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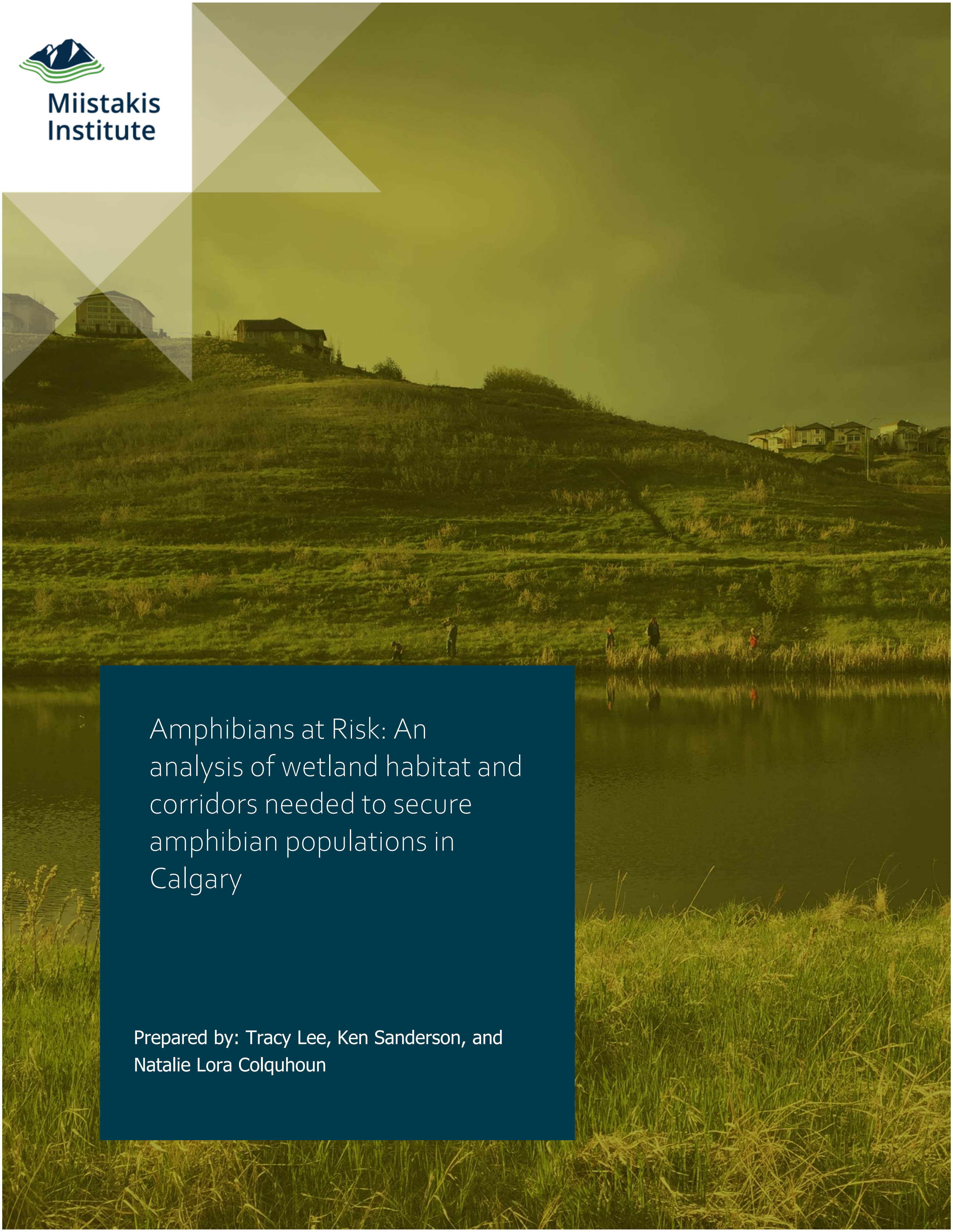

Amphibians at Risk: An analysis of wetland habitat and corridors needed to secure amphibian populations in Calgary

Prepared by: Tracy Lee, Ken Sanderson, and
Natalie Lora Colquhoun

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ALBERTA INNOVATES

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Thank you to the project advisory committee:

- Vanessa Carney, City of Calgary
- Dr. Irena Creed, University of Saskatchewan
- Lea Randall, Calgary Zoo
- Heather Rudd, City of Calgary

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Executive Summary

Our goal is to provide information to The City of Calgary to help maintain amphibian diversity and increase amphibian abundance in the urban environment. Three amphibian species, wood frog (*Lithobates sylvaticus*), boreal chorus frog (*Pseudacris maculata)* and tiger salamander (*Ambystoma mavortium)* currently make Calgary their home. Key concerns for amphibians in Calgary are the impacts of wetland loss, wetland degradation, and fragmentation of the wetland network. We sought to understand which wetlands support amphibians and where amphibians are moving between wetlands in Calgary.

Specifically, we had the following objectives:

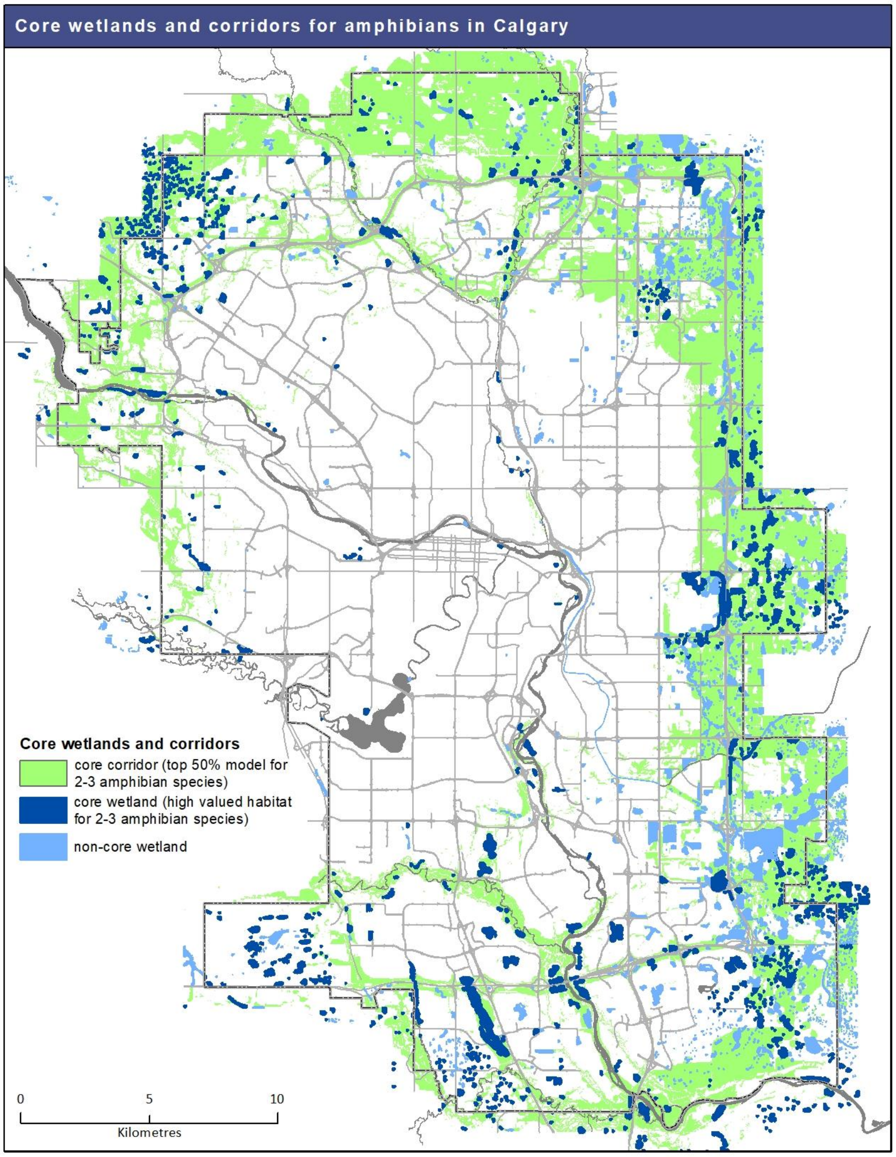
- To map amphibian habitat for wood frog, boreal chorus frog and tiger salamander and identify **core wetlands** (defined here as relatively high quality habitat that best supports two or more amphibian species);
- To map probable movement pathways for wood frog, boreal chorus frog and tiger salamander and identify **wetland corridors** (defined here as movement pathways that support two or more amphibian species);
- To identify **keystone wetlands and corridors** (defined as core wetlands and corridors that could play a significant role in supporting the overall wetland network and that if removed would impact disproportionately amphibian populations); and
- To document **barriers** (defined as features that fragment keystone wetland corridors or prevent movement of amphibians) between keystone wetlands and corridors where restoration/mitigation could improve amphibian abundance in Calgary.

The modelling products include habitat suitability indices, connectivity models, and centrality and barrier maps designed to inform planning, management and restoration of the wetland network to support amphibians in Calgary. For this project, natural wetlands, modified wetlands and stormwater ponds were all included in modelling and are referred to in this report generically as wetlands.

Amphibian habitat occurs for all three species predominately outside the city Ring Road transportation system (including the section of the Ring Road under construction) on the urban fringe or where urbanization has not occurred. Urbanization has resulted in significant wetland loss and therefore habitat loss for amphibians in the inner city (defined here as inside the Ring Road). Amphibian habitat occurring inside the Ring Road includes areas in Fish Creek Provincial Park, along edges of major roads or riparian systems (Bow River, Nose Creek and Beddington Creek) and in small natural areas. The most suitable amphibian habitats identified from species-specific habitat suitability models were overlaid to identify core wetlands. A limitation of the habitat suitability models is a lack of data on aquatic attributes (for example presence of fish or emergent vegetation) which could impact the ability of a wetland to support amphibians. Core wetlands in the inner city may support seasonal amphibian movements between wetland and upland terrestrial habitat but need to be considered in association with connectivity models to determine if species dispersal is possible.

Amphibian connectivity models identified probable movement pathways for dispersing individuals for each of the three species. Movement pathways predominately occur outside the Ring Road on the urban fringe or where urbanization has not occurred. Inside the Ring Road, core wetlands are largely isolated from neighbouring wetlands with exceptions in Fish Creek Provincial Park, along some riparian systems and along some green spaces beside major roads. Isolated core wetlands have a reduced probability of re-colonization after a local extinction event. An overlay of the top 50% of connectivity models for all three species was used to identify priority wetland corridors. Core wetlands should be assessed to understand their potential for wetland protection or opportunities for enhancement. Enhancement of core wetlands may include movement opportunities to aid in dispersal and include identification of restoration projects such as removing barriers (such as roads), restoring wetlands in movement path to aid in dispersal or naturalization opportunities to improve corridor condition.

Models illustrated the impact of the major road network on amphibian ability to disperse to new wetlands in Calgary. There may be concerns associated with promoting road verges as animal corridors due to noise, pollution and increase risk of road mortality, but, with limited movement pathways inside the Ring Road, biodiversity strategies should consider maintaining and managing road-side verges to support amphibians and other wildlife. Policy and guidelines that encourage removal of barriers through road mitigation to facilitate amphibian movement would greatly improve conservation efforts in The City of Calgary



Given the multitude of land uses occurring in the urban environment, and the high expense associated with habitat and connectivity restorations, we ran centrality and barrier models to assist in the identification of keystone wetlands and corridors. A fine scale assessment of these results to aid in local amphibian habitat management goals and development of a citywide prioritized action framework is recommended to guide investment in restoration activities to support urban biodiversity.

Lastly, we provide a series of recommendations on monitoring and research needs, planning, management, restoration actions and policy direction to promote conservation of amphibians in The City of Calgary.

1.0 Introduction

The Call of the Wetland Program[1] identified three species of amphibians occurring within Calgary, wood frog (*Lithobates sylvaticus*), boreal chorus frog (*Pseudacris maculata)* and tiger salamander (*Ambystoma mavortium*). Maintenance of amphibian populations depends on the availability of aquatic habitat across a landscape and terrestrial habitat suitable for foraging, hibernation and dispersal. Amphibians in the urban environment are subjected to habitat loss, habitat fragmentation and habitat degradation (Hamer et al. 2012). Understanding these three impacts is important to effectively manage urban biodiversity. In this report we focus on addressing a key concern for amphibians in the urban environment, the impact of habitat fragmentation on species persistence and dispersal (Semlitsch & Bodie 2003; Hamer & McDonnell 2008; Semlitsch 2008).

Our goal is to maintain amphibian diversity and increase amphibian abundance in the Calgary. The purpose of this analysis is to inform planning, management, and restoration of wetlands and wetland corridors to support amphibians in Calgary.

Specifically, we had the following objectives:

- To map amphibian habitat for wood frog, boreal chorus frog and tiger salamander and identify **core wetlands** (defined here as relatively high quality habitat that best supports two or more amphibian species);
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[1] Call of the wetland was a three year citizen science program developed by the Miistakis Institute in partnership with City of Calgary, Calgary Zoo and Alberta Conservation Association. Learn more at www.callofthewetland.ca

2.0 Methodology

We modelled habitat suitability and probable amphibian connectivity for wood frog, boreal chorus frog and tiger salamander to understand where high value habitat occurs in Calgary and to identify core wetlands and wetland corridors within Calgary. Habitat suitability index (HSI) models were developed using the results from occupancy models for wood frog and boreal chorus frog and by expert opinion for tiger salamander. Amphibian connectivity was modelled using Circuitscape[2] which predicts the probability of movement between focal nodes based on random walks and multiple pathways using two inputs: (1) a resistance surface, and (2) a set of focal nodes. The resistance surface represents the relative effort for an animal moving across each pixel on the landscape, and focal nodes represent the locations where the animal is moving to and from. The modelling process is depicted in Figure 1.

2.1 Study Area

The study area includes the Calgary city limits with a one kilometer buffer. A one kilometer buffer represents the maximum dispersal distance for amphibian species of interest and also represents approximately a 20% buffer recommended to reduce the problems associated with edge bias in modelling (Koen et al. 2014).

Most of the wetlands in Calgary occur outside the city center or in areas where urbanization is limited, with the majority of wetlands occurring along the eastern edge of the city (Figure 2). Wetlands inside the Ring Road (Stoney Trail) are low in number because wetlands have been lost as the city urbanized. Wetlands in this report refer to natural wetlands, modified wetlands and constructed stormwater ponds.

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[2] Circuitscape.jl (v0.1.0)

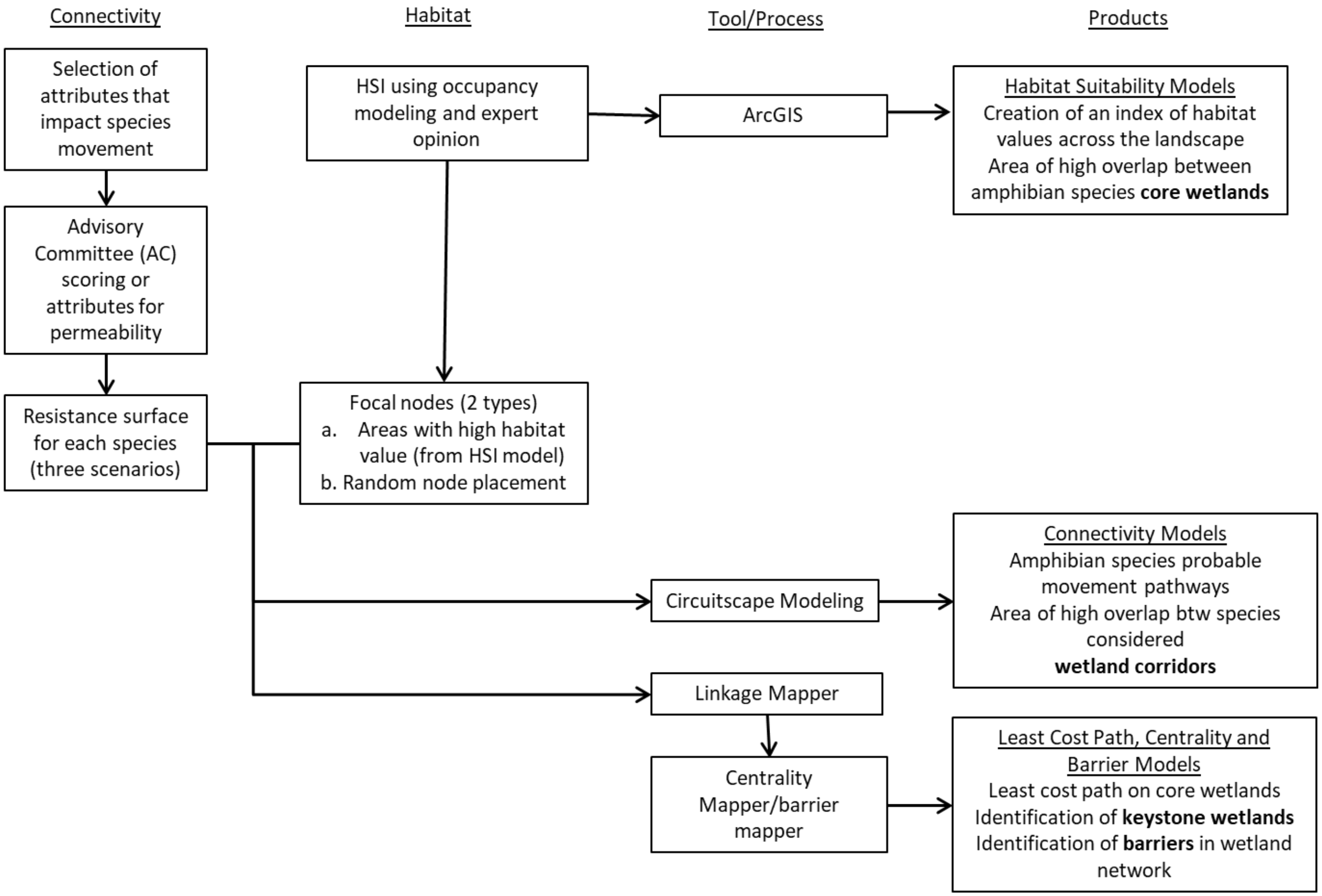

Figure 1: Modelling process

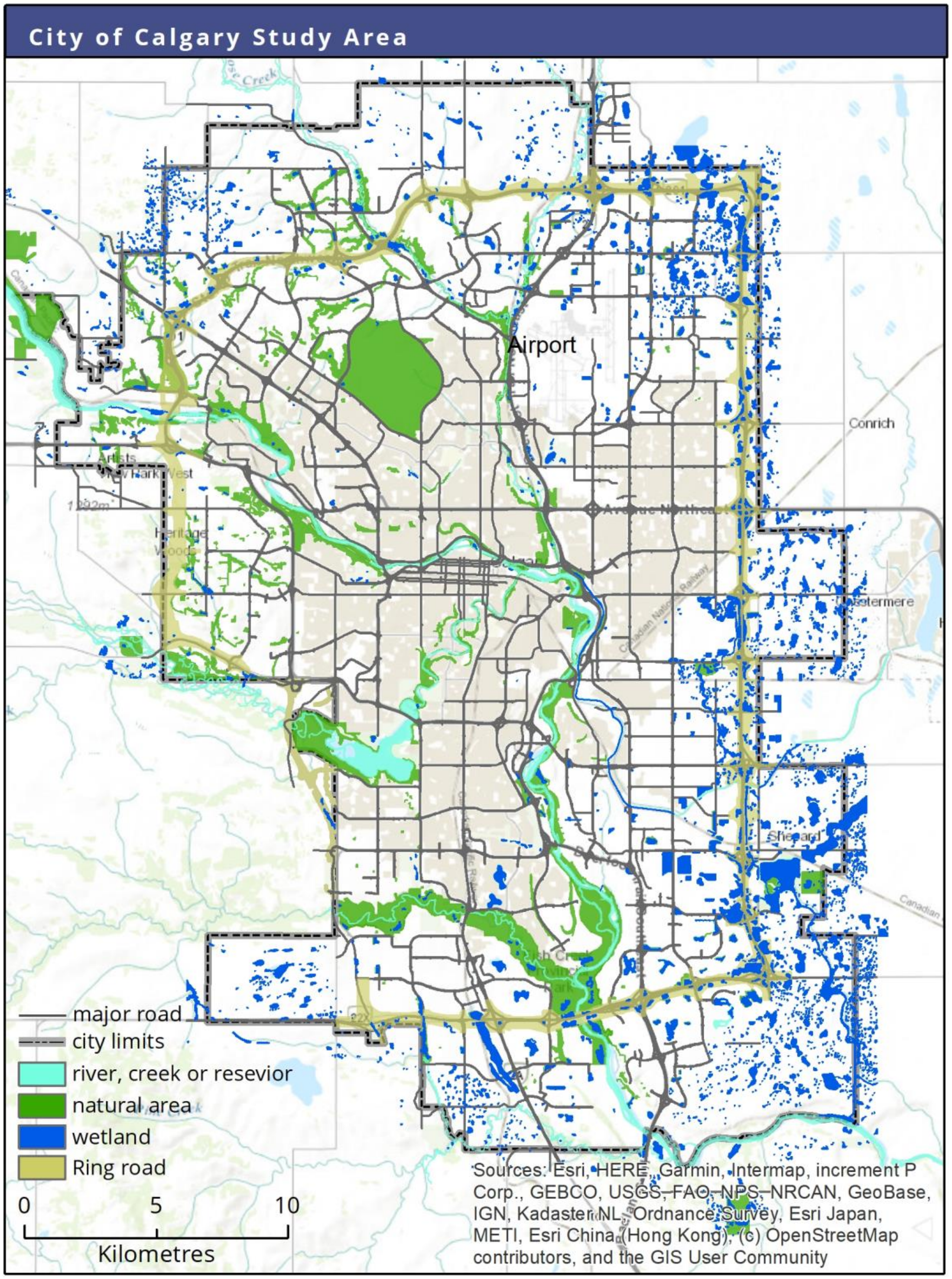

Figure 2: Study area depicting location of wetlands (current in 2015), urbanized neighbourhoods within the City limits (light grey).

2.2 Approach

To inform the development of the habitat suitability index (HSI) model and to build resistance surfaces for the connectivity model for each amphibian species, we considered the results from Call of the Wetland Program occupancy models (unpublished data), reviewed the literature and sought expert opinion to identify and select key landscape attributes. The advisory committee reviewed results and identified terrestrial attributes to include in the HSI and connectivity models.

2.3 Habitat Suitability Index (HSI) Models

To understand where habitat is most suitable in Calgary for amphibians, we developed three habitat suitability index (HSI) models based on Call of the Wetland occupancy results, a literature review and expert opinion (refer to Appendix A). To inform the HSI models, we identified both terrestrial and aquatic attributes, buffered wetlands to represent terrestrial habitat (equal to the typical movement range during a season) and used the relationships between attributes and amphibian species established in occupancy models. The aquatic attributes (e.g. presence of emergent vegetation, wetland depth to size ratio and water quality variables) represented data-gaps for Calgary for all three species and therefore were not included in the final models.

We applied a filter to remove wetlands most likely to support fish populations, a key predator that impacts the aquatic phase for all three amphibian species. Wetlands were removed that occurred in the floodplain of permanent rivers (Bow River, Elbow River, Nose Creek and Beddington Creek) as flooding enables fish populations to reach wetlands in the floodplain. During the validation process, we compared an independent amphibian dataset to the HSI results and found stronger agreement for boreal chorus frog and wood frog when the filter was removed. We therefore removed the floodplain filter for these two species. The floodplain filter for potential fish populations was applied to the tiger salamander HSI as the validation did not indicate species have been found along the floodplain.

Wood Frog and Boreal Chorus Frog HSI

To identify the most suitable habitat for wood frogs, we used the four attributes that had the biggest impact on wood frog occurrence: distance to forest (DF), proportion of grassland (GR), proportion of impervious surface (IPS) and distance to roads (DR). The relationship of each attribute to wood frogs and model weights were informed by occupancy models (analyzed using Presence 2.12.16) from the Call of the Wetland Program (Table 1). We buffered each wetland by 250 m to represent seasonal habitat needs for wood frogs (Baldwin et al. 2006). Akaike's information criterion (AIC) was used to select the most parsimonious model, and calculate model weight (AICW) (Burnham & Anderson 2002).

Table 1: Occupancy modelling results for wood frog

Model	AIC	AICW	Relationship
DF	156.86	0.97	occupancy declines as distance to forest increases
GR	163.89	0.02	occupancy increases as proportion of grassland increases
IPS	167.46	0.01	occupancy declines as proportion of impervious surface increases
DR	167.26	0.01	occupancy increases as distance to road increases

To identify the most suitable habitat for boreal chorus frogs, we used five attributes that had the biggest impact on boreal chorus frog occurrence: proportion of manicured land cover (MA), slope (SL), proportion of forest (FO), proportion of impervious surface (IPS) and proportion of grassland (GR). The relationship of each attribute to boreal chorus frog and model weights were informed by occupancy models from the Call of the Wetland Program (Table 2). We buffered each wetland by 100 m to represent seasonal habitat needs for boreal chorus frog (Scherer et al. 2012).

Table 2: Occupancy models for boreal chorus frog

Model	AIC	AICW	Relationship
MA	417.38	0.82	occupancy increases as proportion of manicured land cover increases
SL	423.00	0.05	occupancy declines as slope increases
FO	423.06	0.05	occupancy declines as proportion of forest increases
IPS	423.00	0.04	occupancy declines as proportion of impervious surface increases
GR	423.00	0.04	occupancy increases as proportion of grassland increases

Distribution curves derived from the occupancy models were used to determine classes for each attribute in the HSI model (see Appendix B). GIS layers were then combined using "Map Algebra" formulas to determine potential site suitability. We used weightings (AICW) from the occupancy models to derive the formula:

- HSI wood frog = (Distance to forest*0.97)+(Grassland*0.02)+(Impervious surface*0.005)+(Distance to roads*0.005)
- HSI boreal chorus frog = (Manicured*0.82)+(Slope*0.05)+(Forest*0.05)+(Impervious*0.04)+ Grassland*0.04)

We took the mean habitat suitability index per wetland and its buffer and classified the HSI into three ranges from 0 to 1, where 1 is the highest valued habitat. We discretized the HSI values into three quantiles to represent low (0 to 0.29, medium (0.3 to 0.59) and high (>0.6) valued habitat.

Focal nodes used in the connectivity modelling were developed from high valued habitat. We applied a road mesh, based on major roads (4 lanes or greater where 95% of road sections have an annual daily traffic greater than 6,000 vehicles per day) because they represent a significant barrier to amphibians (Charry & Jones 2009). Lastly, we removed small patches of habitat less than 60,000 m^2 (6 hectares) to remove sliver habitats and then used the centroid of each area as a focal node.

Tiger Salamander HSI

To identify the most suitable habitat for tiger salamanders, we used five attributes; distance to forest (DF), distance to roads (DR), proportion of grassland (GR), proportion of impervious surface (IPS) and slope (SL). The relationship of each attribute to tiger salamander and model weights were informed by literature review and analytic hierarchy process (AHP) models based on expert opinion (Table 3, Appendix B). We buffered each wetland by 500 m to represent seasonal habitat needs for tiger salamander (Semlitsch & Jensen 2001; Searcy et al. 2013; Bain et al. 2017).

Experts were guided through a discussion on the tiger salamander and the two Analytical Hierarchy Process (AHP) models. The AHPs were completed by each expert individually. We then took the mean from the total summed rank and input the mean value into an AHP calculator to generate the weighting of each variable[3].

Table 3: AHP results for tiger salamander

Model	AHP Weight	Relationship
GR	0.58	Occupancy increases as proportion of grassland increases
DR	0.17	Occupancy increases as distance to road increases
IPS	0.14	Occupancy declines as proportion of impervious surface increases
DF	0.07	Occupancy declines as distance to forest increases
SL	0.04	Occupancy declines as slope increases

Distribution curves derived from the wood frog occupancy were used to determine classes for each attribute in HSI modelling (see Appendix B). GIS layers were then combined using "Map Algebra" formulas to determine the theoretical potential site suitability. We used weightings derived from the AHP to derive the formula:

- HSI = (Grassland*0.58)+(Distance to road*0.17)+ (Impervious surface*0.14)+ (Distance to forest*0.07)+((Slope*0.04)

We used the same process to identify high value habitat and focal nodes as described in methods for wood frog and boreal chorus frog.

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[3] [2] AHP software: https://bpmsg.com/ahp/ahp-calc.php

HSI Validation

All HSI's were validated using independent datasets generated from the Call of the Wetland Program's opportunistic sightings reported between 2017 to 2019 as well as new surveys undertaken at 14 wetlands by undergraduate students in 2020. For tiger salamander, incidental occurrences provided by the city were also included in the dataset. For each species, the validation dataset was compared to the HSI low, medium and high habitat values to determine level of agreement.

Core Wetlands

We generated core wetlands by taking high habitat value for each species, creating a binary surface and adding the three surfaces together. Core wetlands were identified as wetlands supporting 2-3 amphibian species.

2.4 Connectivity Modelling

Connectivity modelling using Circuitscape was used to identify probable movement pathways for amphibians and support identification of wetland corridors in the City of Calgary. Circuitscape requires the development of two inputs; a resistance surface to depict a species ability to move across the landscape and focal nodes to identify where the species is moving to and from (McRae et al. 2008).

Resistance Surface

An expert based approach was used to create resistance surfaces for amphibian species to identify potential amphibian movement pathways within the City of Calgary. Landscape attributes were selected by experts for wood frog, boreal chorus frog and tiger salamander. Each landscape attribute was broken down into categories that we classified for resistance (i.e. not permeable) to amphibian movement. Each feature was given a resistance class of habitat, favourable matrix, less favourable matrix or strong barrier (Churko 2016) (Table 3).

Table 3: Resistance classification based on expert opinion for amphibian species in Calgary

Variables	**boreal chorus frog**	**woof frog**	**tiger salamander**
Transportation	**resistance category**	**resistance category**	**resistance category**
> 4 lane paved roads	strong barrier	strong barrier	strong barrier
4 lane paved roads	strong barrier	strong barrier	strong barrier
neighbourhood roads	less favourable matrix	less favourable matrix	less favourable matrix
LRT track	strong barrier	strong barrier	strong barrier
laneways	less favourable matrix	less favourable matrix	less favourable matrix
park pathway	less favourable matrix	favourable matrix	favourable matrix
railway	strong barrier	strong barrier	strong barrier

Hydrology	**resistance category**	**resistance category**	**resistance category**
river	less favourable matrix	less favourable matrix	less favourable matrix
creek	habitat	habitat	favourable matrix
canal	strong barrier	strong barrier	strong barrier
Glenmore Reservoir inside 15 m buffer	less favourable matrix	less favourable matrix	less favourable matrix
Glenmore Reservoir	strong barrier	strong barrier	strong barrier
Wetland	habitat	habitat	habitat
non-permanent streams	habitat	habitat	favourable matrix
Landcover	**resistance category**	**resistance category**	**resistance category**
forest	habitat	habitat	habitat
grassland	habitat	habitat	habitat
shrubland	habitat	habitat	habitat
agriculture crop	favourable matrix	favourable matrix	favourable matrix
agriculture pasture	habitat	favourable matrix	habitat
golf course	favourable matrix	favourable matrix	favourable matrix
manicured	habitat	favourable matrix	favourable matrix
sports facility	less favourable matrix	less favourable matrix	less favourable matrix
bare ground	less favourable matrix	less favourable matrix	less favourable matrix
construction	strong barrier	strong barrier	strong barrier
Impervious surface	**resistance category**	**resistance category**	**resistance category**
buildings	strong barrier	strong barrier	strong barrier
gravel patches	less favourable matrix	less favourable matrix	less favourable matrix
pavement patches	less favourable matrix	less favourable matrix	less favourable matrix
concrete (driveways, peoples yards)	less favourable matrix	less favourable matrix	less favourable matrix
Slope	**resistance category**	**resistance category**	**resistance category**
>20 slope	strong barrier	strong barrier	n/a
16-20	less favourable matrix	less favourable matrix	n/a
12 to 15	favourable matrix	favourable matrix	n/a
0-11	habitat	habitat	n/a
>35 slope	n/a	n/a	strong barrier

26-35	n/a	n/a	less favourable matrix
16-25	n/a	n/a	favourable matrix
0-15	n/a	n/a	habitat

We converted the four resistance classes into numerical values based on three scenarios (Table 4, Figure 3). Numerical values range from 1 to 1000, where higher values represent more resistance to movement. Resistance surfaces were generated to represent movement opportunity of amphibian species for each of the resistance scenarios.

Table 4: Resistance classification scenarios

Resistance Classification	Sigmoidal	Logarithmic	Exponential
Habitat	1	1	1
Favourable matrix	100	900	10
Less favourable matrix	900	990	100
Strong barrier	1000	1000	1000

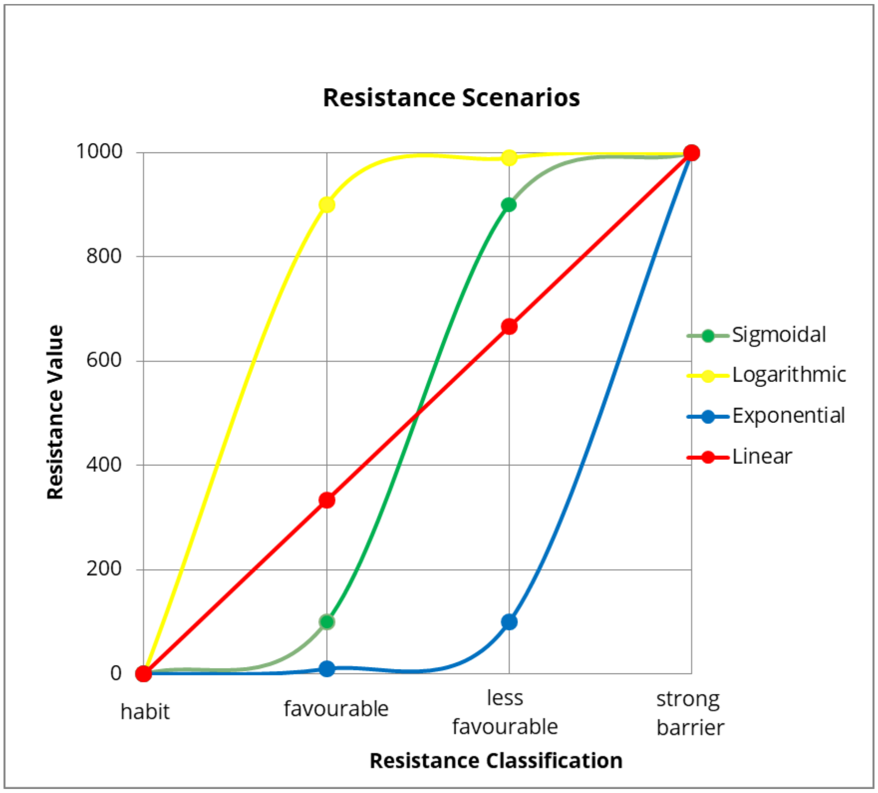


Figure 3: Relationship between resistance classification and numerical resistance value.

We used the three resistance scenarios to test connectivity model sensitivity to a range of resistance options of an amphibian's ability to move through the landscape:

- sigmoidal scenario where resistance starts out low, increases with slope to an inflection point, and then levels off as approaches the higher resistance value;
- logarithmic scenario is the inverse of exponential, where resistance starts out low, and quickly rises to high resistance values; and
- exponential scenario is the inverse of logarithmic, where resistance starts out low, slowly increasing in resistance values.

Lastly, resistance surfaces for each species were clipped to a species maximum dispersal distance around all wetlands in the network; 1000 m for wood frog and tiger salamander and 600 m for boreal chorus frog (refer to Appendix C for background literature review on dispersal distances).

Focal Nodes

We developed two sets of focal nodes to test model sensitivity to node placement for connectivity modelling:

- high valued habitat generated from the HSI models; and
- random selection of 100 focal nodes within the study area.

Wetland Corridors

We used Circuitscape Version 5.0 to run connectivity models for all three species on each resistance scenarios and focal node placement (Anantharaman et al. 2019). Circuitscape models random walks between focal nodes and calculates a resistance distance between nodes and can result in multiple corridors between focal nodes (Boyle et al. 2017). These models represent probabilistic movement along all possible paths and assumes animals do not know the landscape (Wade et al. 2015). The three resistance scenarios were summed to generate a current density map for each species. We took the top 50% of the summed resistance model for each species and created a binary surface. These surfaces were overlaid to identify wetland corridors. Areas of high overlap represent most likely wetland corridors for amphibian movement occurring in Calgary under current conditions.

Keystone Wetlands and Corridors

To understand the importance of core wetlands and corridors in the overall wetland network we used Linkage Mapper toolkit to run least cost path, centrality and barrier analysis using the amphibian sigmoidal resistance scenarios (represents non-extreme movement surface) and core wetlands as focal nodes. Least cost path analysis models the shortest distance between focal nodes in consideration of landscape costs, calculates a least cost path distance and generates one optimal movement path. Least cost path modelling assumes the amphibian has perfect knowledge of the landscape (Wade et al. 2015). If there is only one possible path, the least cost distance and resistance distance will be equal (Marrotte & Bowman 2017). There are however many reasons an amphibian might not follow an optimal path, such as avoiding predators.

Centrality analysis prioritizes core wetlands and wetland corridors in terms of their importance to maintaining the overall wetland network. It calculates the cumulative current flow of a core wetland and wetland corridor based on running a current from each core wetland to all other core wetlands. Higher cumulative current flow represents a more significant role in the network. Core wetlands and corridors with a high centrality score represent important components in the wetland network and are considered keystone wetlands. Removal of keystone wetlands or corridors will have a bigger impact on the wetland network.

3.0 Results

3.1 Habitat Suitability Modelling

Wood Frog

HSI results were categorized into low, medium and high value (Figure 4a) with high valued habitat identified as wetlands with a mean HSI greater than or equal to 0.6 (Figure 4b). High valued wood frog habitat occurs all around Calgary with larger habitat patches in the northwestern corner, the southern region south of Fish Creek Provincial Park, east along the 1A Highway and to the northeast of the airport.

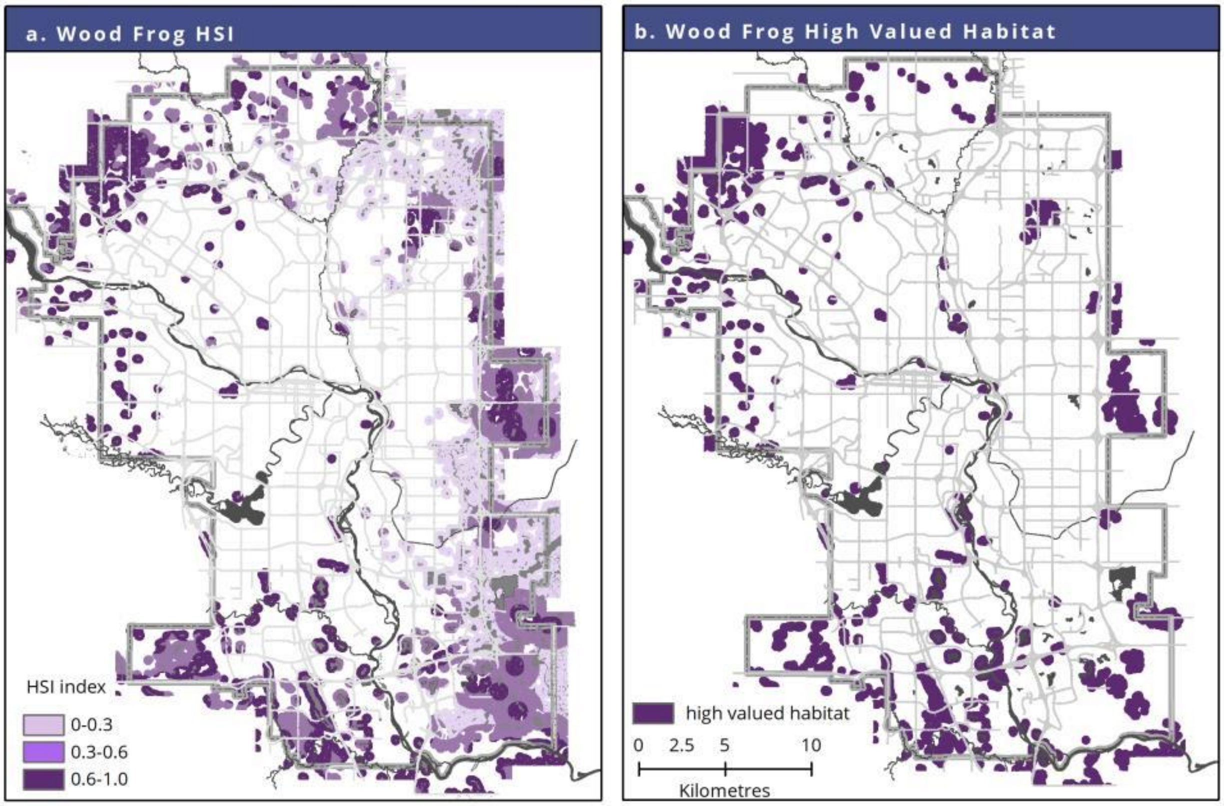


Figure 4: HSI for wood frog (panel a) and high valued habitat (panel b).

We validated the wood frog model using 17 incidental observations reported from 2017 to 2020 for the Call of the Wetland Program. Figure 5 depicts the agreement between wood frog observations and habitat values from the HSI modelling, indicating 71% of the incidental observations occurred in the high habitat value from the HSI model.

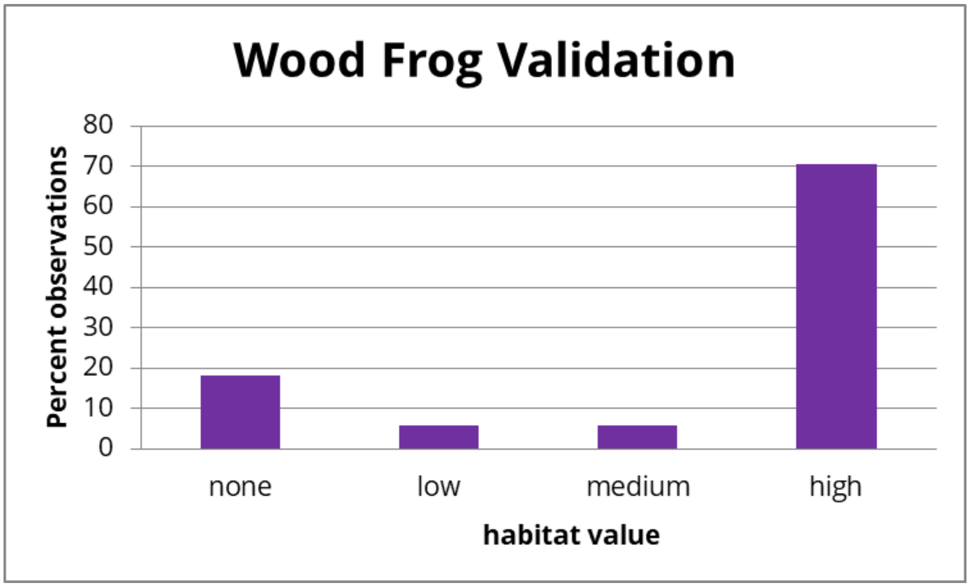


Figure 5: Wood frog validation observations and HSI categories.

Boreal Chorus Frog

HSI results were categorized into low, medium and high value (Figure 6a), with high valued habitat identified as wetlands with a mean HSI greater than or equal to 0.6 (Figure 6b). High valued habitat occurs predominately around the edge of the city but with larger areas occurring on the eastern edge.

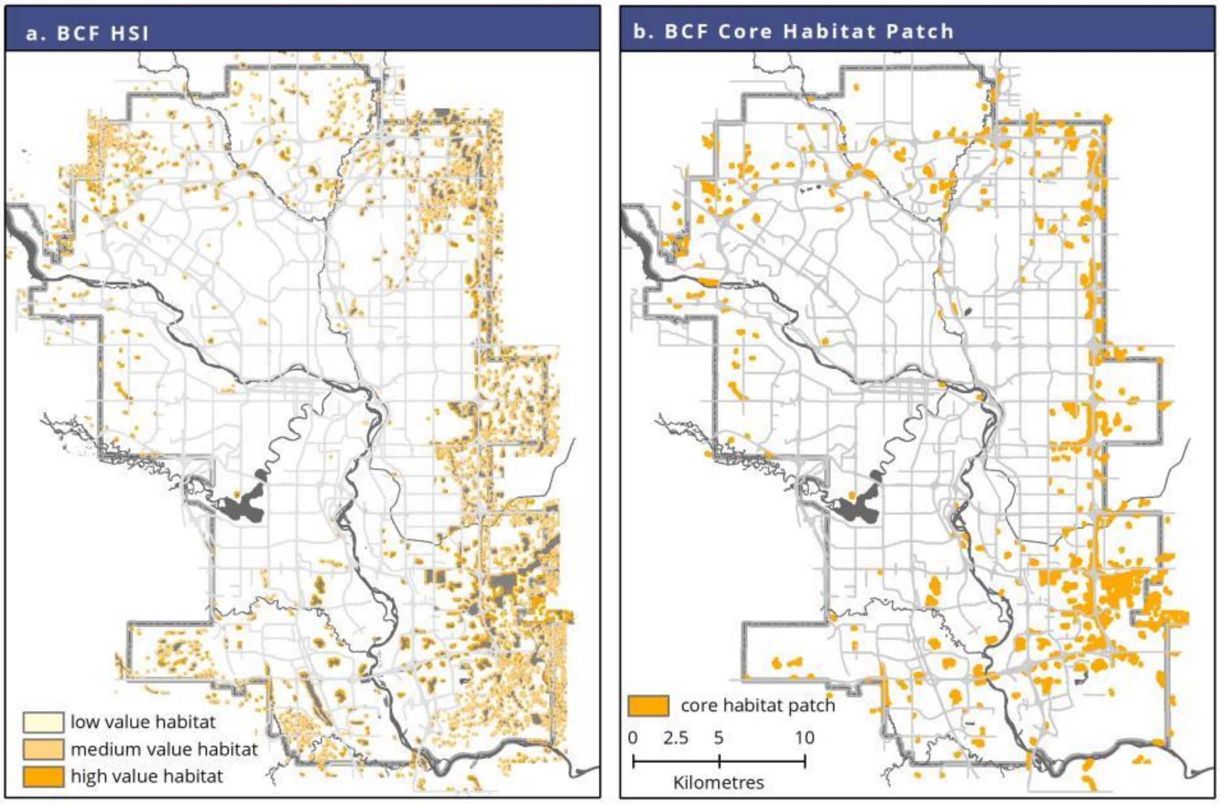


Figure 6: HSI values for boreal chorus frog (panel a) and boreal chorus frog core habitat patches (panel b).

The boreal chorus frog validation dataset consisted of 66 observations of boreal chorus frog reported through the Call of the Wetland Program from 2017 to 2020. Figure 7 shows the agreement between observations and habitat values from the HSI model, indicating 58% of the incidental observations occur in the high habitat value category. Boreal chorus frog observations that were not found on the HSI model were located along riparian habitat and in locations where wetlands are not in the 2015 inventory and may be ephemeral.

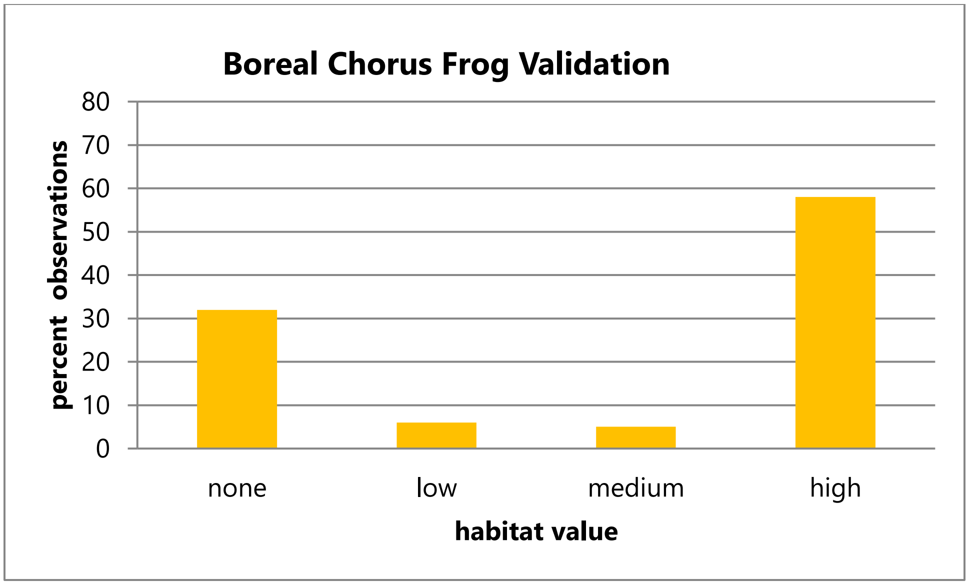


Figure 7: Boreal chorus frog validation observations and HSI categories.

Tiger Salamander

Tiger salamanders are sensitive to predation from fish (Porej et al. 2004; Shulse et al. 2010a). Wetlands in the floodplain were removed from the HSI analysis for their potential to support fish species (145 off the 4,060 wetlands in the study area).

HSI results were categorized into low, medium and high values based on three quantiles (Figure 8a), with high valued habitat identified as wetlands with mean HSI index greater than or equal to HSI index of 0.72 (Figure 8b). We used different threshold categorization for tiger salamander because the HSI had less variability and would have included most wetlands if we used the same threshold as the other species.

High valued tiger salamander habitat occurs predominately around the edge of the city but with larger habitat patches occurring around the edge of the city where development is limited. Core habitat patches occur along riparian systems and in natural areas (e.g. Nose hill, Fish Creek Provincial Park, Griffith woods).

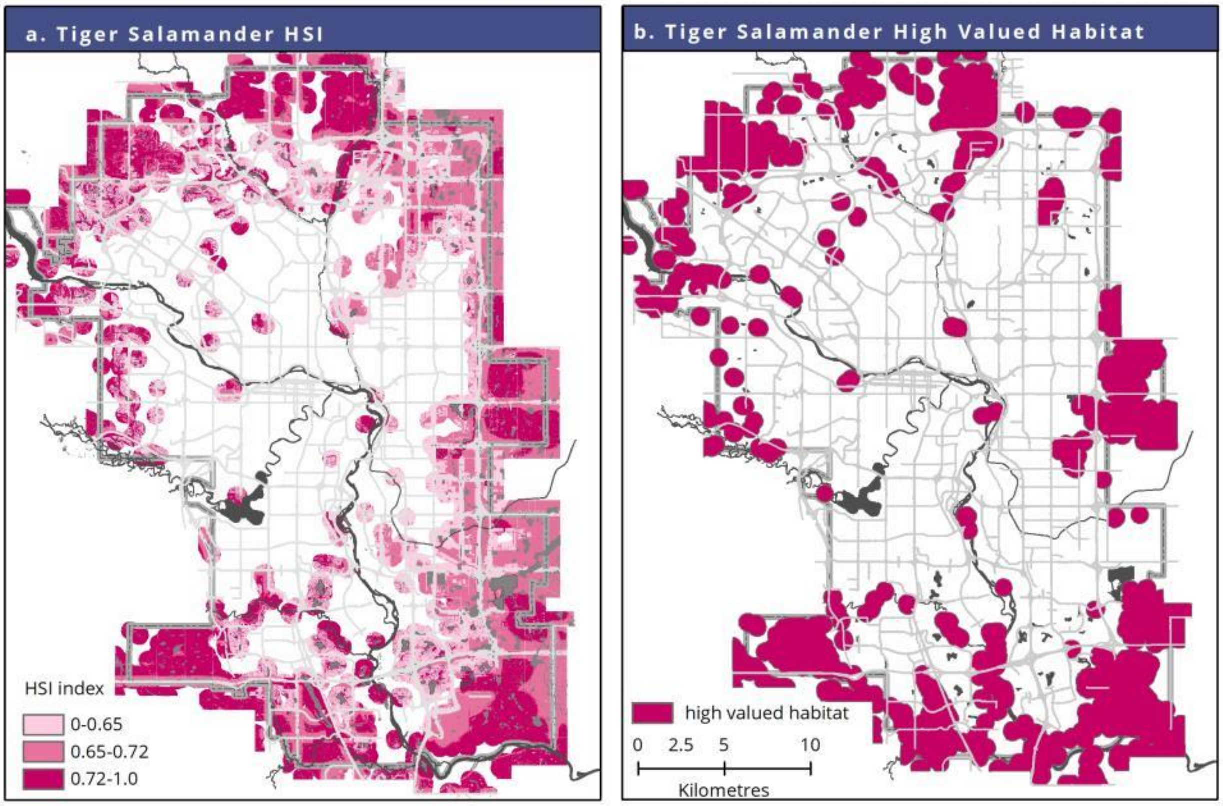


Figure 8: HSI index values for tiger salamander (panel a) and tiger salamander core habitat patches (panel b).

The tiger salamander validation dataset consisted of 17 observations of tiger salamander reported through the Call of the Wetland Program or to the city between 2017 and 2020. Figure 9 shows the agreement between observations and habitat values from the HSI model, indicating 51% occurring in the high habitat value.

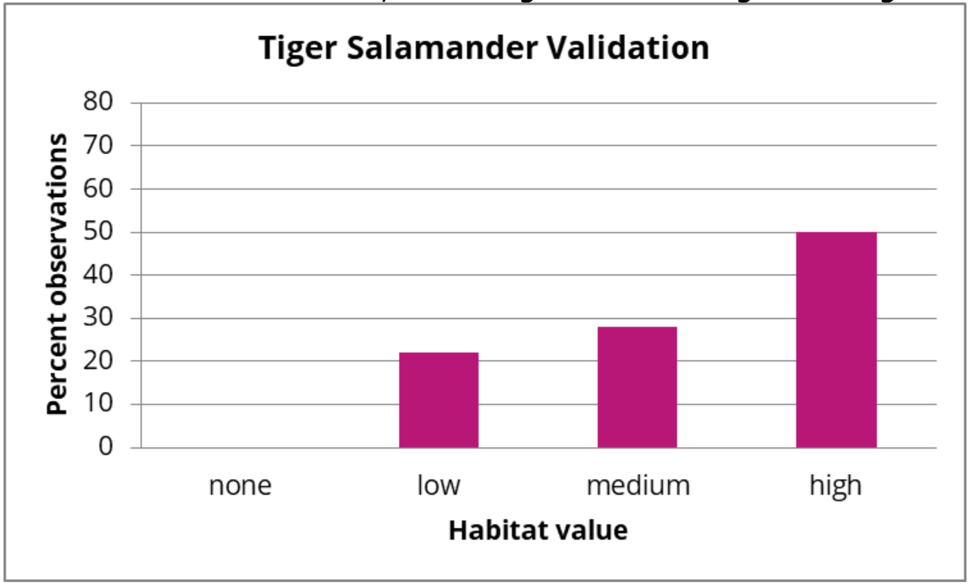


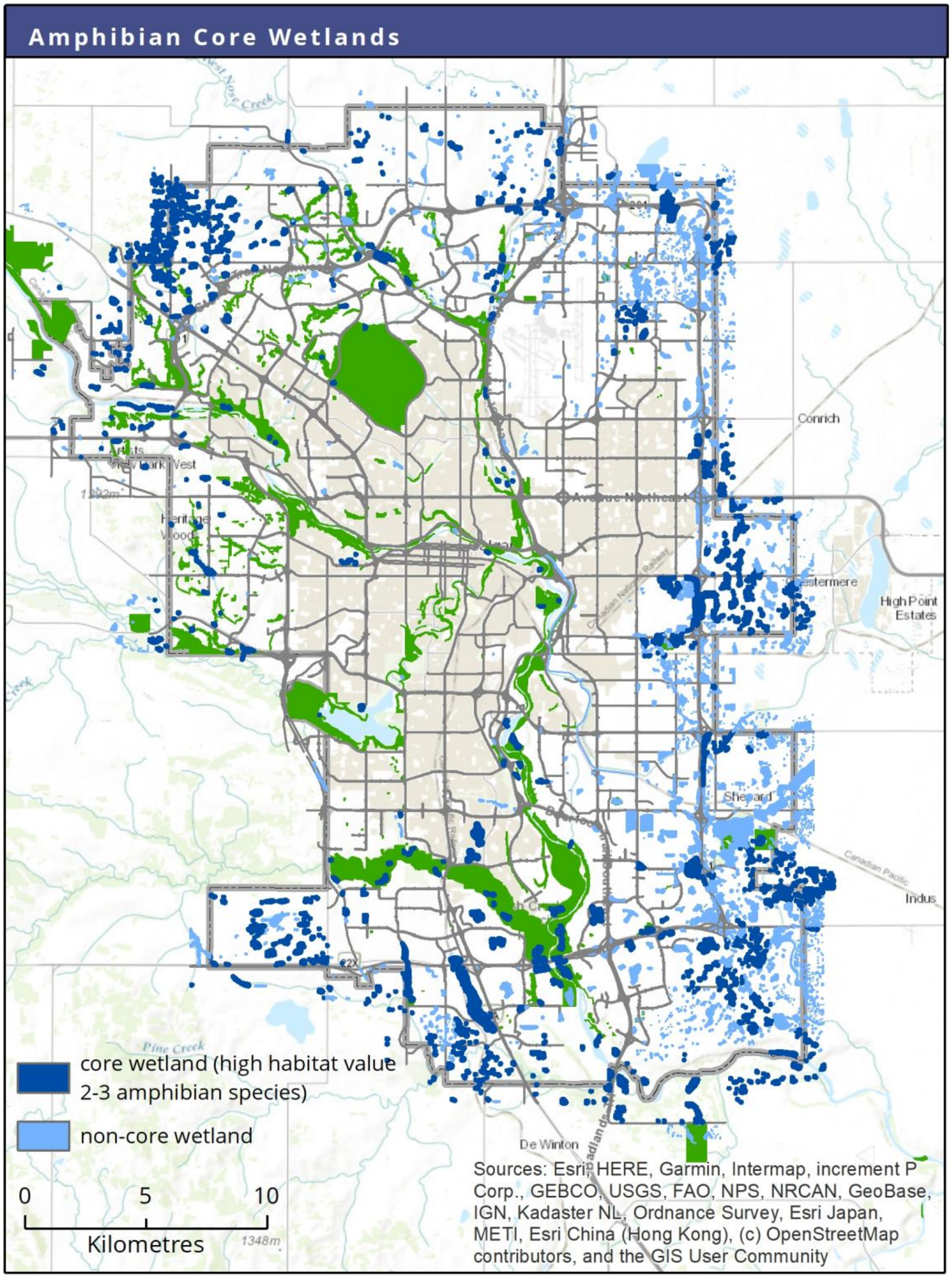
Figure 9: Tiger salamander validation observations and HSI categories.

Core Wetlands for Amphibians

To identify core wetlands for amphibian conservation in Calgary, we overlaid high valued habitat for all three species (Figure 10). Core wetlands that meet the needs of at least two species are most common outside the Ring Road in areas that have not been urbanized or are only lightly urbanized. Core wetlands that occur inside the Ring Road are more limited in number and are located in:

- Small natural areas in Edgemont neighbourhood
- Small natural areas along the top of Canada Olympic Park and Paskapoo slopes
- Springbank Hill
- Small natural areas around Griffith Woods on both side of Highway 8
- Small natural areas in Somerset neighbourhood that used to be continuous with Priddis Slough
- Fish Creek Provincial Park
- Small natural area along the Bow River near Douglasdale neighbourhood
- Southland natural area
- Series of wetlands to the northeast of the airport

Most of the core wetlands inside the Ring Road for amphibians occur in small natural areas managed as green spaces.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 10: Core wetlands for amphibian species with natural areas in green and road network in dark grey.

3.2 Connectivity Models

Wetland Corridors

Connectivity models for each species using different focal node placements and resistance scenarios are outlined in Appendix D. Figure 11 displays the top fifty percent of the connectivity models for wood frog (Figure 11 a), boreal chorus frog (Figure 11 b), tiger salamander (Figure 11c), and an overlay of all three species where wetland corridors are identified as movement pathways supporting two or more amphibian species in Calgary (Figure 11d). Wetland corridors occur predominately where urbanization has not occurred on the edge of the city, in green spaces along major roads and along intact riparian systems, such as Nose Creek, Beddington Creek and Fish Creek. There are limited movement opportunities between wetlands occurring in inner city neighborhoods or in small natural areas within neighbourhoods.

Figure 11 highlights probable movement areas for amphibians; a close up of neighbourhoods depicted in Figure 12 highlights how major roads are an important barrier to wetland corridors

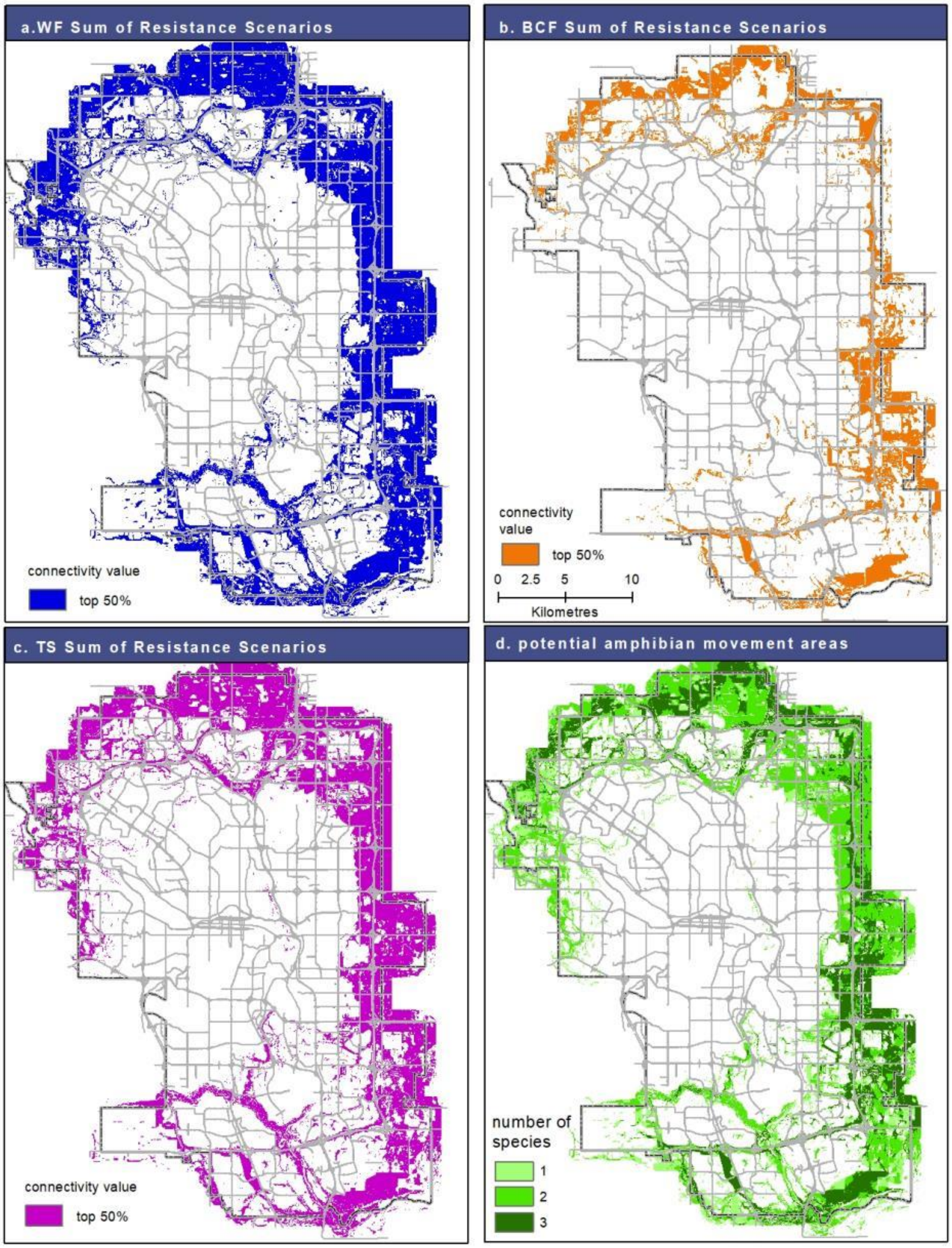
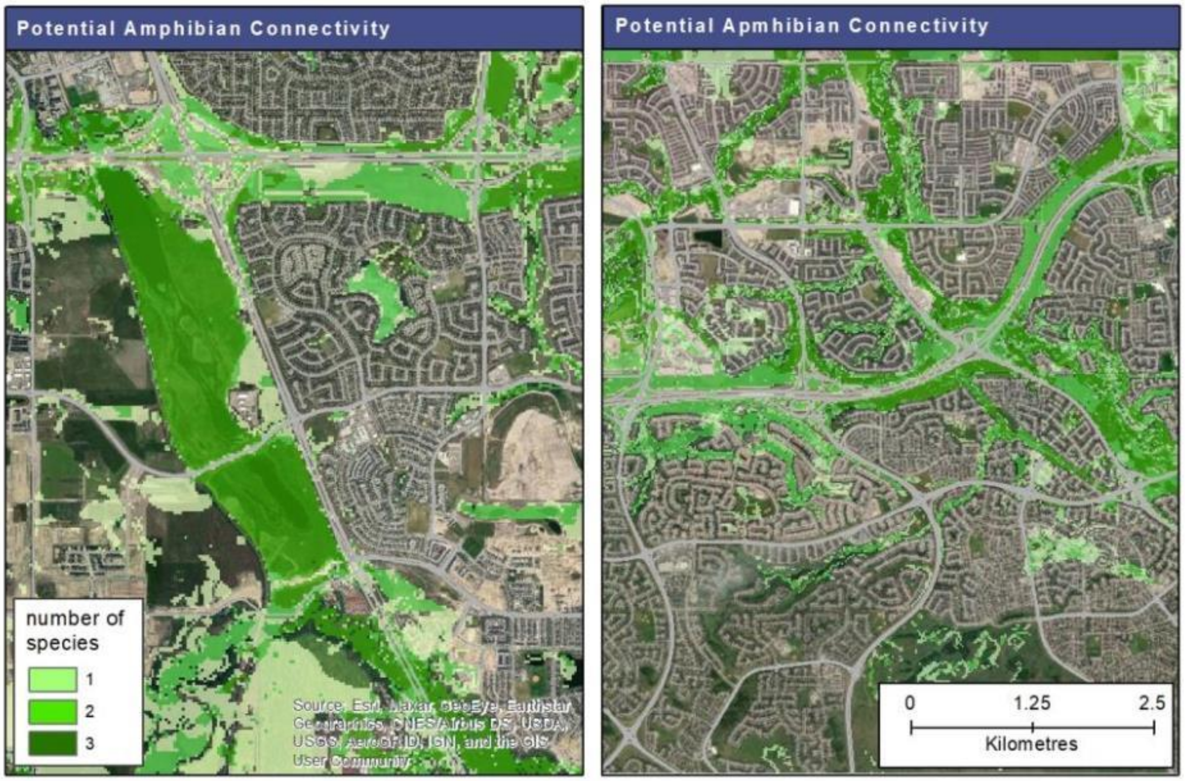


Figure 11: Connectivity models for amphibian species in the City of Calgary, where panel a-c represents top 50% of potential movement opportunity for wood frog (panel a), boreal chorus frog (panel b) and tiger salamander (panel c). Panel d represents wetland corridors based on overlap between all three species of amphibian.



Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 12: Fine scale potential amphibian movement areas.

Amphibian Core Wetlands and Corridors

Keystone wetlands and corridors are displayed in Figure 13, classified to the predicted number of amphibian species the feature supports.

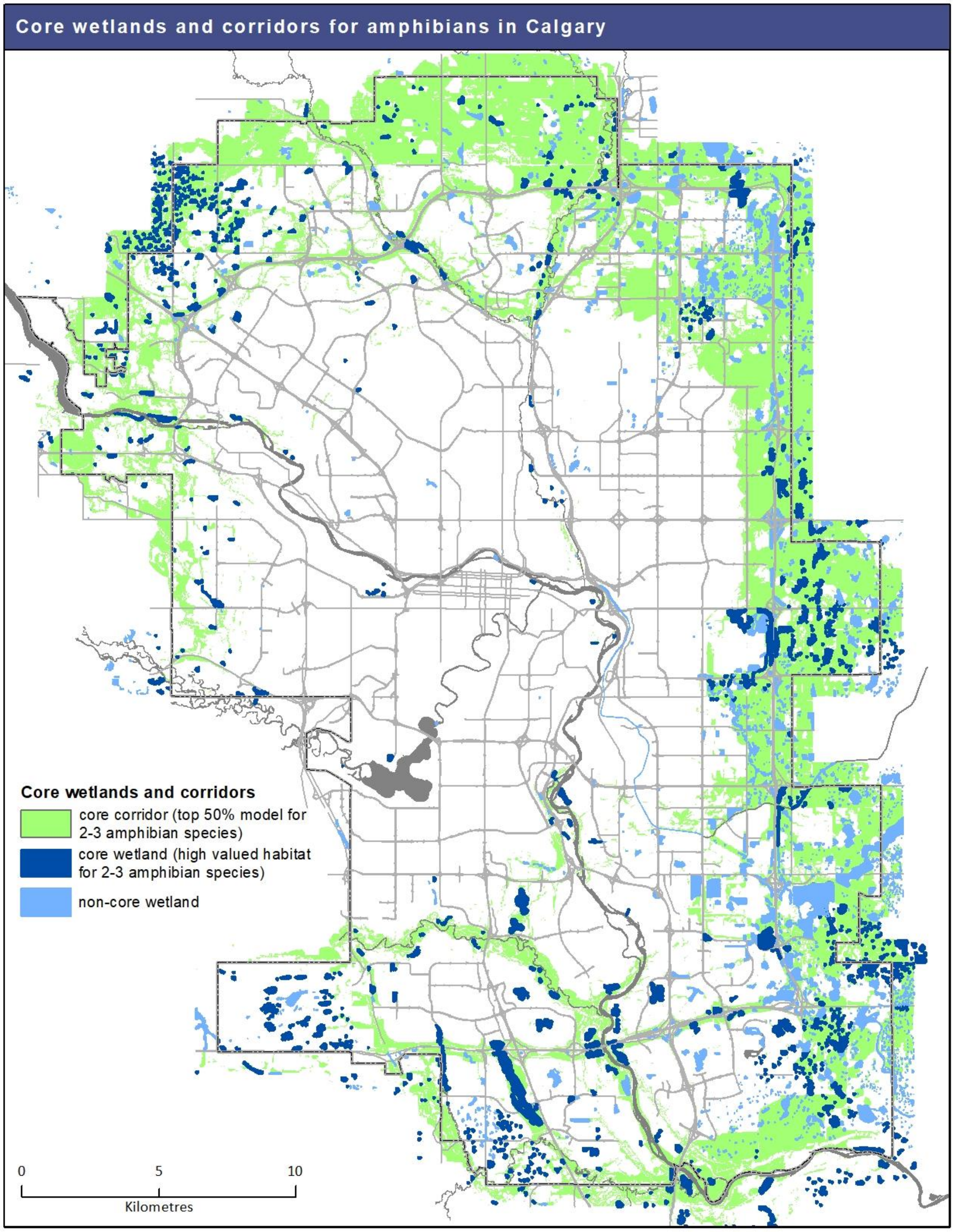


Figure 13: Core wetlands and wetland corridors for amphibians in Calgary.

Amphibian Keystone Wetlands and Corridors

We modelled the least cost path and ran a centrality model to identify which core wetlands are integral to the wetland network for amphibians. Least cost path, centrality and barrier models helped us identify keystone wetlands and corridors and document where amphibians would benefit from restored movement opportunities.

Figure 14a displays the least cost path (top 50% of model) between core wetlands derived from the overlay of high valued amphibian habitat of three species occurring in the city. The least cost path model displays the optimal best single path between core wetlands and will force movement across high resistance values when movement options are limited. Therefore, this analysis represents potential keystone wetlands and corridors if all barriers to movement are addressed enabling safe movement of amphibians.

To help identify keystone corridors, defined as least cost paths that play a substantial role in supporting the wetland network, we ran a centrality analysis (Figure 14b). We identified keystone wetlands and corridors, defined as core wetlands and corridors that play a substantial role in supporting the wetland network, by extracting the top 50% of the centrality model (Figure 14c).

Lastly, to inform restoration planning for an improved wetland network for amphibians we ran Barrier Mapper (Figure 14d). There are a substantial number of barriers occurring within wetland corridors decreasing movement opportunities for amphibians. As demonstrated with the connectivity modelling generated from Circuitscape, roads are a key challenge and reduce movement opportunity for amphibians in Calgary.

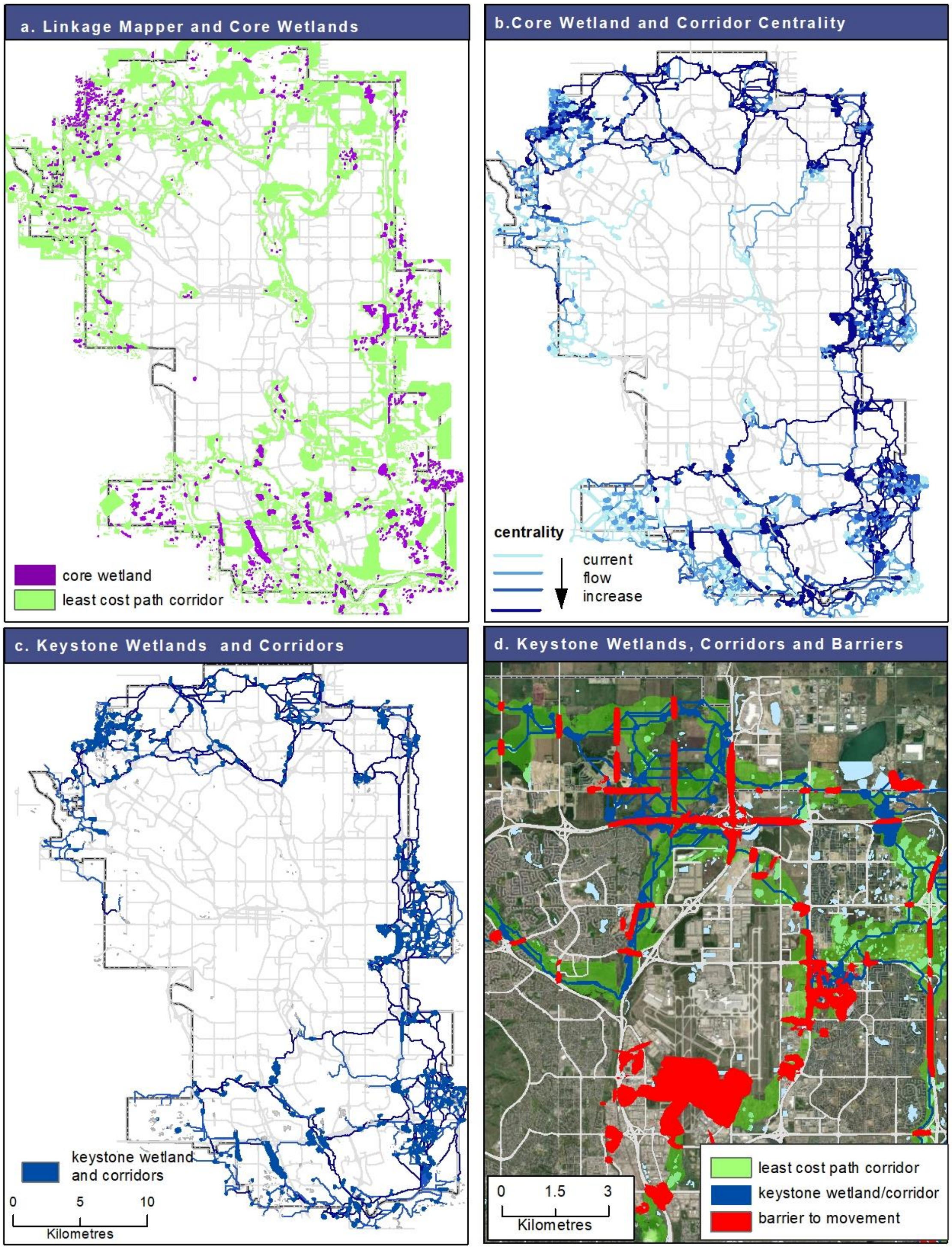


Figure 14: Core wetlands and least cost path corridor results (panel a), a measure of centrality for core wetlands and corridors (panel b), a measure of core wetland and corridor centrality with top 50% of model representing keystone wetlands and corridors in wetland network (panel c); and northeast corner of Calgary displaying least cost path corridors), keystone wetlands and corridors and barriers to the wetland network (panel d).

4.0 Discussion

The HSI and connectivity models developed for wood frog, chorus frog and tiger salamander are important contributions to inform planning, management and restoration for amphibians in Calgary. An important conservation strategy for maintaining amphibian populations is protection or enhancement of core wetlands including consideration of both terrestrial and aquatic habitat condition (Porej et al. 2004). An equally important conservation strategy is ensuring habitat connectivity for amphibian daily movement and dispersal (Cushman 2006). Furthermore, the identified keystone wetlands, corridors and barriers can be used to better understand the role of core wetlands and corridors in maintaining or improving the wetland network for amphibians in Calgary.

4.1 Conserving Core Wetlands

Model results indicate core wetlands for amphibians occur predominately outside the Ring Road (Stoney Trail) where urbanization is limited, within the Ring Road along intact riparian areas, verges of major roads, and in small natural areas and Fish Creek Provincial Park.

Core wetlands along the urban fringe are still abundant but most of these areas are earmarked for new residential neighbourhoods. Core wetlands in the inner city are limited in number. New developments that do not maintain core wetlands will compromise efforts to maintain or restore amphibian abundance in Calgary. Sharing the location of core wetlands with city planners is an important step to helping protect them. However, our results indicate core wetlands inside the Ring Road are mainly along river and creek systems with intact riparian corridors or in smaller natural areas. For these core wetlands, adopting best management practices in support of amphibians is important for preserving amphibian populations within Calgary.

A significant data gap is knowledge on the aquatic condition of urban wetlands. The Call of the Wetland Program reported occurrence of amphibians in natural wetlands, modified wetlands and at constructed stormwater ponds. Other urban amphibian monitoring programs conclude that modified and constructed storm water ponds have potential to support amphibians (Garcia-Gonzalez & Garcia-Vazquez 2012; Hamer et al. 2012; Scheffers & Paszkowski 2012, 2013). Urban amphibian studies report lower occupancy of species when compared to neighboring rural landscapes, but highlighted management intervention to promote good aquatic and terrestrial habitat condition in urban areas as a key strategy for improving amphibian abundance (Hamer et al. 2012; Westgate et al. 2015). Hamer et al (2012) recommended urban wetlands be managed to enhance habitat attributes associated with amphibian species and stressed the need for long-term monitoring to track patterns and trends over time. We recommend a long-term monitoring program that includes aquatic and terrestrial attributes that are important to amphibians to inform wetland management.

Another important data gap is our understanding of which wetlands play a role of source or sink habitat for amphibians. In source habitat, births exceed mortality, while in a sink habitat mortality exceeds births (Zamberletti et al. 2018). We recommend further monitoring to identify where amphibians are breeding successfully to help prioritize wetlands where breeding is not occurring as wetlands in need of restoration.

4.2 Conserving Wetland Corridors

We sought to better understand the role of wetland connectivity in sustaining amphibian abundance and biodiversity in Calgary by identifying probable movement pathways for all three amphibian species. An overlay of high connectivity values identified wetlands corridors. Sustaining a connected wetland network is an important conservation strategy for maintaining or improving urban amphibian abundance (Fortuna et al. 2006; Hamer & McDonnell 2008; Hamer et al. 2012; Albanese & Haukos 2017). Connectivity between wetlands supports both within season movements to and from a natal wetland and dispersing movements away from a natal wetland (Semlitsch 2008). Dispersing individuals travel away from natal ponds at distances much larger than seasonal movements. In our analyses, spatial connections between wetlands were limited to a species maximum dispersal distance; 1000 m for wood frog and tiger salamander and 600 m for boreal chorus frog. Dispersal distances are important considerations for planning of new developments, as attempts should be made to retain wetlands within these distances to allow dispersal. Neighbouring wetlands with distances exceeding these thresholds may limit dispersal capabilities of amphibian species, reducing population resiliency.

Consideration of Inner City Core Wetlands

Most inner city core wetlands support seasonal movements around the wetland, but dispersal potential for amphibians is greatly limited. Most inner city core wetlands are isolated from neighbouring wetlands where the landscape has been urbanized and is no longer permeable to amphibian movement. City planners could help facilitate amphibian movement by ensuring natural connections remain between wetlands with consideration of dispersal distances.

Isolated wetlands, defined as wetlands not able to support dispersing amphibians, have a reduced probability of re-colonization after a local extinction event (Parris 2006). This is an important consideration for identifying areas for wetland restoration and when planning for new development if The City of Calgary plans to maintain or increase the abundance of amphibians. We recommend a closer assessment of core wetlands in the inner city to identify opportunities to re-establish natural connections or improve condition of corridors via naturalization projects.

Consideration of Roads

The road network in Calgary is a significant barrier to amphibian movement between core wetlands, as illustrated in the connectivity models, where movement across major roads is limited. There are numerous studies documenting direct amphibian mortality and fragmentation of amphibian habitat due to roads, ultimately reducing amphibian abundance (Fahrig et al. 1995; Porej et al. 2004; Parris 2006; Beebee 2013; Helldin & Petrovan 2019). A successful conservation strategy includes removing barriers through road mitigation (e.g. crossing structures such as culverts) to reduce amphibian mortality and the fragmentation effects of roads by enabling safe movement under or over the road (Beebee 2013; Helldin & Petrovan 2019; Smith et al. 2019). Two key challenges moving forward include the willingness of The City of Calgary to invest in road mitigation for amphibians and how to prioritize which sites will have the most impact on improving wetland network and amphibian abundance. Road mitigation is not unprecedented by The City of Calgary, where recently a large culvert was installed under 194 Ave SW to retain connection of the Priddis Slough, a large wetland in southern edge of Calgary. Guidelines and policy adjustments to ensure mitigation for amphibians during new road development or upgrades to existing roads could result in significant gains for amphibians. In addition The City of Calgary should consider integration of amphibian movement into transportation maintenance and upgrade projects for the existing road network.

Amphibian movement opportunities in Calgary are common along major road side verges where wetlands remain or are developed as a road maintenance strategy. There is debate in the literature around promoting road side verges as habitat and corridors to promote biodiversity (Villemey et al. 2018). Concerns include impacts of traffic volume, noise and pollution and their effects on amphibian habitat and movement (Fahrig et al. 1995; Sun & Narins 2005; Bee & Swanson 2007; Lengagne 2008; Hall et al. 2017). However, in an urban environment, road side verges represent important opportunities for habitat and amphibian movement extending into many city neighbourhoods. The Call of the Wetland Program indicated amphibian presence along road verges for boreal chorus frog and wood frog where forest habitat is present in Calgary. Management and maintenance of road side verges falls under either provincial (e.g. Ring Road, Deerfoot trail) or municipal jurisdiction. Conservation strategies focused on improving amphibian abundance in our wetland network will require a coordinated approach between municipal and provincial jurisdictions.

4.3 Keystone Wetlands and Corridors

Keystone wetland and corridors were identified within the wetland network to better understand the role core wetlands and corridors play in sustaining the wetland network and to identify barriers in the network.

Least cost path model outputs were similar in appearance to connectivity modelling generated by Circuitscape, which identifies all probable movement pathways for amphibians within Calgary. This indicates amphibian movement is frequently limited to a single path in urbanized areas of the city (Marrotte & Bowman 2017), while in areas with limited urbanization multiple movement pathways occur. Degradation or removal of amphibian corridors where only a single optimal path is available will likely have negative impacts on amphibian abundance over time and could results in further isolating wetlands. Planners have more options to retain amphibian movements outside the Ring Road and in less urbanized areas where multiple pathways support amphibian movement.

Keystone corridors are compromised by the road network which decreases movement opportunities for amphibians and on high volume roads acts as a complete barrier for amphibians. We recommend development of a framework to assist in prioritizing areas where The City of Calgary can realistically invest in restoration or mitigation to improve the wetland network for amphibians.

4.4 Recommendations for Amphibian Conservation

To improve the wetland network and amphibian abundance in Calgary we recommend the following monitoring and research, planning, management, restoration and policy actions:

Monitoring and Research

- Develop a city-wide urban wetland monitoring program that includes both terrestrial and aquatic attributes important to amphibians.
- Continue amphibian monitoring to identify wetlands supporting breeding populations
- Update amphibian occupancy and HSI models to incorporate aquatic variables in identification of core amphibian habitat.

Planning

- Protect core wetlands in the planning of new developments on the urban fringe.
- Maintain wetland corridors to enable dispersal of amphibians from natal wetlands to neighbouring wetlands in the planning of new developments.
- Determine how core wetlands and corridors fit into the ecological network being developed by The City of Calgary to promote maintenance of connectivity for biodiversity.

Management

- Identify and implement best management practices to enhance amphibian abundance for wood frog, boreal chorus frog and tiger salamander at high value core habitat patches.

- Work with both the municipality and the province on a framework to coordinate management of wetlands located along roadside verges as amphibian habitat and movement corridors.

Policy

- Develop policy to promote maintenance of the wetland network.
- Develop road mitigation guidelines for amphibians.

Restoration

- Develop a framework to enable prioritization of restoration projects through removal of barriers identified during modelling for keystone wetlands and corridors.
- Enhance the wetland network for urban biodiversity by restoring connections along optimal wetland corridors by improving conditions or removing or mitigating the effects of barriers.

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Appendix A: Amphibian Habitat Attributes

Table 5 outlines attributes that were considered for wood frog, Table 6 for boreal chorus frog and Table 7 for tiger salamander. Each table documents terrestrial and aquatic attributes, provides supporting references and depicts the relationship of the attribute to each species and guidance on spatial representation of the species. Data limitations prevented us from including many of the attributes in modelling.

Table 5: Attributes considered for wood frog.

Phase	**Attribute**	**Notes/references**	**GIS layer**
Terrestrial			
	Forest	Distance to forest/proportion of forest cover increased occupancy modelling (COTW occupancy modelling) and (Porej et al. 2004; Rubbo & Kiesecker 2005; Gustafson & Newman 2016) forest with leaf litter (Muths et al. 2005). Wood frogs correlated with ponds with over 50% forest cover within 1 km of those ponds (Skidds et al. 2007). Positive correlation with amount of forest cover (Eigenbrod et al. 2008)200-1000m from wetland; average recorded forest cover were wood frog was found: 58% +/- 5.7% (Porej et al. 2004). Positive correlation with closed deciduous and mixed vegetation forests within a 500m scale of wetlands (Browne et al. 2009).	City land cover data, forest category defined as white spruce, aspen or popular whereby a contiguous or combined area of ≥ 0.25 ha or ≥10% of the site is forested. In Parks – broken-out between species
	Grassland	Occupancy increases when grasslands within 20m of wetland (COTW occupancy models), moist grassy meadows (Muths et al. 2005) Habitat suitability: 60.3% of core habitat and habitat tolerance value = 0.785 (Mushet et al. 2012)	City land cover data, grassland category
	Residential development	Negatively correlated within 1km of pond (Skidds et al. 2007)	
	impervious surfaces	Occupancy declines as impervious surface increases (COTW occupancy models, (Scheffers & Paszkowski 2013) Negative relationship to road presence and traffic density (Eigenbrod et al., 2008).	City layer available

	Distance to road	Occupancy increases as distance to road increases (COTW occupancy models) Strongest negative correlation to roads and traffic density was within 500m from the wetland edge; indicating that 500m is a critical scale of dispersal for this species (Eigenbrod et al., 2008). Indirect impacts from road traffic such as noise, vibrations, pollution, etc. may also be attributed to lower population/ species occurrence (Fahrig et al. 1995)	City road layer – Fiera methods for how they looked at effect of traffic volume or road classification system
	Wetlands nearby	Number of wetlands within 100m; habitat preference correlated with nearby wetlands; positive correlation between species occurrence, stormwater wetlands and other wetlands within 100m of breeding wetlands (Scheffers & Paszkowski 2013)	Fiera wetland datasets – updated City wetland inventory (not good for classification between types), Consolidated wetland datasets or City hydrology layer
	Natural vegetation	Positive correlation between species occurrence and native vegetation within 100m of breeding wetlands (Scheffers & Paszkowski 2013)	
Aquatic			
	aquatic vegetation	Occupancy correlated (Scheffers & Paszkowski 2013; Gustafson & Newman 2016) Influence on egg-laying and size at metamorphosis (Scheffers & Paszkowski 2013) Positive correlation between nitrogen concentrations and chlorophyll-a (and algal abundance) - positive relationship with species occurrence	
	emergent vegetation	Occupancy correlated (Muths et al. 2005; Gustafson & Newman 2016) Positive correlation with species occurrence: whereas, submersed aquatic vegetation had a negative correlation (Scheffers & Paszkowski 2013)	LIDAR dataset
	aquatic insects	Occupancy correlated (Gustafson & Newman 2016)	

	hydro-period	Occupancy negatively correlated with hydro-period (Rubbo & Kiesecker 2005), longer hydro-period more breeding (Skidds et al. 2007)	Landsat – over time (30 year period) to understand standing water and wetlands – to determine hydroperiods
	low sloped shores	Occupancy correlated with lower slopes (Muths et al. 2005)	DEM
	pond size and depth	Occupancy correlated with larger deep ponds (Skidds et al. 2007)may be correlated with longer hydro-periods, COTW occupancy models Preference of shallow wetlands; presence is highly correlated with local variables and habitat features of breeding ponds (Browne et al. 2009)	LIDAR dataset
	road salt	slower growth rate of tadpoles and alters foraging behavior (Hall et al. 2017), correlate with distance to road. Affects amphibians that overwinter in ponds and negatively affect reproduction (Scheffers & Paszkowski 2013)	
	Size	Small ephemeral wetlands (Corn et al. 1997)	
	nitrogen concentrations	High levels negative impact (Knutson et al. 2004), attracted to high levels which occurred in natural wetlands; species occurrence was positive relationship with nitrogen concentrations and high phosphorus concentrations (Scheffers & Paszkowski 2013)	Data deficient
	Predatory fish	Occupancy of wetland / species occurrence is negatively associated with the presence of predatory fish (Porej et al. 2004; Scheffers & Paszkowski 2013)	

Table 6: Attributes considered for Boreal Chorus Frog

Phase	**Attribute**	**Notes**	**GIS layer**
Terrestrial			
	Nearest occupied wetland	Positive relationship between occupancy at a wetland and the number of occupied wet- lands within 1000 cost meters (Scherer et al. 2012; Scheffers & Paszkowski 2013)	
	Natural	Strong positive relationship between	

	vegetation	species occurrence by presence of native vegetation surrounding wetlands (within 100m of breeding wetlands (Scheffers & Paszkowski 2013)	
	Grasslands	Associated with upland grasslands (Dodd 2013) Occurrence associated with grasslands and croplands where wetlands were present (Mushet et al., 2012). 36.7% of core habitat grassland, not habitat specialized with a high tolerance value of 0.923 (Mushet et al., 2012).	
	Shrub land	Associated with high shrubs and herbs (Constible et al. 2001) Positive association with occupancy in areas with tall herbaceous plants, shrubs, low canopy cover and extensive ground cover (Ouellet et al. 2009).	City land cover data, no distinction between riparian and upland habitat (invasive species)
	Forest	Associated with variety of forest types (Dodd 2013, Browne et al, 2009), decreases as portion of forest increase (COTW) – include – decrease Forests were not inhabited during breeding season (Ouellet et al. 2009) Positive occurrence in areas with open canopy, and preference for moist / damp habitats (Ouellet et al., 2009).	
	Impervious surfaces	Negative relationship between species occurrence and impervious surfaces within 100m of breeding wetlands (Scheffers and Paszkowski 2013). Occupancy decrease as impervious surface increases (COTW) Negative relationship between breeding sites, pond occupancy and road density and traffic density (Eigenbrod et al., 2008). Negative correlation as traffic increased (likely attributed to higher mortality rates in higher traffic areas) (Fahrig et al., 1994). One study found a positive relationship with urban cover; this relationship may be representative of the species preference for open habitat or its relation and proximity to desirable breeding habitats rather than a preference for urban	

		landscapes in comparison to wetlands that were poor in quality or surrounded by undesirable landforms (Browne et al., 2015).	
	Manicured	Increase with manicured landcover (COTW occupancy modelling) - include	City land cover data, A Grassland where grass, typically non-native, is the predominant life form and is actively managed by mowing.
	Total water near by	Decrease with water resources within 100m (COTW occupancy models)	City land cover data, wetland: Open water and emergent vegetation zones around natural wetlands, streams and rivers: Includes major rivers (stream order ≥ 4 based on AB hydrological layers), large streams (stream order 2 or 3) and gravel/sand shoulders or elbows along major rivers, Reservoirs: Manmade or natural reservoir designed to manage water for municipal use, Storm pond/modified wetland: Storm Ponds/Modified Wetlands
Aquatic			
	Submersed aquatic vegetation	Positive correlation with species occurrence (Scheffers and Paszkowski 2013)	
	Nitrogen concentrations	Correlation with species occurrence (Scheffers and Paszkowski 2013)	
	emergent vegetation	Positive association with species occurrence (Shulse et al. 2010b; Scheffers & Paszkowski 2013) Positive correlation in breeding ponds found in thicket swamps (Ouellet et al., 2009).	
	wetland slope	occupancy negatively impacted by slope (Shulse et al. 2010), Leopard frogs have guideline of less than 20 degree slope	
	Small and Shallow wetlands	Positive correlation with < 35 cm in depth for breeding ponds (Dodd, 2013) & occurrence in upper marshes (Ouellet et al., 2009). Ephemeral ponds (Ouellet et al, 2009). Negative relationship in species occurrence and lower marshes / bogs during breeding season (Ouellet et al., 2009).	Ephemeral wetlands – based on Hydro period
	no fish	Dodd 2013, correlated with total water- rivers and streams Breeding sites were positively correlated with absence of predatory fish (Ouellet et al., 2009).	Data gap

Table 7: Attributes considered for Tiger Salamander

Phase	Attribute	Notes	GIS layer
Terrestrial			
	Forest	Positively correlated with forest cover in the core habitat zone (Porej et al. 2004), distance to forest (Bartelt et al. 2011). Higher % of forest cover in the core zone surrounding wetlands increases probability of occurrence (Porej et al., 2004)	City land cover data, forest category defined as white spruce, aspen or popular whereby a contiguous or combined area of ≥ 0.25 ha or ≥10% of the site is forested.
	Roads	Negatively correlated with cumulative amount of roads within 1km (Porej et al. 2004)	
	grassland, open woodlands	Positive relationship COSEWIC 2012, Recorded as a preference based on emergence from study ponds towards grasslands over forested areas (Richardson et al. 1999). Utilization of the driest areas and microhabitats for migration (migration is linked with precipitation occurrence, therefore these areas commonly become saturated during migration); indicating high landscape permeability (Searcy et al. 2013) Suggestion that the dispersal distance may be due to habitat preference of grasslands (Searcy et al., 2013). Recorded positive correlation with open woodland (isolated oaks) and tiger salamander occurrence: possibly due to presence of small mammalian burrows (a key feature used by tiger salamander (Trenham 2001)	
	Weather / Climate	Positive correlation with rain occurrence. Migration is strongly correlated to rain events during the breeding season; greater movement / dispersal distance and high density of tiger salamander near ponds during wetter years (Searcy et al., 2013).	
Aquatic			
	predatory fish and other predators	negatively correlated (Porej et al. 2004; Shulse et al. 2010b), Bullfrogs are another predatory risk (Loredo & Van Vuren 1996) Ponds with resident turtles are correlated with low density and occurrence of tiger salamanders / larvae (Richardson et al., 1999).	

	Hydro-period	longer periods 3-7 months with water (Wissinger et al. 2010) Paedomorphs: restricted to permanent waterbodies (Denoel et al. 2007) Metamorphs: non-restricted (Denoel et al., 2007). Breeding is common in ephemeral ponds (Loredo & Van Vuren 1996)	
	Sub-mergent vegetation	Species occurrence is positively correlated (Bartelt et al. 2011)	
	woody emergent vegetation	Species occurrence is correlated with absence of woody vegetation (Bartelt et al. 2011)	
	nutrient rich water bodies	Positive relationship (COSEWIC 2012)	
	Sandy to friable soils	Important for burrowing habitat for over winter; below the frost line (Scheffers & Paszkowski, 2013). Soil compaction due to urban development makes over wintering burrowing difficult for the species (Scheffers & Paszkowski, 2013).	
	alkaline or slightly saline environments	Tolerant to these environment (COSEWIC 2012)	

Appendix B: Occupancy Modelling and AHP Results

Wood Frog

We used the four landscape attributes that were above or within 2 AIC of the null model from wood frog occupancy modelling as habitat variables to develop HSI models.

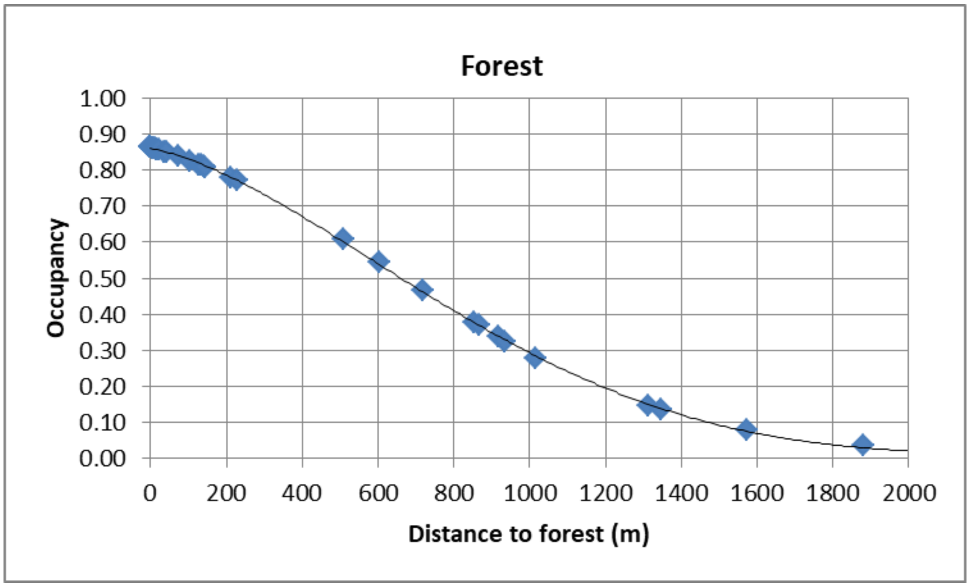


Figure 15: Distance to forest for wood frog

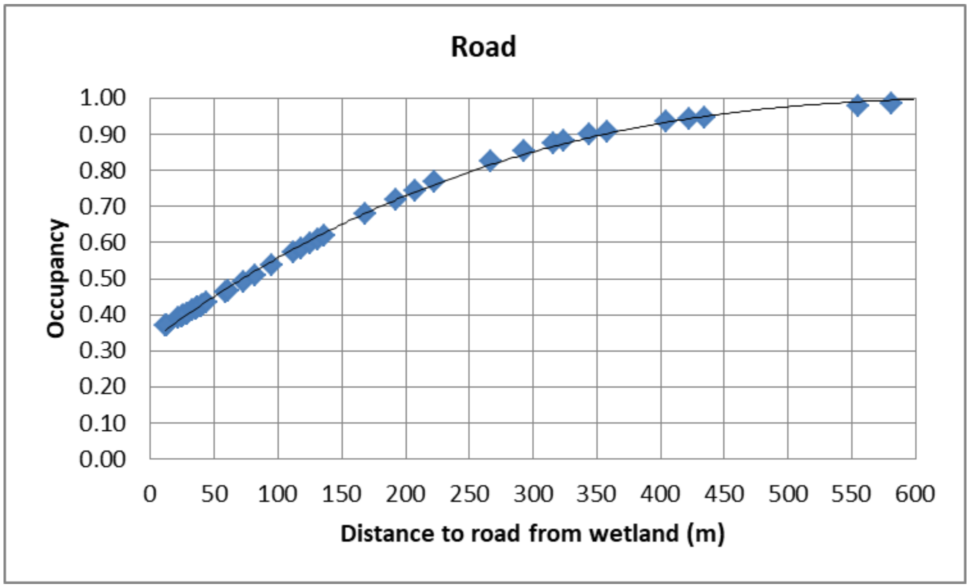


Figure 16: Distance to road for wood frog

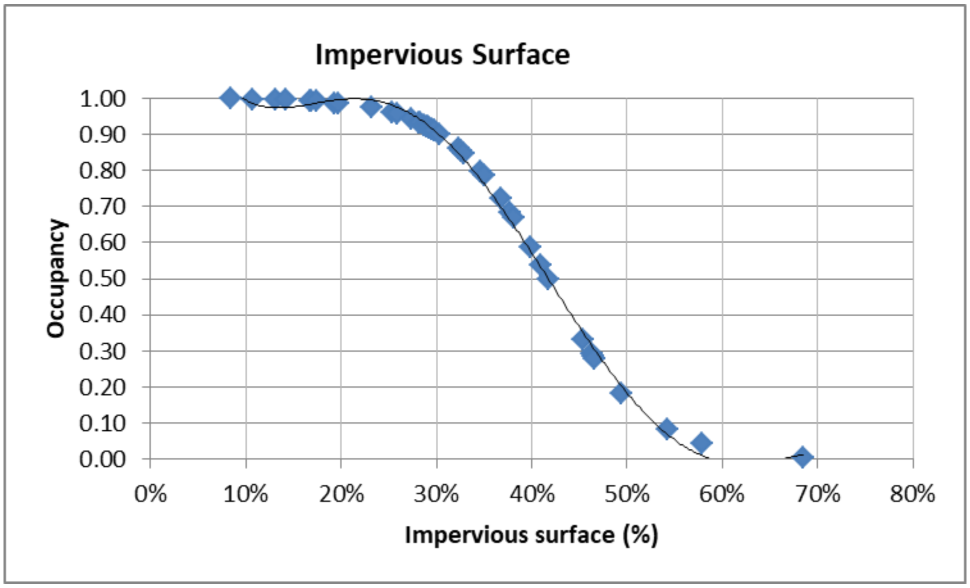


Figure 17: Percent impervious surface for wood frog

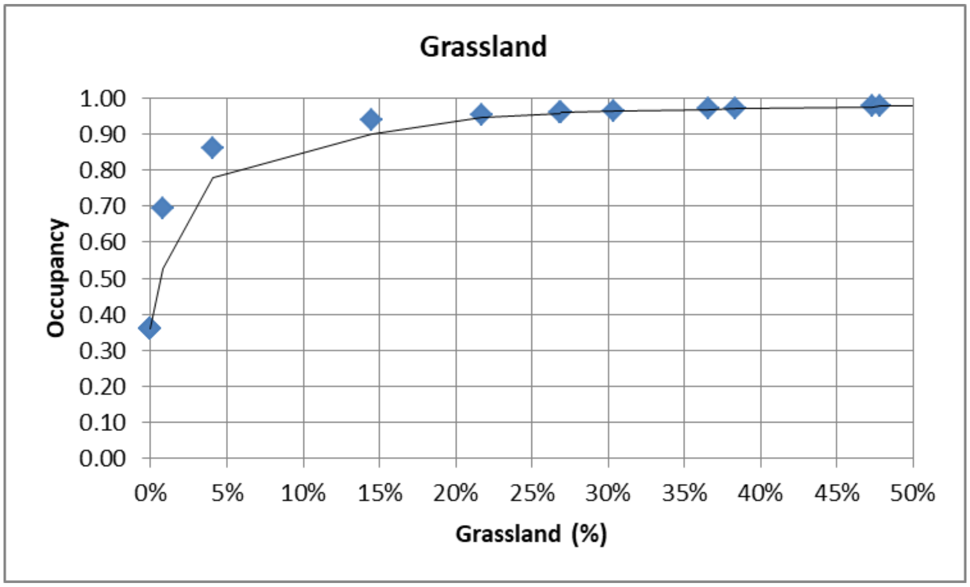


Figure 18: Percent grassland for wood frog

Boreal Chorus Frog

We used five landscape attributes that were within 2 AIC of the null model from boreal chorus frog occupancy modelling as habitat attributes to develop HSI model.

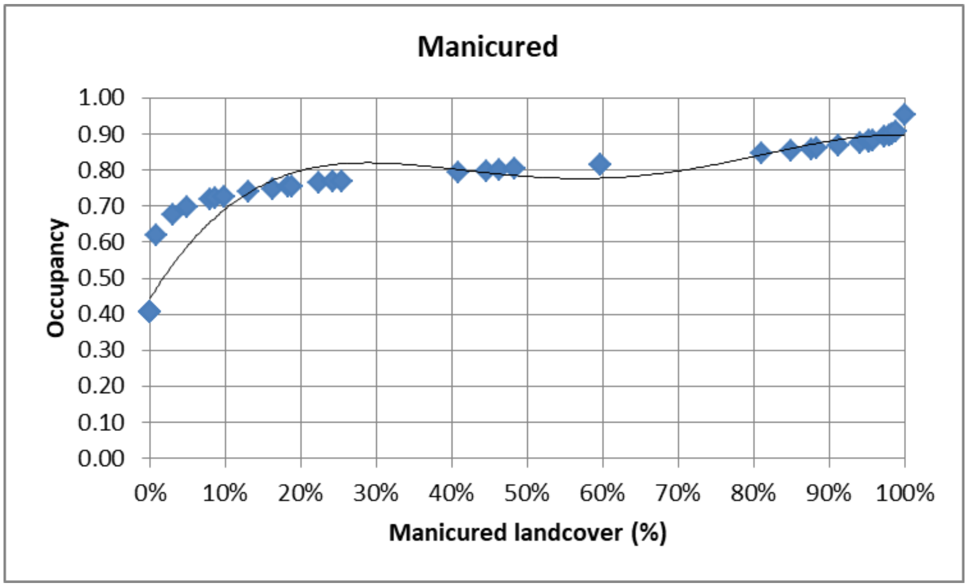


Figure 19: Percent manicured grassland for boreal chorus frog

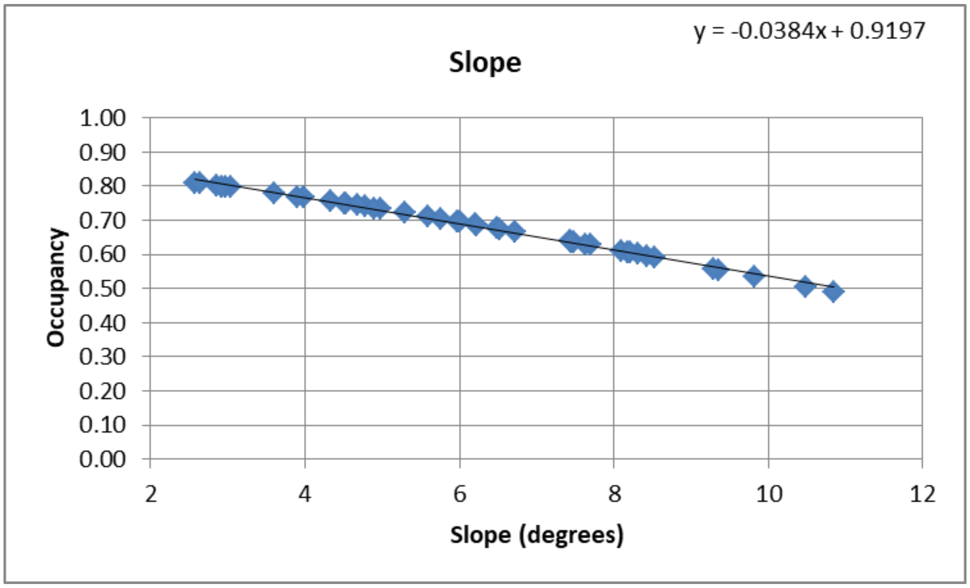


Figure 20: Slope for boreal chorus frog

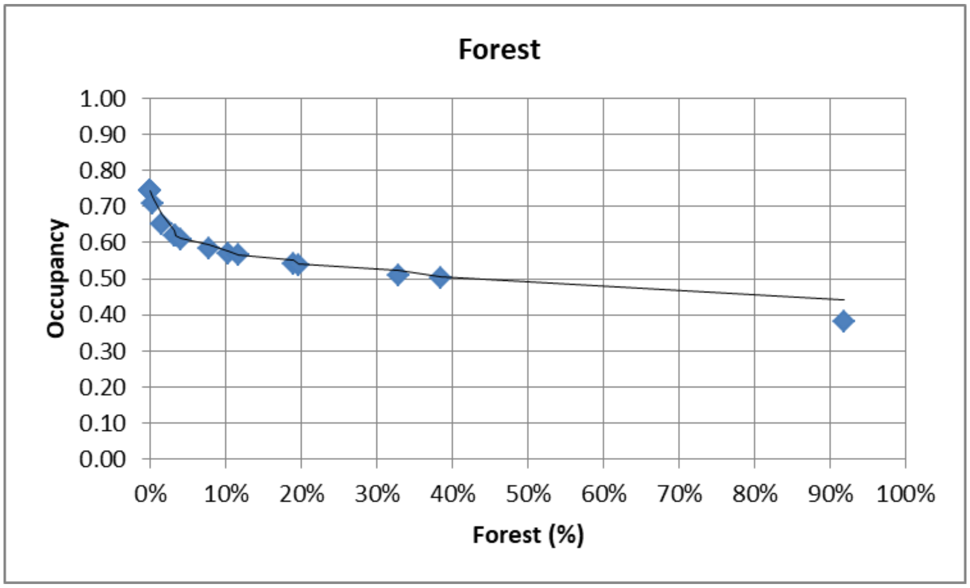


Figure 21: Percent forest for boreal chorus frog

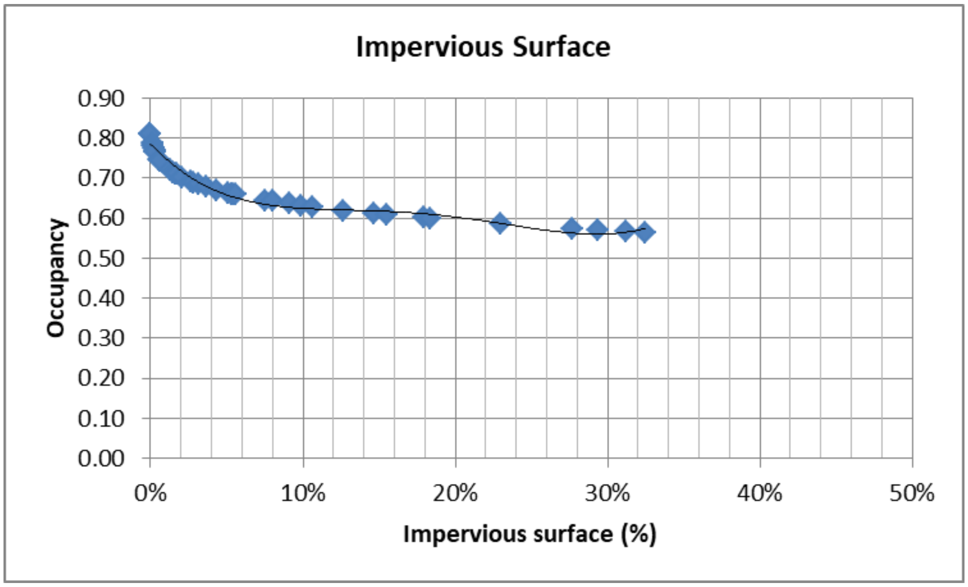


Figure 22: Impervious surface for boreal chorus frog

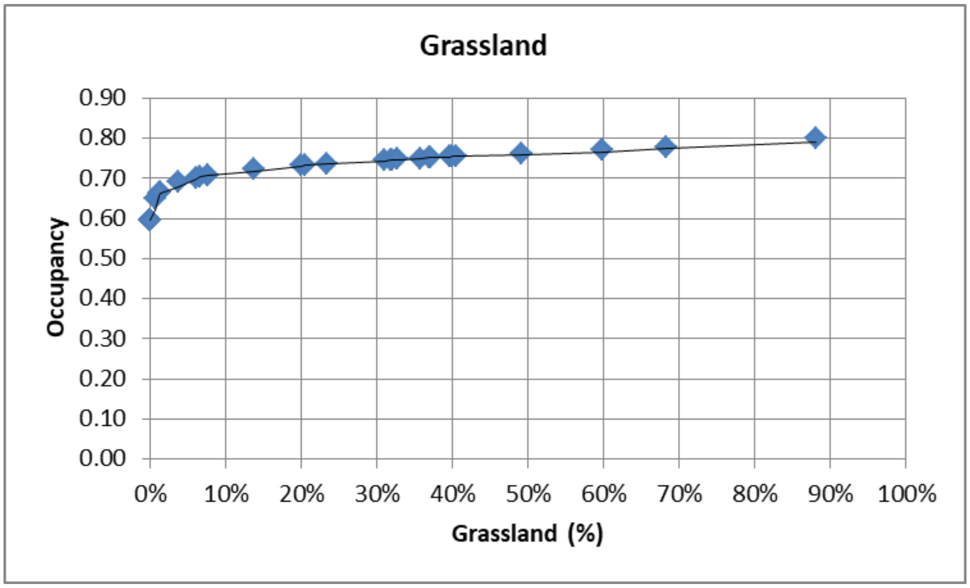


Figure 23: Percent grassland for boreal chorus frog

Tiger Salamander

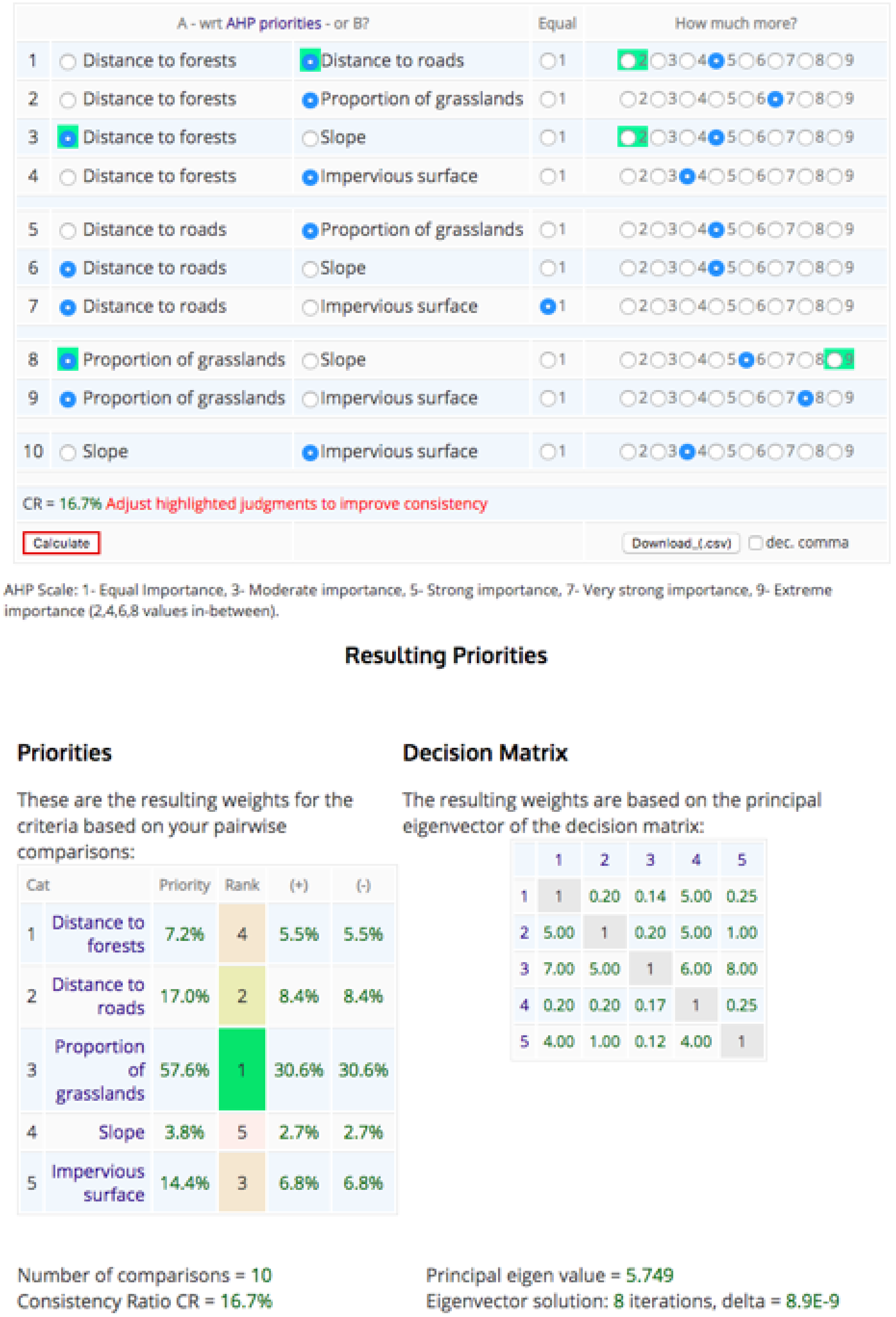
Due to a lack of empirical data within the city of Calgary we were not able to run occupancy modelling for tiger salamander. We therefore used an expert opinion based Analytic Hierarchy Process (AHP) to determine attribute weightings and relationship of attribute to tiger salamander habitat. We chose to use an AHP to determine the weighting of attributes and occupancy relationships because it enabled a pair-wise comparison between the attributes.

Experts involved in the AHP process included:

- Kris Kendell, Senior Biologist, Alberta Conservation Association;
- Kimberly Pearson, Ecosystem Scientist, Parks Canada;
- Heather Rudd, Parks Ecologist, City of Calgary;
- Vanessa Carney, Landscape Data and Analysis Supervisor, City of Calgary; and
- Lea Randall, Conservation Research Population Ecologist, Calgary Zoo.

We ran two AHP models, the first (Figure 24) to determine the weighting of the landscape attributes selected the tiger salamander HSI modelling. The Consistency Ratio for attribute weighting was high, suggesting some inconsistency in responses. Due to time constraints we were not able to re-visit with experts to further discuss the AHP results.

The second AHP, (Figure 25) compared the results of wood frog occupancy models to tiger salamander. Wood frog occupancy models were used for comparison due to the similarities of key habitat attributes between the species. Distribution curves derived from the wood frog occupancy models were used to determine classes for each attribute for HSI modelling. The distributions were shifted for tiger salamander depending on the relationship to wood frog as outlined in the AHP. For example, wood frogs are highly sensitive to distance to forest and the AHP recommended that for tiger salamander this attribute is 7 times less important on a scale of 1-9, where 1 is equal and 9 is extremely less impacted. We adjusted occupancy classes based on AHP scale, where 1 was not adjusted, 2 was shifted by 0.11, 5 by 0.275 and 7 by 0.385. The shift direction (summed or removed) depended on the direction of the relationship.



	A - wrt AHP priorities - or B?		Equal	How much more?
1	○ Distance to forests	● Distance to roads	○1	○2 ○3 ○4 ●5 ○6 ○7 ○8 ○9
2	○ Distance to forests	● Proportion of grasslands	○1	○2 ○3 ○4 ○5 ○6 ●7 ○8 ○9
3	● Distance to forests	○ Slope	○1	○2 ○3 ○4 ●5 ○6 ○7 ○8 ○9
4	○ Distance to forests	● Impervious surface	○1	○2 ○3 ●4 ○5 ○6 ○7 ○8 ○9
5	○ Distance to roads	● Proportion of grasslands	○1	○2 ○3 ○4 ●5 ○6 ○7 ○8 ○9
6	● Distance to roads	○ Slope	○1	○2 ○3 ○4 ●5 ○6 ○7 ○8 ○9
7	● Distance to roads	○ Impervious surface	●1	○2 ○3 ○4 ○5 ○6 ○7 ○8 ○9
8	● Proportion of grasslands	○ Slope	○1	○2 ○3 ○4 ○5 ●6 ○7 ○8 ○9
9	● Proportion of grasslands	○ Impervious surface	○1	○2 ○3 ○4 ○5 ○6 ○7 ●8 ○9
10	○ Slope	● Impervious surface	○1	○2 ○3 ●4 ○5 ○6 ○7 ○8 ○9

CR = 16.7% Adjust highlighted judgments to improve consistency

AHP Scale: 1- Equal Importance, 3- Moderate importance, 5- Strong importance, 7- Very strong importance, 9- Extreme importance (2,4,6,8 values in-between).

Resulting Priorities

Priorities

These are the resulting weights for the criteria based on your pairwise comparisons:

	Cat	Priority	Rank	(+)	(-)
1	Distance to forests	7.2%	4	5.5%	5.5%
2	Distance to roads	17.0%	2	8.4%	8.4%
3	Proportion of grasslands	57.6%	1	30.6%	30.6%
4	Slope	3.8%	5	2.7%	2.7%
5	Impervious surface	14.4%	3	6.8%	6.8%

Decision Matrix

The resulting weights are based on the principal eigenvector of the decision matrix:

	1	2	3	4	5
1	1	0.20	0.14	5.00	0.25
2	5.00	1	0.20	5.00	1.00
3	7.00	5.00	1	6.00	8.00
4	0.20	0.20	0.17	1	0.25
5	4.00	1.00	0.12	4.00	1

Number of comparisons = 10
Consistency Ratio CR = 16.7%

Principal eigen value = 5.749
Eigenvector solution: 8 iterations, delta = 8.9E-9

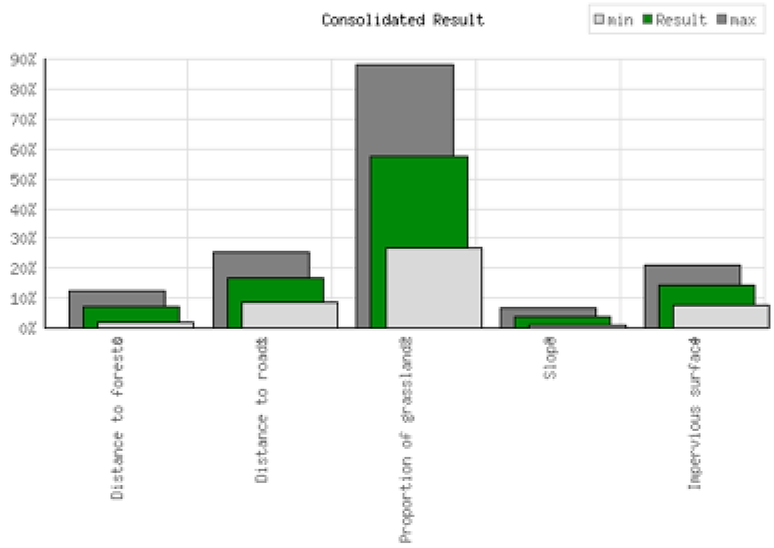
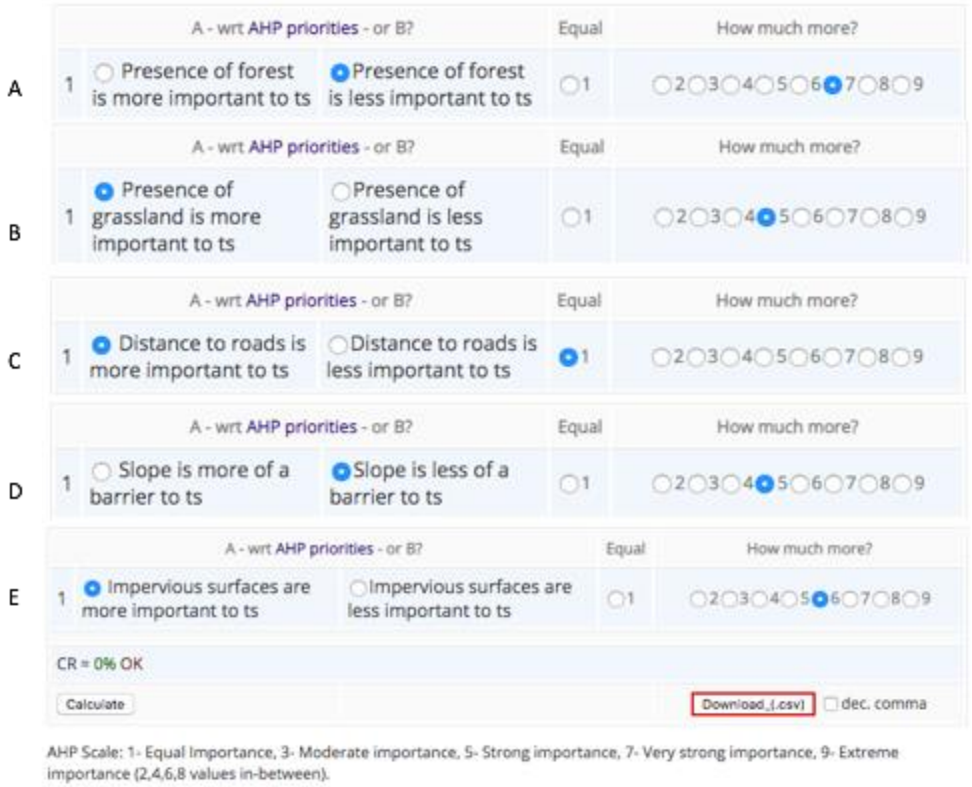


Figure 24: Expert Analytic Hierarchy Process results for tiger salamander HSI variable weighting, priorities and decision matrix.



		A - wrt AHP priorities - or B?		Equal	How much more?
A	1	○ Presence of forest is more important to ts	● Presence of forest is less important to ts	○1	○2○3○4○5○6●7○8○9
B	1	● Presence of grassland is more important to ts	○ Presence of grassland is less important to ts	○1	○2○3○4●5○6○7○8○9
C	1	● Distance to roads is more important to ts	○ Distance to roads is less important to ts	●1	○2○3○4○5○6○7○8○9
D	1	○ Slope is more of a barrier to ts	● Slope is less of a barrier to ts	○1	○2○3○4●5○6○7○8○9
E	1	● Impervious surfaces are more important to ts	○ Impervious surfaces are less important to ts	○1	○2○3○4○5●6○7○8○9

CR = 0% OK

AHP Scale: 1- Equal Importance, 3- Moderate importance, 5- Strong importance, 7- Very strong importance, 9- Extreme importance (2,4,6,8 values in-between).

Figure 25: Wood frog and tiger salamander occupancy comparison Analytic Hierarchy Process results, where a. is the presence of forest, b. presence of grassland, c. distance to roads, d. slope, and e. impervious surfaces.

Appendix C: Dispersal Distances for Amphibians

Table 8 provides literature review of amphibian seasonal and dispersal distances. Dispersal is defined as movements where an individual permanently leaves the natal wetland. Dispersal tends to be unidirectional and occurs over a larger area than migration (Semlitsch 2008). Seasonal is defined as movements around natal wetland between terrestrial and aquatic habitat to meet life requirements.

Table 8: Amphibian dispersal distances for wf (wood frog), bcf (Boreal chorus frog) and ts (tiger salamander)

Species	Distance	Reference	Movement Type	Comment
wf	500 m	(Howard & Kluge 1985)	dispersal	max movement recorded in study
wf	2287 m	(Berven & Grudzien 1990)	dispersal	max movement recorded in study
wf	1000 m	(Berven & Thaddeus 2010)	dispersal	genetic differentiation of frogs over 1000 m between ponds
wf	800 m	(Bishir et al. 2018)	seasonal	over a five day period distance traveled (radio telemetry data)
wf	500m	Browne et al., 2015	dispersal	Scale model for movement recorded in study between wetlands and preferred habitat
cf	680 m	(Spencer 1964)	dispersal	max movement recorded in study
cf	580 m	(Dodd 2013)	dispersal	max movement between recaptures
cf	500m	(Eigenbrod et al. 2008)	dispersal	Correlations with forest cover and/or road and traffic density and species occurrence and dispersal
ts	600 m	(Pechmann et al. 2001)	dispersal	max movement recorded in study
ts	100 m	(Denoel et al. 2007)	seasonal	
ts	250 m	(Steen et al. 2006)	seasonal	radio tagged individuals - rarely moved more than 250m from breeding pond (Eastern TS)
ts	1000 m	(Spear et al. 2005)	seasonal	gene flow diminished > 1km, used COSEWIC to meet life history characteristics
ts	644m	(Bain et al. 2017)	seasonal	Migration corridor for the study population
ts	556m	(Searcy et al. 2013)	seasonal	Average migration distance of adult salamander was 556m from study site
ts	625m	(Semlitsch & Jensen 2001)	seasonal	Adult salamander migration from wetland edge
ts	2200 m	(Orloff 2001)	dispersal	maximum dispersal capability (California salamander)
ts	600m 1000m	(Wang et al. 2009)	dispersal	Dispersal between pond movement

Appendix D: Circuitscape Modelling Results

Wood Frog

CIRCUITSCAPE MOVEMENT PATHWAYS

To identify potential movement pathways for wood frog we summed the results of Circuitscape models from three resistance scenarios. The resistance scenarios help to represent heterogeneity in individual amphibian movements. Figure 26 displays best top movement pathways for wood frog based on high valued habitat as focal nodes. Potential movement pathways are most common in areas where urbanization has not occurred on the urban fringe, in green spaces along major roads and along intact riparian systems, such as Nose Creek, Beddington Creek and Fish Creek. There are limited movement pathways between wetlands in the inner City and therefore many wetlands within residential neighbourhoods are isolated in terms of dispersal ability.

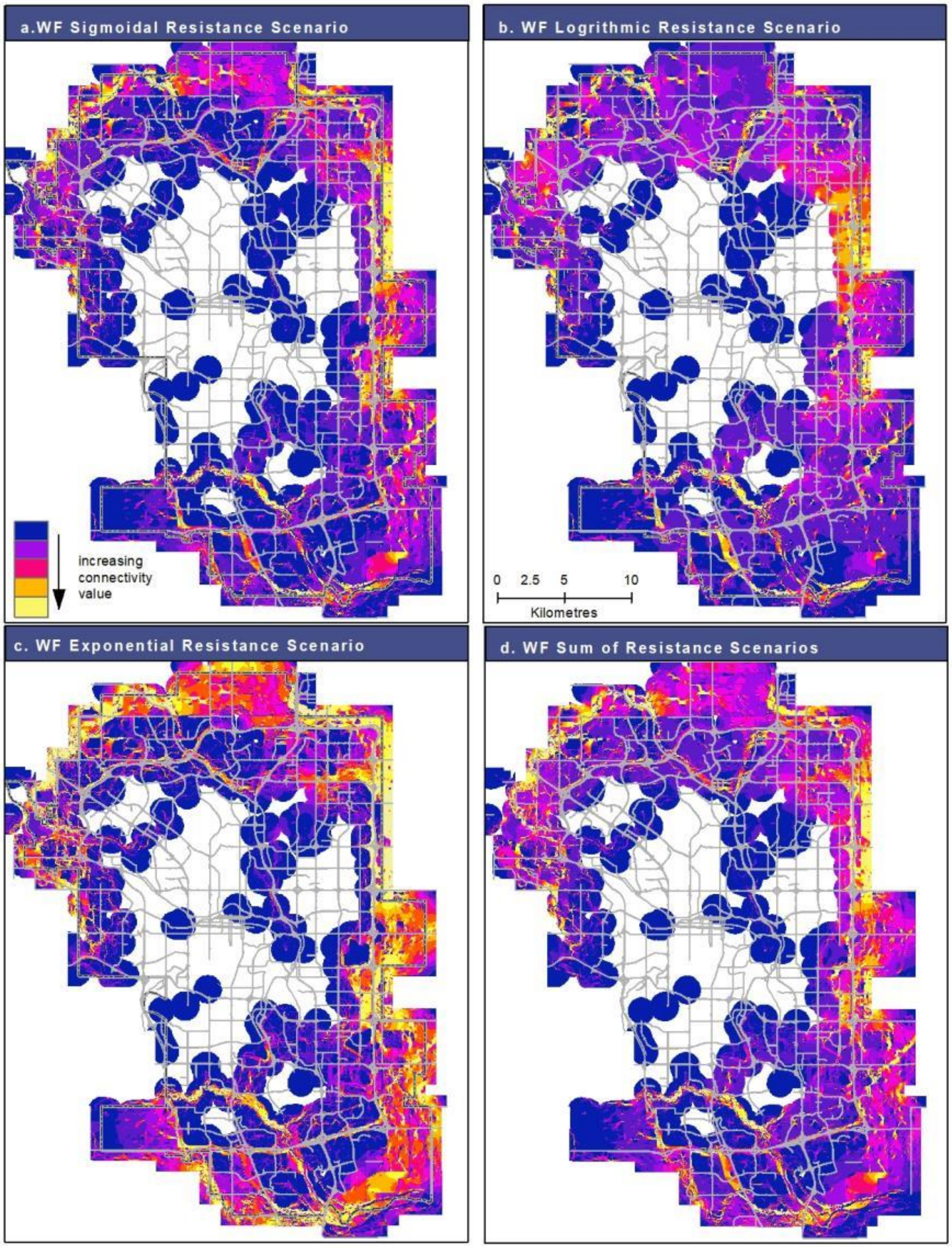


Figure 26: Wood frog Circuitscape results based on high valued habitat as focal nodes for a. sigmoidal resistance scenario, b. logrithmic resistance scenario, c. exponential resistance scenario and d. sum of all three resistance scenarios. Major roads are displayed in the background in grey. Values displayed as current from high (yellow) to low (dark blue).

Figure 27 depicts close up maps with satellite imagery in the background of neighbourhoods in the northwest and south of Calgary. These maps highlight movement pathways and show limited movement across major roads and in residential neighborhoods. Existing wetlands are depicted in light blue and isolated wetlands in residential neighbourhoods are noticeable in the map to the right. These wetlands may support amphibians but are limited in their ability to support dispersing populations.

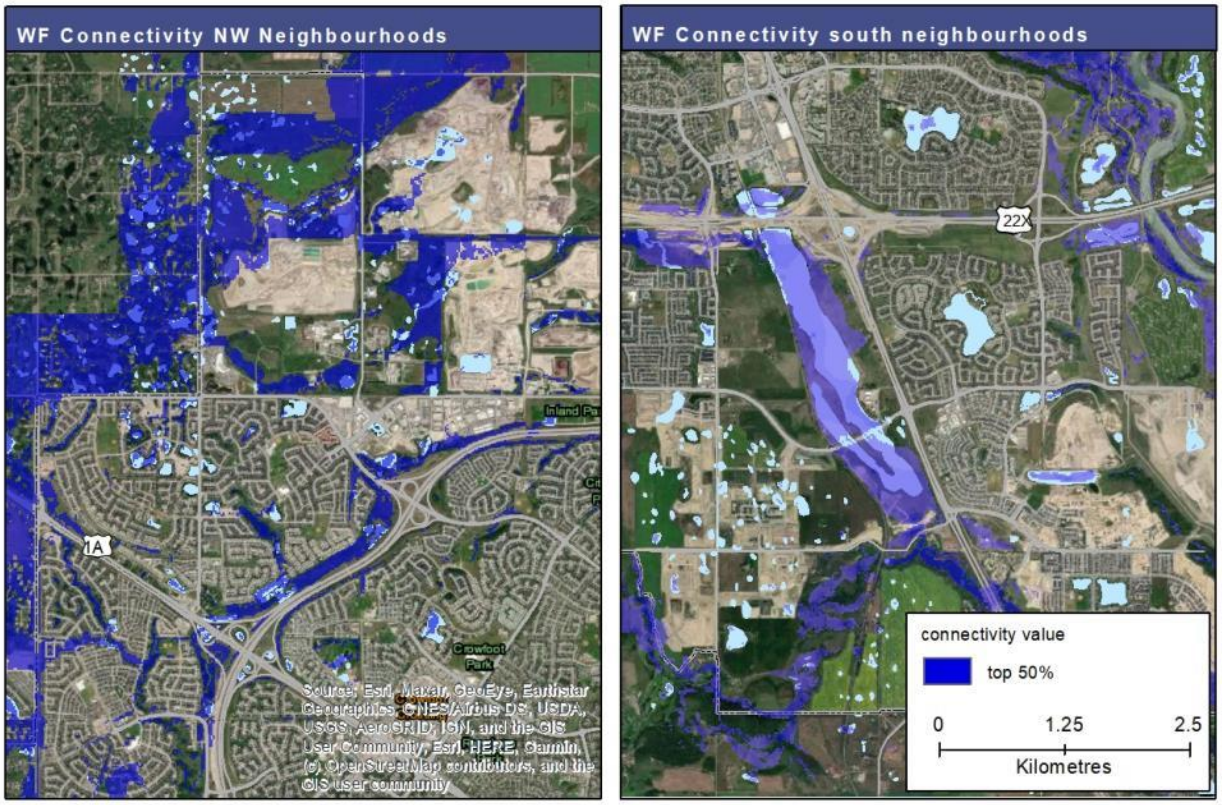


Figure 27: Wood frog top Circuitscape model for summed resistance scenario displaying top 50% of connectivity in blue. The right panel lower left is currently under construction (new road network is visible on image in background) and many of the 2015 wetlands are no longer on the landscape.

Model Sensitivity

Resistance scenarios were compared by extracting the mean and standard deviation for each wood frog Circuitscape model (Figure 28). Resistance scenarios help represent individual heterogeneity in response to a landscape during migration or dispersal. A more prohibitive resistance surface (logarithmic) may represent amphibians in diminished condition and vice versa a less prohibitive resistance surface (exponential) may represent amphibians in extremely good conditions. Therefore, resistance values were summed for each resistance scenarios to create a final movement map for each species.

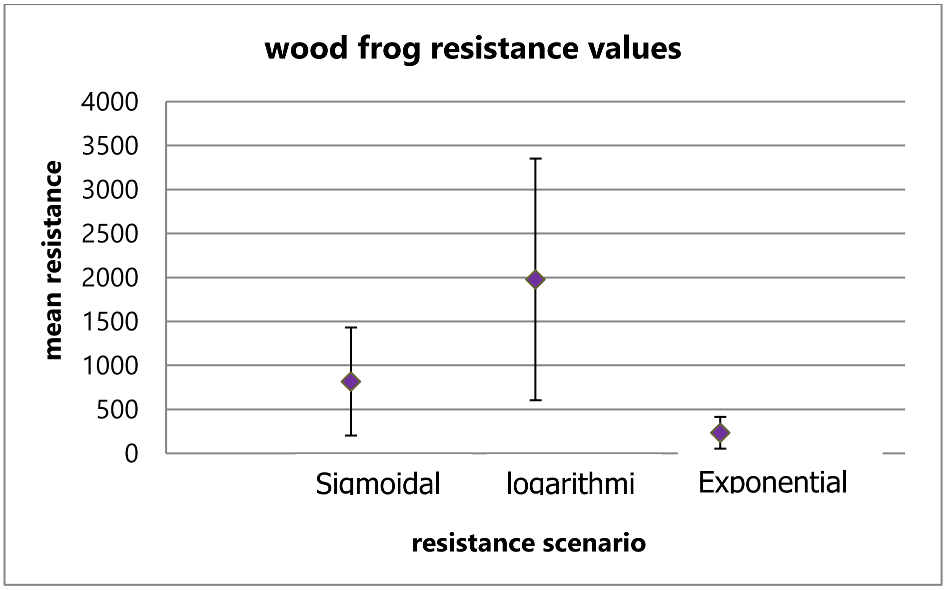
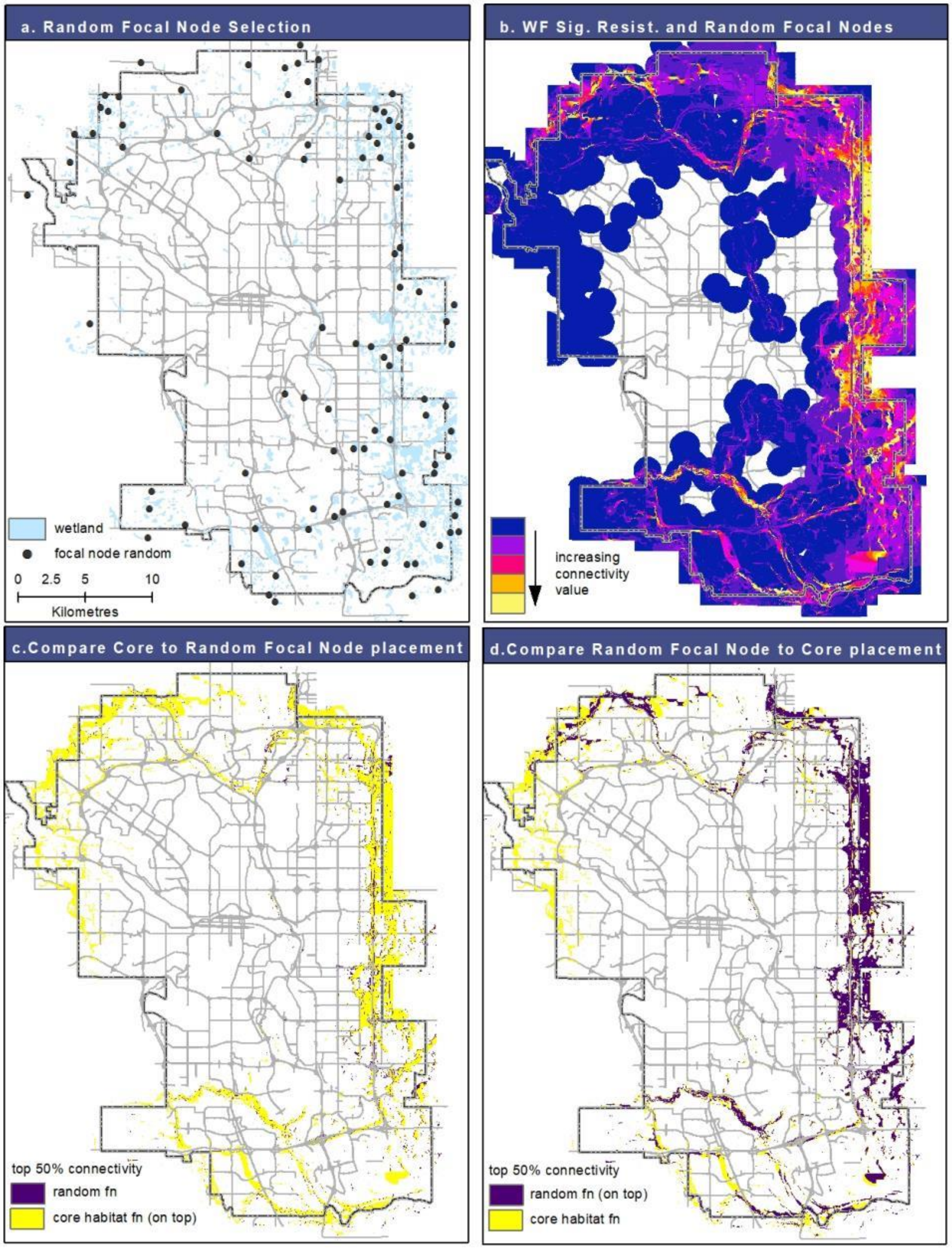


Figure 28: mean resistance, where higher resistance values represent less permeability to movement

To test the sensitivity of movement opportunities to focal node placement, we generated 100 random focal nodes (maximum 500m distance between nodes), and ran Circuitscape using the sigmoidal resistance scenario for wood frog. We selected sigmoidal as it represents the moderate movement opportunity and most likely reflects the average movement potential. 15Figure 29 displays Circuitscape modelling results for 100 random focal nodes run on the sigmoidal resistance surface and compares the top 50% of probable movement pathways with modelling results using high habitat value as focal nodes. Circuitscape modelling is influenced by focal node placement, as a random selection favours areas where there are more wetlands, such as the eastern portion of the City. The modelling based on high valued habitat for wood frog appears to have captured more movement than the random focal node modelling. The modelling results are fairly similar on the eastern edge of the city, but differ along the western edge of the study area. Both models indicate limited movement opportunity to inner city wetlands, which are isolated from neighbouring wetlands.



15*Figure 29: random focal node placement (panel a), and Circuitscape modelling results when run on the sigmoidal resistance scenario for wood frog, where yellow represents highest current value or the most probable movement corridors (panel b); top 50% of movement corridors for modelling based on high valued habitat focal nodes (yellow) and random focal node placement (purple), with model using high valued habitat as focal nodes on top (panel c) and with model using random focal nodes on top (panel d).*

Boreal Chorus Frog

CIRCUITSCAPE MOVEMENT PATHWAYS

To identify potential movement opportunities for boreal chorus frog we summed the results of Circuitscape models from three resistance scenarios. Figure 30 displays best potential movement opportunities for boreal chorus frog base on core habitat patches. Results show a high level of agreement regardless of the resistance scenario used. Potential movement opportunities for boreal chorus frog are limited and are most common in areas where urbanization has not occurred on the edge of the City, in green spaces along major roads and along Beddington Creek. There are limited movement opportunities between wetlands occurring in the inner City neighborhoods.

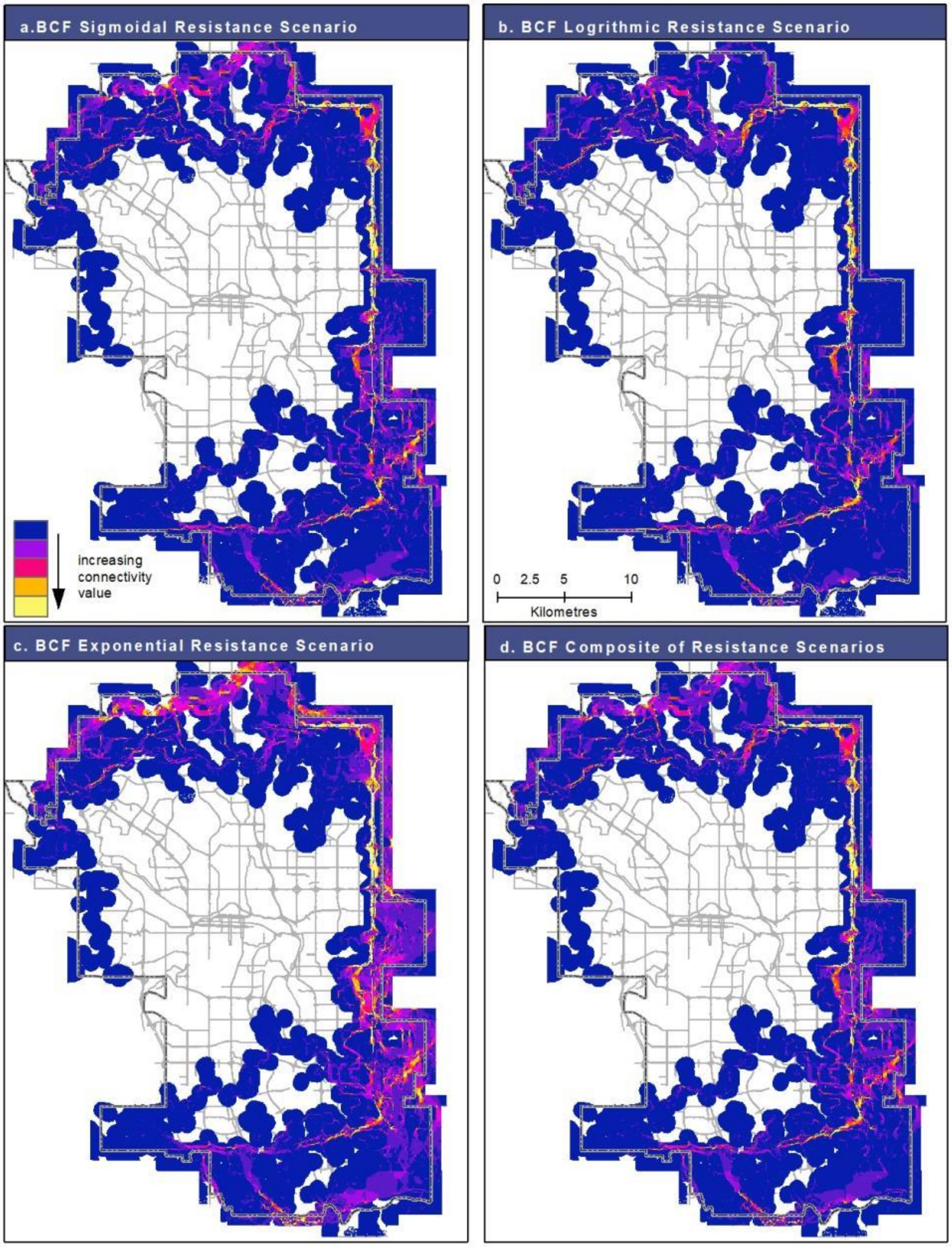
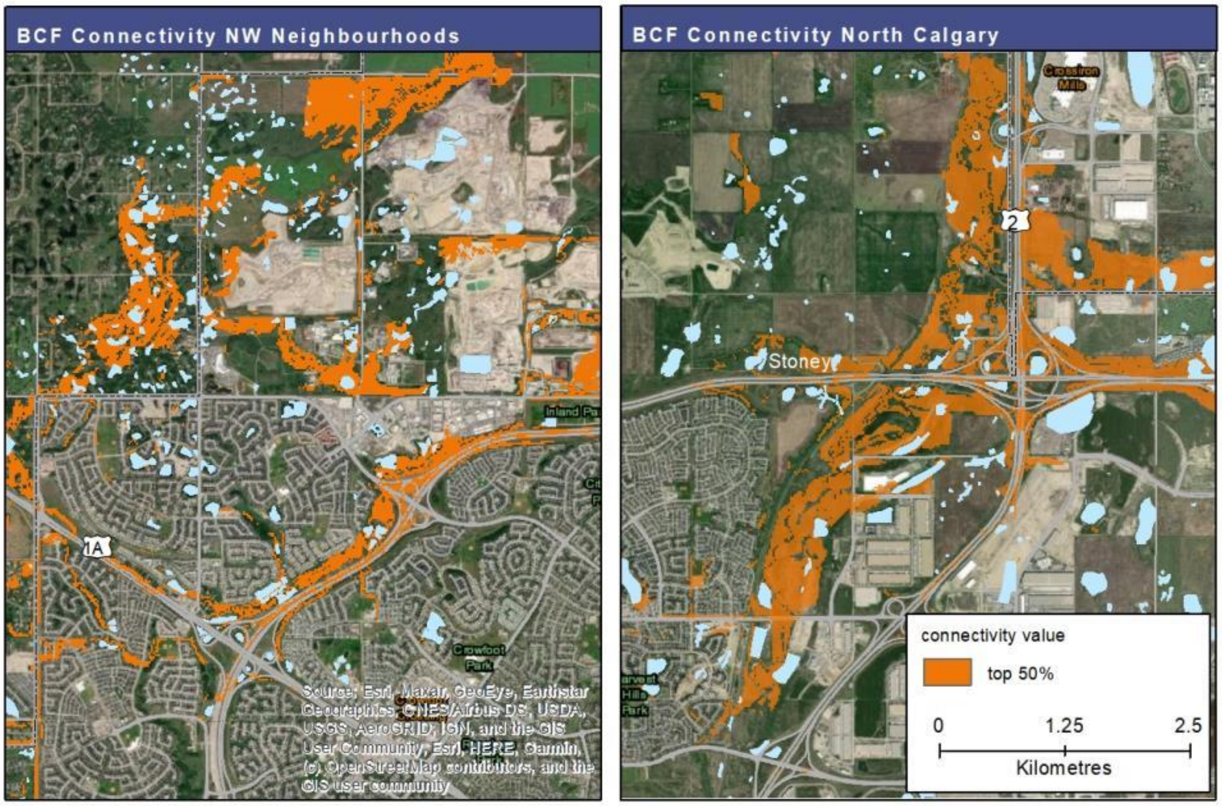


Figure 30: Boreal chorus frog Circuitscape results based on core habitat focal nodes for panel a. sigmoidal resistance scenario, panel b. logarithmic resistance scenario, panel c. exponential resistance scenario and panel d. sum of all three resistance scenarios. Major roads are displayed in the background in grey. Values displayed as current from high (yellow) to low (dark blue) equating to connectivity value from high to low.

Figure 31 depicts close up maps with satellite imagery in the background of neighbourhoods in the northwest and south of Calgary. The maps highlight areas on the urban landscape where movement is limited or not occurring, such as across major roads and in residential neighborhoods.



Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community, Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community

Figure 31: Boreal chorus frog model for summed resistance scenario displaying top 50% of connectivity in orange (extracted from Figure 30 model results)

Tiger Salamander

CIRCUITSCAPE MOVEMENT PATHWAYS

To identify movement opportunities for the tiger salamander based on core habitat we summed the results of Circuitscape models from three resistance scenario. Figure 32 displays best potential movement opportunities for tiger salamander based on core habitat patches. Potential movement opportunities are most common in areas where urbanization has not occurred on the edge of the City, in green spaces along major roads and along intact riparian systems, such as Nose Creek, Beddington Creek and Fish Creek. There are limited movement opportunities between wetlands occurring in the inner City neighborhoods.

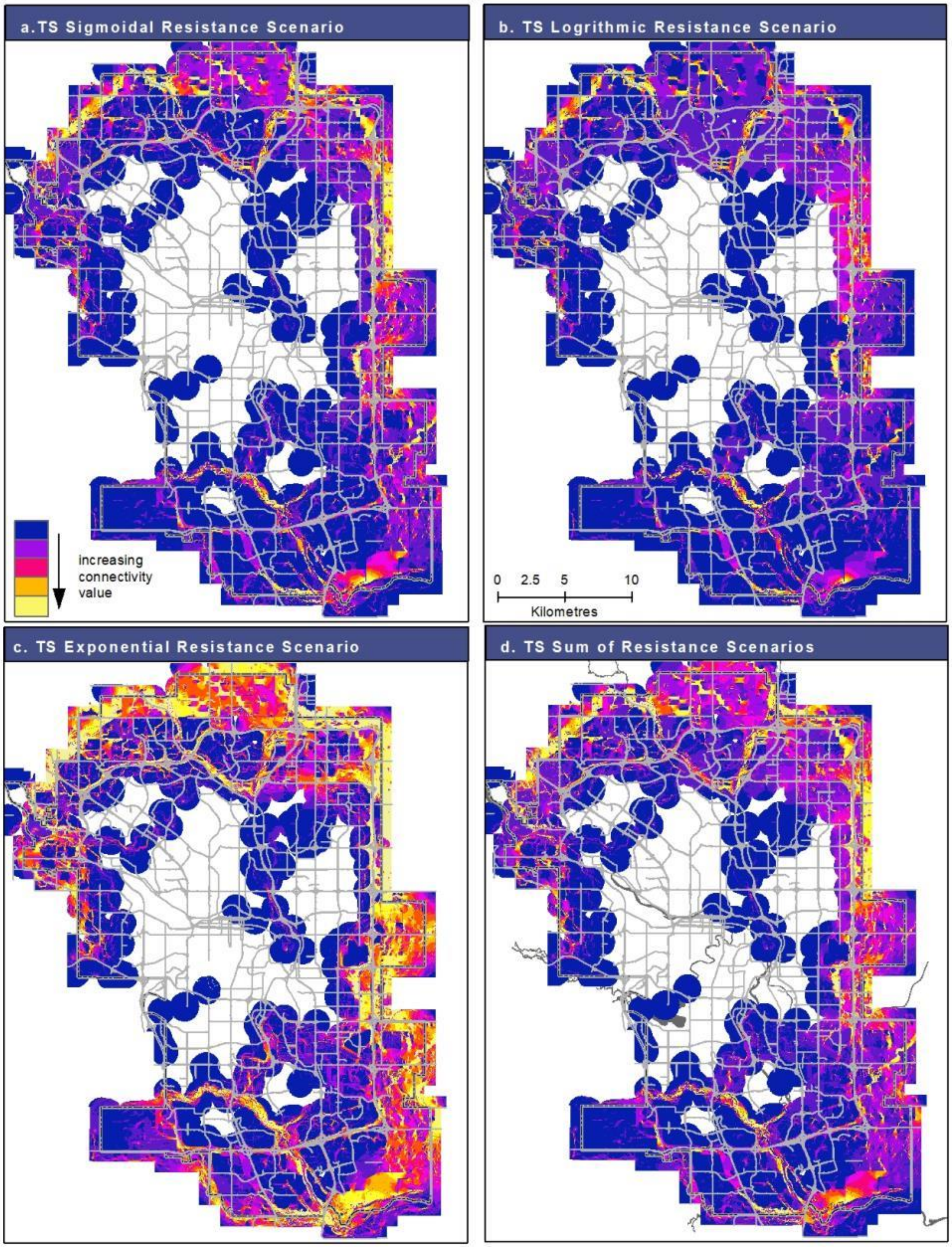


Figure 32: Tiger salamander Circuitscape results based on core habitat focal nodes for panel a. sigmoidal resistance scenario, panel b. logarithmic resistance scenario, panel c. exponential resistance scenario and panel d. sum of all three resistance scenarios. Major roads are displayed in the background in grey. Values displayed as current from high (yellow) to low (dark blue) equating to connectivity value from high to low.