Assessing urban open space network connectivity in semi-arid Windhoek, Namibia

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SOLI DEO GLORIA

ABSTRACT

With more than half of the world’s population living in urban areas, and urbanisation increasing rapidly in sub-Saharan Africa, there is constant pressure on cities to accommodate people. Urbanisation is one of the main factors driving biodiversity loss in urban centres as it can lead to fragmentation and ultimately degradation or loss of natural areas. These natural areas are part of a city’s green infrastructure, responsible for providing valuable ecosystem functions and services. As one of the key principles of urban green infrastructure planning, natural areas in cities should be functionally connected in order to effectively contribute to ecosystem functioning and support a healthy biodiversity.

Efforts to preserve or restore ecological connectivity in urban areas can be costly, especially in a semi-arid, Global South city such as Windhoek in Namibia. Properly informing attempts to assess functional connectivity in the highly heterogeneous landscape of a city requires the use of reliable, efficient, and process-driven models and metrics to map movement corridors, and not merely the shortest routes, between habitat patches. This study tested the use of electrical circuit theory modelling, as applied to ecological concepts, to map multiple movement corridors between open space parcels in Windhoek, based on a resistance-to-movement cost surface and incorporating maximum dispersal distances of small to medium sized mammals to quantify functional connections. Focussing on threatened linkages which play a critical role in keeping the network connected would ensure a more cost-effective use of available resources.

Promising results included mapped least cost corridors and paths, mapped current flows showing pinch points to dispersal movement, and weighted measures of patches’ importance for keeping the entire network connected. Also, based on the parameterization used, a single linkage in a highly resistant area was found to be the only connection between large components of Windhoek’s open space network. Based on interpretations of the mapped outputs, inter-patch areas displaying improvement potential to serve as possible linkages between isolated components were also identified. As a test for improvement potential, in one of these inter-patch areas a vacant lot was “upgraded” to habitat status and the resulting re-run showed clear, run-on improvements to patch importance in that area. Consequently, the circuit theory modelling approach shows promising potential for assessing functional connectivity at city-scale in a semi-arid, sub-Saharan urban setting. Applying this approach in urban areas, specifically those with resource constraints, can greatly enhance urban nature conservation efforts and inform responsible spatial development planning decisions.

Keywords: urban ecology; urban green infrastructure; ecological connectivity; electrical circuit theory; functional connectivity

OPSOMMING

Met meer as die helfte van die wêrelbevolking wat tans in stedelike gebiede woon en met verstedeliking snel aan die toeneem in sub-Sahara Afrika, is daar toenemende druk op stede om mense te akkommodeer. Verstedeliking is een van die dryfvere van biodiversiteitverlies aangesien dit kan lei tot die fragmentasie en uiteindelike degradasie en verlies van natuurlike areas. Sulke natuurlike areas vorm deel van ‘n stad se groen infrastruktuur, wat verantwoordelik is vir die voorsiening van waardevolle ekosisteemdienste en -funksies aan mens en natuur. As een van die kernbeginsels van groen infrastruktuur beplanning behoort natuurlike areas in stede funksioneel gekonnekteerd te wees om effektief te kan bydra tot ekosisteem funksionering en die onderskraging van gesonde biodiversiteit.

Pogings om ekologiese konnektiwiteit in stedelike gebiede te onderhou of te herstel kan duur wees, veral in ‘n semi-ariede stad in die Globale Suide soos Windhoek in Namibië. Om pogings rondom die assessering van funksionele konnektiwiteit in ‘n hoogs heterogene landskap soos dié van ‘n stad behoorlik te rugsteun, word betroubare, doeltreffende, en prosesgedrewe modelle benodig om bewegingsroetes, en nie net die kortste paaie, tussen habitatte te karteer. Hierdie studie het die gebruik van elektriese stroombaanteorie modelering, soos toegepas op konsepte in ekologie, vir die kartering van veelvoudige verbindingskorridors tussen oop ruimtes in Windhoek getoets. Hierdie verbindingskorridors is gebaseer op ‘n GIS-gemodelleerde weerstandskoste oppervlak en inkorporeer die maksimum reikafstande van klein- tot mediumgrootte soogdiere om funksionele verbindings te bepaal en te kwantifiseer. Deur beskikbare hulpbronne toe te spits op kwesbare verbindingskorridors wat ‘n krities belangrike rol speel om die netwerk van oop ruimtes gekonnekteerd te hou, sal verseker dat beperkte hulpbronne meer koste-effektief en doeltreffend toegedien word.

Van die belowende resultate sluit in, gekarteerde korridors en paaie wat laagste koste-van-beweging aandui, gekarteerde stroomvloei wat knyppunte vir verspreidingsbeweging aandui, en geweegde metings van hoe belangrik elke oop ruimte vir die behoud van die totale netwerk is. Verder is ‘n enkele beleërde verbinding in ‘n hoogsontwikkelde gedeelte van Windhoek, volgens die parameters gebruik, geïdentifiseer as die enigste skakel tussen die twee hoofkomponente van die stad se oopruimte netwerk. Gebaseer op interpretasies van die gekarteerde uitsette is sekere areas tussen habitatstroke geïdentifiseer wat opknappingspotensiaal wys om as moontlike verbindingskakels tussen geïsoleerde komponente van die oopruimte netwerk te dien. As ‘n toetslopie rakende opknappingspotensiaal is een van hierdie areas, wat ‘n stuk onbeboude grond beslaan, hipoteties “verbeter” om as habitat te kan dien. Die daaropvolgende heruitvoering van die toepaslike model het duidelike verbeterings aan die belangrikheid van nabygeleë habitatstroke as deel van die oopruimte netwerk tot gevolg gehad.

Gevolglik blyk die elektriese stroombaanteorie modellering benadering belowende potensiaal te wys vir die assessering van funksionele konnektiwiteit op stad-skaal in ‘n semi-ariede, sub-Sahara konteks. Deur hierdie benadering toe te pas in stedelike gebiede, veral diegene met beperkte hulpbronne tot hul beskikking, kan pogings rondom stedelike natuurbewaring vergemaklik word en beplanning rondom ruimtelike ontwikkeling beter ingelig word.

Sleutelterme: stedelike ekologie; stedelike groen infrastruktuur; ekologiese konnektiwiteit; elektriese stroombaanteorie; funksionele konnektiwiteit

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CBNRM	Community-Based Natural Resource Management
CoW	City of Windhoek Municipality
CWD	cost weighted distance
GI	green infrastructure
GIP	Green Infrastructure Planning
GIS	Geographic Information Systems
GPS	Global Positioning System
ha	hectare(s)
ID	identification
IIC	Integral Index of Connectivity
IWRM	Integrated Water Resource Management
LCP	least cost path
N_built	not built (vacant)
NACSO	Namibian Association of CBNRM Support Organisations
NLCC	normalised least cost corridors
NSA	Namibia Statistics Agency (formerly Central Bureau of Statistics)
NUST	Namibia University of Science and Technology (formerly Polytechnic of Namibia)
OS	open space
PC	Probability of Connectivity
PDA	patch distance analysis
POS	public open space
RD	resistance distance
SDG	Sustainable Development Goal(s)
SEPM	spatially explicit population model
UNAM	University of Namibia

CHAPTER 1 INTRODUCTION

1.1 Background

Urban landscapes are highly heterogeneous and often consist of a variety of different land uses and land-cover types with abrupt edges between them (Lookingbill *et al.*, 2022). In order for ecosystems in urban areas to function effectively and support a healthy biodiversity they rely on habitat which is unimpeded by grey infrastructure development (Lookingbill *et al.*, 2022). Functional connections between habitat patches are necessary for the flow of ecosystem processes such as species dispersal as well as to prevent fragmentation and isolation of biotic populations (Rudnick *et al.*, 2012). Human inhabitants also benefit from ecosystem services provided by a city's green infrastructure, such as soil stabilisation, provision of food, and sequestration of carbon dioxide (Pauleit *et al.*, 2021). In fact, in semi-arid cities in the Global South (developing countries) there is an even greater dependence on ecosystem services provided by nature (Dobbs *et al.*, 2021; Escobedo, 2021; Lindley *et al.*, 2018; Shackleton, 2021). In addition, urban areas in developing countries commonly face pressures of increasing urbanization and demand for resources (Cobbinah *et al.*, 2015; Güneralp *et al.*, 2017; Myers, 2021). This pressure on urban natural areas can easily lead to their demise, especially if the resources and willpower to conserve the whole open space network are lacking. Instead of attempting to apply resources to the whole network, city managers could concentrate efforts on preserving or improving those areas that play the most important role in keeping the whole network connected (Cilliers *et al.*, 2021; Pauleit *et al.*, 2021). In order to manage urban areas in this way, knowledge is needed of where exactly these areas are.

Various techniques for assessing different types of connectivity have arisen over the last two decades, with measurement approaches based on graph theory (also called network theory) proving to be some of the most effective (Galpern *et al.*, 2011). Originating from the foundations of graph theory, one of the methods applied with much success to the measurement of connectivity in heterogeneous landscapes is electronic circuit theory (Dickson *et al.*, 2019). By substituting the components of electrical circuits with ecological concepts and injecting "current" into a landscape that has been assigned certain measures of resistance, potential dispersal movements between habitat areas can be mapped using flows of current (McRae & Beier, 2007). In addition, mapped current flow density can indicate pinch points or bottlenecks where movement is constrained in the landscape (McRae *et al.*, 2008). These results can be used to identify areas in the landscape which are critical towards keeping the entire habitat network connected (McRae, 2012a), which can be useful for informing efforts to preserve, improve or restore connectivity in the landscape (Dickson *et al.*, 2019), to the benefit of nature as well as the city's residents.

1.2 Problem statement

The city of Windhoek, Namibia, is under pressure from rapid urbanization and a high demand for developable land to accommodate the influx of people, most of whom are seeking or pursuing employment opportunities (Weber, 2017). Many of the city's open spaces are neglected, used illicitly as dumping sites, and disregarded by the general public due to safety concerns. Coupled with the semi-arid climate and low soil fertility, open spaces in Windhoek require protection and management or risk degradation of the ecosystem. Shortage of resources and funding, lack of willpower from management, and a deficiency in knowledge on their ecological importance, however, is threatening the functionality of the city's open space network (Wijesinghe & Thorn, 2021). Furthermore, due to criminal elements using vegetated open spaces as cover in the pursuit of their illicit activities, the perception has been formed amongst citizens, especially those in higher income areas, that open spaces are unsafe and a source of nuisance (City of Windhoek, 2000; Wijesinghe & Thorn, 2021). Consequently, many open spaces around residential areas have been fenced off and barricaded (Van Mansfeld *et al.*, 2008), presenting a barrier for the movement of animals such as medium-sized mammals, representing the higher levels of the food chain.

No effective methods have been applied to date in quantifying the connectedness of the city's urban open space network. This lack of data hinders effective and informed urban open space planning and urban nature conservation.

1.3 Rationale of study

The significance of this study is highlighted by the apparent absence of studies assessing functional connectivity at city-scale in sub-Saharan Africa and the shortage of such studies in semi-arid cities in general. Studies attempting to quantify functional connectivity (see section 2.5.3 in the Literature Study for the differences between measures of connectivity) in urban settings are sparse (LaPoint *et al.*, 2015), but highly necessary (Bierwagen, 2005). In addition, due to being ecologically informative, research on connectivity in urban areas is important to inform management recommendations (LaPoint *et al.*, 2015). The need for studies assessing functional corridors in Windhoek to inform management of the city's ecology has specifically been expressed in the past (Enviro Dynamics, 2009; Van Mansfeld *et al.*, 2008).

Another aspect that this study addresses is the need to draw attention to the importance of maintaining ecological connectivity in urban areas. Urban open spaces are often overlooked and underappreciated, largely in light of the perception that they are unsafe for citizens (Davoren & Shackleton, 2021; du Toit *et al.*, 2018; Wijesinghe & Thorn, 2021). Connectivity, specifically, is one of the “emerging themes regarding urban ecology in the Global South” (du Toit *et al.*, 2021) making it a relevant topic for research in Windhoek.

There is a pertinent urgency to assimilate research in arid and semi-arid areas in the Global South, as they would be more greatly affected by the effects of climate change than other areas of the world (Childers *et al.*, 2015; du Toit *et al.*, 2018). For example, a shortage of data on ecosystem processes in sub-Saharan countries would impair efforts to address or mitigate the effects of disturbances caused by climate change (Lindley *et al.*, 2018). Windhoek being situated in a semi-arid climatic region further contributes to the relevance of this study.

1.4 Aim of study

This desktop study aims to test the use of circuit theory methodology to model and map the connectivity of Windhoek’s open space network and to evaluate its usefulness in identifying high priority areas for keeping the entire network connected. In order to analyse functional connectivity, the city will be modelled via estimations of landscape resistance to the dispersal of a target animal species group.

1.5 Structure of dissertation content

This study is conducted in the form of a desktop study in order to test the proposed methodology. As it was outside the scope of the study to verify the modelled results with field observations, the need to conduct fieldwork to sample data was eliminated.

After the topic has been introduced and the rationale and aim of the study given here in Chapter 1, the key topics relating to the subject of this research are explored in the literature study in Chapter 2. Chapter 3 introduces the study area, the data analysed, and the methodology followed to realise the modelling of open space network connectivity in Windhoek. Chapter 4 presents the results of the connectivity assessment mainly as mapped linkages between open spaces. An improvement potential scenario is also analysed to demonstrate the influence that patch improvement efforts can have on the network’s connectivity. The chapter also contains a discussion around the interpretation and meaning of the results and why they are considered important. Finally, Chapter 5 will summarise the main conclusions and offer recommendations for future studies on the subject and for using this approach in urban planning, design and management.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

In order to approach the subject of assessing the ecological connectivity of Windhoek's open space network, a review of the available literature on the various topics involved is necessary. This will provide the reader with the necessary theoretical background and discussions on the concepts presented so that the content of the study would be understandable. As this study is conducted specifically at city-scale, urban ecology is a strong focus of this research and will therefore be discussed first, followed by the larger topic of landscape ecology, thereafter the importance of connectivity and the modelling thereof.

2.2 Urban ecology

2.2.1 Defining urban ecology

Urban ecology consists of the consolidation of various disciplines (Alberti, 2008). Accordingly, McDonnell (2011) specifies three disciplines of science, namely, the humanities (social sciences), engineering and planning, and natural sciences. As these different disciplines have different terminologies, methodologies, goals and objectives, they all have relatively different meanings and definitions for the term urban ecology when it comes to their respective fields of expertise. Natural scientists, for example, base the definition on that of ecology, merely in an urban landscape. More specifically, that which concerns the abundance and distribution of living organisms (referred to as biodiversity), in addition to the flow of energy and nutrients in urban ecosystems in the form of ecosystem functions (McDonnell, 2011). Urban planners and engineers approach urban ecology by focussing on designing and implementing facilities in urban landscapes with the aim of creating sustainable cities with a minimum ecological footprint (McDonnell, 2011). The focus of social scientists, on the other hand, is mainly on the social makeup and allocation of natural and institutional resources of a city (Alberti, 2008). Subsequently, social scientists working in the field of urban ecology have been probing ways and methods of creating "greener" urban areas (McDonnell, 2011). Urban ecology is defined by McDonnell (2011) as an integration of "both basic (fundamental) and applied (problem orientated) natural and social science research to explore and elucidate the multiple dimensions of urban ecosystems". Marzluff *et al.* (2008) offer a similar definition, describing urban ecology as an "emerging interdisciplinary field that aims to understand how humans and ecological processes can coexist in human-dominated systems and help societies with their efforts to become more sustainable". The South African researchers Cilliers and Siebert (2012) are of the opinion that the term *transdisciplinary* should also form part of this definition, so that it includes not only academics, but also the broader public as well as managers of various kinds.

2.2.2 The development of urban ecology

Urban ecology as a discipline owes much of its rapid development to the different emergent challenges of increasing urbanization across the globe (McDonnell, 2011). According to McPhearson *et al.* (2016), examples of challenges confronting urban areas, besides infrastructure development not being able to keep up with population growth, include the growth of shantytowns and informal settlements, economic fluxes, shifting demographic characteristics, social inequity, pollution, aging infrastructure, local changes in climate and water systems, to name a few. These challenges are especially pertinent in rapidly urbanizing cities in developing countries in the Global South, seriously threatening the ecosystem services provided by urban green infrastructure (Güneralp *et al.*, 2013) on which their populations often highly depend. Responding to the presence of such challenges through proactive planning, designing and managing urban landscapes across different scales requires understanding of the way in which the multiple interacting components combine to create patterns and processes that influence the system’s dynamics (McPhearson *et al.*, 2016).

Rather than viewing cities as the bane of natural landscapes, they can be regarded for their potential contributions to ecology. Their particular properties provide urban areas with unique opportunities to contribute to biodiversity at local, regional, and global scales (Spotswood *et al.*, 2021). They can provide habitat, even if it’s only as lay-over, and refugia for plant and animal species from pressures acting out in the surrounding habitat, as well as opportunities to adapt to the influences of climate change, explains Spotswood *et al.* (2021).

This historical development of urban ecology has also seen the change of perspectives from considering ecology as a discipline which only exists outside a city, to that of ecology “in” cities, ecology “of” cities, and recently, ecology “for” cities.

According to McDonnell (2011), studies of ecology “in” cities are generally of a single discipline, focussing mainly on remaining natural areas, and located within the boundaries of a city landscape and are therefore on a relatively small scale. The primary interest in research of this kind concerns the non-human, “biophysical dynamics of urban ecosystems” (McPhearson *et al.*, 2016), referring to the biological and geographical aspects of the processes at work. The majority of urban ecological studies currently are of this kind (Alberti, 2008; McPhearson *et al.*, 2016), demonstrating its importance as dominant perspective in urban ecological research.

In comparison, studies of ecology “of” cities are typically interdisciplinary and occur across multiple scales, incorporating the social, ecological (McDonnell, 2011), and built infrastructure drivers and responders of urban ecosystems, thereby considering the city as an ecosystem in itself (McPhearson *et al.*, 2016). For the urban ecology field to advance and improve our understanding of urban ecosystems, more inter- and transdisciplinary studies relating to ecology “of” cities will be required (Alberti, 2008).

In a further development, Childers *et al.* (2015) advocated that in order for cities to become sustainable and resilient, urban ecology should transform from an ecology “of” cities to an ecology “for” cities approach. They advocated that no longer should ecology and urban design be treated as disjunct entities without participation from civil society, government and planners. Accordingly, ecology “for” cities should be participatory and function across disciplines. It should also include participation from communities and government, in addition to academic research, in the practice, planning, management, and governance of urban ecological systems (McPhearson *et al.*, 2016). In conclusion, by integrating inputs from role-players across multiple disciplines, building on a wide-ranging foundation of research interests, engaging with affected communities, and linking the top-down and bottom-up processes of local governance, the holistic nature of urban ecology efforts can be successfully applied (McPhearson *et al.*, 2016).

This study’s research follows the ecology “in” cities approach, as it focuses on natural areas as habitat patches and is confined to the scale of the city. Even though it concentrates on a single discipline and does not explicitly incorporate human drivers, it is still necessary as it contributes to knowledge on bio-physical aspects of the urban landscape and can function as a basis for other approaches (Pickett *et al.*, 2016; Shackleton *et al.*, 2021)

2.3 Landscape ecology

2.3.1 The concept of landscape ecology

The concept of urban ecology is firmly nested in the broader field of landscape ecology. The term landscape ecology is defined in short by Pickett and Cadenasso (1995) as “the study of the reciprocal effects of spatial pattern on ecological processes...”. In other words, how the spatial layout of a landscape determines the ecological processes occurring there and often *vice versa*. The amounts of each habitat type and their spatial arrangement are the two main factors that landscape ecology attempts to describe (Turner & Gardner, 2015). Landscape ecology is regarded as an emerging discipline focussing on viewing the landscape as “an interrelated, interconnected whole”, while specifically highlighting the relationships between landscape components and their functional roles (Pickett *et al.*, 2004). Landscapes themselves are dynamic, though, and are defined by ecological events occurring on a range of spatial and temporal scales (Bannerman, 1997). Spatial heterogeneity in the landscape is regarded as a principal causal factor influencing ecological systems, with both spatial and temporal dynamics playing an equally important role (Pickett & Cadenasso, 1995). Examples of factors playing a role in temporal dynamics are population progression and regulation and community-scale changes or succession (Pickett & Cadenasso, 1995). Concerning spatial dynamics, the influencing factors could be fluxes in energy, living organisms, and materials (Pickett & Cadenasso, 1995). Likewise, in urban ecology a major goal is understanding the "relationship between the spatio-temporal patterns of urbanization and ecological processes" (Wu, 2008).

2.3.2 The Patch, Corridor, Matrix model of landscapes

As one of the chief interests in landscape- as well as urban ecology, the study of spatial landscape patterns refers to heterogeneous landscapes as consisting of a "mosaic" of different elements of habitats (Dunning *et al.*, 1992), land uses, or ecosystems over areas multiple kilometres wide (Bannerman, 1997). Many landscape ecologists refer to this mosaic model as consisting of a combination of three core components, namely patches, corridors, and a surrounding matrix (Ahern, 2007). Where the prevailing element in a landscape mosaic consists mainly of a continuous type of uniform cover it is referred to as a "matrix" (Ahern, 2007; Pickett & Cadenasso, 1995). Interspersed inside the matrix could be discrete, non-linear elements, distinguished from their surroundings by their biotic or abiotic makeup (Pickett & Cadenasso, 1995) and isolated from similar areas, which are referred to as "patches" (Ahern, 2007). "Corridors" are strips of homogenous land cover serving as habitat, providing links between sections of the matrix such as patches (Bannerman, 1997), or even acting as barriers to wildlife movement (Ahern, 2007). In an urban context, examples of urban patches could include not only fragmented natural areas but also parks, sports fields, cemeteries, and vacant lots, while urban riverways and powerlines could function as corridors, with the urban matrix consisting of residential neighbourhoods, business areas, or mixed-use districts, as listed by Ahern (2007).

2.4 Spatial heterogeneity

2.4.1 The role of disturbances in the landscape

Spatial heterogeneity in the landscape mosaic is driven by the processes of disturbance and fragmentation (Alberti, 2008). It can be viewed as the core process facilitating fragmentation, animal dispersal patterns, local and regional extinctions and many other processes acting on the structure and function of landscapes (Farina, 2006). Disturbance is a principal driver of spatial and temporal heterogeneity and is present from local to landscape scale, influencing every level of biotic organisation; causing changes that range from the current to the long-term (Farina, 2006). In urban areas, in particular, habitat fragmentation is distinctly noticeable, due to the typical influences of prolonged disturbance and continual alteration of habitats (Grimm *et al.*, 2008).

Disturbance in landscapes may be triggered by both biotic and abiotic factors, with anthropogenic disturbance playing a significant role (Alberti, 2008). Examples of biotic sources include predation influences and competition for resources among plants and animals, and the activities of bacteria and other pathogens, while abiotic elements include rainfall, wind regimes, wildfires, water runoff, landslides, and solar energy (Farina, 2006).

According to Bannerman (1997), the transformation and disruption of landscape patterns and accompanying ecological processes occurs in five phases, and these extensive arrangements often overlap. The first and most prevalent initial phase is *perforation*, whereby voids form in habitats or landscapes, such as clearings made in forests. The second and sometimes alternative starting phase is *dissection*; the subdivision of areas by lines such as road networks. The third and most infamous phase is the reduction of landscapes into lesser compartments through *fragmentation*. Where habitat patches decrease in size or surface area it is referred to as *shrinkage*. The fifth phase, *attrition*, is where pockets of habitat are grinded down by continuous landscape change, causing them to cease to exist as a functional habitat space. Each of these progressions “result in spatial ecological changes to the landscape mosaic and increased habitat loss and fragmentation” (Bannerman, 1997).

2.4.2 Fragmentation

Fragmentation has been described as “one of the most severe world-wide processes depressing biodiversity” (Farina, 2006). According to Crooks and Sanjayan (2006), fragmentation is regarded as “a major cause of habitat loss, inter-patch dispersal and species’ decline”. The following sections will discuss elements relating to landscape fragmentation to demonstrate the roles they play in landscape dynamics that also apply to urban areas (Aronson *et al.*, 2016). To understand the process of landscape fragmentation, it is beneficial to investigate the mechanisms of fragmentation and the dynamics thereof. The nature of edge effects as a factor influencing the functionality of fragmented patches should also be considered in understanding the dynamics of fragmentation. The consequences of fragmentation will also be listed in order to emphasize the importance of connectivity in the landscape.

2.4.2.1 Mechanisms of fragmentation

According to Bennett (1999), the process of landscape fragmentation has three distinct, interrelated mechanisms, namely, habitat loss, shrinkage of remaining habitat patches' area, and increased isolation of habitat fragments. Once patches have become devoid of species, the probability that they could be recolonized depends strongly on their distance from the main habitat patch or source patch(es) and the quality of habitat in between (Farina, 2006). Different species perceive fragmentation in different ways, and this may vary between seasons as well (Farina, 2006). Clearly, as one of the processes responsible for landscape heterogeneity, fragmentation is a scale-dependant, continuum process; but it is also dynamic (Bennet, 1998; Farina, 2006). Human and natural disturbances could be driving it, whilst at the same time the recovery or re-vegetation of habitats could be relieving it (Farina, 2006). Indeed, the dynamics of fragmentation have been shown to be strongly affected by human decision-making around management and land policy (Farina, 2006).

2.4.2.2 Edge effects

As remaining habitat fragments become increasingly smaller the amount of their area subjected to edge effects increase. These edges refer to the zone between different adjacent patches or parts of the landscape mosaic (Bannerman, 1997). A high perimeter to area ratio has the effect that a significant portion of the patch is near to the edge and thus open to certain influences emanating from outside the patch (Bennet, 1998). Aside from increased threats of invasion (Cilliers *et al.*, 2008) and competition from neighbouring patches, edge effects may lead to microclimatic changes in solar radiation, moisture, temperature, and wind regimes (Bannerman, 1997). Other factors such as changes in soil structure, soil nutritiousness and its other properties, human intrusion and disturbance, and higher levels of parasitism and predation may also contribute to the alteration of remnant habitat patches (Bennet, 1998).

2.4.2.3 Consequences of fragmentation

Little doubt is left that fragmentation has a far-reaching negative effect on the faunal and floral biodiversity of habitats. Fahrig (2003) has outlined the reality of urban open ("green") spaces becoming more fragmented due to the pressures of urban development (Aronson *et al.*, 2016); affecting species richness, intra-specific genetic variation and abundance of individuals within populations. Some of the broader, overarching consequences of fragmentation include native animal and plant species decline, influx of exotic species, intensified soil erosion, and reduced water quality (Farina, 2006). Likewise, Bennet (1998) describes three main ways in which the fauna of remaining habitat patches is negatively impacted by landscape fragmentation. Firstly, there is a loss of species in habitat patches as a result of the three forms of modification accompanying fragmentation, namely, general loss of habitat, fragments becoming increasingly smaller, and greater isolation of residual patches (Farina, 2006). Secondly, the makeup of animal communities is altered as different species respond differently to habitat change based on their diverse characteristics, requirements, and tolerances. Thirdly, changes befall ecological processes involving animals, such as competitive interactions, plant pollination, nutrient cycling, seed dispersal, and predator-prey dynamics. These changes can have wide ranging and lasting impacts on the urban landscape mosaic. Research efforts investigating habitat fragmentation are increasingly acknowledging the significance of functional connectivity in landscapes and how it influences the continued existence of wildlife populations (FitzGibbon *et al.*, 2007).

2.5 Connectivity, connectedness, and corridors

The issue of patch isolation can be addressed by the three different concepts of connectivity, connectedness and corridors (Farina, 2006). It is helpful to take note of the differences between these three terms. Broadly speaking, connectivity measures “the amount of favourable habitat available to a focal species” (Farina, 2006). Connectedness (also called proximity), is viewed as the opposite of isolation and is a description of the spatial attributes of a landscape, i.e. “the degree of physical distance between patches” (Farina, 2006). Certain habitat availability metrics have also been developed specifically for analysing connectedness (e.g. Tischendorf *et al*., 2003). It is intuitive therefore that the matrix represents the element with the highest connectedness in the landscape mosaic (Farina, 2006). It may well occur that a landscape has low connectedness (i.e. patches far apart) but high connectivity (i.e. habitat highly available to species); in such cases it would be due to the presence of one or more functional corridors (Farina, 2006).

Corridors are functional arrangements in the landscape, having the invaluable role of mitigating the effect of landscape fragmentation on species (Farina, 2006). The inverse is also true, in that corridors might facilitate the invasion of alien species into an area (Farina, 2006). Although the term corridor has been defined in a variety of ways, in landscape ecology a habitat corridor can be simply defined as a linear strip (mostly) of vegetation surrounded by other landscape elements, that provides a pathway between habitat patches (Bennet, 1998; Farina, 2006). According to Bennet (1998), other corridor-related terms that have been used in scientific literature include *habitat corridor*, *dispersal corridor*, *wildlife corridor*, *movement corridor*, *linear habitat*, *stepping stone* or *landscape linkage*. Bennett (1999) opted to use the terms *link* or *linkage* as over-arching terms that refer to a habitat arrangement, which is not necessarily continuous or linear, that enables faunal movement or ecological flows such as plant dispersal through the landscape. It is important to note that linkages providing for conservation objectives can function at multiple levels; its relevancy stretches from local conservation attempts to regional or national strategies (Bennett, 1999; Wade *et al.*, 2015).

2.5.1 Connectivity

To apply efficient conservation measures for species populations in fragmented landscapes it is thus essential to identify important habitat connectivity pathways and barriers (Braaker *et al.*, 2014). The influence of structural and functional connectivity on the landscape is another central concept contributing to the spatio-temporal dynamics of landscape ecology (Ahern, 2007). Consensus on a single, concise definition of connectivity appears to be elusive, with landscape ecologists arguing that connectivity is an aspect acting out over the whole landscape, while meta-population ecologists propagate a habitat patch-level definition (Calabrese & Fagan, 2004). Landscape connectivity has been broadly defined as the degree to which the landscape facilitates or impedes the movement of species and other ecological flows among resources in the landscape (Tischendorf & Fahrig, 2000). The urgency behind emphasising connectivity is that dispersal (of individual organisms) is a critical ecological process operating at multiple scales (Calabrese & Fagan, 2004). The physical and functional disconnections of ecological networks in the landscape resulting from changing land use are some of the factors contributing to widespread loss of biodiversity (Zetterberg *et al.*, 2010). Landscape processes such as dispersal, gene flow, and “natural ranging” activities are dependent upon habitat which is unconstrained by fragmentation and where connectivity is maintained (Crooks & Sanjayan, 2006). On the other hand, by reducing connectivity through management, negligent processes such as species invasion and pathogen and pest spread can be curtailed (Minor & Urban, 2008).

Crooks and Sanjayan (2006) have highlighted the irony that research on connectivity is heavily focussed on natural areas, which generally experience less rampant habitat fragmentation than urbanised or urbanising areas, and called for a more intentional focus on the situation in urban landscapes. This bias towards natural areas was echoed in an analysis by Park (2015) on contemporary landscape connectivity research. LaPoint *et al.* (2015) have found that research on connectivity in urban landscapes can meaningfully contribute to ecological knowledge and inform management recommendations on a practical level. Indeed, cityscapes in particular demonstrate where the role of connectivity is specifically pertinent towards preserving the flow of ecological processes and the conservation of urban biodiversity (Ersoy *et al.*, 2019).

2.5.2 Connectivity as Green Infrastructure Planning principle

Key principles of landscape ecology, such as multi-scale approaches focussing on the dynamics between pattern and process, and an underscoring of connectivity, are applied to urban environments through green infrastructure approaches (Ahern, 2007). In order to place natural elements in urban areas on par with other infrastructures such as grey infrastructure, the concept of green infrastructure was put forward to plan, design, and develop green and blue spaces that contribute to urban sustainability, human wellbeing, and climate resilience (Ahern, 2007). The importance of connectivity is highlighted by the fact that it constitutes one of the key principles of green infrastructure planning. Other principles include multifunctionality, integration between green, blue, and grey infrastructures, social inclusion, and planning for the long term (Ahern, 2007).

2.5.3 Different connectivity measures

Connectivity is influenced by certain components pertaining to scale and to the species and landscape in question (Tischendorf & Fahrig, 2000). Many researchers agree that connectivity is species-specific, as different species perceive and adjust to the landscape in different ways (Bennet, 1998:8; Pierik, 2016; Saura & Torné, 2009; Tischendorf & Fahrig, 2000). In other words, measures of connectivity should not only take the physical arrangement of the landscape (referred to as structural connectivity) into account, but also the response of species to the landscape in terms of their dispersal or other behaviour (functional connectivity) (Saura & Torné, 2009). According to Pierik *et al.* (2016), such measures of connectivity “should consider both structural and functional aspects of the landscape in a holistic approach” in order for analyses to be objective and truly representative. Calabrese and Fagan (2004) have offered a further differentiation between the concepts of structural, functional, and actual connectivity, in an attempt to clear up the ubiquity around the term connectivity where it relates to the measurement thereof. Due to the fact that connectivity is an ambiguous term in ecology and conservation, misinterpretations may occur which can drastically influence efforts toward its measurement (LaPoint *et al.*, 2015). As differentiated from structural and functional connectivity, actual connectivity is based on observations and other empirical data on movement of species between habitat patches (Calabrese & Fagan, 2004; Fagan & Calabrese, 2006). This distinction was subsequently widely supported by other researchers (e.g. by Galpern *et al.* (2011), Pietsch (2018), Zhang *et al.* (2019), and others).

In order to preserve and even restore landscape connectivity and conserve urban biodiversity, planning and management actions should appreciate the complex workings of social-ecological systems based on the physical landscape as a point of departure (Zetterberg *et al.*, 2010).

Owing to their fine-scale heterogeneity, cities present unique challenges to the analysis of connectivity within their landscapes (Lookingbill *et al.*, 2022). Analysing such complex landscape systems can be accomplished through the use of graph theory as basis (Urban *et al.*, 2009; Zetterberg *et al.*, 2010).

2.6 Connectivity modelling

2.6.1 Graph theory

Graph theory is a branch of mathematics concerned explicitly with connectivity and other issues in networks such as flow and routing (Urban *et al.*, 2009). Graph theory (also referred to as network analysis) has been successfully applied to research in the fields of landscape ecology and conservation biology, especially for those practices grounded in meta-population theory (Urban & Keitt, 2001; Urban *et al*., 2009). As such, it has become widely-used as an instrument for functional connectivity modelling at landscape scale (Galpern *et al.*, 2011).

2.6.1.1 How graph theory applies to landscape ecology

As opposed to the two other data structures (vector and raster) commonly used by ecologists, graph structures represent a landscape using nodes (points) connected by links (lines) (Urban & Keitt, 2001). This makes them useful for the modelling of landscapes, where nodes represent habitat patches and links denote functional connections (such as corridors) or the dispersal of organisms between such patches (Urban *et al.*, 2009; Zetterberg *et al.*, 2010). Where two habitat nodes are within a set distance from each other, correlated with the target species' dispersal range, a functional connection is considered to exist (Zetterberg *et al.*, 2010). Even though graph theory is also known as network analysis, the concepts *network theory* or *network analysis* are actually embedded in the larger subject of graph theory, which itself contains more pure mathematics than is necessarily relevant to landscape ecology (Urban *et al.*, 2009). Network analysis (or theory) is focused on the topological, or in this case, functional connections between graph nodes (Minor & Urban, 2008; Urban *et al*., 2009), and is therefore the preferred terminology in studies of landscape ecology.

2.6.1.2 The functioning of graph theory

The application of graph theory to landscapes (including urban settings) is convenient for quantitatively determining ecological connectivity, as it models how a target species responds functionally to the pattern and arrangement of its local landscape and thereby provides a representation of the spatial network of habitats (Urban *et al.*, 2009). Graph theory (also called network-based) models can exist in the form of either binary or probability models (Saura &

Pascual-Hortal, 2007). While the output of binary models merely shows whether a link is present or not, probability models enable an analysis of *how* connected the network is, as well as evaluating the contribution of individual habitat patches (Zetterberg *et al.*, 2010). Along with graphs, the habitat availability concept considers “a patch itself as a space where connectivity exists”, combining intrapatch connectivity (the habitat area within patches that is connected in itself) with interpatch connectivity (area between different habitat patches that forms connections amongst them) thereby measuring the reachable habitat in the landscape (Saura & Rubio, 2010). Representing the distances amongst nodes in a graph can be done in the form of Euclidian (straight-line) distance, least-cost path distance, or the distance from patch edge to patch edge (Zetterberg *et al.*, 2010). This enables flexibility in application to different analyses at different scales (Saura & Pascual-Hortal, 2007).

Concerning probability models, two habitat availability metrics, Probability of Connectivity (PC) and Integral Index of Connectivity (IIC) have proven to be satisfactory in prioritising landscape features in order for connectivity to be maintained in the landscape and for basing consequent decision-making on (Saura & Rubio, 2010). These are implemented in software, such as Conefor (Saura & Torné, 2009), used for analysing functional connectivity in landscapes.

The low amounts of input data required give graph theoretical methods the advantage of being relatively simple and quick to compute (Urban & Keitt, 2001). Graph models have also demonstrated to be on par with a more complicated model such as the spatially explicit population model (SEPM), which incorporates nine additional parameters in making predictions (Minor & Urban, 2008). Add to that its strong mathematical foundations and efficient algorithms (Zetterberg *et al.*, 2010), and it becomes clear why network analysis is a useful approach in the evaluation of functional connectivity in regional as well as urban landscapes.

As stated earlier in this review, available literature on the subject is in accord that the degree of connectivity in a landscape depends on the species involved and their response to the landscape pattern (Bennett, 1999), and should therefore preferably be analysed functionally and not merely structurally (Saura & Torné, 2009).

2.6.2 Circuit theory

2.6.2.1 The application of circuit theory to connectivity modelling

Building on the principles of graph theory, between 2006 and 2008 an electrical engineer, Brad McRae, introduced circuit theory as a process-driven method of modelling gene flow and the dispersal routes of organisms (Dickson *et al.*, 2019). By incorporating concepts from electronic circuit theory, multiple linkage pathways, instead of only single paths, between connected patches in a landscape could be quantified using its metrics (McRae *et al.*, 2008). This approach has shown to be effective in contributing to knowledge of ecological dynamics and shows strong potential for use by researchers as well as practitioners in the field of connectivity science and conservation in particular (Dickson *et al.*, 2019). McRae *et al.* (2008) also developed an open-source software program called Circuitscape (McRae & Shah, 2009) to assist in executing the concepts in an accessible manner. Subsequent developments produced the Linkage Mapper connectivity analysis software toolbox (McRae & Kavanagh, 2011), consisting of a suite of different scripts in Python packaged as tools in ArcGIS, which automates the mapping of corridors and current flows.

Combining graph theory with electrical circuit theory, Circuitscape assesses habitat connectivity by quantifying the total flow of current through every individual cell of a resistance surface in between pairs of nodes, with one given current and the other set to ground (McRae *et al.*, 2008). A precise relationship has been found between the measuring elements of electronic circuits and their ecological counterparts in random walk theory (McRae *et al.*, 2008). Current flow represents the predicted net movement probability of a random walker, while resistance is represented by each cell's landscape or friction (resistance) value, and voltage represents a random walker's successful dispersal (McRae *et al.*, 2008). In this way, circuit theory can be used to "identify multiple (i.e., redundant) movement pathways or habitat corridors" (McRae *et al.*, 2008). This process could, for example, expose critical pinch points or bottlenecks in the landscape based on the constraint of current flow amongst focal areas.

2.6.2.2 The relevance of circuit theory to conserving connectivity

The fact that circuit theory is able to evaluate multiple possible movement pathways simultaneously gives it an edge over other popular connectivity metrics based on spatial patterns, such as least cost paths (LCPs), which classify the landscape as either suitable or unfavourable (Braaker *et al.*, 2014). Circuit theory also presides over the ability to deliver swift results using a repeatable methodology based on resistance distance as a form of effective distance between patches (McRae *et al.*, 2008). In addition, circuit theory is well-suited to assess connectivity in highly heterogeneous, fragmented landscapes, at local scales, consisting of different land use types; typical of urban areas (Dickson *et al.*, 2019). The contribution of circuit theory methodology to connectivity research is especially pertinent when it comes to the identification of areas or corridors that are crucial to the preservation of network connectivity and where efforts towards mitigating threats to corridors or restoring connectivity would have the greatest impact (Dickson *et al.*, 2019). Since its development, Circuitscape and its resulting software applications have been updated and refined thanks to advances in technological capabilities, a committed team of developers and its broad base of active users (Dickson *et al.*, 2019). This has enabled the platform to conduct analyses on increasingly larger datasets of higher complexity, broadening its functionality towards connectivity modelling in ecology. According to Dickson *et al.* (2019), the trigger for ecological understanding that circuit theory provides will continue to make it a valuable tool for conservation practitioners and researchers globally.

As a relevant example of an application of circuit theory modelling in an urban landscape, Braaker *et al.* (2014) assessed habitat connectivity for hedgehogs in Zurich, Switzerland. Their study made use of cross-validation and found the connectivity model used to be valid when tested against movement data collected with GPS tracking. Their study demonstrated that “even in the complex habitat patchwork of cities”, movement of ground-dwelling mammals was greatly influenced by habitat connectivity. This supports the notion that data-based maps of functional connectivity can thus play a valuable part in identifying habitat corridors and informing plans towards management and conservation of urban habitats to support biodiversity.

CHAPTER 3 METHODOLOGY

3.1 Study area

The area under scrutiny of this study is the city of Windhoek (22°33'47"S 17°04'09"E / -22.563205°S, 17.069283°E), in the Khomas Region of Namibia (see Figure 3-1). It lies approximately in the centre of Namibia, a sparsely-populated country along the Atlantic Ocean in southern Africa.

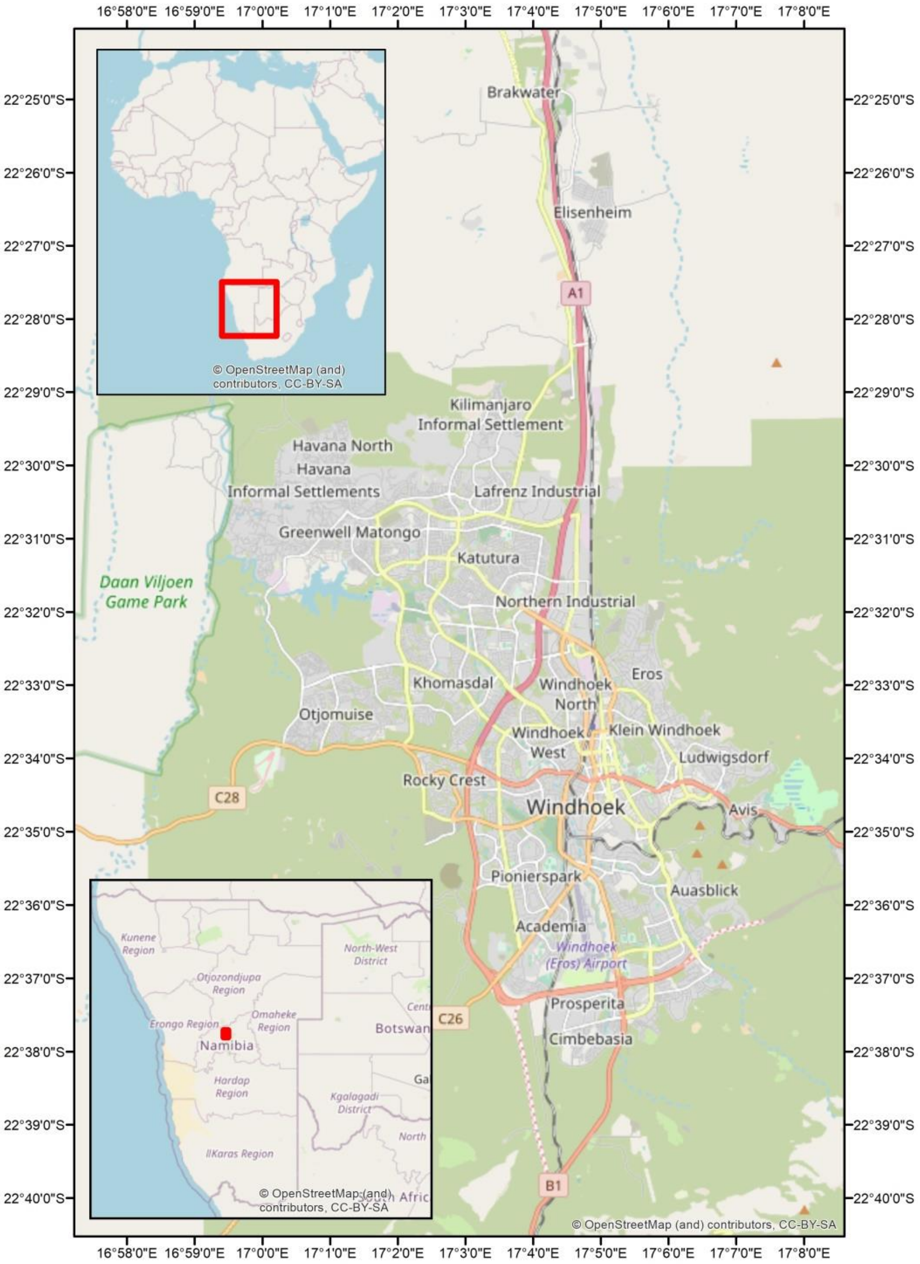


Figure 3-1: Locality map of study area. Basemap: OpenStreetMap

Whereas some semi-arid cities are experiencing a reduction in population, such as Detroit in the USA (Zhang *et al.*, 2019), Windhoek remains an ever-growing city. Windhoek is the capital of Namibia, with approximately 321 000 inhabitants in 2016, projected to reach 470 000 by 2022 (The Atlas of Namibia Team, 2022:307). It houses around 36% of Namibia's urban population (Scott *et al.*, 2018) and 15% of the country's total population of approximately 2.5 million (Shikangalah & Mapani, 2019). With a growth rate of 3.1% per annum (Scott *et al.*, 2018), the city is experiencing a relatively high rate of urbanisation, especially in the informal areas in the north-western parts of the city. This phenomenon places enormous pressure on the city to provide adequately serviced, affordable housing and corresponding services. The lack of adequate housing has led to encroachment of housing structures such as shacks into natural areas outside the city as well as into public open spaces inside more informal areas of the city, mostly along slopes or drainage lines and river courses (Weber, 2017). A relatively clear socio-economic gradient exists in Windhoek, with the poorest households living in the extreme north-west and the most affluent areas generally being in the east and south-east of the city (Shikangalah, 2017). Median expenditure per person is used as a proxy for spending power or wealth to illustrate an overview of this socio-economic gradient in Figure 3-2, which portrays an increase in socio-economic status from the north-west to the south-east of the city.

The built-up area of the city is approximately 18 km long and 12 km wide, and lies in a broad valley with undulating topography around 1 600 – 1 800 m above sea level (Shikangalah & Mapani, 2019) surrounded for the most part by the Eros, Otjihavera, and Auas mountains (Mapani & Schreiber, 2008). Most of Windhoek's uneven substrate is rocky, consisting of biotite schist and quartzites of the Kuiseb formation of the Damara Sequence (Gold *et al.*, 2001; Mendelsohn *et al.*, 2002). The dominant soil type is classified as lithic leptosols (Mendelsohn *et al.*, 2002). As is typical of such soils, the soil horizon has a limited depth, with even the lower areas having shallow sand and gravel layers generally between 1 – 20 cm in depth (Mapani & Schreiber, 2008). As such, these coarse-textured soils have a low water-holding capacity and the relatively low density of vegetation growing there is prone to suffer from drought (Mendelsohn *et al.*, 2002).

Similar to the majority of the country, Windhoek has a hot semi-arid climate (Koppen-Geiger classification type "BSh") and falls within a summer rainfall region (City of Windhoek, 2018) with the average precipitation being 300 - 350 mm per annum (Mendelsohn *et al.*, 2002; Shikangalah & Mapani, 2019). Similarly, rainfall variability is high (Scott *et al.*, 2018), with flash floods occurring some years and droughts in others. Multiple consecutive years of below-average rainfall has led to the city having to implement water restrictions in the past (Shikangalah & Mapani, 2019).

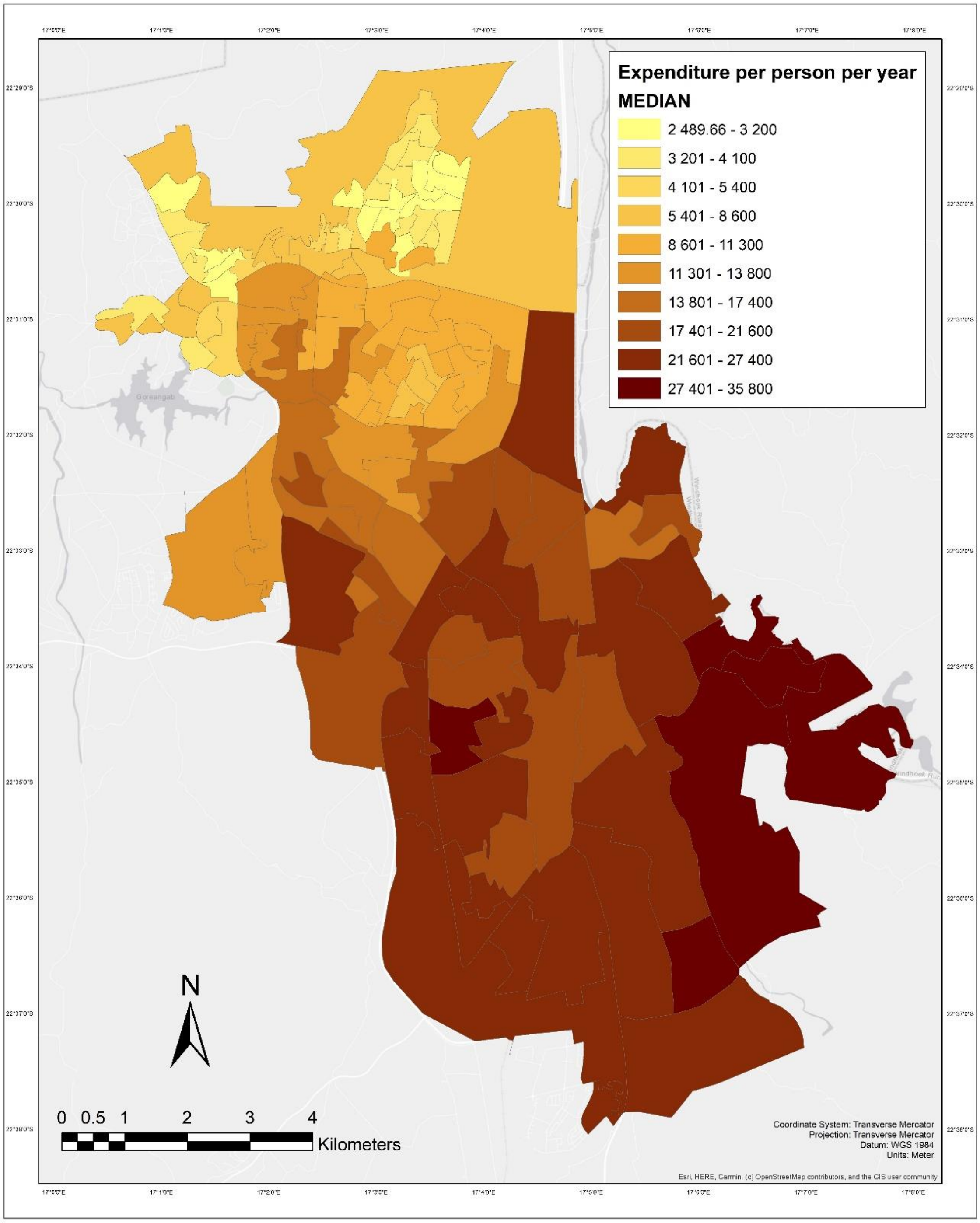


Figure 3-2: Map showing median expenditure (in Namibian Dollars) per person per year as per the different enumeration areas in Windhoek, classified into natural breaks (jenks) with 10 classes and values rounded to the nearest 100. Note that the suburbs of Prosperita, Cimbebasia, the western part of Otjomuise, as well as outward extensions of informal areas around Goreangab and Havana have not been included due to lack of precise data. Source: Adapted from The Atlas of Namibia Team (2022). Basemap: World Light Grey Canvas.

The climatic influence of low rainfall and high evaporation rates, along with the shallow soil character, drives the vegetation status of Windhoek's open spaces (Gold *et al.*, 2001), as the majority are naturally vegetated and don't receive any purposeful irrigation. According to the municipality (City of Windhoek, 2000), it costs a third as much to maintain natural open spaces than it does to maintain parks.

The vast majority of the vegetation type occurring in Windhoek is highland shrubland, along with some thornbush shrubland to a lesser degree (Mendelsohn *et al.*, 2002). The limited vegetation cover consists mostly of *Vachellia* and *Senegalia* shrubs and low-growing trees, annual grasses, and weedy herbs, especially along the river corridors (Gold *et al.*, 2001). Three main ephemeral rivers, the Arebusch, Gammams, and Klein Windhoek (see Figure 3-3), run through the city creating so-called eco-corridors which in effect form the backbone of the city's open space network (IWRM Plan Joint Venture Namibia, 2010).

Open space in and around the city is categorised by the City of Windhoek into four types (City of Windhoek, 2000):

a. Non-urbanised, developable land
b. Proclaimed Public Open Space
c. Mountainous areas and dams
d. Other unproclaimed urban open space

The open spaces scrutinized in this study are mostly erven zoned as Public Open Space and would fall into the second category listed above. Some of the parcels around the ephemeral watercourses are zoned as "undetermined", in order to allow for some flexibility in amending their boundaries, even though they are not to be changed in their character (City of Windhoek, 2000). Some open spaces also function as parks. When it comes to parks, the City differentiates between certain types, based on their character and possible functions, in order to plan for the facilities to be provided there (City of Windhoek, 2000). These include informal playing fields, dog walks, trails, and regional-, city-, suburban-, neighbourhood-, worker's-, and natural parks. In this study, such areas were only changed from Public Open Space to Park for the sake of the analyses where it was clear that the parcel was highly developed for recreational purposes (with artificial structures and lawns, for example) and contained almost no natural elements which could be considered preferred habitat for wildlife.

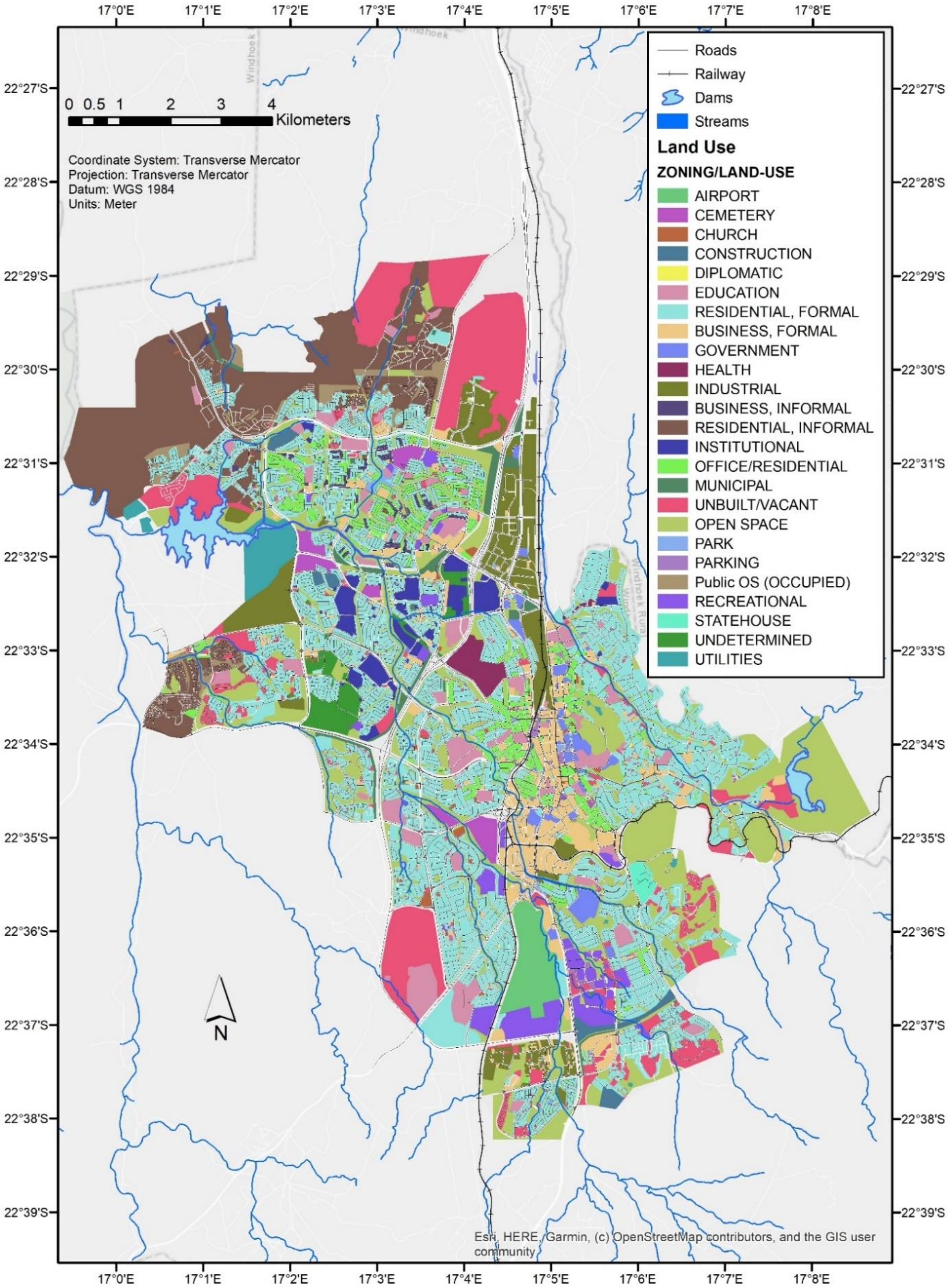


Figure 3-3: Map of Windhoek showing land-use of urban parcels and ephemeral streams. Basemap: World Light Grey Canvas.

According to the municipality document titled “Windhoek Open Space Policy 2000”, Windhoek had 565 proclaimed open spaces on record in the year 2000. It is a goal of the city to have public open spaces available within reasonable distance to all residents (City of Windhoek, 2000), with a distance of no more than 10 minutes’ walk, translating to 800 – 1 000 m, as guidelines. Furthermore, the guidelines suggest 5 000 m^2 of open space per 1 000 people. Taking Windhoek’s population in 2020 into account, this would translate to 225 ha of open space. Based on data used for this study, however, it can be confirmed that the city currently has at least 1 300 ha of open space, not including the so-called “green belt” outside the city. A list of the suburbs differentiated between in this study, as well as the amount of Public Open Spaces (POS) they contain, is given in Table 3-1.

Table 3-1: Suburbs in Windhoek as used in this study (Note that boundaries may differ between source and data used in the study. Also, adjacent open space parcels were counted as one, as lines on a cadastral map don’t necessarily reflect differences on the ground.)

Suburb name:	No. of Public Open Spaces according to CoW (2000)	No. of Public Open Spaces according to study
Academia	10	14
Auasblick	18	18
Avis	-	20
Cimbebasia	6	8
Dorado Park	22	20
Eros	5	17
Goreangab	11	8
Hakahana	6	11
Havana	-	2
Hochland Park	20	18
Katutura Central	92	55
Khomasdal	67	67
Kleine Kuppe	16	17
Klein Windhoek	34	23
Lafrenz	3	2
Ludwigsdorf	-	12
Northern Industrial	-	1
Okuryangava	37	17
Olympia	6	16
Otjomuise	12	22
Pionierspark	38	33

Prosperita	3	5
Rocky Crest	7	18
Southern Industrial	-	5
Suiderhof	-	10
UNAM	-	0
Wanaheda	31	21
Windhoek Central	121	30
Windhoek North		8
Windhoek West		21
Total	**565**	**519**

3.2 Data

Geo-spatial data was used as input to connectivity models based on graph theory (also called network analysis; see section 2.6.1 in Literature Study) for the analysis of the connectivity of open space patches in Windhoek. This geo-spatial data consisted of GIS shapefiles representing hydrological features, such as dams and streams, and other land-use features in the form of cadastral erven, roads, and railways lines occurring within the study area. As this study was conducted in the form of a desktop study, the input data was obtained from third-parties and not from own fieldwork. Spatial data was obtained from academic personnel at Namibia University of Science and Technology (NUST) as well as technical personnel at NACSO (Namibian Association of CBNRM Support Organisations) mostly originating from municipal sources. The Namibia Statistics Agency (NSA) and the Geomatics section of the City of Windhoek were also contacted directly for data but no response was received.

In the source data, open spaces were zoned as public open space (POS) and open or undeveloped erven were zoned in their respective land-use, such as residential or industrial, for example, and labelled as N_built. A process of verifying specifically the open space parcels was undertaken, as it became apparent from the metadata of the supplied open space shapefile (see Figure 3-4) that the data on the open spaces might not be accurate enough to address the objectives of the study. This verification was done by comparing the open space feature classes in the land-use datasets of the different suburbs with a municipality document listing all the formal open spaces in Windhoek (City of Windhoek, 2000). The document listed public open space erven in each suburb within different categories of open space. A basemap of satellite imagery assisted in a remote form of ground-truthing, in discerning whether a parcel listed as open space in the dataset was reflected as such in the imagery. Based on the entries in the above-mentioned document, many parcels were edited and many that were classified as open space were changed to their correct land-use, or those erroneously classified as a different land-use were changed to open space. Google Maps (https://www.google.com/maps) was also used to assist with verification in this regard. In the process, the parcels in the suburb datasets with incorrect land-uses were edited to improve accuracy. Data verification and correction was an extremely time-consuming process, but it is an essential step, because the accuracy of the data directly influences the connectivity results. Examples of the acknowledged quality of some of the other datasets include the feature dataset of the Eros suburb, where a metadata statement indicated it (Figure 3-5). These shapefiles had to be manually corrected in ArcMap (ESRI, 2018).

Windhoek_open_areas_2012_II

File Geodatabase Feature Class

Tags

Windhoek open spaces. Not very accurate, derived from cadastral information, contains also private open spaces.

Summary

for general planning purposes

Description

There is no description for this item.

Credits

Windhoek Municipality

Use limitations

use for general planning, do not use for detailed planning

Extent

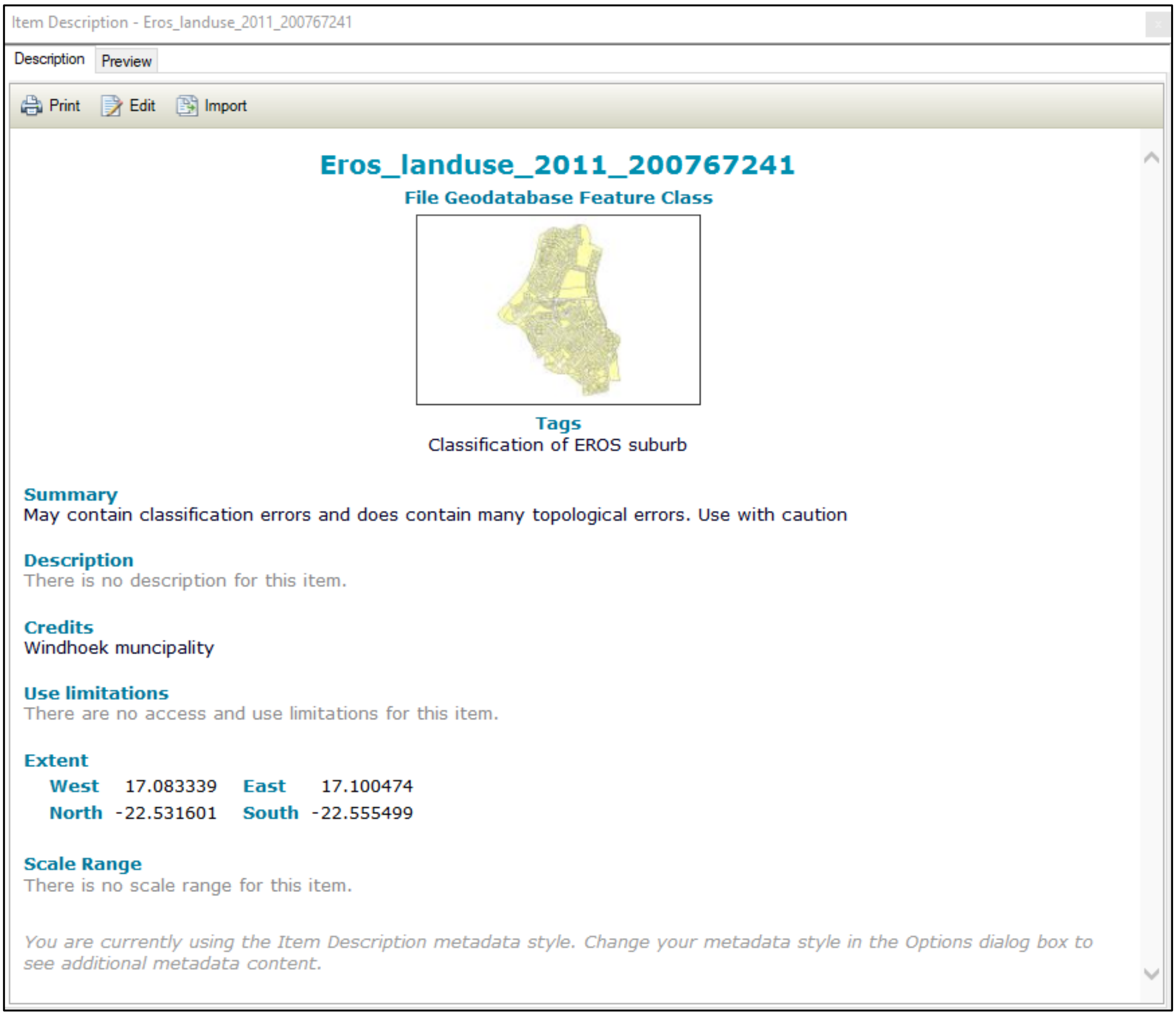
West	17.006552	**East**	17.127066
North	-22.499928	**South**	-22.636343

Scale Range

There is no scale range for this item.

You are currently using the Item Description metadata style. Change your metadata style in the Options dialog box to see additional metadata content.

Figure 3-4: Metadata of shapefile obtained of Windhoek's open spaces, offering a disclaimer of data inaccuracy.



Eros_landuse_2011_200767241

File Geodatabase Feature Class

Tags
Classification of EROS suburb

Summary
May contain classification errors and does contain many topological errors. Use with caution

Description
There is no description for this item.

Credits
Windhoek muncipality

Use limitations
There are no access and use limitations for this item.

Extent

West	17.083339	**East**	17.100474
North	-22.531601	**South**	-22.555499

Scale Range
There is no scale range for this item.

You are currently using the Item Description metadata style. Change your metadata style in the Options dialog box to see additional metadata content.

Figure 3-5: Example of original metadata of Eros land-use shapefile, cautioning prospective users about possible errors in the data.

Of the shapefiles obtained, certain spatial data was also missing. For example, there was no land-use data for the suburbs of Khomasdal, Lafrenz, and Northern Industrial and some missing for Windhoek North, Academia, and Havana. This was supplemented for by copying parcels from a cadastral dataset of the greater Windhoek and surrounding townlands and creating feature datasets of cadastral data for those suburbs. A class in the attribute table specifying the parcels' zoning was used in the absence of specific land-use or land cover designation in the cadastral data. Even so, some parcels did not have any zoning attributed to them and this missing data had to be manually added as part of the verification procedure.

3.3 Analysis procedure

In order for a graph-theoretical analysis of functional connectivity of open spaces to be conducted, a shapefile of the open space patches is required, as well as a resistance raster representing the matrix surrounding the patches (Wade *et al.*, 2015). The outcome of a connectivity assessment based on resistance distance is directly influenced by the heterogeneity of the matrix (how it facilitates or impedes movement between the patches) and not merely Euclidean (straight-line) distances between patches (Dickson *et al.*, 2019). For this reason, a spatial graph representing the study area's physical features must be created with as much realistic representation as possible. The following sections will describe the creation of the so-called core areas and the cost surface raster.

3.3.1 Preparing core area patches

After their validation process (as described in section 3.2), the open space parcels were firstly isolated from the cadastral land-use data using the "Select by Attribute" tool in ArcGIS (ESRI, 2018). These selected areas were then exported as a new multi-part feature representing habitat patches (hereafter referred to as core areas) for the ensuing connectivity analyses. Multiple test runs revealed that some long, continuous polygons did not have only one close connection to other individual polygons but could have several. Therefore, a single least-cost path between them was not a realistic representation of the multiple potential movement corridors between two such adjacent patches. The feature layer contained five such long obscurely shaped polygons. These polygons were subdivided into one or two parts in areas which most closely resembled natural partitions.

The total number of core patches in the study area was 508. Each polygon in the attribute table of the multi-part core area feature was assigned a new unique identification number as a positive integer. This unique ID number, separate from the standard object ID, was necessary for the analysis of core areas using the Linkage Mapper software extension to ArcGIS.

3.3.2 Preparing resistance cost surface

To ascertain how the landscape's arrangement of features influences functional connectivity, resistance surfaces are commonly calculated in a raster GIS setting (Spear *et al.*, 2010). In order to quantify the arbitrary "cost" for an organism of moving across the matrix between patches a resistance cost surface (also called a landscape resistance map) had to be constructed, consisting of a combination of different land-use features into a single resistance surface raster. The land-use features that were used in this study were railways, roads, streams and dams (hydrology), and cadastral zoning. According to a review by Zeller *et al.* (2012), land-use/land cover was the most common variable utilised in modelling resistance to movement, followed by roads, elevation, hydrology, and slope. As this study focussed on how functional connectivity is influenced by the arrangement of features in the landscape, rather than by habitat quality as such, the variables elevation and slope were not factored into the resistance cost surface as they were deemed the least influential. It should be mentioned, as explained by Spear *et al.* (2010), that resistance surfaces are merely representations being modelled and will be subject to certain compromises or assumptions.

The preparation process started with simplifying multipart features using the “Dissolve” tool in ArcGIS on layers such as the streams and the cadastral datasets in order to combine individual attributes of the same type. Secondly, cadastral features of suburbs were cleaned up with the “Integrate” tool using a tolerance of 2 m to address digitizing errors such as overlapping edges and non-shared boundaries. The 29 individual suburb feature datasets were then merged into one single suburbs layer. Furthermore, a 200 m buffer was created around the perimeter of the suburbs and included as part of the suburbs layer. The buffer was assigned a low resistance value and represented the natural areas outside the city as habitat for mammal species, potentially connected to the open space network inside the city. Where land degradation was suspected, based on interpretation of satellite imagery, the buffer was extended around such areas (see A in Figure 3-6), such as new construction sites or areas experiencing urban creeping (the outward expansion of urban structures, often unsanctioned). This was deemed necessary as all areas inside and outside the city that were not characterised by a specific land-use were categorised as NoData cells in the ensuing raster surface of the study area. These NoData cells with no specific land-use were assigned a higher resistance value in the final resistance surface than those areas highly conducive to animal movement such as open space parcels.

Next, the suburbs, hydrology, roads, and railways layers were converted from vector data to raster grid format. The rasters were all created with a cell resolution of five metres (5 x 5 m). This translates to 0.0025 ha each or 400 cells per hectare. This resolution was selected as some significantly large open space patches had a minimum width of 6 m. A similar study on the connectivity of habitat patches for mammals in Haifa, Israel also made use of a 5 x 5 m resolution (see Toger *et al.*, 2016). The resolution used in other city-scale studies of connectivity ranged from 2 m (see Braaker *et al.*, 2014; Ersoy *et al.*, 2019; Verbeylen *et al.*, 2003) to 10 m (see Park, 2015).

After the individual rasters had been created the cell values were reclassified to assign cost weights to each feature class. The assigned weights and the rationale behind them can be viewed in Table 3-2. This is one of the most important aspects of the connectivity modelling process, as it has direct consequences on the outcomes thereof (Wade *et al.*, 2015). The practice of assigning cost-of-movement values to a landscape is still under debate (Zeller *et al.*, 2012) and where empirical data of actual movements is lacking it relies heavily on assumptions of how an organism perceives or experiences the suitability of habitat in a landscape. As no-one truly has certainty about the target species' perspectives, these shall remain assumptions. It must be mentioned that resistance surfaces are "notoriously difficult" (van Strien & Grêt-Regamey, 2016) to define for a specific species, not to mention a group of different species (Spear *et al.*, 2010). As suggested by McRae and Kavanagh (2011) and Wade *et al.* (2015), amongst others, the cost weights were ranged along a gradient from 1 for highly traversable to 100 for highly resistant to movement.

Furthermore, as it was beyond the scope of this study to physically visit each type of land-use in each type of area, assumptions were also made concerning the habitat suitability and general character of the different land-use types. This was based on interpretation of satellite imagery of the study area, as well as casual observations from previous visits to the study area. In addition, literature containing relevant land-use and weight classes was referenced in compiling weights for as many classes as possible. In the few instances where no weight for a specific class was forthcoming from the relevant literature, own judgement was used to assign weights. These judgements were mainly made relative to the weights assigned to other classes in that specific layer.

Table 3-2: Weights used in compiling the resistance surface raster

	Weight	**Reason(s) / Literature support**
Land-use: land-use/zoning		
Open space	1	Most traversable; (Avon & Bergès, 2016; McRae & Kavanagh, 2011)
Municipal/Undetermined/Not built	10	Often under-developed and potentially traversable as corridors; (Zetterberg *et al.*, 2010)
NoData	10	Represents matrix in-between all other land-use types; mostly undeveloped areas such as road verges
Park	30	More developed spaces; relatively low natural quality; not fenced off
Cemetery/Airport	50	Can serve as potential linkages (Gallo *et al.*, 2017; Heunis, 2008?)
Open space – occupied/Low density residential	60	Household/suburban gardens often used as refugia (Grade *et al.*, 2022), but are mostly fenced off in some way in Windhoek. Benefit of the doubt is given as some fence types may be permeable to small to medium mammals.
Recreation/Institution/Church/Edu-	70	Often contain large tracts of underdeveloped

cation		land, although mostly fenced off
Business/Government/Industry/ High density residential	100	High resistance due to abundant grey infrastructure and human activity; (Park, 2015)
Roads: road class		
Residential	20	Lower traffic volumes than local roads
Local	40	(Park, 2015)
Primary/District	60	Primary & district roads in Windhoek have similar character; Higher traffic volumes than local roads
Freeway	80	(Park, 2015); Higher volumes and speed of traffic means higher wildlife mortality risk and deterrence
NoData	0	Resistance weight for the surrounding matrix is already accounted for under *land-use*
Railway		
Railway line	40	Railways in Windhoek less busy than primary roads; mostly not fenced off
NoData	0	Resistance weight for the surrounding matrix is already accounted for under *land-use*
Hydrology: features		
Stream bed	0	Highly conducive to movement, mostly due to riparian vegetation
Dam	60	(Park, 2015)
NoData	1	Represents matrix surrounding streams as slightly less conducive than streams themselves

With reference to the land-use in Table 3-2, the class *low density residential* comprised large (>500 m^2) plots or yards and medium (350-500 m^2) plots in the higher income areas of the city. Whereas *high density residential* referred to small (<350 m^2) and medium (350-500 m^2) plots with more densely constructed housing in lower income areas in the city, as well as townhouses or apartment blocks. The distinction between high and low density residential areas was made to account for the potential role that home gardens play in providing refugia for small to medium mammals (Grade *et al.*, 2022). Studies in South Africa in similar settings have shown that lower income urban areas often have smaller plots with low vegetation cover (Cilliers *et al.*, 2012), reducing the potential of these gardens to act as refugia.

After the four different raster layers representing different landscape features had been assigned the relevant weight classes to their individual features, they were overlaid by summing them together using the “Raster Calculator” tool. In other words, all four layers contributed an equal weight to the resulting raster. Subsequently, the rasters were reclassified again to smooth out certain outlying values. Outlying values occurred as a result of closely adjacent features such as roads and buildings overlapping during the rasterization of vector data, due to the inherent coarseness of the cell resolution. The overlapping cell values are summed and the result is a value that is above the maximum resistance range set. In order to remove such outliers and provide a true representation of the range of resistance values, all counts in the raster’s attribute table less than 200 cells were rounded down and assigned the value of the nearest resistance value. The resulting gradient of values ranged from 1 – 130. These were symbolised using a stretched algorithmic colour ramp with diverging bright red to -green colouring, with the red representing high resistance cost and the green low resistance cost of movement across the landscape (see A in Figure 3-6). As rasters consist of a grid of rectangular cells with a specified resolution they are formed as a right-angled quadrilateral (mostly a rectangle) around the input features of an area in question.

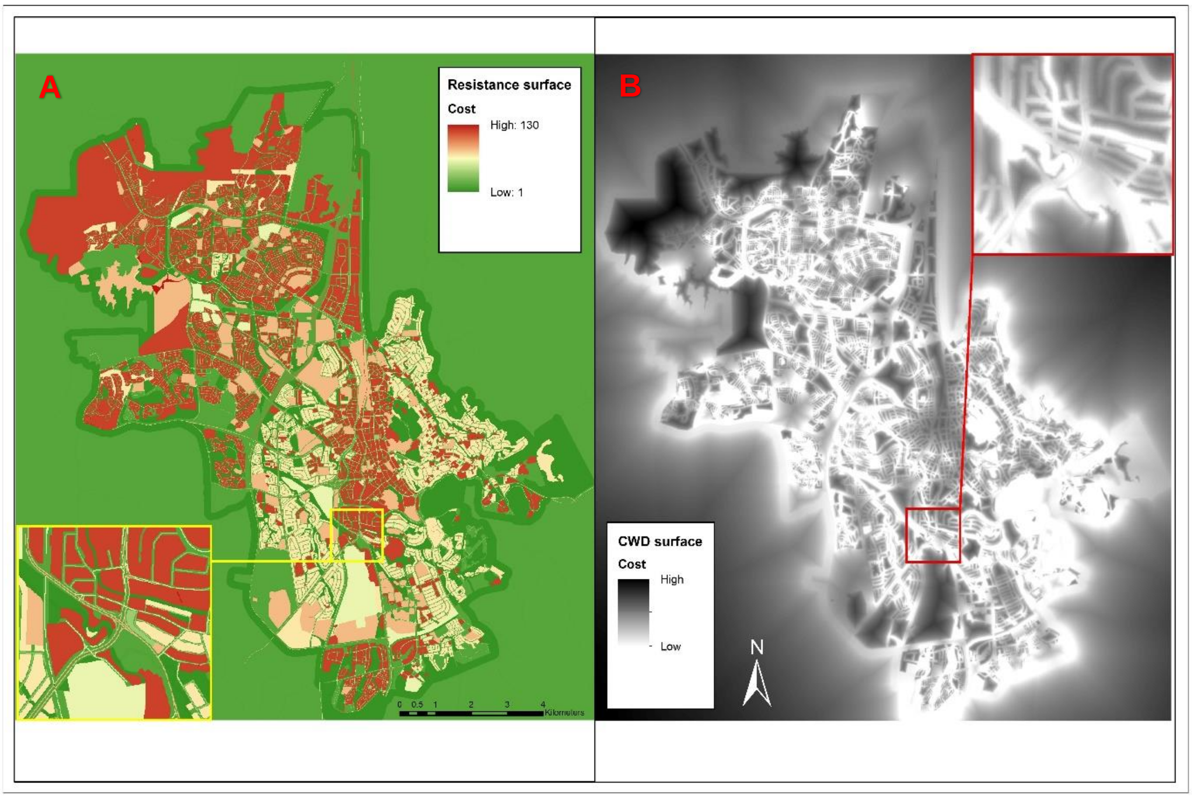


Figure 3-6: Maps of (A) resistance surface raster created, and (B) cost weighted distance (CWD) surface raster created by Linkage Pathways tool. Inset maps show same sample area in closer detail. To provide a more intuitive display of the CWD surface a gamma stretch of order 2 was applied to the symbolisation of the CWD surface raster.

Many connectivity studies make use of expert opinion as a form of input in setting up a resistance (or conversely, a permeability or suitability) surface (Zeller *et al.*, 2012) and/or critically evaluating it (Pierik *et al.*, 2016). The expert opinion approach has been criticised for its subjectivity (Spear *et al.*, 2010), moreover, because the current study was designed only to test the applicability and usefulness of the circuit theory modelling methodology (see section 3.3.4), only published literature was used to aid in decision making regarding resistance surface creation without including expert opinion.

3.3.3 Distances between connected patches

The advantage that measurements of functional (or potential) connectivity have over that of structural connectivity lies in the fact that dispersal distances are used to measure the reachability of patch habitat for species. Previous studies have also shown that using straight-line distances between patches provides a less realistic representation of terrestrial animal species' dispersal through a heterogeneous landscape mosaic as it doesn't account for quantifying the movement possibility or mortality risk to species (Avon & Bergès, 2016), often referred to as effective distance (Spear *et al.*, 2010). Subsequently, this study made use of cost weighted distance (CWD) cut-offs as a more realistic method of quantifying whether two patches are within dispersal range of each other or not.

In order to visualise the relationship between the size of the largest component (group of connected patches/cores) and the maximum Euclidean interpatch distance, the Patch Distance Analysis (also referred to as component analysis) tool of the MatrixGreen extension (Bodin & Zetterberg, 2010) was used. The output is useful to discern whether there are any critical thresholds in interpatch distance in the landscape. The resulting graph was also consulted in deciding on the range of CWD's to be used in the models. The inputs to this tool are simply the core areas feature and a range of straight-line distances with set intervals between them. Refer to section 4.2 for a replica of the graph generated.

Urban-dwelling animals, especially carnivores, are inclined to have significantly smaller home range sizes than in natural areas outside cities, ascribed mainly to a higher availability of food sources generally present in urban areas (Bateman & Fleming, 2012). Reliable literature on the local mammal species' dispersal distances were lacking for most of the species occurring in Windhoek, except for yellow mongoose (*Cynictis penicillata*). In a study on yellow mongoose in a so-called "eco-estate" in an urban area, Cronk and Pillay (2020) found their average total home range to be almost 15 ha, of which the square root would be 387 m. For this study's connectivity analyses, rather than using a single maximum interpatch distance, a range of cost weighted distances were used in order to allow for variation in model parameterization and to account for different behaviour patterns of the local mammals as well as variations in temporal scale (e.g. Avon & Bergès, 2016). The three maximum cost weighted distance thresholds applied in the models were 500 m, 1 000 m, and 1 500 m.

Also, it should be kept in mind that the geographic distance an animal travels between two patches, even along a least-cost path (LCP), is not the same as the resistance distance (RD) accumulated. The latter would be higher than the geographic distance as animals don't necessarily know and follow the optimal route with the least cost (Avon & Bergès, 2016). In addition, whereas modelling an LCP only indicates a single possible pathway, least cost corridors based on RD have the necessary redundancy to permit multiple possible pathways. Accordingly, making use of cost weighted distances represents a more realistic measure of the dispersal possibility by quantifying multiple movement paths or zones in a landscape (Dickson *et al.*, 2019).

3.3.4 Linkage Mapper and Circuitscape analyses

In analysing the functional connectivity of Windhoek's open space network following graph theoretic principles, circuit theory (see section 2.6.2 in Literature Review) was decided upon as a method of mapping multiple possible least-cost corridors among open space patches, as opposed to mapping single LCPs. It's ability to deliver swift results using a repeatable methodology based on resistance distance as a form of effective distance between patches (McRae *et al.*, 2008) largely influenced this decision.

In electronic circuit theory, the landscape under study is conceptualised as a conductive surface in an electrical circuit where each grid cell represents the resistance in that part of the landscape, with the current flow providing a representation of the swath of movement probabilities of an individual animal (McRae *et al.*, 2008). Following from this, circuit theory can also be applied to assess the density of current flow in the landscape, with high densities pointing to areas where current flow, and by extension movement probability, is constrained by pinch points or bottlenecks. This information can then be used to identify corridors or linkages whose removal would lead to a disproportionately high loss of connectivity to the network. To achieve this, the software package Linkage Mapper was used. Linkage Mapper is an open-source toolbox developed by McRae and Kavanagh (2011) run as an extension to ArcGIS consisting of various Python scripts, of which some reference Circuitscape (McRae & Shah, 2009), an open-source software package based on electronic circuit theory modelling.

The Linkage Pathways tool in Linkage Mapper automates the mapping of corridors between habitat patches based on the CWD surface it computes, thereby providing the initial output which all the subsequent tools reference from. Input to the tool consists of the core areas feature mentioned before in section 3.3.1, the resistance surface raster created (see section 3.3.2 and A in Figure 3-6), as well as a text file containing the cost weighted and Euclidean distances between all core areas. This text file was created by the tool through ArcGIS Desktop Advanced. Output of the tool includes multiple cost rasters showing how the CWD increases outward from each core area. These rasters are then mosaicked (combined) into a single CWD raster presenting a cumulative current map of the study area (see B in Figure 3-6) which is used to compute least cost corridors between core areas. Where the resistance distance between two cores is below the maximum threshold value set in the model, current can flow between the cores and a least cost corridor is mapped.

In order to assess the contribution of each core area and LCP link in keeping the total network connected, the Centrality Mapper tool of Linkage Mapper was run. Centrality Mapper calculates current flow centrality across the network by analysing the vector LCPs created with the Linkage Pathways tool (McRae, 2012b). As a measure of patch importance, the results from this tool are useful in indicating where the loss of a core area or linkage would have run-on detrimental effects on the connectivity of the rest of the network.

The Pinchpoint Mapper tool in the Linkage Mapper toolbox was used for assessing vulnerable linkage corridors in the habitat network. The tool also builds on the results from the Linkage Pathways tool and runs Circuitscape to produce current maps of raster centrality (McRae, 2012a). In the resulting maps, areas with high current flow indicate that corridor redundancy is low and movement would be constrained in these bottlenecks or pinch points, thereby highlighting such linkages as highly important in keeping the whole network connected.

CHAPTER 4 RESULTS AND DISCUSSION

4.1 Introduction

As mentioned earlier (see section 1.3 in Chapter 1), in highly heterogeneous, fragmented landscapes such as cities, connectivity between habitat patches is important for the preservation of ecosystem functioning relying on ecological flows, such as animal dispersal, between the remaining habitat sources. Without functional connectivity of habitat areas ecosystems would not be able to function effectively, resident populations would become genetically isolated, habitat quality would decline and local extinctions may occur, leading to reductions in habitat quality and an overall loss of biodiversity (Spear *et al.*, 2010). Well-directed actions to preserve and even enhance the integrity of habitat network connectivity could halt and possibly reduce the negative effects of habitat fragmentation and biodiversity loss. Identifying priority areas keeping the habitat network connected would aid in the effectiveness of such conservation actions. Circuit theory, as applied to model multiple possible movement paths and current flows between habitat cores, provides an effective methodology of quantifying and visualising the state of a network's functional connectivity.

In this chapter, GIS results of mapped least cost corridors and current flow densities will be presented for the city of Windhoek, Namibia. These results will be discussed in light of their meaning and significance, with references to applicable literature, where such is available. The discussion will show the importance and applicability of this relatively novel approach of assessing ecological connectivity for the first time in a semi-arid Sub-Saharan African city.

4.2 Patch distance analysis

In order to assess the open space network of Windhoek and to ascertain whether there were any critical thresholds in terms of distance between open space patches, a so-called component analysis was performed using the Patch Distance Analysis tool in the MatrixGreen toolbox. Note that the analysis uses Euclidean (straight-line) distances and not cost weighted distances (CWDs). Refer to Figure 4-1 for a graph showing the results of this analysis. Based on the results illustrated by the diagram, it can be seen that from a straight-line distance of around 900 m between patches almost all open space patches were connected to each other in a single component (group of connected patches). Stated otherwise, almost all open spaces in Windhoek were within a single, connected component beyond a straight-line interpatch distance of approximately 900 m. As explained by Pierik *et al.* (2016), Saura and Torné (2009), and Tischendorf and Fahrig (2000), connectivity is a species-specific attribute and this must be kept in mind when interpreting this result. For a non-flying invertebrate to disperse 900 metres would be unlikely, but for a medium-sized mammal this distance would not be improbable, when considering the dispersal distance of medium-sized mammals occurring in the greater Windhoek area, such as black-backed jackal (*Canis mesomelas*), for example. The focus in this study on small to medium terrestrial mammal dispersal distances to inform modelling parameters is not unique as mammals are a frequently used indicator in landscape ecological studies. A review by Dickson *et al.* (2019) found that mammals were the most common vertebrate group sampled in studies making use of circuit theory.

The maximum threshold cost weighted distances used in the study's analyses were 500 m, 1 000 m, and 1 500 m. This range of distance used compensated for variation in the parameterization of the model, for variation in dispersal distances of the different size mammal species occurring in Windhoek, as well as allowing for the spatio-temporal range in behaviour patterns of the species (such as daily foraging movement through to lifetime dispersal), similar to an applicable approach by Avon and Bergès (2016).

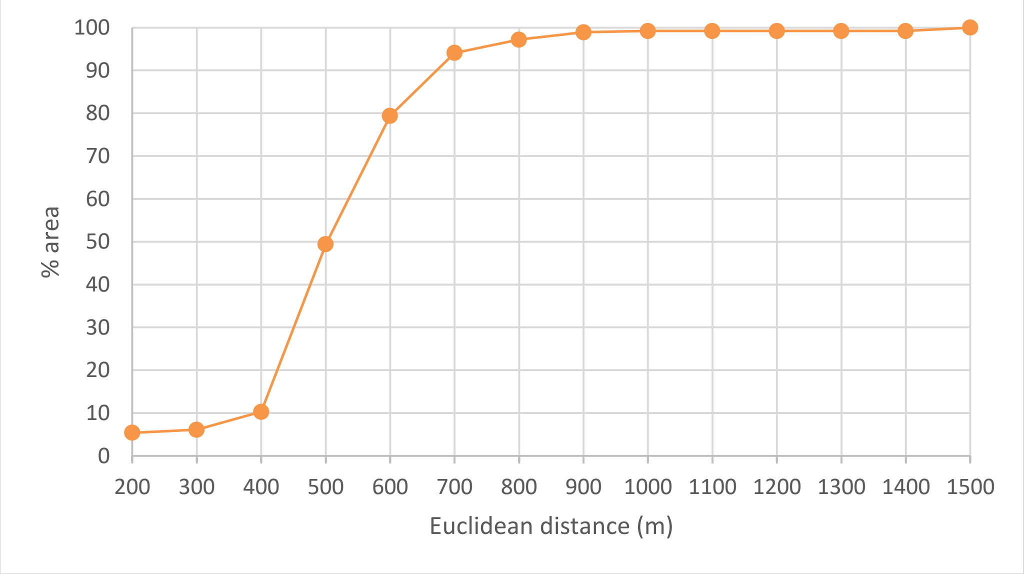


Figure 4-1: Graph indicating the results of a component analysis (also called patch distance analysis) with minimum distance 200 m and maximum distance 1 500 m with 100 m intervals. The percentage area of the largest component of patches remains the same after 1 000 m.

4.3 Least cost corridor mapping

The results from the Linkage Pathways tool executed are the normalised least cost corridors (NLCCs) mapped in figures 4-2, 4-3, and 4-4 between habitat core areas in Windhoek. Least cost corridors were truncated (limited in their extent) to the same CWD as was used for their maximum threshold calculation. This was done in order to symbolise the corridors in the most intuitive manner, as well as to show the reaches of the maximum CWD modelled. The style used in symbolising was imported into ArcGIS from the Linkage Mapper package as the preferred style for symbolising least cost corridors. Stretched rendering is used for displaying continuous raster cell values, with the gradual colour ramp here ranging from yellow to black for low cost to high cost values, respectively.

As can be seen from the map in Figure 4-2, the NLCCs mapped for the 500 m maximum CWD threshold are not visible between most core areas. This is because the calculated CWD between the majority of habitat core areas in Windhoek exceeds 500 m, except for those cores which are close together or have no highly resistant feature between them such as a primary or district road. Also note from the inset map in Figure 4-2 that there are no corridors formed between the cores on either side of the dual road (Mandume Ndemufayo Avenue) running approximately north-south on the map (compare with inset map in Figure 4-4).

In Figure 4-3, the mapped NLCCs at 1 000 m maximum CWD threshold are more noticeable than those mapped in Figure 4-2. This shows that there are more pairs of core areas connected to each other than there were for the 500 m maximum CWD threshold. However, note from the inset map that there are still no corridors mapped between the core areas on either side of Mandume Ndemufayo Ave.

At 1 500 m maximum CWD threshold the NLCCs in Figure 4-4 are noticeably more and longer than in the previous maps, especially around the core areas lying at the edge of the city to the south-east. Notice from the inset map that corridors are mapped at various places between the core areas on either side of Mandume Ndemufayo Ave.

The higher abundance of corridors modelled around the southern and western periphery of the urbanised areas can be attributed to the presence of natural habitat directly adjacent to the core areas. In contrast, where there are core areas close to the urban fringe in the north and west, there are often roads or informal residential areas between them and the natural habitat beyond the city, which would have affected the modelling of least cost corridors. This can be substantiated by van Strien and Grêt-Regamey (2016) stating that habitat network integrity is threatened by anthropogenic networks such as roads and that their influences can reduce habitat connectivity for animals.

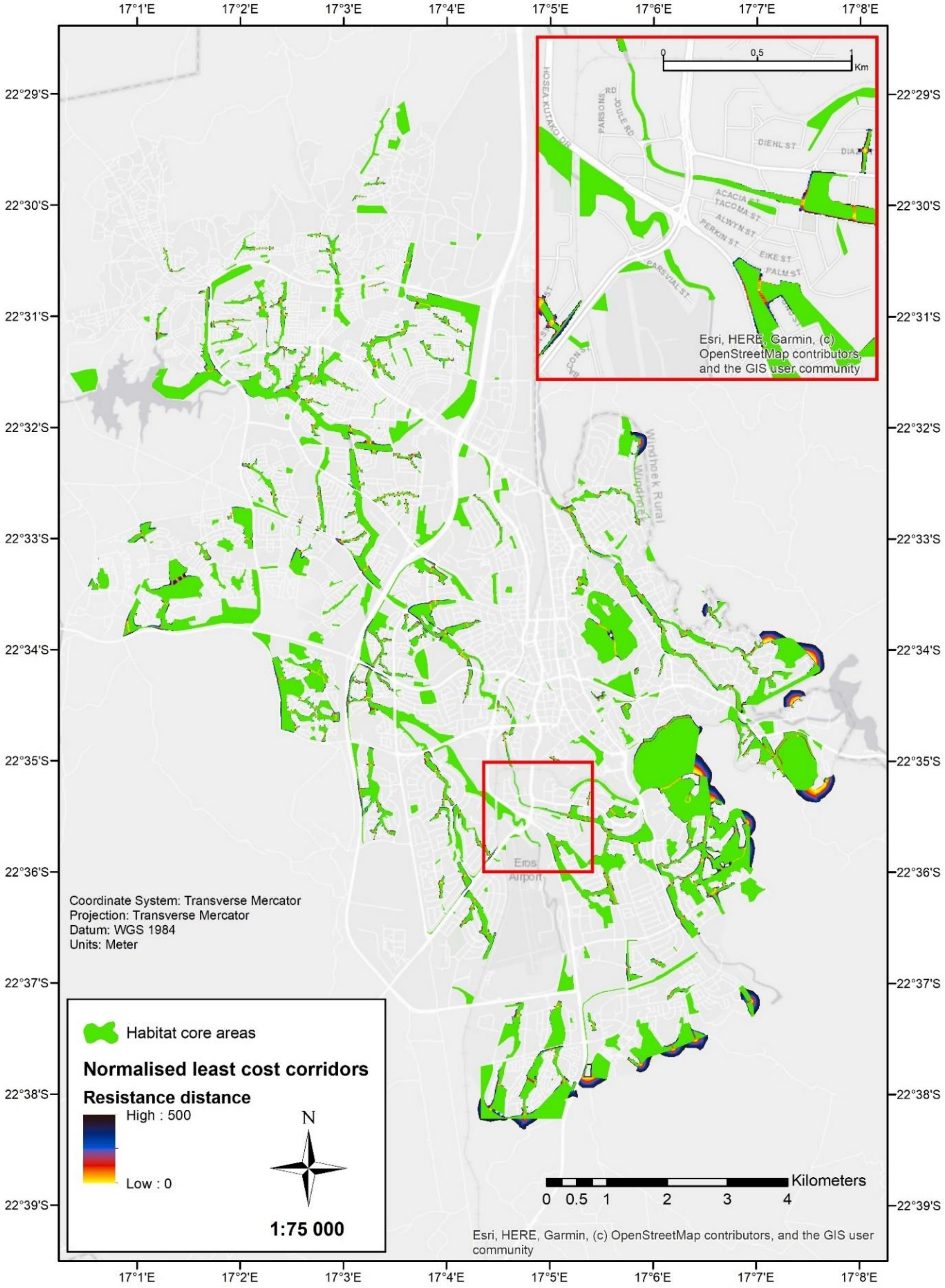


Figure 4-2: Map of Windhoek showing habitat core areas and normalised least cost corridors (NLCCs) with 500 m maximum cost weighted distance (CWD) threshold between them. Inset map shows closer detail in the sample area. Basemap: World Light Grey Canvas Base.

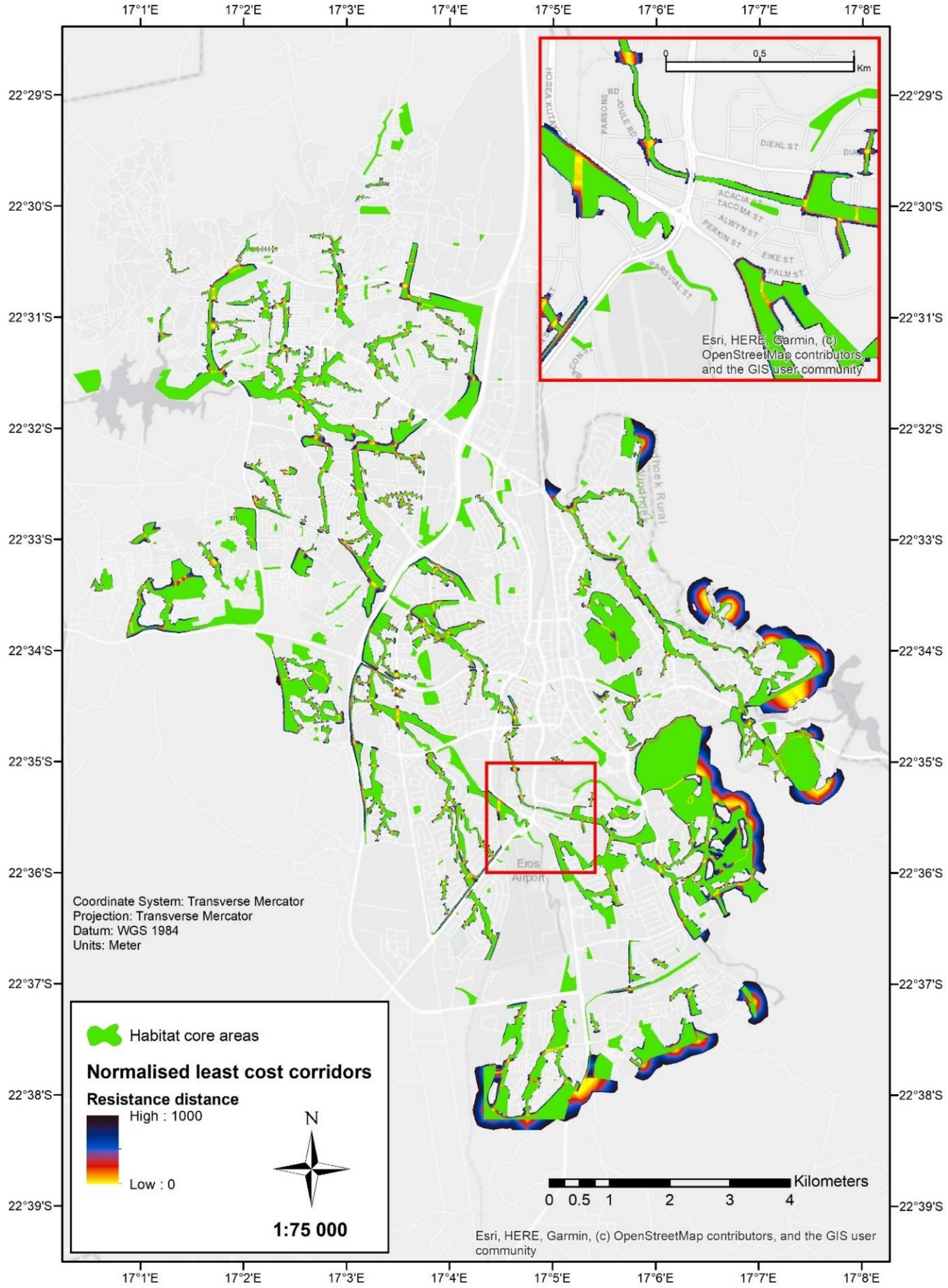


Figure 4-3: Map of Windhoek showing habitat core areas and normalised least cost corridors (NLCCs) with 1 000 m maximum cost weighted distance (CWD) threshold between them. Inset map shows closer detail in the sample area. Basemap: World Light Grey Canvas Base.

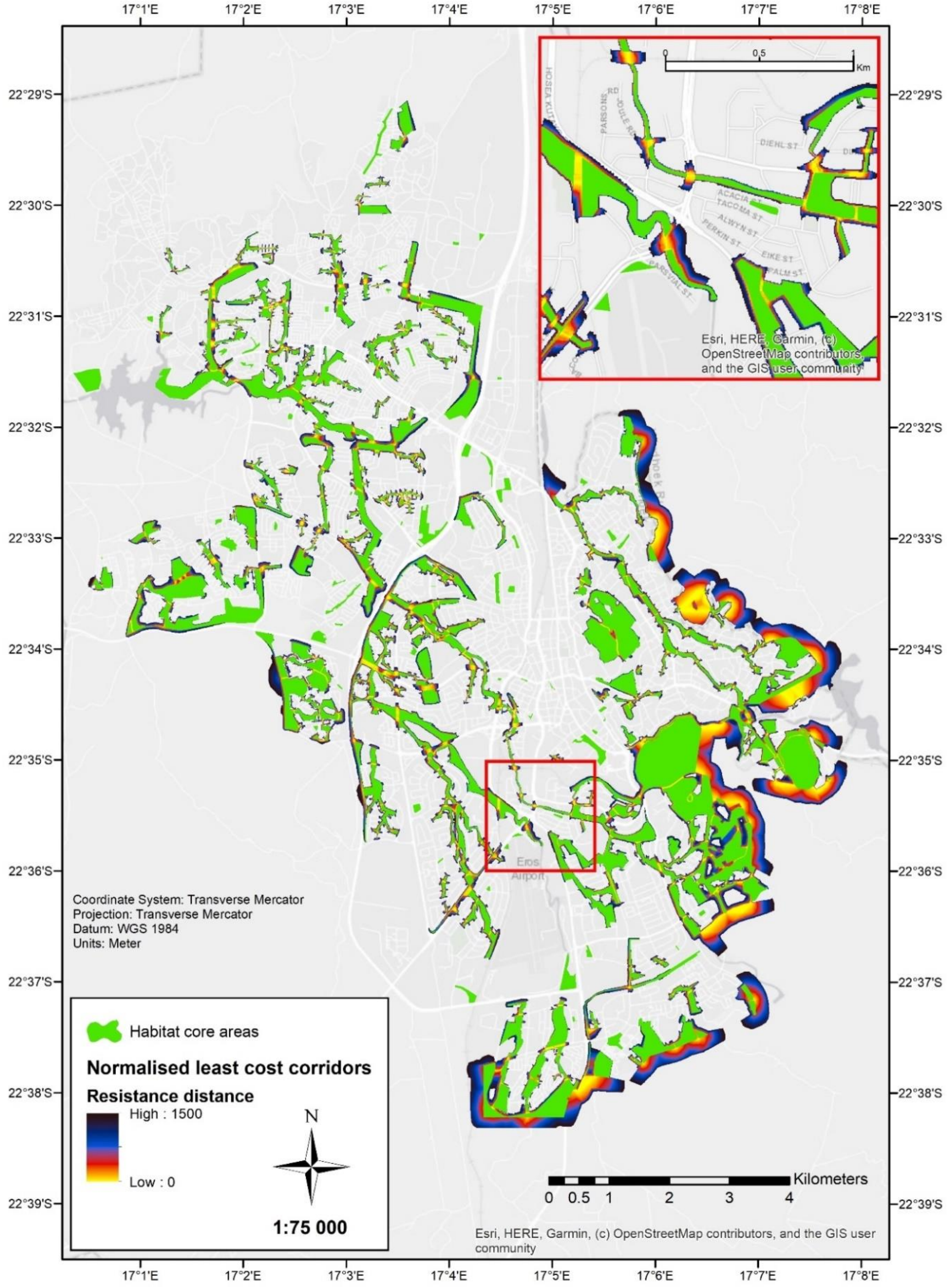


Figure 4-4: Map of Windhoek showing habitat core areas and normalised least cost corridors (NLCCs) with 1 500 m maximum cost weighted distance (CWD) threshold between them. Inset map shows closer detail in the sample area containing the only linkage connecting the eastern and western parts of the open space network. Basemap: World Light Grey Canvas Base.

4.4 Pinch points and centrality mapping

The results of the Pinchpoint Mapper tool are based on a current flow density metric. These mapped flows of current density illustrate estimations of the net probability of movement (or flux) of random walkers through a given grid cell (McRae & Beier, 2007). High density of current flow means current flow is constricted in that area due to structural impediments, such as road networks with busy traffic (van Strien & Grêt-Regamey, 2016). Low current flow density can mean there is no structural hinderance between a pair of patches and that the least cost corridor is broad and therefore high in redundancy. Linkage redundancy reflects the number of likely alternative pathways between habitat patches (Dickson *et al.*, 2019). Higher redundancy means a higher likelihood of the linkage remaining intact if a pathway is lost, thereby making it more robust and resilient to preturbations. The ability to visualise the width of corridors can give decision makers or planners a more comprehensive idea of the contribution of a linkage to keeping the network intact (McRae, 2012a).

Only the Pinchpoint Mapper results for the 1 500 m CWD cutoff are mapped here (see Figure 4-5), as it was considered more intuitive to display the maximum amount of pinch-points or bottlenecks presented by the analyses than to give the pinch-points modelled for each of the three CWD thresholds seperately. The results for the 500 m and 1 000 m threshold distances are therefore contained in the larger 1 500 m results as shown in Figure 4-5.

In symbolising the results from Pinchpoint Mapper, the raster cells illustrating current flow density were truncated at 1 500 m CWD, same as the cost width of the corridor, similar to the approach of Avon and Bergès (2016). The “partial spectrum” colour ramp was used, ranging from dark blue for low current density to yellow for high current flow density. The Pinchpoint Mapper tool references Circuitscape (McRae & Shah, 2009) and produces maps of current flow that identifies and maps pinch-points or bottlenecks (choke points) based on constrictions of current flow in least-cost corridors (McRae, 2012a).

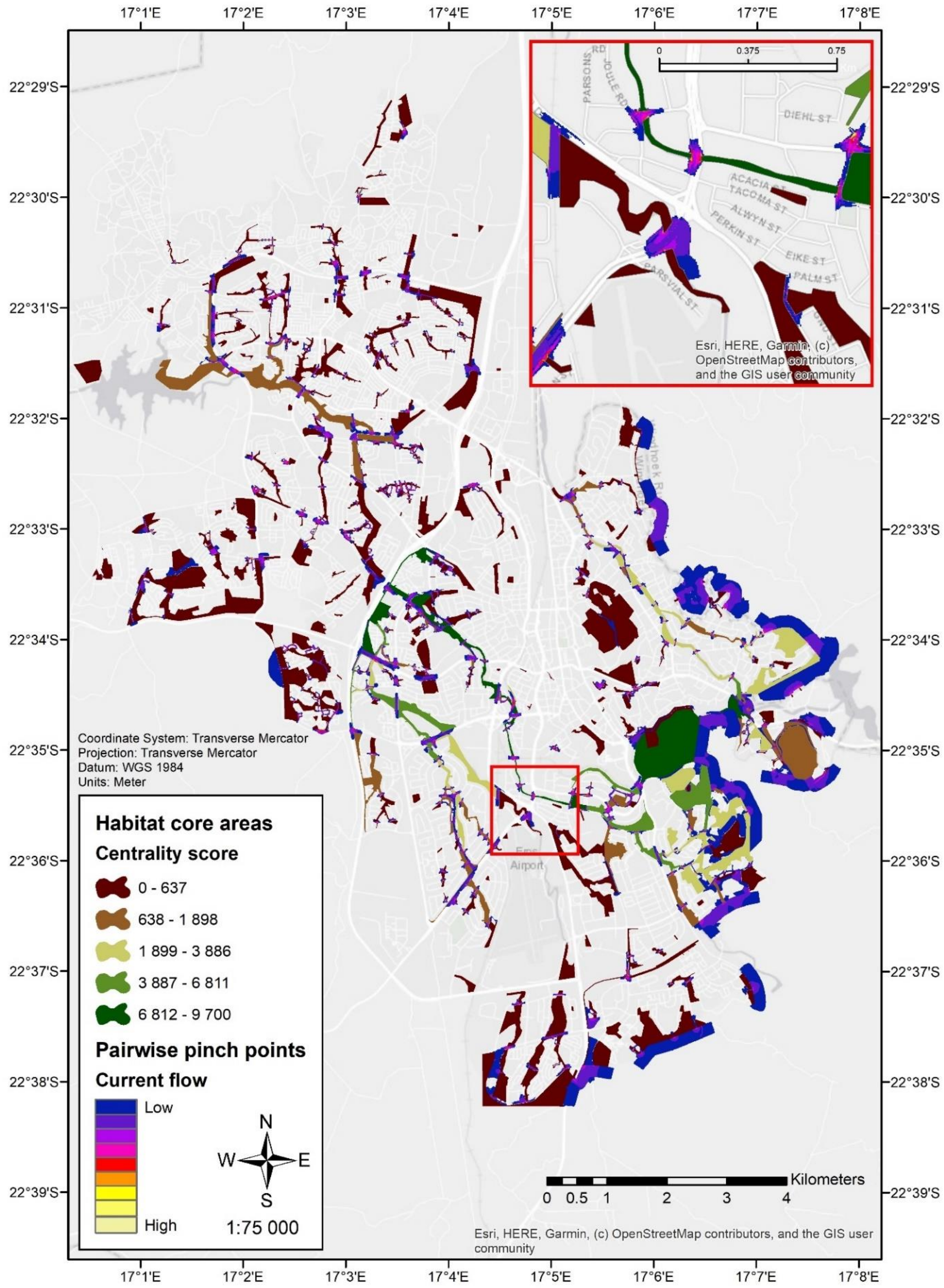


Figure 4-5: Map showing centrality scores of core areas and density of current flow between them at 1 500 m maximum cost weighted distance (CWD) cut-off. Inset map shows closer detail in the sample area. Basemap: World Light Grey Canvas Base.

4.5 Potential for improvements to the open space network's connectivity

4.5.1 Rationale for improvement potential

The goal of the improvement analysis conducted was to showcase an example of how circuit theory and Linkage Mapper tools can be used to investigate and model areas which have the potential to improve as much of the city's open space network as possible, with the least amount of effort and resources (i.e., the most cost-effective manner) by prioritising areas that are critical for the preservation of the network and the conservation of urban biodiversity and ecosystem functioning. Thereby, city managers can ensure that valuable linkages are enhanced and that they are not lost through new developments which are guided by decisions made without knowledge of the relevant ecological processes acting out in Windhoek's open space network.

The mapped results of the Pinchpoint Mapper and Centrality Mapper tools were visually interpreted and scrutinized with the aim of identifying areas showing promise of improvement potential. Specific attention was paid to areas where core pairs had the lowest class of centrality score and were relatively close together, without an obvious highly resistant matrix in between. These areas were evaluated for the size of the component that they would potentially be responsible for connecting. The following paragraphs will briefly describe some areas worthy of mentioning, before explaining the specific improvement potential analysis performed.

4.5.2 Example neighbourhood 1

The map in Figure 4-6 provides an example of specific areas in the lower-income suburbs of Otjomuise and Khomasdal where there are no connections between certain cores according to the 1 500 m CWD cut-off model. As a result, the cores in those areas have a low centrality score. From interpreting the mapped results, however, it can be deduced that prioritising the conservation or enhancement of certain potential linkages in those areas could increase their ability to facilitate the movement of species with lower dispersal distances over distances of higher cumulative resistance. Refer to the red ellipses drawn in Figure 4-6 as specific places of interest for possible improvement. As can be visually interpreted from the satellite imagery, all these places of interest are seemingly relatively undeveloped, making them suitable for improvement as potential linkages.

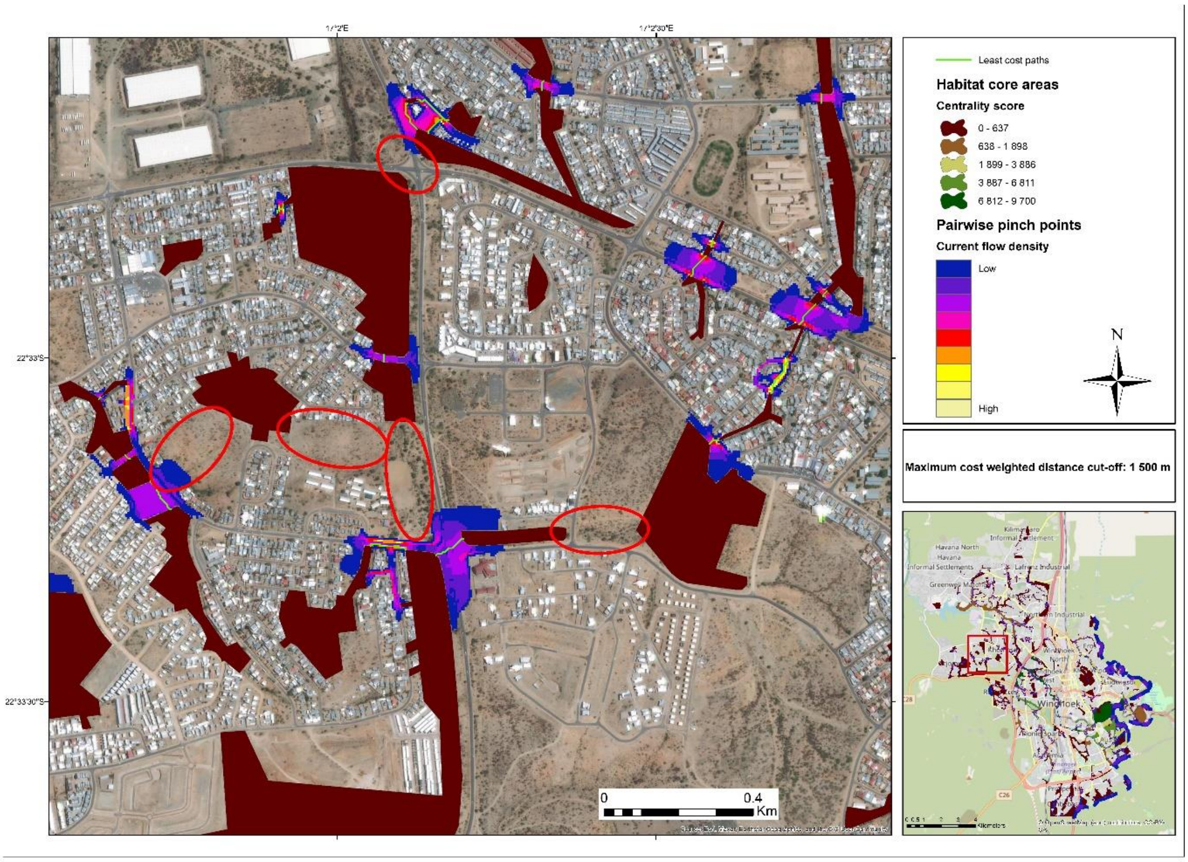


Figure 4-6: Map showing specific areas (indicated by red ellipses) in the suburbs of Otjomuise and Khomasdal which, if enhanced to serve as linkages, could improve the connectivity of the open space network in Otjomuise. Basemap: Satellite Imagery basemap

4.5.3 Example neighbourhood 2

Figure 4-7 shows another example of areas where linkages between core areas can be enhanced to improve the connectivity of a large component of the open space network. The upper red ellipse on the map shows a portion of the Gammams riverbed just north of Moses Garoëb Street and directly west of the Western Bypass dual carriageway. The lower red ellipse on the map shows a portion of the Arebusch riverbed to the south of Moses Garoëb Street and directly west of the Western Bypass. Both these riverbeds pass under the Western Bypass through large culverts. As can be seen on the satellite imagery map in Figure 4-7, these potential linkages are naturally more vegetated than the surrounds, providing natural habitat for mammals to utilise as cover when using the riverbeds as corridors to move through the open space network. Judging by the relatively high difference in centrality score between the nearest cores in Khomasdal to the west and those in Dorado Park to the east, improving the potential linkages between these cores would significantly increase the connectivity of the open space network in these suburbs (see section 4.5.5 for improvement suggestions).

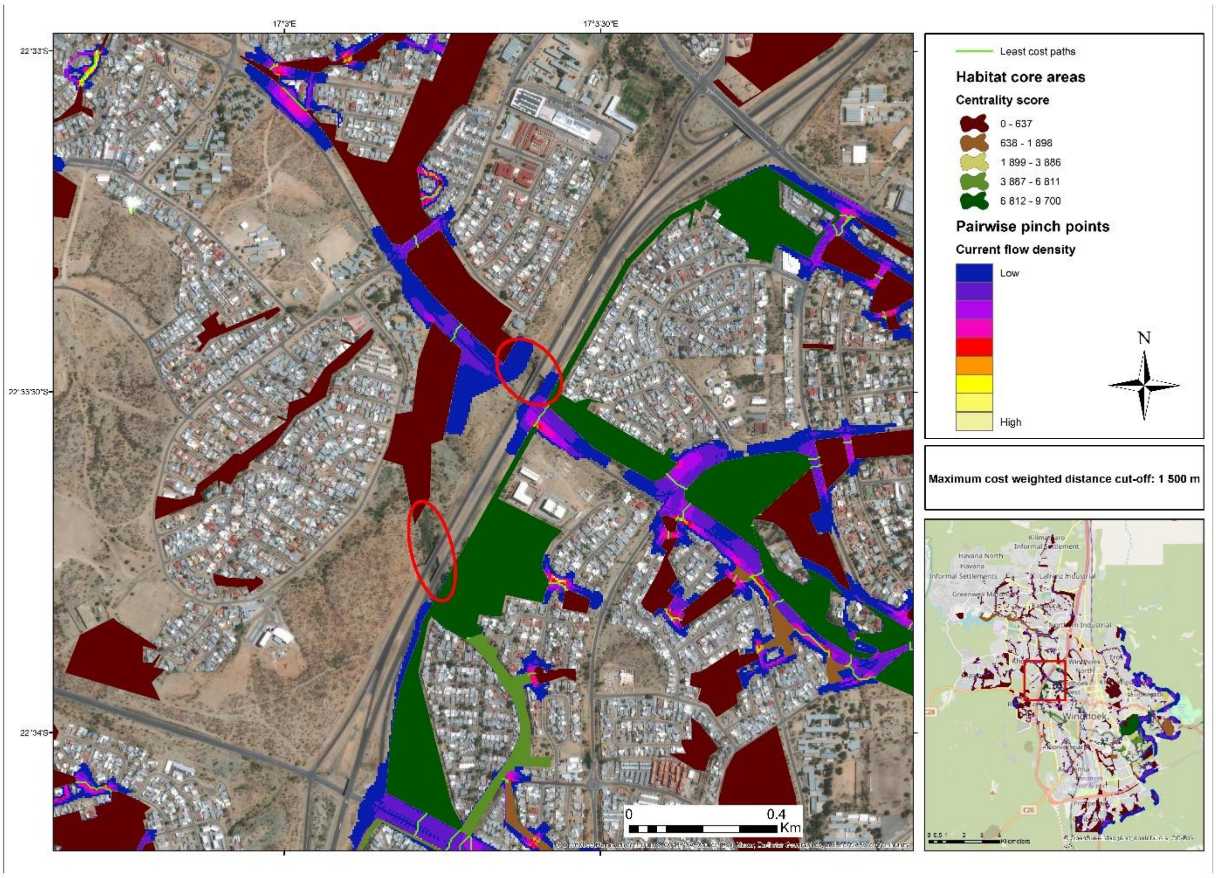


Figure 4-7: Map showing specific areas (indicated by red ellipses) between the suburbs of Khomasdal and Dorado which, if enhanced to serve as linkages, could improve the connectivity of the open space network in both suburbs. Basemap: Satellite Imagery basemap

4.5.4 Sample area

As can be seen in the map in Figure 4-4, at the 1 500 m maximum CWD cut-off a single linkage connects the western part of the city's open space network, mostly formed by the Gammams and Arebusch riverbeds, to the eastern part of the city's open space network, influenced to a lesser extent by the Gammams and Klein Windhoek riverbeds. This specific linkage (link #487) exists in such a highly built-up area because of the Gammams river passing under Mandume Ndemufayo Avenue in Suiderhof. Underneath this dual road is a culvert around one metre in height which forms the corridor. The centrality score of the linkage is calculated by the Centrality Mapper tool as 9 120, which is very high, relative to the range of centrality scores modelled. This score shows that the linkage has a high contribution, and is therefore highly important, in keeping the entire network connected.

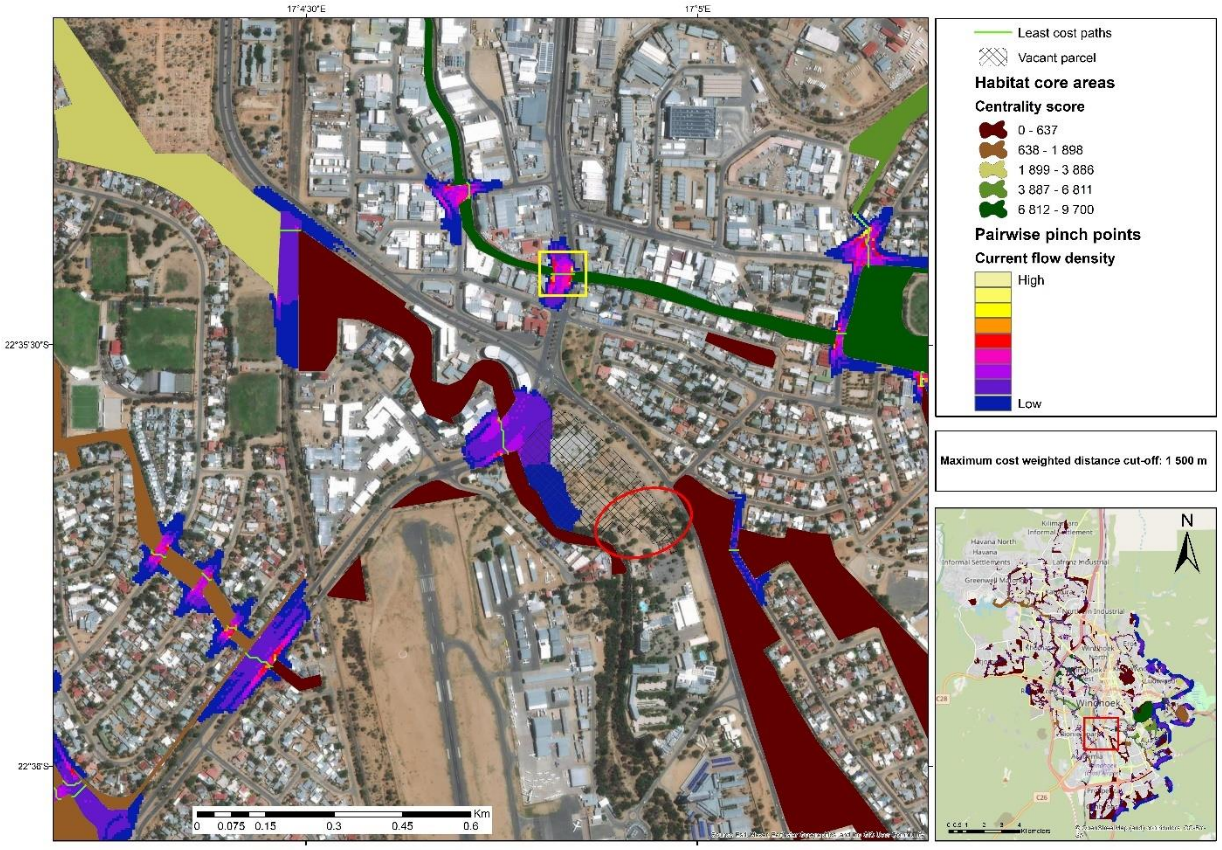


Figure 4-8: Map showing specific areas identified as highly important to the connectivity of the city's entire open space network. The yellow square shows the linkage crossing under Mandume Ndemufayo Ave as the sole linkage between the western and eastern components of the open space network, according to the 1 500 m CWD cut-off modelled. The red ellipse indicates an area between the suburbs of Academia and Suiderhof which, if enhanced to serve as linkage, could improve the connectivity of the open space network to the South-East in Suiderhof and Olympia. The crosshatch polygon indicates the location of a vacant parcel which contains the aforementioned area. Basemap: Satellite Imagery basemap

4.5.5 Improvement analysis

Improving the traversability of the area between two seemingly unconnected patches would enable the formation of a functional linkage. This is supported by LaPoint *et al.* (2015), whose research showed that functional connectivity can be boosted through mitigation efforts by the altering of structural elements and the removal of barriers in the urban landscape. This improvement could be achieved by changing the zoning of a parcel to "public open space" and thereby legally preventing any development which does not contribute to its sustainability and function as an open space. Furthermore, the quality of habitat in such a parcel could be improved in order to facilitate higher usability by animals such as mammals. Lechner *et al.* (2016) has found that restoration efforts such as revegetation could be effective in places where the distance between habitat cores is beyond the maximum dispersal distance of a species of medium-sized carnivore, for example.

To illustrate the effect that the establishment of a novel linkage would have on the connectivity of the patches in the landscape around it, an improvement potential scenario was modelled. In Figure 4-8 the location of a vacant parcel, symbolised by a crosshatch polygon, is shown between core areas #13 and #130, which have low centrality scores. According to the source cadastral data this parcel is currently zoned as “special” as part of the built-up area directly south of it which consists of a fenced-off hotel complex. Changing the zoning of the parcel to “open space” and thereby assigning it a lower resistance weight of 1, caused the resistance distance between parcels #13 and #130 to be below the maximum CWD threshold and subsequently a linkage was mapped by a re-run of the Linkage Mapper tool (see Figure 4-9). As a result of the new linkage, the centrality of core #13 increased from a score of 190 to 6 095 and the centrality of core #130 increased from 286 to 6 205.

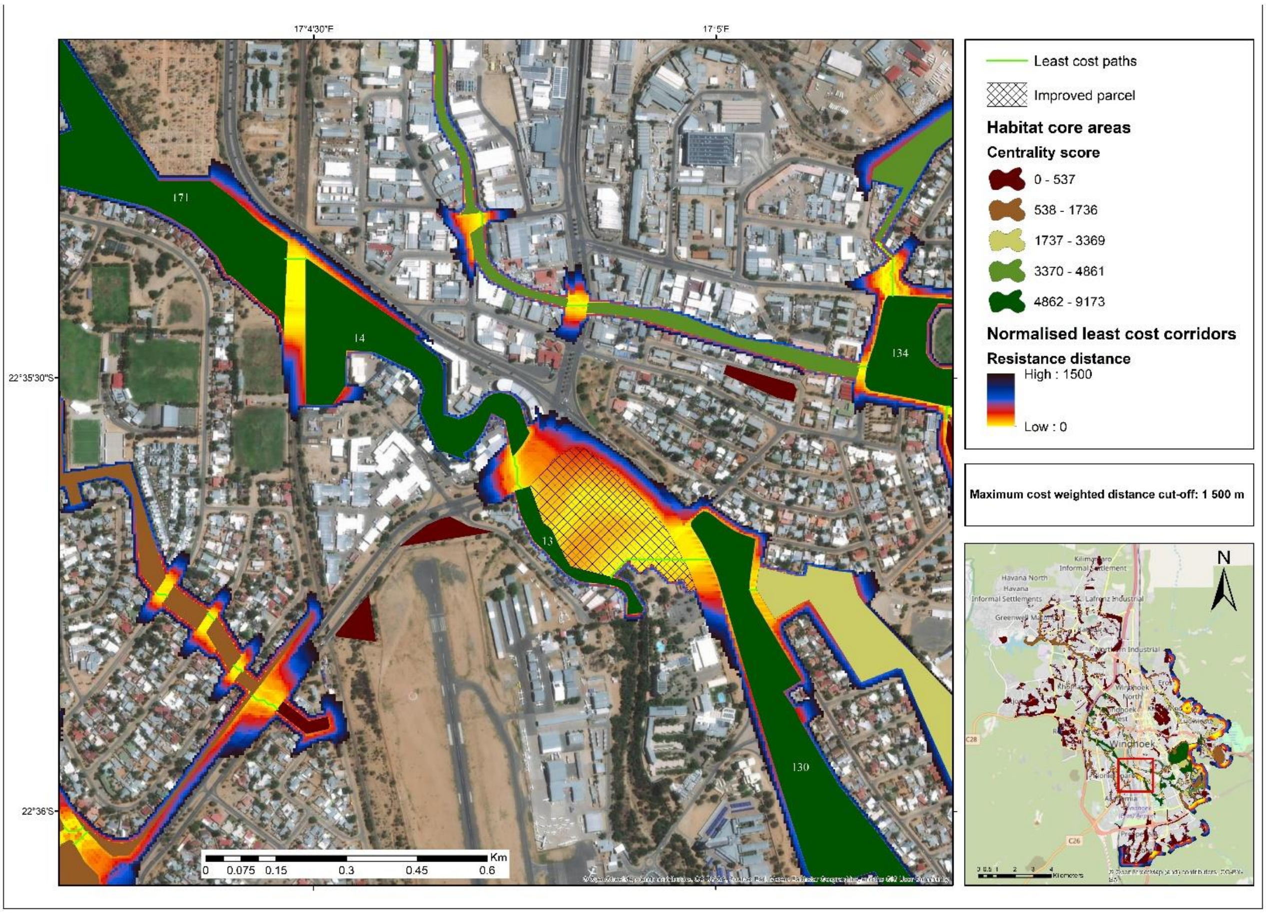


Figure 4-9: Map of sample area showing updated least cost paths, least cost corridors, and centrality scores of core areas following the improvement potential scenario modelled. The crosshatch polygon illustrates the location of the improved parcel in the analysis.

Ideally, empirical data showing actual movement patterns or at least presence-absence data of mammals in Windhoek should be used to run statistical comparisons between model outputs of such a study and field observations to test for model reliability. Unfortunately, such habitat-use data is not available due to a lack of applicable studies on mammals in Windhoek.

CHAPTER 5 CONCLUSION AND RECOMMENDATIONS

5.1 Recommendations for further research

5.1.1 Assess *actual* connectivity

Calabrese and Fagan (2004) offer three classes of connectivity metrics, namely, structural, functional, and actual, listed in order of increasing detail (Galpern *et al.*, 2011). This study considered functional connectivity. Using an *actual* connectivity (approach based on empirical observations of dispersal) metric would provide more realistic outputs, as it makes use of observations of individuals, or other empirical species data, so as to form concrete estimations of movement pathways followed through the landscape (Calabrese & Fagan, 2004). This could contribute positively towards the improved reliability of results generated by models and thereby better inform decisions around the management of dispersal corridors with higher confidence.

5.1.2 Expert opinion

In the event that further studies on the functional connectivity of the open space network of Windhoek, or any other Global South city, is considered, the following recommendations would apply. Considering the methodology followed in this study, in order to improve accuracy and realism in the models, expert opinion is recommended as a further input. Expert opinion is a common input used for the parameterization of connectivity models, such as those that make use of resistance surfaces (Zeller *et al.*, 2012), and to critique them (Pierik *et al.*, 2016). Although expert opinion is viewed as a suboptimal input due to its subjectivity (Spear *et al.*, 2010), it is cheaper and requires less effort than undertaking fieldwork to gather empirical data on species in a landscape (Rudnick *et al.*, 2012).

5.2 Conclusion

This study successfully used a circuit theory approach to model and map the connectivity of Windhoek's open space network and to evaluate its usefulness in identifying high priority areas for keeping the entire network connected. The functional connectivity results with the use of landscape resistance estimations of small to medium-sized terrestrial mammal movement gave easy-to-interpret results. The generated maps can be a very effective and useful tool for planners and managers as a first step to assess urban green infrastructure without needing to hire specialists to do expensive and time-consuming field observations. The results also indicated that the process can be successfully used to do scenario mapping and show where parcel improvement and planning efforts can be best utilized to rapidly improve connectivity and reduce the pressure on other corridors. Informed decision making with concrete results can also help decide where land-use and zoning should be changed to add more open space and where future development can be proposed with minimum impacts on the connectivity of the urban green infrastructure. The current study is one of only a few studies that tested the approach in urban areas, with most studies focussing on regional landscape scales.

This study offered, through the available literature, that circuit theory, as a relatively simple, low-cost, less data-intensive method, is an effective tool in predicting possible movement paths through the urban landscape. Its ability to model and map current flows representing possible movement corridors was demonstrated on the city of Windhoek’s open space network. A potential improvement scenario, based on the enhancement of potential links in the network, was modelled successfully and showed the impact that well-directed restoration efforts could have on the connectivity of the whole network. Also, a single, very important linkage in the network was identified as being potentially the only corridor connecting the eastern and western parts of the city’s open space network, according to the parameters modelled.

To summarise, the heterogeneity of urban ecosystems is under threat from various sources and risks becoming fragmented and losing the functionality of their natural areas. The wellbeing of people as well as ecosystems is dependent upon the healthy functioning of natural elements in the urban landscape and the services and functions they provide. These natural elements have to remain connected in order to be able to contribute to ecosystem functioning. Successful efforts to preserve or improve the functional connectivity of natural urban areas are reliant upon scientific knowledge for prioritisation of critical linkages to keep the landscape connected. Circuit theory can contribute to this knowledge required, through its mapping of multiple potential movement corridors in the urban landscape.

Circuit theory as a modelling basis makes it possible to map possible flows of biota in the urban landscape without having to include extensive biological data as input parameters. Where the modelled output shows areas critical for keeping the entire network connected these can then be prioritised in management efforts to conserve the habitat network.

The methodology followed, and the analyses conducted in this study, provided outputs which show that circuit theory modelling can indeed provide a scientifically-grounded, replicable, intuitive representation of the state of the functional connectivity between open spaces in the urban landscape, which is useful toward informing urban planning, design, and management.

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