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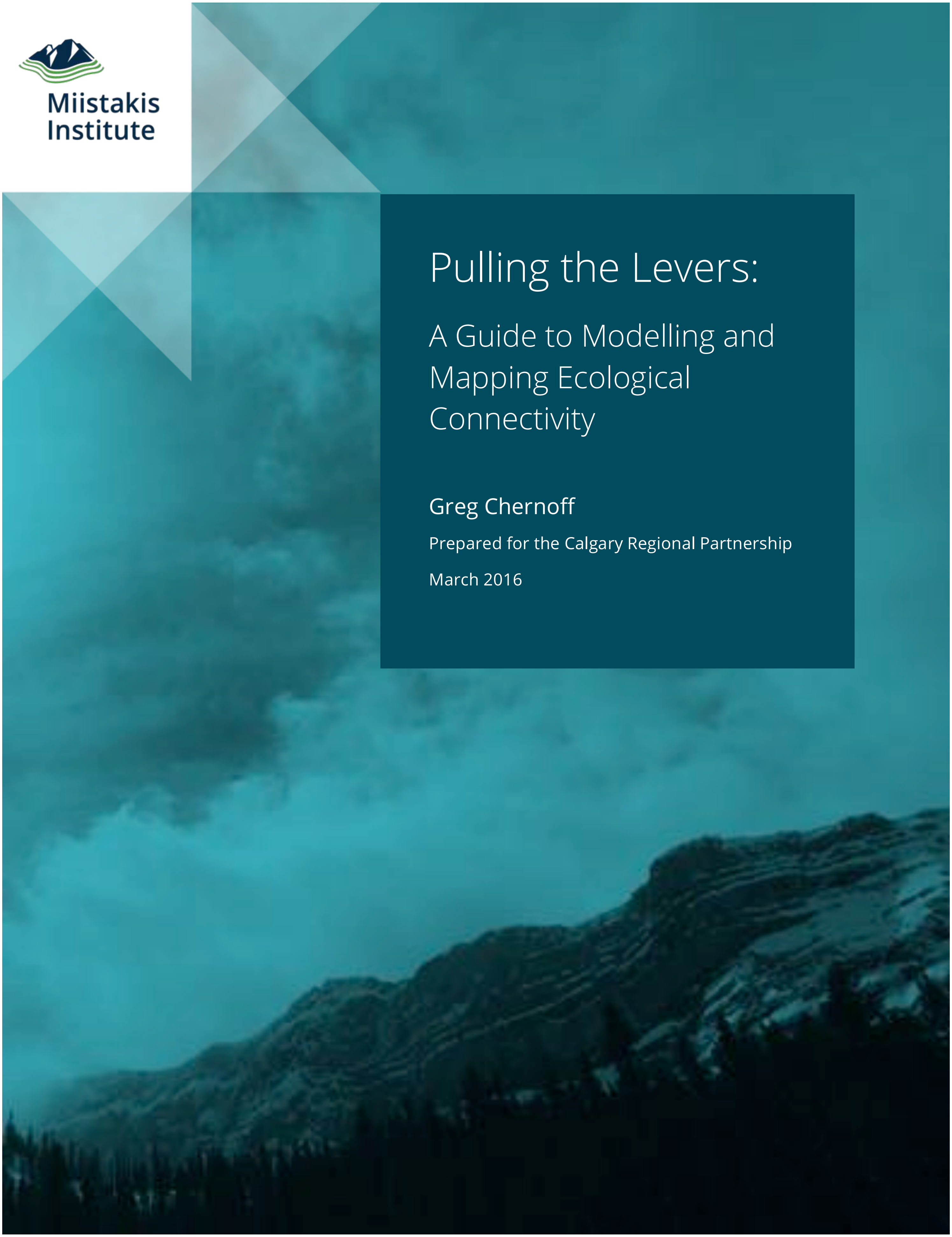

Pulling the Levers:

A Guide to Modelling and Mapping Ecological Connectivity

Greg Chernoff

Prepared for the Calgary Regional Partnership

March 2016

Innovative research. Engaged communities. Healthy landscapes.

Pulling the Levers:

A Guide to Using Ecological Connectivity Modelling in Municipal Planning

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Miistakis Institute
Rm U271, Mount Royal University
4825 Mount Royal Gate SW
Calgary, Alberta T3E 6K6

Phone: (403) 440-8444
Email: institute@rockies.ca
Web: www.rockies.ca

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Introduction

Landscape connectivity is a key component of the CRP's Calgary Metropolitan Plan, and is emerging as a critical sub-theme of the Landscape Health theme within the nascent CRP Ecological Conservation and Protection Initiative (EcoPlan). Connectivity is a key piece of the regional conservation puzzle, and is mentioned as important in the planning documents of many CRP member municipalities.

However, there are many issues working against the meaningful consideration of connectivity in regional or local planning:

1. Loose and Inconsistent Definition of "Connectivity": What does connectivity mean to those who are trying to conserve and maintain it? Is the desired connectivity structural or functional? What structure or function needs to be conserved? For what or which species? Is all connectivity good and desired, or is some connectivity less favourable? Is terrestrial connectivity or aquatic connectivity the primary concern (or both)? To date, connectivity has only been defined in the broadest of contexts, which leaves the door open to various interpretations.
2. Lack of a Well-defined, Transparent Process: Partly due to the loose definition of connectivity, the process of modeling, mapping, and interpreting the results of connectivity analyses is widely variable throughout the region and more broadly. Therefore, when connectivity is modeled and mapped within the region, the results are inconsistent and often difficult to compare. Moreover, the process whereby connectivity has been assessed may frequently be a "black box"; the CRP or a municipality will ask for and receive an "answer", but the nuance and context of the question - and hence the ability to interpret and use the results - may be lost.
3. Static, One-time Outputs: In a landscape that is changing as rapidly as the greater Calgary Region it is conceivable that, in the time it takes to perform connectivity or any landscape analysis, the landscape may change sufficiently enough to render the results out-of-date before they're even in the hands of decision-makers. Since most of the analytical work related to connectivity is currently done by contract, the results are static outputs capturing a snapshot in time. Moreover, the process of modeling connectivity may be unclear or proprietary, will likely change from contractor to contractor, and will be costly to replicate.

To address these challenges, Miistakis has worked with the CRP to build a simple yet effective, robust, flexible, standardized and replicable process for modeling various types of connectivity for the Calgary Region, a portion of the region, or a smaller area (such as a municipality, or a region within a municipality).

This guide documents the process that we've developed, and provides easy-to-follow instruction and technical considerations of how to model and map connectivity.

It was written for use by municipal or regional GIS technical staff, people who work on municipal or regional planning, people who contract GIS consultants to do this work, and anyone that needs to be involved in - or better understand - the technical side of mapping and modeling connectivity. It is accompanied by *Connecting the Dots: A Guide to Using Ecological Connectivity Modelling in Municipal Planning*, which is targeted at planners who are asking for information on connectivity to be incorporated into their planning activities.

How to Use This Guide

This guide is written in an informal tone, often directly addressing YOU, the user, the person with your hands on the levers and knobs of the connectivity modeling and mapping process. It follows a general blueprint or template for how to undertake connectivity projects, as laid out by organizations like LandScope (landscope.org) or the USFS (Wade et al, 2015).

If you read the whole guide you will learn that, although GIS work is required in most steps, that the GIS-heavy portion of a connectivity project is actually a relatively small piece in the middle. Note that the guide is written assuming the reader has little or no experience with connectivity modeling; however, to follow the GIS-related steps below, you will need a solid foundation and at least intermediate skills in GIS and spatial analysis - or access to someone with those skills.

On either side of the actual running of the model are numerous critical process steps, requiring essential input from stakeholders who are not GIS, or modeling, or connectivity experts.

The “Beginner’s Guide” chapter (see below) goes through each step of the process individually:

- Step 1: Framing the Question - Project Scoping.
- Step 2: Building Blocks - Connectivity Model Inputs.
- Step 3: Button Pushing - Running the Model.
- Step 4: Post-Production - Refining Model Outputs.
- Step 5: So What? - Model Results and How To Use Them.

If you don’t want to follow this process step-by-step, or if you’re only concerned with a single step right now, you may wish to go straight to the appropriate section of the guide. If you only need a quick reference, you might find what you need in the Cheat Sheet (Appendix C).

The most broadly-scoped connectivity modeling processes - such as the two listed above - include several steps that are skipped in this guide. These are most notably related to the general type of connectivity model that will be used, and to the modeling software platform that will be employed. This guide has circumvented these discussions by making a couple decisions pre-emptively: We are suggesting a resistance-surface (or cost-surface) based modeling approach, which employs the free, robust, and popular Circuitscape (circuitscape.org) program for the CRP Connectivity Modeling and Mapping process. Although reference is made to Circuitscape throughout this guide and instructions relate to using Circuitscape for connectivity analysis, much of the guide’s content is transferable to those who may wish to explore other modeling options.

To illustrate the use of this guide and to reinforce the connectivity principles discussed, two demonstrations of connectivity modeling and mapping are provided: a connectivity model for deer which covers the entire Calgary Region; and a case study from the City of Chestermere, demonstrating how connectivity might be used to assess and plan future growth around the conservation of wetlands. Full descriptions of these two examples are included as Appendices; they are also referenced in text boxes throughout the guide, as examples of specific aspects of the process.

Background

The steps to modeling connectivity laid out in this guide follow a general procedure for resistance-surface-based connectivity modeling. There are dozens of different applications of this approach, but they all share the common characteristics of assessing the connections between discrete "patches" (or resource patches, or habitat patches, or focal nodes) across a continuous "resistance surface" (or cost surface), representing the relative ease or difficulty of moving through the landscape (Wade et al, 2015). The purpose of this guide is not to explore the theoretical underpinnings of connectivity modeling; however there are great resources available if you wish to dig deeper into this subject (e.g. Wade et al 2015, Ament et al 2014, Aune et al 2011). The explanations below for creating model inputs should be sufficient to provide a basic understanding of focal nodes and resistance surfaces.

This guide refers to Circuitscape, a free, open-source program for modeling connectivity in heterogeneous landscapes (circuitscape.org). Circuitscape is currently one of the most widely-used connectivity modeling tools, and is recommended to the CRP and its partners due to its robustness, ease of use, lack of reliance on commercial software, and supportive and accessible community of users. Two versions of Circuitscape are available for download: A stand-alone version; and a version that runs within ESRI ArcGIS software (ESRI, 1999-2015). The ArcGIS-compatible version is downloadable as a toolbox and can be added to any ArcGIS application (e.g. ArcCatalog or ArcMap). Along with the "Circuitscape for ArcGIS" tool, the toolbox also includes a tool for exporting ESRI-format data into formats readable by Circuitscape (see next chapter, Step 2 "Building Blocks", for more details on required formats). Tests showed negligible difference in processing time between the stand-alone and ArcGIS versions, and the stand-alone version is more visually intuitive, so all figures in this guide will be screenshots from the stand-alone version. However, the same functionality is available from either version.

A note of caution: Connectivity modeling can be quite computationally expensive. Depending on your model inputs, it can take a long time to run a connectivity model, even on a fast and powerful machine. It's in your best interest to think carefully about all your model inputs and the ideas that go into them, and to make sure your computer is ready to run a long process, before you hit the "RUN" button!

Connectivity models can take a very long time to run. Even on a powerful workstation, processing the region-wide deer connectivity model that is described in Appendix A took almost 200 hours!

Lastly, although we have selected Circuitscape as the application of choice for the CRP Connectivity Modeling and Mapping Standard, it is far from the only option. CRP or its members may choose to employ other methods and software platforms for any number of reasons. Also, very little is static in the world of modeling, or conservation science, or computer software. In time, a new preferred connectivity modeling application will likely come to the fore. In any case, the authors have taken efforts to ensure that the relevance of this guide will go beyond a specific piece of software, and should introduce or reinforce the basic steps and technical considerations to modeling, mapping, and helping people understand connectivity, regardless of what software you're using.

A Beginner's Guide to Understanding, Modeling, and Mapping Connectivity

The following chapters guide you step-by-step through a process of meaningfully modeling connectivity in your regional, sub-regional or local landscape; mapping the results of your modeling exercise; and helping others understand why this matters to conservation and land use planning.

Each step in the process is described in detail below. For those of you requiring less detail though, a Connectivity Modeling Cheat Sheet is included in Appendix C of this Guide.

Before you begin to map and model anything, it's helpful to have a research objective in mind; this focuses your thoughts and efforts, helps gather consensus among collaborators and stakeholders, and hopefully makes the end results of your efforts more intuitive and informative to the people who will use them.
In the broadest general sense, all connectivity models address these questions: What aspect(s) of ecology do we need to understand? What are the critical patches in our ecological landscape? And how are those patches interconnected across our area of interest?

To yield anything more useful to the CRP EcoPlan or to conservation and land use planning, those questions obviously need to be fleshed out with some critical details. Each step of the process below unpacks a piece of the above questions, and explores it in detail.

Step 1: Framing the Question – Project Scoping

Virtually every municipality in the Calgary Region has expressed interest in ecological connectivity as a local and larger conservation priority. But what is meant by connectivity? The context can be very different between different interested parties and at different scales of time or space. The first step of your connectivity modeling project is all about understanding this context, identifying stakeholders and project partners, and aligning expectations for everyone involved.

If you're reading this guide, you're likely a technical person - GIS professional or otherwise - who has been asked to map connectivity by someone else in your organization. Your goal in this step of the process is to discuss the specific goals and anticipated outcomes of the connectivity project you're about to begin, with the other people in your organization who have an interest in understanding connectivity.

Chapter 6 in the USFS Connectivity Report (Wade et al 2015, pp.65-68) includes a very detailed list of questions to guide this discussion; the first step of the LandScope connectivity process (landscope.org) suggests a much-abridged list. Below is a list of the bare essential questions that must be asked and answered before you proceed:

- **Why Connectivity?** What conservation or land use planning decisions will be informed by the assessment of connectivity that you're being asked to provide? Who will be making these decisions or weighing into this discussion, and what do they need from you?

- **Connectivity for What?** What kind of connectivity is being modeled?

> *For the Chestermere wetland connectivity project described in Appendix B, a City of Chestermere Councillor approached Miistakis at a CRP meeting, wondering how a better understanding of the connectivity between priority wetlands could inform ongoing discussions about future growth of the City.*

  Structural connectivity, which is not species-specific and measures the contiguity and connections between important patches of landscape? Or functional connectivity, which identifies resource patches and connections between them that relate to some of all ecological functions of a species, group of species, or ecological process (Wade et al 2015, p11)? If modeling functional connectivity, what species, functions, and movements are you trying to represent? What elements of the landscape are critical to the specific type of connectivity you're modeling? What exactly is being connected to what? What elements of the landscape serve to assist or impede movement between them?

- **Connectivity Where?** What is the area of interest for your connectivity project? Is it confined to your organization's administrative boundary, or does it extend further beyond that to a sub-regional or regional scale? Sometimes the area of interest or area of ecological importance can be larger than the area over which your organization has decision-making authority. In these cases, it may be valuable to consider the larger perspective, even though the scope of your action may be confined to a smaller area.

The demonstrations in Appendices A and B present both a functional connectivity model, designed to reflect the daily resource requirements of deer throughout the Calgary Region, and a structural connectivity model, designed to assess connections between high-priority wetlands within the City of

- **What Outputs are Required?** How should your model results be communicated, and with whom? What do you need to produce from your connectivity modeling efforts? If they are maps depicting connectivity, should you display your findings as definite, discrete connectivity zones (i.e. polygons), or as continuous surfaces showing graduated connectivity metrics? Or are both types of outputs required? What other layers will you need to consider or analyze in association with your connectivity model outputs? How will these outputs inform discussions and improve decisions on land use and conservation planning?

As the connectivity modeling technician, it would be unwise for you to try to answer all of these questions on your own. You will certainly need to involve others within your organization; you may also need to draw from a wider range of stakeholders in order to scope your project appropriately. In most cases, the best approach is to start with internal discussion of the above questions, and then identify and engage stakeholders if you find there are gaps in your understanding of the issues, and capacity to scope your project. If stakeholder engagement is prioritized at this stage, you may require a facilitated workshop to make sure everyone is heard and you get the information you require efficiently.

Step 2: Building Blocks – Connectivity Model Inputs

Now that your connectivity project is clearly scoped and your research question is articulated, you're ready to start assembling the necessary input information and data.

In this step you need to identify and map three things: study area; resource patches; and resistance surface.

Study Area: Over what area or region are you interested in modeling connectivity? Are the boundaries of this area of interest natural/ecological, or administrative/jurisdictional? These questions will have been discussed in the previous step, but now you need to clearly define your study area boundary, and draw some lines on the map.

Your research question will define the appropriate spatial extent of your analysis. You may be concerned with a small portion of your municipality if you're evaluating the impacts on connectivity of a proposed new development. You may be concerned with connectivity across your entire jurisdiction, to inform discussions around bylaws, development or growth plans, or sustainability plans. You may recognize a need to look beyond your own administrative boundaries to understand connectivity to the surrounding landscape. Or you may be interested in building a region-wide picture of connectivity.

In any of these instances and wherever you choose to draw the line, it's important to note that most ecological phenomena and aspects of connectivity - functional or structural - will continue beyond your study area boundaries. The spatial context of the ecology you're trying to map and model is every bit as important as the "sphere of influence" of the land use decisions that your work informs. So choose your study area carefully, and try to be forward-thinking in choosing it; if your work is informing a decision in one area, but on an issue that your organization is expected to face repeatedly in the future, it's much more efficient to expand your study area and model connectivity once for all foreseeable areas of interest.

Lastly, you will need to buffer you study area boundary appropriately, in order to address problems arising from edge effect. Edge effect is the misrepresentation - typically underrepresentation - of connectivity around the outer boundary of the study area, and is common to almost all connectivity modeling methods. It arises from the problem that we have to draw the study area boundary somewhere, but the landscape continues to be connected off the edges of our map, and we can't map what (from the model's perspective) doesn't exist. We address edge effect by buffering our area of interest. This artificially expands the study area during analysis, and forces the edge-affected portions of our connectivity map outside of the actual area of interest. Dealing with edge effect is discussed further in Step 4.

As a general guideline, here are some recommended buffer widths for typical connectivity study areas:

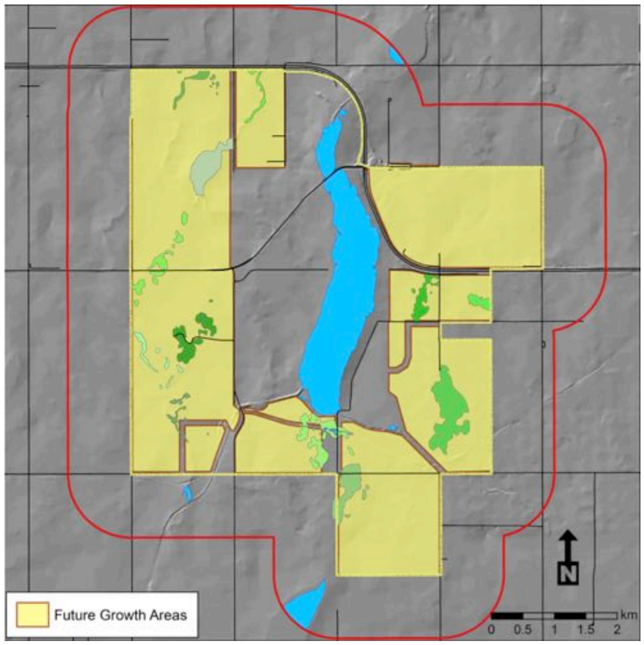
STUDY AREA	BUFFER WIDTH
Urban Municipality	1 km
Rural Municipality, or large Urban	5 km
Greater Calgary Region	20 km

Note that, if the buffered study area extends across municipal (or provincial, national, etc.) boundaries, you may have to find surrogate data to cover the buffered regions (e.g. you have a high-resolution DEM for your municipality, but the coverage ends at your administrative boundary). Although it's ideal to match the data quality within your actual area of interest, it isn't essential, and often you'll be forced to settle for whatever data is available on the periphery. Your model results will be presented with the buffered areas erased anyway though, so this doesn't impact your end product.

Your resource patches can be limited to the spatial extent of your actual area of interest; however, your resistance surface must include the entire buffered study area.

Resource Patches: What are the critical elements of your study area that your model will connect to each other? These may be important wildlife habitat, native prairie or other natural vegetation, designated "open spaces" or protected areas, or other features on the landscape. They are variously referred to as habitat patches, core areas, resource patches - Circuitscape refers to them as "focal nodes". We will use the term "resource patches" in this guide, since it encompasses the broadest range of landscape elements that the CRP and its members may wish to connect.

Below is a map showing the study area for the Chestermere demonstration project. The study area (outlined in red) consists of the City of Chestermere administrative boundary, buffered by 1 km.



The wetlands around Chestermere are part of the Shepard Slough Complex, which covers portions of neighboring municipalities; despite the fact that Chestermere is using connectivity to inform City planning decisions, it may be valuable to consider the broader ecological context of the Shepard Slough in future connectivity modeling efforts. See Appendix B for a full description of the Chestermere demonstration project.

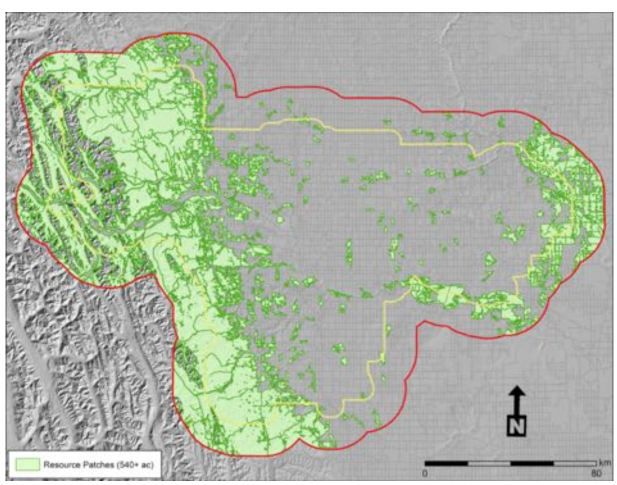
If you're modeling functional connectivity, the species, group of species, or ecological function you're modeling and the specific ecological function (or functions) you're interested in, are key considerations. If you're modeling connectivity that meets the daily habitat requirements of a given species, you will want to map resource patches that could meet the food, water, and shelter requirements for that species (Wade et al, 2015).

The effort required to map resource patches for functional connectivity models is scalable along a wide-ranging spectrum. Where you land on that spectrum depends on the specific needs, interests, data availability, time and resource capacity, and skill set of your modeling team.

At one end of the spectrum is a mapping approach based on intuition or expert opinion, and built upon readily available spatial data. For example, you may be interested in mapping connectivity for sage grouse. A scan of the literature and discussion with biologists reveals that sage grouse spend the majority of their lives in and around sagebrush-dominated areas. You find a land cover layer showing the current distribution of sagebrush in your study area, and use this to create patch layer from all polygons with 50% or more sagebrush cover.

At the other end of the spectrum is a mapping approach based on the empirical modeling of the landscape, to represent the functional ecological requirements of your species of interest. This may constitute a research effort unto itself, and would be warranted if your connectivity research requires the highest possible level of certainty in its identification of resource patches (e.g. perhaps resource patches would become candidate areas for protection or conservation, and patches that are currently on private land would require negotiation with landowners). Mapping resource patches at this level of rigour would require the involvement of specialists

This map shows the resource patches used in the region-wide deer connectivity demonstration model, which is presented in Appendix A:



These patches were derived from ABMI land cover data, and represent natural vegetation patches of 540 acres in area or larger. Deer habitat or occurrence data might have been preferred, but none was available that covered the entire study

- landscape ecologists, wildlife biologists, GIS modeling experts - and the creation of resource selection functions or other habitat models as a precursor to mapping patches.

Of course, there are many intermittent levels of effort - and commensurate levels of accuracy/certainty around patch identification - along this spectrum. In the luckiest cases, you may be able to draw from existing data or previous research to inform the creation of your resource patches.

Resource patches for structural connectivity models are sometimes derived using similar methods to those described above. In other cases, the patches that the modeler wants to connect have already been identified or designated for their ecological significance (e.g. parks, recreation areas, protected wetlands, conservation easements, etc.).

Regardless of the method you choose for identifying resource patches for your connectivity model, they must be mapped discretely - that is, your end result of resource patch mapping must identify regions as either being designated as resource patches, or not.

Resistance Surface: The resistance surface is a continuous raster across your study area, with raster values representing the relative ease or difficulty associated with passing through any given pixel. It is sometimes called a "friction surface" since higher values represent greater amounts of friction (or resistance) to movement. This is what governs how, where, and to what degree the resources patches you've identified are connected to one another.

Resistance surfaces belong to a special class of raster spatial data called spatial indices. A spatial index is a raster layer in which a specific variable - in this case, resistance to movement - is measured and mapped using one or a combination of features that quantify the natural or built environment.

The simplest resistance surfaces to create are based on single input layers. In many cases though, an accurate representation of resistance to movement across a landscape will require you to build your resistance surface by combining several input layers into a composite index. In these cases you will need to standardize your range of possible resistance values before combining input layers, and then determine appropriate weighting for each input layer in the final composite.

How do you determine what landscape metrics to include as input layers to the final resistance surface? The possible answers to this question run across a similar spectrum as for the identification and mapping of resource patches; from simple, relatively quick, and intuitive approaches to more rigorous, empirical, and time-intensive ones. The more effort you invest in creating your resistance surface, the more accuracy and certainty you will have that it truly represents movement. However, the law of diminishing returns definitely applies here, and the "sweet spot" along the spectrum for your project will depend largely on the time, resources, and skills of experts available to you. Keep in mind that a basic model you create quickly now can always be validated or modified later, if or when more rigorous research comes available.

Here are some common landscape metrics - including a brief description, possible data sources, and work required to convert raw data to resistance layers - that are used in the creation of resistance surfaces:

- **Human Footprint Data:** Almost every aspect of ecology that moves through a landscape exhibits some kind of reaction to people and the infrastructure that we build: bears are attracted to garbage but avoid roads; deer are attracted to certain crops but avoid heavy industrial areas; many invasive plants are eradicated from cropland by spraying, but disperse via roadside ditches. Individual municipalities may have highly detailed data describing the built environment, but luckily, an excellent default resource exists in the freely downloadable ABMI Human Footprint Inventory (abmi.ca), which covers the whole province and maps all footprint types. Resistance scores can be assigned to different footprint types based on consensus, expert opinion, published literature, or dedicated study.

- **Land Cover:** Most subjects of connectivity analysis will respond differently to different land cover types: some species' habitat and movement may be confined to specific cover types; others will use a wide range of land cover types according to varying preference. Numerous sources for land cover data are available throughout much of the CRP, but the most appropriate will likely be the ABMI Wall-to-Wall Land Cover Inventory (abmi.ca), or possibly the provincial government's Grasslands Vegetation Inventory (data.alberta.ca). Very high-resolution or species-specific land cover data are not included in these resources, and would likely need to be mapped by contract if needed. The most straightforward way to convert land cover data to a resistance surface is by assigning scores directly to land cover types. Other approaches may include mapping distance to nearest land cover patch of interest, or densities of patches or of edges between patches.

- **Topography-Related Metrics:** In many aspects of ecology, land form dictates land function: different plant communities thrive at different elevations and aspects. Ridges shed and depressions collect water. All of these factors create a dynamic landscape that different species respond to in different ways, that can affect resistance and connectivity across a landscape. Sadly, there are not many good, free resources for high-resolution, high-precision, accurate Digital Elevation Models (DEMs), from which all topography-related metrics are derived. The best one-stop resource for elevation data is the University of Maryland's Global Land Cover Facility (landcover.org), a distribution point for global SRTM data. At last check, 30m SRTM data was available for most of the Calgary Region, but they contain voids in complex terrain and areas of high relief. Many municipalities may have DEMs that were produced under contract, but few of these are likely to extend beyond their boundaries. In some cases DEMs can be converted directly to resistance scores (e.g. for species that are known to avoid areas above or below a specific elevation), but in most cases they will need to be manipulated to create some sort of landscape metric. Simple examples are slope, aspect, or landform; more complex metrics like curvature, terrain ruggedness, or wetness can also be derived from DEMs. The website "GIS for Geomorphology" (gis4geomorphology.com) is an outstanding resource with instructions for creating all kinds of topography-related metrics. Many of these metrics produce raster surfaces with a continuous range of values, which can readily be rescaled to resistance values.

- **Wildlife Habitat / Movement Models:** If you have access to spatial modeling or data of wildlife habitat, resource requirements, mo

For the region-wide deer connectivity model, a resistance surface was calculated using ABMI land use (human footprint) and land cover data as the only input, with resistance values assigned to each use/cover type. For the Chestermere wetland model, resistance was represented by a weighted calculation of land use/cover and a topographic wetness metric derived from a DEM. See Appendices A and B for full descriptions of how these resistance layers were calculated.

- vement, or dispersal, or you have the wherewithal to create these data, you can incorporate them into the creation of your resistance surface. Even if these layers have been used to identify and map resource patches, you can still use them as inputs to your resistance surface. The ABMI Species site (species.abmi.ca) contains resources that you may find useful, especially if you're working on a larger (region-wide or slightly smaller) spatial extent.

Regardless of the input layers you choose, the process for converting them into a resistance surface is more or less the same:

1. Determine which values in your input layer represent areas that facilitate movement or connectivity (low resistance), which values impede movement or connectivity (high resistance), and which values are somewhere in the middle.
2. Assign resistance values to input layer values. If your input layer contains discrete values (like land cover types) you can assign resistance values to each discrete value; if your input layer contains continuous values, you will need to employ some arithmetic adjustments - usually linear transformations - of the raster to fit the values into your standardized range. If you are combining multiple layers to create your resistance surface, all input layers must be scaled to the same standardized range of possible values.

The actual values in resistance layers are typically unitless and relative, meaning they only matter in relation to other resistance values in the same layer. Circuitscape and many other connectivity modeling programs have no restrictions regarding the range of values you assign to your resistance layer - except Circuitscape will not allow 0 (zero) as a resistance value, treating it as NODATA. For the CRP standardized process, we recommend a range of resistance values between 1 and 11. This provides enough variability to distinguish between most discrete input layer types (e.g. land use/cover), with a value (6) that is right in the middle. It also keeps numbers low and raster file sizes smaller.
The merit in having a standardized range of resistance values across the region is that it makes data more exchangeable and comparable between

3. If you're using more than one input layer to create your resistance surface, you will need combine these inputs into a single resistance surface. This requires you to weight each input layer, then merge them together. Achieve this through the following formula:

Resistance = {(w1 * [input 1]) + (w2 * [input 2]) + … + (w*n* * [input *n*])} / 100
for *n* input layers, where
-- w is the weight assigned to each input layer, and
-- [input #] is the input layer (in raster format)
NOTE: all w values must add up to 100.

As an example, say we have 4 input layers that we want to weight 60%, 10%, 20% and 10%, respectively. The equation would be:
Resistance = {(60 * [input 1]) + (10 * [input 2]) + (20 * [input 3]) + (10 * [input 4])} / 100

Remember that your resistance surface needs to cover the entire buffered study area. However, it will not necessarily cover the entirety of that area; if you know there are portions of your study area where the movement you're modeling between patches is impossible, you can assign these areas a NODATA value, and they will appear as voids and be excluded from the connectivity analysis.

In the Chestermere wetland demonstration (see Appendix B), Chestermere Lake was represented as NODATA in the resistance layer. Chestermere Lake is a reservoir, and even though it does serve an ecological function, it is not part of the natural hydrology of the area, and being a large wet area in the middle of Chestermere, we were concerned that including it would skew model results and muffle the importance of connectivity between natural wetlands. In the future Chestermere may wish to re-run connectivity with the Lake included in the resistance surface, and conduct a sensitivity analysis to see how this changes model results.

Step 3: Button-Pushing – Running the Model

Now that you have assembled all of the required inputs, you're ready to run your connectivity model. Almost.
There are two more preliminary steps to cover before you actually run the model. One of them is obvious, and the other less so.

1. **Download and Install Circuitscape:** The modeling platform recommended for the standardized CRP Connectivity Process is Circuitscape (circuitscape.org). As mentioned above, there are dozens of options for connectivity modeling applications, but Circuitscape is currently among the most popular and most widely used. An excellent summary of other modeling approaches and applications is presented in Ament et al 2014 (pp.20-21). For many of the other options you may choose, the information in

this guide will still apply; the directions found in this step, however, relate specifically to the use of Circuitscape.

Download Circuitscape directly from the web site, and follow the installation instructions found in the User's Guide (McRae et al, 2013). You may also find it helpful to review the cautionary notes about computational intensity of connectivity models, and technical considerations for computers on which you'll be running these models.

Note that there are two available instances of Circuitscape: one which runs in ESRI ArcGIS; and one which runs as a stand-alone application. All instruction in this guide refers to the stand-alone version.

2. **Prepare your data for use in the model:** It is recommended to run Circuitscape in Raster Mode, and the only accepted raster format is ASCII (either .asc or.txt file extensions are accepted). Most GIS software allows you to convert from whatever format your data is in (including vector polygons files, in which your resource patch data may have been created) to ASCII format.

   For Resource Patch Data: Each patch (or group of patches, if you would like them to be treated as a single node in the connectivity network) must have a unique identifier assigned to it. This ID field will be the value assigned to your "focal node raster" that you create for use in Circuitscape. Any place outside of a resource patch must be assigned a value of "NODATA" (most raster converters will do this automatically). **NOTE:** Regardless of the actual spatial extent of your resource patches, you must ensure that the extent of the focal node raster is identical to that of the resistance surface (and buffered study area) - otherwise Circuitscape will return an error.

   For Resistance Surface Data: The raster resolution, geographic coordinate system, and spatial extent must match precisely with the focal node raster, or Circuitscape will not run. Remember to "mask out" (assign NODATA values) to any areas for which you do not want to model connectivity (e.g. if modeling connectivity for a prairie species and your study area contains other natural subregions, you may want to include only prairie portions of the landscape in your resistance surface). Note that in order for connectivity to be accurately assessed, there needs to be at least one possible path

For the region-wide deer connectivity model (see Appendix A), the desired perceptual scale was 50 m pixels. However, attempts to run the model with 500+ focal nodes and input rasters of this resolution caused the program and computer to crash. The compromise was to use 500 m pixels in the input rasters. This compromised the perceptual grain of the model slightly, but was within the computational capacity of

between each focal node and all other focal nodes - that is, your resistance surface must not contain isolated “islands”, surrounded on all sides by NODATA pixels. Also note that your focal nodes cannot overlap with any NODATA (or any resistance value = 0) pixels.
The raster resolution that you choose when exporting your resource patches and resistance surface is not arbitrary. It is dependent on two things (in order of importance): the “perceptual scale” (Wade et al 2015, p.12) of the species or process being modeled; and the processing power of the computer being used to run the model (higher resolution rasters dramatically increase processing time, and there is a limit to the resolution of input data that most computers can accommodate).

If you are running Circuitscape in Advanced Mode, you may need to generate other inputs. Please consult the Circuitscape User’s Guide (McRae et al, 2013) for guidance on creating these inputs.

3.

Once you’ve completed these two preliminary steps, you’re finally ready to run Circuitscape!
First, open Circuitscape. The user interface looks like this (Figure 1):

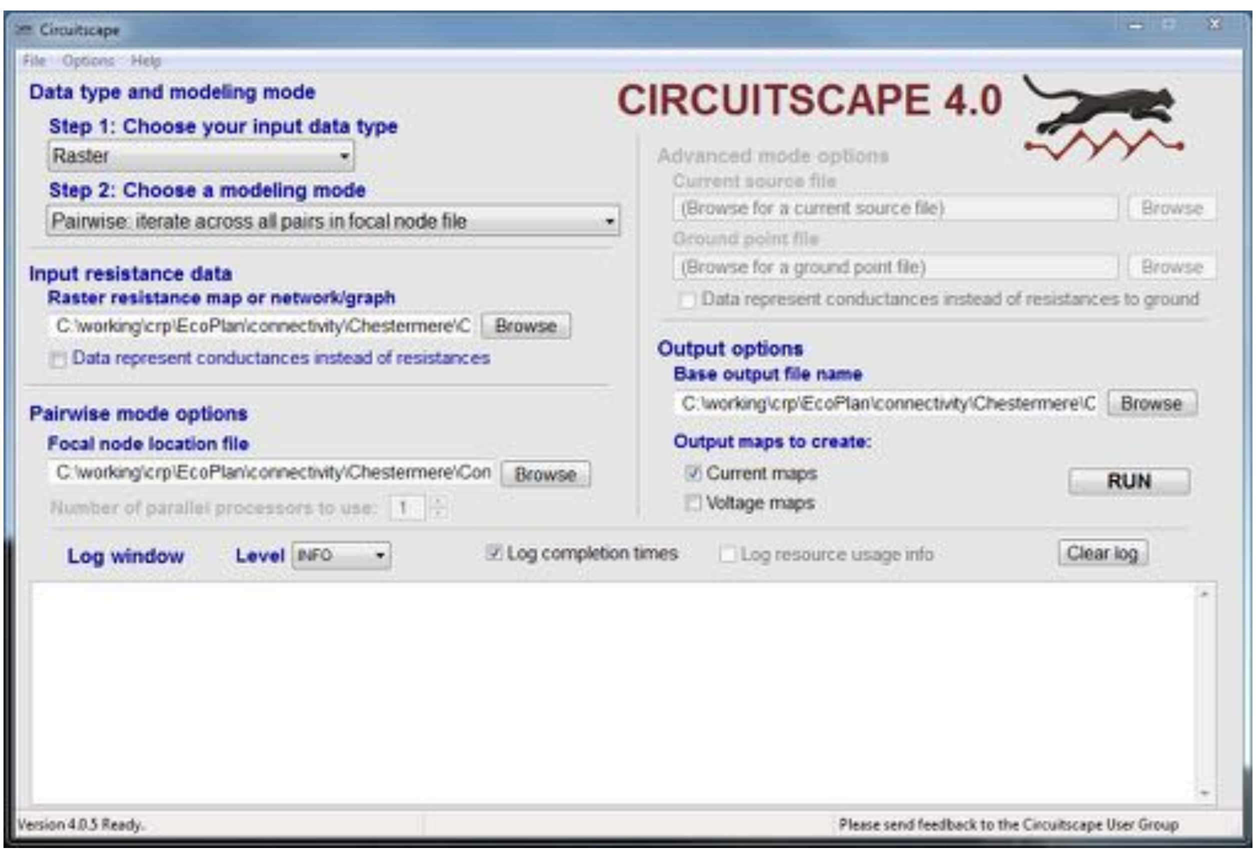


Figure 1 - Circuitscape Stand-alone Interface

The majority of inputs you will enter before running the model are found in this window. The Circuitscape User Guide (McRae et al, 2013) offers a detailed description of all the program's functionality, but here we'll stick to the most commonly used functions.

1. Set the Input Data Type to "Raster." This indicates that your input layers you just created are in raster format.
2. Choose a modeling mode. In the vast majority of cases this will be "Pairwise," although as you become more familiar with connectivity modeling, you may wish to use some of the added functionality that Advanced Mode allows. The other two modes are rarely used. Note that, unless you choose to run Advanced Mode, all advanced mode options on this and the "Options" window (see Figure 2, below) will be greyed and inaccessible.
3. Enter your resistance surface by browsing to the ASCII file you created in the preliminary steps above, using the "Browse" button to the right of the "Raster resistance map or network/graph" text box. Make sure that the checkbox below is UNCHECKED, or the resistance values will be inverted.
4. Similarly, enter the resource patch ASCII file into the "Focal node location file" text box.
5. In the "Output options" pane of the window, choose a location for your output files and give them a base name. It's a good idea to create a new folder for each model run, and to choose a base name that will help identify this run and distinguish it from others (e.g. "wetland_connectivity_predevelopment"). All files you create in this run of the model will receive the same base name. Unless you have a good reason for wanting voltage maps, make sure that only the "Current Maps" checkbox is checked (mapping voltage is seldom required for understanding connectivity, and it drastically increases model run times).
6. Click on "Options" in the top left corner to open the Options window (Figure 2): Just as on the main interface window, only those options available for the mode you've selected will be accessible.

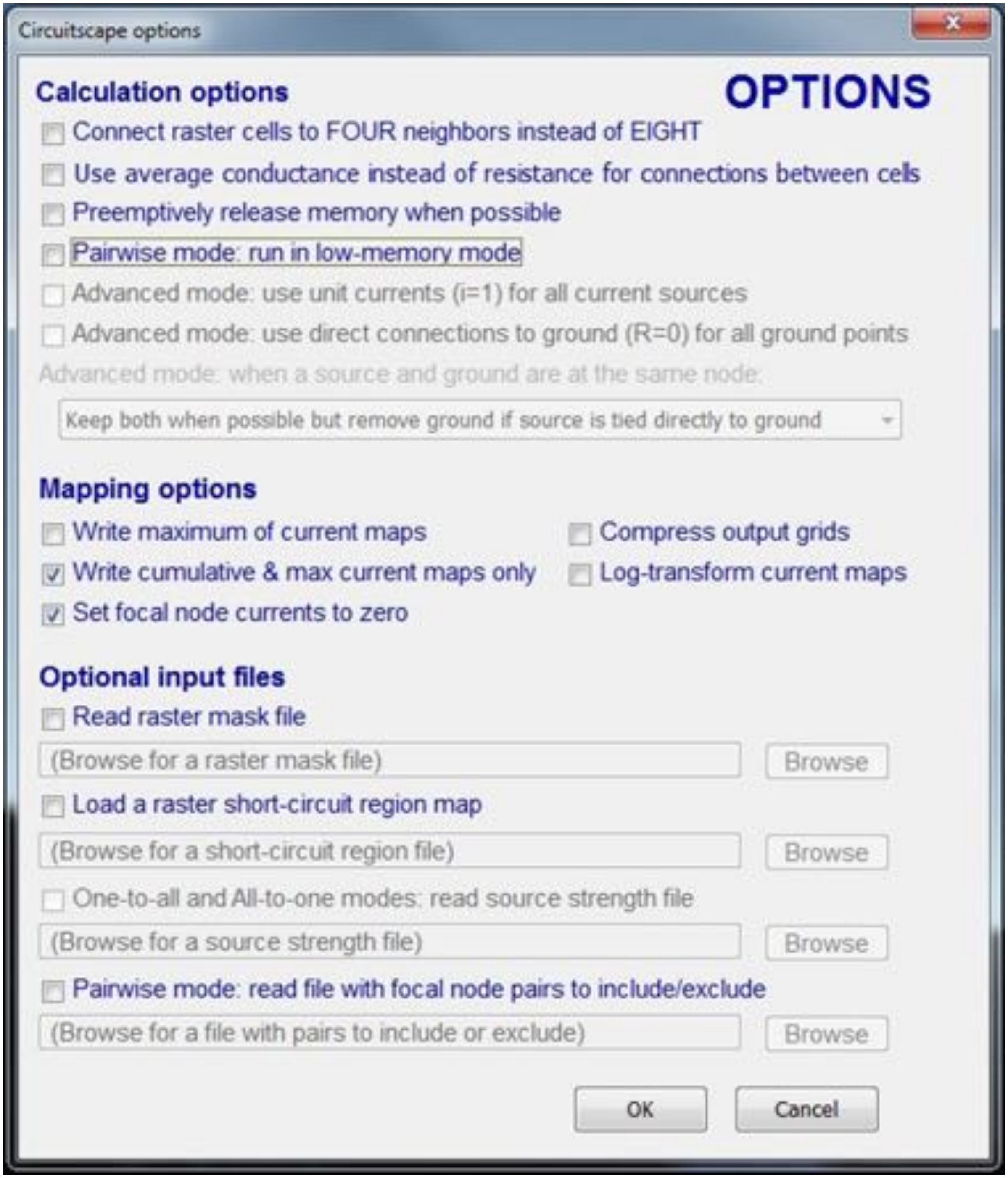


Figure 2 – Circuitscape Options Dialogue

You can read up on any of the options in the Circuitscape User's Guide (McRae et al, 2013), but the most commonly used options are discussed here:
Calculation options:

- The "Connect raster cells to FOUR neighbours instead of EIGHT" box should be UNCHECKED.

Mapping options:

- In most cases, you will want to CHECK the “Write cumulative & max current maps only” box - unless you are interested in the individual pairwise connections between specific resource patches. The volume of output data your model run produces will be drastically increased by unchecking this box.
- CHECK the “Set focal node currents to zero” box - this allows current to pass freely through focal nodes when connecting other pairs of nodes.
- You may choose to check the “Log-transform current maps” box, especially if your connectivity grid contains narrow high-connectivity areas (resulting in very high cumulative currency values), as well as wider more diffuse connectivity areas (lower cumulative currency areas, spread across a wider contiguous area), and you are interested in both. Log-transforming your cumulative current map will reduce the difference between values in these two types of connectivity “zones”; but it will also reduce the range of values across the whole map, which might not be ideal. In most cases, it’s best to leave this box UNCHECKED. You can always log-transform your output raster afterwards if you examine the data and feel it’s important to do so.

When you’re finished, review the options you’ve selected and deselected, and click “OK” to return to the main interface.

7. You’re almost ready to start the model running, but before you do, it’s important to prepare your machine for a potentially computationally expensive process:
    a. If possible, close all other programs. You may wish to leave a program open that monitors your computer’s processor and memory use, so you can track how hard it’s working (and assess whether or not it can afford for you to continue working on other things while the model runs).
    b. Check your computer’s display and power settings and make sure that it won’t power itself off 19 hours into a 20-hour model run. Once you start a Circuitscape model run there is no way to pause or resume it!

    c. Similarly, if your computer is set to install system updates automatically, disable this function. Updates often require a system reboot, which would abort your model run.
    d. As a precaution, you may wish to save your model settings - go to "File > Save Settings" - before running the model. If something happens, this will at least allow you to restart the model without having to enter in all your model parameters again.
8. Review your model settings (and options) one last time, then hit the "**RUN**" button!

If you run into any errors, problems, unexpected results, or other issues, a valuable resource for discussing them is the Circuitscape Forum Google Group. Here you can post questions and get answers from experienced Circuitscape users; you can also search the forum to see if someone else has already encountered a similar problem and found resolution through the group.

Step 4: Post-Production – Refining Model Outputs

When your model finishes running, you can locate the output files in the folder you specified in the "Base output file name" text box. The contents of the folder will depend on the options you selected before running the model, but the two most important output files will be:

- Your cumulative current map, which is the map of connectivity across your study area, and the base input from which you will build all spatial data layers described below. The file will end in "_cum_curmap.asc".
- The log file, which tells you about the results of your modeling and confirms that everything worked. The file will end in ".log" (there may be a second .log file ending in "_rusages.log" - this shows computer processing times, if you have chosen to log them) and can be viewed in any text editor.

In this step of the process, your main objective is to prepare the data for the manipulation, analysis, and mapping that you'll do in the next step. Three critical tasks must be fulfilled:

1. **Quality Control:** Inspect your log file and make sure that there are no reported errors, and that the modeling process ran its full course. Next, open the cumulative current map raster in a GIS, and give it a once-over. Does it look like you thought it would? Does Circuitscape appear to have done what you asked it to? At this point you're not digging deep into the model results,

you're just scanning the output to assess whether or not it makes intuitive sense.

2. **Clip to Study Area:** Recall that in preparing to run your connectivity model, you buffered the study area by a set width; this was done to minimize the "edge effect" inherent in connectivity modeling. The connectivity information contained within the buffer is not usable, and should be removed before presenting your results. Clip the cumulative current map back to the original study area using whatever method you're comfortable with.
3. **Documentation:** Once you have a model output that has produced useful information, it is absolutely critical that you document the steps you followed to produce it. This is important so that anyone using this data will understand how it was made, and also so that you or anyone else will have a blueprint to work from if they want to replicate this process, alter it slightly to see how results change, or apply the same technique to different inputs. Your documentation should be specific enough for someone to replicate the process you followed, solely from the information you provide. Your document should contain a description of the process through all steps, and should include a list of inputs, assumptions, intended uses, limitations, outputs, and anticipated (or suggested) future improvements. This documentation should be available as a separate file, and also as a metadata file attached to any spatial data that is produced from your work. NOTE: If you have contracted someone to model connectivity for you, it is every bit as essential that you receive thorough documentation as it is that you receive a spatial data layer or map.

Step 5: "So What?" – Model Results and How to Use Them

At the beginning of this process, your project team articulated a vision for this connectivity modeling work, which has guided your efforts throughout all subsequent steps. Now that you've modeled connectivity for your study area, what can you use this new understanding of your landscape for? How can the decision-makers involved or interested in your work use this information to better inform the conservation and land use planning discussions that need to consider connectivity? And how can you present and illustrate the results of all of your hard work in the most effective and impactful way possible?

This technical guide will be accompanied by a less technical (or *differently* technical) guide, designed for people who will use the results of this modeling in their municipal or regional planning and decision-making. So as keep focus on the objectives of this guide, this chapter will focus on advice for modelers on producing meaningful and understandable results from your connectivity models and data.

Once your modeling is completed and you've had the opportunity to review your outputs, it will be useful to compile a brief summary of your work. This should be one or two pages, and should briefly describe the connectivity question you set out to address, your study area, a description of your resource patches and resistance surface (including inputs), your model results (including a connectivity map), and some general interpretation of these results that is pertinent to the original question. Think of this as an executive summary of your connectivity project; it should provide enough detail that technical people will be able to determine their interest in digging deeper, but be general and narrative enough to pique the interest and increase the understanding of less technically inclined readers. You can create this report by trimming down and repurposing the information you've provided in your data documentation (see above).

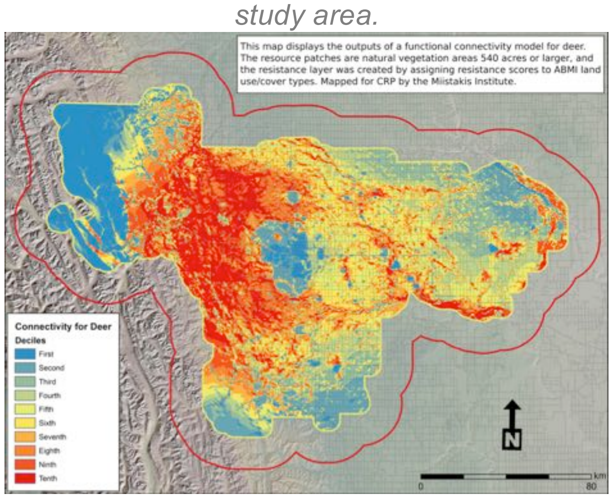
The descriptions of demonstration models in Appendix A and B are too long and too technical to serve as a brief summary like the one described above. Those appendices contain enough information to replicate the work, but are a little less detailed than the kind of documentation you would require from step 4 (see above). Your executive summary should be much

You should also plan to meet with the stakeholders, project partners, and end users of your connectivity maps that you identified in step 1. This will give you a chance to present the results of your work, share some preliminary impressions, and initiate the discussion that will arise from everyone having a new perspective on their surrounding landscape. It also provides a chance to check back in with stakeholders and ensure that you've delivered on what they were expecting to come out of this work.

What's the best way to map connectivity model outputs? This will depend largely on your initial research question, but here are some commonly employed options:

1. **Map the continuous connectivity surface:** This involves mapping the entire connectivity surface (clipped to your study area) in a way that shows the differences between high-current (high connectivity) regions, and regions with moderate, low, or no connectivity. You will want to display connectivity as some form of "heat map", where graduated colours intuitively represent different levels of current/movement across the landscape (e.g. graduated from blue for "cool" or low-connectivity values, to red for "hot" or high-connectivity values).
   The advantage of presenting data in this fashion is that it allows the reader to understand the full representation of connectivity across the entire landscape: from narrow, focused regions of movement to broader, more diffuse regions, and everything in between. If one is presented with only the areas of highest cumulative current/connectivity, one can be misled that these are the only portions of the landscape that are important in connecting the landscape. Presenting connectivity as a complete and continuous surface, while not delineating clear "zones" on the landscape, does offer a more comprehensive perspective on connectivity.

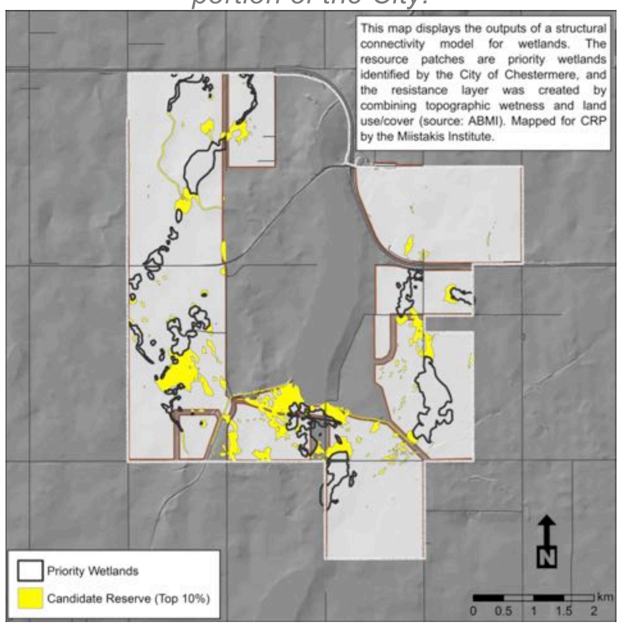
The map below - from the region-wide deer connectivity model (see Appendix A) - displays cumulative current as a "heat map" across the entire study area.



Data is displayed in deciles, so that each colour represents 10% of the study area. "Hottest" colours

2. **Map discrete "zones" of connectivity:** As valuable as it is to have a broader perspective on connectivity across the landscape, the realities of municipal and regional decision-making often dictate a need for clear lines to be drawn on a map. For such instances, it may be useful to extract and delineate the highest connectivity regions within your study area.
   You can achieve this by analysing the histogram of your cumulative current raster values, setting an appropriate threshold, and reclassifying your data

This map, from the Chestermere demonstration (see Appendix B), shows the highest 10% of all connectivity values within the planned future growth portion of the City.



The yellow areas represent the top 10% connectivity areas, and are mapped as "Candidate Reserve." However, it may be more useful to Council to show the top 3 deciles (highest, and next two highest-valued 10% of pixels) as graduated regions, to better depict connectivity between wetlands, and leave

accordingly. Where you set thresholds and how you choose to map out connectivity on the landscape will depend largely on the decisions your organization is making that are informed by connectivity. You may wish to identify "areas of high connectivity" in a binary fashion - that is, pick a single threshold, above which values are "in" and below which they are "out." Alternatively, you may wish to classify your image into connectivity classes - "high/moderate/low", "high/higher/highest", and so on.

Ideally, you should present discrete maps of connectivity as a complement to the continuous connectivity maps described above. This will give decision-makers what they need in terms of a clearly-drawn line, without losing the valuable perspective that you can only get from a continuous map of connectivity.

3. **Change detection and other overlays:** If there is a temporal component to your connectivity research question - for example, understanding how connectivity will change within your jurisdiction as a result of planned or historic growth - you may wish to overlay connectivity grids from "before" and "after" landscapes, to get a sense of what has changed.
   You can create a change detection overlay map by either of these two methods:
   a. Arithmetic overlay of cumulative current rasters: You can detect change by running your connectivity model for "before" and "after" scenarios (make sure you don't change the model settings in Circuitscape between runs), and then subtracting one raster from the other to identify areas of change. NOTE: It is unlikely that your two model runs will result in identical ranges of cumulative current values, so it will be essential to standardize the two outputs to a common range of values before overlaying the raster layers.
   b. Comparison of discrete "connectivity zone" layers: Alternatively, you can compare connectivity model run outputs by first classifying your raster layer, then analyzing the "before" and "after" discrete connectivity maps for areas of overlap, agreement, and discordance.

      You can also employ similar overlay methods if you want to compare or overlay connectivity outputs from different model runs. No single model run can represent all connectivity that matters across an entire landscape. You may have several different connectivity model outputs for your area of interest, all of which were developed in response to different research questions. And it may be a valuable exercise to compare these results, and determine where the highest connectivity areas are for a broad range of ecological phenomena.

Closing Thoughts

A few key points are worth reiterating:

- There are an infinite variety of ways to define, measure, and map connectivity, and countless different approaches and software platforms that you can use for your connectivity project. Not one of them is the universally right approach, and none will guarantee the ideal answer to every question, every time.

- A great deal of thought is required at the outset of a connectivity research project, to ensure that objectives are clear, methods are transparent and appropriate to the goals, and expectations are aligned across interested parties.

- Connectivity modeling is a time- and labour-intensive process. Before initiating a project you should make sure you have the required capacity to see the project through.

- Whether you are doing the work yourself or contracting someone to do it for you, it is absolutely essential that you have detailed documentation of the process followed. This information is as important as the model results themselves.

- There are lots of different ways to present connectivity model results. For any given project, the "right way" depends on the bigger discussion that improved knowledge of connectivity is informing, and the target audience you're trying to reach.

This guide should not be considered the *de facto*, once-and-for-all authority on how to model connectivity. There are other more in-depth resources available for those who need more detail, and the modeling and mapping process this guide recommends may not fit all of the needs of the CRP and its partners. Moreover, connectivity modeling is an evolving practice, and the tools and approaches suggested here will eventually be replaced by new methods, approaches and programs.

Hopefully this guide has suggested a framework on which to base modeling efforts throughout the CRP for the coming years. And, perhaps it can serve as a foundation on which to build a growing and supportive community of practice, and as a forum for sharing ideas, best practices, and results.

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Wade, Alisa A.; McKelvey, Kevin S.; Schwartz, Michael K. 2015. Resistance-surface-based wildlife conservation connectivity modeling: Summary of efforts in the United States and guide for practitioners. Gen. Tech. Rep. RMRS-GTR-333. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Spatial Data Resources

Alberta Biodiversity Monitoring Institute:

Human Footprint Inventory: http://www.abmi.ca/home/data/gis-data/human-footprint-download.html

Land Cover:
http://www.abmi.ca/home/data/gis-data/land-cover-inventory.html

Species Data (distribution, habitat, relative abundance, etc.):
http://species.abmi.ca/pages/species.html

Alberta Grasslands Vegetation Inventory (Polygon Sites View):
http://data.alberta.ca/data/grassland-vegetation-inventory-gvi-polygons-sites-view-1

Global Land Cover Facility (University of Maryland):
http://glcf.umd.edu/data/

Internet Resources:

Circuitscape:
http://www.circuitscape.org/

Circuitscape Google Group:
https://groups.google.com/forum/?hl=en#!forum/circuitscape

Conservation Corridor (North Carolina State University):
http://conservationcorridor.org/

GIS for Geomorphology (S.W. Cooley, 2015):
http://gis4geomorphology.com/

Landscope - Connecting Landscapes:
http://www.landscope.org/focus/connectivity/

Appendix A: Connectivity Modeling Demonstration – Region-wide Deer Connectivity

To demonstrate the application of Calgary Region-wide connectivity modeling, a generalized functional connectivity model was created for deer.

Framing the Question – Project Scoping

This connectivity model was developed mostly for purposes of demonstration - that is to say, it hasn't evolved from a specific need that was articulated by the CRP or its members, nor has it engaged a broad range of stakeholders to define a conservation question or project scope.

In choosing to model general functional connectivity for deer, we were striving to meet the following objectives:

- Demonstrate connectivity modeling and mapping at the spatial scale of the "idealized" Calgary Region (see Figure A1).
- Model connectivity for a species, group of species, or process that is ecologically meaningful across the entire study area, and is conceivably useful to conservation and land-use planning discussions at this broader scale.
- Model connectivity for something that might represent broader significance for regional-scale landscape connectivity, beyond the individual species being mapped.

Discussions with an Advisory Group of CRP and partner representatives, and subsequent discussions with local ecologists, biologists, and connectivity modeling experts confirmed that these objectives could be met by modeling functional connectivity for deer species, related to their basic daily needs, would meet the objectives stated above.

Building Blocks – Connectivity Model Inputs

Study Area:

The study area for this project is the greater Calgary Region, comprised of landscape under jurisdiction of current CRP members, the rural municipalities of MD Bighorn, MD Foothills, Rocky View County, and Wheatland Counties, and the

First nations of Tsuu T'ina and Stoney Nakoda. In order to include the towns of Banff and Nanton which are outside of the contiguous region described above, a 5 km buffer was applied. The Study area is presented in Figure 3, along with the 20 km study area buffer, which was used to mitigate against edge effect in the creation of connectivity models.

Resource Patches:

Ideally, we would have preferred ABMI species data on deer habitat (species.abmi.ca) to identify resource/habitat patches for this model. Unfortunately, the predicted relative abundance data does not currently cover the entire study area, leaving out most of the foothills and subalpine natural subregions.

Instead, resource patches were mapped from 2010 ABMI Land Cover data (abmi.ca). Based on the notion that deer will use any contiguous patch of natural vegetative cover to fulfill one or several daily resource requirements, all natural tree, shrub, and grassland cover types were extracted from the ABMI land cover data. Borders between adjacent polygons (e.g. adjacent coniferous forest and shrubland patches) were dissolved, and any contiguous patch of natural cover greater than 540 acres (one section of land) was identified and mapped as a discrete resource patch. In total, this selection process resulted in over 500 individual resource patches.

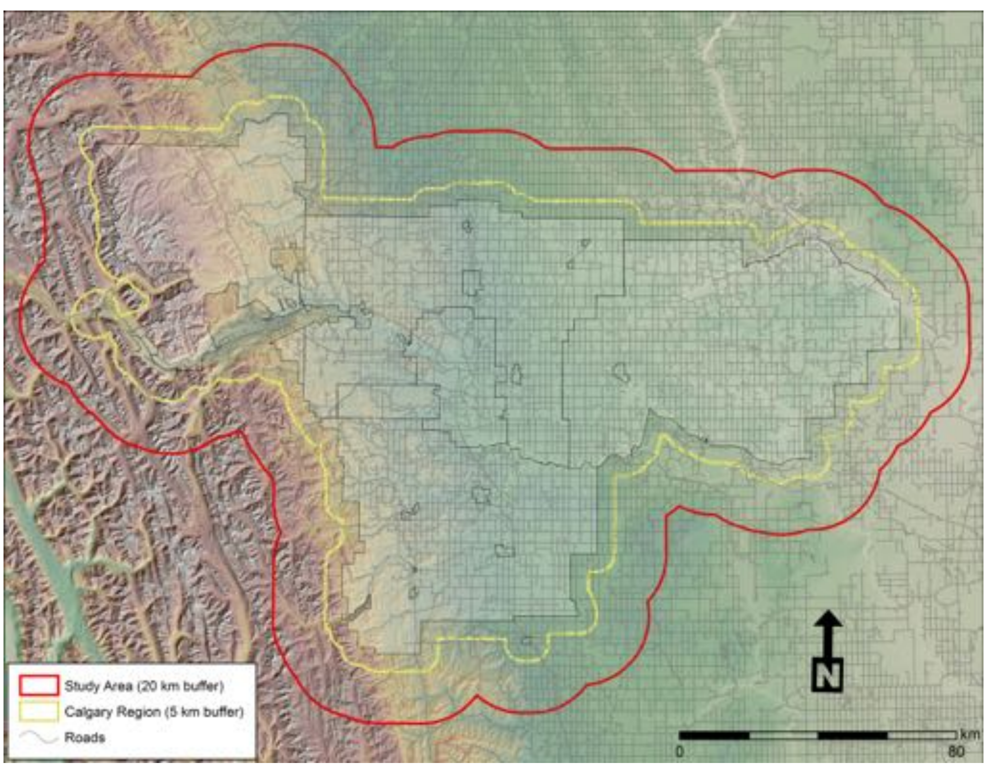


Figure 3 - Deer Connectivity Study Area.

Figure 4 shows all resource patches (focal nodes) within the buffered study area.

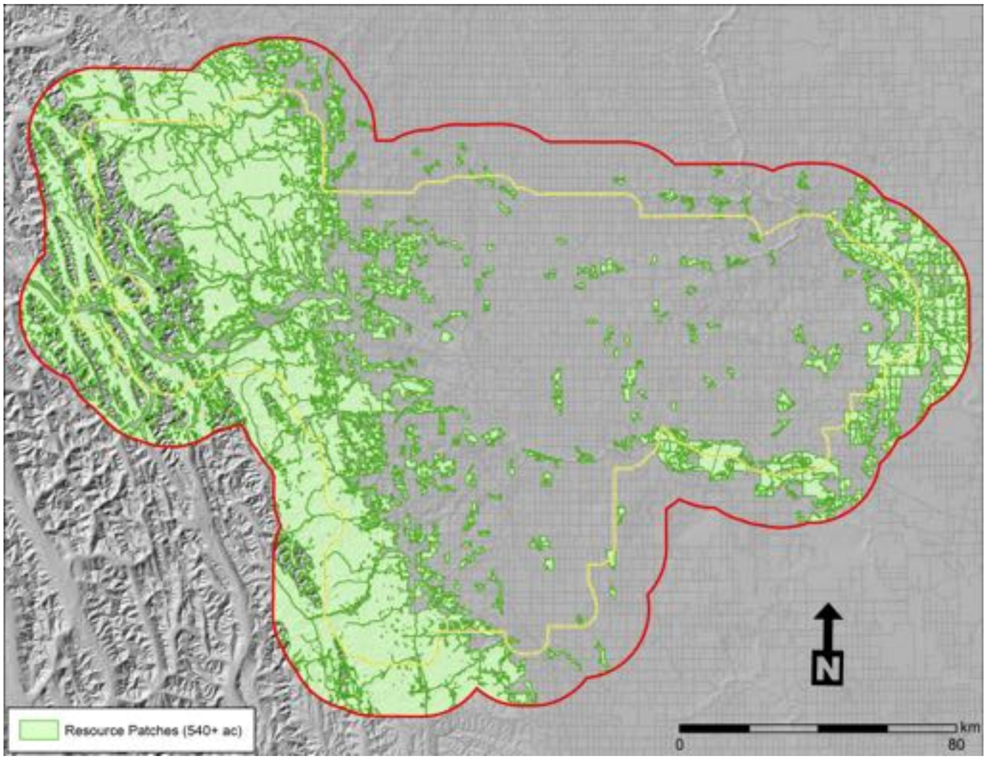


Figure 4 - Resource Patches for Deer Model

Many of the resource patches mapped in this exercise are on private land. Although they serve a valuable ecological function, there is nothing to protect them from future development and their management is largely outside of the authority of provincial, regional, or municipal decision-makers. The choice of these patches as focal nodes for a functional connectivity model makes good sense; however, it would be interesting to compare modeling results using these patches to a model run which uses designated municipal, provincial, and federal protected areas as resource patches. This would provide a structural counterpoint to the functional model, and perhaps provide insight on the land management perspective on maintaining connectivity for deer.

Resistance Surface:

Based on the premise that movement of deer is largely governed by response to elements of the natural and built landscapes, a resistance surface was constructed from ABMI Land Cover (2010) and Human Footprint (2012, v.3) Inventories. The two data sets were merged for all 1:50,000 NTS map sheets that intersect the buffered study area (Land Cover data was used to fill in the voids in the Human Footprint

Inventory, where no built features exist) Resistance scores were then assigned to each land use/cover type, representing the impedance to movement for deer, based on a brief review of deer ecology and some general intuition about response to different footprint types. The following table shows resistance values assigned to each land use/cover type:

CRP Land Use/Cover	ABMI Source	Resistance
Agricultural Land	HF_2012	3
Agriculture	LC_2010	3
Airstrips	HF_2012	11
Broadleaf Forest	LC_2010	1
Coniferous Forest	LC_2010	1
Constructed Depressions	HF_2012	5
Country Residential/Acreages	HF_2012	4
Developed	LC_2010	9
Exposed Land	LC_2010	5
Feedlots	HF_2012	11
Forestry Cut Blocks	HF_2012	4
Four-Lane Paved Road	HF_2012	10
Grassland	LC_2010	1
Heavy Industry	HF_2012	11
High Voltage Transmission Lines	HF_2012	3
Irrigation Canals	HF_2012	8
Landfill Sites	HF_2012	9
Light/Medium Industry	HF_2012	10
Major Thoroughfare Roads	HF_2012	11

CRP Land Use/Cover	ABMI Source	Resistance
Mixedwood Forest	LC_2010	1
Municipal Water Treatment	HF_2012	10
One-lane Gravel Road	HF_2012	6
One-lane Paved Road	HF_2012	8
Open Mines	HF_2012	9
Open Vegetated Sites	HF_2012	3
Pipelines	HF_2012	4
Railway	HF_2012	8
Railway Verge	HF_2012	4
Reservoirs	HF_2012	9
Road - Intersection	HF_2012	9
Roads - Ramps and Interchanges	HF_2012	11
Rock and Rubble	LC_2010	10
Seismic Lines	HF_2012	2
Shrubland	LC_2010	1
Snow and Ice	LC_2010	11
Two-lane Gravel Road	HF_2012	7
Two-Lane Paved Road	HF_2012	9
Unimproved Roads & Trails	HF_2012	2
Urban Settlements	HF_2012	8
Verge - Four-lane Paved Road	HF_2012	7
Verge - Major Thoroughfare	HF_2012	8

CRP Land Use/Cover	ABMI Source	Resistance
Roads		
Verge - One-lane Gravel Road	HF_2012	3
Verge - One-lane Paved Road	HF_2012	5
Verge - Ramps and Interchanges	HF_2012	8
Verge - Road Intersections	HF_2012	7
Verge - Two-lane Gravel Road	HF_2012	4
Verge - Two-lane Paved Road	HF_2012	6
Water	LC_2010	9
Wellpads	HF_2012	9
Wind Turbines	HF_2012	4

Values range from 1 (lowest resistance) to 11 (highest resistance) and are integers. Figure 5 shows the input ABMI land use/cover polygons, with the table of resistance scores joined.

These scores were applied to all Land Use/Cover polygons, and then the file was converted to raster. The original conversion was at a 5m pixel resolution to capture as much detail as possible from the data source.

A perceptual grain - and raster resolution for resistance surface and focal node inputs - of 50 m would have been preferred, but this resolution exceeded available computational capacity. In the end, the model had to be run at a resolution of 500 m pixels; this may understate the perceptual grain of deer moving across the landscape, but it is still ecologically defensible, and it was within the ability of the most powerful computer available.

Figure 6 shows the resistance surface at 500 m pixel resolution.

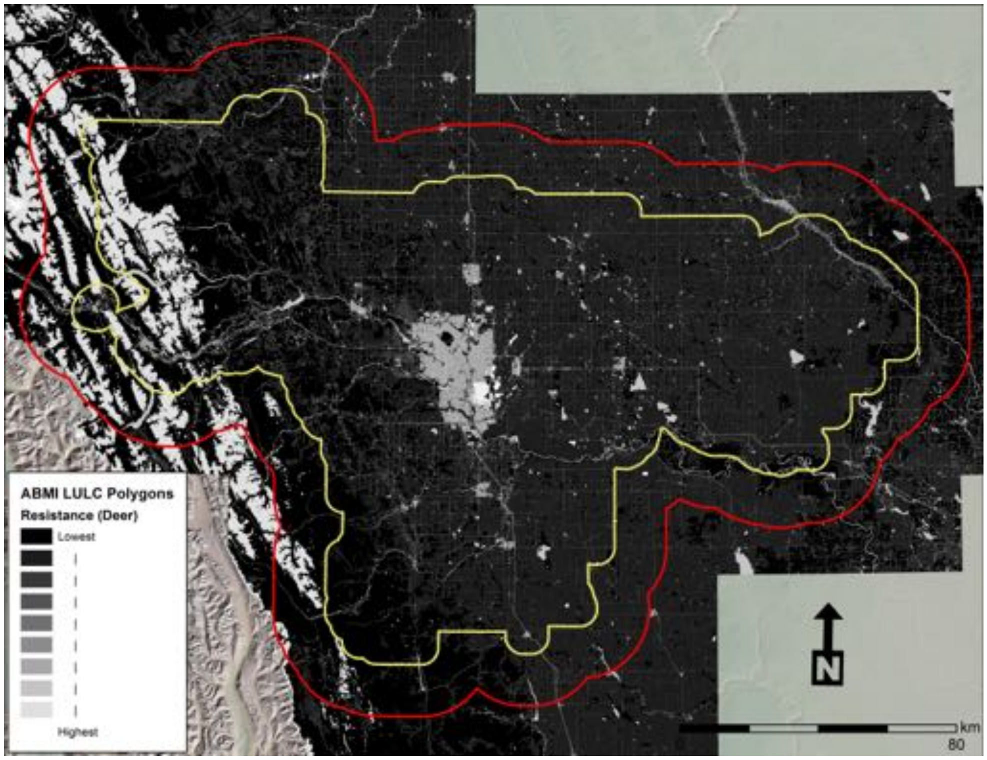


Figure 5 - Resistance-scored Land Use/Cover Polygons

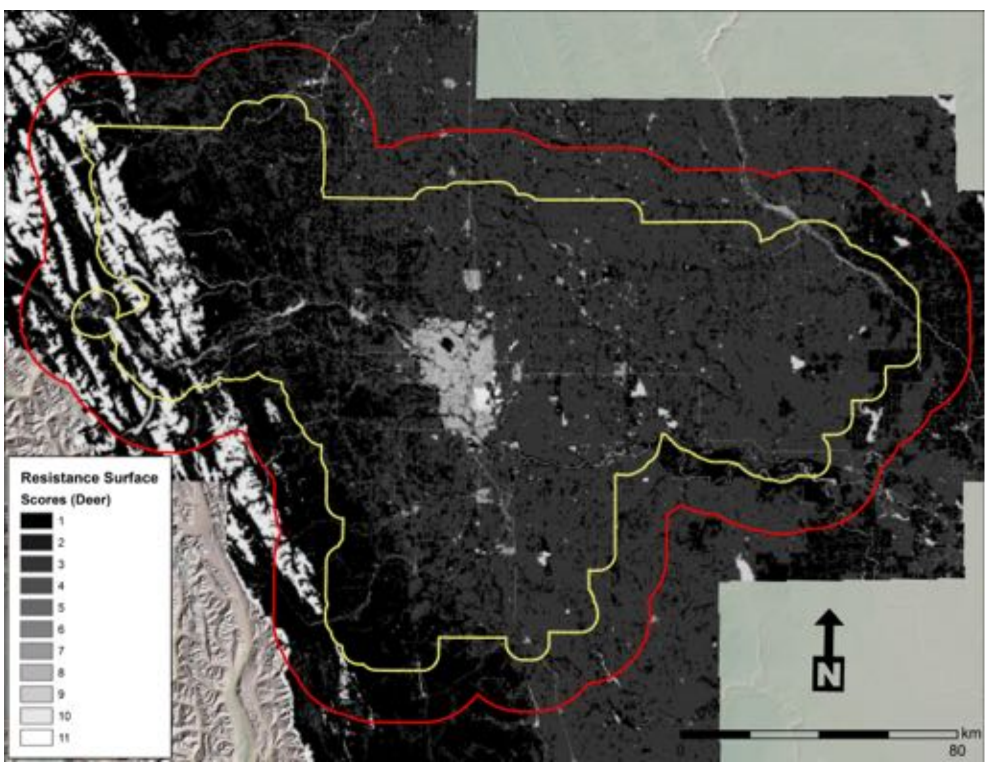


Figure 6 - 500 m Raster Resistance Surface

Button Pushing - Running the Model

Circuitscape was run in pairwise mode, using the 500+ natural vegetation patches as focal nodes and the resistance layer described above (see Figure 6). Using 500m input raster resolutions and a reasonably powerful desktop computer (Dell Precision T3500 Workstation, 3 GHz dual processor, 12 GB RAM), the model took over a week to run (begin Monday night, finish the following Monday night). The raw output connectivity grid is presented in Figure 7. The focal nodes are highlighted in green.

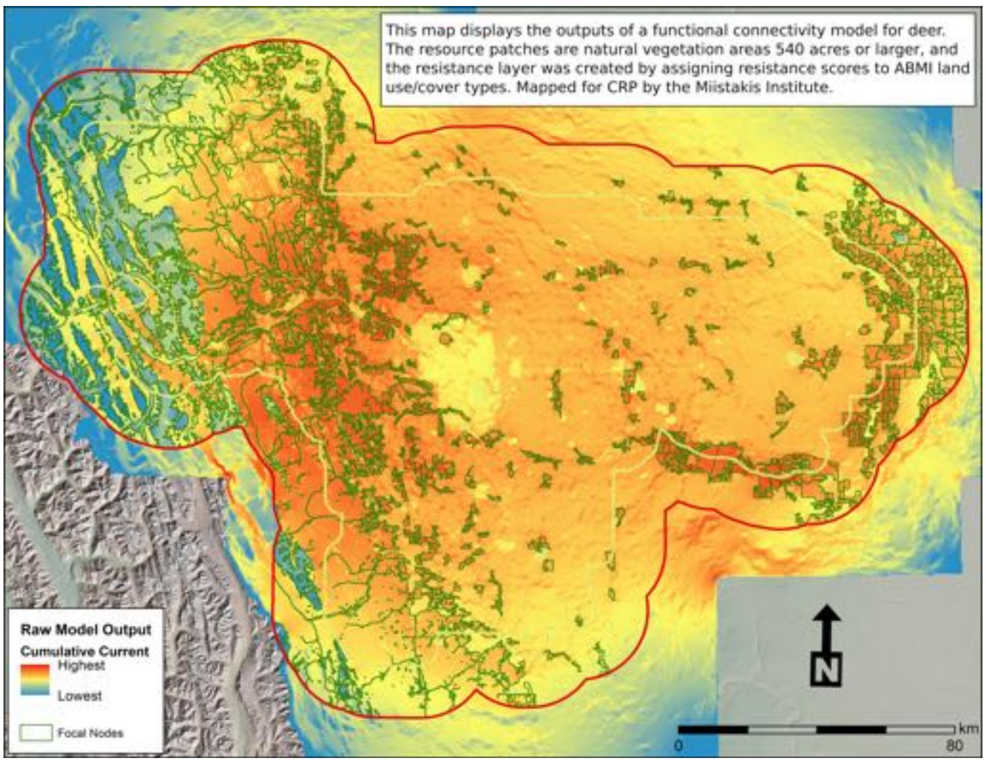


Figure 7 - Deer Connectivity Model - Raw Output

Post-Production – Refining Model Outputs

Figure 8 shows the cumulative current (connectivity) map, clipped to the Calgary Regional study area.

Data are presented in deciles, meaning that exactly 10% of study area pixels are displayed in each colour. This provides the reader with an assessment of which areas, according to the model, are most important for deer connectivity in a regional context. Note that even within and around urban areas, some degree of connectivity is apparent - especially along drainages and through open space and protected areas. Drainages and riparian zones appear to be especially important to connectivity in the more eastern portions of the region.

"So What?" – Model Results and How to Use Them

This was presented as a demonstration, and is a very generalized model, based on a limited amount of expert knowledge and a great deal of ecological intuition or common sense. Before using this information for critical land use decisions, it would be advisable to validate the model against empirical data related to deer habitat, movement, and resource requirements.

However, it does provide a good overview of terrestrial ecological connectivity at a regional scale, and deer connectivity can be taken as a general surrogate for a number of other wildlife species that react similarly to natural and built environments.

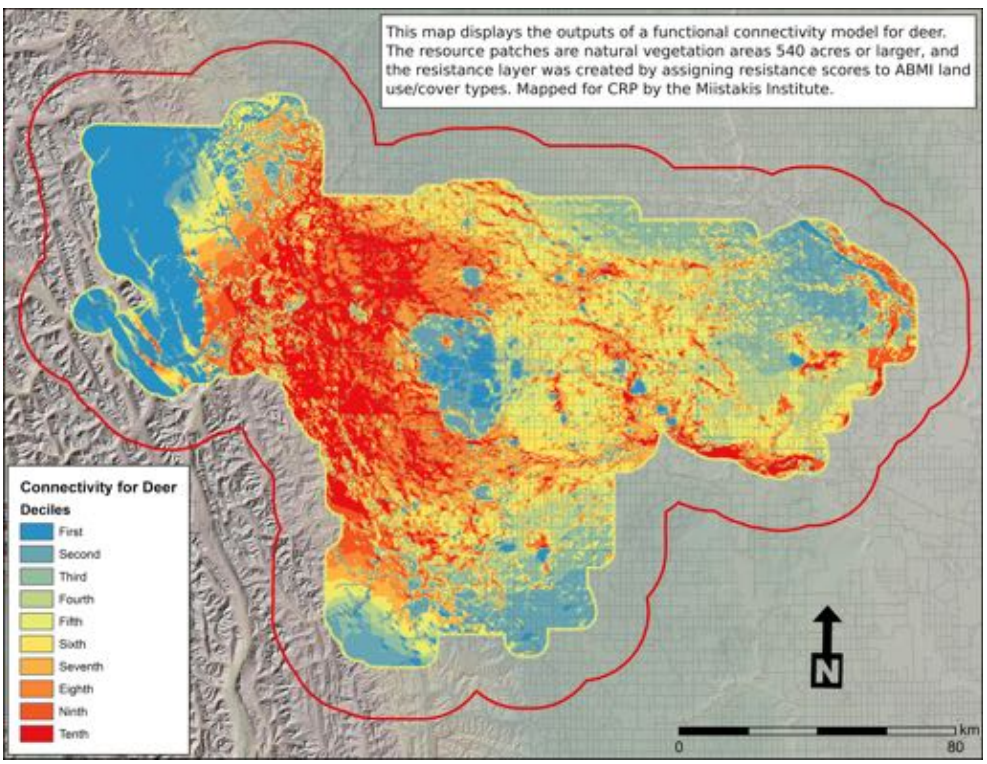


Figure 8 - Clipped Regional Deer Connectivity Model

Some ideas for further exploration from this initial model include:

- Validating this connectivity model against observation data for government, wildlife biologists, citizens, conservation groups, ABMI (species.abmi.ca), etc.
- Comparing connectivity under "current" (most recently mapped - in this case, 2012) conditions to historic conditions, and assessing how and where

connectivity has changed.

- Running the connectivity model using the same study area and resistance surface, but instead of natural vegetation patches, using protected areas as the focal nodes that are being connected. This would allow for a region-wide assessment of the extent to which the landscape supports connections between areas that are designated as parks, ecological reserves, wildlands, etc.
- “Zooming in” to a specific area of interest, and running connectivity at that scale using similar inputs, measured at a higher resolution (e.g. natural vegetation patches 160 acres or greater, and a pixel resolution of 50 metres, for the foothills area just west of Calgary), and examining how connectivity relates to itself, when measured at these different - but equally important - scales.
- Incorporating some measure of landform (terrain ruggedness, viewsheds, etc.) into the resistance surface to see how this affects the model outputs.

Appendix B: Connectivity Modeling Demonstration – Wetland Connectivity for the City of Chestermere

For the second demonstration case, the City of Chestermere presented a real-world example of an instance where improved understanding of connectivity could inform decisions around planning of future growth.

Framing the Question – Project Scoping

Chestermere Council is presently considering zoning changes that will lead to a doubling of its area. There is an acknowledged desire for the City to plan new growth and development in consideration of a healthy and connected ecological landscape, but it lacks the necessary tools that would support meaningful consideration of these factors.

In the absence of any guidance from the City, proponents will commonly structure reserve lands or “open space” in planned developments as a default, after all desired built areas have been identified. What is left over from the built footprint becomes the de facto “green space”.

The goal for this connectivity research was therefore to inform Chestermere Council discussions around planning future growth, in a way which will help them remain mindful of the structural connectivity between high-priority wetlands. Figure 9 shows these wetlands in relation to zones of anticipated future growth.

Building Blocks – Connectivity Model Inputs

Study Area:

The study area for this project is the current boundary of the City of Chestermere. The City is interested in assessing connectivity across its entire jurisdiction, but especially for areas of planned future growth (shown in Figure B1 as yellow polygons). The study area was buffered by 1 km to mitigate against issues related to edge effect. The buffered study area is shown as a red outline in Figure 9.

The wetlands that surround Chestermere are part of the Shepard Slough Wetland complex, which covers portions of surrounding municipalities as well. In the future it may be of interest to consider prioritized wetland protection, and structural connectivity between prioritized patches, at this larger but ecologically important spatial scale.

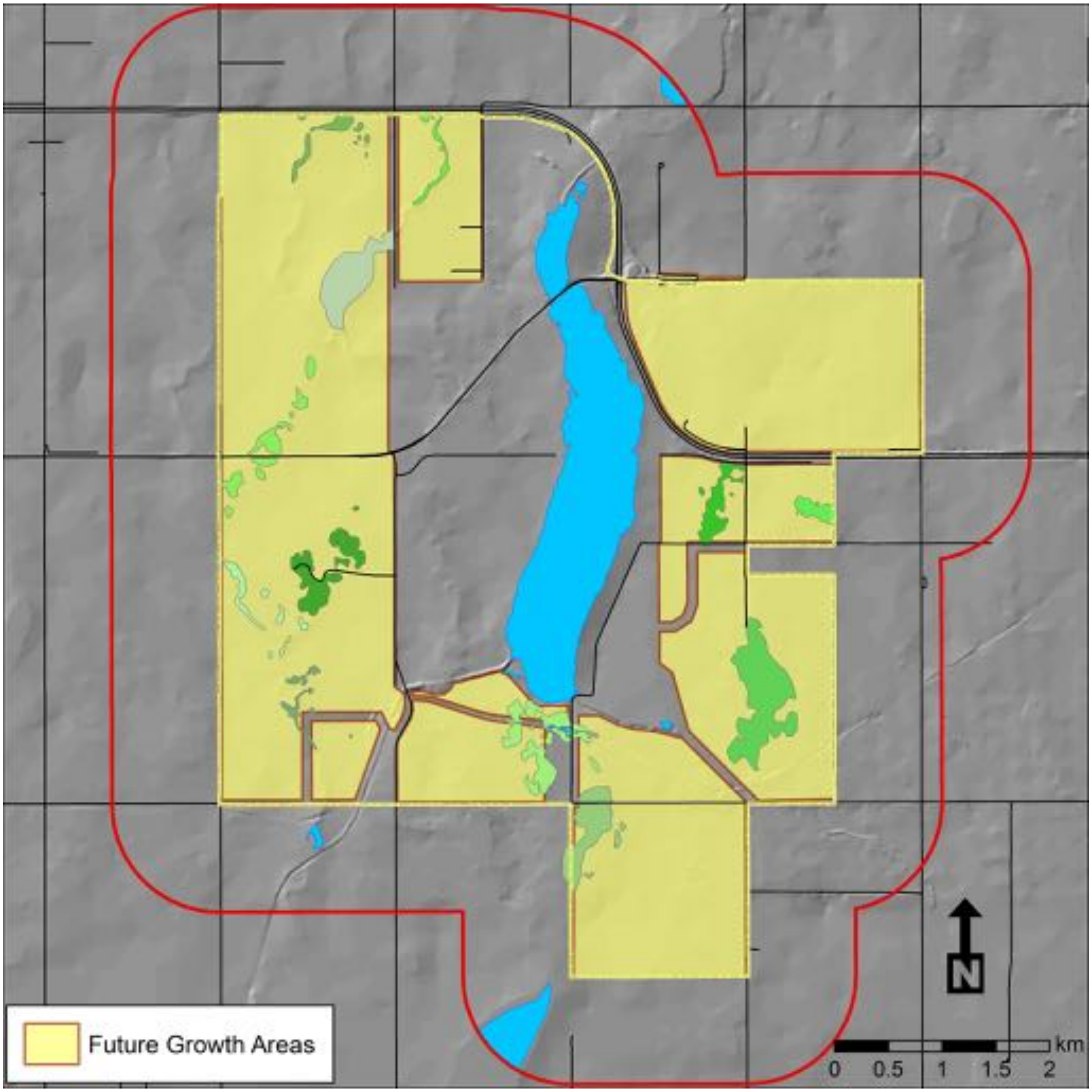


Figure 9 - Chestermere Study Area Map

Resource Patches:

Luckily, resource patches were already identified for this project, thanks to previous work the City of Chestermere had undertaken to map and prioritize wetlands within its boundaries. This work was undertaken by a consultant, and was used by Chestermere to recognize 12 wetland complexes - 9 for general ecological significance, and 3 for their provision of the ecological service of water retention and flood prevention - in their Municipal Bylaws. Figure 10 shows these 12 wetland complexes, which became the resource patches or focal nodes of our connectivity model.

Note that some of the patches are actually collections of several polygons, which together constitute a single wetland complex. As long as they have the same unique ID value, Circuitscape treats these collections of polygons as individual Focal Nodes.

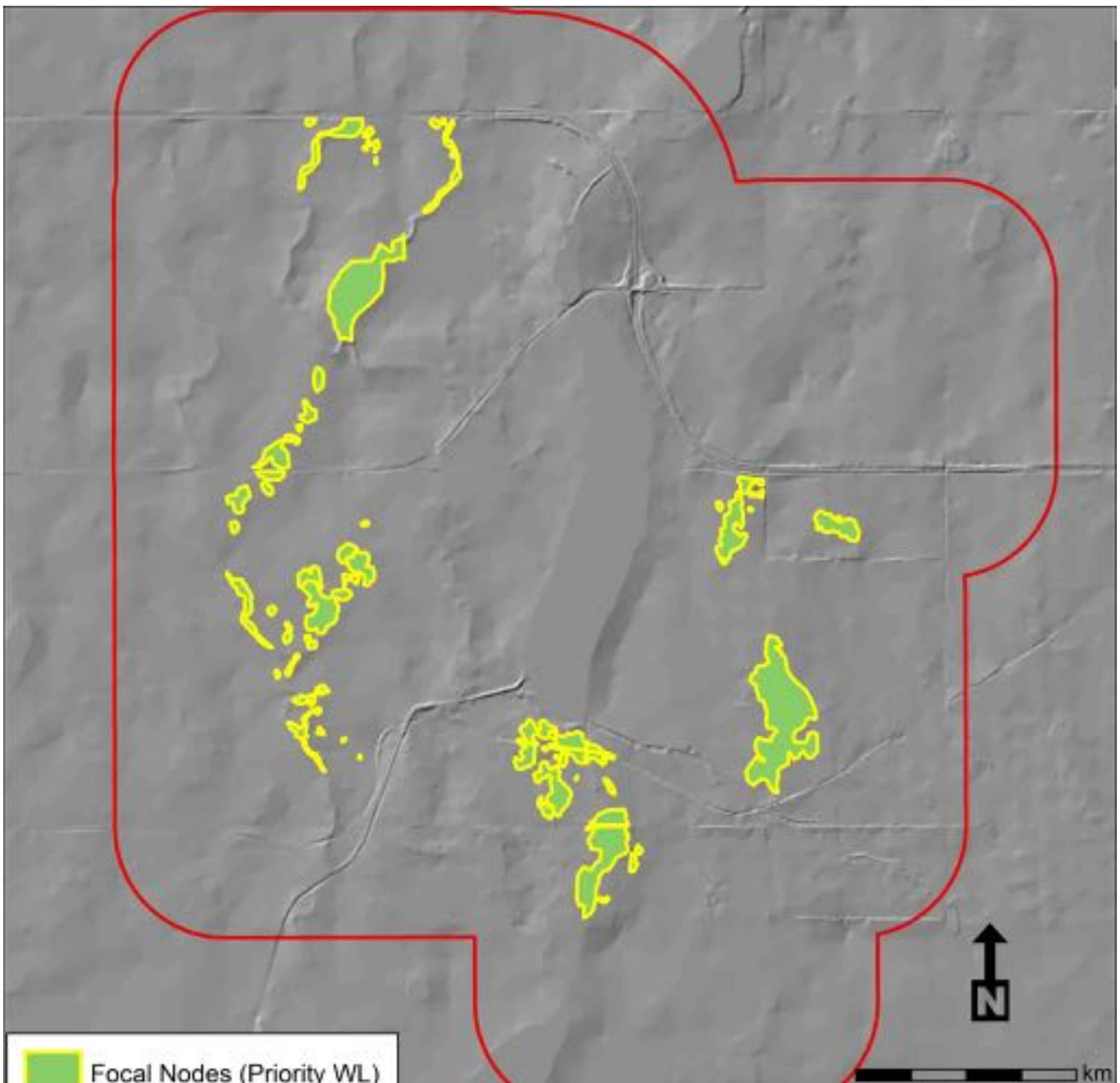
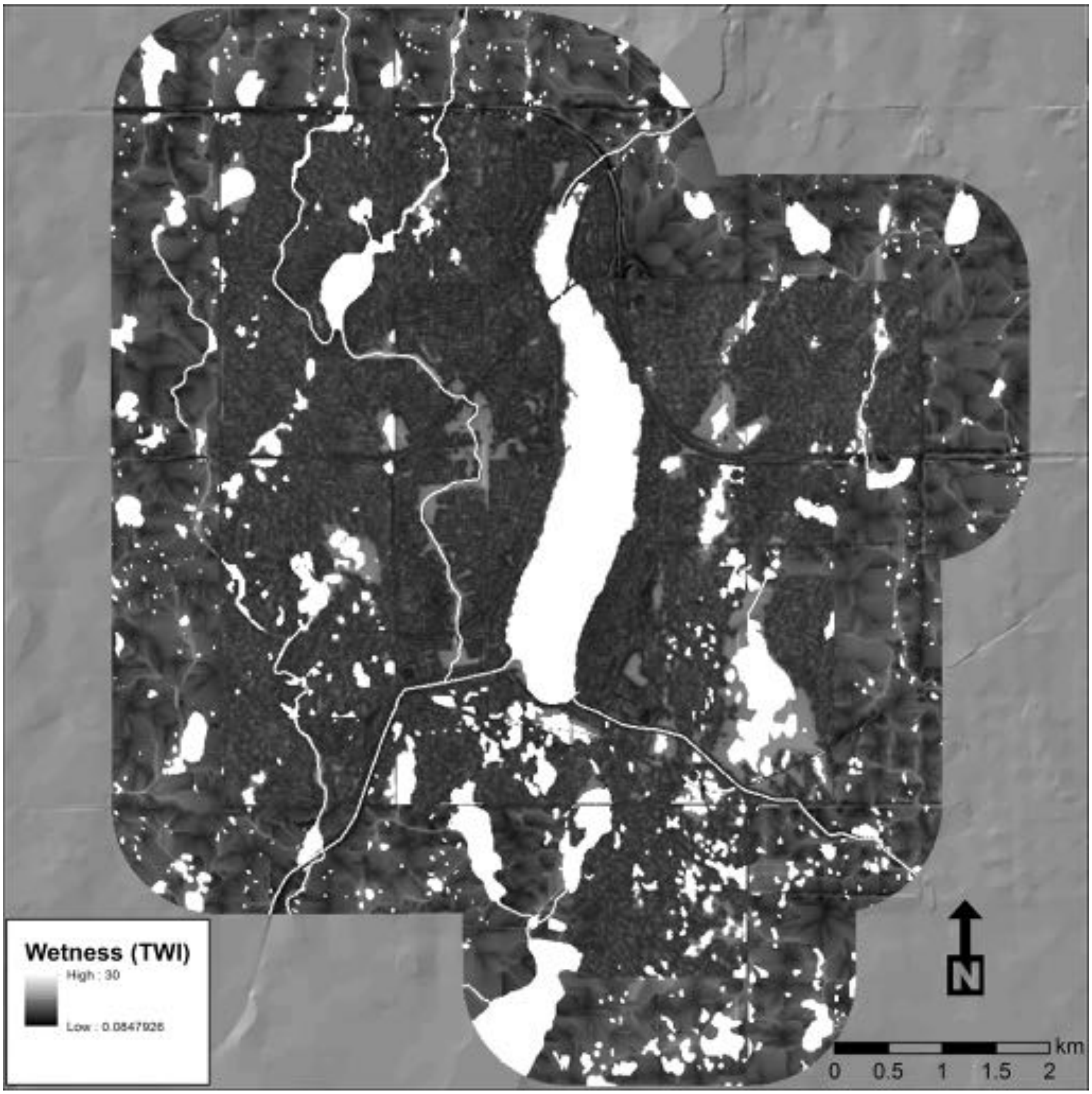


Figure 10 - Resource Patches (Focal Nodes) for Chestermere - Priority Wetlands

Resistance Surface:

From a structural connectivity perspective, two components were deemed important in the creation of a resistance surface: topography and human use.

Topographically, an input layer to the resistance surface was built from digital elevation models (DEMs), based on the assumption that lower-lying areas are conduits for ecological flows across the landscape and between high-priority wetlands. To represent this aspect of resistance, a topographic wetness index (TWI) was calculated. For description of TWI and instructions on how to calculate it, consult the GIS for Geomorphology website (gis4geomorphology.com). A high-



resolution DEM was available for Chestermere, but the 1 km buffer area required use of a slightly lower-resolution DEM; the resolution of the buffer DEM was 10 metres, and this determined the perceptual scale and raster resolution for the resistance surface.

After calculating TWI for the buffered study area, an average filter was applied to the TWI on a 3x3 kernel, which smoothed the wetness values slightly and removed "noise" from the data, especially within the city boundaries where the input DEM resolution is higher. Any area mapped as containing open water was assigned the highest possible wetness value (TWI is a unitless, relative index, and the highest value in this case was 30), since these areas are obviously the wettest regardless of topography. Figure 11 shows the topography-based wetness values across the buffered study area.

The last step in processing this input layer was to convert wetness values to resistance values. In our model higher topographic wetness denotes lower resistance, so the conversion required an inverse linear transformation of raster values (i.e. raster values of 30 became values of 1; raster values of 0 became values of 11, and a linear equation was applied to adjust all values in between).

For human use, a second input resistance raster was created to reflect the different impacts on hydrological connectivity resulting from different land-use and land-cover types. The combined ABMI human footprint and land cover layer described above (see the description of the region-wide deer connectivity model in Appendix A) was clipped to the buffered Chestermere study area. Permeability scores were assigned to each respective land use or land cover type, according to the following table:

CRP Land Use/Cover	ABMI Source	Resistance
Agricultural Land	HF_2012	4
Agriculture	LC_2010	4
Coniferous Forest	LC_2010	3
Constructed Depressions	HF_2012	2
Country Residential/Acreages	HF_2012	7

Figure 11 - Topographic Wetness Input to Resistance Surface

CRP Land Use/Cover	ABMI Source	Resistance
Developed	LC_2010	9
Grassland	LC_2010	3
High Voltage Transmission Lines	HF_2012	6
Irrigation Canals	HF_2012	1
Landfill Sites	HF_2012	11
Light/Medium Industry	HF_2012	11
Major Thoroughfare Roads	HF_2012	11
One-lane Gravel Road	HF_2012	10
One-lane Paved Road	HF_2012	10
Open Vegetated Sites	HF_2012	4
Pipelines	HF_2012	8
Railway	HF_2012	10
Railway Verge	HF_2012	5
Road - Intersection	HF_2012	11
Roads - Ramps and Interchanges	HF_2012	11
Seismic Lines	HF_2012	6
Two-lane Gravel Road	HF_2012	10
Two-Lane Paved Road	HF_2012	10
Unimproved Roads & Trails	HF_2012	9
Urban Settlements	HF_2012	8
Verge - Major Thoroughfare Roads	HF_2012	5
Verge - One-lane Gravel Road	HF_2012	5

CRP Land Use/Cover	ABMI Source	Resistance
Verge - One-lane Paved Road	HF_2012	5
Verge - Ramps and Interchanges	HF_2012	5
Verge - Road Intersections	HF_2012	5
Verge - Two-lane Gravel Road	HF_2012	5
Verge - Two-lane Paved Road	HF_2012	5
Water	LC_2010	1
Wellpads	HF_2012	9

Lastly, permeability scores were converted to resistance values such that land use/cover types with the highest permeability were assigned the lowest resistance values, and vice-versa. A resistance raster layer was generated from resistance scores, as shown in Figure 12.

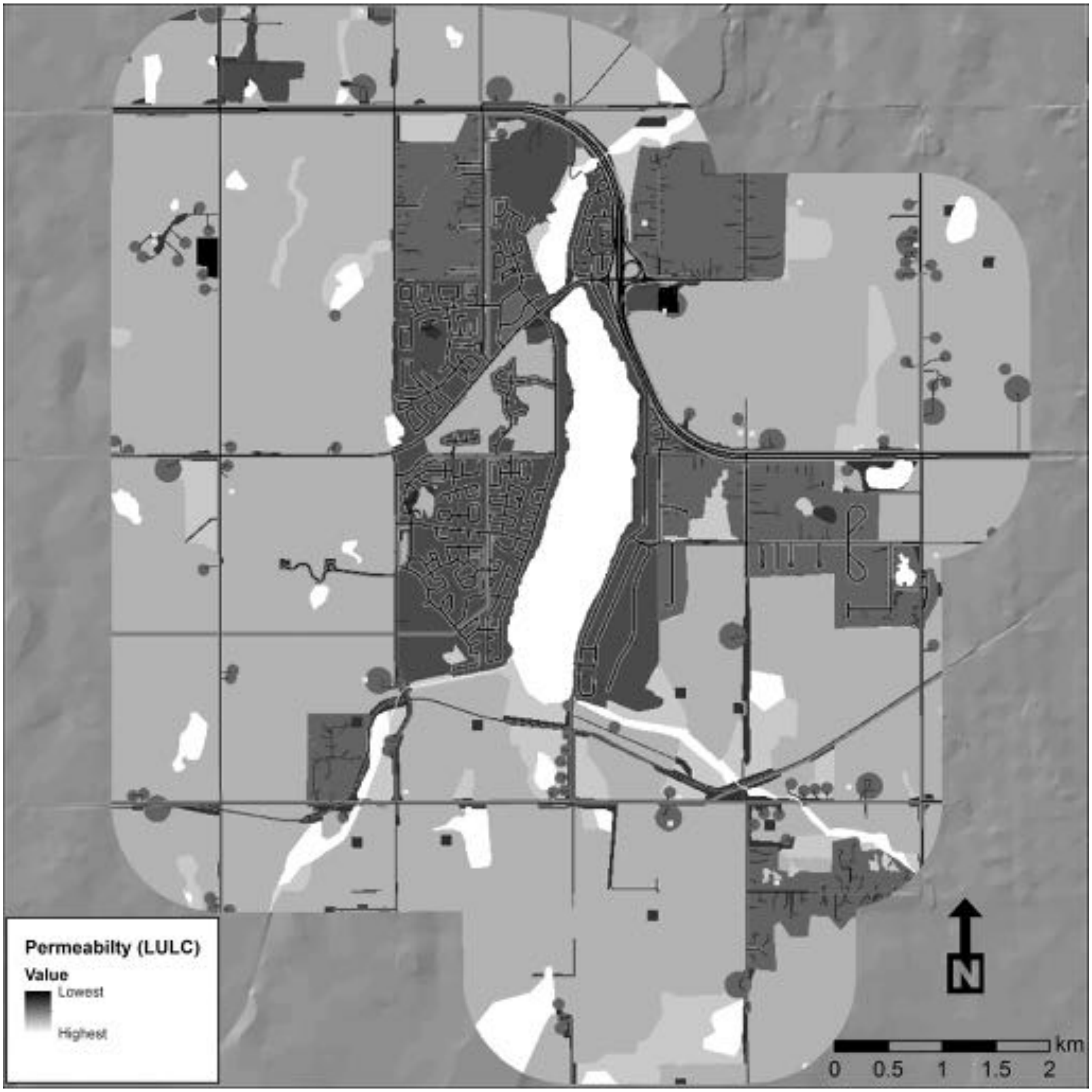


Figure 12 - Land Use/Cover-Derived Permeability Input Layer

Since both input layers were scaled to a standardized range between 1 (lowest resistance) and 11 (highest resistance), a simple raster calculator equation was all required to combine the two inputs into a single resistance surface. The following equation was applied:

Resistance = {(70*[R_TWI]) + (30*[R_LULC])} /100, which weights topographic wetness at 70% and land use/cover at 30% in the calculation of overall resistance. Obviously, changing the relative weighting assigned to these two inputs will impact the way the model behaves, and change the character of the output connectivity maps.

Figure 13 shows the final resistance surface, with focal nodes (resource patches) also highlighted in yellow.

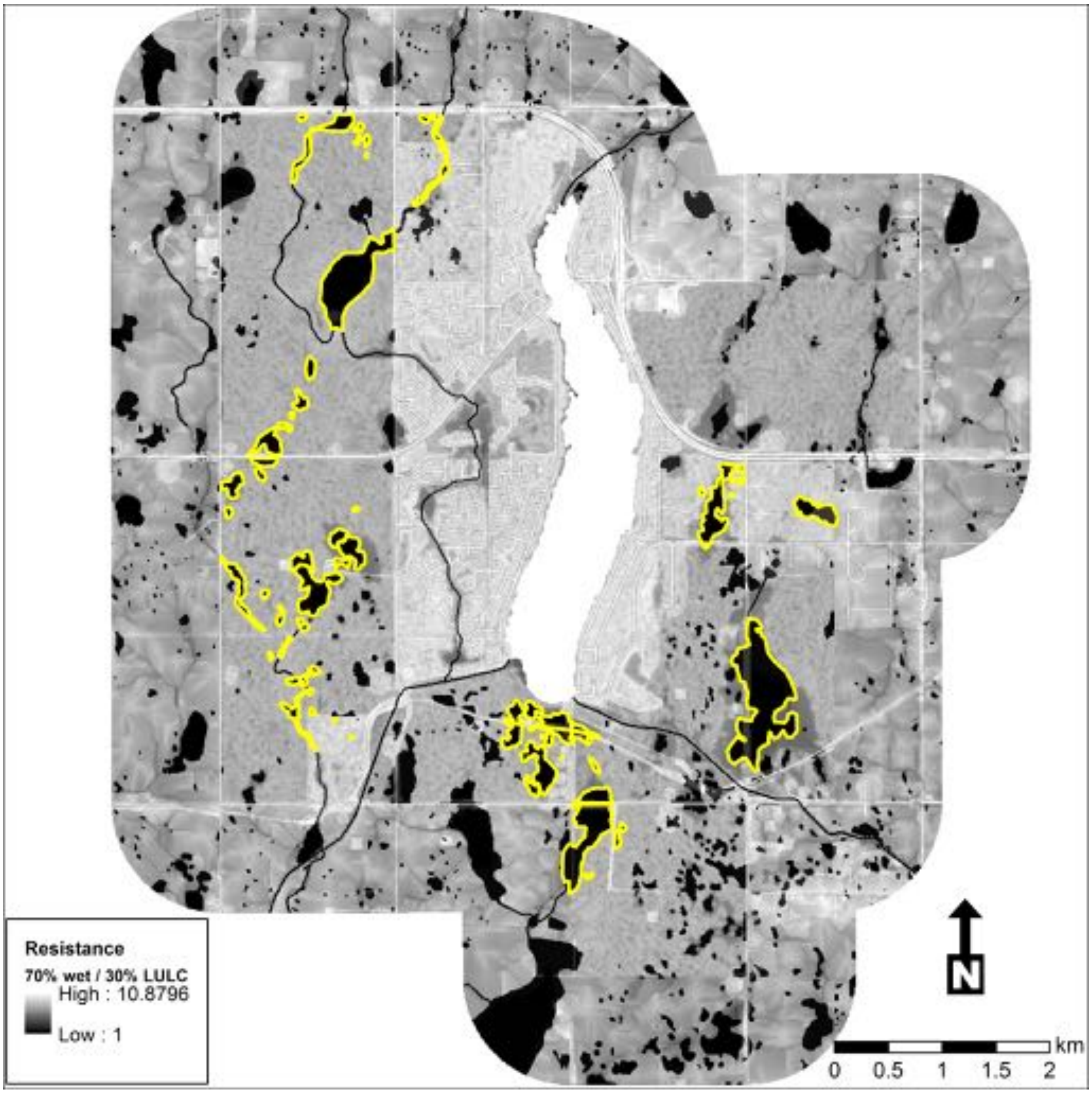


Figure 13 - Final Resistance Surface for Chestermere Wetland Connectivity Model

Note that Chestermere Lake has been removed from the resistance surface and assigned a resistance value of NODATA. This was to emphasize the connectivity between natural wetlands that are the focus of Chestermere's planning discussions; without removing this feature, it is likely that all connectivity would be routed through this large, human-made, wet feature in the middle of the study area.

Button Pushing – Running the Model

Circuitscape was run in pairwise mode, using the 12 priority wetland complexes as focal nodes and the resistance layer described above (see Figure B5). Using 10m input raster resolutions and a reasonably powerful desktop computer (Dell Precision T3500 Workstation, 3 GHz dual processor, 12 GB RAM) , the model took

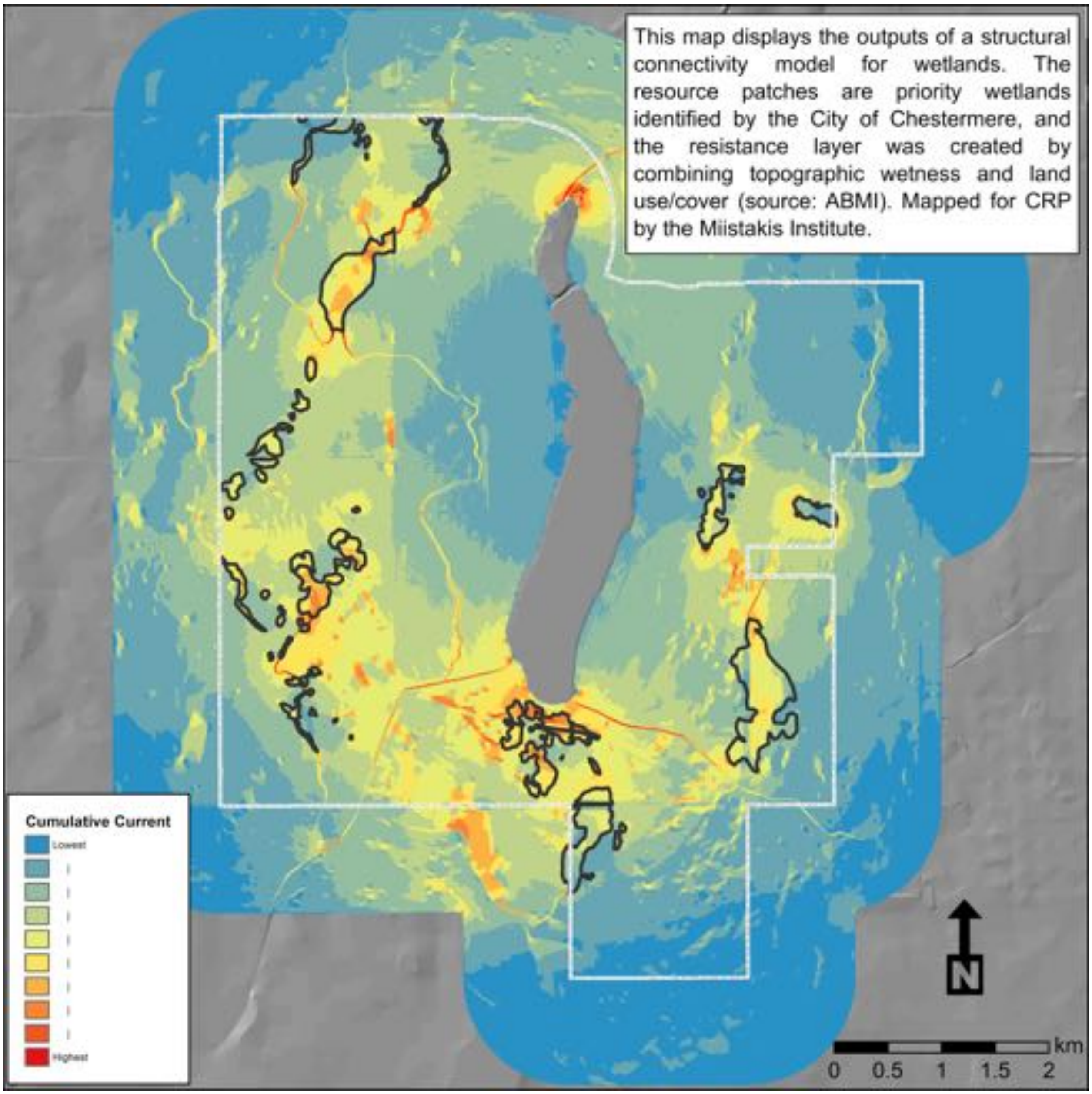


Figure 14 - Chestermere Wetland Connectivity - Raw Model Output (Cumulative Current Map)

approximately 15 minutes to run. The raw output connectivity grid is presented in Figure 14. The priority wetland focal nodes are highlighted in black.

Post-Production – Refining Model Outputs

Figure 15 shows the output cumulative current map, clipped to the City of Chestermere Boundary.
Data is presented in deciles, which means that exactly 10% of the pixels are displayed in each colour. This allows the reader to see the top 10% of the City's jurisdiction connectivity-wise (in darkest red), the next highest 10% (in darkest

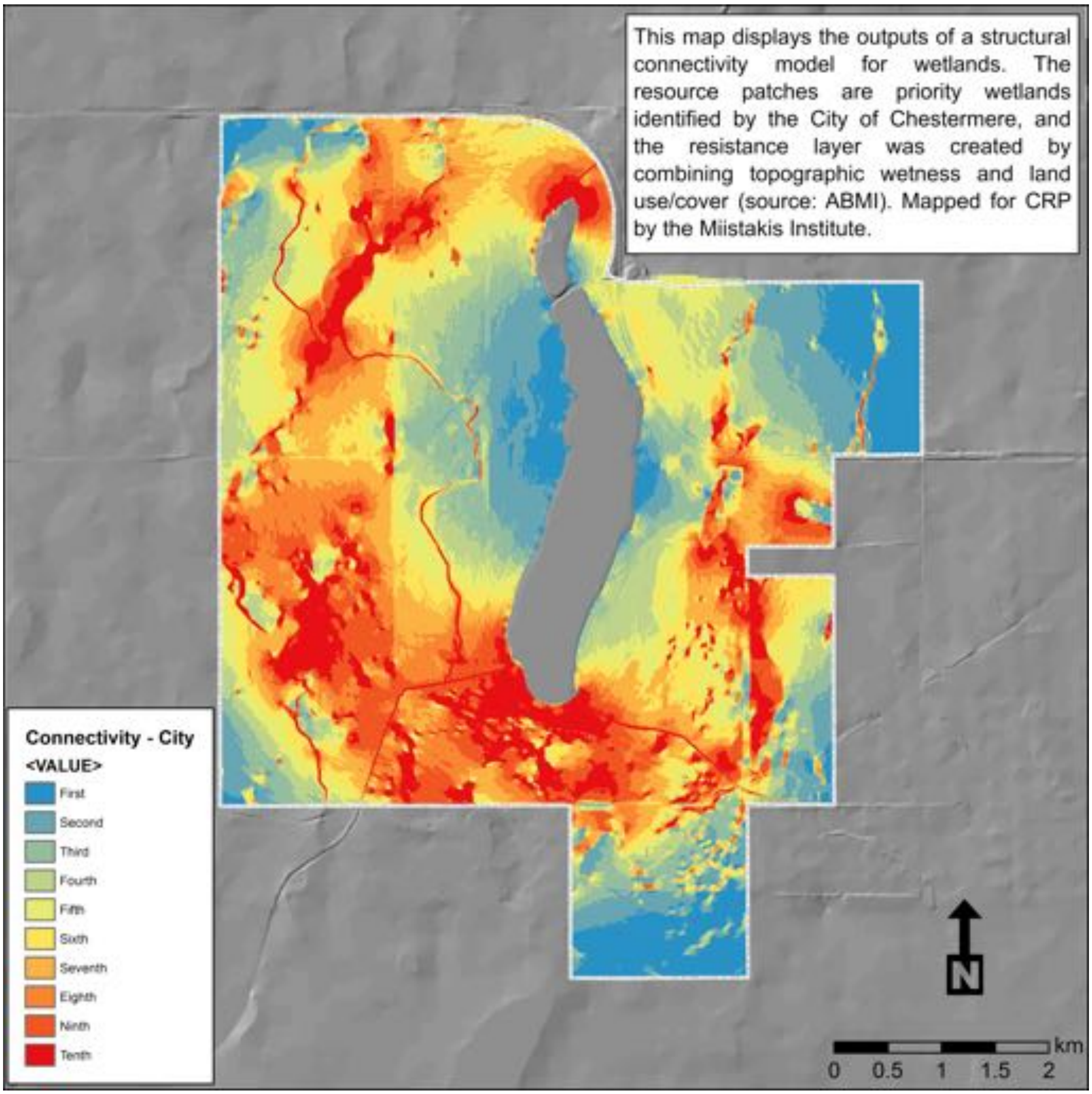


Figure 15 - Chestermere Connectivity Heat Map (Deciles) - Whole City

orange), and so on. Based on the model inputs and the actual landscape, the model outputs appear to make intuitive sense.

"So What?" – Model Results and How to Use Them

Recall that the question before Chestermere, which in discussing they will use the results of this work, is "How do we plan future growth in a way that preserves the connectivity between our most important wetlands?"

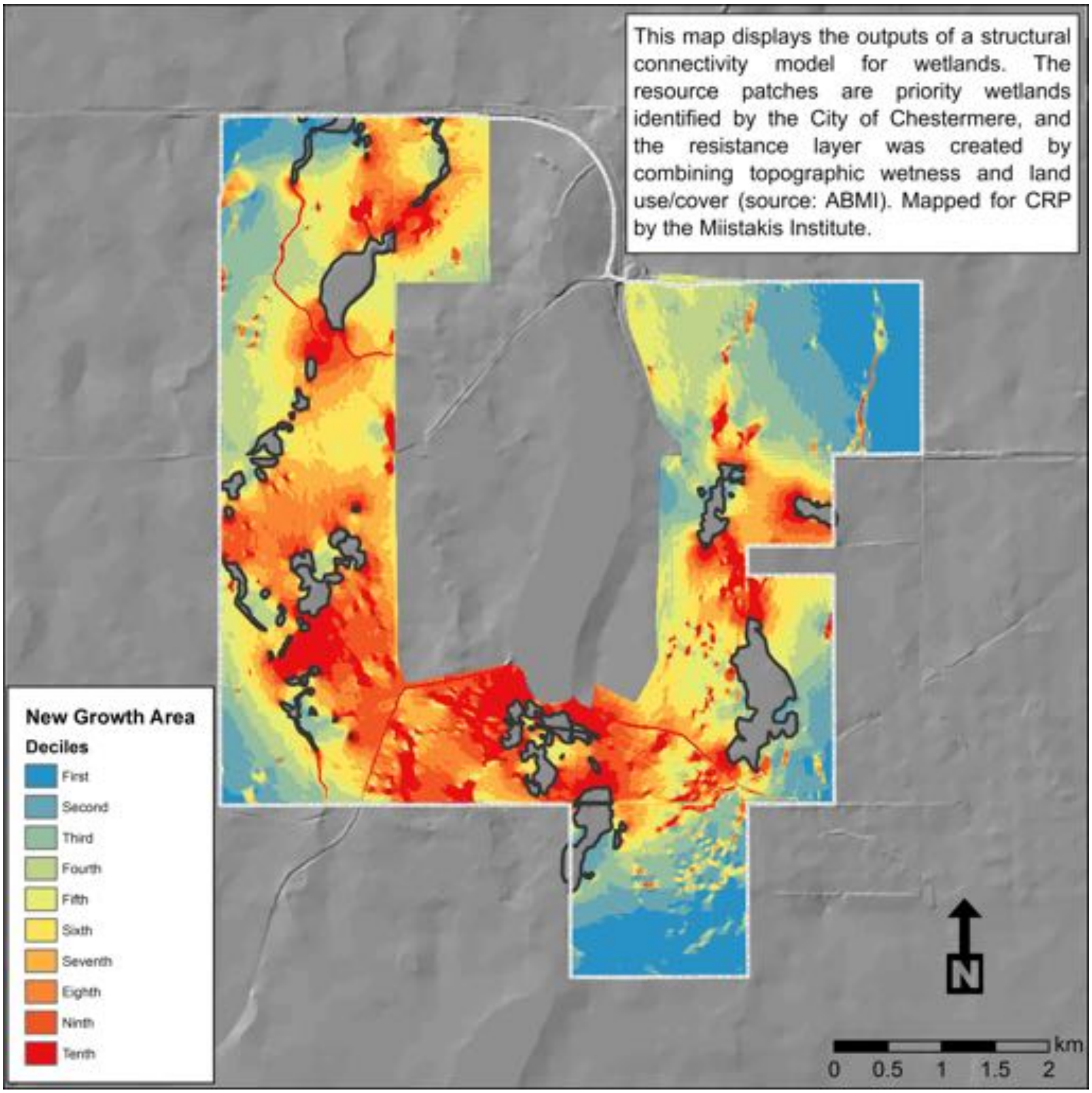


Figure 16 - Connectivity Heat Map, Clipped to Future Growth Area, with Priority Wetlands Excluded

Since the focus of their discussion is on areas of future growth, the first step in producing useful maps should be to clip the connectivity raster to the boundaries of these future growth areas. This is presented in Figure 16.

Cumulative current values have also been removed from areas covered by priority wetlands. This assumes that these areas are already afforded some protection or special consideration in Chestermere's Land Use Bylaw, and focuses the discussion on the areas in between priority wetlands and how best to connect them.

Because Chestermere is concerned with planning for growth and development, and because Municipal Law allows for placing 10% of new development in reserve, it may be valuable to see where the top 10% of land is, in terms of prioritizing

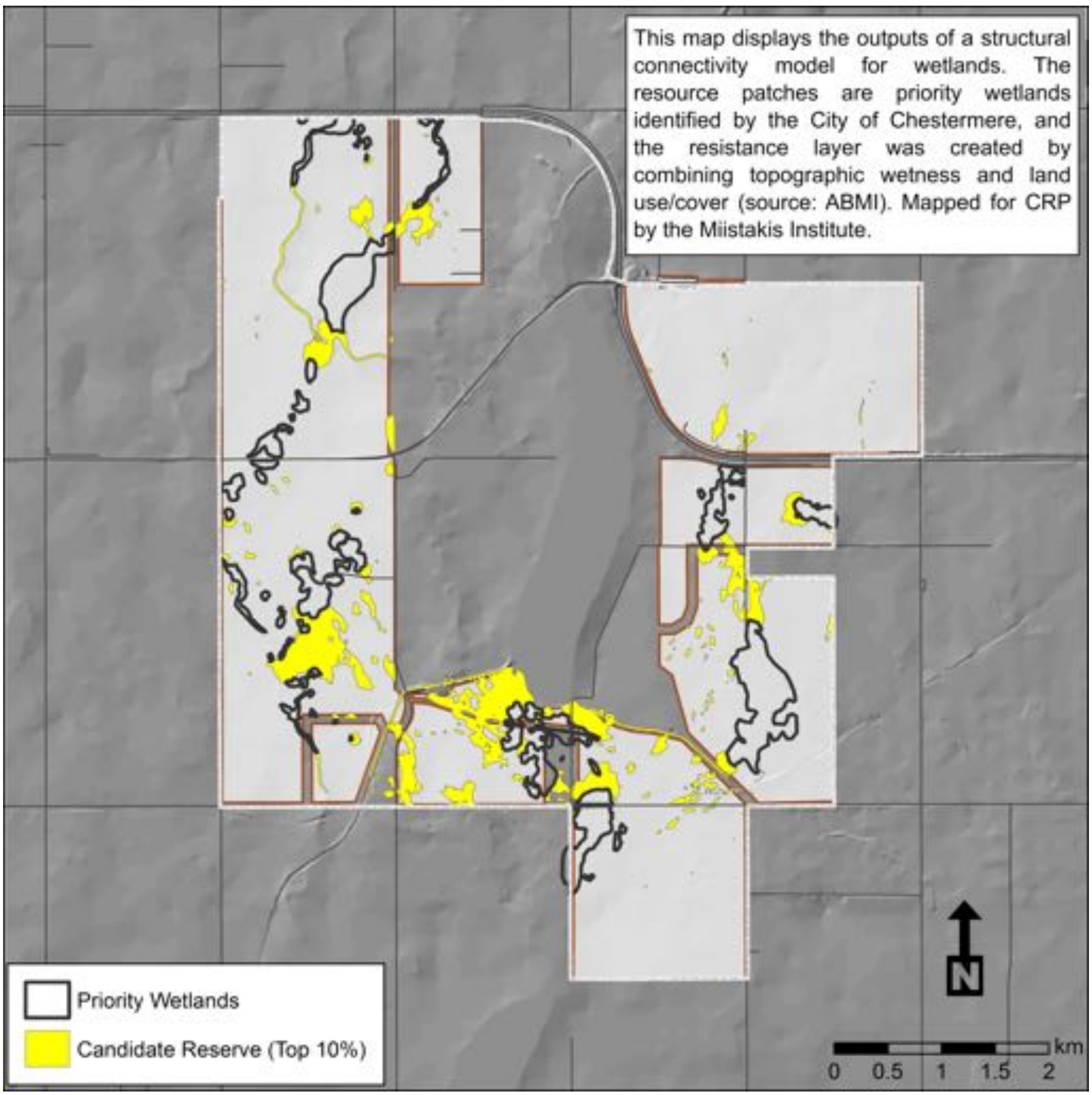


Figure 17 - Most Important Connectivity Zones between Priority Wetlands (top 10%)

structural connectivity between wetlands. Figure 17 shows these highest-priority connectivity areas (mapped in yellow).

This polygon layer was created by classifying the cumulative current map - clipped to the “future growth” zones of Chestermere, with the focal nodes extracted - into 10 quantiles (or deciles), reclassifying the data so the top decile pixels are assigned a value of 1 and all other pixels are assigned NODATA, then converting the reclassified raster to a vector polygon layer.

This provides a meaningful picture of the future growth areas of Chestermere as a whole, but development will not happen across these areas *en masse*. Therefore, it might be useful to also map highest-priority connectivity zones within each individual zone of future growth - by ASP, or even by subdivision - since this is the scale on which many land-use decisions are made.

To facilitate discussion among Council and negotiation with proponents of future development, it may also be of value to present suggested connectivity conservation or reserve areas as less of an absolute, and more of a range of possibilities. This could be achieved by mapping not only the highest decile of connectivity values, but perhaps the top 3 deciles.

Appendix C: Connectivity Modeling Cheat Sheet

CONNECTIVITY MODELING CHEAT SHEET

STEP 1: FRAMING THE QUESTION – PROJECT SCOPING

Articulate the Question. Identify Needs. Align Expectations

- Who is involved?
- What decisions are they making?
- Stakeholders (workshop)?
- How does connectivity fit in?
- Who needs what from this work?
- What are the expected outcomes?
- Connectivity for what?
- Structural or functional (or both)?
- What is the area of interest/influence?
- Interested in change over time?
- Identify project needs and resources (budget,data, and people)

STEP 2: BUILDING BLOCKS – MODEL INPUTS

Assemble the Required Pieces

Study Area:

- Where?
- Buffer appropriately!

Perceptual Scale

Resource Patches:

- What's being connected?
- How to map it?
- Input data sources?
- Required certainty/effort?

Resistance Surface:

- What affects movement?
- How to map it?
- Input data sources?
- Required certainty/effort?

STEP 3:BUTTON PUSHING – RUNNING THE MODEL

(In Circuitscape)

Prepare your data:

- Export to Raster
- Match extents, raster resolutions, coordinate systems

Model Parameters:

- Input raster data
- Modes, settings, and options
- Select desired outputs

Press the button:

- Prepare your machine! (power settings, updates, etc.)
- Hit **"RUN"!**

STEP 4: POST-PRODUCTION – REFINING MODEL OUTPUTS

In between the Model and the Maps

Clip Outputs:

- Remove buffered (edge effect) area

Quality Control:

- Visually inspect model outputs
- Check log file

DOCUMENTATION!:

- Keep excellent notes
- Document whole process
- Goal: replicability

STEP 5: SO WHAT? - MODEL RESULTS AND HOW TO USE THEM

Translating Model Outputs into Useful Information

Project Summary:

- Brief (1-2 pages)
- Narrative, not overly technical
- Interesting!

Presentation:

- To project partners
- To other stakeholders?

Map outputs:

- Recall your research question & answer it
- Map continuous surface, or discrete, or both?