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Bow River BASIN Council

Watershed Simulation Tool – Methods and Outcomes for the Bow River Basin

Prepared For

Bow River Basin Watershed Simulation Project – Working Group members

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1 Introduction

1.1 A Planning Tool for the WRRP

The Watershed Resiliency and Restoration Program (WRRP) Bow River Basin Watershed Simulation Project (Watershed Simulation Project) was a collaborative between the Bow River Basin Council (BRBC), the ALCES Group, and Alberta WaterSMART. The BRBC was the project lead responsible for stakeholder engagement; with modelling and technical support from the ALCES Group. Alberta WaterSMART provided expertise in workshop facilitation for the purpose of enhancing stakeholder engagement. Ultimately, the goal of the project was to provide the BRBC and its membership with analytical tool for assessing watershed conservation and restoration strategies in the context of the cumulative effects of historical, present, and expected future land use and climate change.

The Watershed Simulation Project was designed to demonstrate reduction of environmental and socioeconomic risk obtainable through conservation and restoration strategies aimed at building resilience. This work highlights the value of investing in programs to develop watershed resilience. The project had a strong scientific basis and focused on building quantitative relationships and scenario analysis capacity, aiding the BRBC in identifying strategic priorities for building resilience in the Bow River Basin.

The project consisted of three phases. Stakeholder engagement was initiated in Phase 1, with a Working Group meeting on January 12, 2016, and attracted participants from numerous stakeholder groups representing various perspectives in the basin (see Appendix A). The first Working Group meeting focused on a working definition of watershed resilience specific to this project, determining indicators of resilience to be used in Phase 2 modelling work, and potential conservation and restoration strategies to be tested in the model. The second Working Group meeting focused on providing a final list of indicators to be used in the project and a final list of conservation and restoration strategies for the basin, and to determine the most suitable scenario for future land use to be used in this project for evaluating the strategies that are implemented. Results from this phase are provided in a separate report (WaterSMART, 2016).

Phase 2 of the project focused on analytical work to simulate hydrologic processes as well as a range of restoration, conservation, and climate scenarios for the Bow River Basin. This phase had two primary objectives:

1) Derive quantitative relationships between restoration/conservation strategies and indicators of hydrologic change in the Bow River Basin

2) Develop a web-based tool for assessing the long-term consequences of watershed restoration and conservation in the Bow River Basin. The tool was a customized version of ALCES Online that provides the BRBC with a powerful analytical tool for identifying restoration and conservation priorities.

Phase 3 of the project focused on providing a clear set of opportunities to improve watershed resiliency as well as the dissemination of project learnings to the BRBC, WRRP, and public. This report outlines the key findings from this Phase 2 and Phase 3.

1.2 The Bow River Basin

The Bow River Basin encompasses an area of approximately 26,200 km^2 from alpine headwaters in the Canadian Rocky Mountains to the prairies of south eastern Alberta. The Bow River's initial water source is Bow Glacier, which is part of the Wapta Icefield, and is located along the Continental Divide in Banff National Park, Alberta. The river then flows south to Lake Louise, and then turns east to the towns of Banff and Canmore and the eastern slopes of the Rocky Mountains. East of Canmore, AB, the Bow River meets the Kananaskis River, which joins from the south, and flows eastward out of the mountains. Upstream of Cochrane, AB, the Bow River reaches the Ghost Lake Reservoir and the Ghost River. The river then flows east to the city of Calgary, AB, where it meets the Elbow River. East of Calgary, the Bow River flows through prairie and agricultural lands, past a series of weirs and Bassano Dam. The river continues eastward until it reaches its confluence with the Oldman River, and becomes the South Saskatchewan River (Figure 1).

The climate of the Bow River Basin shows considerable east-west variability and reflects the diverse character of regions within the basin. At Lake Louise, AB (ID 3053760, Environment Canada, 2017), air temperatures are cold, averaging -12.0 °C in January and 12.6 °C in July. Air temperatures increase further east in the basin, and at lower elevations, especially during the summer months. At Calgary International Airport (ID 3031093), January air temperatures average -7.3 °C and July averages 16.5 °C, while at Medicine Hat (ID 3034480), January air temperatures average -8.3 °C and July averages 20.0 °C. There is a significant east-west precipitation gradient within in the basin. Average annual precipitation at Lake Louise is 543 mm, of which approximately half falls as snow. At Calgary, average annual precipitation is 418 mm, of which approximately a quarter falls as snow. Medicine Hat only receives 322 mm of precipitation annually, of which approximately a quarter falls as snow.

The Bow River Basin has a history of hydroelectric development that dates back at least 100 years. In 1911, construction of Horseshoe Dam, a run-of-the-river hydro-electric plant, was completed along the main stem of the Bow River, at Seebe, AB. In 1912, a reservoir was created at Lake Minnewanka, adjacent to Banff townsite, by diverting water out of the upper Ghost River and Cascade River. In 1913, a dam and reservoir were constructed along the Kananaskis River. Significant developments since then include the Ghost Reservoir (1929) and Bearspaw Dam (1954), which were designed to control water level fluctuations along the Bow River, and the Spray River (1952) facilities, which were designed for power generation.

In addition to hydro-electric and flood-control demands on the river, the Bow River Basin also sustains three Irrigation Districts and a growing urban population. The Bassano Dam, west of Brooks, AB, opened in 1914, and diverts water out of the Bow River into the Eastern Irrigation District. The Calgary Weir supplies the Western Irrigation District, while the Bow River Irrigation District diverts water out of the Bow River at the Carseland Weir. Finally, drinking water for much of the southern

portion of the city of Calgary is obtained from the Glenmore Reservoir, which is created by a dam on the Elbow River, upstream of its confluence with the Bow River.

This geographic, climatic, and water management setting renders the Bow River Basin one of the diverse river basins in the Province of Alberta. With well over a million residents reliant on sustainable water supply accompanied by important aquatic and terrestrial ecosystems, maintaining watershed resilience is paramount.

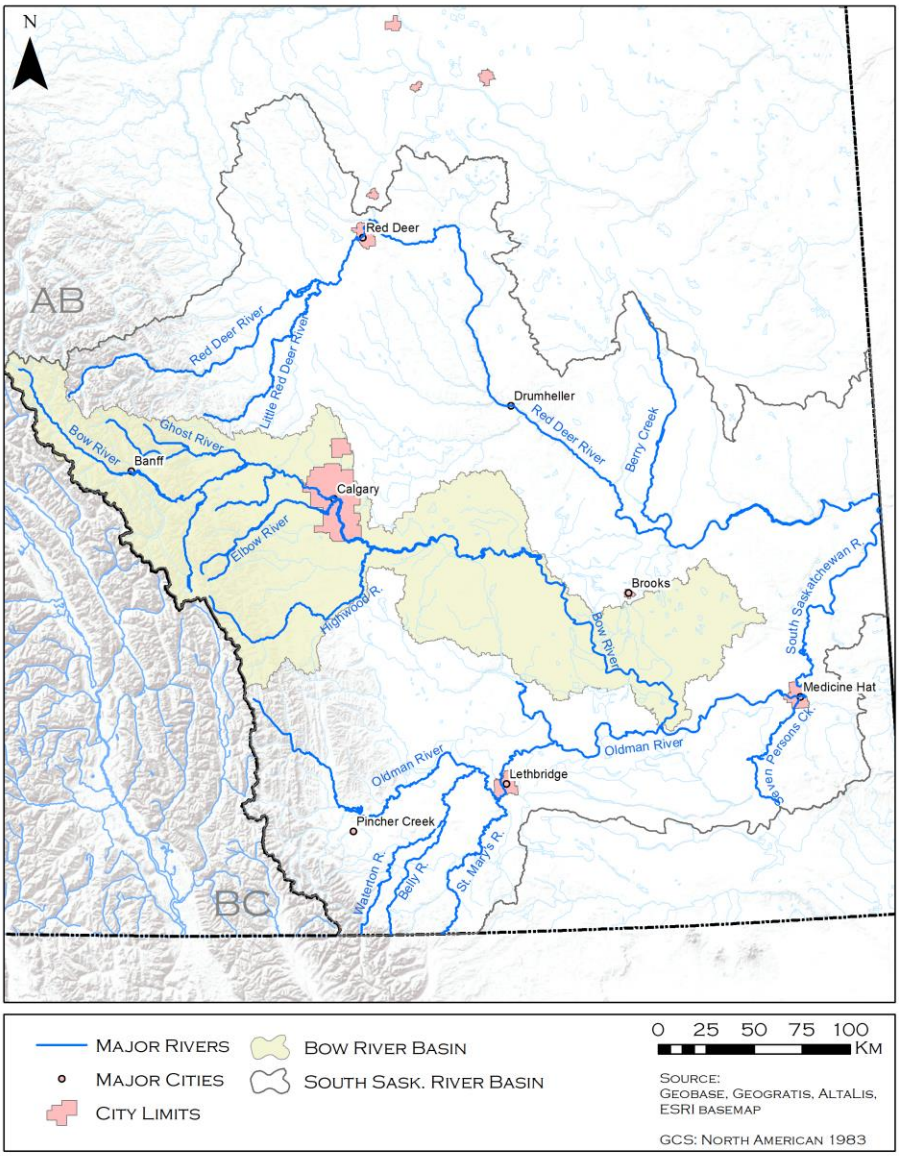

Figure 1 Bow River Basin nested within the Alberta portion of the South Saskatchewan River Basin.

1.3 Simulation Models

The ALCES Online landscape simulation model and the Raven hydrological modeling framework are being applied as an integrated decision support tool for prioritizing conservation and restoration strategies for the Bow River Basin.

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. Through an intuitive web-delivered interface, ALCES Online enhances the accessibility of scenario analysis to stakeholders and planners, thereby increasing its potential to influence policy.

Raven is 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. The model can be used to evaluate single storm events or to develop long-term water balances for resource management. 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).

Indicators were developed to assess the implications of changes to landscape composition and climate to watershed resilience. 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.

2 Methods

The decision support tool is designed for the following hierarchical approach to the identification of conservation and restoration priorities in the Bow River Basin:

1. For each indicator of concern, compare its response across a suite of conservation and restoration scenarios to prioritize mitigation strategies;
2. For each prioritized mitigation strategy, map its effect on indicator performance to identify where the strategy should be implemented.
3. Assess current and future status of watershed resilience indicators to identify key issues;

Developing the decision support tool required the following steps:

1. Assemble geospatial data describing the current composition of the Bow River Basin (BRB);

2. Simulate potential change in the BRB's composition over the next five decades in response to plausible rates of development and natural disturbance;
3. Calculate the response watershed resilience indicators to current and potential future composition of the BRB; and
4. Simulate a suite of conservation and restoration scenarios to assess their capacity to improve indicator response over the next five decades.

2.1 Assess current composition of the Bow River Basin

ALCES Online was parameterized with spatial data layers to depict current land cover and anthropogenic footprint in the Bow River Basin. A depiction of the pre-industrial landscape was also prepared and included in ALCES Online by removing anthropogenic footprint and integrating other data sources such as the combined wetlands inventory.

2.2 Simulate future land use and natural disturbance

Plausible 50-year trajectories for land use, climate, and natural disturbance were derived and applied in ALCES Online to map potential future changes in landscape composition across the basin. Sources of change included in the simulation were: oil and gas development, aggregate extraction, forestry, population growth, recreation development, agriculture, and wildfire. Key assumptions used to simulate future dynamics of each sector are summarized below. A more thorough description of simulation assumptions is provided in Appendix C.

- Oil and gas development was informed by projections from the Alberta Energy Regulator (2016) and the National Energy Board (2016), the location of deposits (Mossop and Shetsen 1994), and recent footprint patterns.
- Aggregate extraction was informed by historical patterns and was constrained to occur within aggregate deposits.
- Forestry activity was informed by the Spray Lake Sawmills Detailed Forest Management Plan.
- Urban and acreage footprint as well as golf courses expanded according to the Alberta Government's medium population growth trajectory (Alberta Treasury Board and Finance 2016). Use of recreation areas did not expand in the simulation because day use and camping use in parks has declined slightly in recent years, despite the growing population in the Calgary region.
- Agriculture declined due to conversion to expanding settlement.
- Fire was simulated according to historical wildfire patterns.

2.3 Simulate streamflow of representative sub-basins

In order to obtain hydrological indicators for the Eastern Slopes region of the Bow River Basin, a hydrological model was designed for the Ghost River watershed. Daily streamflow in the Ghost River watershed was simulated using Raven hydrological modelling framework to emulate a semi-distributed hydrological model with minor variations in a "level 1 (near-perfect) emulation" (Craig et al.

2016) of the HBV-EC hydrologic model. The HBV-EC model is a Canadian version of the original Scandinavian watershed model (Bergström et al. 1995; Canadian Hydraulics Centre 2010) and has been used extensively to simulate mountain streamflow in British Columbia and Alberta (e.g. Mahat and Anderson 2013; Jost et al. 2012; Stahl et al. 2008). The model's algorithms employ a combination of empirical and physically based parameterizations; descriptions of major processes are described in Section 3.2.2, while all model algorithms are described in further detail in Stahl et al. (2008) and Canadian Hydraulics Centre (2010). A full discussion of the methods employed in the hydrological model, as well as several extensions used to generate climate and land use scenarios, can be found in Chernos et al. (2017).

2.3.1 Hydrological Model Processes

The model used hydrological response units (HRUs) to spatially represent landscape attributes that vary in their hydrologic response. The model was driven by daily air temperature (minimum, maximum, and average) and total precipitation, which were spatially distributed across the watershed. Initially, water delivered as precipitation was intercepted the forest canopy. Precipitation was intercepted only so long as canopy storage was less than the maximum canopy storage capacity for the specific land-use type. Water remaining in the canopy was lost to the atmosphere.

Precipitation that was not intercepted reaches the surface as rain or snow. Snowmelt was calculated using a spatially corrected temperature index model (Hock 2003; Jost et al. 2012). Snowmelt was computed for each HRU as a function of daily air temperature and where a global base melt factor (mm/d/ºC) varies sinusoidally between a maximum and minimum at summer and winter solstices; accounting for seasonal variations in solar radiation related to day length. The global base melt factor was corrected for vegetation cover to account for the effect of forest cover on shading. A further correction was applied to account for the global sensitivity of the melt factor to the slope and aspect of each HRU.

Rain and snowmelt were routed into the soil as infiltration or lost to the atmosphere through evapotranspiration. Once water entered the three-layer soil, it moved downwards through percolation and upwards by capillary rise. Soil water returned to the surface from the middle soil layer through a faster linear baseflow response, while the deepest layer had a much slower two-parameter power-law response. Routing between sub-basins was calculated assuming simple plug flow (Craig et al. 2015). Given that HRUs were treated as non-contiguous units in Raven, routing between HRUs within a sub-watershed was not considered, and water released from HRUs was received at the sub-watershed outlet following a delay defined by a triangular unit hydrograph (Craig et al. 2015).

2.3.2 Model Calibration and Verification

Model parameters were calibrated using daily streamflow measurements from Ghost River above Black Rock and Waiparous Creek at the Mouth WSC hydrometric stations from 1978 – 1989 (4,100 days). Model parameters were calibrated using software tool OSTRICH (Matott 2005; Matott and Rabideau 2008) to implement dynamically dimensioned search (DDS) (Tolson and Shoemaker 2007) and Levenberg-Marquardt (Marquardt 1963) algorithms.

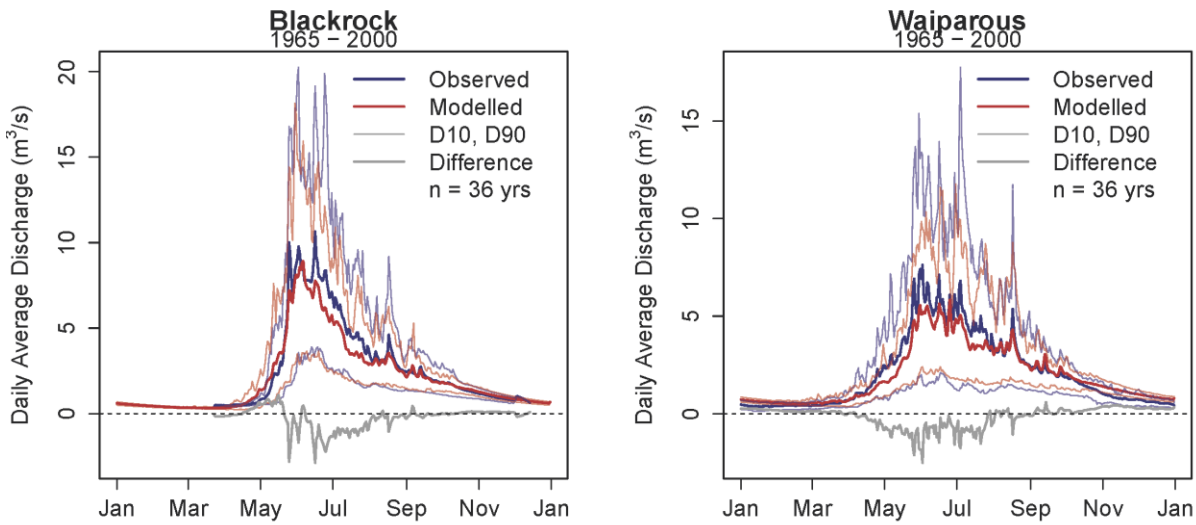

Figure 2 Simulated and observed daily average streamflow for the Ghost River at Blackrock and Waiparous Creek at the mouth.

The model was able to reproduce streamflow over a range of conditions for the calibration and verification periods. This was evaluated using the Nash-Sutcliffe Efficiency (NSE) coefficient, which is a measure of how well the model reproduces an observed hydrograph (Nash and Sutcliffe 1970). The model NSE of 0.80 for the calibration period, and 0.83 for the verification period for Ghost River at Blackrock. For Waiparous at the Mouth, the model produced NSE = 0.66 for the calibration period and NSE = 0.74 for the verification period (Figure 2). Waiparous below Meadow Creek had lower performance (NSE = 0.54), though the statistic was only calculated over 4 complete hydrological years.

2.3.3 Model Scenarios

2.3.3.1 Land Use Scenarios

A varying number of HRUs in selected sub-watersheds with a 'Forest' land-use class were converted to 'Harvested' in order to simulate the effect of forest cover removal on streamflow in the Ghost River watershed. The 'Harvested' land-use class was assigned the same parameter set as 'Forest', though interception was reduced by 30% to account for the effect of canopy removal, approximating regrowth and sparse canopy retention (Varhola et al. 2010). These scenarios were run in three sub-watersheds: Ghost Blackrock, Waiparous below Meadow, and Waiparous at Mouth. In each scenario, varying percentages of the upstream area was converted to 'Harvested', ranging from 5% – 56%, while scenarios also controlled for aspect and elevation variations.

A varying number of HRUs below 1500 m was converted to the land-use type 'Developed' to simulate the effect of urban development on the hydrology of the basin. Developed parameter sets are characterized with very low interception fractions (5%), high impermeability (80%), and very shallow soil depth (3 cm). Development scenarios were run in the Waiparous Mouth and Ghost Cochrane

sub-watersheds. In each scenario, varying percentages of the total watershed area were developed, ranging from 5% to 20%. Given that slope and aspect were very low in the considered sub-watersheds, and development only occurred below 1500 m, these variables were not controlled for in scenarios.

A varying number HRUs in watersheds Waiparous Mouth, Ghost Waiparous, and Ghost Cochrane with slopes of 5° or lower were converted to the land-use type 'Wetland' to simulate the effect of wetland restoration/construction on streamflow in the Ghost Watershed. Scenarios involved changing 5 – 22% of the landscape to wetland. An additional scenario was designed where all wetlands in the watershed (< 0.5% of basin area), which were located entirely within the three sub-watersheds and low slope angles prescribed for restoration scenarios, were converted to Grassland, simulating agricultural development, or wetland draining. Wetlands were characterized by deep, highly permeable soils with high moisture holding capacity, low-moderate canopy interception capacity (18%), and snow melt rates approximately half-way between open and forested land-use types.

2.3.3.2 Climate Scenarios

Four scenarios were used to evaluate the potential effects of climate change on streamflow. Projected changes in monthly air temperature (maximum, minimum, average) and monthly precipitation were generated using the CanEnSM2 global circulation model for scenarios RCP 4.5 and RCP 8.5. Values were obtained from ClimateWNA (Wang et al. 2012) for both scenarios for the period 2010 – 2040 and 2040 – 2070, as well as normals for the period 1971 – 2000 (Environment Canada 2017). Projected changes for the entire Ghost Watershed were extracted for the approximate centre of the watershed (51.37◦, -115.12◦, 1599 m).

Maximum, minimum, and mean daily air temperature scaling factors were found by calculating the absolute monthly difference between monthly climate normals and projected future normals. Monthly precipitation scaling factors were found by calculating the relative (percent) change. Monthly scaling factors were interpolated to daily values using a cubic spline function (spline() in R). Unique scaling factors for each meteorological variable were then applied to observed (baseline) weather data.

2.3.4 Empirical Hydrology Relations

In total, 22 forest cover change, 8 development, and 8 wetland change scenarios were evaluated under observed climate, as well as 4 climate change scenarios, for the period 1966 – 2000. Mean annual flow (MAF), annual minimum 7-day mean flow (Q7), peak annual spring flow, mean August-September flow, and freshet Day-of-Year (DOY) were calculated for simulated streamflow from each scenario. Additionally, the RB-Index (Baker et al. 2004) was calculated to quantify the 'flashiness' of streamflow response to meteorological inputs (rainfall and snowmelt). Peak flows were only tabulated for the spring (April – July) in order to examine peak flows due to freshet, and to remove peak flows, which periodically occurred in the fall as a result of ephemeral rainstorms. These results were compared against simulated statistics for the baseline scenario, and in each case the percent difference was calculated.

Stepwise linear regression was employed in order to create empirical relations between land-use change, sub-watershed response, and streamflow. The method takes a linear model encompassing all available variables, and systematically removes them in order to maximize the Akaike Information Criterion (AIC) of the resulting model. Available variables were sub-watershed specific (Percent Forest Cover, Percent Alpine), HRU specific (Elevation, Slope, Aspect), and scenario specific (Percent Basin Affected). Additional variables absolute (Maximum, Minimum, Mean Monthly) air temperature change and percent change in precipitation were added to climate change simulation models. Stepwise regression was completed using the stepAIC() function in R "MASS" package (Venables and Ripley 2002).

2.4 Calculate the response of watershed resilience indicators

Indicators of watershed resilience were identified by the Working Group comprised of representatives from stakeholder groups representing various perspectives in the Bow River Basin (Appendix A). The Working Group defined a resilient watershed to mean:

"A well-managed watershed that can maintain key ecosystem features, is able to perform diverse functions (ecological and hydrological) and can recover from natural and anthropogenic disturbance".

Indicators of resilience were selected to represent key elements of the aquatic and terrestrial ecosystem, as well as human values (Table 1). The suite of indicators makes it possible to assess individual components of the basin independently. Indicators were converted to a uniform hazard scale and averaged to calculate overall hazard to derive a synthetic index of resilience. The approach used to calculate each indicator and assess hazard is described below. Indicators were reported at the scale of assessment watersheds as defined by the HYDAT database (Environment Canada 1997). The HYDAT database was used for watershed delineation because it provided smaller assessment units than other available systems for watershed delineation such as the hydrologic unit code (HUC) watersheds of Alberta. The exception was stream crossing density, which was approximated using a relationship between road length and crossing density calculated at the HUC8 scale.

Table 1. Resilience indicators.

Watershed Component	Resilience Indicator	Concept
Aquatic Ecosystems	Change in Mean Annual Flow	Used to assess the watershed's ability to retain water in the terrestrial landscape
	Change in Peak Annual Spring Flow	Used to assess the watershed's ability to absorb runoff

	RB-Index[1]	Used to assess hydrologic alteration in terms of how flashy a particular watershed is
	Change in Base Flow (mean August - September flow)	Used to assess the watershed's ability to supply water essential to the watershed, even during low flow times of the year
	Index of Native Fish Community Integrity	Used to assess the health of the fish community in relation to the pre-industrial state
	Stream Crossing Density	Used as a measure of aquatic habitat fragmentation.
	Water Quality Index	Water quality is an effective consolidating indicator of watershed health and can be used to evaluate how land use affects water resources.
Terrestrial Ecosystems	Change in Proportion of Wetland Area	Used as a measure of the numerous services provided by wetlands (e.g., water storage, water purification, wildlife habitat, carbon storage)
	Change in Forest Age Class Distribution	Used as a coarse measure of forest health and resilience in terms of hydrologic events. A decrease in runoff is expected in response to an aging forest stand due to increases in evaporation and interception (Winkler et al., 2010).
	Total Linear Footprint Density	Used as a measure of landscape fragmentation. Fragmentation is

[1] The RB Index is a measure of the "flashiness" of the hydrograph. A high RB Index would mean that a stream responds rapidly to precipitation events, resulting in rapid increase and subsequently rapid decrease in streamflow.

		detrimental to species requiring intact landscapes such as grizzly bear, and can alter ecological processes including hydrology.
Human Values	Flood damage risk	Used as a measure of the cumulative financial liability associated with development in flood-prone areas.

2.4.1 Landscape composition

Two indicators were calculated to summarize current and potential future landscape composition: wetland coverage and linear disturbance density. Wetland coverage was calculated as percent of natural wetland coverage. Natural (i.e., pre-industrial) wetland coverage was estimated using the provincial combined wetlands inventory. Linear disturbance density incorporated roads, trails, seismic lines, and pipelines.

2.4.2 Forest age

An index was calculated that summarizes deviation of coniferous forest age class composition from a benchmark seral age-class distribution prepared for the Spray Lakes Sawmills FMA (Rogeau 2013)[2] to assess forest age class composition. Coniferous forest was the focus when assessing forest age because there is substantially more coniferous forest than deciduous or mixedwood forest in the basin. The range of natural variation for the representation of age-classes are presented by Rogeau (2013) to be within one standard deviation of the mean as estimated from simulations of the fire regime. To calculate a forest age-class index, we compared the proportional representation of each age-class in a watershed to intervals defined by the benchmark age-class mean and standard deviation. The index was calculated for each of three age classes: young (<= 70 years), mature (71 to 170 years), and old (>170 years). he index received a value of 1 if representation of an age-class was within 1 standard deviation of the mean (no deviation from preindustrial condition), a value of 2 if representation was within 2 standard deviations of the mean (moderate deviation from preindustrial condition), a value of 3 if representation was within 3 standard deviations of the mean (high deviation from preindustrial condition), and a value of 4 if representation was more than 3 standard deviations from the mean (very high deviation from preindustrial condition). An overall index of forest age deviation from preindustrial condition was calculated as the average value of the index across the three age classes. Larger departures from the average benchmark seral age-class distribution are

[2] Rogeau (2013) provides benchmark seral stage distribution for each combination of FMU and natural subregion present in the FMA. The benchmark seral stage distribution used here was that for the FMU (B10 upper) and natural subregion (subalpine) containing the most coniferous forest in the basin.

assumed to indicate higher levels of risk to ecosystem components (e.g., wildlife) and processes (e.g., fire, hydrology).

Table 2. Mean and standard deviation estimates for preindustrial coniferous age-class representation (Rogeau 2013).

	Mean	Standard deviation
%Young forest	71.03	24.74
%Mature forest	20.28	7.42
%Old forest	8.69	3.22

2.4.3 Hydrology

2.4.3.1 Forest Harvest Scenarios

Forest harvest scenarios displayed increases in mean annual flow, maximum annual spring flow, and minimum 7-day annual flow for all three sub-basins (Figure 3). There was a positive linear increase in all four streamflow indicators with upstream forestry where a 2% disturbance generated approximately a 1% increase MAF, maximum annual spring flow, and RB-Index. However, annual changes in peak flow exhibited considerable variability; ranging from 0 – 100% for 55% of the basin disturbed. Minimum 7-day annual flows displayed a more muted response, where a 3% disturbance was required, on average, to generate a 1% increase in low flows. There was a positive linear increase in August-September mean flow, where a 10% increase flow occurred under a 35% harvest scenario. There was no systematic change in freshet DOY timing observed under forestry scenarios. In all indicators, simulated changes in streamflow were lower further upstream; positive increases were lower in Blackrock than in Waiparous Mouth and Waiparous Meadow.

The streamflow response was predicted as a function of the percent of basin affected for all streamflow indicators, and significant relationships were found for all indicators except freshet DOY. The percent forest cover was a significant predictor for MAF, Q7, and RB-Index, while the percent alpine was additionally a significant predictor of MAF, mean Aug-Sept flow, and Q7. The percent of upstream area disturbed was by far the most importance variable. Model fit ranged from R^2 = 0.33 for maximum annual spring flow, to R^2 = 0.94 for MAF.

2.4.3.2 Wetland Scenarios

Wetland restoration/construction scenarios displayed a positive increase in mean annual flow and minimum 7-day low flows with increasing wetland area (Figure 3). A 10% increase in wetland area had approximately a 10% increase in MAF, a 15% increase in mean Aug-Sept flow, and a 15% increase in minimum 7-day annual flow. Conversely, the RB-Index decreased with increasing wetland coverage, where a 10% increase wetland area decreased the RB-Index by 10%. There was no significant change

in maximum annual spring flows with wetland area change, while there is some indication that Freshet DOY is earlier in some instances.

The streamflow response was predicted as a function of the percent of upstream area disturbed for streamflow indicators peak spring flow, MAF, mean Aug-Sept flow, and RB-Index, while percent forest cover was an additional significant predictor. The percent of upstream area disturbed was the dominant variable. Model fit ranged from R^2 = 0.87 – 0.96 for MAF, Q7 and RB-Index; however, no model was able to derive a good fit for peak spring flow (R2 = 0.04) and freshet DOY (R^2 = 0).

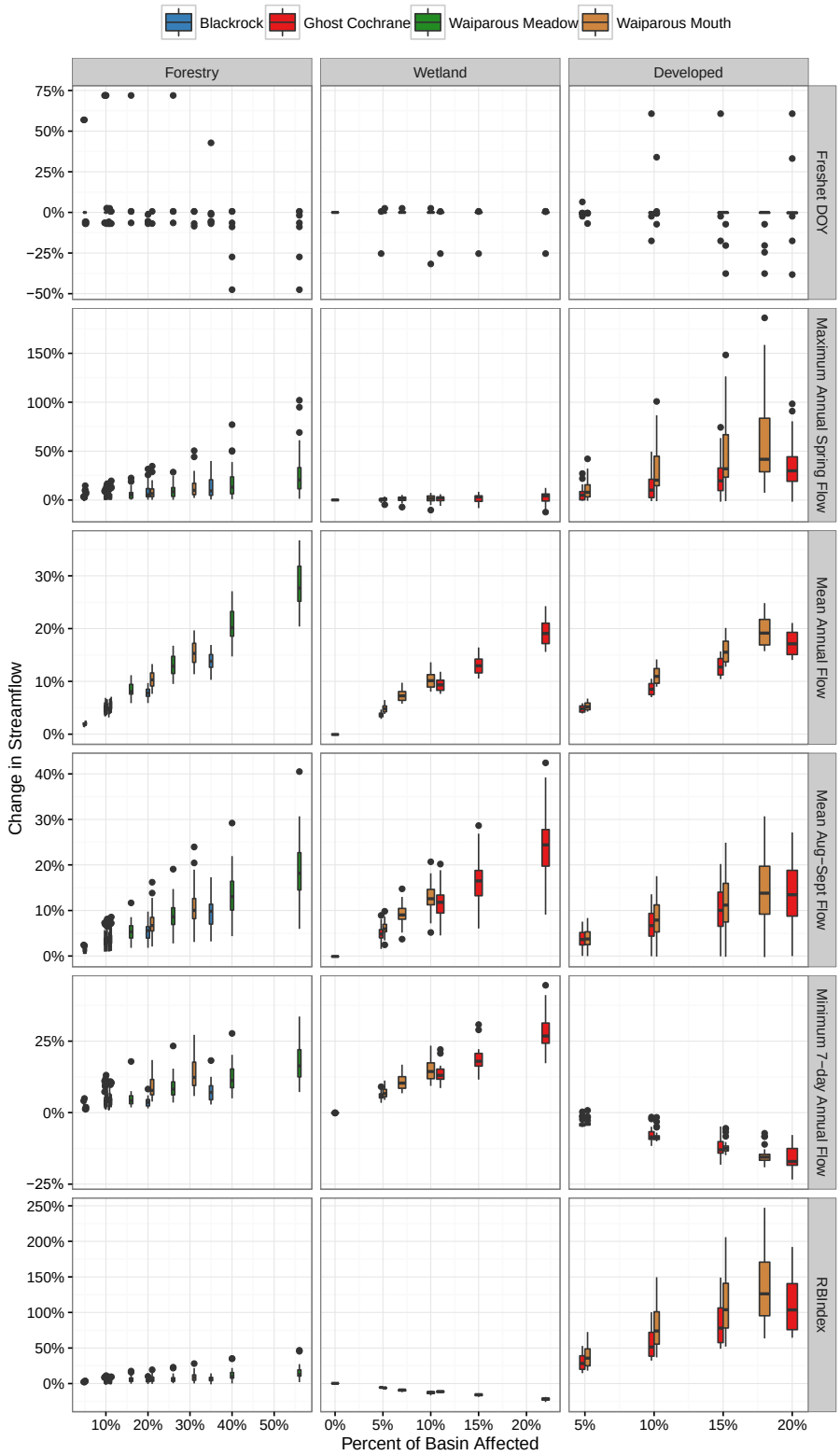

Figure 3. Change in streamflow indicators for four Ghost River watershed sub-watersheds under forestry, wetland, and development scenarios and observed climate. Each data point represents annual value.

2.4.3.3 Development Scenarios

Development scenarios displayed a positive increase in maximum annual spring flow, MAF, mean Aug-Sept flow, and RB-Index (Figure 3). The increase in maximum annual spring flow was approximately 2% for every 1% of watershed area developed; roughly double the response of MAF and close to triple the response of mean Aug-Sept flow. Increases in RB-Index were significantly more substantive; a 1% increase in developed area led to a 5 – 7% increase in RB-Index. Increased development yielded a decrease in low flows; a 10% increase in development resulted in approximately an 8% decrease in minimum 7-day annual flow. There was some indication that development decreases the freshet DOY (i.e. it occurs earlier in the season).

The streamflow response to development was predicted as a function of the percent of upstream area disturbed for all streamflow indicators except freshet DOY. The percent forest cover was a significant predictor for MAF, mean Aug-Sept flow, peak spring flow, and RB-Index. The percent of upstream area disturbed was the most important variable. Additionally, the percent forest cover was an important variable for predicting peak spring flow. Model fit was moderate (R^2 = 0.29) for maximum annual spring flow and RB-Index (R^2 = 0.52), while MAF and Q7 had fits of R^2 = 0.76 – 0.87. No significant relationship was found for freshet DOY.

2.4.3.4 Climate Scenarios

Changes in streamflow due to four climate change scenarios showed responses that vary by scenario and, less significantly, by sub-watershed. Under all climate scenarios (Figure 4), freshet occurred earlier in the season, on average, while the degree of change was more severe for lower elevation sub-watersheds. Changes in maximum annual spring flow were ambiguous for all climate scenarios and simulation periods. While median values did not exhibit significant change, scenario distributions are right-skewed and some years experienced increases in peak flow of over 100% in the RCP 4.5 scenario, and up to 200% in RCP 8.5. Variability was greatest for lowest-elevation sub-basins.

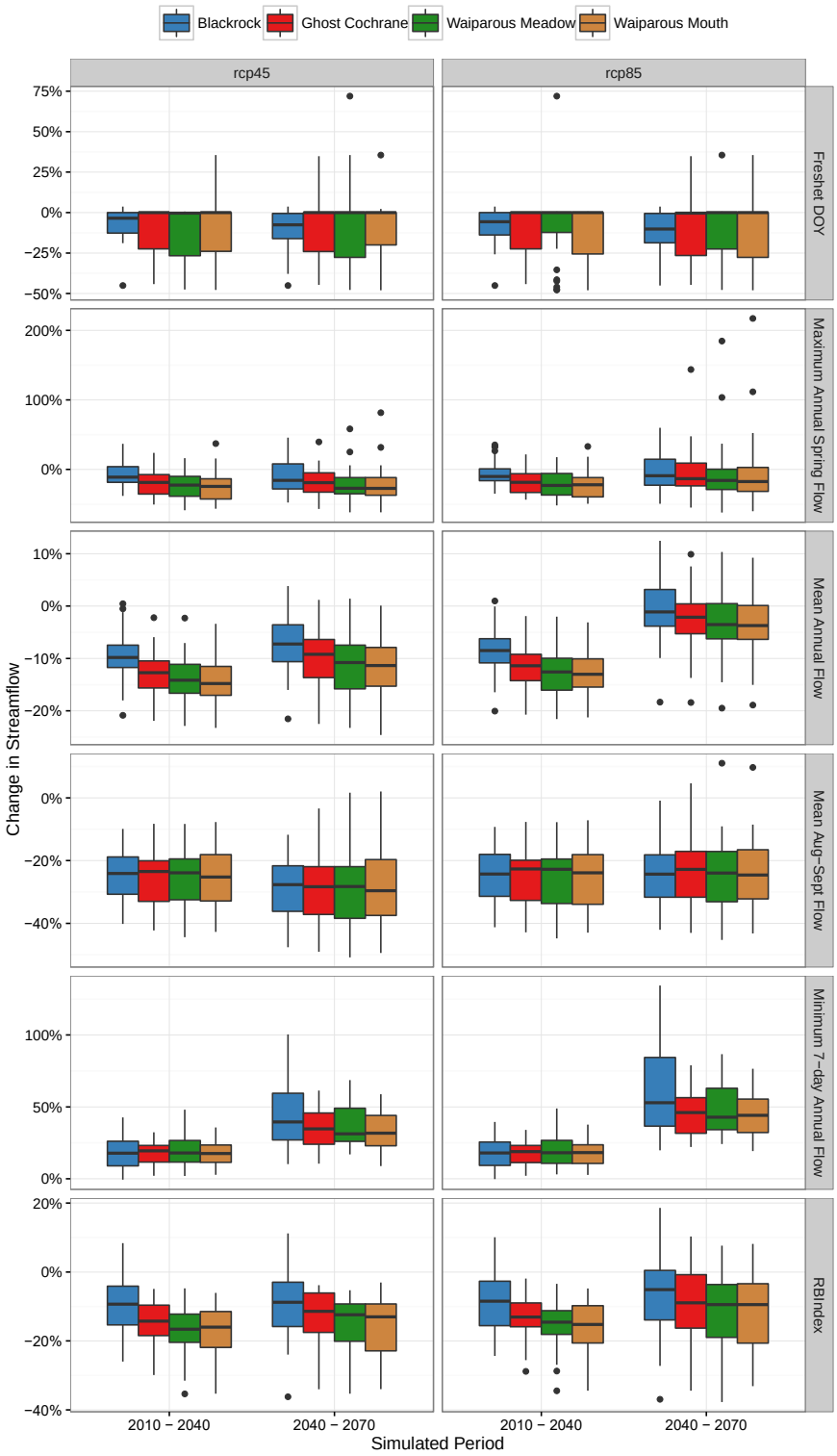

Figure 4. Change in streamflow indicators for four Ghost River watershed sub-basins under four climate change scenarios. Individual data points represent annual values.

MAF showed a modest decrease of approximately 10% for both RCP 4.5 scenarios, as well as RCP 8.5 from 2010 – 2040. The response was greater for Waiparous Creek sub-watersheds. Mean Aug-Sept flows decreased by 20-30% under all climate scenarios, and the response was similar for all sub-watersheds. Minimum 7-day low flows increased for all climate scenarios. Changes were largest for RCP 8.5, and for period 2040 – 2070 and for the Ghost at Blackrock sub-watershed. The RB-Index decreased by 5 – 15% under all climate scenarios, though changes were more severe in the Waiparous Creek sub-watersheds and 2010 – 2040 scenarios.

Streamflow response to climate change was predicted primarily as a function of meteorological variables. Mean Annual Flow was predicted (R^2 = 0.71) primarily as a function of the percent of precipitation falling as snow in the watershed, the percent change in precipitation, and the absolute change in maximum daily air temperature, making up a combined 90% of the model's explanatory power. The rest of the model was constructed from variables percent forest and percent alpine in the sub-watershed. Mean Aug-Sept flow had a poor fit (R^2 = 0.06) and was predicted by the percent precipitation falling as snow, and the absolute change in average and maximum temperature.

Minimum 7-day low flow was predicted (R^2 = 0.44) primarily as function of the absolute change in maximum daily air temperature. The balance of the model was made up of average basin elevation, percent forest, and percent of precipitation falling as snow. Models for freshet DOY (R^2 = 0.02), peak spring flow (R^2 = 0.06) and RB-Index (R^2 = 0.13) are not significant. However, freshet DOY was primarily dictated by the percent snowfall, peak spring flow was primarily a function of the percent change in precipitation, while RB-Index was a function of the percent change in precipitation, percent forest, and absolute change in maximum daily air temperature.

2.4.3.5 Cumulative Effects Scenarios

Adding the climate change effect to land use change scenarios primarily altered the total change in streamflow, rather than the rate of change relative to the percent of basin affected (Figure 5). For all scenarios, only the most severe climate change scenario (RCP 8.5 for 2055) yielded significant increases MAF and peak spring flow relative to climatic baseline conditions. Changes in Q7 were observed for all scenarios, where more severe climatic changes generated higher average Q7 flows. Changes in mean Aug-Sept flow due to climate run counter to land use change and show marked decreases under all scenarios. In general, there were only minor changes in the RB-Index and freshet timing when climate change scenarios were incorporated.

For forestry scenarios, peak spring flow and freshet DOY regressions incorporating climatic changes had low predictive power (R^2 = 0.04, 0.07). MAF had good predictive power (R^2 = 0.81) and was predicted primarily as a function of the percent of watershed affected (48%, see Figure 8), while the percent change in precipitation, absolute change in maximum, minimum, and mean air temperature, and the percent of precipitation falling as snow were all significant variables. Mean Aug-Sept streamflow had moderate predictive power (R^2 = 0.43) and was driven relatively equally by percent of basin affected, maximum, minimum, and mean air temperature changes, precipitation, and the percentage of precipitation falling as snow. Minimum 7-day annual flow (R^2 = 0.60) was predicted primarily by changes in precipitation, maximum, and mean air temperature, while the percent of basin

affected had a secondary effect. RB-Index was primarily a function of the percent of basin affected, with small contributions from a range of climatic and landscape variables.

For wetland scenarios, peak flows and freshet DOY relationships had low predictive power (R^2 = 0.07, 0.04), and were a function of climate variables percent of precipitation as snow, percent change in precipitation, and absolute change in (maximum, minimum, mean) air temperature. Changes in MAF were well predicted (R^2 = 0.82) and were primarily a function of the percent of watershed area affected (relative importance of 48%), while additional explanatory power was derived from a collection of climatic variables. Mean Aug-Sept flow was predicted (R^2 = 0.50) primarily as a function of percent of basin affected (44%). Minimum flows (R^2 = 0.71) were driven relatively equally between changes in precipitation and temperature, and percentage of basin affected. RB-Index (R^2 = 0.43) was driven primarily by the percent of basin affected (68%).

For developed scenarios, freshet DOY was not well predicted (R^2 = 0.03) and was a function of the percent of basin forested, and changes in temperature and precipitation. Peak spring flows (R^2 = 0.14) was predicted primarily as a function of the percent of watershed affected, while percent of basin forested and percent precipitation as snow were also important variables. MAF was well predicted (R^2 = 0.78) and was driven primarily by percent of watershed affected and change in precipitation. Mean Aug-Sept flow (R^2 = 0.35) was driven primarily by changes in precipitation, maximum and minimum air temperature, and percent of basin affected. Minimum flows (R^2 = 0.68) were predicted in large part by changes in precipitation and air temperature, while changes in RB-Index (R^2 = 0.56) were driven almost entirely by the percent of watershed affected.

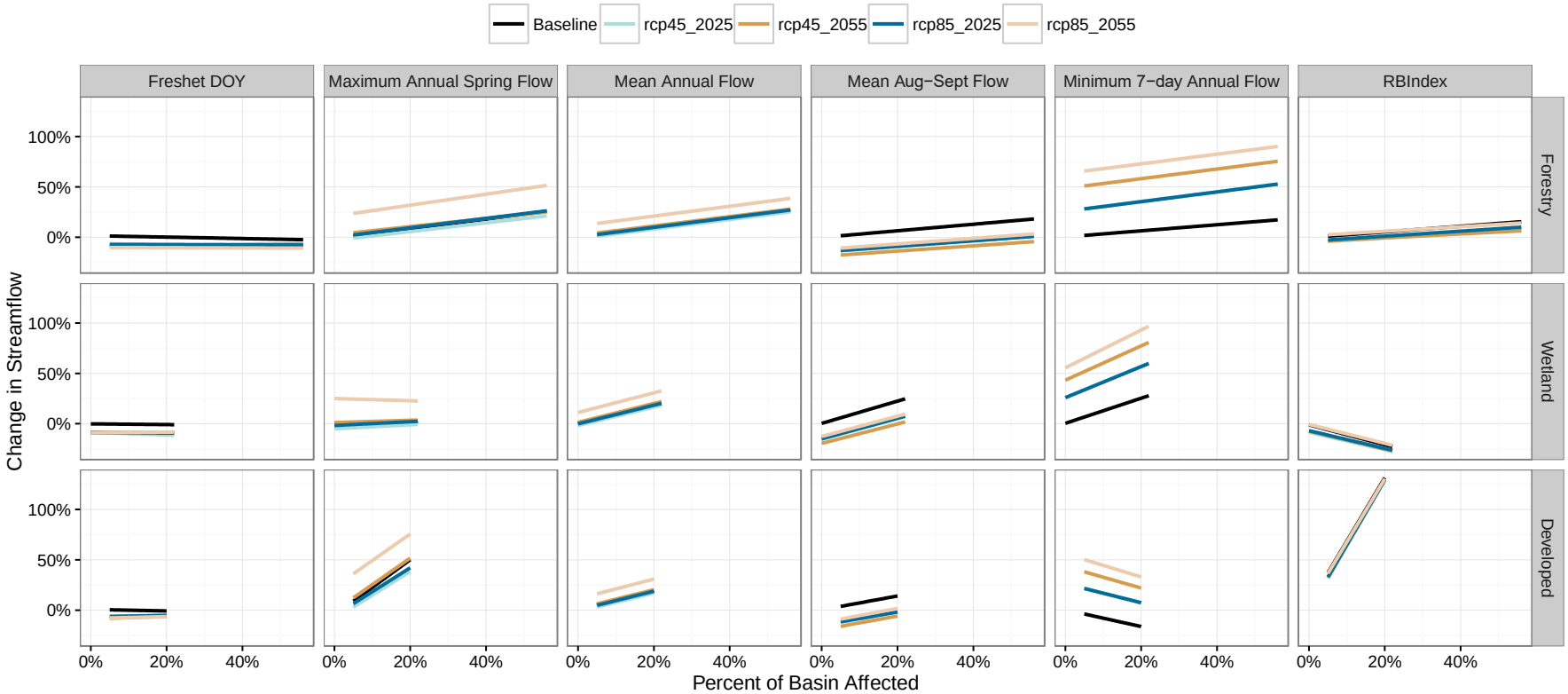

Figure 5. Linear regression lines for cumulative effect simulations, where each land use experiment is run with four climate change scenarios. Individual data points are removed for legibility.

2.4.4 Stream crossings and watershed discontinuity

Stream crossings with the potential to impede fish movement were assumed to occur at the intersection of roads and permanent and indefinite streams[3] because culverts are likely to be utilized. In contrast, bridges instead of culverts were assumed to be used where roads intersect with rivers, and recurring streams were assumed to be non-fish bearing. Stream crossing density was assessed for each HUC8 assessment watershed as the number of road crossings per km of permanent/indefinite stream. Stream crossings increased during simulations in response to expansion of the road network, in proportion with the existing density of crossings per km of road in a sub-watershed.

Culverts can become impassable by fish over time due to effects such as blockage and scouring. Fifty percent of culverts were assumed to be hanging based on the findings of a study of culverts in northeastern Alberta (Park et al. 2008). By blocking fish movement, an impassable (i.e., hanging) culvert renders upstream habitat inaccessible. Stream fragmentation due to impassable culverts was assessed using a relationship between the density of impassable culverts (#/stream km) and the percent of stream habitat lost, as derived from actual and simulated stream crossings for the Christina, Calling, Swan, and Notikiwin watersheds in northern Alberta (Michael Sullivan, pers. comm.). The data from the northern watersheds were summarized using the equation $y = 1.6445x^{0.7381}$ ($R^2 = 0.939$), where y is the proportion of stream habitat lost and x is the number of impassable culverts per km of stream.

2.4.5 Water Quality Index (WQI)

Water quality was assessed by tracking changes to nitrogen, phosphorus, and sediment runoff, parameters that are negatively related to overall water quality. Nutrient and sediment runoff associated with simulated landscapes were estimated by applying runoff (tonnes/ha/year) coefficients by land cover and footprint types from Donahue (2013) that varied by Natural Region (see Appendix C). The coefficients were based on event mean concentrations and associated methods from the literature, yielding a linear relationship between precipitation and runoff. Donahue (2013) provides coefficients for intensive (i.e., manure application) and extensive cropland and pasture. The relative abundance of intensive and extensive farming practices was based on the percent of farmland within each census division receiving manure application according to the 2011 agricultural census (Statistics Canada 2011).

Simulated runoff was applied to calculate water quality indices for nitrogen, phosphorus, and sediment with values ranging from 0 to 1, with lower values indicating compromised water quality. The Water Quality Index (WQI) was calculated by dividing the runoff expected from undisturbed landscape by the runoff calculated for the simulated landscape. An overall water quality index was quality as the average of the nitrogen, phosphorus, and sediment indices for each assessment watershed.

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[3] Indefinite refers to a perennial or intermittent stream whose channel cannot be clearly distinguished due to vegetation or high water. Because such streams may be permanent (i.e., perennial), they may be fish bearing and culverts may be used at crossings.

2.4.6 Index of Native Fish Integrity (INFI)

The status of the fish community was assessed using the Index of Native Fish Integrity (INFI), a measure that conveys changes in native fish species and age composition with a value ranging from 1 (undisturbed community) to 0 (highly disturbed community). Undisturbed communities are characterized by abundant large lake sturgeon, walleye, and sauger in prairie streams and abundant large westslope cutthroat and bull trout in foothill streams. Highly disturbed communities are characterized by abundant fathead minnows and brook sticklebacks in Prairie streams and remnant populations of mountain whitefish in Foothill streams. The index does not measure the status of fish populations directly, but rather considers the conditions that influence fish community health. INFI response to scenarios was estimated using dose-response relationships for southern Alberta fish communities defined by fishery experts (Sullivan 2009). Stressors included linear edge density[4], watershed discontinuity, water quality, and increase in mean annual air temperature. The influence of hydrology (e.g., positive effect of flooding) is not included directly, although the discontinuity index assesses the ability of fish to access spawning areas created during flood events. Sullivan (2009) provides separate dose-response relationships for Foothills and Prairie regions. When assessing the current and potential future status of the fish community in the Bow River Basin, Foothills dose-response relationships were applied to assessment watersheds that are predominantly in the Foothills and Rocky Mountain Natural Regions. Prairie dose-response relationships were applied to watersheds that are predominantly in the Prairie and Parkland natural regions. Dose-response relationships between each stressor and INFI are summarized in Figure 6.

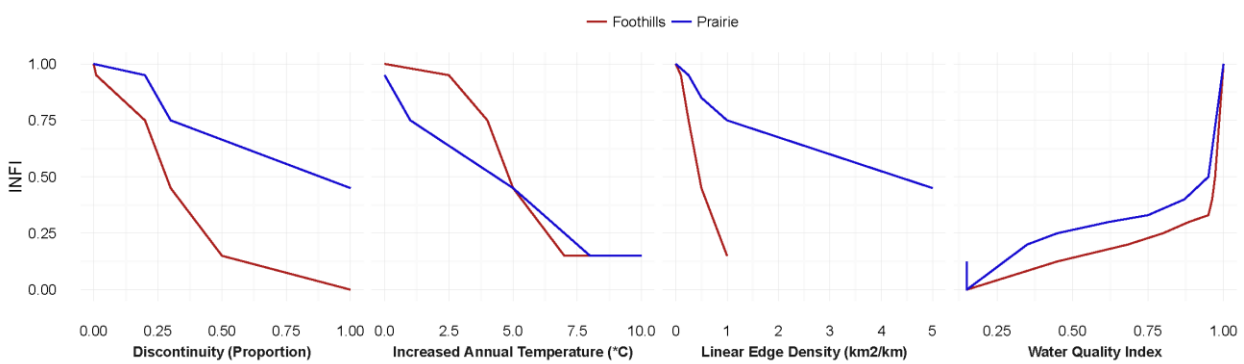

Figure 6. Dose-response relationships applied to landscape simulations to assess consequences to INFI.

Stressors were summarized at the scale of assessment watersheds and dose-response relationships applied to calculate the status of each watershed's fish community. The average INFI value across the four stressors was calculated to assess their combined effect (Sullivan 2009).

[4] Following Sullivan (2009), linear edge density for INFI purposed included roads, trails, and seismic lines.

2.4.7 Flood damage risk

Flood damages in urban areas were estimated using an assessment of flood damages in the City of Calgary prepared for the provincial government. Direct damages to residential and commercial structures by a 1:100 year flood event in the City of Calgary were estimated by IBI Group and Golder Associates (2015) to equal $797,870,000[5]. Settlement footprint (i.e., residential and commercial structures) covers 10.0115 km^2 of the flood hazard zone occurring within the City of Calgary. As such, the average direct flood damage to residential and commercial structures is $79,695,350/$km^2$ of settlement footprint in the flood hazard zone. To calculate flood damage risk in other cities and towns, Calgary's average flood damage coefficient was applied to settlement footprint occurring within the flood hazard zone. The flood damage estimate excludes indirect damages, damages to infrastructure, and damages to the Stampede grounds. These other damages were excluded out of concern that they will differ substantially between Calgary and other cities and towns in the Bow River Basin. For example, indirect commercial damages will be substantially higher in Calgary than elsewhere due to the high value of professional work occurring within downtown Calgary.

In rural areas, flood damages were calculated by applying a flood damage estimate for Bragg Creek. Direct damages to residential and commercial structures by a 1:100 year flood event in Bragg Creek's flood hazard zone have been estimated to equal $12,700,000 (IBI Group 2015). Settlement footprint covers 0.8332 km^2 of the flood hazard zone occurring within the Bragg Creek. As such, the average direct flood damage to residential and commercial structures is $15,242,439/$km^2$ of settlement footprint in the flood hazard zone. To calculate flood damage risk in other rural areas (i.e., outside of cities and towns) in the Bow River Basin, Bragg Creek's average flood damage coefficient was applied to settlement footprint within the flood hazard zone. The flood hazard zone has not been mapped for most rural areas in the basin. For those areas where flood hazard mapping is not available, the flood hazard zone was estimated as a 200 m buffer applied to major rivers.

2.4.8 Hazard index

Indicator values were converted to hazard indices to aid interpretation by managers that may not always be familiar with the raw indicator metrics. Another benefit of the hazard index is that it provides a common scale across indicators, making it easier to compare and summarize impacts to multiple aspects of watershed resilience. The hazard indices were calculated at the scale of HYDAT watersheds by applying thresholds that convey low, moderate, high, and very high levels of risk. The thresholds were based on those applied in previous land-use planning initiatives or, if such examples were not available, expert opinion. Rationale for each indicator's hazard thresholds are as follows:

[5] A more recent analysis completed for the City of Calgary estimated direct damages from a 1:100 year flood in Calgary to be $1.78 billion (IBI Group and Golder Associates 2017). This higher damage estimate is likely primarily due to the use of updated hydrologic and hydraulics data resulting in a larger flood zone. We used the more conservative damage estimate (i.e., $0.798 billion) when estimating flood damage risk because it is based on the provincial flood hazard mapping that was used in the scenario analysis. Applying the higher damage estimate derived from a larger inundation area could result in an exaggerated flood damage risk estimates when combined with the provincial flood hazard mapping in Calgary and elsewhere in the study area (S. Davis, pers comm).

- INFI and wetland hazard thresholds are those used for the Alberta Fish Sustainability Index (FSI; MacPherson et al. 2014). INFI and FSI both assess risk using a 0 (very high risk) to 1 (low risk) scale, with INFI assessing risk to the fish community and FSI assessing risk to fish populations. The FSI risk categories were deemed suitable for the wetland indicator as well because the risk categories are based on those used for broader biodiversity assessments such as Alberta's Biodiversity Management System and NatureServe (MacPherson et al. 2014). The risk categories are: low risk, when a metric is at least 70% of natural condition; moderate risk, when a metric is between 50% and 70% of natural condition; high risk, when a metric is between 20% and 50% of natural condition; and very high risk when a metric is less than 20% of natural condition.
- WQI hazard thresholds are based on expert opinion because suitable thresholds could not be identified in the literature. Salmo Consulting Inc. (2004) proposed target and critical thresholds for the Deh Cho territory in southern Northwest Territories. Their target threshold (WQI = 0.9) for long-term protection was based on a commonly applied turbidity criterion. Their critical threshold (WQI = 0.8) for the highest amount of stress that can be supported without long-term harm was based on a significance standard for ecological risk assessment. We concluded that these thresholds were too sensitive for the Bow Basin, given that they would result in much of the basin (including portions of protection areas) beings assessed as exceeding critical threshold. Instead, we divided the range of possible index values (0 to 1) into thirds to set low, moderate, and high-risk categories. WQI values < 0.33 receive a hazard score of 3 (high risk); values between 0.33 and 0.67 receive a hazard score of 2 (moderate risk); and values between 0.67 and 1 receive a hazard score of 1 (low risk). The suitability of these thresholds was assessed by way of comparison with the Bow River WQI prepared by Alberta Environment and Parks through analysis of water samples for nutrients, metals, bacteria, and pesticides. Bow River WQI scores were available for five watersheds. Bow River WQI scores were consistent with WQI hazard scores for three of the watersheds, in that watersheds with a moderate hazard score had a fair Bow River WQI score whereas watersheds with a low hazard score had a good Bow River WQI score[6]. Hazard scores were inconsistent with Bow River WQI scores for the other two watersheds, in that a watershed (Carsleland to Bassano) receiving a moderate hazard score received a good Bow River WQI but a watershed (Elbow River) receiving a low hazard score received only a fair Bow River WQI. However, these inconsistencies are explainable. Substantial effort has gone into treating water downstream of Calgary, such that it is not surprising that sampled water quality (i.e., Bow River WQI) in the Carsleland to Bassano watershed is higher than the modeled hazard score that is does not take into account water treatment. In contrast, the Elbow River watershed receives substantial effluent with minimal treatment from residential areas, an impact that is not accounted for by the modeled hazard score. Therefore, it is not surprising that sampled water quality in that watershed is lower than the modeled hazard score.

[6] Bassano to Oldman River and Highwood to Carsleland watersheds both received a moderate hazard score and a fair Bow River WQI score; and Seebe to Bearspaw received a low hazard score and a good Bow River WQI score.

- Linear feature hazard thresholds are those identified as disturbance limits for all linear features for the Oldman Watershed Headwaters (Fiera Biological Consulting 2014) and the Athabasca Watershed Council (Fiera Biological Consulting 2012), which were based on wildlife responses to linear feature density. We applied the disturbance limits to prepare a hazard index as follows: linear feature density within the negligible or low-pressure thresholds (< 1.2 km/km^2) receives a hazard score of 1; linear feature density within the moderate pressure threshold (1.2 to 3km/km^2) receives a hazard score of 2; and linear feature density in the high-pressure category (> 3 km/km^2) receives a hazard score of 3.

- Stream crossing thresholds are based on those used by the Fiera Biological Consulting (2012) and BC Interior Watershed Assessment Procedure (B.C. Ministry of Forests, 2001). According to these sources, watersheds with less than 0.4 crossings per km^2 are under low pressure or hazard, watersheds with less than 0.6 crossings per km^2 are under moderate pressure or hazard, and watersheds with more than 0.6 crossings per km^2 are under high pressure or hazard. We prepared a hazard index by applying values of 1, 2, and 3 to the low, moderate, and high categories, respectively. In addition, a hazard index of 4 was applied to watersheds with more than 0.8 crossings per km^2. The thresholds apply to all types of stream crossing structures and all sizes of streams.

- The forest age index levels (1, 2, 3) were used for the hazard index.

- Hazard scores for the flow variables (Change in max spring flow, change in annual flow, change in Aug-Sept flow, and RB Index) were based on the logic that risk increases with higher peak flow (i.e., max spring flow) and flashiness (i.e., RB Index), with lower baseflow (i.e., Aug-Sept flow), and with positive or negative changes in annual flow. The thresholds applied when calculating the hazard indices for flow variables were based on expert opinion.

- Hazard scores were not calculated for the 1:100 flood damage risk because the indicator's metric ($'s) is already a direct and easily interpreted expression of financial hazard.

Table 3. Hazard index thresholds.

Indicator	Hazard = 1	Hazard = 2	Hazard = 3
INFI	> 0.7	0.5 to 0.7	< 0.5
Wetland % of natural	> 70	50 to 70	< 50
WQI	> 0.67	0.33 to 0.67	< 0.33
Stream crossings (#/km2)	< 0.4	0.4 to 0.6	> 0.6
Linear disturbance (km/km2)	< 1.2	1.2 to 3	> 3
Change in max spring flow	<5%	5 to 10%	> 10%

Change in annual flow	-2% to 2%	-5 to -2% or 2 to 5%	< -5% or > 5%
Change in Aug-Sept flow	> -5%	-5 to -10%	< -10%
RB Index	< 5%	5 to 10%	> 10%

2.5 Simulate conservation and restoration strategies

A suite of candidate restoration and conservation strategies for improving the performance of the resilience indicators were identified by the Working Group (Appendix A). The strategies address restoration and conservation opportunities in both the green and white area portions of the basin. In the white area, where ownership is private and conversion of natural land to other uses (e.g., agriculture, residential, energy) is widespread, mitigation opportunities focus on restoring natural land cover (wetland restoration and reclamation of energy sector footprint) and excluding future development from important remaining natural areas (protecting the floodplain). In the green area, where ownership is public and the dominant landcover is forest, conservation opportunities focus on protecting the integrity of natural land cover (forest protection or reduced rate of development), limiting human access (reclaiming seismic lines and trails that are used for off-road access), and enhancing the landscape's natural capacity to deliver ecosystem services (creating wetlands). Using ALCES Online, a 50-year scenario was simulated for each strategy to assess capacity to improve indicator performance. Strategies were simulated across the entire basin and improvement in indicator performance mapped at the scale of sub-watersheds to identify where strategies can be implemented for maximum impact.

2.5.1 Wetland restoration

An estimated 190 km^2 of wetlands have been lost to farmland in the basin. The loss of wetlands was estimated based on areas that are currently cropland or pasture but were historically wetland according to the combined wetlands inventory. These areas were gradually returned to wetland during the 50-year wetland restoration simulation. As well, no wetlands were converted to farmland during the simulation.

2.5.2 Wetland creation

Due to the location past conversion of wetlands to other uses such as agriculture, the wetland restoration strategy predominantly affects areas downstream of Calgary. To explore opportunities to increase wetland function upstream of Calgary, 43 km^2 (0.5%) of the green area was converted to wetlands during the first decade of the simulation. Wetland creation was permitted in areas occurring below 1500 m elevation and where slope is less than 10%.

2.5.3 Wellsite reclamation

Wells were selected as the focus of a restoration scenario because of the prevalence of well footprint relative to other types of energy sector footprint in the basin. Wells cover more area (124 km^2) in the basin than pipelines (65 km^2), seismic lines (34 km^2) and well access truck trails (19 km^2) combined.

Non-producing wells account for over half (74 km^2) of the existing well footprint. For the restoration scenario, non-producing wells and associated access truck trails were reclaimed over a 20-year period with priority being given to older wells. Exploratory wells created during the simulation had a 20-year lifespan. Producing wells were assumed to have a 30-year active life, in addition to a 20-year post-closure reclamation period, for a total lifespan of 50 years.

2.5.4 Seismic line and trail reclamation

Seismic lines and trails were a focus of the restoration scenario because they account for more edge than all other types of footprint combined in forested portions of the study area. In the Green Area portion of the basin (i.e., public lands with the exception of Banff National Park), there are 3,178 km of seismic lines and 2,532 km of trails compared to 1,108 km of minor roads, 253 km of major roads, 179 km of truck trails, 155 km of pipeline right of ways, and 159 km of powerline right of ways. Existing seismic lines in the green area were reclaimed over a 10-year period, and new seismic had a 10-year lifespan. Existing trails located in the green area and outside of protected areas were reclaimed (2,026 km), based on the assumption that most important designated trails occur within protected areas.

2.5.5 Forest conservation

Two levels of forest conservation were simulated: protection and reduced development. In the forest protection scenario, land in green area (i.e., public land) was removed from future development. Forestry was the primary land use affected, as well as a small portion of the basin's overall gas development. In the reduced development scenario, forestry declined by 50% as a proxy for management practices (e.g., old forest retention, forest disturbance thresholds) intended to reduce the intensity of forest development. It is not anticipated that forest conservation strategies would be applied across the entire green area. Rather, the scenarios are intended to assess the effectiveness of forest conservation relative to other strategies and to identify where forest conservation may have the biggest impact.

2.5.6 Protection of the flood hazard zone

The flood hazard zone was excluded from development. Where available, flood hazard mapping was applied to delineate the flood hazard zone. If flood hazard zone mapping was not available, a 200 m buffer adjacent to major rivers was protected. The strategy resulted in protection of 3.6% (609 km^2) of the white area portion of the basin. The overall development rate did not change, but rather influenced where development was permitted to occur.

3 Results

3.1 Current and potential future watershed composition

Agricultural land (cropland and pasture) is the dominant anthropogenic feature, covering 25.4% (6,516 km^2) of the basin predominantly to the east of Calgary (Figure 7). Other types of anthropogenic footprint cover 7.2% (1,837 km^2) of the basin. Anthropogenic footprint (excluding agriculture) reaches

its highest concentration in the Calgary region, but is also abundant in the eastern portion of the basin due to the road network and gas development, and along the eastern slopes due to forestry development, hydrocarbon exploration, and rural residential. During the simulation, anthropogenic footprint increased to 9.5% (2,831 km^2), with the largest contributor to footprint expansion being urban and rural residential development. Accordingly, footprint growth was focused in the central portion of the basin near Calgary.

The average age of coniferous forest, the dominant forest type in the basin, is estimated to currently equal 105 years, with spatial variation in age caused by the legacy of fires (in the parks) and timber harvest (in the forest management units). During the simulation, average age of coniferous forest increased to 125 years.

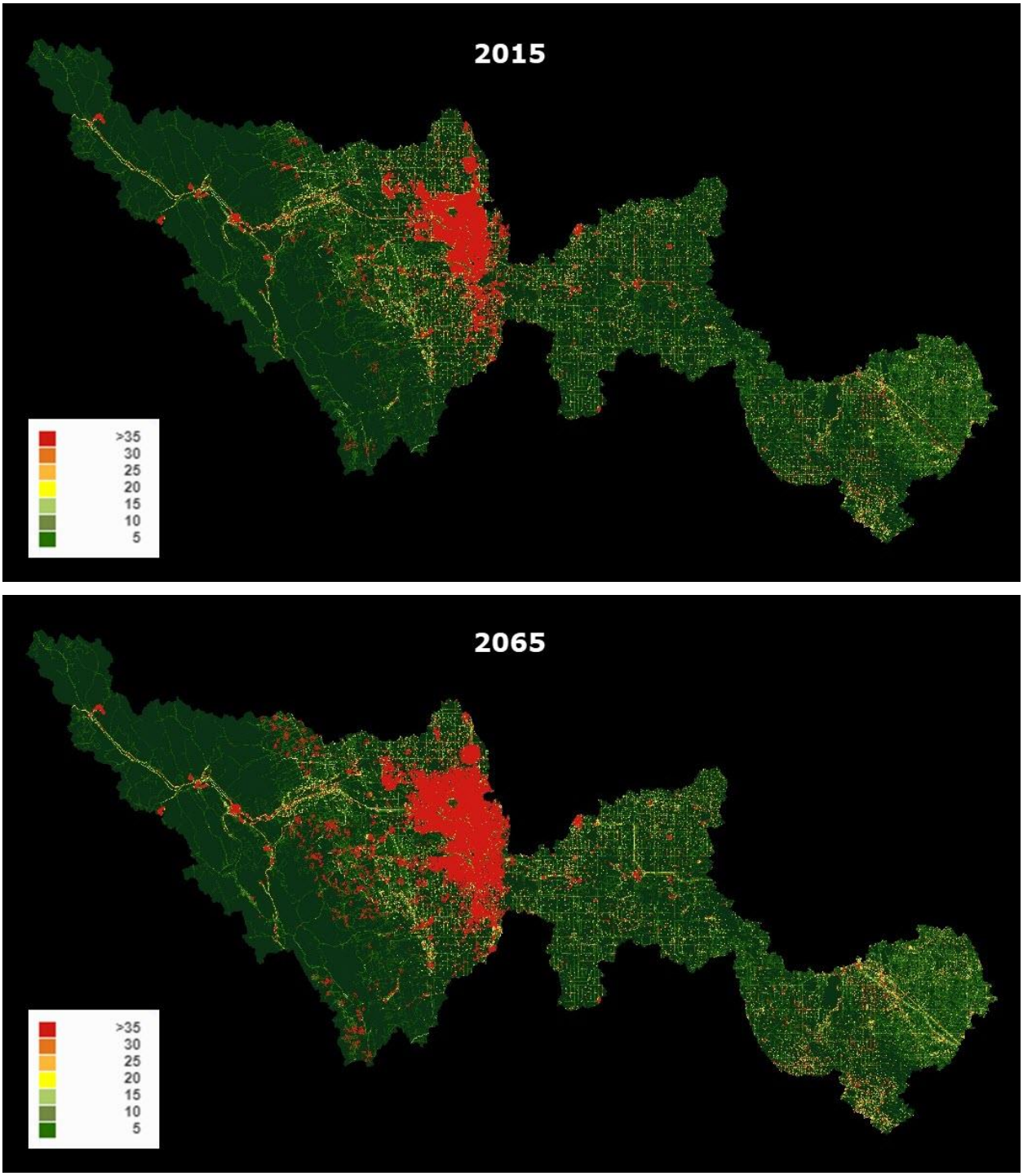

Figure 7. Current and simulated future anthropogenic footprint (not including agricultural land) under the BAU scenario.

3.2 Mitigation strategy prioritization

Following the hierarchical approach described in the methods, three types of information are presented to inform the prioritization of mitigation options: a) current hazard status and simulated change in hazard under BAU; b) a comparison of the effect of mitigation strategies on indicator performance; and c) identification of watersheds where mitigation strategies has the greatest effect on indicator performance. Taken together, this information provides managers with an understanding of current and potential future hazards, which mitigation strategies are best suited for reducing each type of hazard, and where mitigation should occur to maximize its effectiveness.

3.2.1 Current and future threats to resilience

Hazard indices were used when exploring current and future performance of resilience indicators in order to permit comparison of threats to different components of the basin's aquatic and terrestrial ecosystem. The current proportion of the basin assessed as having high hazard differed substantially across indicators. Current hazard was greatest for the wetland indicator, with 30% of the basin occurring within high hazard assessment watersheds. Other indicators for which high hazard watersheds are currently relatively abundant (~10% coverage) included linear edge, forest age, INFI, and stream crossings. None of the assessment watersheds exhibited high current hazard for the hydrology indicators because current condition was used as the baseline (i.e., low hazard) when assessing hazard. Hazard increased during the 50-year simulation for all resilience indicators with the exception of baseflow. Growth in hazard tended to be greater for aquatic indicators including INFI, stream crossings, annual flow, and WQI (Figure 8).

A map of average hazard across indicators identifies the central portion of the basin as having the lowest overall resilience (i.e., high hazard), an outcome of the high level of development in Calgary and its surrounding assessment watersheds (Figure 9).

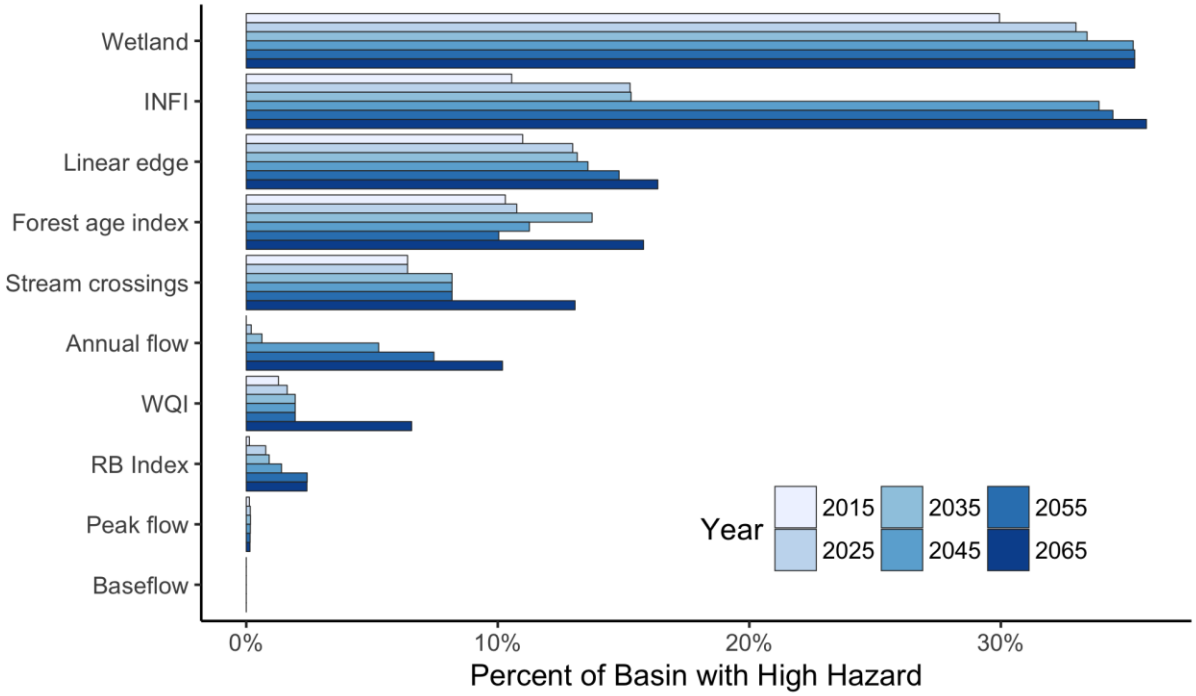

Figure 8. Current and simulated future (under the BAU Scenario) percent of the Bow Basin with a high hazard by indicator.

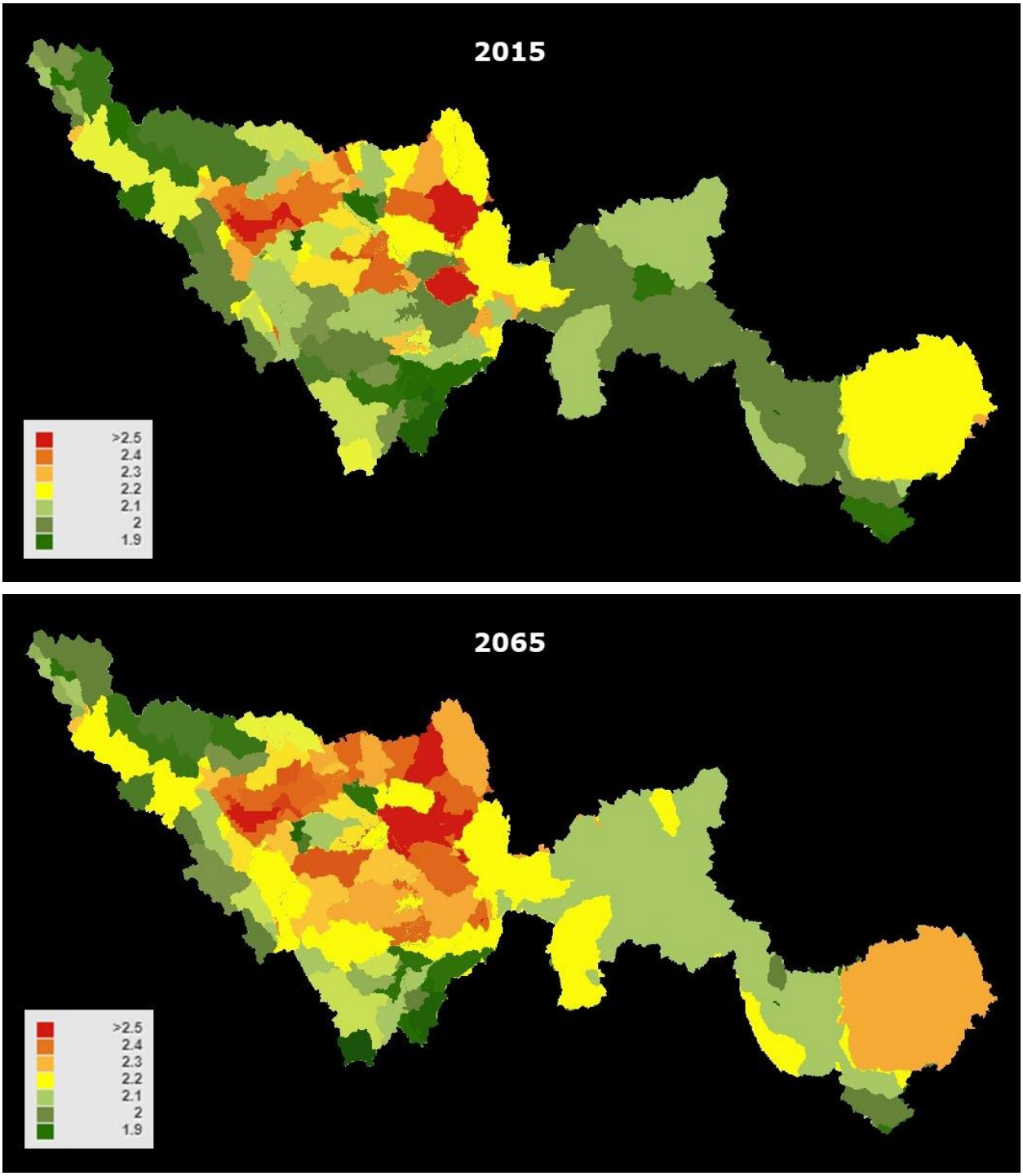

Figure 9. Current and future average hazard across all indicators under the BAU scenario.

Flood risk results are presented separately because the indicator was not converted to a hazard metric. Flood risk grew from $2.02 billion to $3.66 billion during the 50-year simulation. The 82% growth in flood risk was similar to that of residential footprint (72%) and was concentrated in Calgary and its surrounding assessment watersheds where population growth is expected to be greatest.

Maps and graphs presenting the response of each indicator are provided in Appendix E.

3.2.2 Performance of mitigation strategies

Mitigation strategies were ranked based on their mitigation effect, which was calculated as the difference between simulated indicator status with and without the mitigation strategy in place. The difference was calculated such that a reduction in impact had a positive value. For example, a positive value reflects a reduction linear disturbance and an increase in wetlands. Mitigation effect was calculated for each decade of the simulation and averaged to calculate the average mitigation effect during the simulation period. The mitigation effect achieved by an indicator's highest ranked strategy was then mapped to identify where the strategy has the highest potential to reduce impact.

3.2.2.1 Wetlands

Wetland restoration exhibited the highest mitigation effect, restoring on average 18.3% of each assessment watershed's natural wetland coverage (Figure 10). Wetland creation had the next highest mitigation effect (3.8%). The mitigation effect of other strategies was negligible. Mitigation effect of wetland restoration was highest in the eastern portion of the basin where historical loss of wetlands to agriculture is greatest. The maximum mitigation effect achieved by wetland restoration was 98% in the assessment watershed "Parflesh Creek Near Chancellor" located to the east of Strathmore (Figure11).

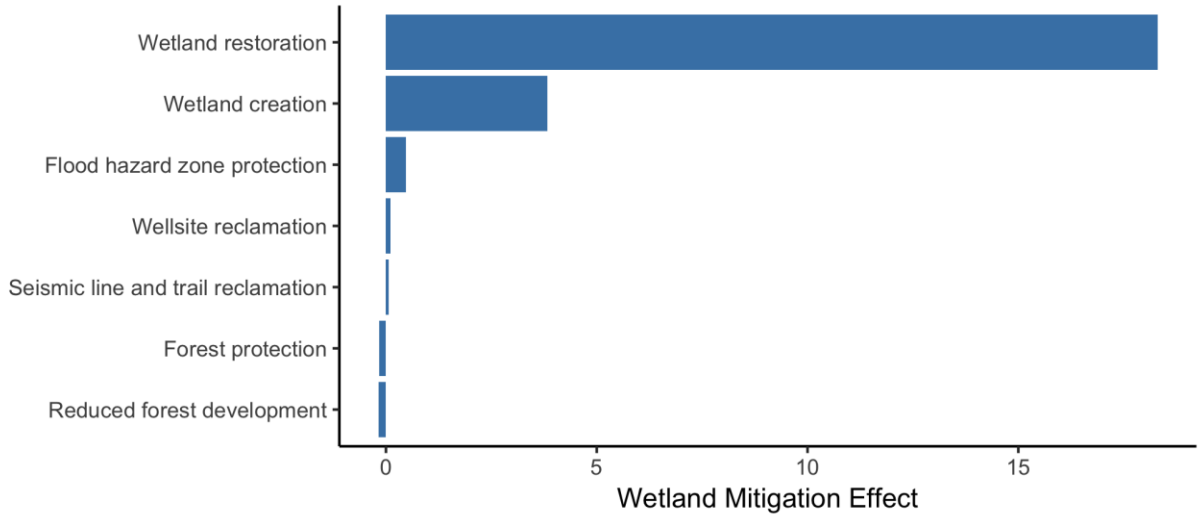

Figure 10. The capacity of each mitigation strategy to restore wetland coverage (% of natural) relative to BAU. A higher bar indicates greater mitigation potential. Mitigation effect calculated as the average effect across simulation years and assessment watersheds.

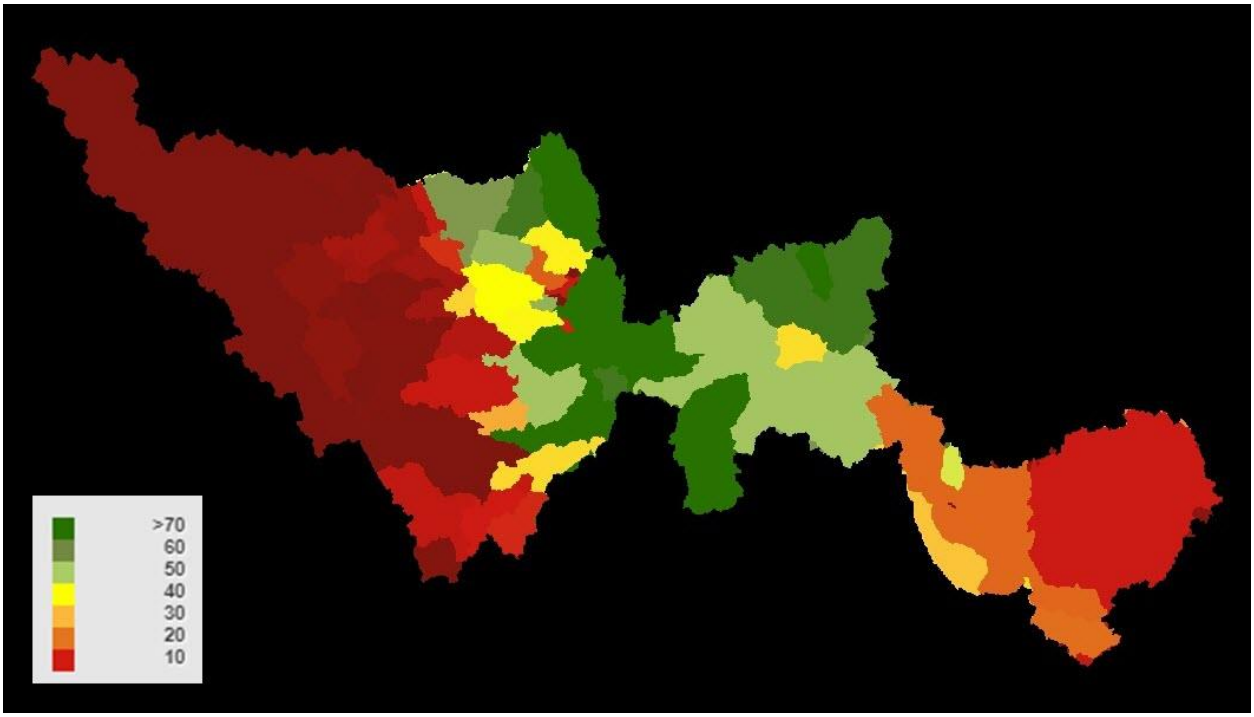

Figure 11. The capacity of the wetland restoration strategy to restore wetland coverage (% of natural) relative to BAU. A higher value indicates greater mitigation potential. Mitigation effect is for the year 2065.

3.2.2.2 Linear edge

Seismic line and trail reclamation exhibited the greatest potential to reduce linear edge density, removing 8,531 km of linear footprint and achieving an average reduction of 0.33 km/km^2 per assessment watershed (Figure 12). With the exception of a few very small watersheds (i.e., < 5km^2), the largest reduction in linear edge density was -3.1 km/km^2, which occurred at the Elbow River (Research) at Bragg Creek assessment watershed located immediately west of Bragg Creek. Mitigation effect was highest in the eastern slopes portion of the basin due to the high density of seismic lines and trails (Figure 13).

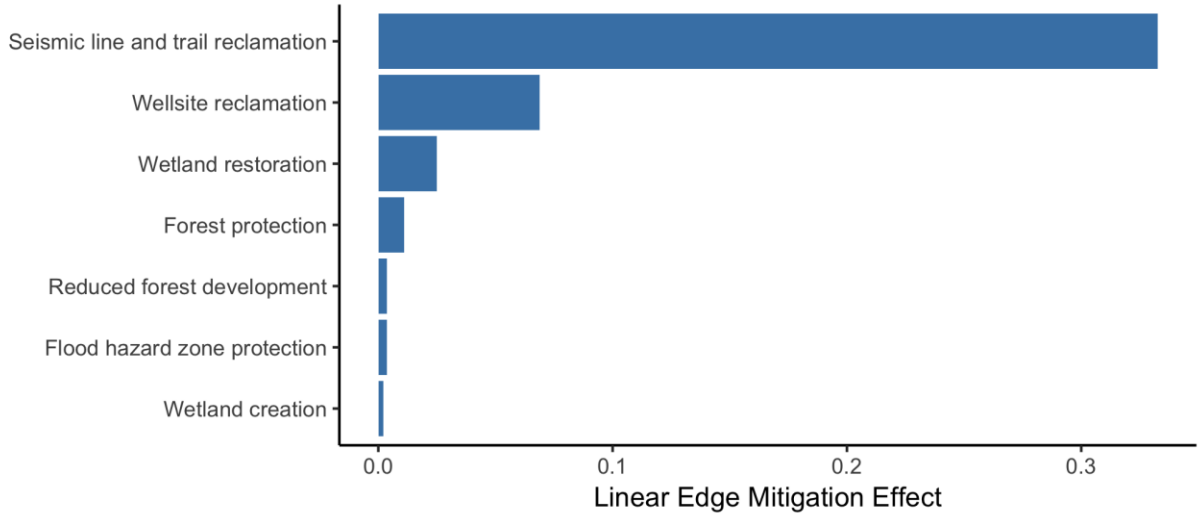

Figure 12. The capacity of each mitigation strategy to reduce linear edge density (km/km^2) relative to BAU. A higher bar indicates greater mitigation potential. Mitigation effect calculated as the average effect across simulation years and assessment watersheds.

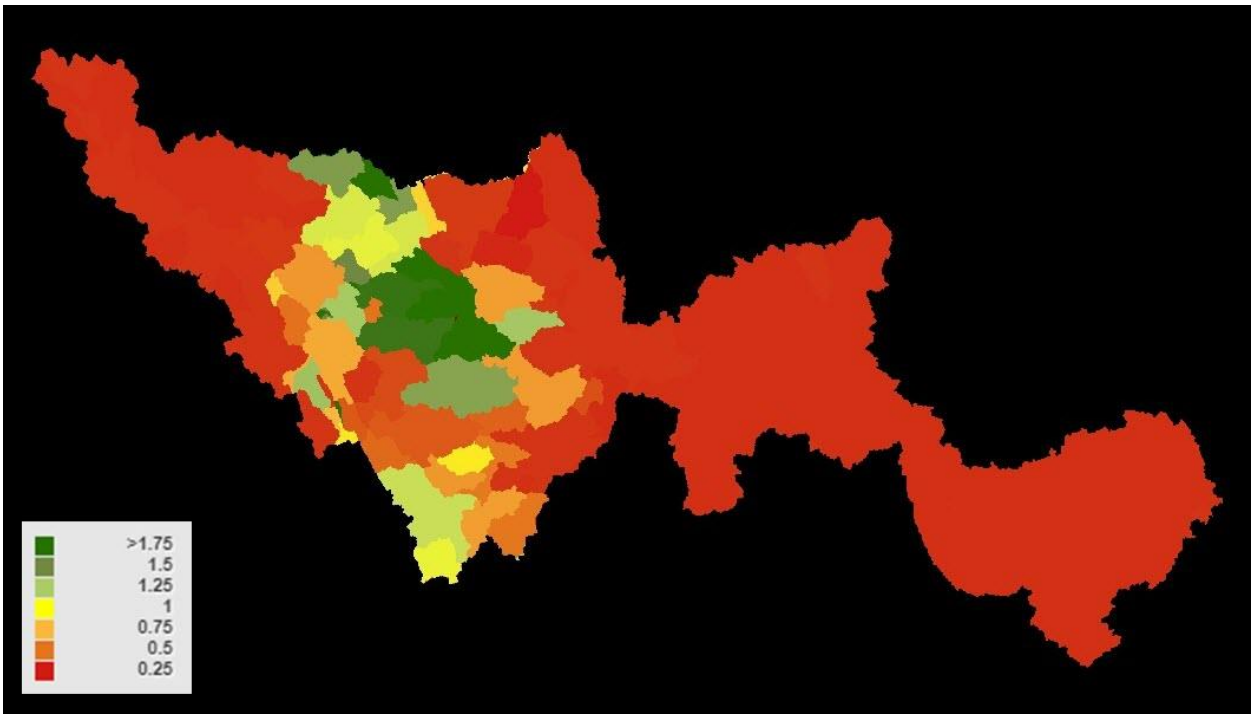

Figure 13. The capacity of the seismic line and trail reclamation strategy to reduce linear disturbance density (km/km^2) relative to BAU. A higher value indicates greater mitigation potential. Mitigation effect is for the year 2065.

3.2.2.3 Forest age index

None of the strategies displayed a capacity to reduce forest age impact, where impact refers to divergence from the natural forest age-class structure (Figure 14). Forest protection and reduced forest development caused increased divergence form the natural forest age class structure by increasing the area of old forest, which is assessed to already exceed natural levels in the forested portion of the basin.

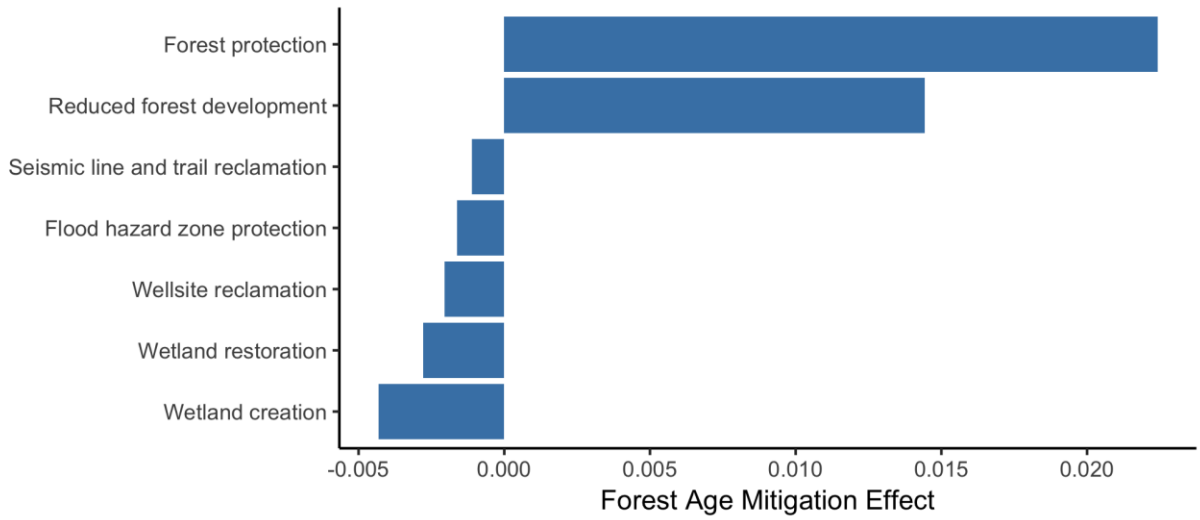

Figure 14. The capacity of each mitigation strategy to reduce the forest age index relative to BAU. Mitigation effect calculated as the average effect across simulation years and assessment watersheds. A higher bar indicates greater mitigation potential.

3.2.2.4 Index of native fish integrity

Seismic line and trail reclamation exhibited the highest mitigation effect, causing on average a 0.025 increase in the index of native fish integrity across assessment watersheds (Figure 15). Mitigation effect was substantially higher in some assessment watersheds, reaching a maximum of 0.2 at the assessment watershed Highwood River at Diebel's Ranch located in the eastern slopes to the west of Longview (Figure 16). Mitigation effect was highest in the eastern slopes due to the abundance of seismic lines and trails and the sensitivity of the index to linear disturbance in that portion of the basin (i.e., due to angler access).

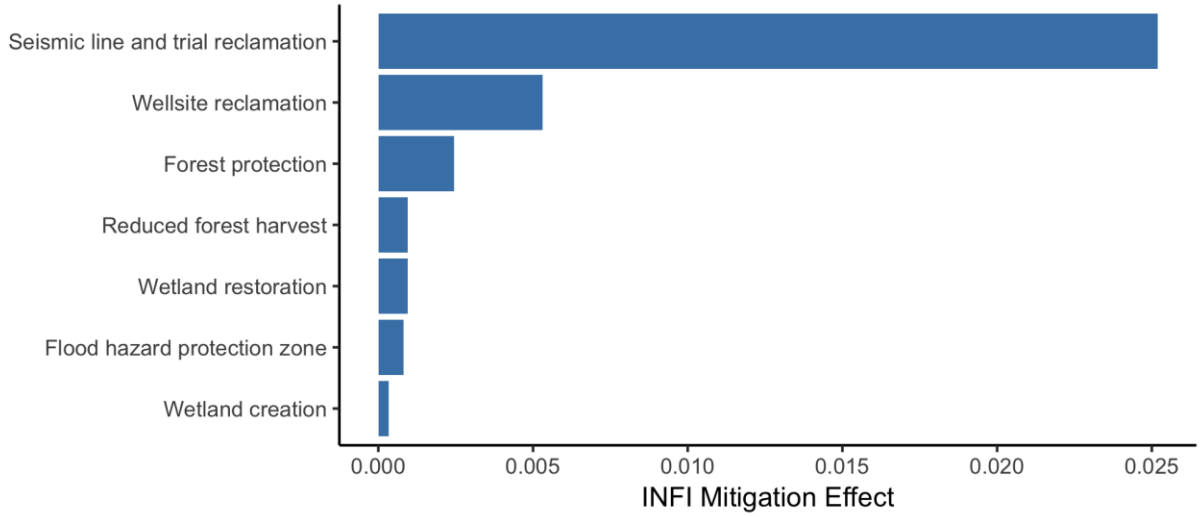

Figure 15. The capacity of each mitigation strategy to increase the index of native fish community integrity (INFI) relative to BAU. A higher bar indicates greater mitigation potential. Mitigation effect calculated as the average effect across simulation years and assessment watersheds.

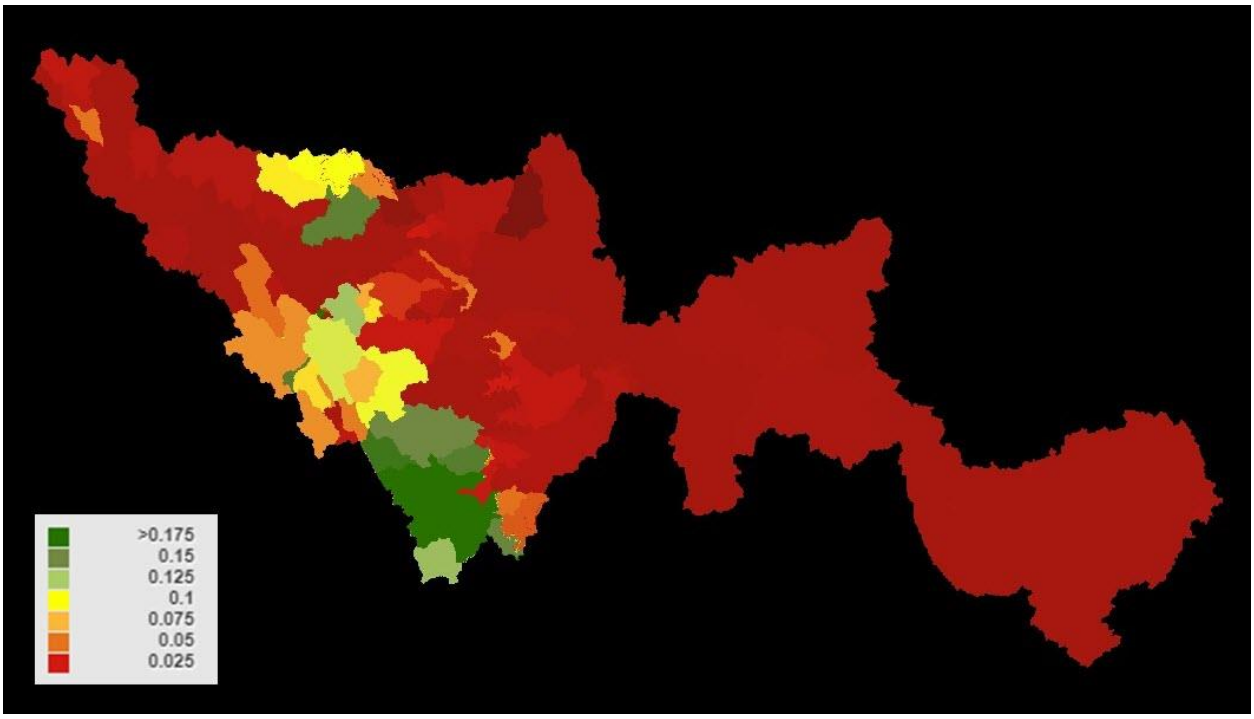

Figure 16. The capacity of the seismic line and trail reclamation strategy to increase the index of native fish community integrity (INFI) relative to BAU. A higher value indicates greater mitigation potential. Mitigation effect is for the year 2065.

3.2.2.5 Stream crossings

Wellsite reclamation exhibited the greatest potential to reduce stream crossing density (Figure 17), although the improvement was minor (average reduction of 0.014 crossings/km of stream relative to BAU). The capacity of other strategies to reduce stream crossing density was negligible. The higher performance of wellsite reclamation relative to other strategies was due to the removal of access road associated with well sites. The reduction in stream crossing density was greatest in the eastern portion of the basin where well density is highest. Maximum mitigation effect occurred in the HUC8 assessment watershed "Lower Bow and Twelve Mile Coulee" (stream crossing density reduction of 0.184; Figure 18).

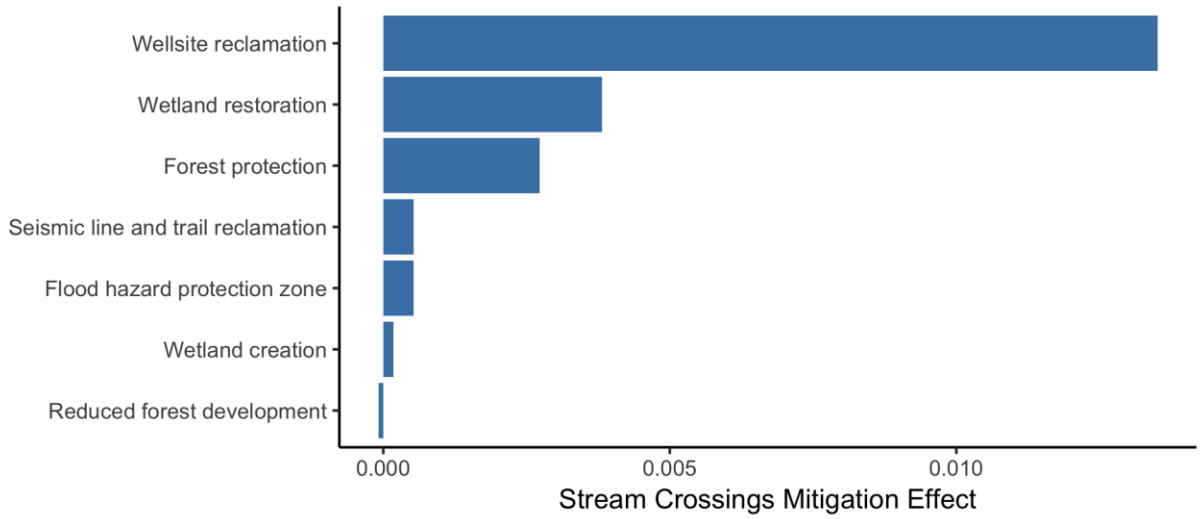

Figure 17. The capacity of each mitigation strategy to reduce stream crossing density (#/km of stream) relative to BAU. A higher bar indicates greater mitigation potential. Mitigation effect calculated as the average effect across simulation years and assessment watersheds.

Figure 18. The capacity of the wellsite reclamation strategy to reduce stream crossing density (#/km of stream) relative to BAU. A higher value indicates greater mitigation potential. Mitigation effect is for the year 2065.

3.2.2.6 Water quality index

Wellsite reclamation exhibited the greatest potential to improve the water quality index (WQI), although the improvement was minor (average increase less than 0.01 relative to BAU; Figure 19). The capacity of other strategies to improve WQI was negligible. The higher performance of wellsite reclamation relative to other strategies was due to the potential for well and associated access road footprint to elevate nutrient and sediment loading. Wellsite reclamation was highest in the eastern portion of the basin where well density is highest. Maximum mitigation effect occurred in the assessment watersheds "Bow River as the Mouth" (WQI increase of 0.13) and "Twelve Mile Creek Near Cecil" (WQI increase of 0.08; Figure 20).

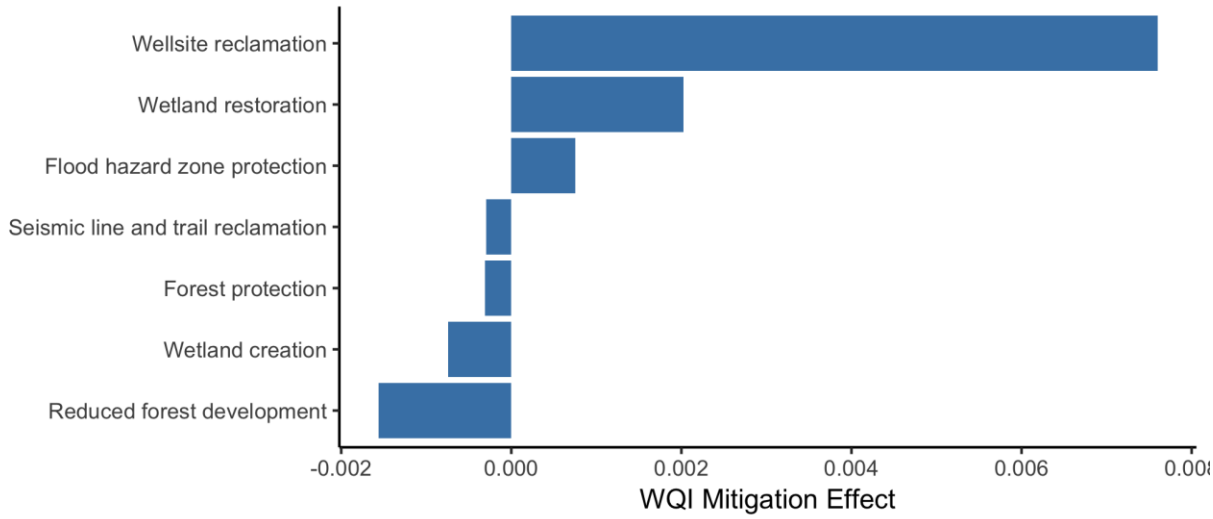

Figure 19. The capacity of each mitigation strategy to improve the water quality index (WQI) relative to BAU. A higher bar indicates greater mitigation potential. Mitigation effect is calculated as the average effect across simulation years and assessment watersheds.

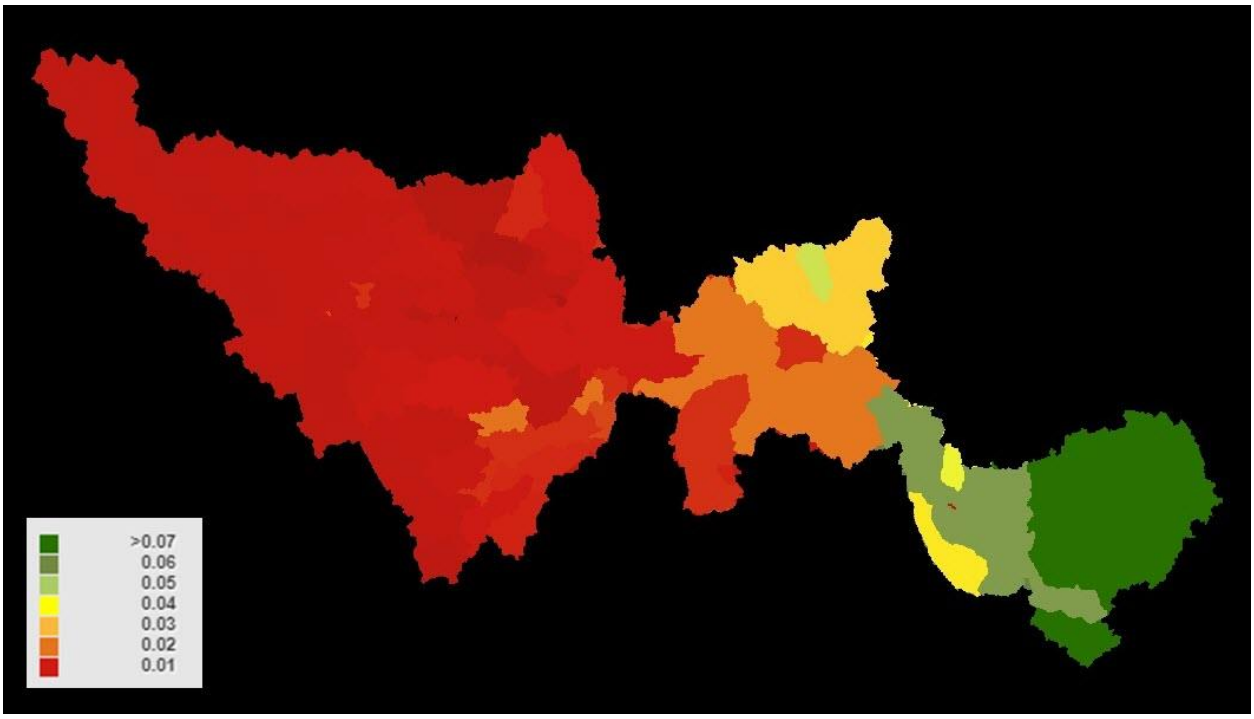

Figure 20. The capacity of wellsite reclamation to increase the water quality index (WQI) relative to BAU. A higher value indicates greater mitigation potential. Mitigation effect is for the year 2065.

3.2.2.7 Mean Annual Flow

Wetland restoration exhibited the highest mitigation effect, reducing the average change in annual flow relative to current from 0.8% to -4.1% (Figure 21). The mitigation potential of wetland restoration is due to the capacity of wetlands to store water that otherwise runs off to the lotic system. The mitigation effect of other strategies was negligible. Mitigation effect of wetland restoration was highest in the eastern portion of the basin where historical loss of wetlands to agricultural development is greatest. The maximum mitigation effect occurred in the "Highwood River Near the Mouth" assessment watershed located to the east of Okotoks, where the change in mean annual flow relative to current was -38.2% with wetland restoration compared to +19.3% without mitigation (Figure 22).

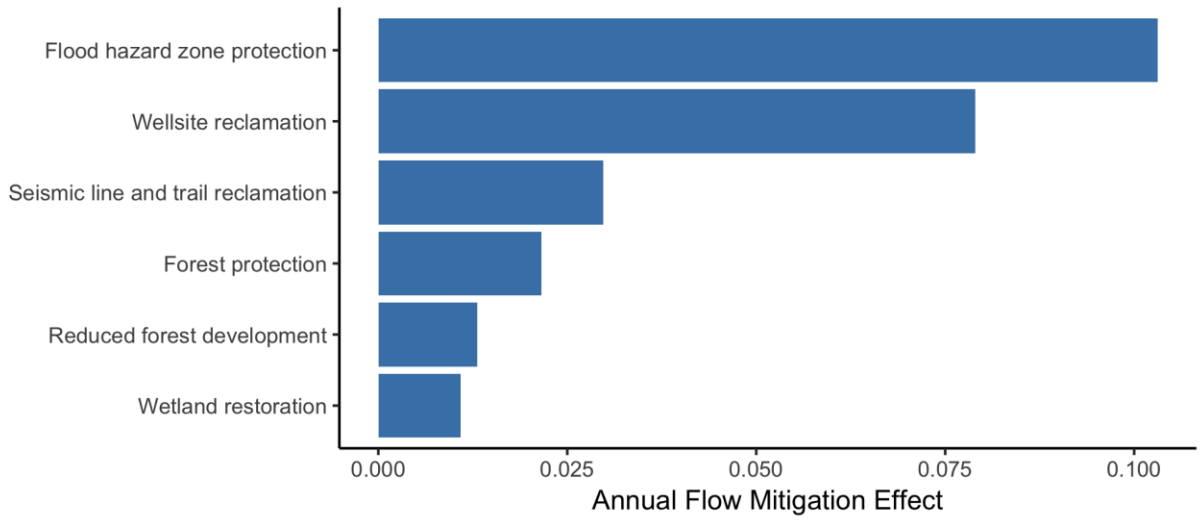

Figure 21. The capacity of each mitigation strategy to reduce the % increase in annual flow compared to current, relative to BAU. A higher bar indicates greater mitigation potential. Mitigation effect calculated as the average effect across simulation years and assessment watersheds.

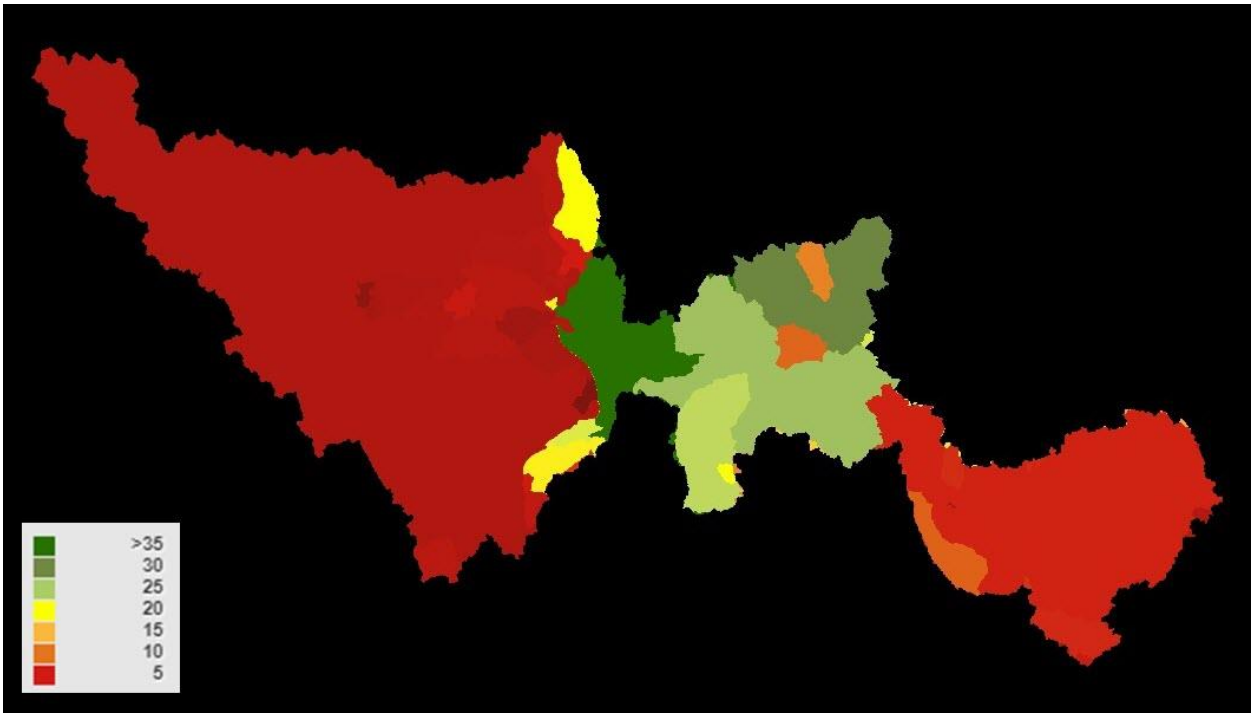

Figure 22. The capacity of wetland restoration to reduce, relative to BAU, the % increase in annual flow compared to current. A higher value indicates greater mitigation potential. Mitigation effect is for the year 2065.

3.2.2.8 RB-Index

As described previously, the RB-Index was insensitive to the land-use simulations when averaged across the study area (Figure 23). The insensitivity of the metric was largely because current condition was used as the benchmark when assessing impact and simulated future changes in landscape composition are relatively minor in comparison to the historical large-scale conversion to agriculture and settlement. However, assessment watersheds that are relatively intact did exhibit substantial change in the RB-Index if future development was simulated to occur and mitigation strategies were effective at reducing the impact. Seismic line and trail reclamation achieved the largest mitigation effect, reducing the average increase in RB Index relative to current by more than half (from 0.55% to 0.22%). The maximum mitigation effect occurring in the "Kananaskis River Near Seebe" assessment watershed to the east of Canmore, where the change in RB Index relative to current was -21.3% with seismic line and trail reclamation compared to +24.9% without mitigation (Figure 24). Other mitigation strategies with high relative performance were forest protection and wellsite reclamation. The mitigation potential of these strategies was due to the capacity of natural vegetation to intercept overland flow, thereby reducing the rate at which precipitation is transferred from the terrestrial to aquatic system. The mitigation effect was greatest in the eastern slopes portion of the basin where natural land cover, linear disturbance density, topographic relief, and precipitation are high.

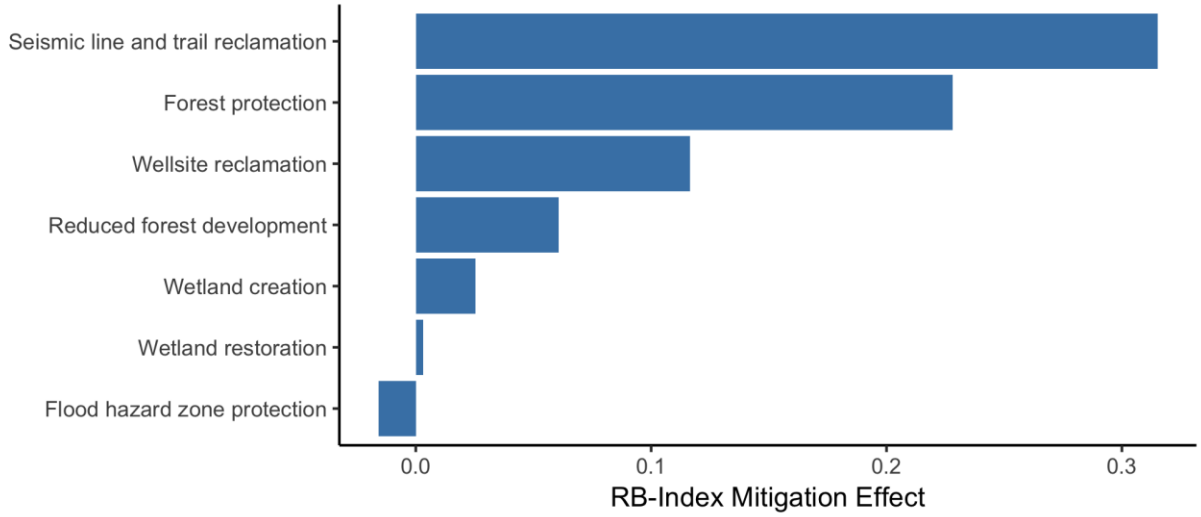

Figure 23. The capacity of each mitigation strategy to reduce, relative to BAU, the % increase in RB index compared to current. A higher bar indicates greater mitigation potential. Mitigation effect calculated as the average effect across simulation years and assessment watersheds.

Figure 24. The capacity of seismic line and trail reclamation to reduce, relative to BAU, the % increase in RB index compared to current. A higher value indicates greater mitigation potential. Mitigation effect is for the year 2065.

3.2.2.9 Maximum Annual Spring Flow

Forest protection achieved the largest peak flow mitigation effect due to the older forest's capacity to intercept precipitation and thereby moderate springtime peak flow (Figure 25). Even forest protection; however, had a small mitigation effect. The highest effect occurred in the "Cataract Creek Near Forestry road" assessment watershed located along the southern edge of the basin along the border with British Columbia. In that assessment watershed, increase in peak annual spring flow relative to current was 5.68% without mitigation and 0% with forest protection. The mitigation effect was highest in the eastern slopes where topographic relief and precipitation are relatively high (Figure 26). That said, the effect was still relatively small.

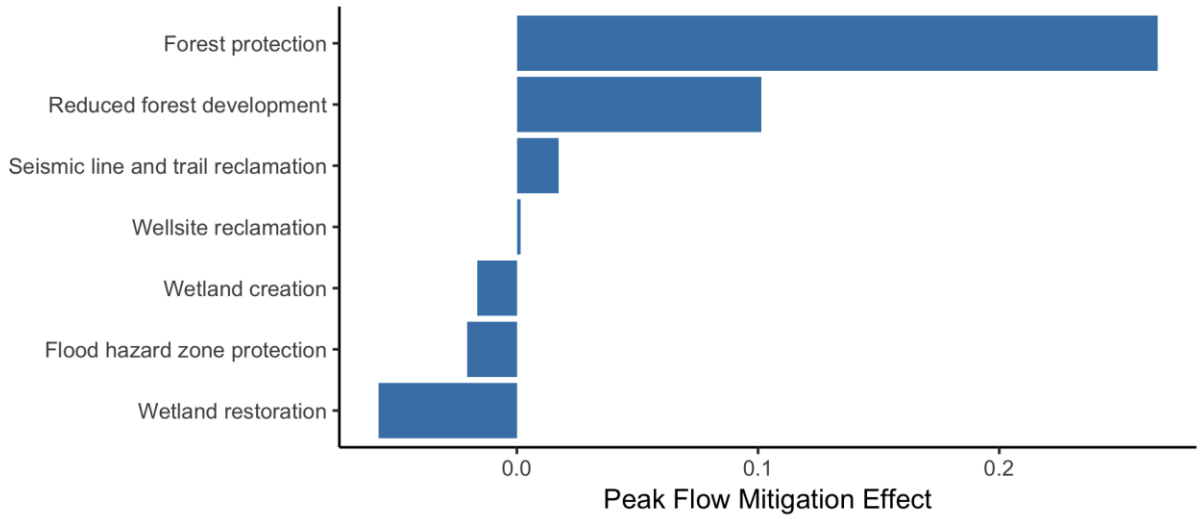

Figure 25. The capacity of each mitigation strategy to reduce, relative to BAU, the % increase in peak flow compared to current. A higher bar indicates greater mitigation potential. Mitigation effect calculated as the average effect across simulation years and assessment watersheds.

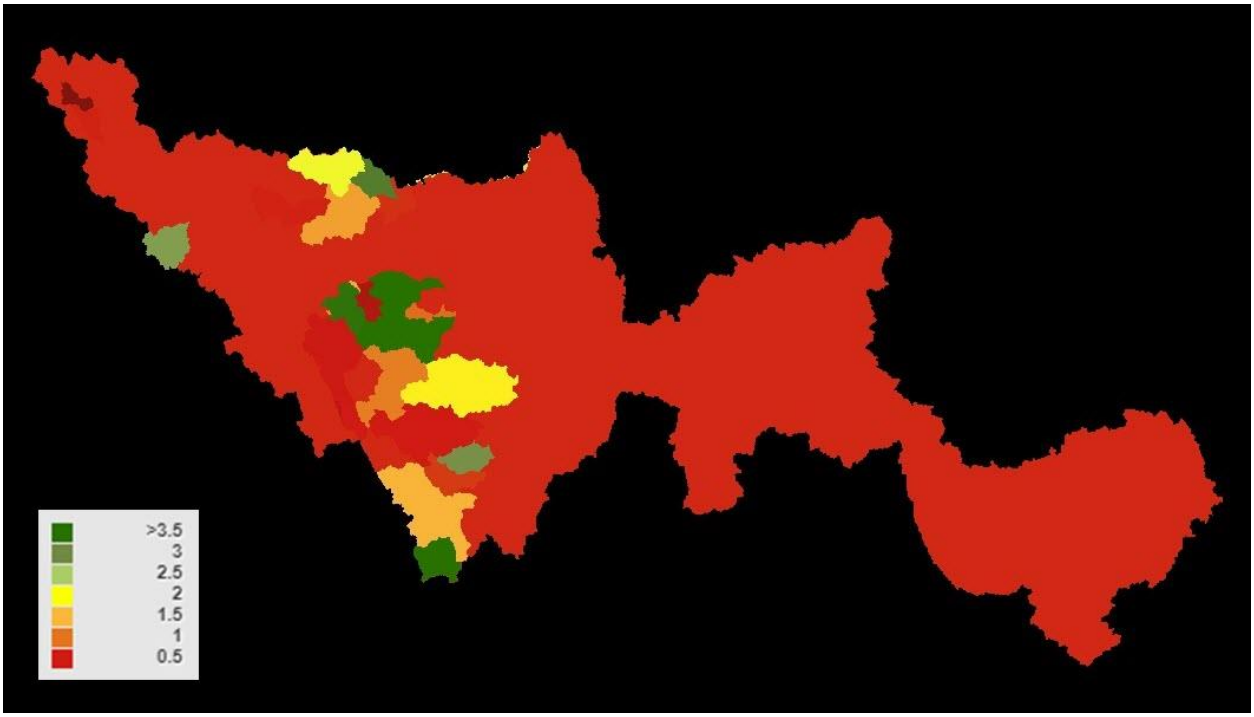

Figure 26. The capacity of forest protection to reduce, relative to BAU, the % increase in peak flow compared to current. A higher value indicates greater mitigation potential. Mitigation effect is for the year 2065.

3.2.2.10 Baseflow (mean August – September streamflow)

None of the strategies displayed a capacity increase baseflow (Figure 27). Forest protection and reduced forest development mitigation measures resulted in baseflow reductions in some assessment watersheds, due to increased interception of precipitation. These effects were small though. There were also relatively small effects of wetland restoration and other mitigation measures, but these were not noticeable at the scale assessed. However, it is likely that the effects of wetland restoration would be more noticeable at smaller spatial scales.

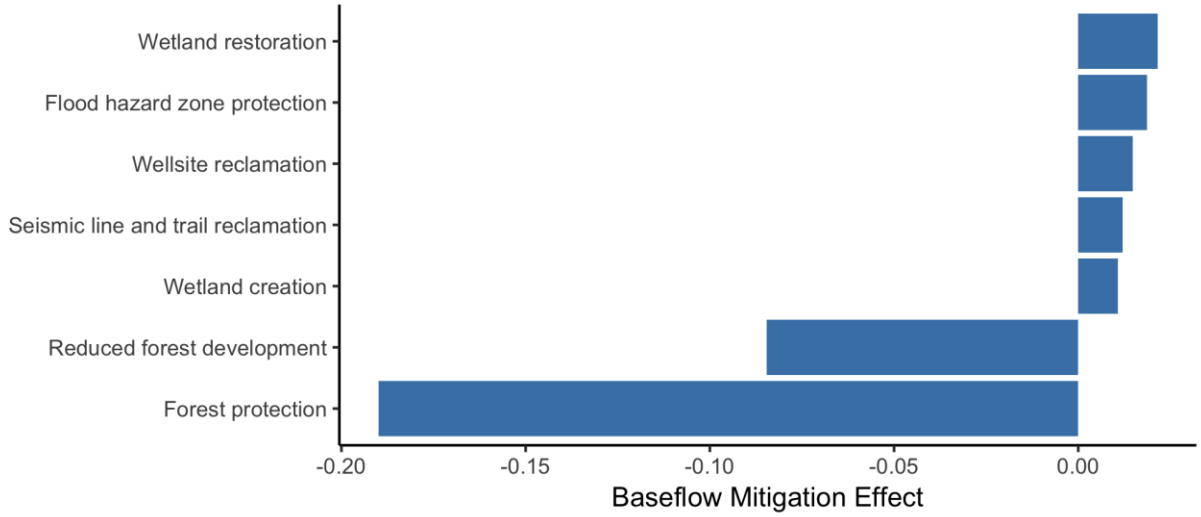

Figure 27. The capacity of each mitigation strategy to reduce, relative to BAU, the % change in baseflow compared to current. A higher bar indicates greater mitigation potential. Mitigation effect calculated as the average effect across simulation years and assessment watersheds.

3.2.2.11 Flood Risk

By the end of the simulation, protection of the flood hazard zone reduced flood risk by $1.6 billion relative to the BAU (Figure 28). Average reduction in flood risk across decades was $1.1 billion. Wetland restoration achieved the next highest mitigation effect, reducing flood risk by $453 million by the end of the simulation (average across decades of $280 million). The mitigation effect of the other strategies was negligible. The mitigation effect of flood hazard zone protection was greatest in assessment watersheds on the outskirts of Calgary, with a maximum mitigation effect per unit area at the end of the simulation of $2.6 million occurring in the assessment watershed "Elbow River Above Glenmore Dam" (Figure 29). These results suggest the most effective means of reducing flood risk assessed here is to not develop in areas where flooding is likely to occur.

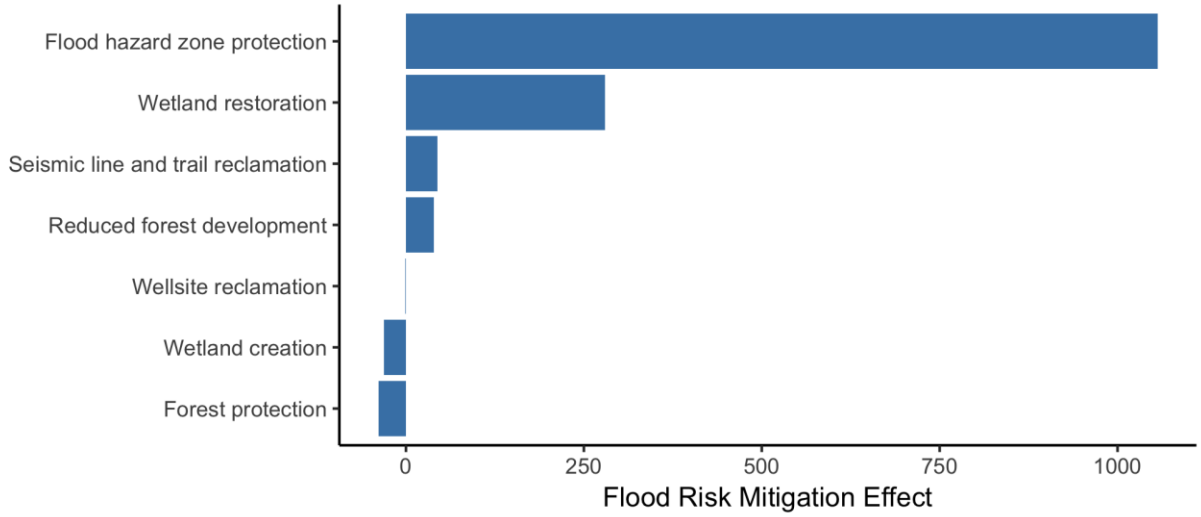

Figure 28. The capacity of each mitigation strategy to reduce flood risk (million $) relative to BAU. A higher bar indicates greater mitigation potential. Mitigation effect calculated as the average effect across simulation years and assessment watersheds.

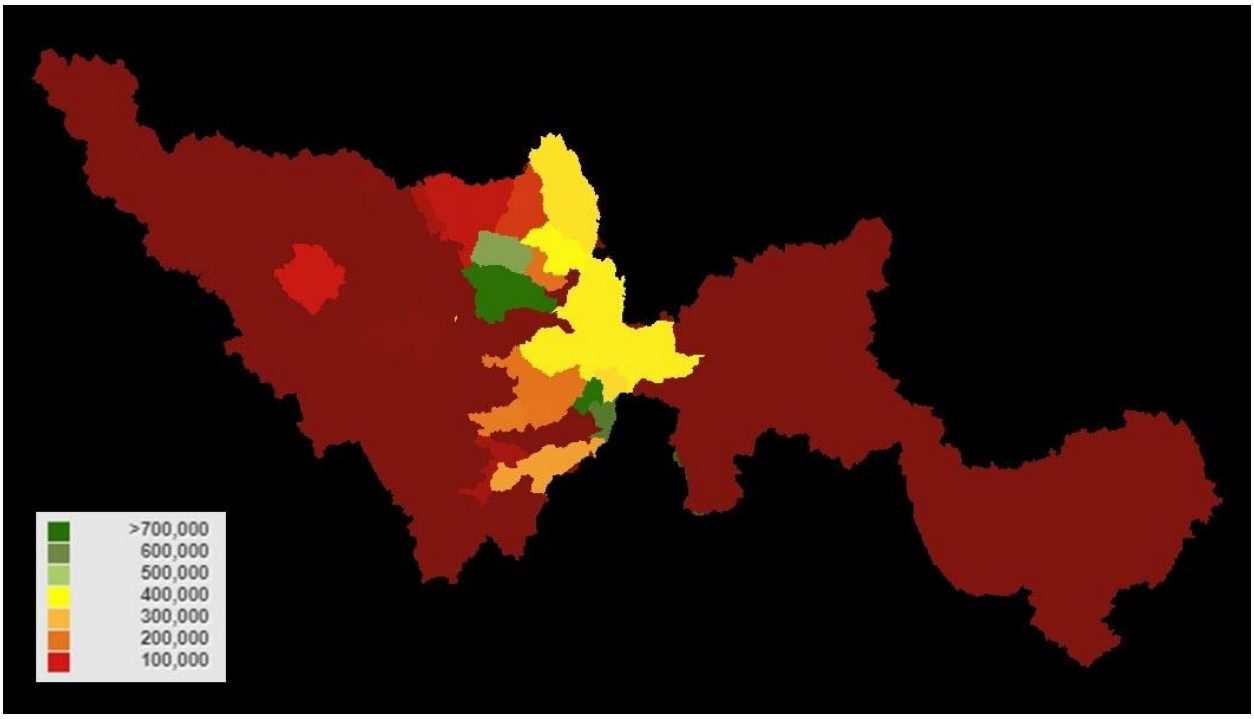

Figure 29. The capacity of flood hazard zone protection to reduce flood risk ($/km2) relative to BAU. A higher value indicates greater mitigation potential. Mitigation effect is for the year 2065.

4 Summary

The Watershed Simulation Tool for the Bow River Basin was a unique application of hydrologic and land use models, allowing for a robust and scientifically-defensible evaluation of watershed conservation and restoration strategies. Through these tools, the BRBC has the ability to provide guidance on strategic and tactical land use decisions related to watershed conservation and restoration that have the potential to influence watershed resilience.

In terms of the most effective strategies, the Watershed Simulation Tool has identified wetland restoration, linear feature reclamation, headwater forest protection, and flood hazard zone protection as providing the most potential benefit (see Table 4 below). Overall, linear feature reclamation had an effect on the greatest number of indicators. However, the effects of these strategies varied widely, depending on the indicator chosen. For example, forest protection was shown to have an effect on changes in peak streamflow; however, the relative change is extremely small. Contrary to this, wetland restoration was shown to have substantive effect on changes in annual streamflow. Although this is intuitive, it is likely to be one of the higher priority strategies that would have substantive influence on watershed resilience Table 4).

An important finding of this work is that although changes in streamflow indicators are small, conserving and restoring important watershed features has been shown to have an effect on resilience indicators chosen by the Working Group. No single strategy could be seen as the "silver bullet" in terms of watershed resilience. However, the effects of conservation and restoration strategies are cumulative, and together may form long-term strategies for maintaining or improving watershed resilience in the Bow River Basin.

Further analysis of individual priorities at the sub-watershed scale is required and can now be conducted by the BRBC and its membership to help define conservation and restoration strategies. It is the hope of the project team that the tools provided can be used on an ongoing basis to help educate the public and to provide support for decision makers across the basin.

Table 4. Summary of mitigation effectiveness. The table can be used to identify: indicators that are of greatest concern (using the % high risk status column); indicators that have the greatest potential to be improved through mitigation (using the average and maximum mitigation effectiveness columns); which mitigation strategy has the greatest potential to improve an indicator; and where the mitigation strategy has the greatest potential.

Indicator	Projected status		Mitigation strategy	Mitigation location	Mitigation effectiveness[7]	
	Value	% high risk			Average (average effect)	Maximum (maximum effect)
Wetlands (% below natural)	70.7	35	Wetland restoration	Central prairie	High	High
Linear edge (km/km^2)	2.4	16	Linear feature reclamation	Eastern slopes	Moderate	High
Forest age index	2.6	16	None	None	Negligible	Negligible
INFI	0.6	36	Linear feature reclamation	Eastern slopes	Low	Moderate
Stream crossings (#/km of stream)	0.4	13	Wellsite reclamation	Eastern prairie	Low	Moderate
Water quality index	0.7	7	Wellsite reclamation	Eastern prairie	Low	Moderate
Annual flow (% change relative to current)	1.6	10	Wetland restoration	Central prairie	High	High
RB Index (% change relative to current)	0.8	2	Linear feature reclamation	Eastern slopes	Moderate	High
Peak flow (% change relative to current)	0.3	<1	Forest protection	Eastern slopes	Moderate	High
Baseflow (% change relative to current)	1.4	<1	None	None	Negligible	Negligible
Flood risk ($)	140458	n/a	Flood hazard zone protection	Calgary region	Moderate	High

[7] A mitigation strategy's average or maximum effectiveness is assessed by dividing it's average or maximum effect by the indicator's projected value in 2065 under the future scenario. Effectiveness categories are as follows: >0.5=High; 0.1-0.5=Moderate; <0.1=Low; <0.01=Negligible. When assessing effectiveness for wetlands, WQI, and INFI, the indicator's projected value is expressed in terms of how much it is below the highest possible value.

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Appendix A – Working Group Membership

Workshop participant	Affiliation
Alan Breakey	Action for Agriculture
Andy Lamb	Alberta Environment and Parks
Andrew Wilson	Alberta Environment and Parks
Brad Stelfox	ALCES
Breana Jones	Ducks Unlimited Canada
Carolyn Campbell	Alberta Wilderness Association
Cathy Maniego	Alberta Environment and Parks
Emma Hawksworth	Foothills Research Institute
Flora Giesbrecht	Elbow River Watershed Partnership
Gerry Guy	Agriculture and Agri-Food Canada
Jason Mogilefsky	Spray Lakes Sawmills
Jerry Brunen	Western Sky Land Trust
Katie Morrison	Canadian Parks and Wilderness Society
Kelley Kissner	Green Fuse Inc.
Kevin Brayford	Alberta Environment and Parks
Kevin Van Tighem	Independent participant, BRBC member
Kristina Wantola	Cows and Fish
Lesley Peterson	Trout Unlimited Canada
Marina Krainer	Ghost Watershed Alliance Society
Mark Bennett	Bow River Basin Council
Matt Carlson	ALCES Group
Megan Van Ham	Alberta WaterSMART
Michael Wagner	Alberta Agriculture and Forestry
Mike Murray	Bow River Basin Council
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Milana Simikian	Ducks Unlimited Canada
Monique Dietrich	Alberta Environment and Parks
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Quincy Brown	Calgary Regional Partnership
Rachelle Haddock	Miistakis Institute
Richard Phillips	Bow River Irrigation District/Alberta Irrigation Projects Association
Rick Wiljamaa	Rockyview County
Ron McMullin	Alberta Irrigation Projects Association
Ryan MacDonald	Alberta WaterSMART and ALCES Group
Sandra Code	Alberta Environment and Parks
Shirley Pickering	Integrated Highwood Management Public Advisory Committee

Appendix B - Land Use Simulation Assumptions

Assumptions used to simulate plausible 50-year trajectories for land use and natural disturbance are described below.

Oil and Gas

The rate of oil and conventional gas well completions was based on projections developed by the Alberta Energy Regulator (AER) for 2016 to 2025 (Alberta Energy Regulator 2016). The projections are provided by the AER by Petroleum Services Association of Canada (PSAC) region. PSAC regions 1, 2, and 3 occur partially within the Bow River Basin. Projections were scaled to the study area based on the proportion of each PSAC's oil and gas deposits occurring within the basin according to the Geological Survey of the Western Canadian Sedimentary Basin (Mossop and Shetsen 1994). After 2025, year over year percent change in oil and gas well completions from 2026 to 2040 was assumed to equal year over year percent change in Alberta oil and gas production as projected by National Energy Board (NEB) (NEB 2016). NEB provides projections for light and heavy oil production. Annual change in light oil production was applied when preparing the completion trajectory for horizontal oil wells, and annual change in heavy oil production was applied when preparing the vertical oil well completion trajectory. For PSAC Region 3, completions were separated into horizontal and vertical wells using information provided by the AER. Although completions for PSAC Region 2 are not separated into horizontal and vertical, the completions were assumed to be horizontal given the focus on horizontal drilling in these areas. Completions in PSAC Region 1 were assumed to be vertical. Year over year percent change in well completions from 2041 onwards was assumed equal to that projected for 2040. Within each PSAC region, the simulated location of oil and gas completions was informed by the location and size of oil deposits according to the Geological Survey of the Western Canadian Sedimentary Basin (Mossop and Shetsen 1994).

The rate of Coal Bed Methane (CBM) and shale gas completions during the first decade of the simulation was based on projections developed by the AER for 2016 to 2025 (AER 2016). After 2025, year over year percent change in well completions from 2026 to 2040 was assumed to equal year over year percent change in Alberta CBM and shale gas production as projection by NEB. Year over year percent change in well completions from 2041 onwards was assumed equal to that projected for 2040. Projections were scaled to the Bow River Basin based on the proportion of estimated reserves occurring within the basin. For CBM, the basin contains portions of Horseshoe Canyon subdivision 1 and 2; based on the proportion of each subdivision occurring within the basin, and the remaining established reserves of each subdivision, the basin is estimated to contain 13.5% of provincial CBM reserves. CBM completions were distributed between subdivisions 1 and 2 according to the distribution of remaining established reserves. Based on relative reserve size estimates informed by ERCB (2012), the basin is estimated to contain 2% of shale gas reserves. Completions occurred within the shale gas deposit.

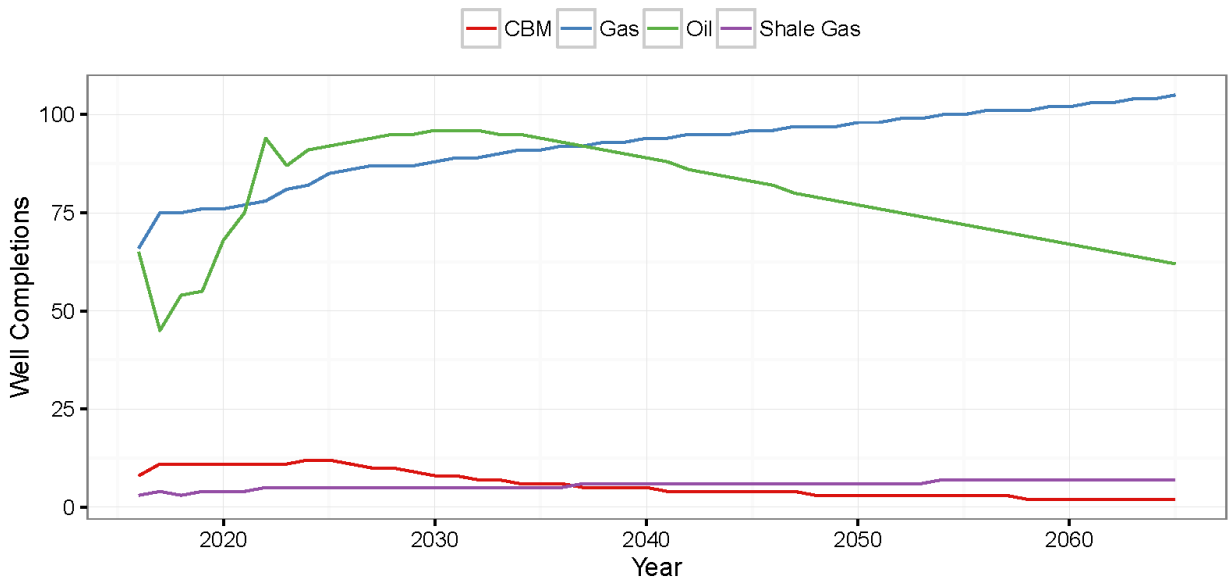

Figure 30. Well completion trajectories applied in land use simulations.

The length of seismic line, the number of exploratory wells, and the area of industrial plant associated with each well were based on the relationships between these features in Alberta. Canadian Association of Petroleum Producers (CAPP) Statistical Handbook Table 1.3b; CAPP 2015) indicates that, over the past decade (2006 to 2015), there have been 20,041 exploratory wells and 103,428 development wells drilled in western Canada for an average of 0.194 exploratory wells per development well. From 2000 to 2009, 114,497 wells were completed (CAPP, 2015) and 277,061 km of seismic line was created, for an average rate of 2.42 km of seismic line per well. Data from 2000 to 2009 were used because that is the most recent decade for which date of seismic creation data were available (Alberta Biodiversity Monitoring Institute 2016). Seismic footprint was not created in the white zone due to the prevalence of agricultural and grassland areas where disturbance from seismic does not persist. The size of well pads was 1 ha for conventional oil and 0.1 ha for conventional gas, CBM, and non-producers. Each productive conventional oil and gas well (including CBM) well occupied a 0.1 ha well pad. Multiple wells per pad were simulated for shale gas, with four wells occurring at each 2 ha pad (Nishi and Antoniuk 2010). Each production well was associated with 0.2 km of access road. Pipelines were not created because the majority of energy development in the basin occurs in the white zone where pipeline footprint will be recovered to agricultural use. Restoration of energy sector footprint is limited in the region, as demonstrated by the large accumulation of energy sector footprint and the existence of energy sector footprint (e.g., wells) in the basin. Energy sector footprint was permanent within the context of a 50 year simulation. As such, Business As Usual (BAU) reflects a scenario where effort is not allocated to reclaim energy sector footprints (Figure 30).

Aggregate

Gravel and sand production in Alberta in 2015 was 73,800 kilotonne kt (Natural Resources Canada 2016). Since the 1990's, production has increased by approximately 1,849 kt/year. This growth rate was applied to increase sand and gravel production through time, after adjusting for the proportion of the provincial gravel pit footprint occurring within the Bow Basin. Of the 340.4 km2 of gravel pit footprint in Alberta (according to ALCES Online), 40.6 km2 (11.9%) occurs in the Bow Basin. Applying this proportion resulted in a production trajectory of 220.8 kt/year for the basin.

The majority of production is assumed to be gravel as opposed to sand, given the presence of 339 km2 of gravel mines in Alberta but only 2.5 km2 of sand mines [8]. Assuming an average economic deposit depth of 5 m and a yield of 1.7 tonne/m3[9] , a kt of gravel production requires the disturbance of 117.6 m2. This factor was applied to convert the simulated production trajectory (tonne/year) to footprint creation (m2/year). The size of each gravel pit was 12.5 ha, based on the average current size of a gravel mine in Alberta. Future gravel pits were distributed across census divisions in proportion to the current distribution, and were constrained to occur in the location of aggregate deposits. Gravel pits were excluded from protected areas.

Forestry

Eight compartments from the Spray Lake Sawmills Forest Management Area occur wholly or partially within the study area: Atkinson Creek, B9 Quota, Burnt Timber Creek, Ghost River, Highwood River, Jumpingpound Creek, McLean Creek, and Sullivan Creek. Simulated forest harvest area for each compartment was as per that scheduled for the Preferred Forest Management Strategy as presented in Chapter 8 of the Spray Lake Sawmills Detailed Forest Management Plan (DFMP). The DFMP provides harvest area by compartment for multi-year intervals from 2001 to 2198 (Figure 31). For a given multi-year interval, harvest area was assumed to be equal distributed across years within the multi-year interval. Atkinson Creek, Burnt Timber Creek, and B9 Quota are only partially within the Bow River Basin. Annual harvest area for these compartments was adjusted based on the proportion of each occurring within the basin. Harvest rules were also based on the Spray Lakes Sawmills DFMP, including harvest sequencing by forest age, a minimum harvest age of 80 years, avoidance of slopes steeper than 45 degrees, and a maximum block size of 100 ha[10]. Roads were built during the simulation to connect harvest blocks to the road network. In-block roads were assumed to recover with forest post-harvest, and were therefore not tracked as a footprint. Harvest blocks regenerated to their pre-harvest forest type without a regeneration delay.

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[8] Based on a compilation of anthropogenic footprint inventories that was prepared for ALCES Online. Sources of inventories indlude: AEP, ABMI, AltaLIS, CanVec, and GVI.

[9] Table 1 of the document 2013_11_08_Full_Report_Aggregate_Supply_Demand_Update_and_Analysis.

[10] The spatial harvest sequence prepared for the DFMP identified only one block larger than 100 ha.

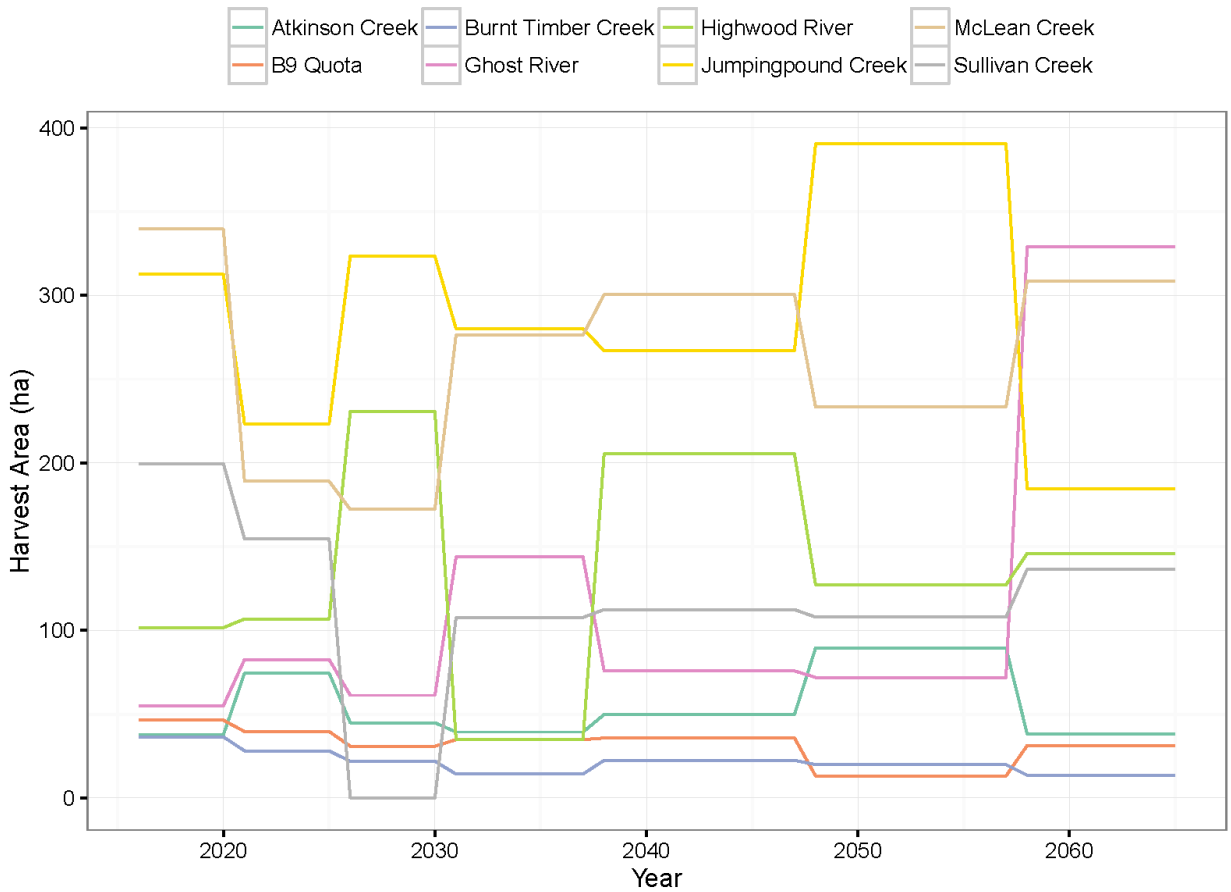


Figure 31. Harvest area projections applied in land use simulations.

Settlements

The future population growth rate within the study area was based on the medium population growth projection from Alberta Government for the period of 2016 to 2041 (Alberta Treasury Board and Finance 2016). The population projection was extended out to 2065 by assuming a constant population growth rate after 2041 (Figure 32). The projection is provided by the Alberta Government by Census Division (CD). CD's overlapping the study area are 2, 5, 6, and 15[11]. Urban and acreage (but not farm) settlement footprint within a CD was expanded at the same rate as the CD's population growth rate.

[11] A small portion of CD 1 also occurs within the study area, but the overlapping portion does not contain any settlements.

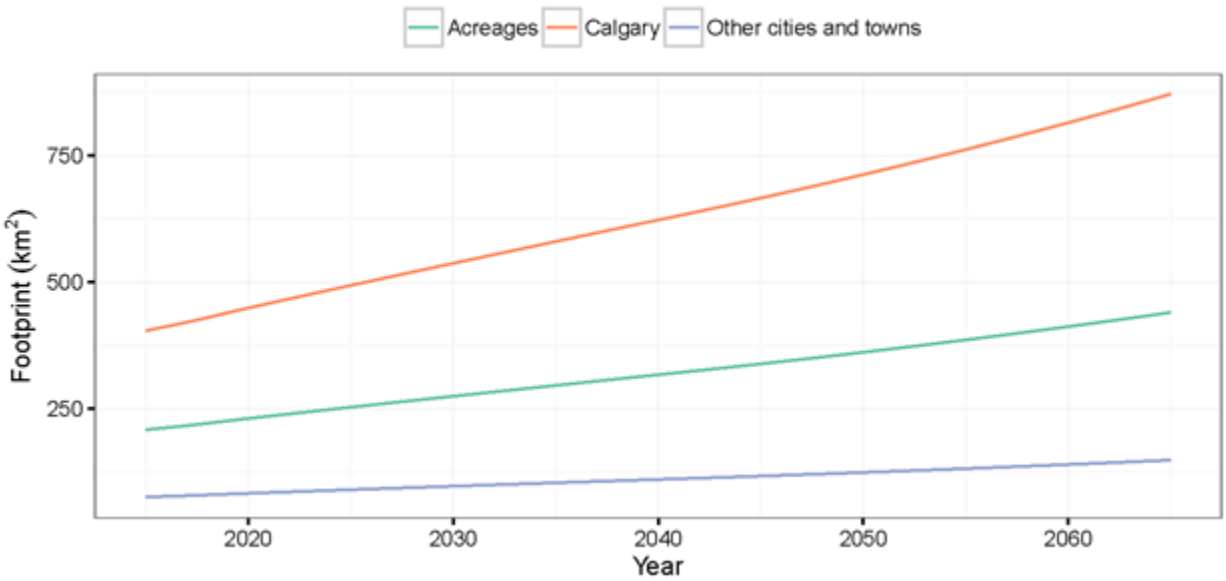


Figure 32. Settlement footprint projections applied in land use simulations.

The majority of settlement growth occurred in CD 6 where Calgary is located. Towns and cities grew outwards at their CD's growth rate, initially within municipal boundaries and thereafter to the periphery of municipal boundaries (if required). Rural residential development consisted of acreages within 1 km of existing acreage footprint and excluding public lands, protected areas, cities, and towns (Figure 32).

Recreation

Simulation of recreation footprint focused on golf courses, which account for 62% of the recreation footprint in the province[12]. The simulated expansion of golf course footprint was proportional to the expansion of urban and rural residential footprint, based on the current ratio between golf course footprint and urban/rural residential footprint in each census division[13]. Golf courses were simulated as either 0.5 km2 (54% of new golf courses) or 1 km2 (46% of new golf courses) based on the current

[12] 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.

[13] The ratio of golf course to urban/rural residential footprint within each census division is: CD1=0.022, CD2=0.021, CD3=0.021, CD4=0.009, CD5=0.016, CD6=0.044, CD7=0.015, CD8=0.015, CD9=0.006, CD10=0.018, CD11=0.029, CD12=0.011, CD13=0.009, CD14=0.038, CD15=0.28, CD16=0.044, CD17=0.01, CD18=0.022, and CD19=0.017.

size class distribution of golf courses in the province[14]. Golf courses were located within 30 km of cities and towns, a buffer that accounts for 92% of current golf course footprint in Alberta[15].

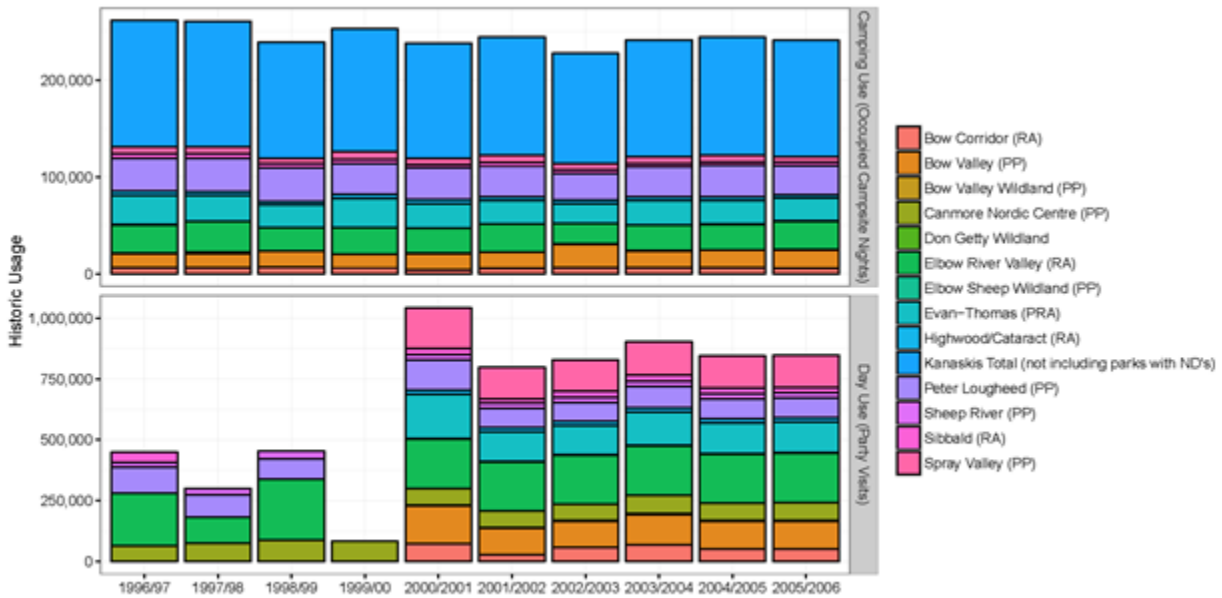


Figure 33. Recent trends in visitation for camping and day use.

Increased use of recreation areas was also considered as a land use to include in simulations. However, after reviewing visitation statistics for parks (Figure 33)[16], it was determined that this was not required. Day use and camping use in parks declined slightly in recent years, despite the growing population in the Calgary region.

Agriculture

Cropland and pasture declined during the simulation due to conversion to expanding settlement. Expansion of cropland and pasture to compensate for loss of farmland to settlement was assumed to occur elsewhere in Alberta, with the exception of ongoing draining of wetlands with cropland. Between 1990 and 2010, an average of 0.53 km2/year of wetland was converted to cropland in the Bow River Basin based on comparison of the 1990 and 2010 land use data sets (Agriculture and Agri-

[14] 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.

[15] 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.

[16] Visitation statistics were obtained from the most recent report available from the Government of Alberta website: "Visitation Statistics Provincial Parks & Recreation Areas 2005/06 Fiscal Year".

Food Canada 2016). Wetlands were assumed to be lost at this same rated during the future simulation.

Wildfire

Percent annual area burned was based on Alberta's historical wildfire data (1931 to 2011) for Foothills, Mountain, and Parkland regions. The average burn rate over the past 80 years outside of the Boreal Region was 0.19%/year, which is substantially lower than the estimated natural burn rate of 1.1%/year (Johnson and Larsen 1991). Wildfire was simulated deterministically. Burns were distributed across size classes based on the size class distribution of fires according to Alberta's historical wildfire data.

Appendix C – Phosphorus, Nitrogen, and Sediment Runoff Coefficients (Donahue, 2013)

Landscape/footprint type	Phosphorous runoff (kg/ha/year)				
	Boreal	Mountain	Foothills	Grassland	Shield
Forest	0.29	0.49	0.37	0.23	0.23
Shrubland	0.39	0.67	0.5	0.31	0.32
Grassland	0.04	0.11	0.07	0.04	0.04
Exposed/rock/snow	0.2	0.2	0.2	0.22	0.2
Water/wetland	0	0	0	0	0
Cropland (with manure application)	6.105	33.58	3.789	.158	na
Cropland (without manure application)	0.152	.194	.042	.042	na
Pasture (with manure application)	6.105	.194	3.789	.238	na
Pasture (without manure application)	0.152	.194	.042	.042	na
Major road	1.47	2.51	1.89	1.17	1.19
Minor road/inblock road	5.68	9.66	7.3	4.53	4.6
Small pit	0.32	0.54	0.41	0.25	0.26
Transmission line	0.63	1.07	0.81	0.5	0.51
Feedlot	152.06	258.73	195.51	121.26	123.21
Recreation facility	0.88	1.49	1.13	0.7	0.71
Rural residential	0.12	0.21	0.16	0.1	0.1
Town	0.8	1.35	1.02	0.63	0.64
Industrial	0.86	1.47	1.11	0.69	0.7
Seismic line	0.47	0.8	0.61	0.38	0.38
Pipeline	0.94	1.61	1.21	0.75	0.77
Well	3.23	5.5	4.16	2.58	2.62
Energy mine	0.32	0.54	0.41	0.25	0.26

Landscape/footprint type	Nitrogen runoff (kg/ha/year)					
	Boreal	Parkland	Mountain	Foothills	Grassland	Shield
Forest	1.6	1.52	2.72	2.05	1.27	1.29
Shrubland	2.17	2.07	3.7	2.79	1.73	1.76
Grassland	0.2	0.19	0.51	0.32	0.16	0.16
Exposed/rock/snow	2.95	2.95	2.95	2.95	7	2.95
Water/wetland	0	0	0	0	0	0
Cropland (with manure application)	16.40	6.232	72.54	10.819	1.228	na
Cropland (without manure application)	1.391	0.661	0.967	0.334	0.334	na
Pasture (with manure application)	24.6	9.348	108.8	16.23	1.842	na
Pasture (without manure application)	2.087	0.991	1.451	0.501	0.501	na
Major road	46.08	43.92	78.4	59.24	36.74	37.33
Minor road/inblock road	6.75	6.44	11.49	8.68	5.39	5.47
Small pit	2.49	2.37	4.24	3.2	1.99	2.02
Transmission line	1.62	1.55	2.76	2.09	1.29	1.31
Feedlot	759.84	724.19	1292.86	976.93	605.92	615.65
Recreation facility	5.27	5.03	8.97	6.78	4.2	4.27
Rural residential	1.48	1.41	2.52	1.9	1.18	1.2
Town	5.19	4.95	8.84	6.68	4.14	4.21
Industrial	6.69	6.37	11.38	8.6	5.33	5.42
Seismic line	1.22	1.16	2.07	1.56	0.97	0.99
Pipeline	2.43	2.32	4.14	3.13	1.94	1.97
Well	6.42	6.11	10.92	8.25	5.12	5.2
Energy mine	2.49	2.37	4.24	3.2	1.99	2.02

Landscape/footprint type	Sediment runoff (kg/ha/year)					
	Boreal	Parkland	Mountain	Foothills	Grassland	Shield
Forest	259.59	247.41	441.69	333.76	207.01	210.33
Shrubland	353	336	601	454	282	286
Grassland	34	32	84	53	27	27
Exposed/rock/snow	0	0	0	0	0	0
Water/wetland	0	0	0	0	0	0
Farmland (with manure application)	50.2	4.7	170	53.5	66.7	na
Farmland (without manure application)	50.2	4.7	170	53.5	53.5	na
Major road	194	185	330	249	155	157
Minor road/inblock road	1292.19	1269.89	1625.55	1427.96	1195.92	1202
Small pit	198	189	337	255	158	161
Transmission line	169	161	288	217	135	137

Feedlot	2342	2232	3984	3011	1867	1897
Recreation facility	207	197.3	352	266	165.33	168
Rural residential	30	28	50	38	24	24
Town	228.5	217.5	388.5	293.5	182	185
Industrial	510	486	868	656	407	413
Seismic line	127	121	216	163	101	103
Pipeline	254	242	431	326	202	205
Well	909.26	866.61	1547	1169.05	725.09	736.72
Energy mine	198	189	337	255	158	161

Appendix D – Watershed Simulation Tool Description

• Introduction

The Bow River Basin Watershed Simulation Tool is designed for the following hierarchical identification of conservation and restoration priorities in the Bow River Basin:

1. Assess current and future status of watershed resilience indicators to identify key issues;
2. For each indicator of concern, compare its response across a suite of conservation and restoration scenarios to prioritize mitigation strategies;
3. For each prioritized mitigation strategy, map its effect on indicator performance to identify where the strategy should be implemented.

A suite of dashboards guide the user through these steps. First, the user can view the *Watershed Hazards* dashboard to assess which indicators are good candidates for mitigation based on their risk level and the potential for risk reduction through mitigation. The user can also view the *Watershed Status* dashboard to view maps and graphs that depict current and potential future status of resilience indicators in the absence of mitigation. After identifying a candidate indicator for mitigation, the user can open its *Mitigation* dashboard to identify which mitigation strategies are the most beneficial, and where those mitigation strategies should be applied for the biggest effect.

• How to Use the Tool

To access the Bow River Basin Watershed Tool, visit online.alces.ca. Click Log In in the top right, and enter the user name BRBC_Tool. If you do not have the password, contact the Bow River Basin Council. The welcome page includes thumbnails for three types of dashboards: Watershed Status, Watershed Hazards, and Mitigation. To navigate to a dashboard, click its thumbnail. The contents of each type of dashboard are described below. When you are finished viewing a dashboard, click the home icon in the top left corner to return to the welcome page, from where you can navigate to another dashboard.

When viewing a map, the "i" icon in the top right corner can be clicked to view additional information about map, or to launch the map in the Map Window. The Map Window is a mapping and analytical tool with flexible options for modifying map formats and creating new indicators. Training is recommended prior to using the Map Window. Training can be arranged by contacting info@alces.ca.

When viewing a chart, the indicator names appearing at the bottom of the chart can be clicked to view additional info or to launch the indicator in the Map Window. Other options that are available include hiding the series (i.e., indicator), renaming the series, removing the series, and changing the colour. Any changes that are made using these options will not appear the next time that the dashboard is opened, unless the save icon in the bottom left hand corner is used to save a new version of the dashboard. If a user saves a new version of a dashboard, it can be opened at a later time from the folder icon located beside the save icon.

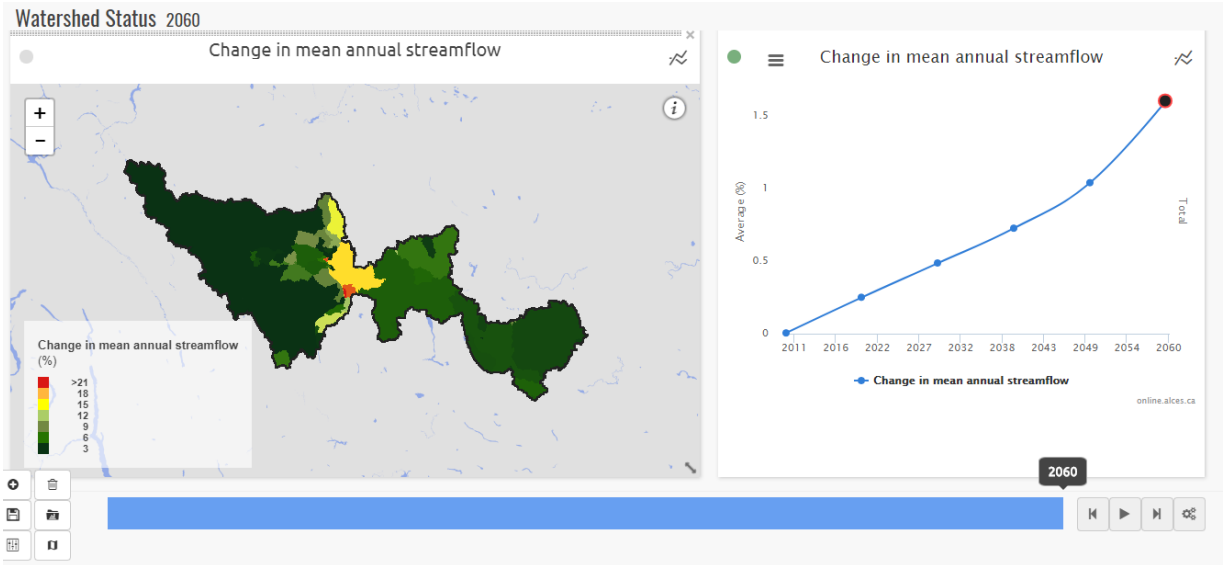
The user is cautioned against using the other icons in the bottom left corner. These icons are used for developing new dashboards, which requires comprehensive understanding of the ALCES Online toolkit. Training is recommended prior to developing new dashboards. Training can be arranged by contacting info@alces.ca.

• Dashboard Contents

The contents of each dashboard are now described in greater detail.

• Watershed Status Dashboard

The role of the Watershed Status dashboard is to present current and potential future status of watershed resilience indicators in the absence of mitigation. By exploring the performance of resilience indicators, the user can gain an appreciation of current and potential future issues of concern, and where the issues occur. To help the user appreciate underlying drivers of indicator performance, the dashboard also reports on the composition of the watershed in terms of the extent of footprint and the age of forest. Figures for each indicator and landscape composition metric can be accessed by scrolling down.



• Watershed Hazards Dashboard

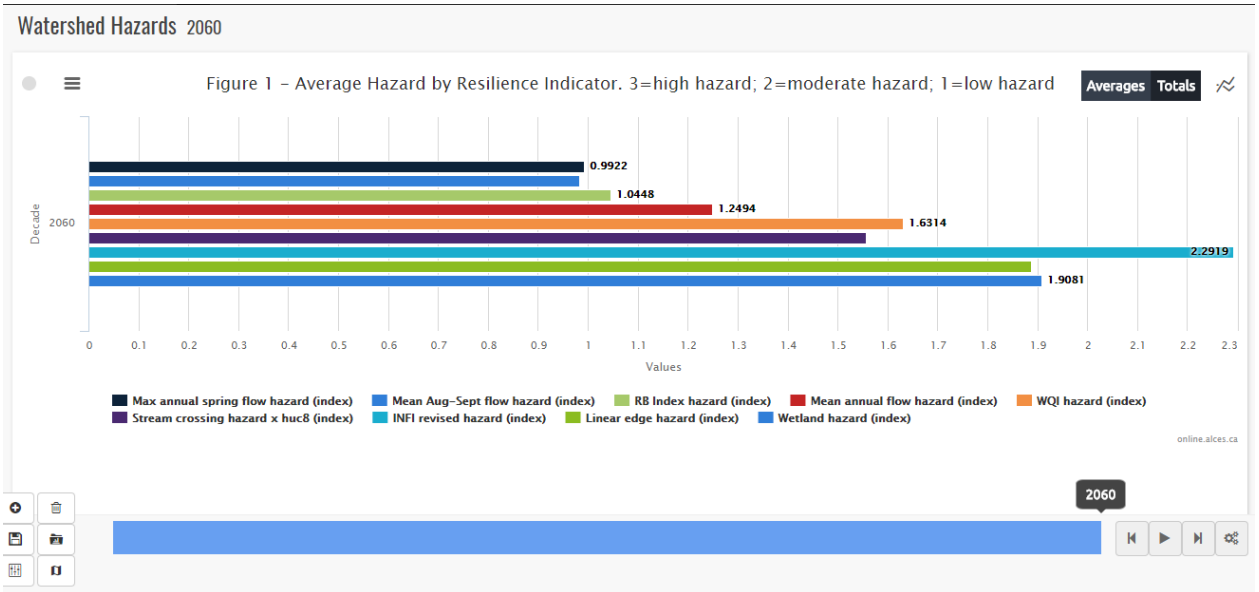
The role of the Hazards dashboard is to identify watershed resilience indicators that are good candidates for mitigation. There are three figures, which can be accessed by scrolling down. Figures in the dashboard are as follows:

Figure 1 - Average Hazard by Resilience Indicator. Presents the average hazard level (i.e., across assessment watersheds) for each indicator in the absence of mitigation. Hazard ranges from 1 (low risk) to 3 (high risk). Managers will often be interested in mitigating issues (i.e., indicators) with higher hazard. The approach for assessing hazard is described in section 2.3.8.

Figure 2 – Maximum Hazard Reduction by Resilience Indicator. Presents the reduction in hazard achieved by the most effective mitigation strategy for each indicator. Managers will often be interested in mitigating issues (i.e., indicators) for which there is higher potential to reduce hazard. The top performing mitigation strategies for each indicator can be identified using its mitigation dashboard.

Figure 3 – Combined Hazard. This map presents the average hazard, across all resilience indicators, in the absence of mitigation. Managers will often be interested in pursuing mitigation where hazard is higher.

The Hazards dashboard is available across all reporting years (i.e., 2010, 2020, …, 2060) to convey how hazard is projected to change in the absence of mitigation. The time slider at the bottom of the page is used to change the reporting year. When viewing Figure 2, the time slider should be set into the future (e.g., 2060).

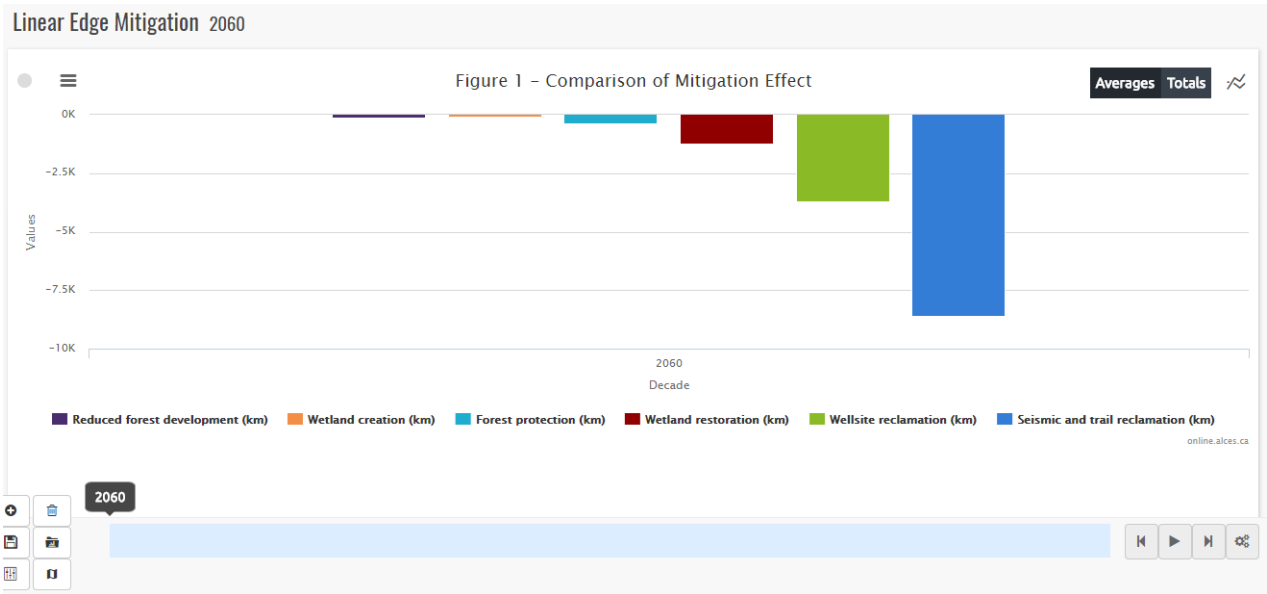


• Mitigation Dashboards

For each indicator, there is a mitigation dashboard (e.g., % Natural Wetland Mitigation). The role of an indicator's Mitigation dashboard is to identify which mitigation strategies are the most beneficial for that indicator, and where those mitigation strategies should be applied for the biggest effect. Figures in each indicator's Mitigation dashboard are as follows:

- Figure 1 – Comparison of Mitigation Effect. The bar chart presents the effect of each mitigation strategy on indicator performance. Mitigation effect is calculated as indicator status with the mitigation strategy minus indicator status without the mitigation strategy. Mitigation effect can be a positive or negative value; which is advantageous depends on the indicator. Indicators for which a positive effect is advantageous are: index of native fish community integrity (INFI), water quality index (WQI), and % natural wetland. Indicators for which a negative effect if advantageous are: linear edge, mean annual streamflow, peak flow, RB Index, stream crossings, and flood risk. Mitigation effect is calculated for the final year of the simulation.
- Figure 2 – Effect of the Best Mitigation Strategy. The map presents mitigation effects, by assessment watershed, for the top performing mitigation strategy for a given indicator. Managers will typically be interested in applying a mitigation strategy where it has a greater effect. Assessment watersheds where mitigation effect is higher are identified in green whereas assessment watersheds where mitigation effect is lower are identified in red. As described previously, a positive effect is desirable for some indicators (e.g., % natural wetland) whereas, for other indicators, a negative effective is desirable (e.g., flood risk). As such, assessment with high mitigation effect (i.e., green) are associated with positive mitigation effect for some indicators and negative mitigation effect for other indicators.
- Figure 3 – Effect of the 2nd Best Mitigation Strategy. The same as Figure 2, except for the 2nd best performing mitigation strategy for a given indicator. Across all indicators,

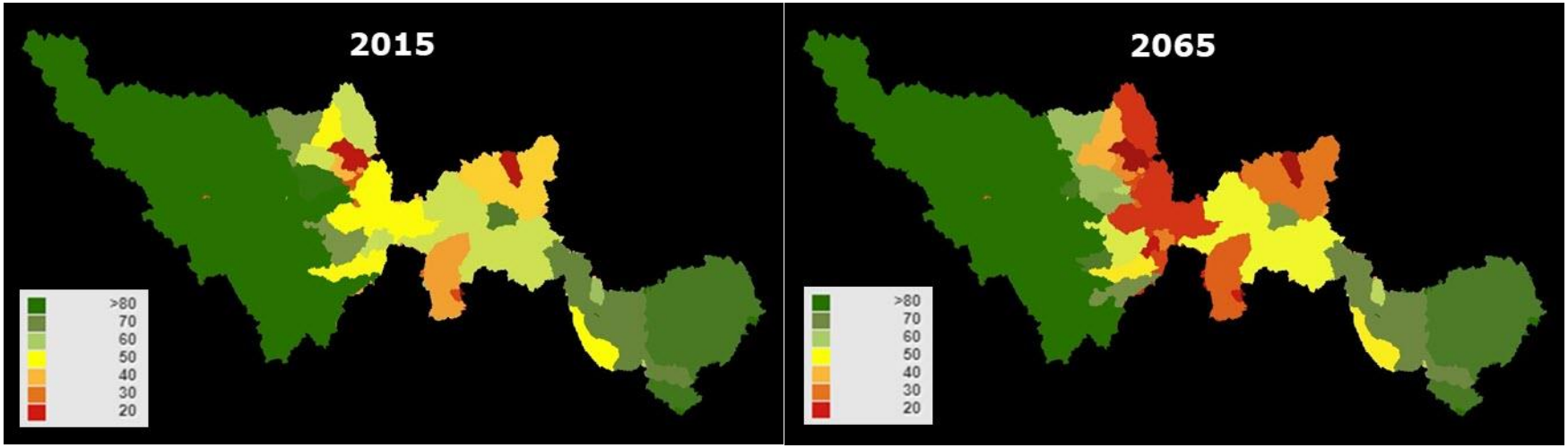
the top one or two mitigation strategies substantially out-performed the remaining strategies. For this reason, maps are incorporated for the top two performing mitigation strategies.

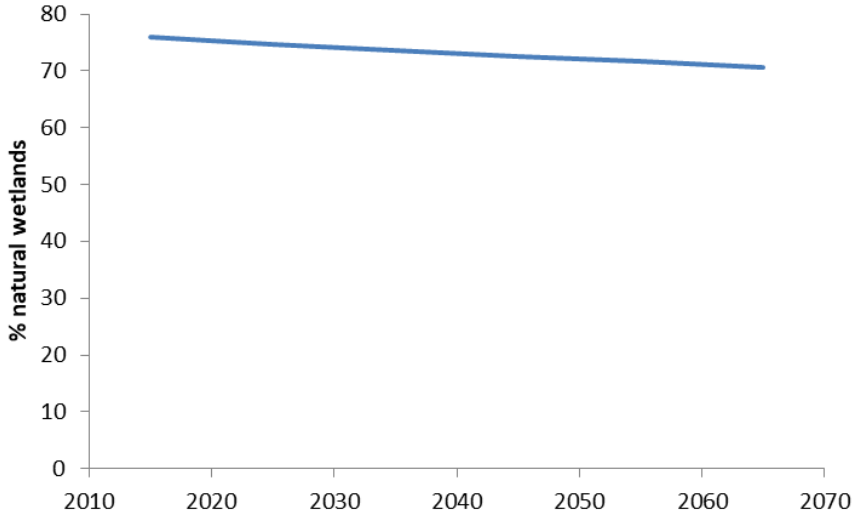


Appendix E – Indicator Maps

Wetlands

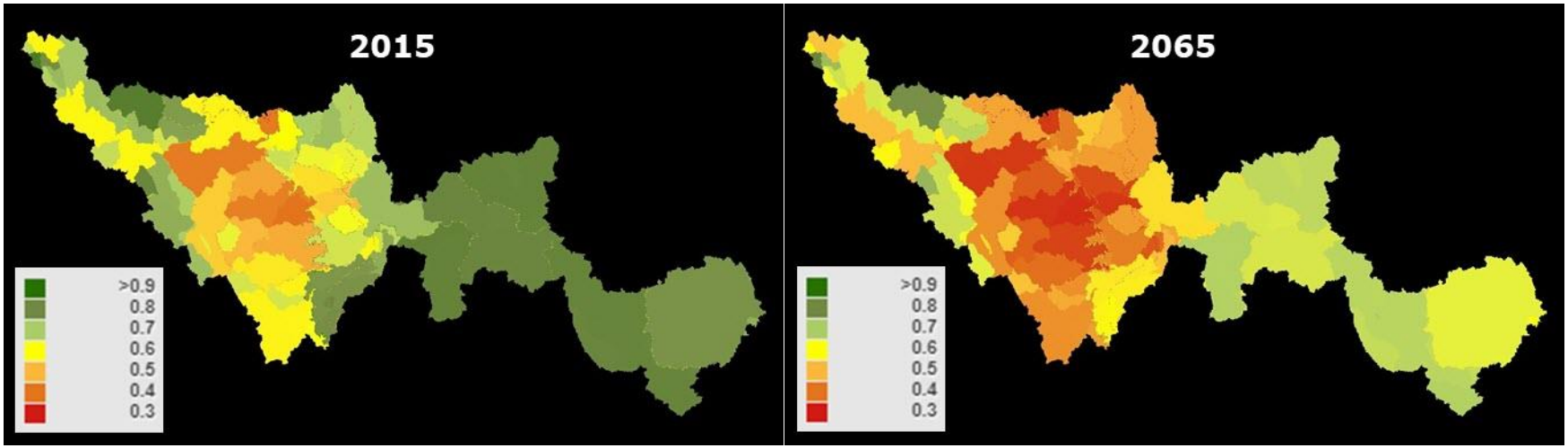
The response of wetlands (% of natural) to the BAU scenario.

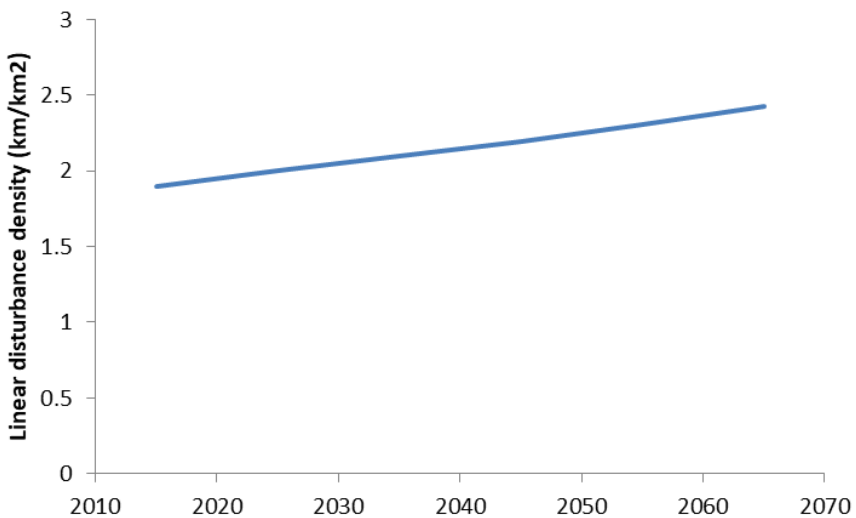




Linear disturbance

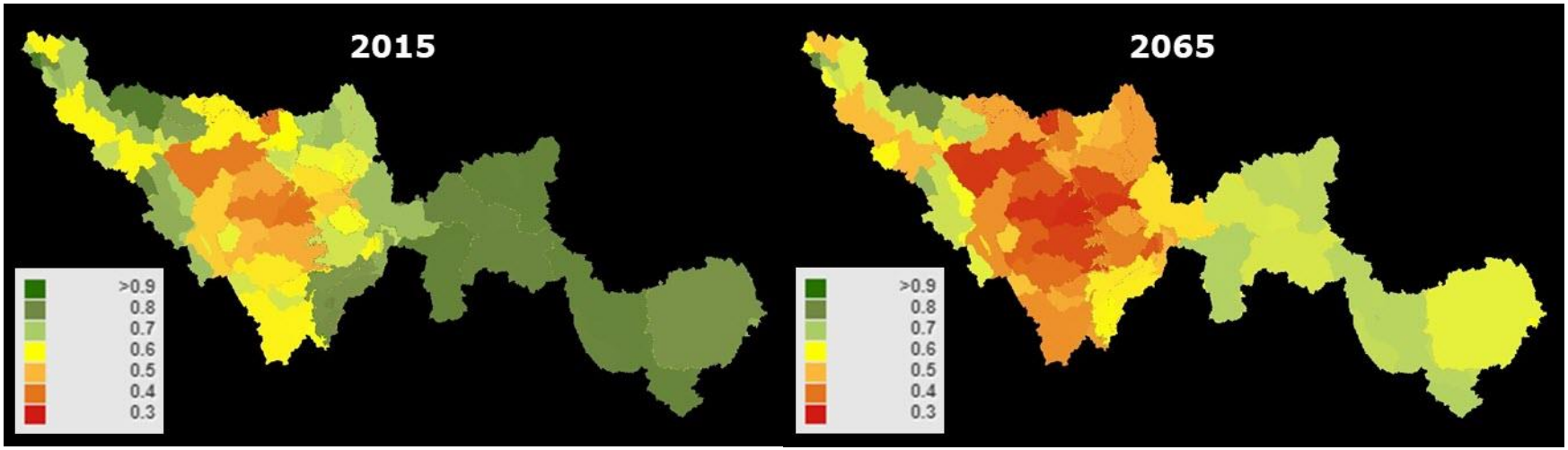
The response of linear disturbance density (km/km2) to the BAU scenario.

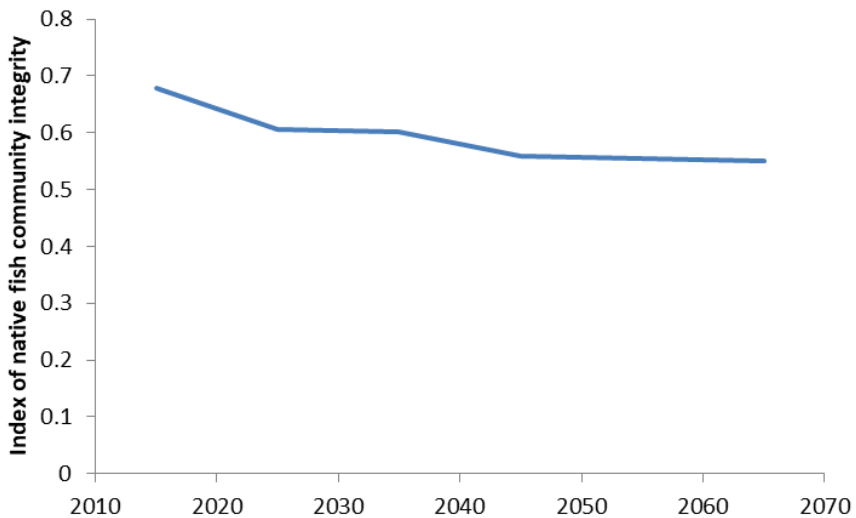




INFI

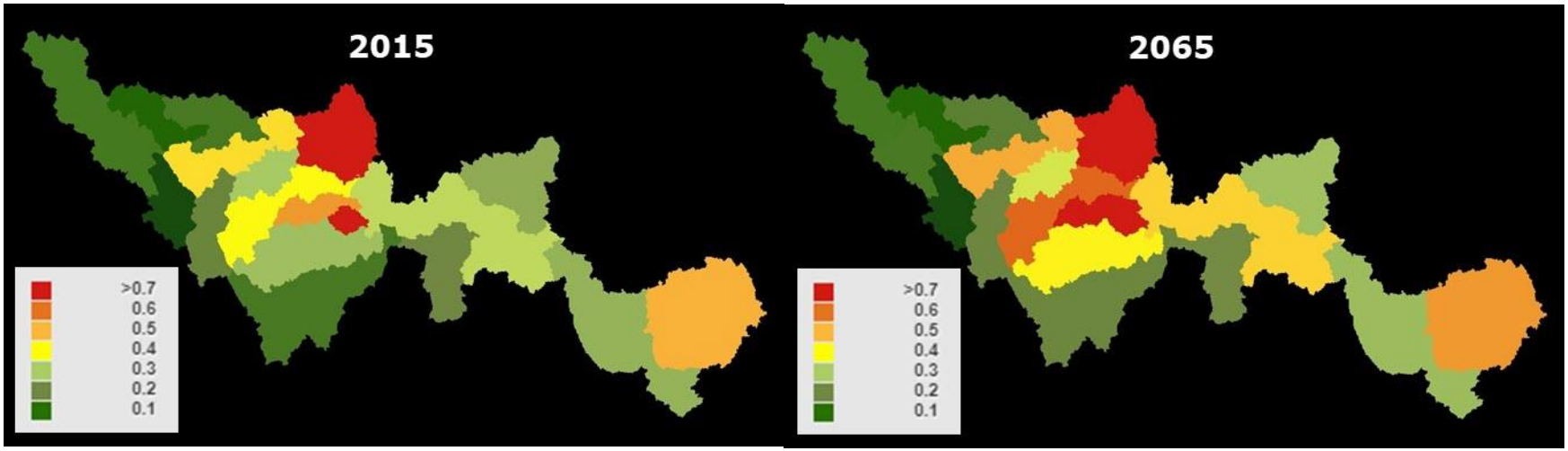
The response the index of native fish community integrity (INFI) to the BAU scenario.

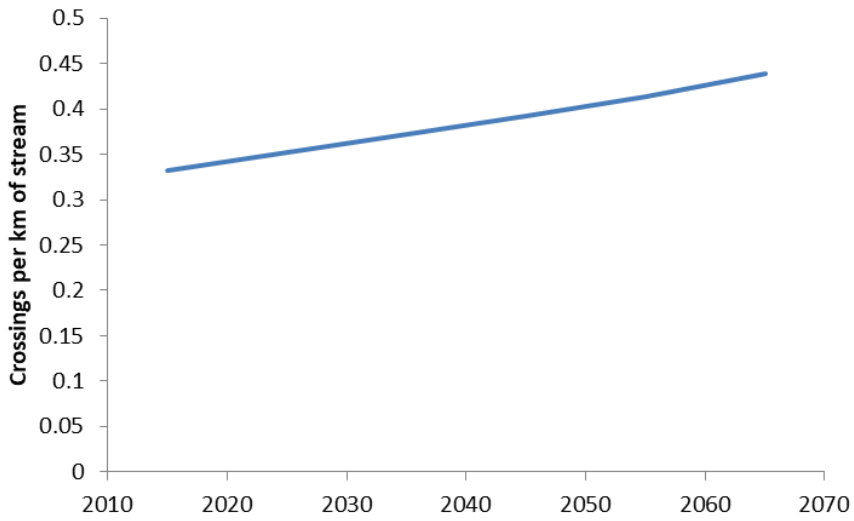




Stream Crossings

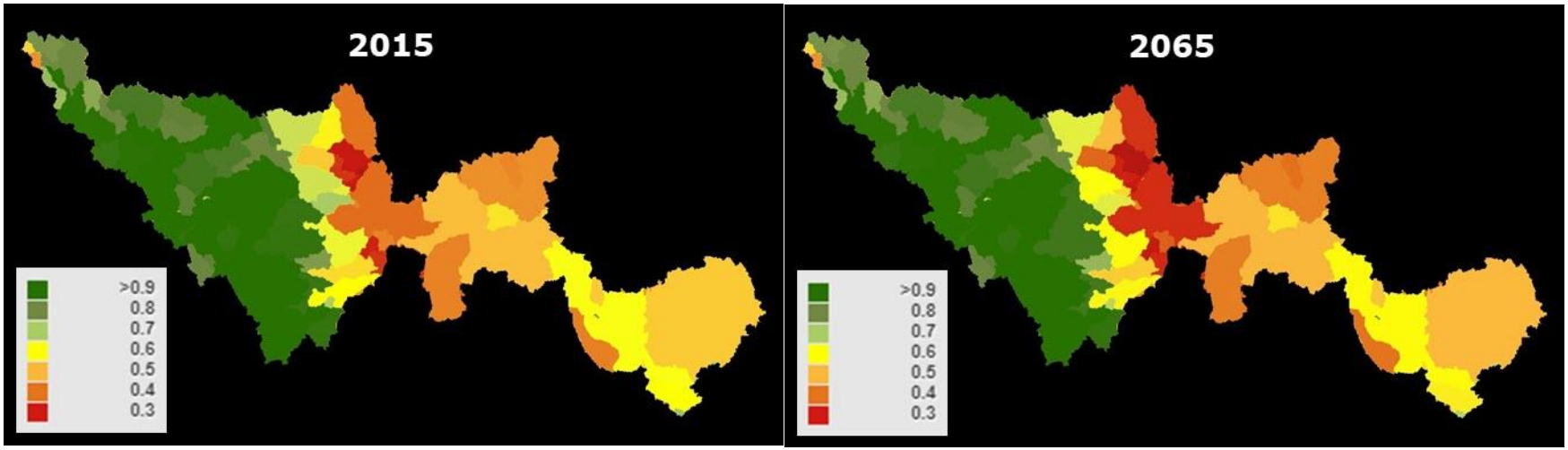
The response of stream crossing density (#/km of stream) to the BAU scenario.

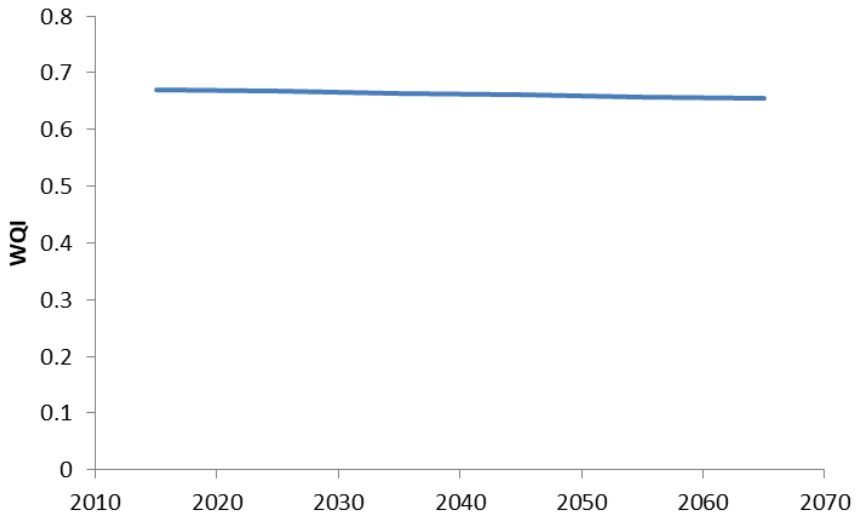




Water Quality Index

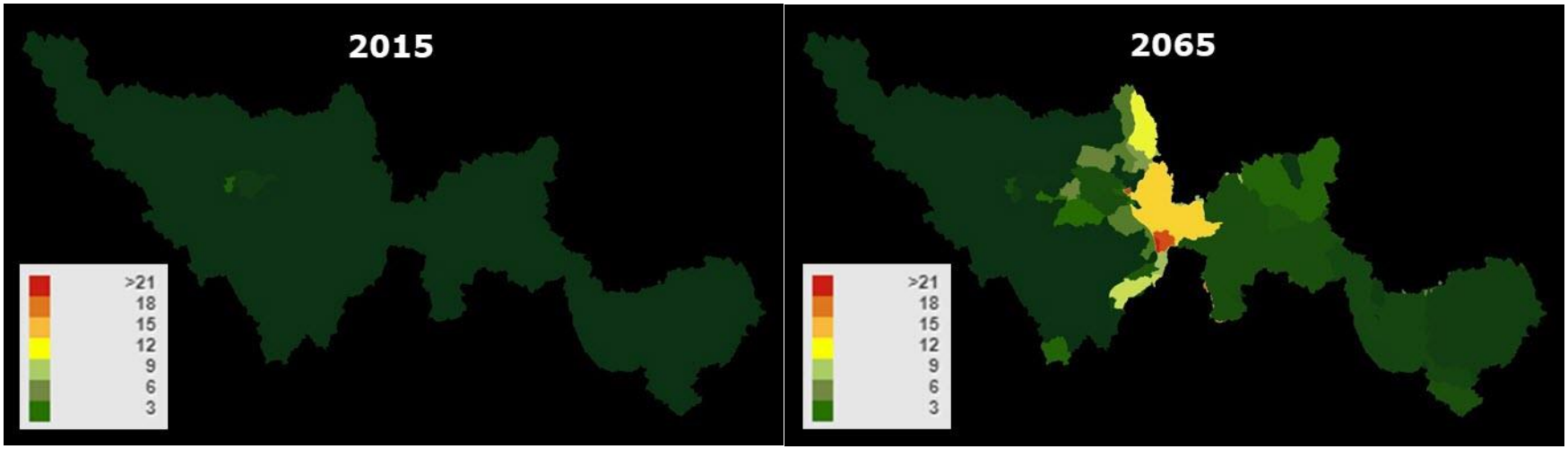
Response of the water quality index (WQI) to the BAU scenario.

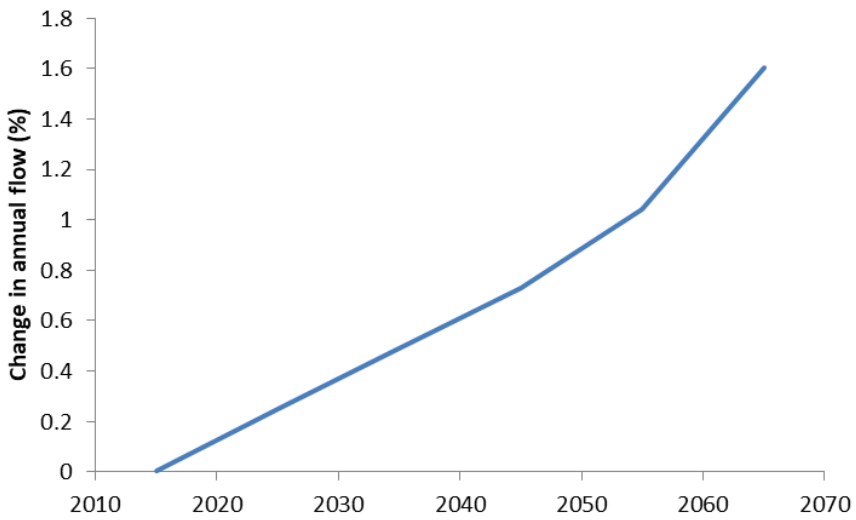




Annual flow

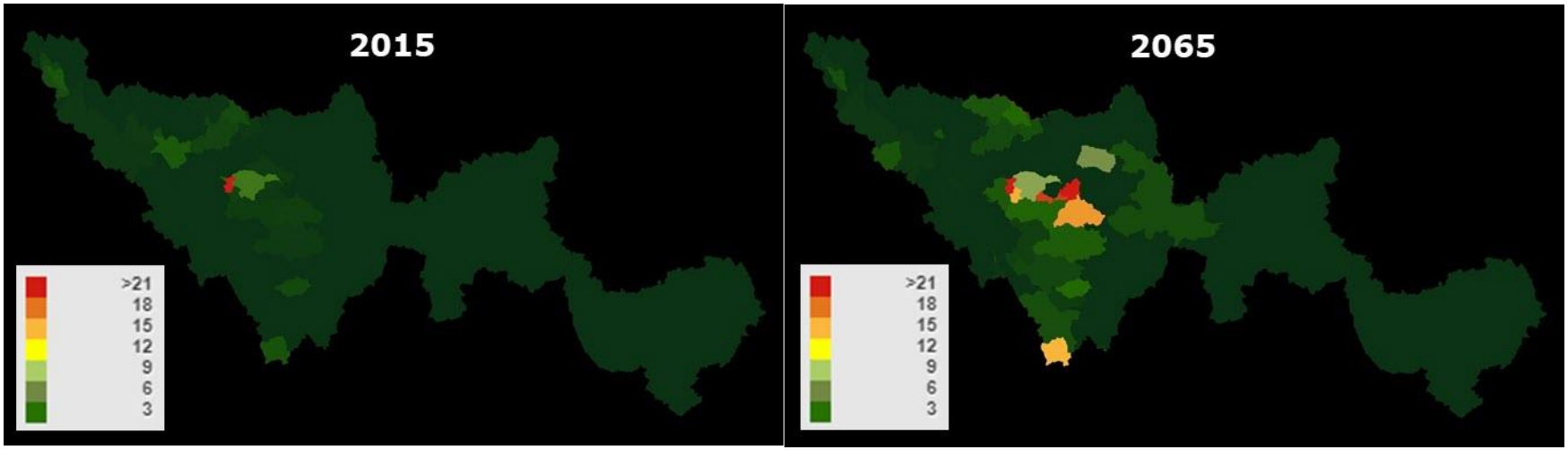
Response of annual flow to the BAU scenario. Annual flow is expressed as % relative to current.

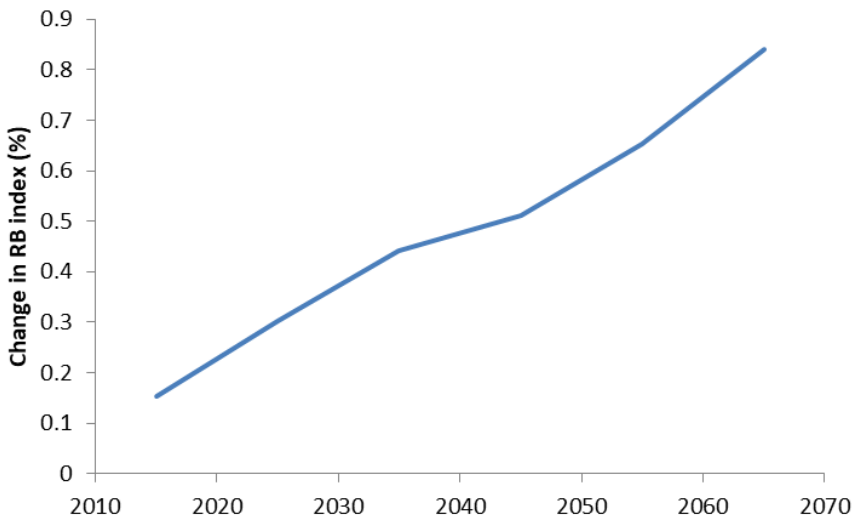




RB Index

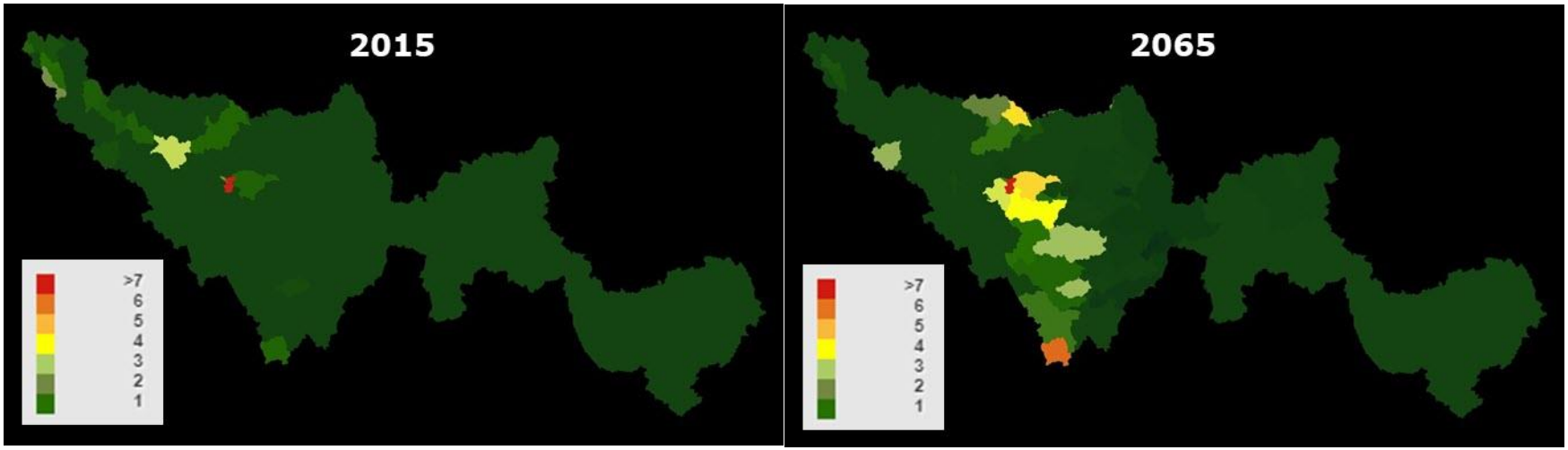
Response of RB index to the BAU scenario. RB index is expressed as % relative to current.

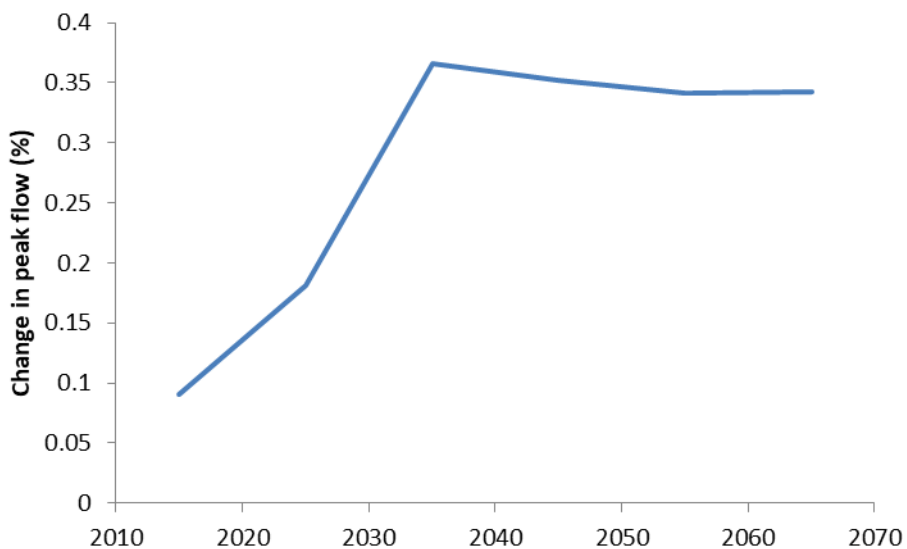




Peak flow

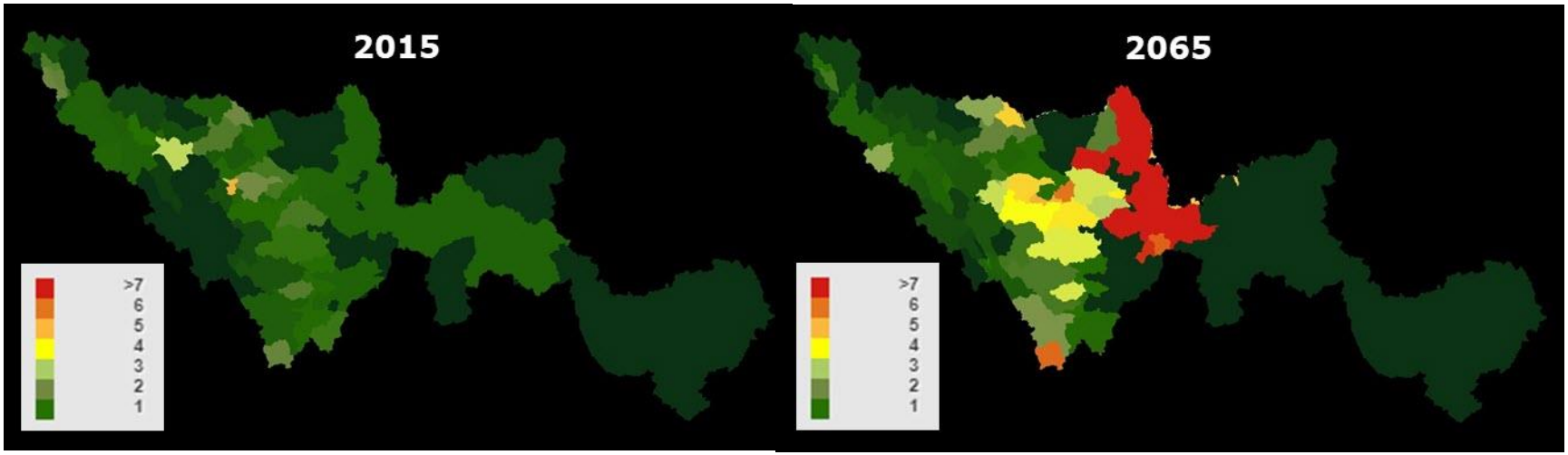
Response of peak flow to the BAU scenario. Peak flow is expressed as % relative to current.

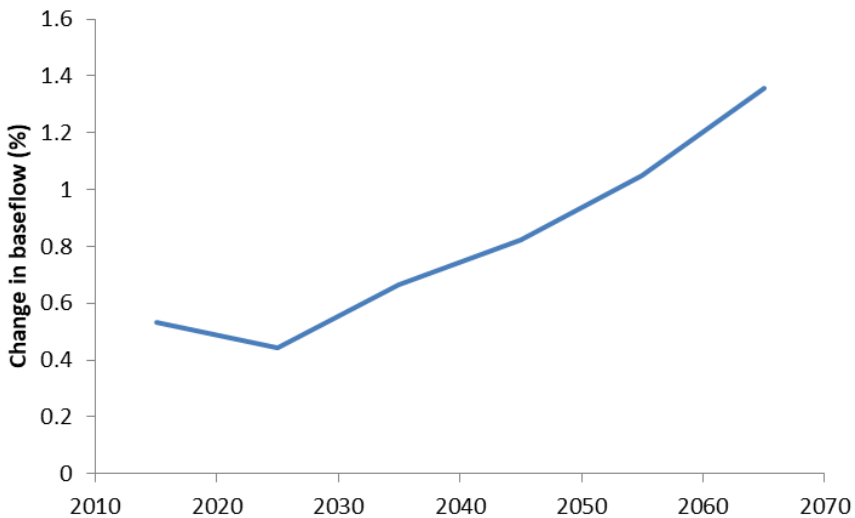




Baseflow

Response of baseflow to the BAU scenario. Baseflow is expressed as % relative to current.





Flood risk

Response of flood risk ($/km^2) to the BAU scenario.