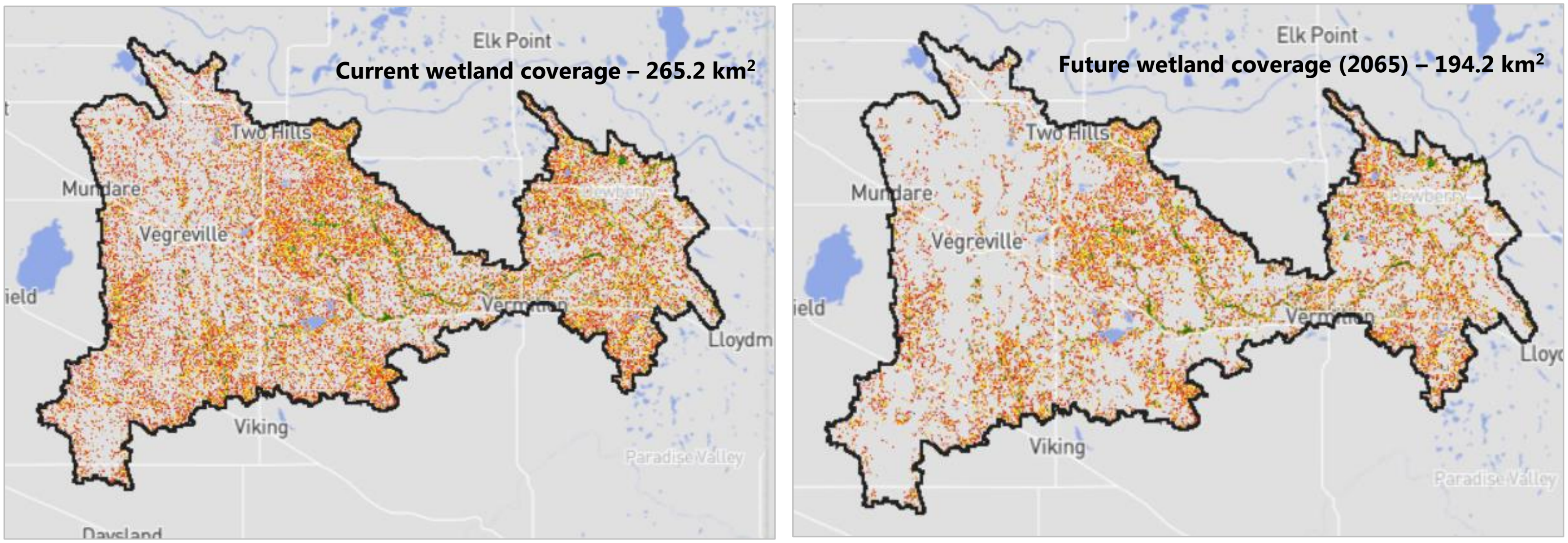

Figure 16. Total current wetland coverage relative to projected wetland coverage in 2065 under BAU.

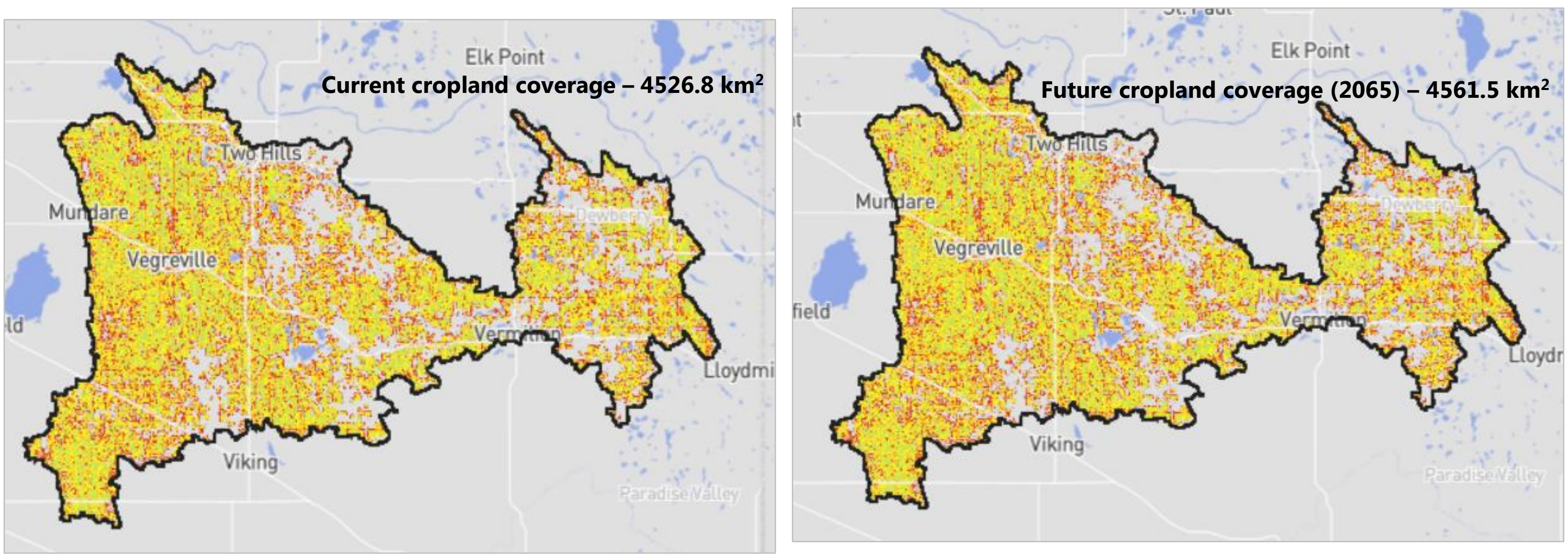

Figure 17. Total current cropland coverage relative to projected cropland coverage in 2065 under BAU.

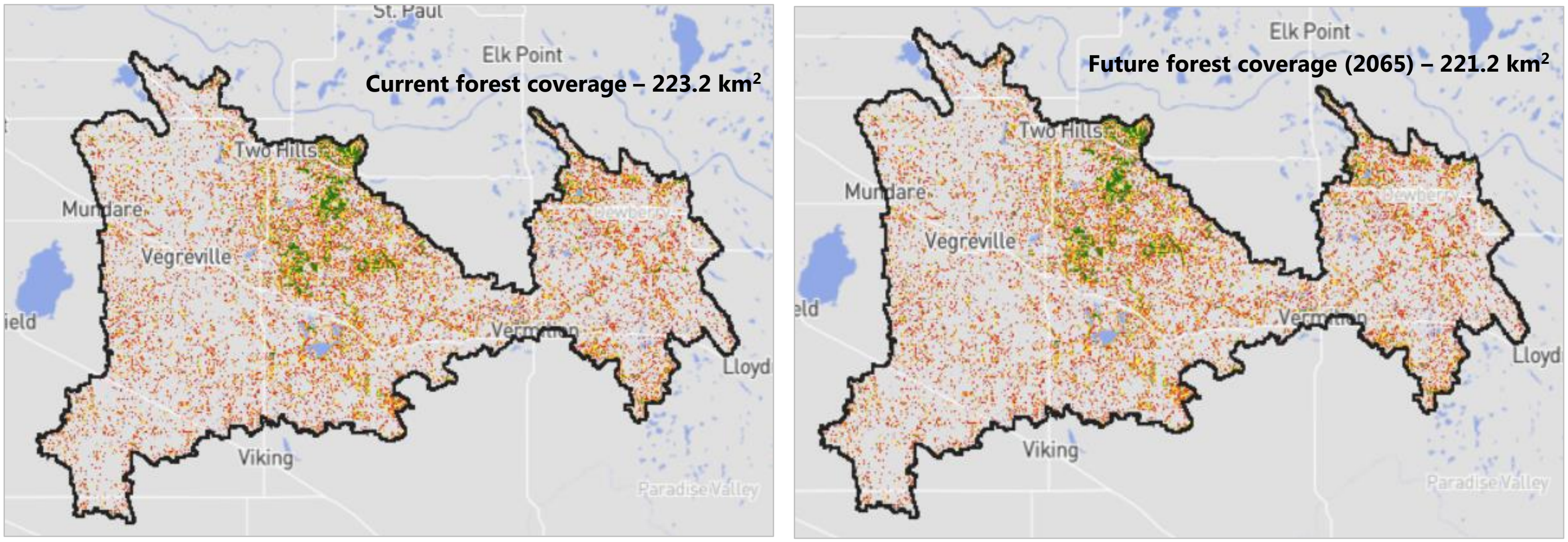

Figure 18. Total current forest coverage relative to projected total forest coverage in 2065 under BAU.

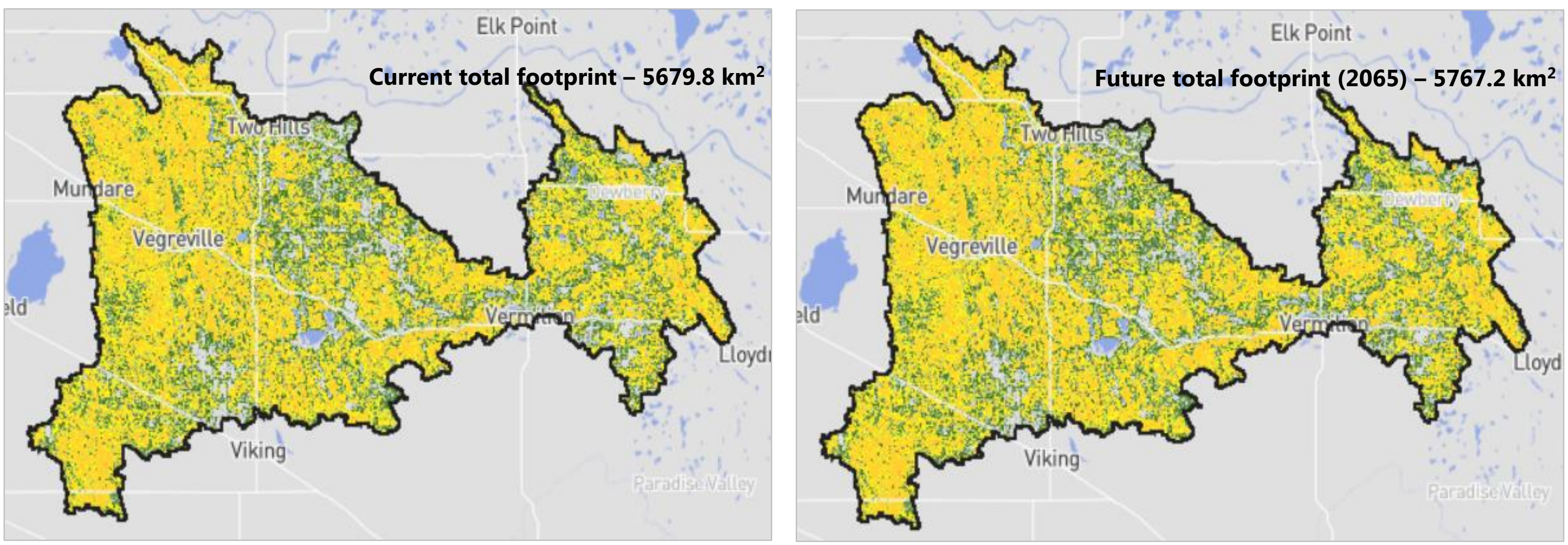

Figure 19. Total current footprint relative to projected total footprint in 2065 under BAU.

3.2 Hydrological model

3.2.1 Model Performance

3.2.1.1 Parameter Sensitivity

To better understand the parameters (Table 8) 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 8. 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

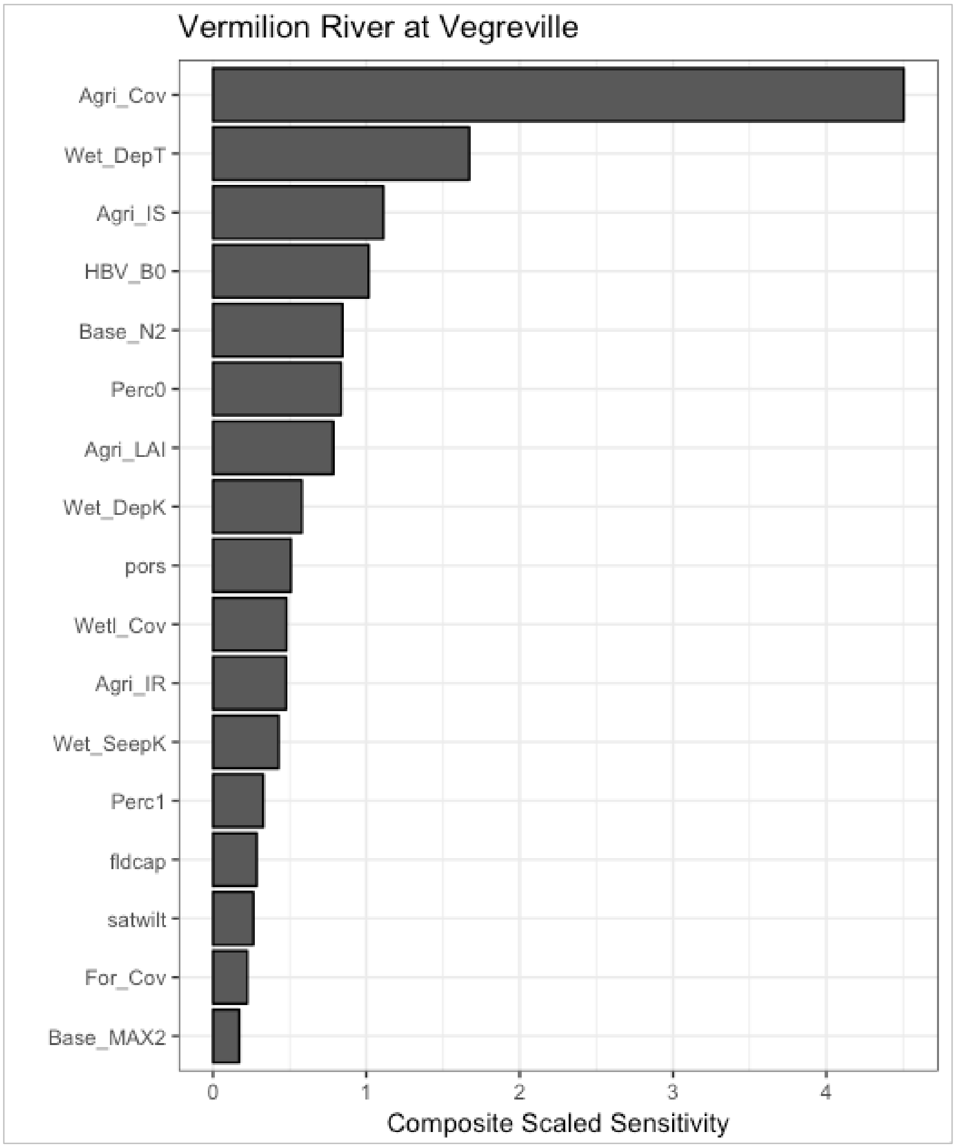

Figure 20. Parameter sensitivity for Vermilion River watershed hydrological model

3.2.1.2 Meteorology

Simulated monthly snow water equivalent (SWE) closely followed observed values from three independent verification sites throughout the study region (Figure 21). For the entire study period (1986-2015), r^2 values displayed good results for the periodic snow survey sites (0.52 – 0.63). 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. In addition, given the lack of forest cover in most of the region, wind-transport and redistribution processes are likely to play an important role, and given difficulties in emulating these phenomena, it likely leads to reduced accuracy of SWE values within the model.

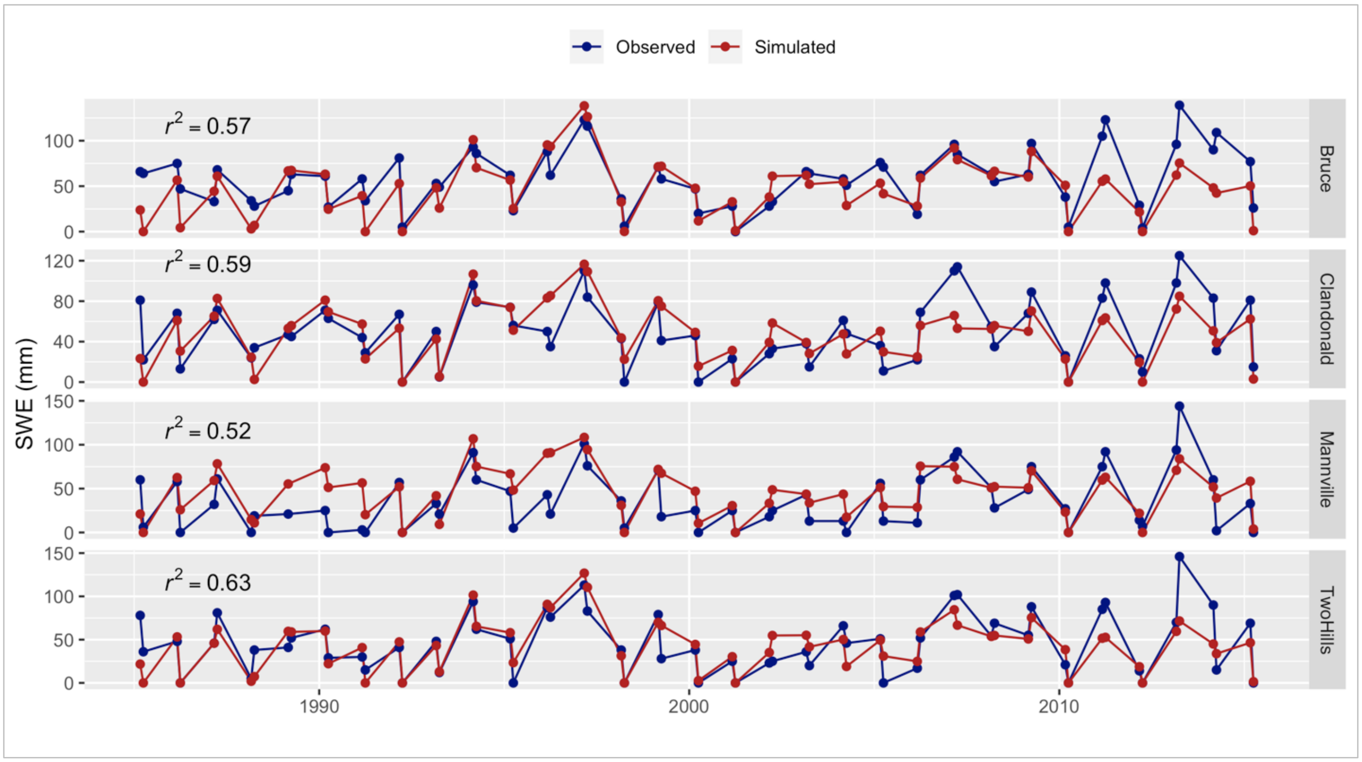

Figure 21. Simulated and observed monthly snow water equivalent (SWE) for the entire simulation period

3.2.1.3 Streamflow

The model demonstrated moderate performance, with comparable statistics over the calibration and verification period for monthly streamflow (Table 9, Figure 22). In general, streamflow showed low bias at the three hydrometric stations with long-term hydrometric records. 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 it could make up a relatively large fraction of the sub-basin area.

Table 9. Model performance statistics for the hydrological model. NSE is the Nash-Sutcliffe Efficiency and PBIAS is the percent bias

Site	Variable	NSE	PBIAS	r^2
STRETTON CREEK NEAR MARWAYNE	Monthly Streamflow	0.38	-7.7	-
VERMILION RIVER AT VEGREVILLE	Monthly Streamflow	0.51	2.8	-
VERMILION RIVER NEAR MARWAYNE	Monthly Streamflow	0.27	-6.1	-
BRUCE	Daily Snow Water Equivalent	0.39	-18.8	0.57
CLANDONALD	Daily Snow Water Equivalent	0.57	-4.3	0.59
MANNVILLE	Daily Snow Water Equivalent	0.4	27.9	0.52
TWOHILLS	Daily Snow Water Equivalent	0.62	-6.1	0.63

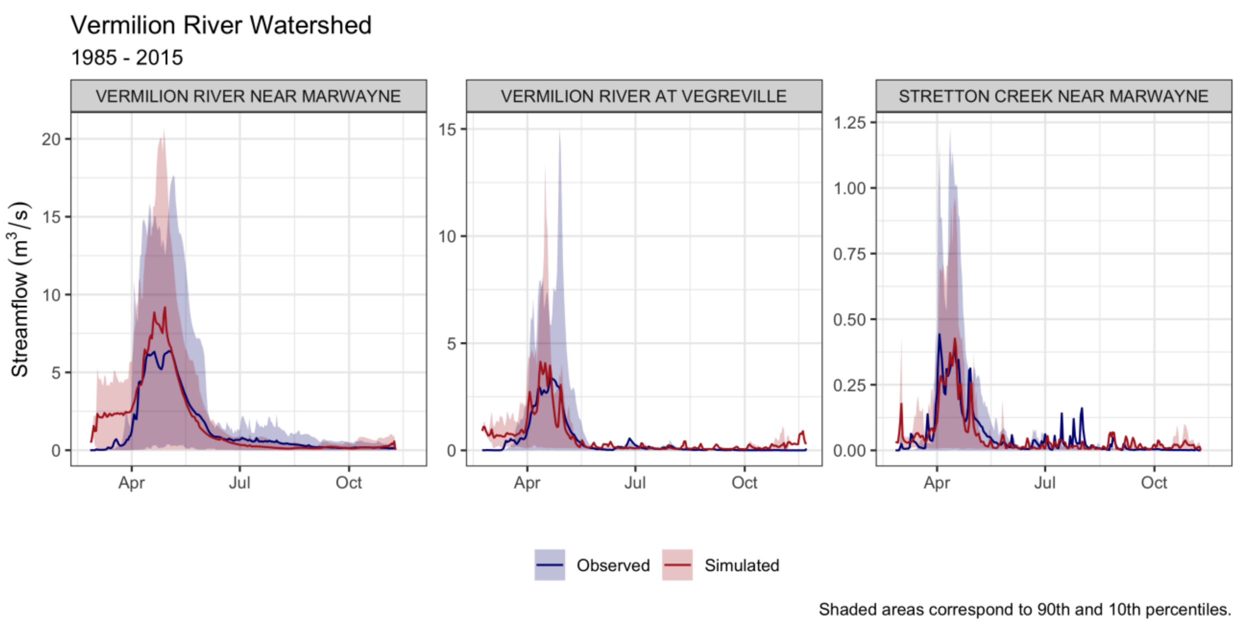

Figure 22. Observed and simulated streamflow for two hydrometric sites in the model domain. Shaded areas correspond to 10% and 90% quantiles

3.2.2 Hydrologic Findings

Water allocations for the Vermilion River watershed increased substantially since 1990 and currently amount to approximately 0.14 m^3/s during ice-free months (Figure 23). The majority of water allocations are located near Vegreville, AB, meaning they originate most likely in urban areas or nearby agricultural operations. Since 1960, there has been a strongly seasonal pattern in the data, with water allocations more than doubling during the summer months (June – October). A large 1-year spike in summer allocations occurred in the 2000 and has been traced to 'Confined Feeding Operations/Feedlots – April to June 2000'.

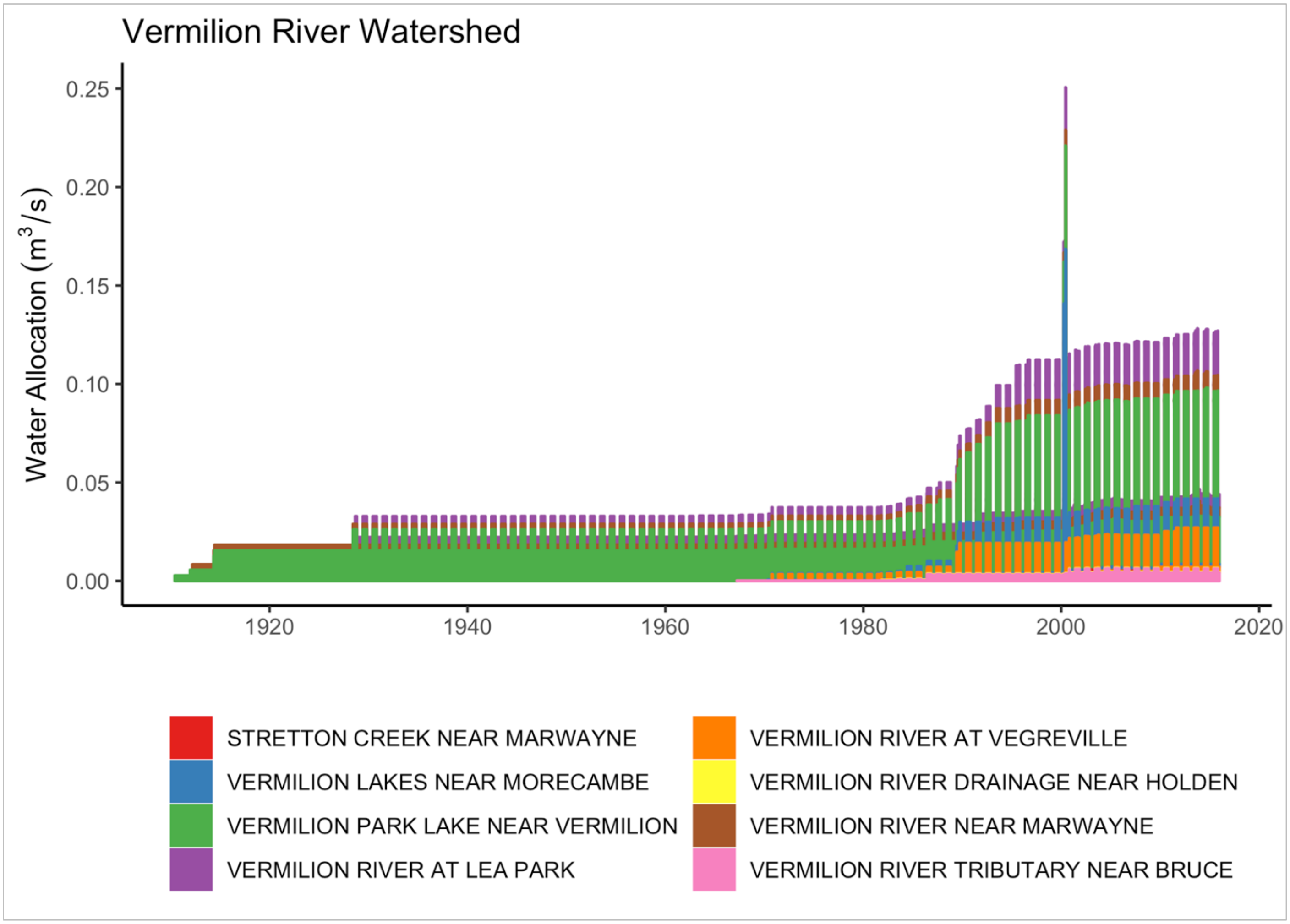

Figure 23. Water allocations in the Vermilion River watershed, separated by sub-basin

The model was able to quantitatively determine the most impactful processes controlling of the water balance for the Vermilion River watershed (Figure 24). Precipitation is relatively low in the watershed, providing approximately 393 mm per year on average, of which only 19 mm becomes snowmelt. Of the precipitation input to the watershed, 379 mm evaporates, 1 mm is removed for water use, and 1 mm is stored in deep groundwater; leaving only 9 mm to become runoff. This emphasizes that evaporation is a dominant factor driving the water balance in the watershed and that very little of the water in the watershed actually makes its way into streams and rivers. 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.

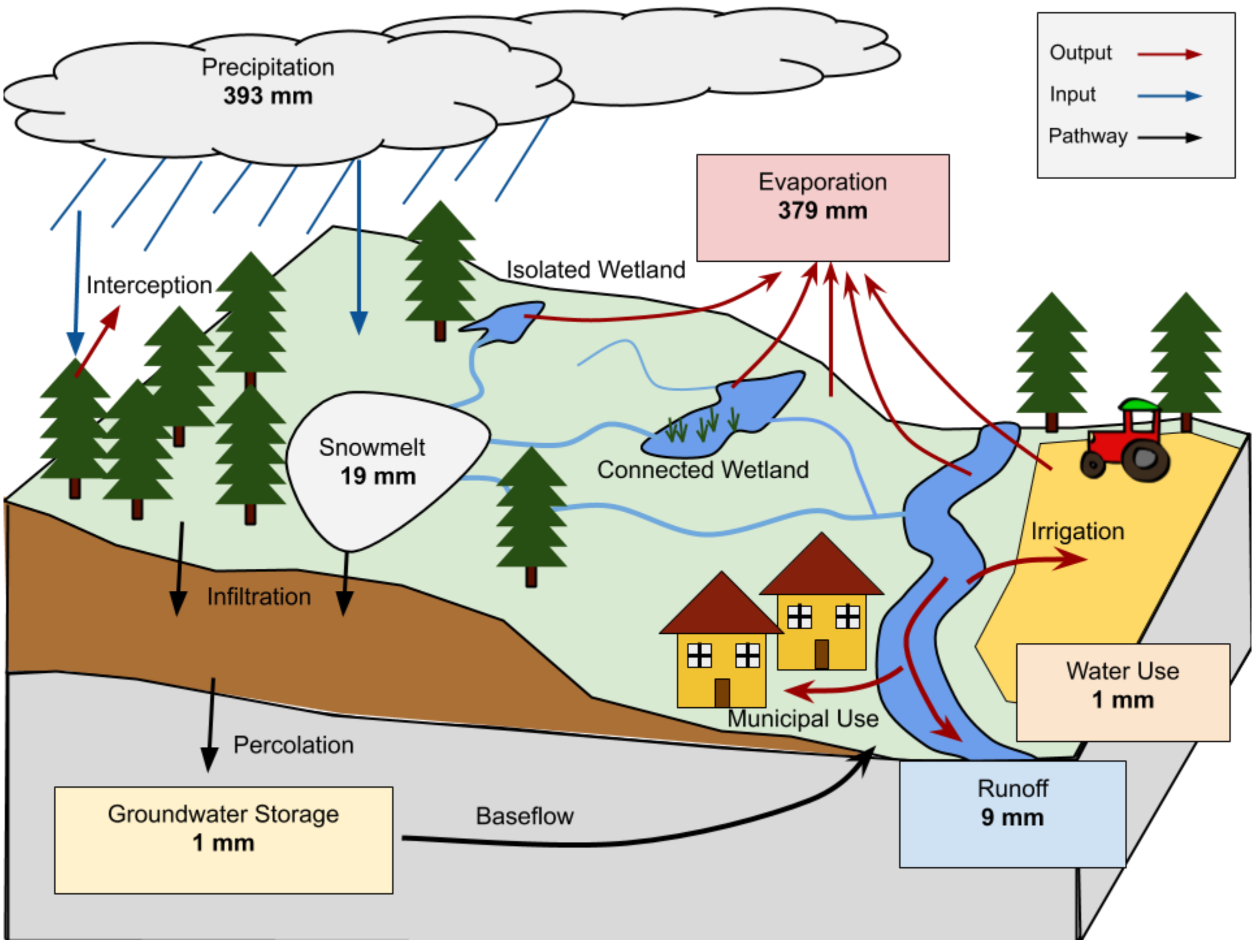

Figure 24. Full water balance for the Vermilion River watershed

Water balance results from this study were compared against values derived from a previous report (Golder, 2009) and climate normals from Alberta Environment and Parks to ensure consistency in the most important climate variables, and proper process-representation (Table 10). Higher precipitation (and therefore also evaporation) was reported in Golder 2009. However, the period of study for that report occurred earlier than this study. Conversely, this study closely follows climate normals from AEP, both in terms of precipitation and evaporation. This reinforces confidence in the model process-emulation and suggests lower precipitation over the last 15 years than during the Golder 2009 period of study.

Table 10. Comparison of water balance terms in the Vermilion River watershed to other studies

Water Balance	This Study (1985 - 2002)	This Study (1985 - 2015)	Golder 2009 (1976-2002)	Climate Normals (1981-2010)
PRECIPITATION	393 mm	393 mm	454 mm	393 mm
ACTUAL EVAPOTRANSPIRATION (AET)	379 mm	378 mm	447 mm	388 mm*
PRECIPITATION/AET	96%	96%	98%	99%
RUNOFF	9 mm	7 mm	7 mm	-

*AET obtained from Alberta Environment and Parks estimates using Horton method for a distance-weighted average of Cold Lake and Edmonton.

Soil water simulations from this model showed good agreement with observations and simulations from Pomeroy et al. (2012). Both models display similar trends in summer soil water depletion and sporadic increases following large rainfall events over four years of overlapping simulations and observed records. This provides additional confidence in model process-representation, especially given the importance of soil water processes in the Vermilion 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 are 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. No storage curves exist for either Vermilion Lakes (near Morecambe) or Vermilion Park Lake (near Vegreville); therefore, the influence of these lakes on streamflow storage and flow attenuation are estimated in the case of Vermilion Park Lake and neglected for Vermilion Lakes. In addition, human influence, particularly lake management or engineering, and lake sedimentation likely impact storage and are subject to change over time. These factors are not captured in the current model configuration, and even if they were, estimates would have such high uncertainty as to make their inclusion in the model highly unlikely to improve simulation accuracy.

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. In addition, reports of human intervention within these areas; in particular digging trenches and waterways to connect isolated (non-contributing) areas to surface water pathways; in effect rendering them connected, presents additional challenge as these areas could have variable connectivity over time. 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 Vermilion 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 Vermilion 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.

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 Vermilion River Watershed Alliance, 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 because 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 near Holden, where the timing of peak streamflow responded substantially (Figure 25 and Figure 26). This is an area with relatively little forest cover currently and substantial drainage infrastructure. Results suggest that intercepting more of the water from this area and providing shade would likely have a large effect on how fast water runs off during high runoff periods. Overall, these results suggest that forest restoration can have desired effects on watershed processes, resulting in a more regulated streamflow regime; however, this effect is modest at the scale of the overall watershed.

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 eastern portion of the watershed showed the greatest effect in terms of reducing the frequency of low flow events and the low flow index. Whereas the timing of low flow events was mostly affected in the west and central portions of the watershed (Figure 25 and Figure 26).

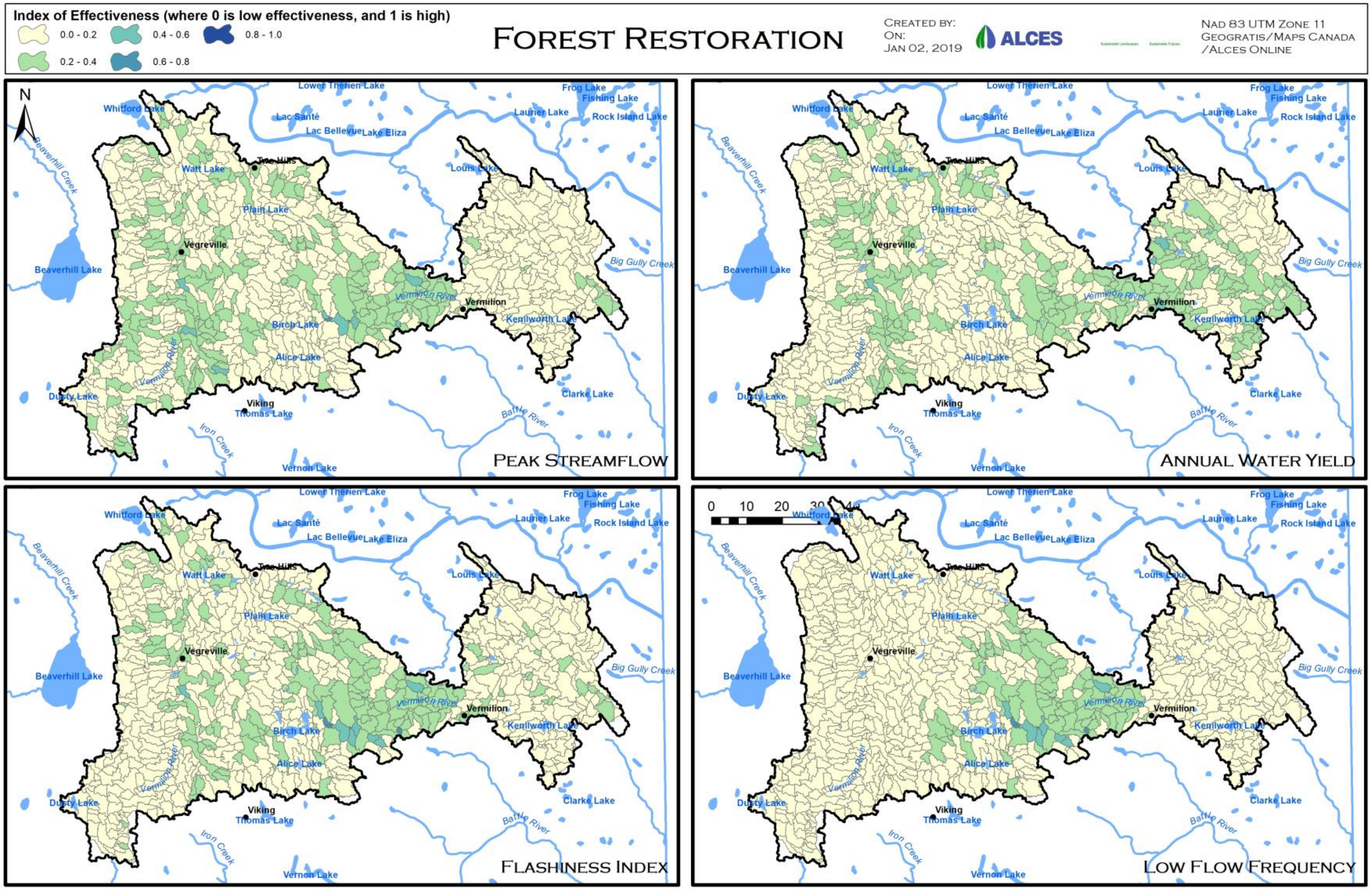

Figure 25. Response of peak streamflow, annual water yield, flashiness index, and low flow frequency to the forest restoration strategy.

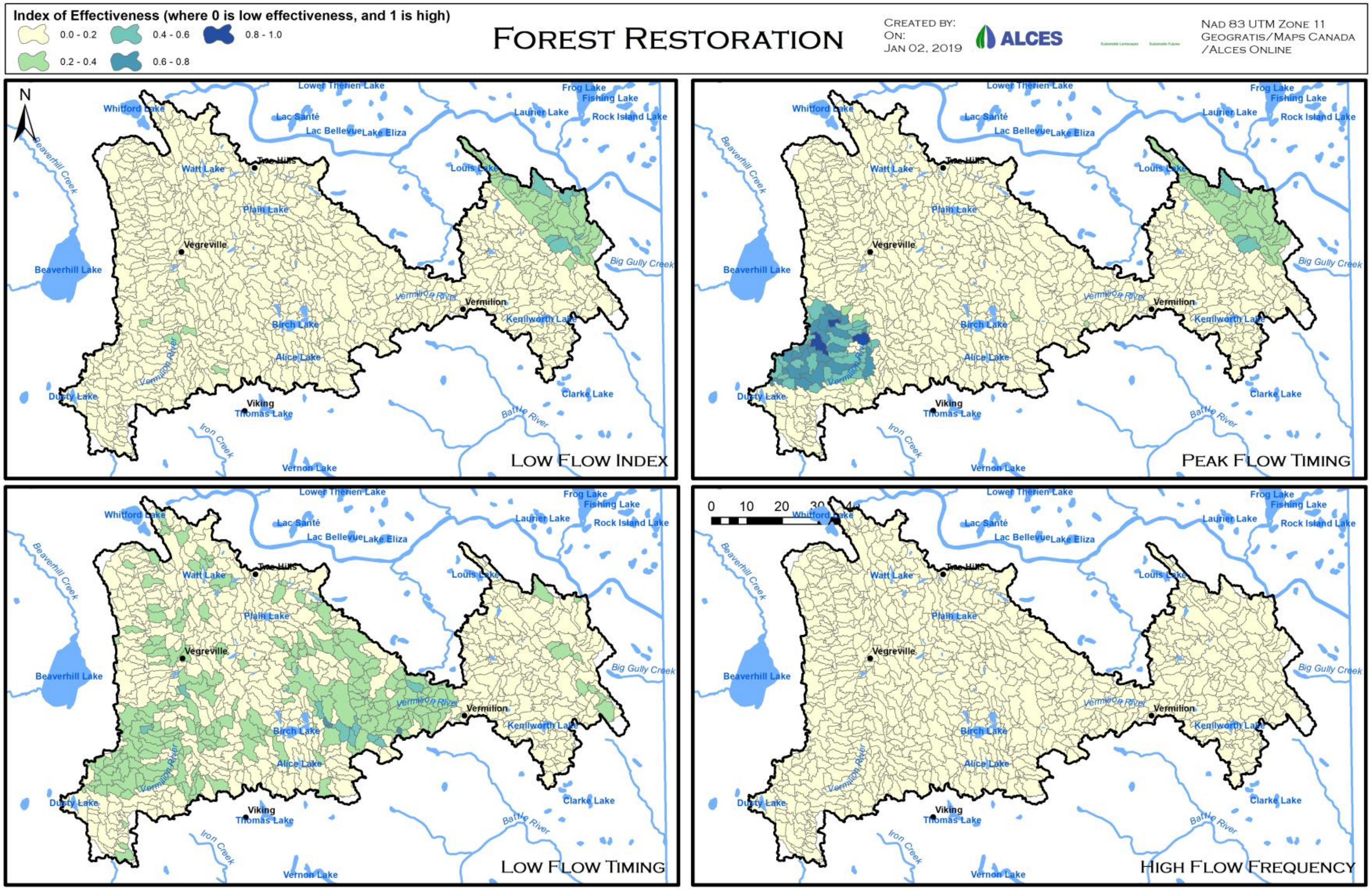

Figure 26. Response of high flow frequency, peak flow timing, low flow index, and low flow timing to the forest restoration strategy.

3.3.2 Grassland restoration

Grassland restoration had the greatest effect on annual water yield in the western and eastern portions of the Vermilion River watershed. Reductions in peak streamflow and flashiness were obtained for several sub-basins in the western portion of the watershed (Figure 27). These effects were, however, modest. Changes in the timing of peak flow were also mostly noticed along the central and western portions of the watershed (Figure 28).

Low flow indicator effects were similarly distributed, with the largest effects again occurring in the eastern and western portions of the watershed (Figure 28). These are areas that likely had more opportunity for and therefore a more noticeable desired response to grassland restoration.

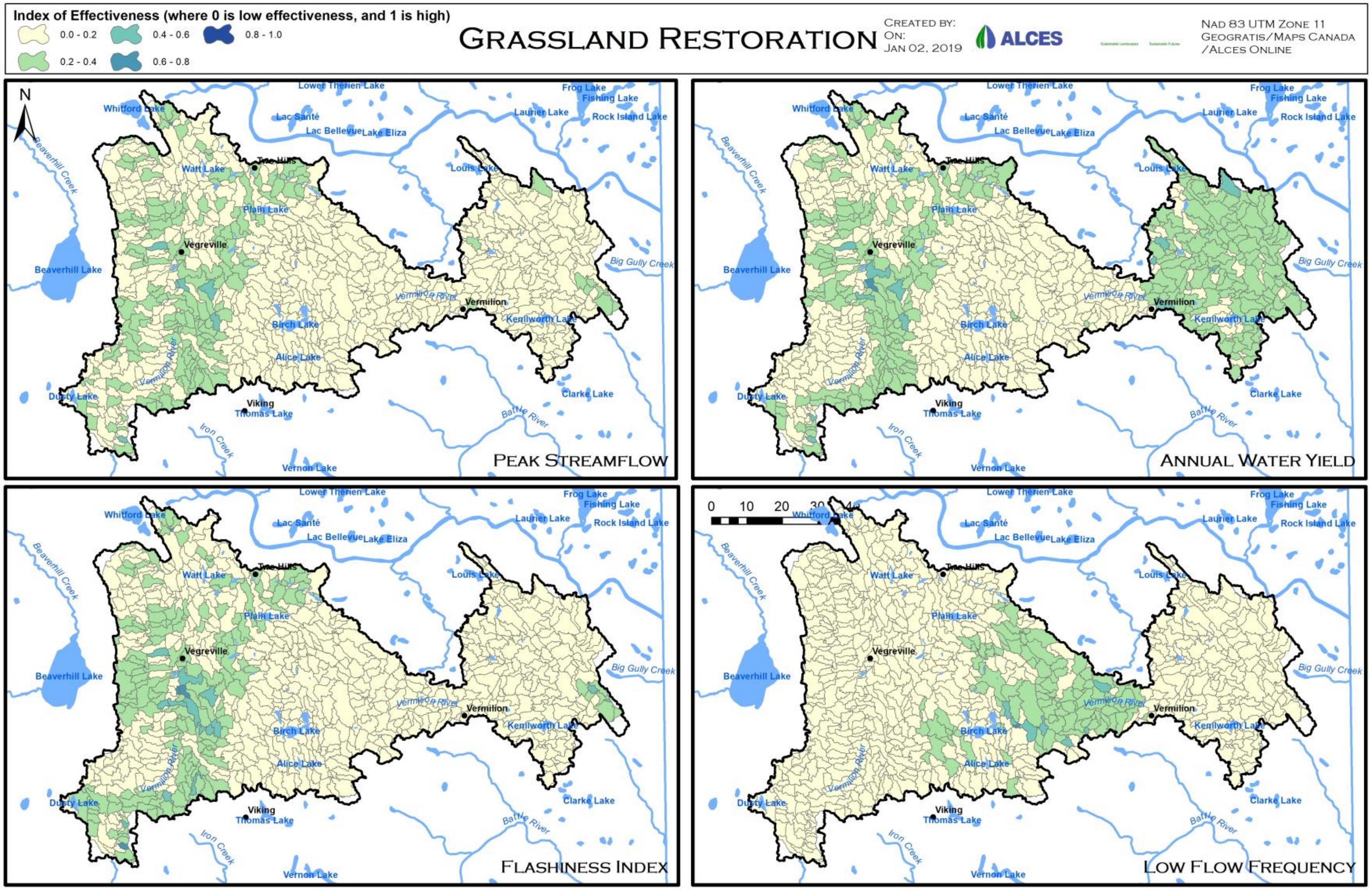

Figure 27. Response of peak streamflow, annual water yield, flashiness index, and low flow frequency to the grassland restoration strategy.

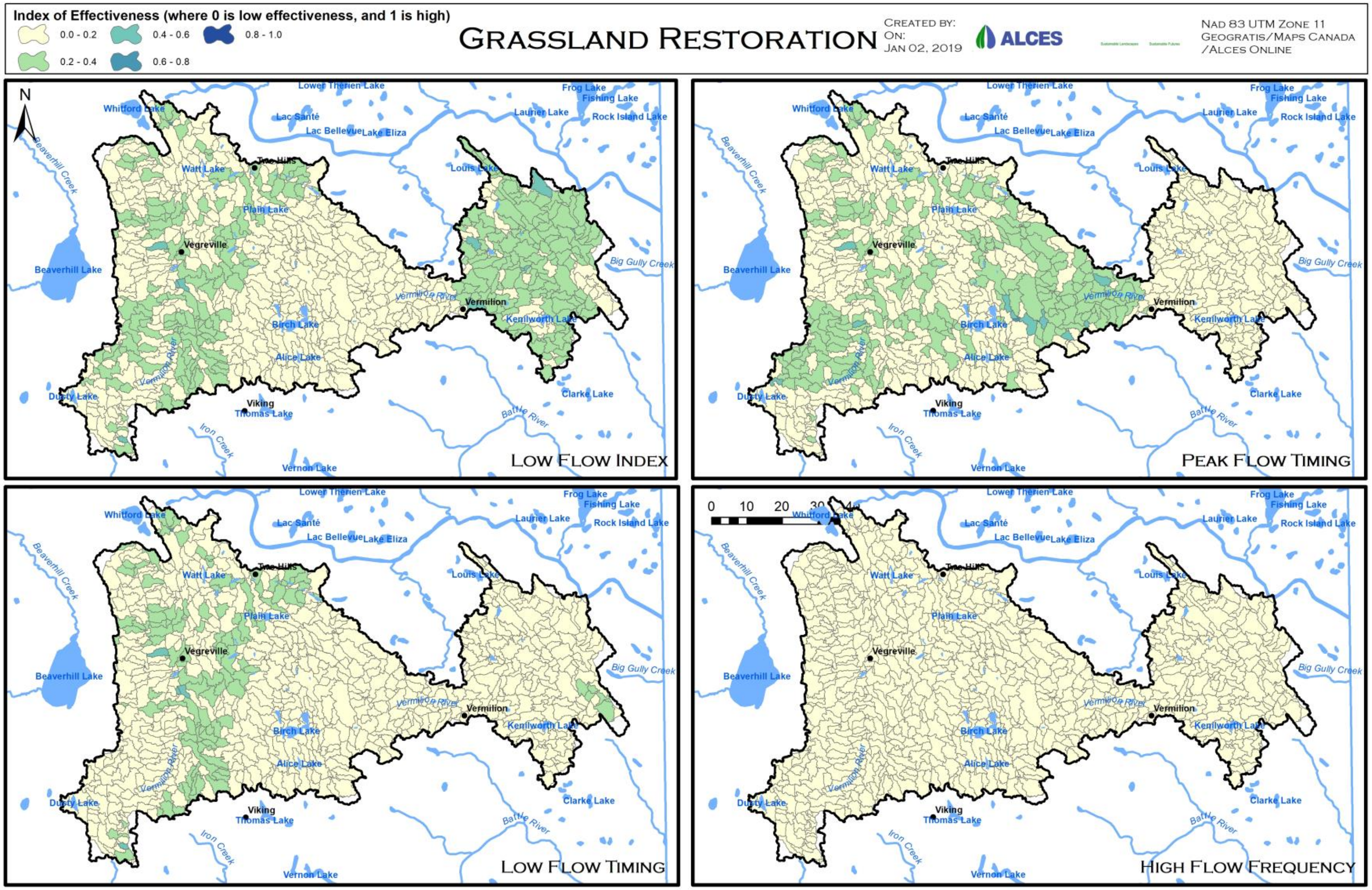

Figure 28. Response of high flow frequency, peak flow timing, low flow index, and low flow timing to the grassland restoration strategy.

3.3.3 Wetland protection

Wetland protection was an effective strategy for reducing peak streamflow timing in the northwest portion of the watershed (Figure 29). This implies that wetlands in this portion of the watershed are serving a hydrologic role in terms of damping streamflow response to runoff events. Wetlands are playing a small role in providing reliable water yields in the east and west portions of the watershed. Low flow indicators were marginally affected by this strategy as well, with the greatest effects noticed in low flow timing (Figure 30).

The fact that wetland protection did not result in large hydrologic change suggests the wetland loss that has occurred does not differ substantially 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.

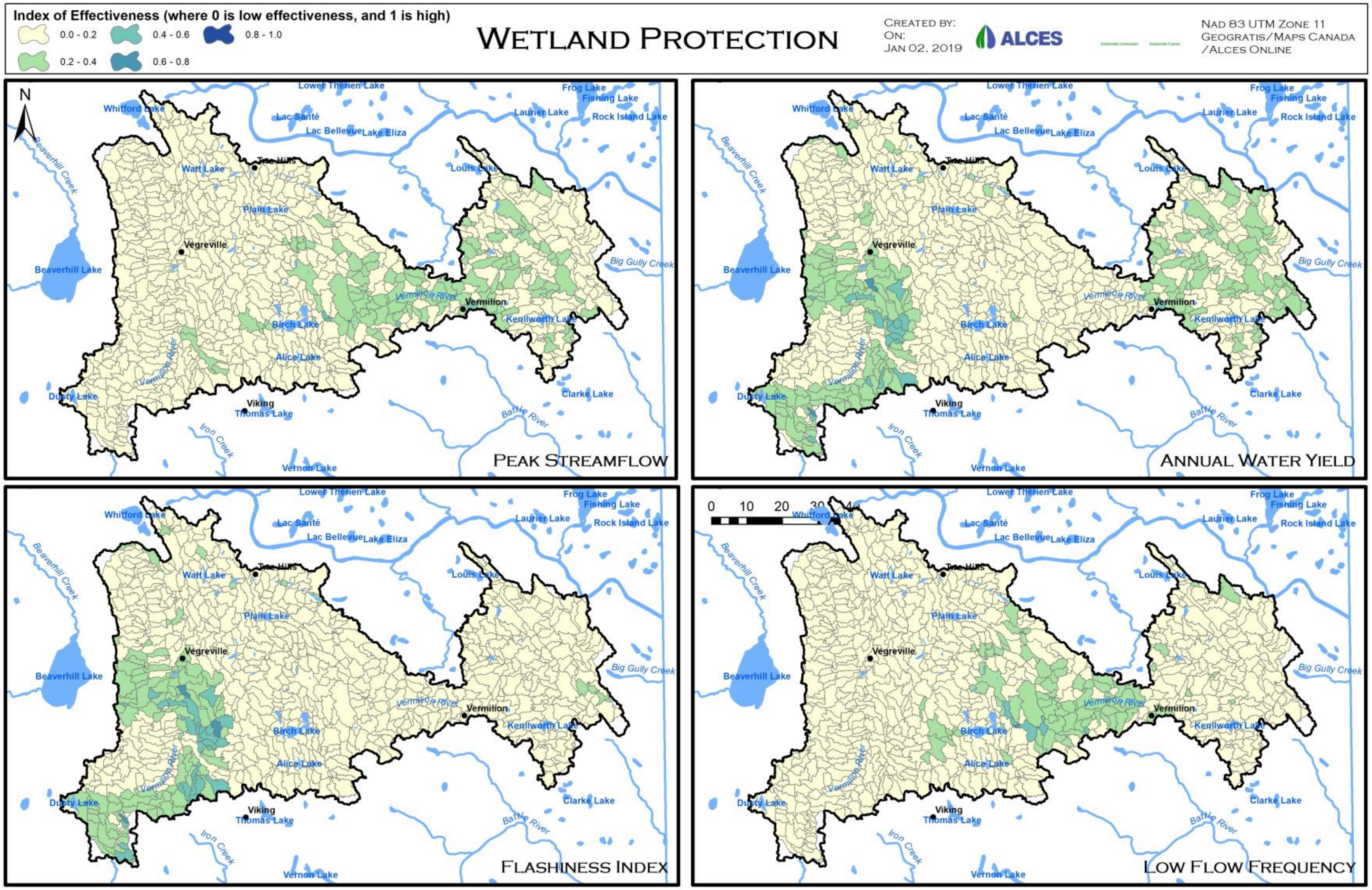

Figure 29. Response of peak streamflow, annual water yield, flashiness index, and low flow frequency to the wetland protection strategy

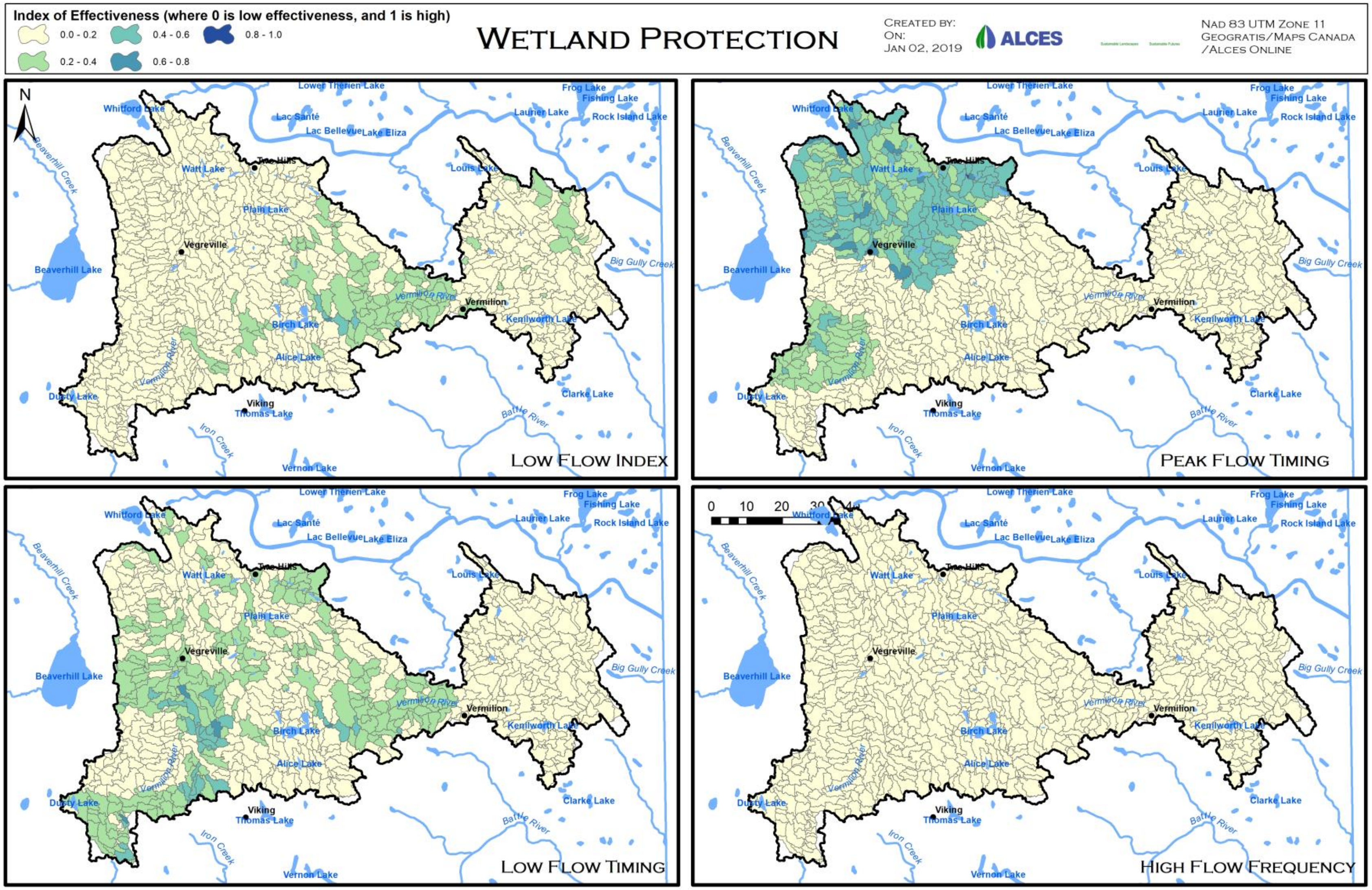

Figure 30. Response of high flow frequency, peak flow timing, low flow index, and low flow timing to the wetland protection strategy

3.3.4 Wetland restoration

Wetland restoration was by far the most effective strategy for altering peak and low streamflow, providing annual water supply, reducing flashiness, and ensuring reliable timing of peak flow (Figure 31 and Figure 32). This suggests that wetland loss throughout the Vermilion River watershed has been substantial and the hydrologic role of those wetlands is high. The greatest effects were simulated to occur in the headwaters for most indicators, suggesting there is high potential for restoration in these sub-basins. Importantly, sub-basins with substantial drainage infrastructure were shown to have the highest potential for hydrologic change, suggesting again that restoring wetlands in these areas could have a desired effect on watershed resilience

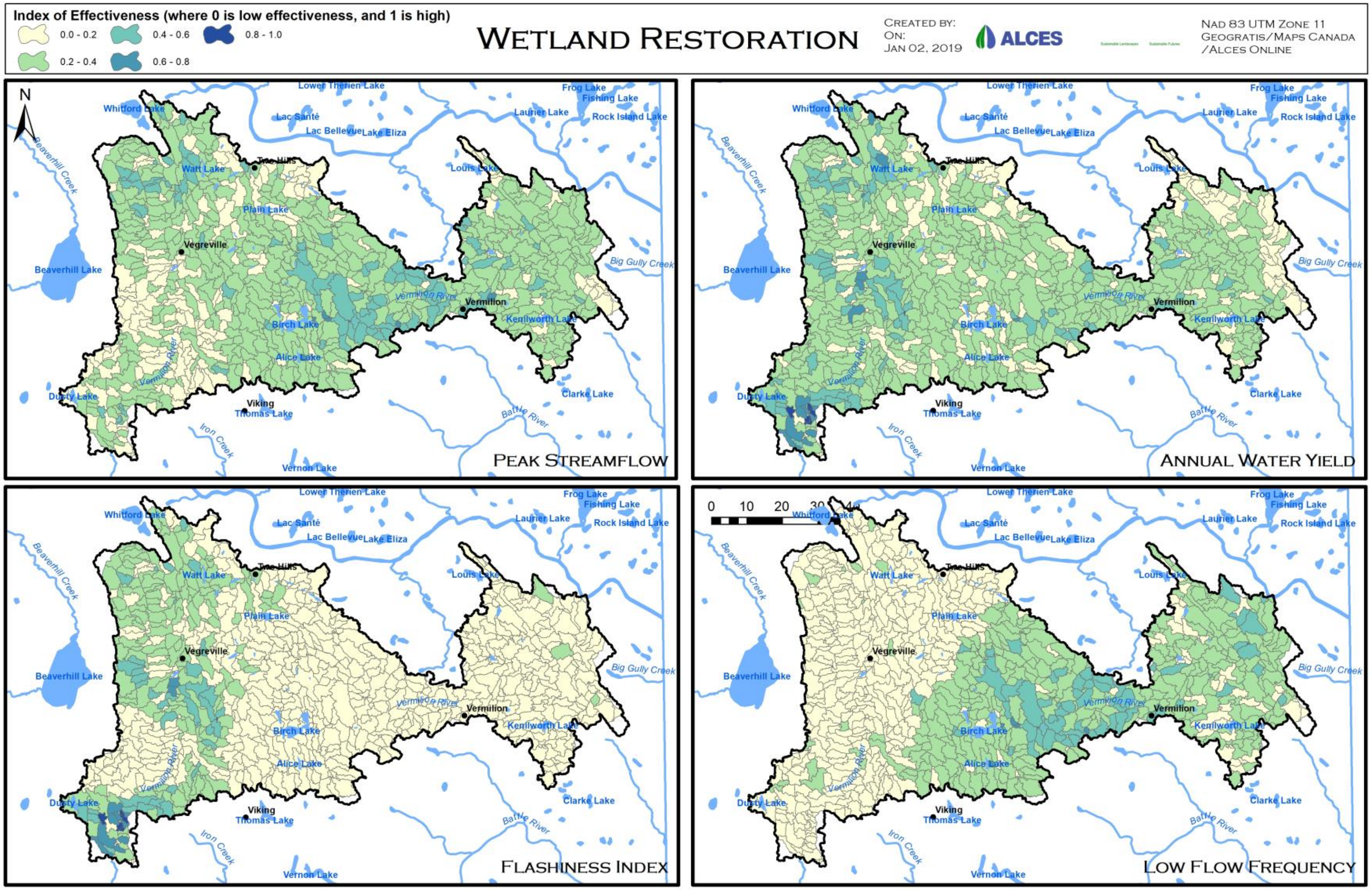

Figure 31. Response of peak streamflow, annual water yield, flashiness index, and low flow frequency to the wetland restoration strategy

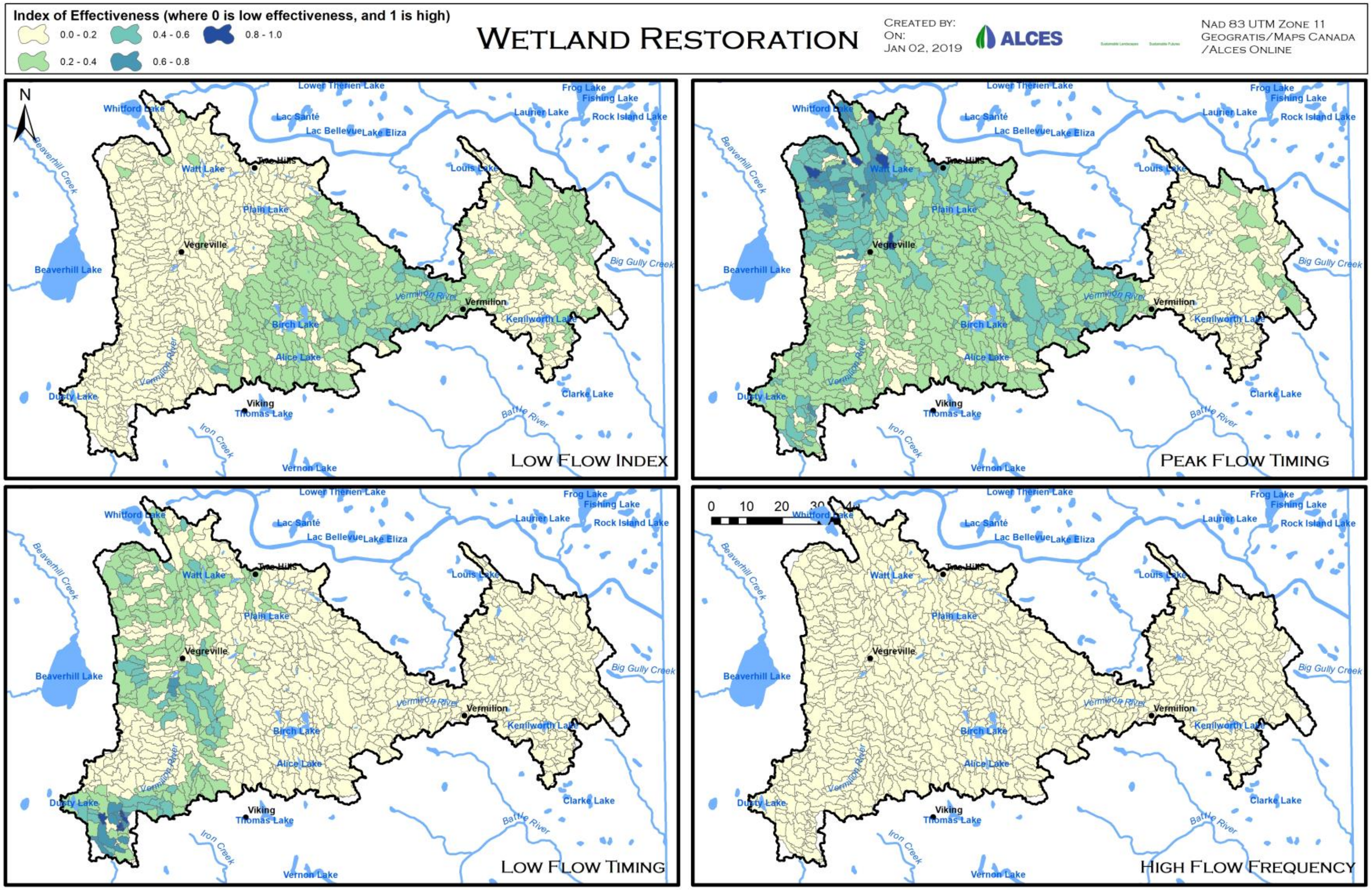

Figure 32. Response of high flow frequency, peak flow timing, low flow index, and low flow timing to the wetland restoration strategy

4 Conclusions and Recommendations

This study has assessed the potential benefits of implementing various conservation and restoration strategies in the Vermilion River watershed. This was achieved using a coupled hydrologic-land use 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 if desired. In addition, a publicly-available web-based application is being developed to demonstrate results in a user-friendly manner.

This study suggests that it is not likely that the landscape will dramatically change as a result of human development under a "Business-As-Usual" future growth scenario. This is important as there are opportunities to improve watershed function. The model that has been developed can be used to target these locations for these types of opportunities, while detailed fieldwork at targeted locations can determine how best to implement these opportunities.

Implementing conservation and restoration strategies is a substantial challenge, particularly given that current land use activities often offer economic benefit. Therefore, a strategic approach to determining where and when conservation and restoration activities can be implemented is required. In addition, it is important to evaluate the full range of costs and benefits associated with conservation and restoration. 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 fish and wildlife habitat, recreation, economic value, and others to further develop a strategic plan for implementation.

Overall, this work suggests conservation has some potential; however, limited. Restoration is a much more substantial challenge but has more potential in terms of affecting hydrologic function. The restoration strategy that would result in the greatest improvement relative to hydrology is wetland restoration. This is consistent with our understanding of wetland functions in this landscape. Grassland and forest restoration also show promise but are likely to provide more local benefits.

It is recommended that this work be carried forward in consideration of the VRWMP, as this is ultimately an initial step in long-term conservation and restoration planning in the Vermillion 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 VRWA (in partnership with the NSWA) 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 determine whether or not conservation and restoration activities in particular locations are feasible.
- Ongoing engagement and outreach be conducted with stakeholders and potential funders, enabling buy-in to implementation over the long-term.

5 Literature cited

AAFC (Agriculture and Agri-Food Canada). 2015. Land Use 1990, 2000 & 2010. Retrieved from: https://open.canada.ca/data/en/dataset/18e3ef1a-497c-40c6-8326-aac1a34a0dec (accessed 02.04.2017).

ABMI (Alberta Biodiversity Monitoring Institute). 2010a. Wall-to-wall Land Cover Inventory. Retrieved from: https://abmi.ca/home/data-analytics/da-top/da-product-overview/GIS-Land-Surface/Land-Cover.html?scroll=true (accessed 29.03.2019)

ABMI (Alberta Biodiversity Monitoring Institute). 2010b. Wall-to-Wall Human Footprint Inventory. Retrieved from: https://abmi.ca/home/data-analytics/da-top/da-product-overview/GIS-Land-Surface/HF-inventory.html?scroll=true (accessed 29.03.2019)

Alberta Climate Information Service. 2018. Interpolated Weather Data Since 1961 for Alberta Townships. Obtained January 2, 2018 from http://agriculture.alberta.ca/acis/township-data-viewer.jsp

ALCES Group. 2014. ALCES Online Scenario Analysis Methods. Retrieved from: https://www.online.alces.ca/static/pdfs/modeling_methods.pdf (accessed 19.06.2019)

ALCES Landscape & Land-Use Ltd. 2016. Alberta dataset. Accessed December, 2017.

Alberta Energy Regulator (AER). 2018. Report Data. Retrieved from: https://www.aer.ca/providing-information/data-and-reports/statistical-reports/report-data (accessed 07.06.2018)

Alberta Environment and Parks. 2016. Grassland Vegetation Inventory (GVI). Retrieved from: https://geodiscover.alberta.ca/geoportal/catalog/search/resource/fullMetadata.page?uuid=%7BD3AB9031-8EC0-4589-9335-C1E50AE05992%7D (accessed 29.03.2019)

AltaLIS. 2018. Hydrography. Retreieved from: https://www.altalis.com/map;id=116 (accessed 29.03.2019)

Associated Engineering Ltd. 2004. Big Lake Stormwater Management Plan. 366 pp.

Baker, D., Richards, R.P., Loftus, T.T., & Kramer, J.W. 2004. A new flashiness index: characteristics and applications to Midwestern rivers and streams. Journal of the American Water Resources Association 40(2) 503-522.

Canadian Hydraulics Centre. 2010. Green Kenue Reference Manual. National Research Council. 340 pp.

Carlson, M., Stelfox, B., Purves-Smith, N., Straker, J., Berryman, S., Barker, T. and Wilson, B. 2014. ALCES Online: Web-delivered Scenario Analysis to Inform Sustainable Land-use Decisions.

International Environmental Modelling and Software Society (iEMSs) 7th Intl. Congress on Env. Modelling and Software.

Carpenter, S., Walker, B., Anderies, J.M. & Abel, N. 2001. From Metaphor to Measurement: Resilience of What to What? Ecosystems (2001) 4: 765–781 DOI: 10.1007/s10021-001-0045-9.

Chernos, M., MacDonald, R.J., & Craig, J. 2017. Efficient semi-distributed hydrological modelling workflow for simulating streamflow and characterizing hydrologic processes. Confluence Journal of Watershed Science and Management. (in press)

City of Spruce Grove. 2010. Your Bright Future: Municipal Development Plan 2010-2020. Retrieved from: http://www.capitalregionboard.ab.ca/images/Documents/SharedFiles/REF/REF2010-012/BylawC-711-09-MDP.pdf (accessed 07.06.2018)

City of St. Albert. 2017. Municipal Development Plan Bylaw 15/2007 Consolidated by Bylaw 8/2017. Retrieved from: https://stalbert.ca/uploads/PDF-reports/Complete-MDP.pdf (accessed 07.06.2018)

Craig, J.R., Huang, S., Khedr, A., Pearson, S., Spraakman, S., Stonebridge, G., Werstuck, C., & Zhang, C. 2016. Raven: User's and Developer's Manual. Raven Version 2.1.

Edwards, W.A.D. and Budney, H.D. 2009. Alberta Sand and Gravel Deposits with Aggregate Potential. Retrieved from: http://ags.aer.ca/publications/DIG_2004_0034.html (access 13.06.2018).

Golder 2009. Vermilion River Water Supply and Demand Study. Prepared for the NSWA. 103 pp.

Gunderson, L.H. 2000. Ecological Resilience – In Theory and Application. Annu. Rev. Ecol. Syst. 2000. 31:425–39

Hill, M. 1998. Methods and guidelines for effective model calibration. Denver, CO.

Hofierka, J., Suri, M. 2002. The solar radiation model for Open source GIS: implementation and applications. International GRASS users conference in Trento, Italy, September 2002.

Jost, G., Moore, R. D., Menounos, B., & Wheate, R. 2012. Quantifying the contribution of glacier runoff to streamflow in the upper Columbia River Basin, Canada. Hydrology and Earth System Sciences, 16(3), 849-860.

Matott, L. S. 2005. OSTRICH: An Optimization Software Tool; Documentation and User's Guide. Version 1.8, http://www.civil.uwaterloo.ca/lsmatott/Ostrich/OstrichMain.html.

Matott, L. S. and Rabideau, A. J. 2008. Calibration of complex subsurface reaction models using a surrogate-model approach. Advances in water resources, 31(12):1697–1707.

Mossop, G.D. and Shetsen, I., comp. 1994. Geological atlas of the Western Canada Sedimentary Basin; Canadian Society of Petroleum Geologists and Alberta Research Council, URL <http://ags.aer.ca/reports/atlas-of-the-western-canada-sedimentary-basin.htm>, [13.06.2018].

North Saskatchewan Watershed Alliance (NSWA). 2016. Isle Lake and Lac Ste Anne Water Balance Assessment. Prepared by S. Figliuzzi and Associates, Ltd., Edmonton, AB., for the North Saskatchewan Watershed Alliance, Edmonton, AB. Available on the internet at: http://www.nswa.ab.ca/resources/nswa_publications.

Natural Resources Canada (NRCAN). 1995. National Topographic Database, 1:50 000, Ottawa: Natural Resources Canada, Geomatics Canada, 1995. Accessed December, 2018.

Poff, N.L., & Ward, J. V. 1989. Implications of streamflow variability and predictability for lotic community structure: A regional analysis of streamflow patterns. Canadian Journal of Fisheries and Aquatic Sciences, (46) 1805-1817.

Pomeroy, J., Fang, X., Westbrook, C., Minke, A., Guo, X., and Brown, T. 2010. Prairie Hydrological Model Study Final Report. Centre for Hydrology Report No. 7. 113 pp.

Pomeroy, J., Fang, X., Shook, K., Westbrook, C., and Brown T. 2012. Informing the Vermilion River Watershed Plan through Application of the Cold Regions Hydrological Model Platform. Centre for Hydrology Report No. 12. 155 pp.

Rokosh, C.D., Lyster, S., Anderson, S.D.A., Beaton, A.P., Berhane, H., Brazzoni, T., Chen, D., Cheng, Y., Mack, T., Pana, C. and Pawlowicz, J.G. 2012. Summary of Alberta's shale- and siltstone-hosted hydrocarbon resource potential; Energy Resources Conservation Board, ERCB/AGS Open File Report 2012-06, 327 pp.

Shook, K., Pomeroy, J., Spence, C., Boychuck, L. 2013. Storage dynamics simulations in prairie wetland hydrology models: evaluation and parameterization. Hydrological Processes. DOI: 10.1002/hyp.9867.

Stahl, K., Moore, R. D., Shea, J. M., Hutchinson, D., & Cannon, A. J. 2008. Coupled modelling of glacier and streamflow response to future climate scenarios. Water Resources Research, 44(2).

Town of Vermilion. 2011. Municipal Development Plan. Retrieved from: http://vermilion.ca/municipal-development-plan/ (accessed 07.06.2018)

Town of Morinville. 2017. Municipal Development Plan: Bylaw 11/2012 as amended by Bylaw 9/2017. Retrieved from: https://www.morinville.ca/government/governance/bylaws/280-municipal-development-plan-bylaw-11-2012/file (accessed on 07.06.2018)

Town of Bon Accord. 2016. Integrated Municipal Development and Sustainability Plan: Bylaw 2016-08. Retrieved from: http://www.bonaccord.ca/assets/2016-08-town-of-bon-accord-municipal-development-plan-5july2017_jd.pdf (accessed 07.06.2018)

Town of Entwistle. 2013. Entwistle Area Structure Plan Bylaw No. 23-2012. Last Consolidation July 2013. Retrieved from: https://www.parklandcounty.com/en/do-business/resources/planning/Entwistle-ASP-FINAL-Consolidation-2013.pdf [22.10.2018]