Climate Change Vulnerability Assessment for Aquatic Ecosystems in the Mississippi and Rideau Conservation Authority Watersheds

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RIDEAU VALLEY CONSERVATION AUTHORITY

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Preamble

This study represents a collaborative effort between several agencies and individuals concerned with the effects of climate change on the natural assets of eastern Ontario. It was made possible by funding from the Ontario Ministry of Natural Resources Science and Research Section as part of the *Sustainability in a Changing Climate strategy*. Dr. Chu served as the scientific lead and primary author conducting the vulnerability analysis and developing recommendations for future research and monitoring. Other collaborators; staff at Mississippi Valley, Rideau Valley Conservation Authorities and Ontario Ministry of Natural Resources – Kemptville District, contributed to the discussion of the results and development of the recommendations. Gary Nielsen and Jenny Gleeson coordinated the effort.

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Summary

Climate change is impacting aquatic ecosystems. Water temperatures are warming, species ranges are shifting and trophic dynamics are changing. Alternations in the timing of the spring freshet, the duration of ice-cover, the composition of wetlands, and the establishment of invasive species have been documented in several systems. The wetlands, streams and lakes, which are located in the Mississippi Valley and Rideau Valley Conservation Authority watersheds, are also being impacted by climate change.

The objectives of this study are to assess the vulnerability of different indicators to inform the development of a climate change adaptation strategy for the aquatic ecosystems within the Mississippi-Rideau region. The indicators are: 1) wetland vulnerability, 2) habitat availability for wetland-dependent bird species, 3) stream temperatures and change in temperatures throughout the region, and 4) maximum lake surface temperatures.

Most of the wetlands in the region may have mid or high vulnerability to shrinkage or drying due to increases in air temperature and decreases in precipitation. All of the wetlands currently inhabited by American Coot (*Fulica americana*) may have a mid or high vulnerability ranking by the 2080s due to the loss of wetland habitats.

All streams in the region may experience some warming with the maximum weekly temperatures warming by at least 0.5°C. The greatest warming will occur in the southeastern portion of the region with stream temperatures rising by ~2.5°C by the 2080s under both the B1 and A2 emissions scenarios. Streams will have a mid vulnerability to climate change.

Maximum surface temperatures in lakes will increase gradually from the 2020s to the 2080s. Under the B1 emissions scenario, lakes surface temperatures of all lakes will warm by 2–4°C and these temperatures will range from 26.25–29.0°C by the 2080s. Under the A2 scenario, warming may be more extreme with temperatures increasing by 4 to 6°C and ranging from 28.3 to 30.9°C. This indicator may have a low to mid vulnerability to climate change.

Recommendations are proposed to highlight existing programs in the region, outline approaches, which may be used to address uncertainties and knowledge gaps, and integrate these existing and future efforts with climate change initiatives. The results presented in this report do not include the potential impacts of anthropogenic stressors such as groundwater withdrawals, stream regulation, pollution or invasive species, which may exacerbate the changes in the quality and quantity of aquatic ecosystems in the Mississippi Valley and Rideau Valley watersheds.

1 Introduction

Climate change is significantly impacting aquatic ecosystems around the world. Long-term warming in stream (all flowing waters) water temperatures and associated changes in stream biota have been already detected (e.g., Durance and Ormerod, 2007). Permafrost is melting in peatlands (Parish et al. 2008). Surface temperatures of lakes worldwide have been increasing, and these increases have had biological consequences such as changes in fish community dynamics and production (e.g., Schneider and Hook 2010; Jeppesen 2010).

In Ontario, higher air temperatures could lead to overall reductions in lake volume, warmer surface water temperatures, longer ice-free periods, increased growing seasons and greater risks of hypoxia (Dove et al. 2011). Climate change may also alter the timing of the spring freshet, affect groundwater dynamics and disrupt annual stream flow patterns (Mohseni et al. 2003). In some regions of Ontario, increases in stream temperatures may provide more suitable habitat for species with warmwater thermal preferences throughout the ice-free season, but they may limit the distribution of other species that prefer cooler temperatures (Chu et al. 2008). The impacts of climate change in wetlands are variable and depend on the conditions in the surrounding watershed and the sources of water into the system. For example, changes in precipitation patterns will have significant impacts on the water budgets of bogs where the main influx of water is derived from precipitation. In fens, where water influx comes mainly from groundwater, climate change may have a more variable impact depending on the amount of precipitation, recharge rates and geomorphology of the system (Mortsch et al. 2006).

In the Mississippi and Rideau Valley watersheds of eastern Ontario, mean annual air temperatures have been increasing at an average rate of $0.005°C\cdot yr^{-1}$ since 1950 however, the rate of warming has increased to $0.08°C\cdot yr^{-1}$ since 1995. Climate models project increases of 4.5°C over the next 100 years (Casselman et al. 2011). Total annual precipitation may increase from 849 mm to 907 mm by 2099. Spring discharge may peak seven weeks earlier, summer flows may decrease in volume by as much as 44% and low flows may be sustained for longer periods. Water budget models suggest a 23% increase in evapotranspiration (ET) in the region as a result of warmer air temperatures (Casselman et al. 2011). These changes will significantly impact the quantity and quality of the wetlands, streams and lakes in this region.

While there is widespread agreement on the need to recognize and prepare for climate change, and to develop and integrate risk management strategies into current and new programs, climate-sensitive adaptive processes are only now being designed and tested. There are a number of steps in an adaptive management process that include an assessment of readiness and capacity to respond (e.g., assess organizational readiness and where necessary improve the capacity to respond), followed by vulnerability analyses to identify and prioritize adaptation needs, the development of adaptation strategies, and monitoring programs to measure adaptation success and to determine if vulnerabilities have disappeared (Figure 1). This project was commissioned to complete a vulnerability assessment in support of the Ministry of Natural Resources' *Sustainability in a Changing Climate strategy*.

Following the vulnerability and adaptation framework, the main objective of this study is to identify vulnerability indicators for the wetland, stream and lake ecosystems within the Mississippi Valley and Rideau Valley watersheds. These indicators represent measures that can be used to quantify the sensitivity of each system to climate change, develop adaptation strategies for each ecosystem and inform regional monitoring and planning programs.

2 Methods

2.1 Study area

The Mississippi Valley and Rideau Valley watersheds are located near Ottawa, Ontario and make up the Mississippi-Rideau region (MR region). They correspond to the 02KF (Mississippi Valley) and 02LA (Rideau Valley) watersheds defined by the Water Survey of Canada (WSC 1977). The watersheds span areas of ~3,880 km^2 (Rideau Valley) and ~4,450 km^2 (Mississippi Valley). There are 383 lakes >0.1 km^2 in size, 1,479 km^2 of wetlands (evaluated and unevaluated) and 10,452 km of streams. Lakes are prominent on the landscape in the western region of the study area whereas as wetlands are prominent in the eastern region. The watersheds are heavily regulated and have a number of small urban centres with a few cities, the most populated being Ottawa, Ontario (Figure 2).

After consultation with staff of Ontario Ministry of Natural Resources, Mississippi Valley and Rideau Valley Conservation Authorities, four ecological indicators were identified; 1) wetland vulnerability, 2) habitat availability for wetland-dependent bird species, 3) stream temperatures and change in temperatures throughout the region, and 4) maximum lake surface temperatures. These indicators reflect the state of aquatic ecosystems within the Mississippi-Rideau watersheds and build on previous climate change assessments in the region.

Existing empirical models were used to relate the ecosystem indicators to climate. Current climate conditions were estimated using the 1971-2000 climate normals (McKenney et al. 2006). Future conditions were projected using ensemble estimates of air temperature and precipitation under the B1 and A2 emissions scenarios for the 2011-2040, 2041-2070 and 2071-2100 time periods, hereafter the 2020s, 2050s and 2080s, respectively. The ensemble estimates represent air temperature and precipitation changes predicted from the Canadian Coupled Global Climate Model 3 (CGCM-3), U.S. National Center for Atmospheric Research (NRCAR-3) model, Japanese Model for Interdisciplinary Research on Climate (MIROC32) and Australian Commonwealth Scientific and Industrial Research Organization (CSIRO) models. The ensemble approach has been endorsed by the Intergovernmental Panel on Climate Change (IPCC 2007; Lalonde et al. 2012). B1 scenarios represent an environmentally focused future with lower emission levels than the A2 scenarios in which high emission levels are driven by rapid economic development (IPCC 2007). Seamless coverages of mean annual, maximum annual, mean July air temperature and total precipitation in the growing season were used to project the changes in the indicators (McKenney et al. 2006; Lalonde et al. 2012).

2.1.1 Wetlands

Mapped wetlands were acquired from the OMNR Wetland Unit layer within the Land Information Ontario database (OMNR 2011). Wetlands within the MR region were extracted using ArcGIS®9.3 (Environmental Systems Research Institute Inc., Redlands, California, USA). Only wetlands which have been evaluated were used in the analyses because the existence and spatial extents of those wetlands have been ground-truthed. As a result, 8,355 of the 20,604 wetland polygons identified in the Wetland Unit layer were included in the analyses.

Wetland vulnerability is defined as degraded quality or loss due to drying that may result from increased evapotranspiration at warmer air temperatures, water loss associated with decreased precipitation and/or low groundwater inflow. It was assessed using projected mean air temperature and total precipitation during the growing season (April to September) and groundwater discharge potential. Air temperature and precipitation values came from the ensemble model projections under the B1 and A2 emissions scenarios and the 2020s, 2050s and 2080s time periods. Groundwater discharge potential was based on a *base flow index*, which relates groundwater potential to underlying surficial geology (Neff et al. 2005). These variables were selected because changes in any one will affect the water budget of these systems. Each wetland polygon was spatially joined to the air temperature, precipitation and base flow index data layers.

As noted previously, vulnerability is defined as degraded quality or loss due to drying that may result from increased evapotranspiration at warmer air temperatures, water loss associated with decreased precipitation, and/or low groundwater inflow. A rule of thumb of 1:10 % was adopted from Trenberth (2011) who found that a 10% increase in precipitation is needed to offset the increases in evapotranspiration associated with 1ºC of warming, although this relationship has not been explicitly tested in the MR region. Vulnerabilities of the wetlands were calculated in two stages:

$$\textit{Vulnerability} = \frac{\textit{Change in air temperature}}{\textit{Per cent change in precipitation}} \tag{1}$$

where ratios < 10 = low vulnerability

ratios 10 – 11.5 = mid vulnerability

ratios > 11.5 = high vulnerability

The value 11.5 was the 75th percentile of the air temperature:precipitation data for both scenarios and all time periods. Therefore, it represented the more extreme increases in air temperature and decreases in precipitation across the study area. Wetlands exposed to these ratios were interpreted as experiencing harsher conditions than wetlands not exposed to these conditions and were assigned higher vulnerability to climate change.

The air temperature:precipitation vulnerabilities were then compared to the base flow index to account for the influence of potential groundwater influxes into the wetlands. The index has five values, which range from 0 to 0.821, with 0.821 representing a high potential for groundwater discharge and 0 representing little or no ground water (Neff et al. 2005). The air temperature and precipitation ratios were combined with the base flow index values to assign vulnerabilities to each wetland. The general premise was that high groundwater potential would buffer against high air temperature-precipitation ratios because influxes of groundwater would reduce the likelihood of drying that is, decrease vulnerability (Table 1). Base flow index values did not change with climate because no estimates of changes in recharge rates and groundwater temperature were available (Chu et al. 2008).

2.1.1.1 Wetland bird species habitat

Using the Hydrological Vulnerability Index (HVI) developed by Mortsh et al. (2006), an indicator wetland-dependent bird species was identified. The HVI ranks species based on life history characteristics such as marsh dependency, nesting habitat, nest location and foraging habitat. American Coot (Fulica americana), which is sensitive to changes in wetland habitats, and is widely distributed throughout the MR region was included in these analyses. Wetland vulnerabilities were mapped onto the known distributions of American Coot to visually assess the overlap between wetland vulnerability and the species distributions. Wetlands with high vulnerability are likely to shrink or dry with climate change therefore, suitable habitat for this species would decline in those areas. American Coot distribution data were acquired from Bird Studies Canada (BSC 2008). The ~10 km x 10 km grids used to denote species presence were mapped onto the study area.

2.1.2 Streams

An empirical model of maximum weekly average stream temperature (Melles et al. in prep.) was used to predict temperatures in the mainstems: the longest streams (and their tributaries) in the watersheds from the outlet to the headwaters. This included all of the streams in Rideau Valley and more than 75% of the streams in Mississippi Valley. Maximum weekly average stream temperature (MWAT) was selected because it has been linked to fish species distributions, and it quantifies the hottest and potentially biologically limiting conditions for biota in streams (Wehrly et al. 2009; Moore et al. 2013). The predictive model is:

$$MWAT = 13.835 + 0.268 \times MAXTA - 4.999 \times GW - 0.0069 \times SLOPE + 2.286 \times \log(SHREVE) \quad (1)$$

where *MWAT* is the maximum weekly average temperature, *MAXTA* is the maximum air temperature, *GW* is groundwater discharge, *SLOPE* is the elevation range and *SHREVE* is the stream order of different segments of the tributaries. Root mean square error (RMSE) for that model, which was validated using data from 105 sites across the GLB was 2.71. This model was used to estimate current and forecast future stream MWAT with climate change. Maximum weekly stream temperatures were not available throughout the study area therefore, direct comparisons between the observed and predicted MWAT could not be calculated. However, RMSE was calculated from observed maximum stream temperature (as opposed to maximum weekly temperature) data for 183 sites to provide an indication of the accuracy of the model.

The ensemble climate change model provided the maximum air temperature used in the analyses. Streams, slopes and Shreve value of the streams were acquired from the OMNR's Integrated Hydrology (OMNR 2013). Groundwater discharge potential was estimated from the base flow index layer used for the wetlands. The data for these variables were entered into the models to determine the MWAT for streams using the B1 and A2 emissions scenarios and the 2020s, 2050s and 2080s time periods. Monitoring data from streams within the study area were used to validate the predictions. The differences between the current and predicted temperatures for each scenario and time period were calculated and mapped to highlight regions within the study area sensitive to climate change.

2.1.2.1 Thermal habitat for stream fishes

The predicted current and projected MWAT in the streams were used to estimate the amount of suitable habitat for coldwater, coolwater and warmwater fishes inhabiting these systems. Cold, cool and warm water habitat were defined as streams having MWATs of <19°C, ≥19≤25°C and >25°C, respectively based on a national synthesis of the life history characteristics of Canadian fishes (Coker et al. 2001). Potential changes in habitat availability were assessed spatially and also summarized as total lengths (km) of suitable habitat for each thermal guild.

Stream temperature monitoring and fish sampling data were used to validate the thermal habitat results. Thermal classifications (coldwater, coolwater and warmwater; classified using the protocol of Stoneman and Jones 1996) of 183 stream sites throughout the study area were compared to the predicted thermal classification for the current time period. The numbers of sites correctly or incorrectly classified were calculated to evaluate the performance of the model. The distribution of Northern Pike (*Esox lucius*) within the study area was mapped and used to visually assess the fit of the temperature predictions and habitat delineations with Northern Pike occurrences. These fish are coolwater species preferring temperatures of 22.5°C (Coker et al. 2001).

2.1.3 Lakes

Maximum surface lake temperatures were used to an indicator of the potential impacts of climate change on lake ecosystems. Mainstem lakes (lakes hydrologically connected to the mainstem streams) greater than 0.1 km^2 (n = 383) were selected from the Ontario Provincial Hydrometric Network (OMNR 2010) using ArcGIS®9.3. This removed ponds from the analysis because they may have different thermal patterns than lakes. Current and future mean July and mean annual air temperatures were calculated for each lake. Maximum surface temperatures in the lakes were predicted using an existing model developed by Sharma et al. (2007) for Canadian lakes. It estimates MST as:

$$MST = -57.88 + 0.79 \times MJT + 0.26 \times MAT - 0.00151 \times (J)^2 + 0.617 \times J - 0.019 \times longitude + \beta \quad (2)$$

where *MST* is maximum surface temperature (°C), *MJT* is mean July temperature (°C), *MAT* is mean annual air temperature (°C), *J* is day of the year, longitude is the location of centroid of lake (decimal degrees) and β is a coefficient describing the interannual variability. For our purposes, *J* was set to 212 (July 31) and β was set to zero. The RMSE reported by Sharma et al. (2007) for 872 validation lakes equalled 2.53. The longitude of each lake as well as the ensemble projections of mean July and mean annual air temperature of each lake were entered into the model to predict MST for the B1 and A2 emissions scenarios for the three time periods.

Lake temperature monitoring data (thermal profiles periodically sampled throughout the ice-free season) were used to validate the MST estimates. The maximum surface (0.1 m depth) temperature recorded between June and August of 2006 to 2010 were queried from the lake monitoring data. Twenty-four lakes had at least four years of data between 2006 and 2010 and the average of the maximum surface temperatures for each year were used to validate the MST estimates using RMSE.

3 Results

3.1 Wetlands

The A2 emissions scenarios had a greater impact on wetland vulnerability than the B1 emissions scenario projections (Figure 3). Most of the wetlands will remain intact and have low vulnerability to climate change by the 2050s. Wetlands on the eastern side of the study area show higher vulnerability to climate change than the west-central wetlands (Figure 3). By the 2080s, however, most of the wetlands in the watersheds may have mid or high vulnerability with a pocket of wetlands at the centre of the study area having low vulnerability. Overall vulnerability of wetlands will increase from **low to high** by the 2080s (Figure 3; Table 3).

Wetland-dependent species may be significantly impacted by the shrinking or drying of wetland habitats. By the 2080s, most of the wetlands currently inhabited by American Coot may have a mid or high vulnerability to climate change (Figure 4; Table 3).

3.2 Streams

Predicted MWAT for the current time period ranged from 15.5 to 27.3°C with headwaters having cooler temperatures than the downstream segments of the streams (Figure 5). Streams in the Rideau watershed are warmer than the Mississippi watershed. Although data were not available to directly compare observed and predicted MWAT, maximum temperature data from 183 stream sites equalled 24.09 on average while the predicted MWAT were 20.95. Root mean square error for this validation dataset was 4.8°C. This suggested that the model is underestimating maximum stream temperatures.

By the 2080s under the B1 scenario, all of the streams may warm with MWAT ranging between 16.2 and 28.3°C. Under the A2 scenario, temperatures may range from 16.7 to 28.8°C. The greatest temperature changes will be seen in the southeastern portion of the study area with stream temperatures rising by ~2.5°C by the 2020s with both the B1 and A2 scenarios (Figure 5). It is difficult to detect at the scale of the maps in Figure 5, but the most extreme changes in temperatures occurred in streams reaches that spanned transitions in underlying geology for example, stream reaches that spans a shift from glacial till to clay or vice versa. The overall vulnerability for this indicator was assigned a **mid** because although temperatures are increasing, the overall pattern of relatively warmer and cooler areas will remain similar to the current conditions (Figure 5; Table 3).

The MWAT validation results suggest that the suitable habitat results should be interpreted with caution as the MWAT model may be underestimating stream temperatures. Coolwater and warmwater habitats were abundant throughout Rideau Valley whereas coolwater and coldwater habitat dominated Mississippi Valley (Figure 6). Currently, coldwater habitats occupy ~65% of the available habitat in the region (Table 2). By the 2080s, coldwater habitat may be reduced to 47% under the B1 scenario, and 38% under the A2 scenario. Coolwater habitats will increase from 34% of the streams to 51% under the B1 scenario, and 59% under the A2 scenario by the 2080s. Warmwater habitat may increase from less than 0.8% to 2.6% by the 2080s under the A2 scenario (Table 2).

Validation with the thermal classification (coldwater, coolwater or warmwater) data indicated that 78% of the 183 sites were assigned to the appropriate thermal class. Twenty-two percent were underestimated that is, based on the predicted MWAT they were incorrectly classified as coldwater or coolwater when they should have been classed as coolwater or warmwater, respectively. There was good concordance between the Northern Pike distributions and suitable coolwater habitat (Figure 6). The overall vulnerability for thermal stream habitat was set to **mid** for all of the time periods because although in-stream temperatures are projected to increase, these systems already support coolwater and warmwater fish communities with few coldwater species (Casselman et al. 2011; Table 3).

3.3 Lakes

Currently, maximum lake surface temperatures range from 23.5 to 25°C (Figure 7). Root mean square error with observed maximum surface data from 24 lakes was 0.85°C, which suggested that the MST model accurately predicts maximum surface temperatures in the region. Lakes in the Rideau River watershed are warmer than lakes in the Mississippi River watershed with an approximately 2°C change from south to north (Figure 7).

By the 2080s under the A2 scenario, all lakes will warm by 4 to 6°C with a range of 28.3–30.9°C. The B1 scenario is less extreme with lakes warming by 2–4°C and ranging from 26.25–29.0°C (Figure 7). The overall vulnerability for this indicator will increase from **low to mid** from the 2020s, 2050s and 2080s as the lake surface warming may occur gradually.

4 Discussion

4.1 Wetlands and Wetland Species

Potential drying and shrinking of the wetlands could lead to reductions in suitable habitat for wetland-dependent species. In this study, each wetland polygon was treated as a single entity. The low, mid and high vulnerability rankings were applied uniformly across each of the wetlands. However, it is possible that the entire wetland patch may not be affected by changes in air temperature and/or precipitation. For example, drying or shrinking of the wetlands may occur around the edges leaving the middle of the wetlands intact. If this was true, wetland vulnerability in this study may be overestimated. Alternatively, if the ground water influxes are less than expected in this study, wetland vulnerability may be underestimated.

Wetland vulnerabilities were calculated by pairwise comparisons between current conditions and each of the scenarios that is, the 2020s, 2050s and 2080s were each individually compared to the current conditions. Therefore, the cumulative effects of decades of possible drying or alternatively, wet conditions, which would promote wetland persistence, have not been included in this study. Future studies of the resilience and recovery of wetlands after perturbations (e.g., droughts, floods, low water conditions) would allow one to determine the long-term and compounded effects of changes in air temperature and precipitation on the wetlands during the three climate change time periods.

The American Coot results suggest that their suitable habitat may be significantly impacted by climate change. However, these analyses do not account for adaptation of the birds to new habitat conditions or migration of the birds to other wetlands within or adjacent to the study area. This study also does not consider the fact that other species may come to occupy the wetlands. More detailed estimates of habitat use and how wetlands may change (e.g., spatial extent and plant community composition) would provide more informed estimates of how species distributions may change with climate.

4.2 Streams and Thermal Habitat in Streams

The stream temperature and thermal habitat results should be interpreted with caution because an RMSE of 4.8°C suggested that the model is underestimating maximum stream temperatures. Although, a portion of that error is attributable to the fact that maximum temperatures as opposed to maximum weekly temperatures were compared in the validation. Daily monitoring of stream temperatures (via data loggers) at different sites during July and August would allow one to get a more accurate measure of MWAT. These data also could be used to re-evaluate the model, and if it is shown to still be inaccurate, the data could be used to develop a new MWAT model.

The stream indicators were assigned a vulnerability of ‘mid’ because although temperatures will increase, the spatial pattern of cold, cool and warm water areas will remain similar to current conditions. However, other changes that have been projected for streams will worsen their vulnerability. Casselman et al. (2011) estimated that spring discharges may peak 7 weeks earlier, summer flows may decrease in volume by 44% and low flows may be sustained for longer periods. These changes compounded with the changes in temperatures could have significant impacts on ecosystem function and biota.

The potential impacts of connectivity changes associated with climate change (e.g., dry stream reaches in the summer) and/or human activities (e.g., improper culver installations) should also be evaluated in future studies. Connectivity maintains access to critical habitats for different life stages and may provide routes to refugia for species to escape warm temperatures in the summer or ice-free zones in the winter.

4.3 Lakes

Warmer maximum surface water temperatures could lead to shifted thermocline depths, longer periods of stratification and increased duration of the ice-free season. This will affect the nutrient dynamics, dissolved oxygen concentrations, production, and availability of suitable habitat for warmwater species inhabiting the epilimnion, coolwater species in the metalimnion and coldwater species in the hypolimnion (Dove et al. 2011). Increases in lake surface temperatures would provide more suitable habitat for warmwater species, but this study does not take into account the metalimnetic and hypolimnetic changes in lakes that stratify. Future research could use the lake monitoring data: thermal profiles, bathymetry and dissolved oxygen profiles to quantify the changes in suitable coldwater, coolwater and warmwater habitat within lakes throughout the ice-free season. These data could then be linked to fish community production in these systems to provide estimates of potential shifts in fisheries production and harvest with climate change.

4.3.1 Non-Climatic Influences and Impacts

Non-climatic stressors such as agricultural activities and urban development also affect wetland conditions. Run-off from urban and agricultural lands may contain pollutants, nutrients and sediments that compromise water quality. This may in turn negatively impact plant growth, community composition and overall availability of wetland habitats (Mortsch et al. 2006).

In highly urbanized landscapes such as the eastern portion of the study area, anthropogenic refugia may exist or be developed for aquatic species. Chester and Robson (2013) found that urban drainage ditches and transport canals could support diverse aquatic communities while little is know about the roles of urban artificial ponds, golf course lakes and disused industrial ponds as refugia. Future research should explore the importance of anthropogenic refugia on the regional or local aquatic biodiversity in the watersheds.

This study provides simple assessments of the impacts of climate change on wetlands, streams and lakes in the Mississippi Valley and Rideau Valley Conservation Authority watersheds. These results and identified areas of vulnerability should be incorporated into a cumulative effects approach that will allow researchers and practitioners to assess the impacts of both climatic and non-climatic stressors such as anthropogenic species introductions (baitfish and vegetation), increasing expansion of urban areas and non-point source pollution on the wetlands, streams and lakes of the watersheds.

4.4 Strengths and Uncertainties of the Analyses

4.4.1 Strengths

- Incorporate the dominant physical variables (air temperature, precipitation and groundwater inflows) that influence wetlands
- Offer easily interpretable guides for setting priority areas for wetland, stream and lake monitoring and management
- Provide a framework for assessing how wetland changes may influence habitat availability and the distribution of wetland-dependent species
- Incorporate the dominant physical variables (air temperature and groundwater inflows) that influence the thermal regimes of streams
- Streams with the greatest changes in temperature are easily identified
- Predicted current and future temperatures along every length of stream provides a framework for other fish species (other than Northern Pike) assessments and other community patterns e.g., invertebrate community responses to climate change
- Offer easily interpretable guides highlighting sensitivity of different lakes to climate change

4.4.2 Uncertainties and knowledge gaps

- The pattern of drying in each wetland. In this study, each wetland was treated as a unit and assigned a vulnerability ranking. However, entire wetlands may not be affected uniformly. For example, drying or shrinking may occur around the edges only leaving the middle intact.
- Wetland type and plant diversity. Climate change will have different effects on the wetland types (e.g., bog, fen etc.) and changes in plant community composition will affect the structure and function of wetlands.
- General rule of thumb of a 10% change in precipitation to offset evapotranspiration associated with a 1°C increase in air temperature from Trenberth (2011) needs to be validated for the study area.
- Coolwater and coldwater refugia in lakes that stratify within the study area. The availability of metalimnetic and hypolimnetic coolwater and coldwater habitats should be estimated in future analyses.
- Other factors such as stream regulation and surrounding land use should be incorporated into future analyses for each ecosystem

5 Recommendations

Preamble

Healthy natural systems are likely more resilient to extremes and changes in climate than those which are under stress, therefore the objectives of climate change adaptation are first to protect and retain the current functionality and diversity of natural systems and then to identify ways to ensure the continued health of the systems under changing climate regimes and conditions. This in turn allows natural systems to continue to deliver the multiple 'free' services which are often not recognized until they are absent. Reducing the vulnerability of aquatic (and terrestrial) habitat under current and future conditions serves multiple purposes and underlines the critical need for effective land use policies and land stewardship strategies which are supported by realistic implementation plans.

Recognition of potentially changing vulnerabilities of aquatic systems must be followed by addressing knowledge gaps where necessary, identifying adaptive measures, and finally through timely integration into policy and processes at all levels, from provincial to municipal, and in all associated sectors.

Recommendations are proposed to highlight existing programs in the region, outline approaches which may be used to address uncertainties and knowledge gaps, and integrate these existing and future efforts with climate change initiatives. The following recommendations should be initiated as soon as possible as many of the aquatic ecosystems within the region are already under stress due to anthropogenic activities. Some recommendations may require a multi-year effort. These results and identified areas of vulnerability should be incorporated into a cumulative effects approach that will allow researchers and practitioners to assess the impacts of both climatic and non-climatic stressors on aquatic resources.

5.1 Wetlands

In the 1980s planning agencies in Ontario began to recognize the critical role of wetlands on the landscape for hydrology and habitat (water quality, water storage, flood attenuation, base flow augmentation, aquatic, avian and herptile habitat), and they began to address the protection and conservation through special planning designations. Thirty five years later, we are beginning to understand that in addition to ongoing land use and development pressure, wetlands are now also under threat from climate change. This significantly increases the need to conserve our remaining wetlands.

Wetlands play a regulatory role in flood attenuation and water storage and therefore are important features to retain for their functionality as well as their value as habitat. This study indicates that many local wetlands may decrease in size over time due to increased temperatures and increased evapotranspiration. However, given the projections of the increased frequency of extreme rainfall events, the future value of wetlands will increase through potentially reducing peak downstream flooding and storing overland flows.

1. In the short term, provide an appropriate level of planning protection for *all* wetlands, following a precautionary approach to minimizing current and future anthropogenic stressors. This includes identification and retention of current wetland boundaries.
2. Continue to evaluate existing wetlands in the Mississippi and Rideau watersheds according to the OWES. Given the large number of unevaluated wetlands found within the region, it is suggested that for the purposes of further understanding vulnerabilities that a mapping and characterization exercise be carried out, prioritizing evaluations through predetermined characteristics such as size, habitat potential, and/or location. Key wetland types can be identified (i.e. bog, fen, swamp, marsh) and where possible sub-types should be identified (i.e. open water marsh, robust emergent marsh, tall shrub swamp, conifer swamp, hardwood swamp, treed fen, etc).

3. Prescribe that where development and planning applications have potential to impact wetlands that consideration of future climate scenarios be included in the sensitivity analysis to determine potential cumulative negative impacts, and that this analysis be applied to reduce impacts through development design and implementation.
4. Prescribe that all planning documents (i.e. municipal, regional OPs, provincial PPS, etc.) adopt a targets and thresholds approach to wetlands by assigning a desired percent cover target for wetlands in all subwatersheds to guide planning and development through conservation and restoration bylaws, programs and strategies and requiring the incorporation of changes associated with climate change in this exercise.
5. Develop specific water budget information for each wetland type to assist in further determination of vulnerability, and ground-truth where possible. Enhancing current monitoring programs will be required as a first step to calculating water budgets for individual wetlands.
6. Identify priority/indicator wetland species for further focused monitoring of distribution and population levels.
7. Further study the effects of climate change on overall diversity of wetland types found within the region.
8. Study the resilience and recovery (example metric: wetland spatial area) of wetlands after perturbations (e.g., droughts, floods, low water conditions) to determine the long-term and compounded effects of changes in air temperature and precipitation on the wetlands through time.

5.2 Streams

The region has thousands of kilometres of streams, many with minimal legislative protection to ensure that their vital functions as aquatic habitat and contributors to our larger rivers and lakes are protected. Many of the streams that occur in urban areas show signs of stress and associated degradation.

Maintenance of stream temperatures, especially in headwaters, will be partially dependent on base flow contributions, shading provided by riparian vegetation and thermal control of surface water inflows. Stream temperatures are projected to increase by approximately three degrees under changing climate regimes so retention of base flow contributions and riparian vegetation are important to offset temperature increases and reduce losses of cool and coldwater habitat.

As storm water structures become more prevalent in the region, it is important to develop a clear understanding of their influence on receiving water temperatures and volumes, and ensure that planning policies include requirements for protection of aquatic habitats. This may be accomplished through incorporation of design elements that will reduce water temperatures within the structures and requirements to monitor the effectiveness of these designs.

1. Continue coordinated efforts to monitor stream temperature and flows throughout the region. Expand long-term stream temperature monitoring network.

2. Develop an inventory of stream crossings by type and distribution and from that carry out an analysis of the impacts of stream crossings and dams on stream connectivity.

3. Prioritize refugia areas (e.g., coldwater stream areas) for restoration, conservation and management as many of them will transition to coolwater systems in the next 100 years.
4. Develop empirical models of stream temperatures that incorporate landscape factors such as anthropogenic constructs e.g., impervious cover, stormwater structures, and from that develop temperature and flow projections for key streams.
5. Monitor temperature/volume relationships of on-line and off-line stormwater ponds to examine their influence on receiving waters.
6. Explore the importance of anthropogenic refugia on the regional or local aquatic biodiversity in the watersheds.
7. Develop an additional study for Carp River watershed as it is important and under significant development pressure but was considered to be beyond the scope of the current exercise.
8. Further study inter-annual variation of temperatures in local streams and rivers with a priority on cool and coldwater reaches.
9. Identify changing vulnerability and risks of modifying and/or developing riparian areas due to increased climate variability.

5.3 Lakes

Many of the hundreds of lakes in the region are subject to a high degree of anthropogenic activity, some through seasonal recreational use and in others throughout the year. Policies are needed in the short term to ensure protection of the aquatic habitat these lakes provide and to focus on ensuring that adequate protection of shorelines and waterways is in place.

As storm water structures become more prevalent in the region, it is important to develop a clear understanding of their influence on receiving water temperatures and volumes, and ensure that planning policies include requirements for protection of aquatic habitat. This may be accomplished through incorporation of design elements that will reduce water temperatures within the structures and requirements to monitor the effectiveness of these designs.

1. Continue inventory and monitoring of lake temperatures and dissolved oxygen profiles in the region.
2. Use existing lake monitoring thermal profiles, bathymetric and dissolved oxygen data to quantify the changes in suitable coldwater, coolwater and warmwater habitat within lakes throughout the ice-free season. These data could then be linked to fish community production in these systems.
3. Identify potential cumulative impacts of climate change and anthropogenic structures and activities in riparian areas and their impacts on local lakes.

4. Continue monitoring of stormwater ponds and other anthropogenic structures in relation to their impacts on local lakes as receiving waters in combination with changing temperature and precipitation projections:

- Monitor temperature/volume relationships of on-line and off-line stormwater ponds to understand the influence of on-line systems on receiving waters,
- Study effectiveness of existing thermal mitigation designs, and
- Identify the most effective designs and measures for integration into new and remediated systems and designs.

5. Study importance of anthropogenic structure type and location on aquatic diversity in the region.

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7 Tables

Table 1: Criteria used to assign the vulnerability of wetlands to changes in air temperature and precipitation associated with climate change. Brackets show ranking scheme representing the wetland vulnerability based on groundwater influxes (e.g., 0.821 equals high influx therefore low vulnerability to drying and climate change).

Air temperature : precipitation	Base flow index	Wetland vulnerability
Low	0.821 (low)	Low
Low	0.589 (mid)	Low
Low	0.321 (mid)	Low
Low	0.098 (high)	Low
Low	0 (high)	Low
Mid	0.821 (low)	Low
Mid	0.589 (mid)	Mid
Mid	0.321 (mid)	Mid
Mid	0.098 (high)	Mid
Mid	0 (high)	Mid
High	0.821 (low)	Mid
High	0.589 (mid)	High
High	0.321 (mid)	High
High	0.098 (high)	High
High	0 (high)	High

Table 2: Thermal habitat availability (km of stream) for coldwater (<19 °C), coolwater (19–25 °C) and warmwater (>25 °C) fishes in the Mississippi Valley and Rideau Valley Conservation Authority watersheds. Maximum weekly average temperature was used to delineate the habitat types estimated under current conditions, and under an ensemble climate model of air temperature under the A2 and B1 emissions scenarios for the 2020s, 2050s and 2080s. Total length of the streams in the study area is ~10,452 km.

Climate scenario	Time period	Thermal guild		
		Cold	Cool	Warm
	Current	6828.17	3535.48	88.35
B1	2020s	6854.68	3472.30	125.02
	2050s	5938.94	4361.55	151.51
	2080s	4886.36	5336.66	228.98
A2	2020s	6590.70	3720.07	141.23
	2050s	4884.56	5338.64	228.80
	2080s	4009.48	6167.82	274.70

Table 3: Projected vulnerability rankings of aquatic ecosystem indicators in the Mississippi Valley and Rideau Valley Conservation Authority jurisdictions under an ensemble of climate change projections during the 2020s, 2050s and 2080s. Red indicates high vulnerability (negative change) of an indicator to climate change, orange represents mid vulnerability, and green indicates low vulnerability to climate change.

			Vulnerability and Time period		
Ecosystem	**Indicator**	**Description**	**2020s**	**2050s**	**2080s**
Wetlands	Vulnerability to drying	Drying due to increases in air temperatures and/or decreases in precipitation			
	Wetland-dependent bird species	Changes in American Coot distributions			
Streams	Water temperature	Maximum weekly stream temperature			
	Thermal habitat	Coldwater (<19°C), Coolwater (≥19≤25°C) Warmwater (>25°C) habitat			
Lakes	Water temperature	Maximum surface water temperature			

8 Figures

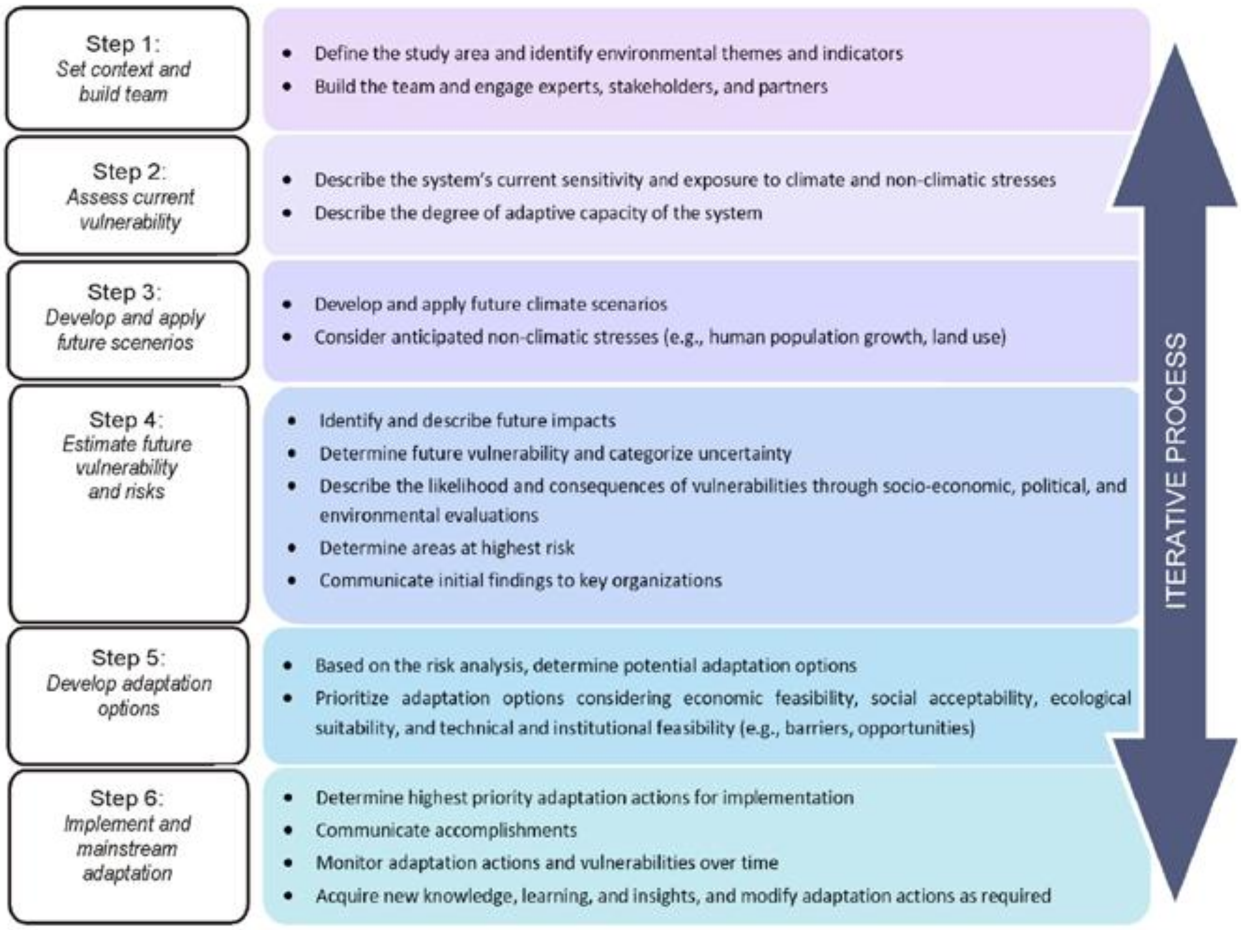

Figure 1. A conceptual framework to help determine organizational readiness, complete vulnerability analyses, and develop, implement, monitor, and adjust adaptation options as required (Source: Gleeson et al. 2011).

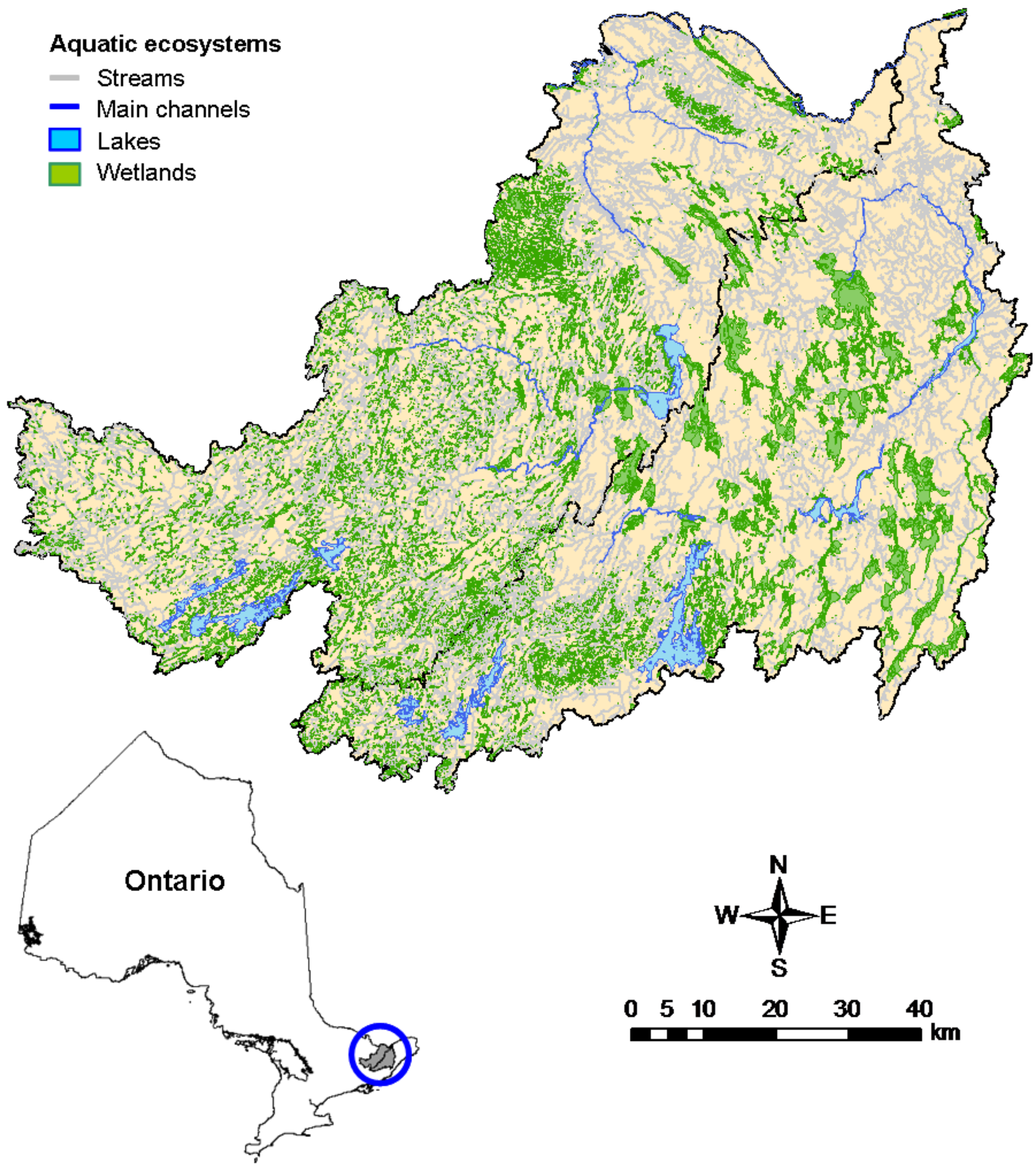

Figure 2. Aquatic ecosystems within the Mississippi Valley and Rideau Valley Conservation Authority watersheds.

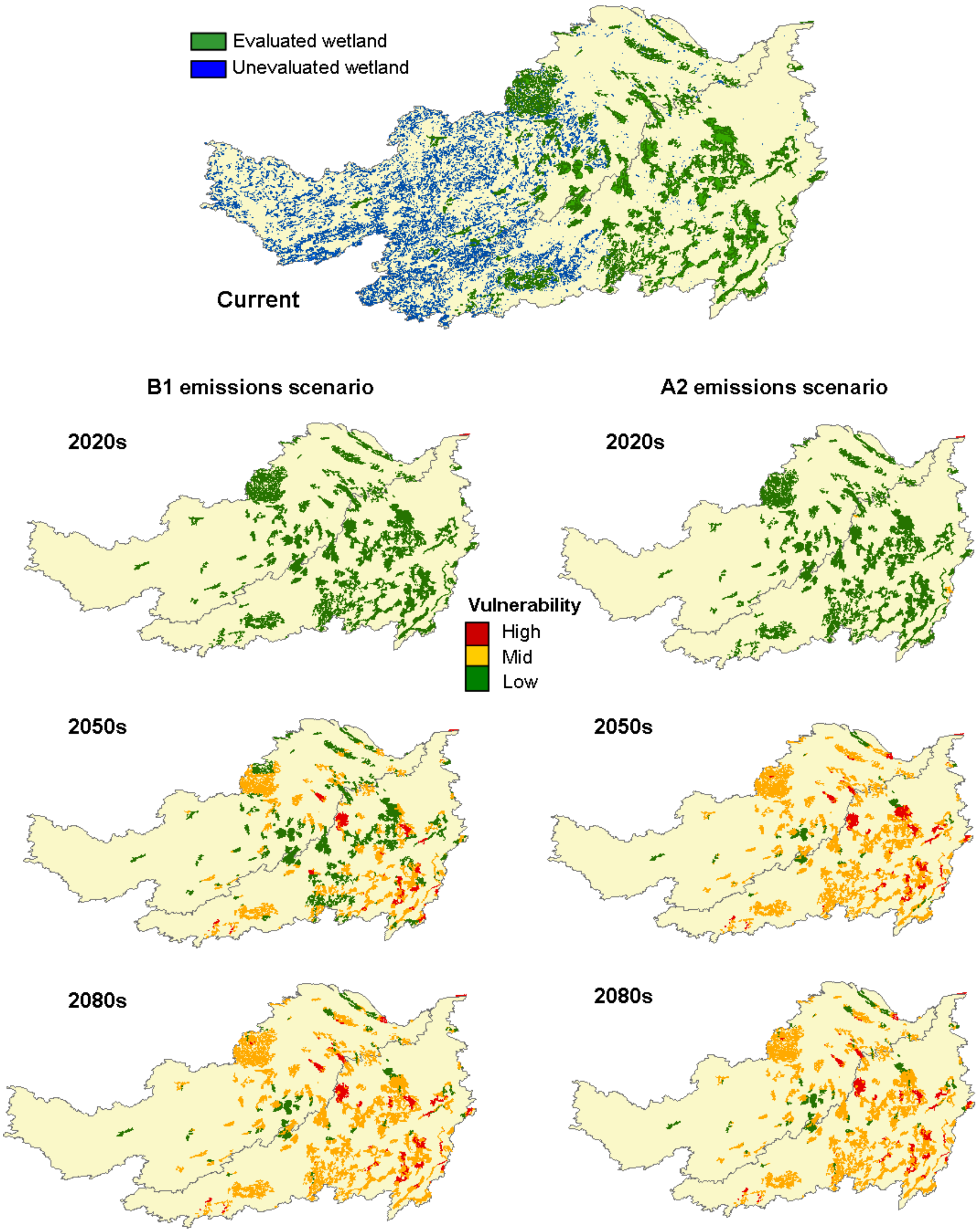

Figure 3. Vulnerability of wetlands in Mississippi Valley and Rideau Valley Conservation Authority watersheds to groundwater inflows and changes in air temperature and precipitation associated with climate change projected using an ensemble of climate change models and the B1 and A2 emissions scenarios for the present, 2011-2040, 2041-2070 and 2071-2100 time periods (Geographic projection).

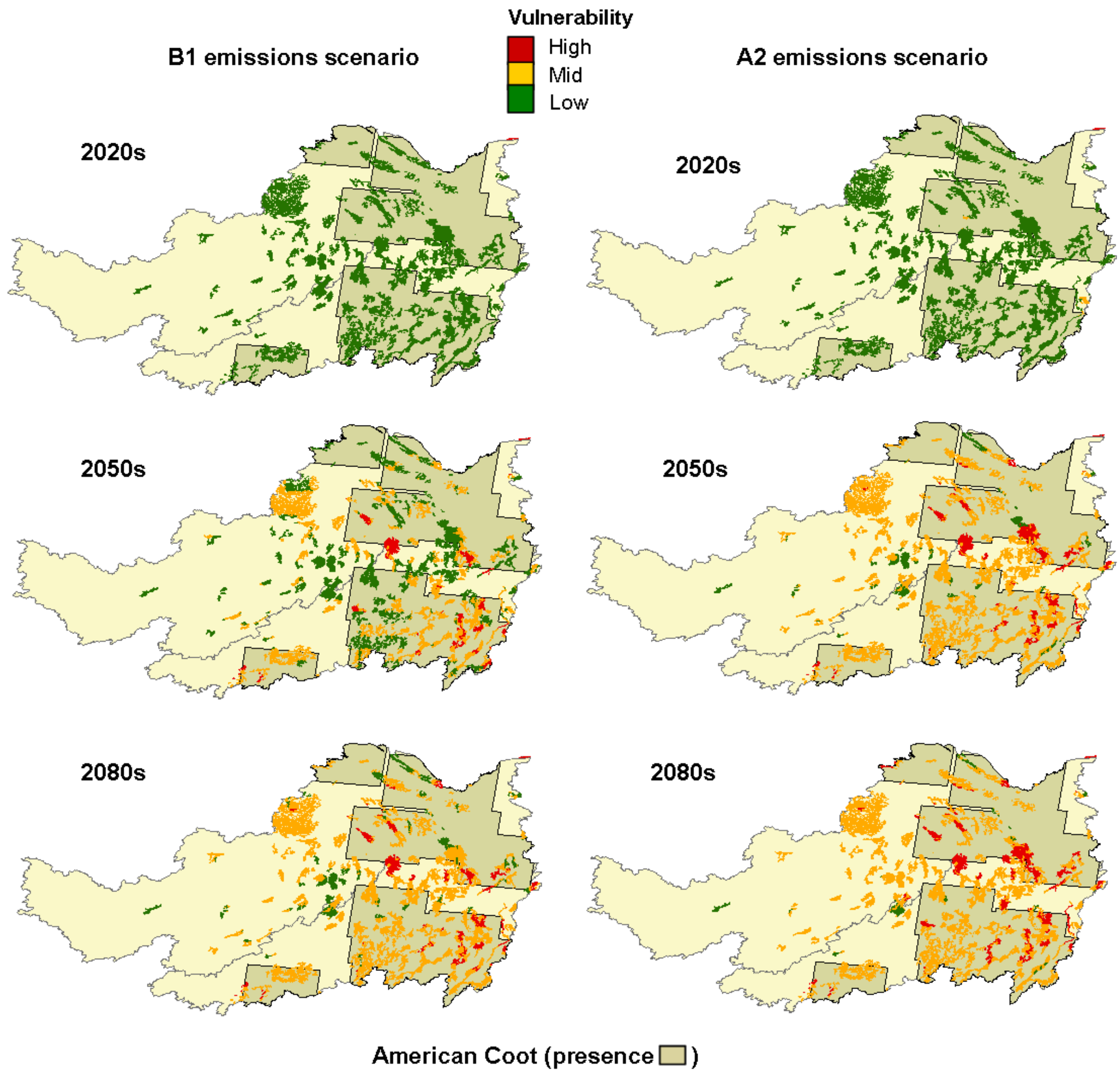

Figure 4. Vulnerability of wetlands to climate change and American Coot (*Fulica americana*) distributions likely to be impacted by air temperature and precipitation changes associated with climate change within the Mississippi Valley and Rideau Valley Conservation Authority watersheds (Geographic projection).

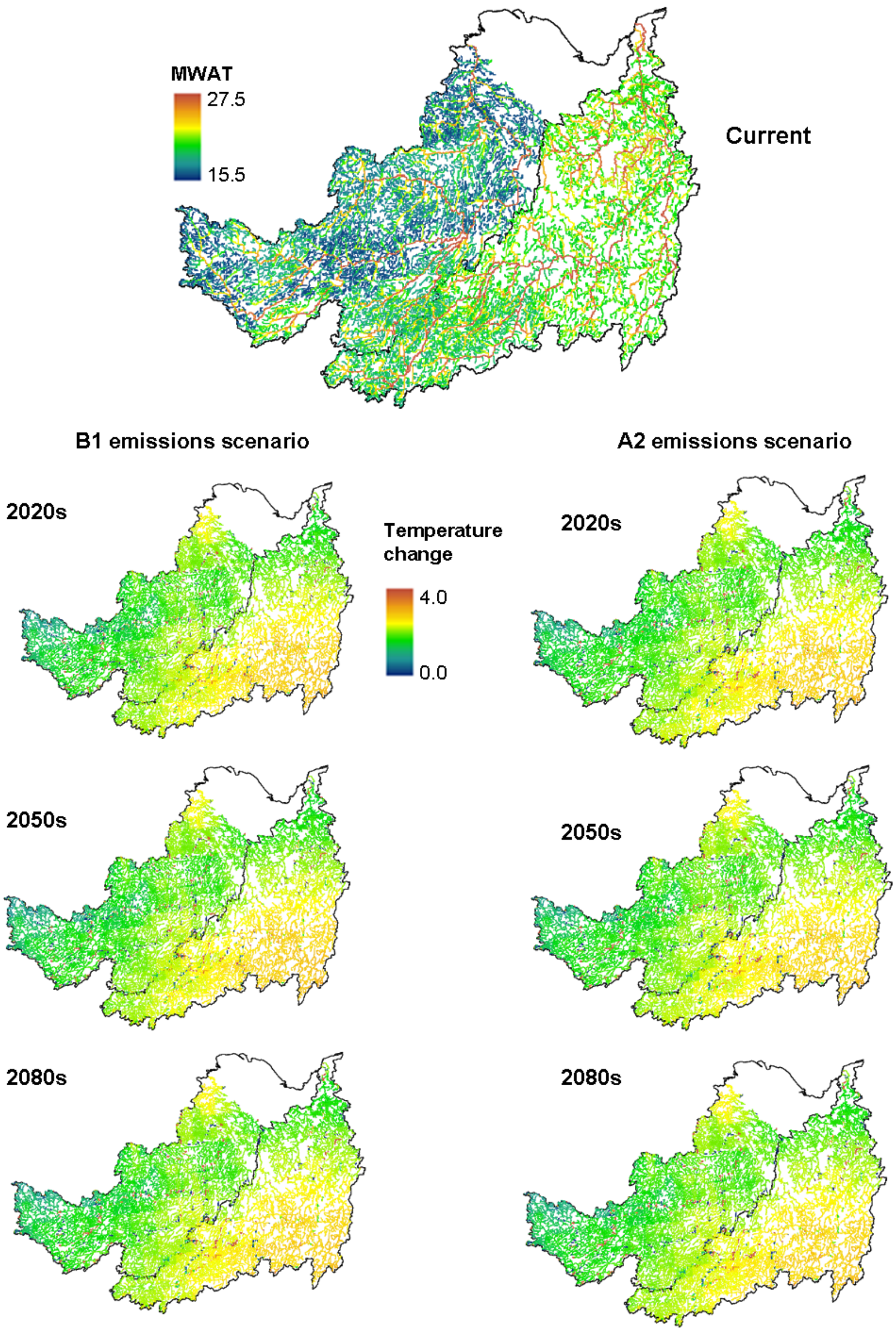

Figure 5. Predicted maximum weekly average temperature (MWAT) for streams throughout the Mississippi Valley and Rideau Valley Conservation Authority watersheds, and regional changes in MWAT under the 2011-2040, 2041-2070, and 2071-2100 air temperature projections of an ensemble of climate change models and the B1 and A2 emissions scenarios.

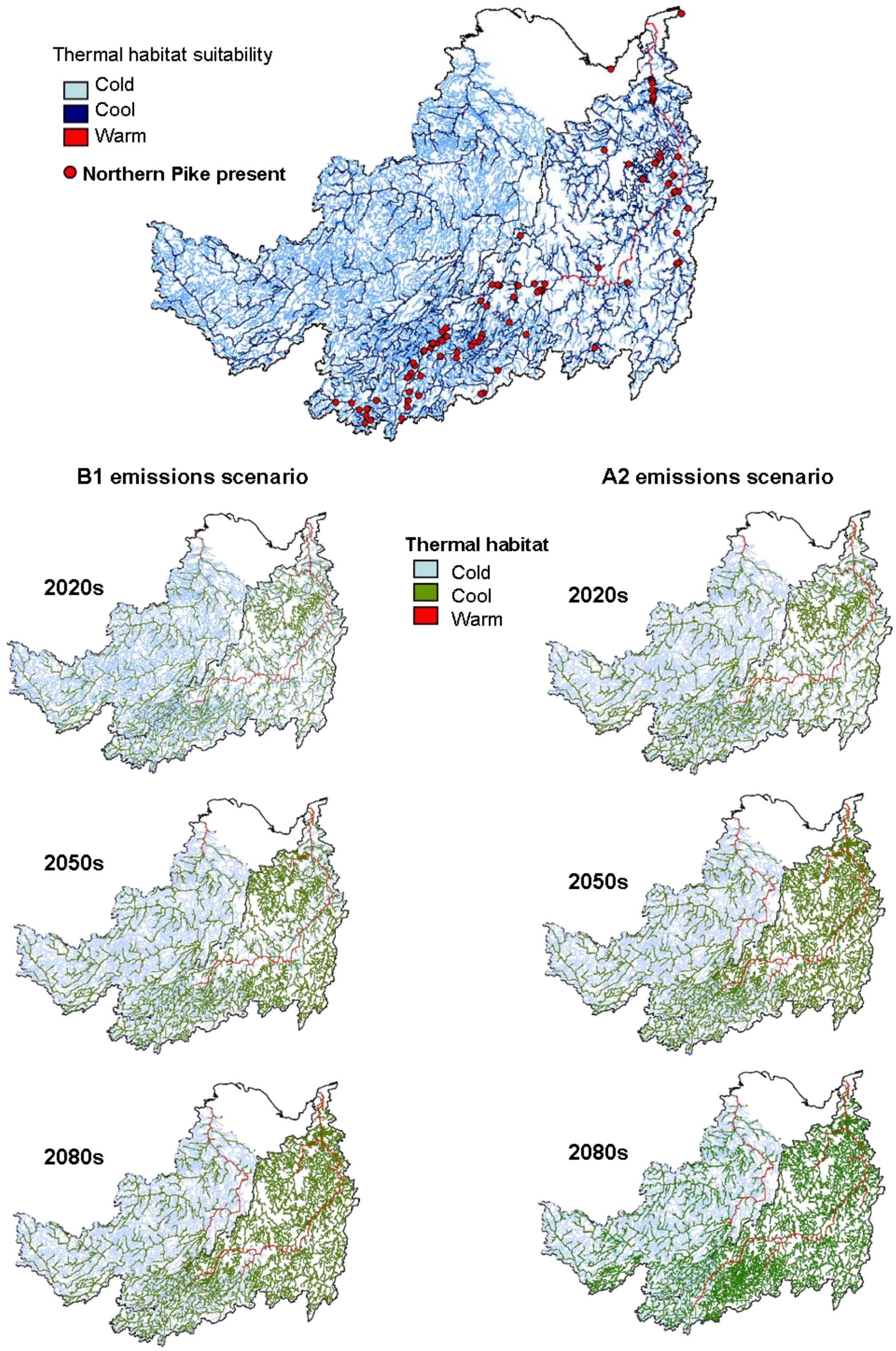

Figure 6: Current distribution of Northern Pike, coldwater (<19 °C), coolwater (≥19 ≤25 °C) and warmwater (>25°C) habitats in the Mississippi Valley and Rideau Valley Conservation Authority watersheds. Future projections are estimated using data from an ensemble climate model with B1 and A2 emissions scenarios for the 2011-2040, 2041-2070, and 2071-2100 time periods.

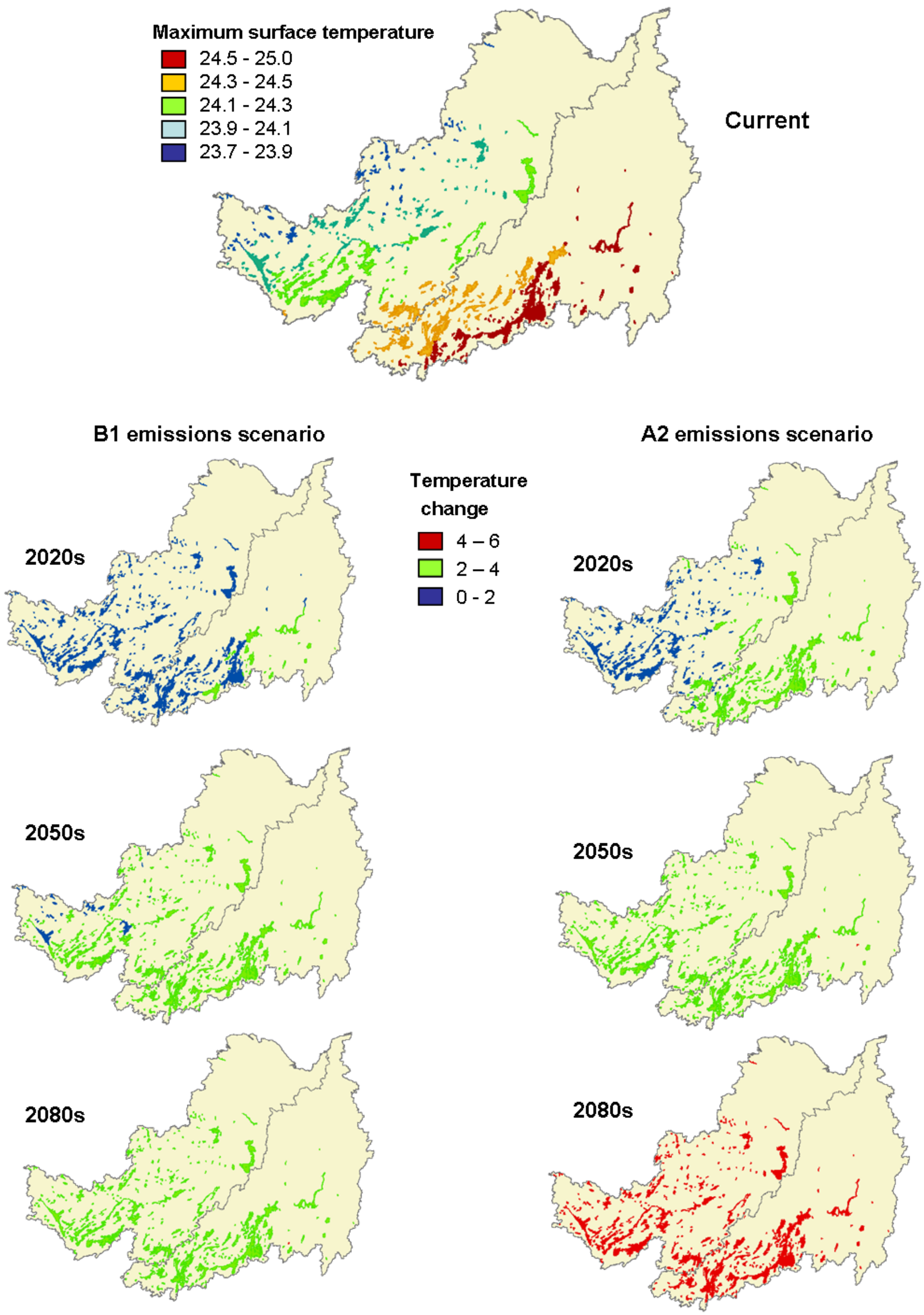

Figure 7: Predicted maximum surface lake temperatures throughout the Mississippi Valley and Rideau Valley Conservation Authority watersheds under the 2011-2040, 2041-2070, and 2071-2100 air temperature projections of an ensemble of climate change models and the B1 and A2 emissions scenarios.