AMPHIBIAN CONSERVATION IN AN URBAN PARK:

A spatial approach to quantifying threats to Anura on the Cape peninsula

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DECLARATION

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ABSTRACT

Species' threat assessments produce generalized threat impact scores, often by considering regional-scale representations of threats. Cities, on the other hand, produce municipal-scale, high resolution data that are proxies for threats; furthermore, cities in mega-diverse regions are home to a high number of threatened species. Prioritization of conservation action is biased for where more information is known (about the ecosystem), and where a positive outcome can be anticipated. Eight Cape peninsula amphibian species have a threatened conservation status. They are isolated on highlands or are restricted to remnant and suburban habitats, dependent on both urban and protected terrestrial and freshwater habitats found in the City of Cape Town and Table Mountain National Park.

In Chapter Two, I used spatial data (shapefiles) to represent threats in a Geographic Information System to spatially define threats to eight amphibian species (five lowland, three upland). I used two approaches: weighted and un-weighted by a threat impact-score, to produce five indices of local threats. The Micro Frog (*Microbatrachella capensis*) is assessed as the most threatened peninsula frog species by three of the five indices considered. The results show that for lowland species, the threat-class of greatest extent is 'Residential and commercial development'. The three lowland species most exposed to this threat are *M. capensis* (100% exposed to potential development), *Breviceps gibbosus* (55.6% of its 8.5 km^2 putative peninsula distribution), and *Sclerophrys pantherina* (38.4% of its 199.7 km^2 distribution). The Compounded and the General Threat Index correlate to the (global) Redlist Index ($P < 0.05$); but no correlation to the regional Red Listing, indicating congruency of threats and threat status.

The Critically Endangered Table Mountain Ghost Frog (*Heleophryne rosei*) is torrent adapted, and found only on the Table Mountain massif. CapeNature monitors tadpoles, and SANParks monitors (selected) stream parameters. In Chapter Three, I analyse water-habitat monitoring data (controlled for altitude) to show where threats of habitat alteration, drought, or temperature extremes may affect the *H. rosei* metapopulation. Permanence of water-flow and water temperature are shown to be very highly significant predictors of tadpole presence ($p = 0.0005$, $r = 0.78$). The lower the water temperature, the more likely tadpoles are present. Streams with a mean summer temperature greater than 17.2°C (n=3) at 400 to 300 meters above sea level were found to have no tadpoles at this altitude. Permanence of water flow is significant, as tadpoles need more than one year to reach metamorphosis. Summer water temperatures over an average of 17.2°C should be a red-flag for management authorities responsible for bulk-water supply, threat mitigation efforts, and biodiversity conservation.

Spatial indices of threat are useful to illustrate the relative exposure to threats at a local (city) scale. Threats to different lowland amphibians are similar (e.g. residential and commercial development), which varies from the mutual threats to different upland amphibians. Fundamental to stream species' conservation is water supply and demand management, while upland terrestrial species are most affected by veld age and invasive alien flora. Some threats are common for both areas (e.g. invasive alien species).

Key words: Threat impact score, threatened areas, GIS, habitat loss, amphibians, Table Mountain National Park, Cape Town, environmental water requirement, water temperature, habitat.

OPSOMMING

Spesies bedreigingsassesserings produseer algemene bedreigingsimpakte, dikwels deur die oorweging van streeksskaalse voorstellings van bedreigings in ag te neem. Stede, aan die ander kant, produseer munisipale skaal, hoë resolusie data wat voorstellings vir bedreigings bied. Daarbenewens is stede in mega-diverse gebiede die tuiste van 'n groot aantal bedreigde spesies. Agt Kaapse skiereiland amfibiese spesies het 'n bedreigde bewaringsstatus. Hulle is geïsoleerd op hooglande of beperk tot residensiële en voorstedelike habitats, afhangende van beide stedelike en beskermde land- en varswaterhabitats wat in die Stad Kaapstad en Tafelberg Nasionale Park gevind word.

In Hoofstuk twee word ruimtelike data (Shapefiles) gebruik om bedreigings in 'n geografiese inligtingstelsel voor te stel om bedreigings vir agt amfibiese spesies (vyf laaglande, drie hooglande) ruimtelik te definieer. Twee benaderings word gebruik: geweegde en ongeweegde deur 'n bedreigingsimpak-telling om vyf indekse van plaaslike bedreigings te produseer. Die mikro padda (*Microbatrachella capensis*) word beskou as die mees bedreigde skiereiland padda spesies deur drie van die vyf indekse wat oorweeg word. Die resultate toon dat vir laaglandspesies die bedreigingsklas die grootste mate 'Residensiële en kommersiële ontwikkeling' is. Die drie laaglandse spesies wat die meeste bedreig word, is *M. capensis* (100% blootgestel aan potensiële ontwikkeling), *Breviceps gibbosus* (55,6% van sy vermeende skiereiland verspreiding van 8.5 km^2) en *Sclerophrys pantherina* (38,4% van sy verspreiding van 199,7 km^2). Die saamgestelde en die algemene bedreigingsindeks korreleer met die (globale) Redlist Indeks (P <0.05), maar daar is geen korrelasie met die plaaslike Redlist, wat dui op kongruensie van bedreigings en bedreigingsstatus.

Die kritiek bedreigde Tafelberg spook padda (*Heleophryne rosei*) is aangepas tot vining vloeiende water, en word net op die Tafelberg-massief gevind. CapeNature moniteer padda vissie getalle, en SANParke moniteer geselekteerde water kwaliteit stroomparameters. In hoofstuk drie, ontleed ek water-habitat monitering data (beheer vir die hoogte) om te wys waar bedreigings van habitat verandering, droogte of temperatuur uiterstes die metapopulasie van *H. rosei* kan beïnvloed. Permanensie van watervloei en watertemperatuur word getoon as baie hoogs betekenisvolle voorspellers van die teenwoordigheid van die padda vissies ($p = 0.0005$, $r = 0.78$). Hoe laer die watertemperatuur, hoe meer waarskynlik is die teenwoordigheid van padda vissies. Strome met 'n gemiddelde somertemperatuur van meer as 17.2°C ($n = 3$) by 400 tot 300 meter bo seespieël het gevind dat daar geen padda vissies op hierdie hoogte is nie. Permanensie van watervloei is beduidend, aangesien padda vissies meer as een jaar nodig het om metamorfose te bereik. Somerwatertemperature oor 'n gemiddelde van 17.2°C moet 'n rooi vlag wees vir bestuursowerhede wat verantwoordelik is vir grootmaatwatervoorsiening, bedreigingsbeperkingspogings en biodiversiteitsbewaring.

Ruimtelike indikse van bedreiging is nuttig om die relatiewe blootstelling aan bedreigings op 'n plaaslike (stad) skaal te illustreer. Bedreigings vir verskillende laerlandse amfibieë is soortgelyk (bv. Residensiële en kommersiële ontwikkeling), maar wissel van die onderlinge bedreigings vir verskillende amfibieë in hoërliggende gebiede. Fundamenteel tot die bewaring van varswater spesies is die bestuur van watervoorsiening en -aanvraag, terwyl die veldleeftyd en indringerplante die grootste invloed het op hoogliggende spesies. Sommige bedreigings is algemeen vir beide gebiede (bv. Indringerplante).

Sleutelwoorde: Bedreigingsklas, bedreigde gebiede, GIS, habitatverlies, amfibieë, Tafelberg Nasionale Park, Kaapstad, omgewingswatervereiste, watertemperatuur, habitat.

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DEDICATION

To the one who instilled in me the notion of taking ownership of *his* and *my* and *our* Mountain. To my Grandfather, Ganief Samsodien.

ONE: Introduction

1.1. Amphibian conservation in an urban park.

The greater Cape Floristic Region (CFR) of southern Africa has a Mediterranean type climate with a cool winter rainfall regime, and includes the fynbos biome. Not only is it a hotspot for floral diversity, the same trend is seen in selected faunal taxa (Colville *et al.*, 2014), including amphibians (Holt *et al.*, 2013). The Cape peninsula is home to over 194 endemic plants (Raimondo *et al.*, 2009), over 110 endemic invertebrates (Picker and Samways, 1996), while the only (extant) endemic vertebrates are four anuran species (Channing, 2001; Channing *et al.*, 2013, 2017). As a result of this endemism in an expanding urban and agricultural landscape, amphibians are among the priority animal species of special concern on the Cape peninsula.

Conservation within the study area is the mandate of four authorities: South African National Parks (SANParks), the South African National Biodiversity Institute (SANBI), provincial CapeNature (CN), and the municipality of the City of Cape Town (CoCT). One lowland amphibian species (*Sclerophrys pantherina*) has a dedicated conservation committee which has representation from each authority as well as citizen interest groups. Within the City of Cape Town, and on its peninsula is one national park, and several municipal nature reserves and riverine greenbelts. Challenges to conservation include urban encroachment, degradation by alien invasive plants (Holmes *et al.,* 2012), and maintaining sustainable ecosystem services. Urban parks are the ideal subject of a spatial threat assessment to identify hotspots of biodiversity threats.

1.2. A spatial approach to quantifying threats to Anura on the Cape peninsula

Population numbers for many amphibian species are unknown (Minter *et al.*, 2004; Stuart *et al.*, 2008; Measey *et al.*, 2011), and as a result many conservation assessments are based only on size of and threat to entire distributions. However, threats are not uniform across a species' distribution. A Geographic Information System (GIS) is the appropriate format to map and quantify threats. In GIS, polygons can represent ecosystem features (e.g. water catchment, a species' area of occupancy), geographical features (e.g. island, peninsula), as well as administrative features (e.g. cadastres, management units, monitoring grids). Furthermore, a spatial study needs to define boundaries. The boundaries of threats are its spatial limits, while the boundaries of a habitat are characterized by dispersal potential (informing this study's putative distribution of amphibians) and ecosystem conditions marking the observed presence or absence of a breeding population (hereafter referred to as a niche).

Threats can be represented by the two planar dimensions of length and breadth (geographic: longitude and latitude, Cartesian: x and y). The spatial subjects of Chapter Two of this study are the distributions of threatened amphibians and representations of threats on the Cape peninsula (southern Africa), while the impact of respective threats is informed by the IUCN's scores of threat impacts published in their threat assessments. Chapter Three considers a subset of the distribution of one Critically Endangered amphibian in its lower stream habitat. I measured water conditions of twelve streams over ten seasons from summer 2014 to autumn 2016, controlled for altitude (two sample heights), and informed by annual tadpole counts.

CHAPTER TWO: Spatially defining threats on the Cape Peninsula

2.1. Introduction

Conservation biology is the scientific endeavour to understand natural processes and systems with the aim of mitigating anthropogenic loss of biodiversity by maintaining and managing for the stability of an ecosystem (McCann, 2000) and the life-supporting services it provides (Chapin *et al*. 2000; Tilman 2000). A change to an ecosystem can be a threat to communities of species relying thereon, as their habitat is altered; anthropogenic drivers of ecosystem change are usually drivers of biodiversity loss. The Millennium Ecosystem Assessment (2005) highlighted five of these drivers: climate change, habitat destruction, alien invasive species, over-exploitation, and pollution. Threats associated with drivers of change (and loss) have a negative effect on individuals that are in proximity of a given threat. The greater the duration, size, or magnitude of a threat, the more individuals of a species are affected. Where several threats are present, that system may be influenced by the synergistic effects of compounded threats.

The World Conservation Union (IUCN) adopted the Salafsky *et al.* (2008) lexicon in its Threats Classification Scheme (Version 3.2), comprising 11 threat classes and some 45 sub-classes. These threats are causes of ecological change and are inputs considered in species' conservation assessments, because they may contribute to the 'continuing decline, observed, inferred or projected' of habitat and distributions. Such a standard is intended to enable conservationists to share data and experiences of their conservation efforts globally (Master *et al.*, 2012), and standardize the nomenclature used when assessing threats in conservation assessments. The conservation status of species of unknown population size is partly or totally based on size, decline, and fragmentation of geographic range (criterion 'B' of IUCN, 2001). Since reliable population estimates are not available for many taxa (e.g. amphibians), assessments often can only be made in relation to actual or perceived threats to the 'area, extent and/or quality of habitat'.

The extent of threats are often generalized to a taxon's entire extent of occurrence; thus it is an over-estimation of where a threat is. To increase the resolution of threats data, and to direct conservation action, it is important to spatially define specific threats at a relevant regional scale. Considering threats discretely, and assessing them cumulatively is a way of increasing the spatial resolution of threats, as represented by shapefiles. The IUCN's threat assessments asks assessors to score the impact of the threat in terms of timing (duration), scope (size) and severity (magnitude). The value of the IUCN and the Species Survival Commission's (SSC) conservation assessments are in providing a comparative framework for conservation, applicable to a wide range of taxa and geographical scales (Gärdenfors, 2001; Rodrigues *et al.*, 2006). It would be worthwhile to implement a local scale threat-assessment in hotspots of biodiversity, within a geographic information system (GIS), to identify hotspots of threats. The underlying Information System is a database which one can attribute qualitative and/or quantitative data (such as duration, size, and magnitude of threat) to a spatial extent. Several threats can be analysed relatively and cumulatively (Mitchell, 1999) based on the location of a feature interpreted as a threat. Biodiverse areas harbour many threatened species (Myers *et al.*, 2000), which invariably face similar threats (Simberloff, 1998).

Twenty-one indigenous amphibian species can be found on the Cape Peninsula, eight of which have a threatened status (IUCN 2010, 2011, 2013, 2016, 2017), and are of special concern to the Cape peninsula (Rebelo *et al*. 2011a). These eight species (Table 2.2) are the subject of this study. They represent eight genera, five families, four peninsula endemics and all eight are endemic to the Cape Floristic Region (CFR); three montane and five lowland species, six aquatic and two terrestrial breeders. Perceived threats to these species include: habitat destruction and fragmentation, alien invasive species, climate change, erosion/siltation, and water abstraction (Minter *et al.* 2004). The anthropogenic impacts on both habitat quality and ecosystem connectivity can have severe consequences for endemic, range restricted, threatened species. The effect of each threat can be assessed per taxa or based on a life-history strategy. This initial spatial threat assessment is for the order Anura. Cities and agriculture are two of the biggest agents of habitat change in low-lying areas (Holmes *et al.* 2012; Rebelo *et al.* 2011b), and are characterized by permanent habitat loss (at worst) and habitat fragmentation (at best) at lower altitudes. In contrast, the uplands of the Cape peninsula (within the metropolitan area of the City of Cape Town) are protected yet isolated from the rest of the CFR's Cape Fold Mountains. Anthropogenic impacts on critical biodiversity areas, and the challenges to conservation within a biodiversity hotspot of the City of Cape Town (hereafter the City) are daunting (Holmes *et al*. 2012). Challenges include meeting conservation targets for the lowland vegetation types, alien invasive species, and loss of wetlands. Eight of the minimum conservation targets (to conserve up to 30% of original extent) for the City's nineteen national vegetation types are not achievable, as too little remains intact (Mucina and Rutherford, 2006; Holmes *et al.* 2012).

The Cape peninsula is within a City and would be an ideal subject for a spatially explicit threat assessment. The main aim of this project is to spatially define the extent of threats and estimate the impact of co-occurring threats to the distributions of amphibians on the Cape peninsula of South Africa. In this thesis I attempt to answer the following questions: a) What are the threats on the Cape peninsula that can be spatially defined, and which of them overlap the distribution of eight Threatened or Near Threatened amphibians found there? b) Are these threats the same or different for each species? c) What percentage of each species' putative distribution range on the Cape peninsula is affected by these threats? d) Can the severity (magnitude) and scope (size) of known threats be used to calculate a spatially defined threat-index? e) Do these spatially-defined threats on the Cape peninsula support the regional and global conservation Red List statuses of these species? f) Can the understanding of the spatial heterogeneity of threats direct threat-mitigation efforts to threat hotspots?

2.2. Methods and Materials

A Geographic Information System (GIS) is an information system that models or represents spatial features found in the real world using a database of relevant and related attributes (Burrough *et al.*, 2015). GIS functionality includes techniques for analysing spatial data, such as geometry calculations and spatial analysis. These techniques require the spatial extent of features as well as their attributes; together these make up the vector-data inputs in this study. A shapefile is a geospatial vector-data format, for displaying the shape (point, line or polygon), location (coordinates), and attributes (e.g. a threat's scope and severity) of geographic features. Many sub-classes of threats (or proxies to threats) have already been captured in this format, e.g. the road network, municipal property zonation (City of Cape Town, 2015), agricultural footprints (see entire list in Appendix 2.1). The underlying shapefiles used in this study are produced by the City of Cape Town, the National Geo-Spatial Information office, and are freely available to the public (subject to fair-use). Additionally, South African National Parks and the Extended Public Works Programme (EPWP) produce park-specific shapefiles. The spatial extent of multiple threats was edited and managed in the GIS software application: ArcMAP10 (ESRI, California).

Study species and study area

Eight threatened anuran species have populations on the Cape peninsula (IUCN, 2016): The Cape Peninsula Moss Frog (*Arthroleptella lightfooti*), the Smooth Dainty Frog (*Cacosternum platys*), the Table Mountain Ghost Frog (*Heleophryne rosei*), and Rose's Peninsula Dwarf Mountain Toadlet (*Capensibufo rosei*), the Cape Rain Frog (*Breviceps gibbosus*), the Cape Platanna (*Xenopus gilli*), the Western Leopard Toad (*Sclerophrys* *pantherina*), and the Micro Frog (*Microbatrachella capensis*). The first four species have their global distribution on the Cape peninsula. The latter four are endemic to narrow distributions of lowlands within strandveld and fynbos wetlands, as well as renosterveld shale slopes of the CFR's winter rainfall climate (Poynton, 1964; Colville *et al.* 2014).

As the results should only be interpreted in the context of threats to and conservation of populations on the Cape peninsula a regional assessment of conservation status is conducted for the four species not endemic to the Cape peninsula (see below). It should be noted that populations on the Cape peninsula are the westernmost lobe of extant; the success or failure of the peninsula populations have a significant effect on the Extent of Occurrence and genetic diversity of the four respective species. The putative distribution ranges used in this study are derived by extending a buffer (size- and dispersal-related radius, Table 2.3) around points of known occurrence (FrogMAP, Museums, SANBI, CapeNature, SAIAB, iSpot). These buffered areas provide this study with a core distribution range for the Cape peninsula, bounded by the 18.3° and 18.5° lines of longitude (east), and the 33.9° and 34.4° lines of latitude (south). The species distributions used in this study are termed 'putative' because it is one version of the distribution, not the official distribution of a species, but a core distribution. It is important for this type of study that the species distribution used represent areas of occupancy (migration routes, foraging & breeding areas), and not a generalized or ubiquitous distribution, such as the Extent of Occurrence referenced with the IUCN's threat assessment. Figure 2.1 shows the study area and the putative core distributions of eight species. The distributions of the two largest amphibians, *X. gilli* and *S. pantherina* (a 1500m buffer was used for both lowland species), are cut off at their upper limits of 140m and 500m altitude respectively (Minter *et al.*, 2004). Within these spatial representations of species' distributions, two approaches to threat quantification are considered: weighted and un-weighted (area only) by threat impact scores. The study area is that part of the metropolitan City of Cape Town which includes the Cape peninsula (~470 km^2), and Table Mountain National Park (~62% of the Cape peninsula).

Methods: Rationale for putting forward candidate indices

When threat assessments rely heavily on the estimated size (quantitative) and perceived quality (qualitative) of a species' distribution, especially in an urban context, it may fail to take into account the possibility that multiple threats are acting synergistically. A spatial threat index seeks to determine the intensity co-occurring threats. The estimated size of a distribution is quantitative, the IUCN assessment can be made without a quantitative appraisal of the threats present; thus lending itself to subjective variance particularly at different spatial scales.

I propose two approaches (one builds on the other) to spatially quantify threats: using absolute areas which represent threats, and using a taxon's threat impact-scores (derived from IUCN threat assessments) to calculate the effect of co-occurring threat-classes (Salafsky *et al.* 2008). This desktop study produced five indices by approaching a collection of overlaying threat layers in two ways. As a result threat layers were prepared in two steps – step one being the input for the Area Approach, step two being the input for the Score Approach. Firstly one layer (one shapefile) for nine classes of threat (Salafsky *et al*. 2008) was prepared by merging the spatial representations of sub-classes of known threats. Secondly, a threat impact score was assigned to each category of threat. Threat-calculators based on the IUCN classification places the weight of the threat assessment on the threat's scope and severity (Baillie *et al.* 2004; Master *et al*. 2012). The timing of the threat was, thus, not weighted and all threats are considered ‘ongoing’. The indices presented in figure 2.5 are scaled to the species most threatened (i.e. the species’ whose distribution is most threatened has its threat index value set at 1), while the same indices presented in table 2.3 are not scaled.

Data characterisation

Most threat classes (Salafsky *et al.*, 2008) are represented: residential and commercial developments, agriculture, transport, mining, intrusions and disturbances, system modifications, invasive alien species, pollution, and geological events; based respectively on (Appendix 2.1): property zonations, traced from aerial images, road categories as mapped, topographic maps, recreational land-use and military lands, dam surface extent and fire extent, alien invasive plant density estimations (SANParks, unpublished) and invasive amphibian extents, perennial waters (Budzik *et al.* 2014), and slope angle from a digital elevation model. Most are vector inputs. There are no records for biological resource use of amphibians, as amphibians in the Cape are not harvested as food, thus threat class ‘Biological resource use’ is also excluded. Domestic predators (of tadpoles, e.g. crabs, fish) are not classified as a threat according to Salafsky *et al*. (2008). The extents of ubiquitous exotic predators, like cats, dogs, and carnivorous birds are not included. The chytrid fungus (*Batrachochytrium dendrobatidis*), is similarly excluded as its presence is not discretely known, and there are no known detrimental examples of its occurrence in the Cape (Tarrant *et al.* 2013). Representations of exotic predation, climate change and disease can be included in this study if data is available to map threats at a local-scale (e.g. areas of exotic distributions, or catchment per altitude). I excluded threat-class ‘climate change’ due to the coarse region resolution of potential input data. A recent model of climate change was produced at a resolution better than the 10km data-standard (Joppa *et al.* 2016); an appropriate 4km cell size for the Cape Floristic Region. However, a 4000m cell size is not appropriate for the scale of the Cape peninsula.

The lowest resolution raster in this study was a cell size of 100m (i.e. a digital elevation modelled of slope angle, and pre-2010 fire extents). 'System modifications' is the threat-class that includes threat sub-class 'fire & fire suppression', but this dataset is limited to outside the urban edge. I considered 15 years of fire-scar records since (after) the peninsula fires of 2000. Three categories of threat was scored: where two or more fires co-occur that mutual footprint is scored as an inappropriate fire regime for fynbos, where no fires occurred since 2000 represents an appropriate fire regime (once every 16 to 20 years), fire excluded for longer is also scored as a threat (Appendix 2.2). The alien density estimations (as at 2014) used in this study are also limited to records for larger swaths of open land outside the urban edge (e.g. for TMNP). As a result of the bias (park specific, non-continuous threat layers), I use two different boundaries to approximate the non-viable amphibian habitat when assessing compounded threats (Figure 2.3 and 2.4).

Indices using Area.

This approach sums the areas of each polygon, but is only comparable to indices that use the same number of threat-classes. The three variations used here are as a result of the number and type of threat layers included. See table 1.1.

i. *Landcover threat index (LTI)*: Landcover represents a simple (no overlap, one-layered) depiction of threats derived from remote sensing (RS). The input data is a multiband satellite raster format of which various pixels (resolution) sizes are available. The Landcover index is the most simple of the five indices as it only interprets a binary representation of apparent threats based on surface feature reflectance. For this study, the Landcover threat index was extracted from a national land-cover layer (Van Wilgen & Herbst, in press) where each pixel represents 900m^2 (30x30m). It consists of nine mutually exclusive categories, seven considered threatening to amphibians. The categories of land-cover interpreted as threatening to amphibian biodiversity are the surface reflectance associated with: urban, plantation, degraded, artificial water-bodies (impoundments, not wetlands), cultivation, other (coastal), and mining. Threats are assumed to be absent from two land-cover categories: Wetlands and Natural (including potential alien shrubs amongst the fynbos).

ii. *Discrete Threat Index (DTI):* areas representing threats are summed for limited number of threat-classes. The DTI limits its spatial inputs to boundaries that discriminate on cadastral vector accuracy (e.g. property boundaries) or 1:50000 accuracy (e.g. plantation footprint, agricultural land traced from orthophotographs) or a raster resolution no larger than 100x100m (e.g. radar and satellite sources). For Anura of the Cape peninsula and for many cities this scale of data is available for seven threat-class (Salafsky *et al*. 2008: threat-class #1, 2, 3, 4, 6, 9, 10). Where threat-class #5 (Biological resource use) is applicable and available the DTI will include it. Shapefiles which cover only a subsection (non-continuous coverage) of the study area should be excluded. For Cape Town threat-classes that only represent the protected uplands would bias for upland threats. Thus this method excludes 'Natural systems modifications' and estimations of 'Invasive & other problematic species' plant densities (but not invasive genes and diseases). This is because representations of post-fire vegetation age and estimations of alien plant cover are only made for a (semi-)natural sections of the study area even though fires occur and alien plants grow in urban sections. See table 2.1.

iii. *General Threat Index (GTI):* areas of available representations of threats were summed, even if not continuous for the study area (spatially limited to subsection of the study area). Nine threat-classes (Appendix 2.1) for each of the species' distributions are used. This method assumes that it is best to incorporate all available representations of threats, eleven being the maximum.

Indices using Threat Impact Scores.

The Score Approach assigns the IUCN's threat impact scores to each of the overlaying areas representing threats. This approach builds on the area approach as it assigns values 0-10 to the presence (0-1) absence of the threat area, thus increasing the resolution. Each of the nine threat classes are converted to a raster grids of 5x5m cells. The IUCN's threat impact scores were assessed by the South African Frog Re-assessment Group (SA-FRoG). It is a general threat impact score (i.e. of low resolution) assigned based on five categories of threat-scope (pervasive, large, restricted, small, and unknown) and threat-severity (extreme, serious, moderate, slight, and unknown). This score applies to the impact of the threat to a species in general. I use SA-FRoG's impact scores directly where they apply (e.g. Streets are attributed the threat score of 6, but it is not so attributed to all types of roads, highways or paths). Deviations from the IUCN's threat impact scores for the variety of categories or features in existing shapefiles (Appendix 2.2) results in the increased resolution for threat impacts produced in this study. For example, for threat class 'Transportation Corridors', two shapefiles representing roads and railways were merged to create one shapefile that represents that threat-class. The different categories of road-types allow for a differential or divergent impact score extrapolated from the IUCN's impact score and based on comparative logic, amphibian ecology, and expert opinion. That is, the impact score of 6 for roads in general, would be appropriately attributed only to the 'Street' category; but for a 'National Highway' the impact score would be higher (perhaps 10). Railways might have a lower impact (perhaps 4) due to the small surface area of the rails. Aviation flight paths would be included if the taxa being assessed were birds. The IUCN's scores, and logical deviations thereof, were attributed to the nine threat-classes (Appendix 2.2), as represented by nine shapefiles.

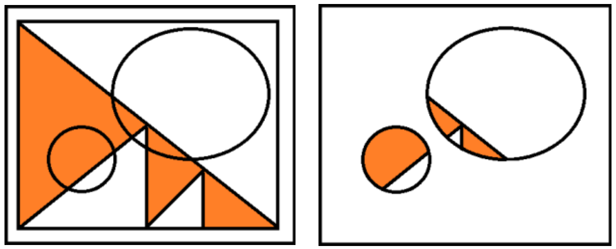
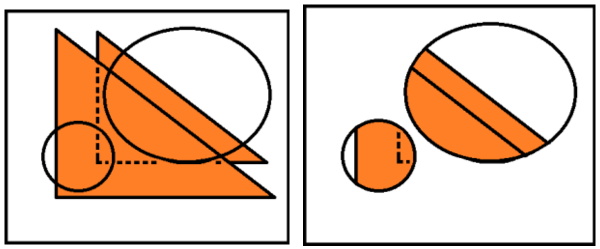
The area of these nine shapefiles (cut to the species' distribution) is the basis of two threat-area indices (one using all nine, another using seven shapefiles/threat-classes). All nine are converted ('Feature to Raster' tool in ArcMap3) to nine raster layers using the 'ThreatScore' attribute (Appendix 2.2). A raster output cell size of 5x5m (25m^2) was chosen. The Transverse Mercator (LO19) projection (WGS84 datum) was used, bounded by 64500 and 45900 metres west of Longitude 19°, and 3751000 and 3804000 metres south of Latitude 00 (the equator); an extent slightly larger than the amphibian distributions used in thus study. This produced a raster grid of 39432000 (3720x10600) cells. Null-data cells (absence of threat) are converted to zero-valued cells (using the 'Raster reclassify' tool). As it would be nonsensical to multiply by zero, the penultimate step in data preparation was to duplicate the database: in one copy one (+1) was added to every cell, and (using the 'Raster Calculate' tool) multiply overlaying threat impact scores; in the original add (again using the 'Raster Calculate' tool) overlaying impact scores. This produced two raster outputs representing cumulative (summed) and compounded (multiplied, i.e. product of) threats. Finally these two layers are cut to the respective distribution of species (using 'Clip' tool).

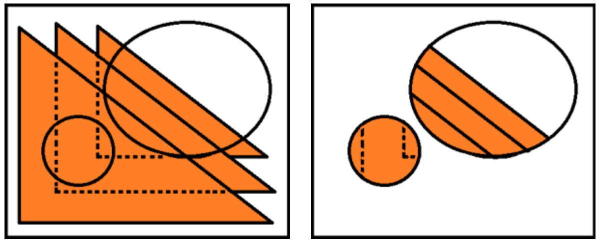
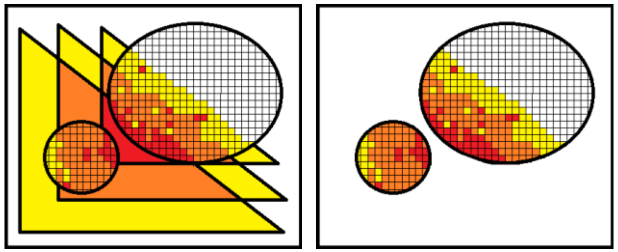
iv. *Cumulative threat index i.e. Sum of threats) (STI):* threat impact scores are summed for overlaying threats per 5x5m cell (25m^2) of the Cape peninsula, which is summed for and normalized by species distribution.

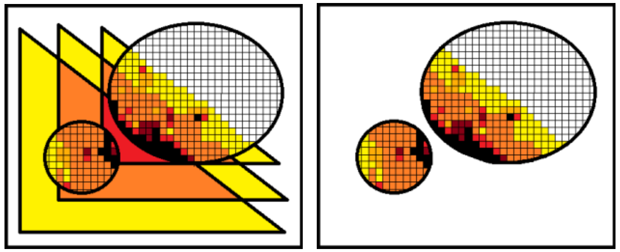
v. *Compounded threat index i.e. Product of threats (PTI):* threat impact scores are multiplied for overlaying threats, per 25m^2 of the Cape peninsula, which is summed for and normalized by the species' distribution. This methods assumes that compounded effect of overlaying threats are greater than the sum of individual threats, thereby exaggerating the effect of overlaying threats. See table 2.1.

Multiple approaches are warranted, so as to compare several candidate indices; the appropriate index is the one that significantly correlates to the regional threat status, as opposed to the global threat status or no correlation. Different threat-raster or threat indices might be appropriate for different contexts. The null hypothesis assumes that the distribution of the most threatened species of the region would be most under threat. While near threatened species or species of least concern would have a distribution least (spatially) associated with threats. I compare each type of threat index (continuous variables) to an index associated with conservation status trends (Red List, categorical).

Table 2.1: The calculations for two spatial approaches to quantifying threats to Anura on the Cape peninsula. Methods using binary (0/1) and incremental (0-10) quantifications of threats are proposed. Three proposed indices use the former, a further two proposed indices is derived by attributing the IUCN's threat impact scores to spatial representations of threats. The five indices are identified as i-v in this table and by acronym in discussion.

ID	Index name and equation	Illustration of methods.	Calculation to derive index. (The numerator is shown).	Example of results, simplified.	
				Within small circle ($1m^2$)	Within large circle ($5m^2$)
i	**Landcover Threat Index (LCI).** Remotely censed threat inputs. (Single layer of threat or no threat)		The area derived from Landcover types considered to be a threat within an amphibian's distribution, divided by its distribution on the Cape peninsula. $\boxed{\Sigma_{\text{Ta (n=1)}}}$ Ta = threat area (m^2)	$0.8\ m^2 / 1m^2$ = 0.8 (80% of distribution)	0.7 / 5 = 0.14 (14% of distribution)
ii	**Discrete Threat Index (DTI)**. Sum of scale-appropriate threat coverage (m^2). n = 7 (depicted as 2 layers in the illustration).		The sum of areas (triangles) representing overlaying threat classes (min. 7), divided by the distribution area (circles). It includes only continuous discrete vector representations of threats, and raster inputs below 100m res. Thus excludes Natural Systems Modifications and Invasive Alien Species. A Variation of this method includes threat-class #5 Biological Recourse Use were applicable. $\boxed{\Sigma_{\text{Ta(n=7)}}}$	(T1 + T2 + …T7)m^2 / $1m^2$ = (0.9 + 0.1) / $1m^2$ = 1.0	(T1 + T2 + …T7) / $5m^2$ = (2.5 + 2.0) / $5m^2$ 0.9

iii	**General Threat Index (GTI).** Sum of threat coverage (continuous and non-cont. data). n = 9 (depicted as 3 layers in the illustration).		The sum of areas (triangles) overlaying threat classes, divided by the distribution area on the Cape peninsula (circles). It includes less discrete, landscape scale, representations of threats (depicted by the largest triangle in the foreground). Extent of data may be logically biased to certain section of the study area. A variation of this method includes threat-class #11 Climate Change (effects per upper-catchment as opposed to 4km raster). $\boxed{\Sigma_{Ta(n=9)}}$ Ta = threat area (m^2)	(T1 + T2 + T3 …T9) / $1m^2$ = (1.0 + 0.9 + 0.1) m^2 / $1m^2$ = 2.0 (200%)	(T1 + T2 + T3…T9) / $5m^2$ = (0.5 + 2.5 + 2.0) m^2 / $5m^2$ = 1.0 (100%)
iv	**Cumulative Threat Index (STI).** <u>Sum</u> of threat impact scores (cumulative impact)		The raster grid is derived by attributing threat-impact scores (Appendix 2.2) to the areas used in the GTI. The **sum** of overlaying impact scores (of nine threat classes), per 5x5m2 cell. Each cell within respective regional distributions is added for that species. This illustration depicts the grid only within the circular species' distribution, but it extends to the entire study area. $\boxed{\Sigma\ (\Sigma_{Ts(n=9)}.Cn.Ca)}$ Ts = threat score Cn = number of cells Ca = area of cell	Σ C(n) [(T1 + T2 + T3 …T9) x 100cells x $25m^2$] / $1m^2$ = {[(1+2+3)+(4+5+6)+(7+8+9)…Tn_{100}] x 100cells x $25m^2$} / $1m^2$ = 112500 / 1	Σcells(n)[(T1 + T2 + T3…T9) x 500cells x $25m^2$] / $5m^2$ = {[(10+9+8) +(7+6+5) +(4+3+2)…Tn_{500}] x 500cells x 25 m^2 } / $5m^2$ = 675000 / 5 = 135000

v	**Compounded Threat Index (PTI).** Product of threat impact scores (compounded impact)		The **product** of overlaying cells' threat impact scores (of nine threat classes) **summed** for cells of respective distributions, divided by overall distribution area The product of threats (v) is an exaggeration of the sum of threats (iv) $\boxed{\Sigma\ (\Pi_{Ts(n=9)}.Cn.Ca)}$ Ts = threat score Cn = number of cells Ca = area of cell	Σcells(n) [(T1 x T2 x T3 …T9) x 100cells x 25m^2] / 1m^2 = {[(1x2x3) +(4x5x6) +(7x8x9).. Tn_{100}] x 100cells x 25m^2} / 1m^2 = 1575000 / 1	Σcells(n) [(T1 x T2 x T3 …T9) x 500cells x 25m^2] / 5m^2 = {[(10x9x8) +(7x6x5) +(4x3x2)..Tn_{500}] x 500cells x 25m^2} / 5m^2 =11925000 / 5 = 2385000

Sources of spatial error or spatial inconsistencies

Temporal error: Spatial data (shapefiles) may be updated months or years after a development on the ground, and alien invasion estimations are produced irregularly (e.g. Kotzé *et al*. (2010), and SANParks, unpublished), while invasion and fire fronts are not static. Updates of property zonation and transport networks are lagged in time. Error of omission: urban properties that are un-zoned were excluded. Also, the error of under-estimating the distribution of (locally) invasive amphibians (omission of sighting records) is acknowledged.

Ideally monitoring data or observations would be continuous for the study area. But often it is limited to management units and priorities. In this case, EPWP's (Extended Public Works Programme) alien clearing (working for water) and fire efforts (working on fire), and SANParks alien density estimations does not extend to urban and suburban private lands. Landscape-scale fires scars are recorded, but not small scale nor residential property fires. Fire and alien plant densities are reflected in two threat classes – Salafsky *et al*. (2008) threat lasses #7 and #8 respectively. For this reason, one of the indices produced in this study excludes generalized or indiscrete or non-continuous representations of threats. Associated with this, the boundary chosen for the exclusionary effects of compounded threats is based on the assumption that a high threat impact score (of say, 9 or 10) would exclude individuals from that given site, while for the uplands there are effectively two extra layers of threat computed (multiplied). Thus for Figure 2.3 I use a boundary an order-of-magnitude higher for upland species (the product of impact score greater than 99) than for lowland species (the product of impact scores of 9 or more), shown if Figure 2.4. See also adjusted distribution in Table 2.3

Methods: Regional Threat Assessments.

The IUCN Guidelines for Application of IUCN Red List Criteria at Regional and National Levels (IUCN, 2012) is used to assess the regional (peninsula) status of the Cape Rain Frog (*Breviceps gibbosus*), the Cape Platanna (*Xenopus gilli*), the Western Leopard Toad (*Sclerophrys pantherina*), and the Micro Frog (*Microbatrachella capensis*). The latter two remain the same as their global distribution. The former two are uplisted by one category (Table 2.3). The peninsula distributions (AOO) used the Regional Threat Assessment are of the same methodology used for global threat assessments: the smallest convex polygons around known locations, then cutting the study area out of the global distribution. The peninsula AOO of *Breviceps gibbosus* is below 5000km^2, thus regionally Endangered. While the AOO of *Xenopus gilli* is below 100km^2, thus regionally Critically Endangered.

Comparative spatial threat indices:

The Red List Index is derived from changes to the conservation status per taxa over time (Butchart *et al.,* 2004); where the highest possible category (EX) is given the value of one. It is re-purposed for this study as a categorical variable, and is hypothesised to have a positive proportional relationship to the threat indices produced in this study. For this study the highest category and status is Critically Endangered (CR). Variance can be tested by plotting the numerical value of regional Red List status to the five spatial threat indices (Figure 2.5). Analysis of variance (single factor, alpha 0.05) between the Red list index and each of five threat indices is conducted in Microsoft Excel. If no variability is found ($p > 0.05$), then the null hypothesis is accepted: no difference between spatial threat indices and the categorical Red List status. Analysis of variance (single factor, alpha 0.05) is also conducted between the threat coverage for the distribution of upland species compared to lowland species.

2.3. Results

Threats to the eight amphibian species, as represented by shapefiles, are not spatially congruent because threats and their representations are not congruent. The threat-classes (shapefiles) that were present in parts of each species' putative distribution are 'residential and commercial development', 'transport corridors', 'human intrusions', and 'invasive species' (non-native). The sum of respective areas representing threats can be found in Table 2.2.

The results show that for lowland species, the threat of greatest extent is threat class 'Residential and commercial development' (Table 2.2). This is so for *Breviceps gibbosus* (55.6% of its 8.5 km^2 putative peninsula distribution), *Sclerophrys pantherina* (38.4% of its 199.7 km^2 distribution), and *Xenopus gill* (7.4 % of the 43.9 km^2 distribution assessed). The peninsula distribution of *Microbatrachella capensis* (CR) is limited to the infield of Kenilworth Racecourse. The infield is zoned as communal use ('Community: local' not as 'open-space' or 'conservation', Appendix 2.2), the property is vulnerable to the threat of development as well as the pressures of tourism, recreational, and other civic uses. The Micro Frog (*M. capensis*) is the species assessed as most threatened by three of the five indices considered in Figure 2.5; The Landcover Treat Index, the Discrete Threat Index, the Cumulative (summed) Threat Index. This is expected of a Critically Endangered species. On the other hand, the species with the highest threat index – as measured by the Compounded (PTI) and the General Treat Index – is the Peninsula Moss Frog (*A. lightfooti*).

An ANOVA (single factor, alpha 0.05) analyses was conducted of the variance between a Red list index (global and regional status) and each of the five indices produced in this study. When compared to the regional status, none of the indices has a p-value less than 0.05. We accept the Null hypothesis that the regional conservation status reflects the degree to which respective distributions are under threat. The index with P-value approaching 1 is the DTI.

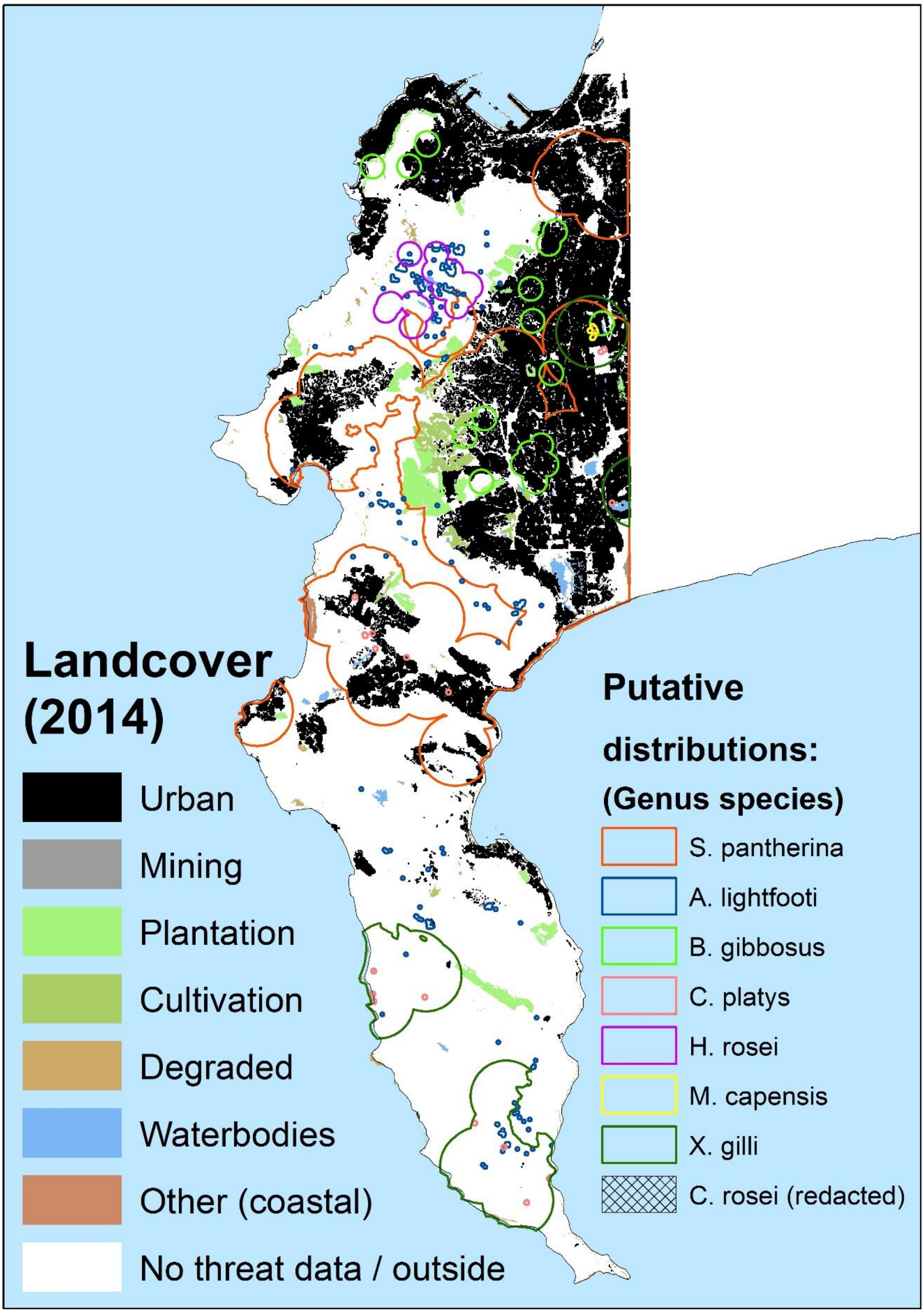


Figure 2.1 Spatial coverage (area) of data representing threats relative to the distribution of eight threatened amphibian species across the Cape peninsula. Threat coverage as derived from nine classes of land-cover (LandSat, remote sensing), of which seven classes are considered threats. The area under threat, within species' distributions, are used to derive the Landcover Threat Index.

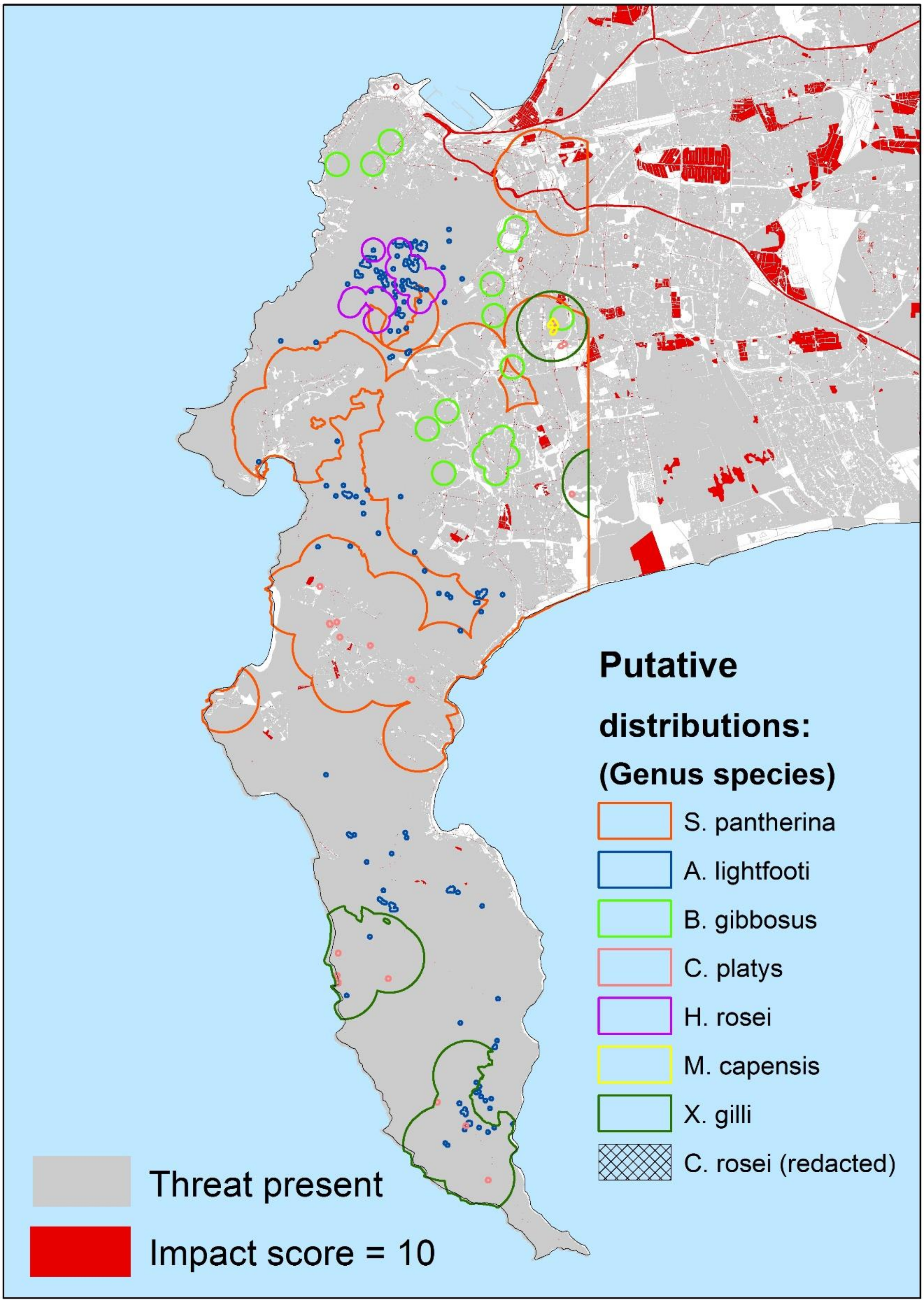


Figure 2.2: Spatial coverage (area) of data representing threats relative to the distribution of eight threatened amphibian species across the Cape peninsula. Threat coverage as derived from shapefiles (Appendix 2.1) that represent threats. The database consists of all known threat-classes (nine layers) and is the bases of the General Threat Index. The Discrete Threat Index is derived from a subset of this, all known discrete representations (seven layers) of threats.

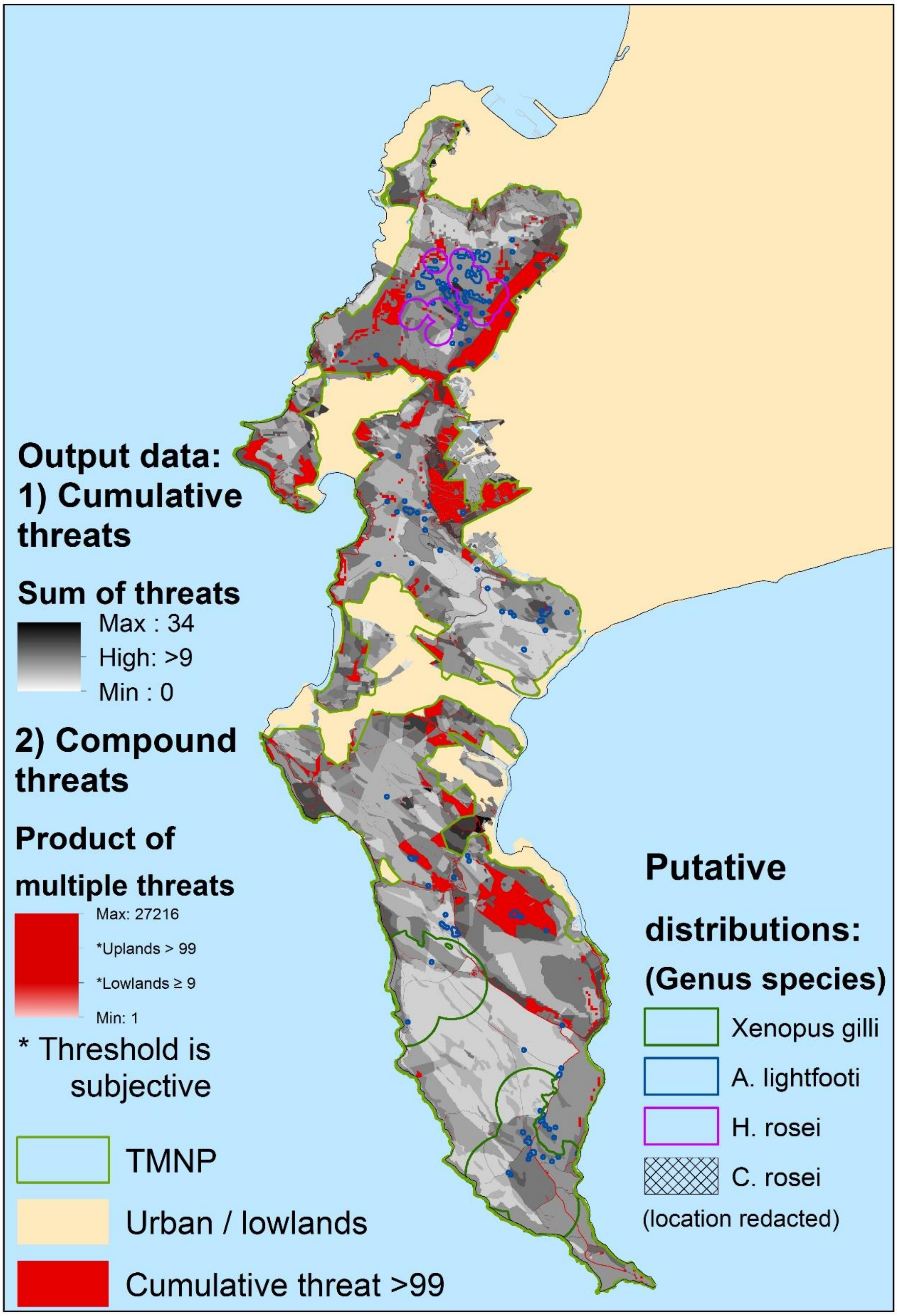


Figure 2.3: The cumulative impact of threats (as per 'ImpactScore' of Appendix 2.2) for uplands of the Cape peninsula. The sum of overlaying threat impact scores (per 5x5m pixel) is represented in shades of grey. The sum of impact score are summed within distributions to derive the Cumulative Threat Index. The product of threat impacts (threat impact scores multiplied per overlaying 5x5m cell) is used to propose a score that represents a tolerance boundary that may exclude amphibians. A score higher than 99 represent threat hotspots for upland species, in red.

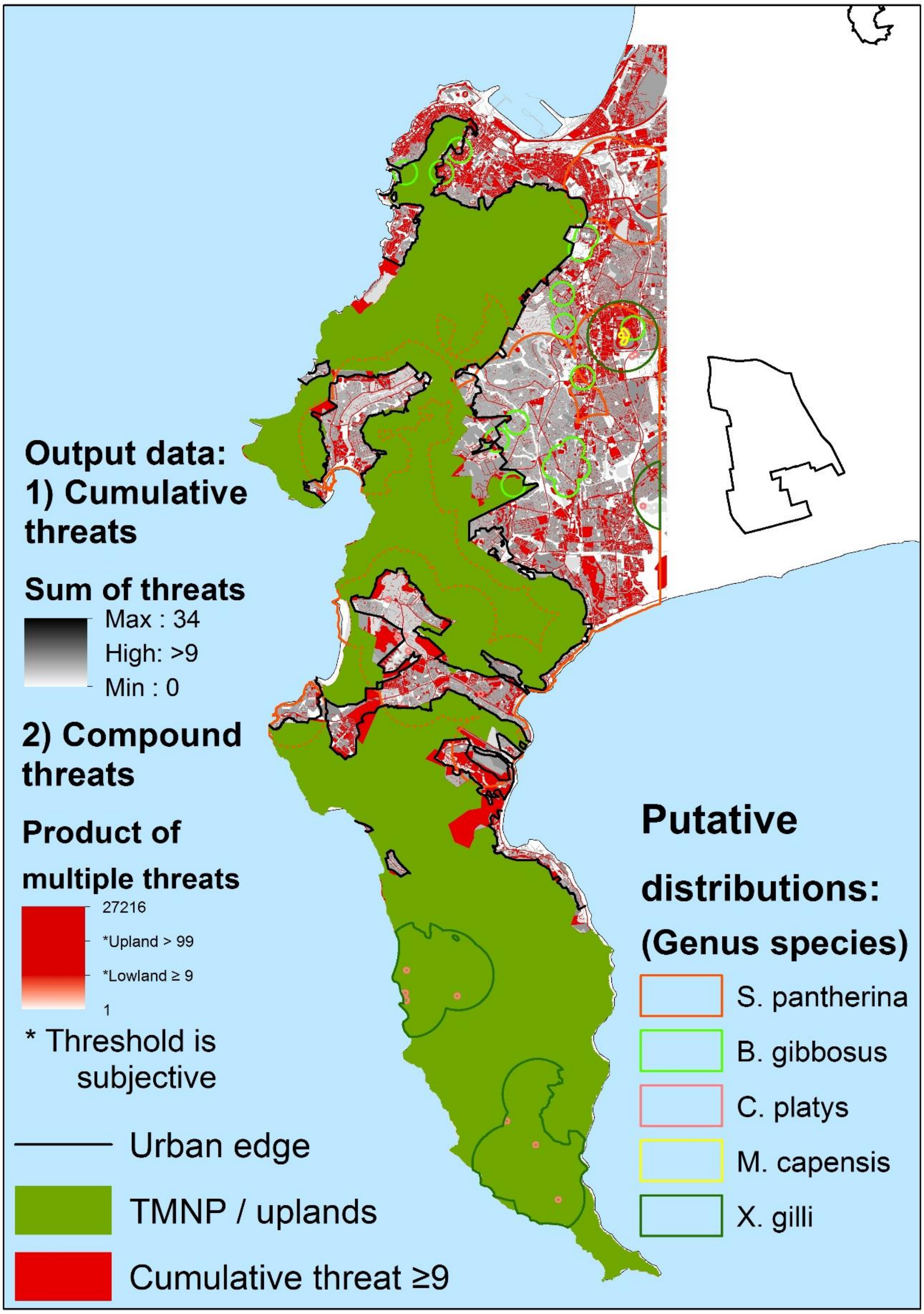


Figure 2.4: The cumulative impact of threats (as per 'ImpactScore' of Appendix 2.2) for lowlands of the Cape peninsula. The sum of overlaying threat impact scores (per 5x5m pixel) is represented in shades of grey. The sum of impact score are summed within distributions to derive the Cumulative Threat Index. The product of threat impacts (threat impact scores multiplied per overlaying 5x5m cell) is used to propose a score that represents a tolerance boundary that may exclude amphibians. A score of 9 or greater represent threat hotspots for lowland species, in red.

Table 2.2. Area [m^2] of each threat-class (Salafsky *et al.*, 2008) in the respective Cape peninsula distributions of *Heleophryne rosei, Microbatrachella capensis, Capensibufo rosei, Sclerophrys pantherina, Xenopus gilli, Arthroleptella lightfooti, Breviceps gibbosus,* and *Cacosternum platys*. Note that the sum of areas under threat could add up to greater than the distribution of respective species (great than 100% coverage), as some threats co-occur and overlay each other. The greatest threat area is highlighted in orange, and the next considerable threat area is highlighted in yellow. Threat-classes #7 (system modifications) and #8 (invasions) are unlike the other classes, as invasive flora are not represented continuous for the study area, but is only represented outside the urban edge (TMNP and adjacent vegetation).

	Areas (m^2) representing threat classes (Salafsky *et al.*, 2008), and percentage treat cover to eight regional amphibian distributions								Endemism	
Genus species / Threat	**Developments** Threat Class 1	**Agriculture** Threat Class 2	**Mining** Threat Class 3	**Transport** Threat Class 4	**Intrusions** Threat Class 6	**Modifications** Threat Class 7	**Invasions** Threat Class 8	**Pollution** Threat Class 9	**Geological** Threat Class 10	**Spatial**	**Ecological**
Heleophryne rosei	4524	0	0	60047	651832	8547335	8547335	0	410607	Peninsula	Uplands
Threat as % of distribution	0.1			0.7	7.6	100.0	100.0		4.8		mountain stream
Microbatrachella capensis	168207	0	0	10312	36232	0	168207	0	0	CFR	Lowlands
Threat as % of distribution	100.0			6.1	21.5	-	100.0				seasonal wetlands
Capensibufo rosei	3907	0	0	137534	78291	1669983	1669983	214280	0	Peninsula	Uplands
Threat as % of distribution	0.2			8.2	4.7	100.0	100.0	12.8			seasonal wetlands
Sclerophrys pantherina	76768918	31800911	89596	28256154	5309048	59538105	169553525	5510938	114106	CFR	Lowlands
Threat as % of distribution	38.4	15.9	0.04	14.1	2.7	29.8	84.8	2.8	0.1		terrestial / ponds
Xenopus gilli	5467536	2022801	0	2705362	456617	34289589	43531237	3676627	0	CFR	Lowlands
Threat as % of distribution	7.4	2.7		3.7	0.6	46.4	58.9	5.0			shallow wetlands
Arthroleptella lightfooti	12172	517759	0	126091	197926	3265464	3268845	312942	8347	Peninsula	Uplands
Threat as % of distribution	0.4	15.8		3.8	6.0	99.5	99.6	9.5	0.3		terrestrial / moss
Breviceps gibbosus	6979859	989703	0	2593159	183729	1697067	11303221	46791	3610	CFR	Lowlands
Threat as % of distribution	55.6	7.9		20.7	1.5	13.5	90.1	0.4	0.0		terrestrial
Cacosternum platys	143785	0	0	31803	8898	223188	49166	166329	0	Peninsula	Lowlands
Threat as % of distribution	24.7			5.5	1.5	38.3	8.4	28.6			wetlands

Table 2.3: Five threat indices are presented, for eight amphibian species (*Heleophryne rosei, Microbatrachella capensis, Capensibufo rosei, Sclerophrys pantherina, Xenopus gilli, Arthroleptella lightfooti, Breviceps gibbosus,* and *Cacosternum platys*). The putative distribution areas on the Cape peninsula used in this study, and the radius it is computed from, is shown along with the regional conservation status and family. A simple equation is presented for each of the five indices (Ta = Threat area, Ts = Threat impact-score (informed by the South African Frog Re-assessment Group's conservation assessments), Cn = Number of cells with that respective score, Ca = Cell size of 25m^2). The distribution that may be lost due to a saturation of threats is calculated based on a logical tolerance of cumulative threats. *X. gilli* distribution that may be lost in the Cape of Good Hope section of TMNP is assessed at a compounded threat impact score greater than 99, like that of upland species; other lowland habitat-cells are assessed as 'saturated' with a compounded threat impact score of 9 or greater. *Underestimates of area of occurrence, due to lack of extensive observation records.

	Equations:	Ta = Threat area	Cn = Number of cells	Threats indices						
		Ts = Threat score	Ca = Cell area = 25m^2	$\Sigma\ Ta_{(n=1)}$	$\Sigma Ta_{(n=7)}$	$\Sigma Ta_{(n=9)}$	$\Sigma\ (\Sigma Ts_{(n=9)}.Cn.Ca)$	$\Sigma\ (\Pi Ts_{(n=9)}.Cn.Ca)$		
Family	**Red List Index**	**Distribution (m^2)**	**Genus species**	**Landcover (LTI)**	**Discrete (DTI)**	**General (GTI)**	**Cumulative (STI)**	**Compounded (PTI)**	**Distribution (m^2) exl.**	**Adjusted Distribution**
	Butchart *et al*. 2005	& buffer	(Sub-title: descriptive)	One area [m^2]	Sum of areas [m^2]	Sum of areas [m^2]	Sum of 9 scores	Product of 9 scores	@ score ≥ 9, or > 99	less excluded cells
Heleophrynidae	CR	**8547335**	***Heleophryne rosei***	192453	1127010	18221680	2863404	13167164	1017550	7529785
		Radius 500m	normalized by distribution	2.3	13.2	213.2	0.3350	1.5	11.9	88.1
Pyxicephalidae	CR (global & regionally)	**168207**	***Microbatrachella capensis***	168207	214751	382958	58927	148328	46625	121582
		Radius 100m	normalized by distribution	**100.0**	**127.7**	227.7	**0.3503**	0.9	27.7	72.3
Bufonidae	CR	**1669983**	***Capensibufo rosei***	2257	434012	3773978	575684	2968123	140575	1529408
		Radius 250m	normalized by distribution	0.1	26.0	226.0	0.3447	1.8	8.4	91.6
Bufonidae	EN (global & regionally)	**199683273**	***Sclerophrys pantherina***	110698290	147849671	376941301	51736474	237657432	77288650	122394623
		Radius 1500m	normalized by distribution	55.4	74.0	188.8	0.2591	1.2	38.7	61.3
Pipidae	CR (regionally)	**43922588**	***Xenopus gilli***	8546636	14328943	92149769	9938247	31366203	2698500	41224088
		Radius 1500m	normalized by distribution	19.5	19.4	209.8	0.2263	0.7	6.1	93.9
Pyxicephalidae	NT	**3283279***	***Arthroleptella lightfooti***	172163	1175237	7709546	1074087	6900624	343250	2940029*
		Radius 75m	normalized by distribution	5.2	35.8	**234.8**	0.3271	**2.1**	10.5	89.5
Brevicipitidae	EN (regionally)	**12546203**	***Breviceps gibbosus***	9426322	10796851	23797139	3360877	12508273	3906075	8640128
		Radius 500m	normalized by distribution	75.1	86.1	189.7	0.2679	1.0	31.1	68.9
Pyxicephalidae	NT	**582040***	***Cacosternum platys***	191485	350815	623169	133906	460159	267100	314940*
		Radius 100m	normalized by distribution	32.9	60.3	107.1	0.2301	0.8	45.9	54.1

Table 2.4: ANOVA results. The five threat indices each compared to the Regional and Global Red list index. Regionally there is no difference between the degree to which an amphibian's distribution is under threat and the regional threat status. Threats to upland species (n=3) and lowland species (n=5) are significantly different from each other when using the Landcover representations of threat and the Compounded threat index.

Threat Indices	P value. Threat indices compared to the Regional RLI	P value. Threat indices of Upland species compared to lowland species	P value. When compared to the global RLI
Landcover (LTI)	0.543	**0.031**	0.939
Discrete (DTI)	0.786	0.054	0.760
General (GTI)	0.102	0.202	**0.028**
Cumulative (STI)	0.112	0.062	**0.030**
Compounded (PTI)	0.672	**0.002**	0.304

An ANOVA was also conducted between the threat indices of upland versus lowland species. The Landcover index (LTI) shows a greater threat for the lowland species compared to upland species [$F(1,6) = 7.86$, $p = 0.031$]. While the Compounded TI (PTI, product of cells) shows greater threat representations for the uplands [$F(1,6) = 30.01$, $p = 0.0015$]. ANOVA results (p-values) are in Table 2.4.

If land-cover were used as a spatially congruent threat index for a species' threat assessment, then the most threatened species (other than the one location of *M. capensis*) would be the 'Near Threatened' *Breviceps gibbosus*. But if the threats are weighted by threat impact-scores then *C. rosei* (adding impact scores) and *A. lightfooti* (the product of impact score) are impacted the most (again excluding *M. capensis*). The indices compared in figure 2.5 are scaled to the species most threatened (i.e. the species' whose distribution is most threatened has its threat index value set at 1). The same indices presented in table 2.3 are the absolute indices.

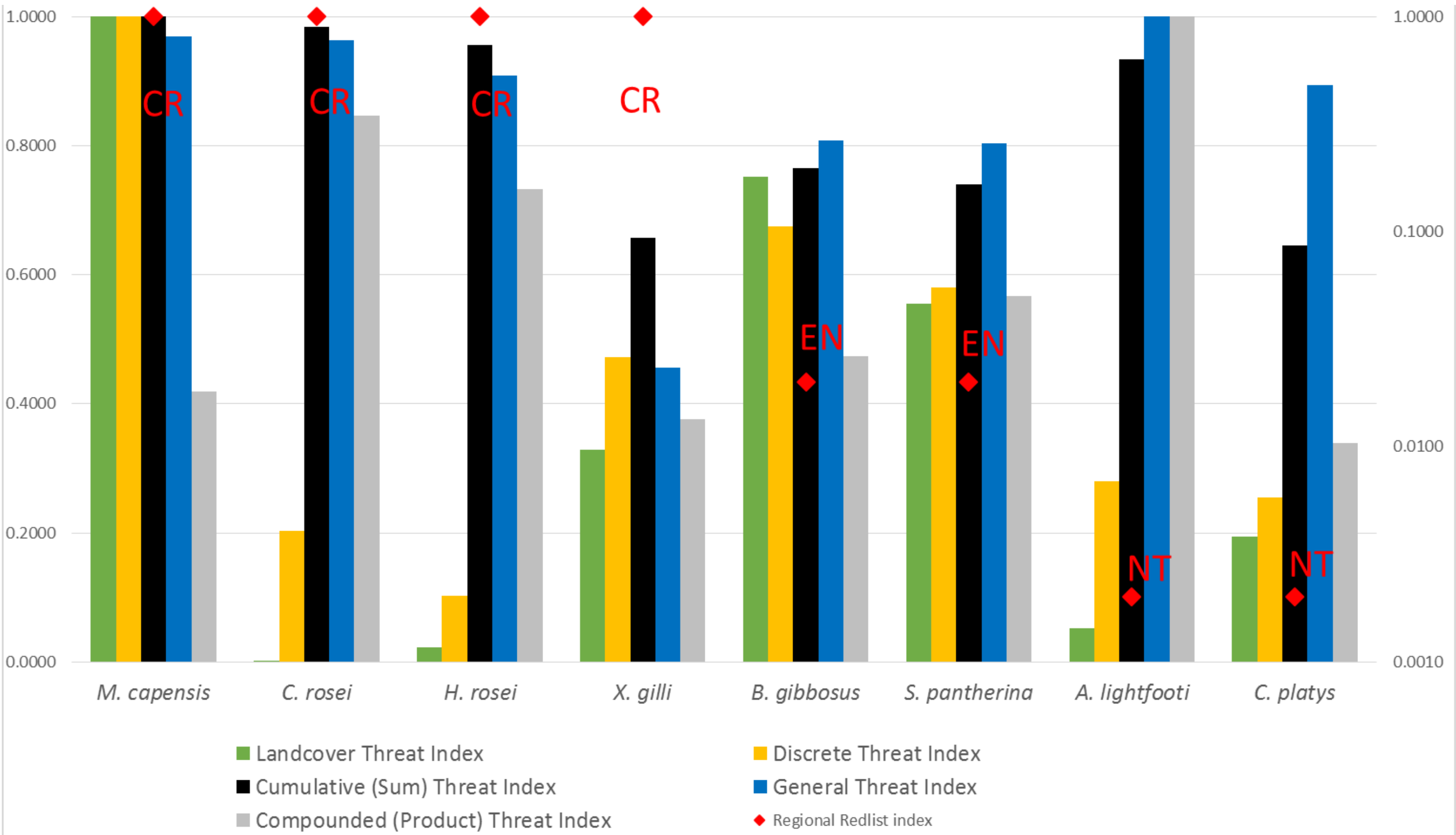


Figure 2.5: Five versions of a spatial threat index (scaled to 1) is presented for eight amphibian species of the Cape peninsula (*Microbatrachella capensis, Breviceps gibbosus, Arthroleptella lightfooti, Sclerophrys pantherina, Capensibufo rosei, Heleophryne rosei, Cacosternum platys,* and *Xenopus gilli*). The Landcover Threat Index uses the area of threats derived from seven land-type categories at 30x30m resolution. Discrete Threat Index sum the area of threat classes (n=7) that are mapped discretely. The General Threat Index includes the threat classes of the Discrete TI, but adds non-continuous and non-discrete spatial data as well (n=9). The Cumulative Threat Index sums the nine overlaying threat impact-scores per 5x5m cell (possible max: 90, observed max: 34). The Compounded Threat Index multiplies the nine threat overlays, thereby exaggerating the effect of multiple overlaying threats (possible max: 109, observed max: 27216). Indices are relative as they are scaled to 1, representing the most threated distribution assessed.

Distribution potentially lost, as calculated by Compounded threats on the lowlands (Figure 2.4), is greatest for *C. plays* (45.9% of putative distributions may be saturated with threats), then *S. pantherina* (38.7%), then *B. gibbosus* (31.1%). The upland species whose distribution is calculated to be most threatened (Figure 2.3) is *H. rosei* (11.9% may be uninhabitable); followed by *A. lightfooti* (10.5%). All other species' habitat threat saturation is calculated at below 10% of distribution.

2.4. Discussion

The threats which have the greatest coverage (table 2.2) over amphibian distributions in the lowlands are ‘Residential & commercial developments’ and ‘agriculture’, while for the uplands it is ‘natural systems modifications’ and ‘invasive & other problematic species’. All six questions posed in the introduction are addressed through this study.

The Cape peninsula forms an isolated (upland) and fragmented (lowland) habitat for local amphibian populations, which are of conservation concern to local managers. The results show that mapped threats overlay partially for all species, to the degree that the sum of the areas of overlaying threats to each species (nine input threat-classes) exceeds respective distribution areas (Table 2.2). The threat-classes not available for this assessment are absent either because that threat is absent (e.g., amphibians are not know to be harvested), or the scale of representations of threats are too large or ubiquitous such that there is no discretion thereof at the regional level (e.g. reduced precipitation do to climate change). The index that would be most useful for the spatial assessment of threats is the Discrete Threat Index (DTI), as it is most similar to the regional Red List status (table 2.4), and excludes non-continuous data. Spatial threat assessments have their limitations, data availability and scale are two such limitations. A minimum of seven threat-classes are included in the DTI, and that all representations of threat are discrete and continuous for the study area. As soon as any of the spatial representations of threats are non-continuous or indiscrete (like wildfires or density estimations in protected areas only) then the index derived from it conforms to a General Threat Index.

The upper threshold of threat, beyond which individual amphibians are not found, can only be established with empirical data (perhaps by a ground-truthing exercise); but for the purposes of this study, the threshold is based on the threat impact scale of 0 - 10. Where zero results in no mortalities due to a given threat, and ten results in 100% mortality to individuals exposed to a given threat. Two representations of threat are available for TMNP (only), which are not available for the urban landscape, as a result the threats calculated for upland species are subject to two more layers of threats (i.e. fire and invasive plant density estimations); and two different thresholds are used to define hotspots. To avoid this differential treatment (methodologies), fire regimes and alien plant densities need to be represented discretely for the urban landscape as well. The Discrete Threat Index removes data of a limited spatial extent or inappropriate scale. In-so doing it removes or discounts threat of the landscape-scale (alien plant and fire-regimes). Generally the DTI would be accurate for the lowlands and the GTI would be biased for (by emphasising) threat to protected areas. Uplands are better conserved, such that land is not subdivided and re-zoned, but conservation and monitoring efforts in protected areas results in more representations of threats for protected areas.

The results of the GTI would show correlation with upland threatened species that may be highly threatened, not because of a saturation of threats, but because of exposure to inappropriate fire regimes and potential deleterious effect of alien plant in addition to other threats (e.g. pollution of perennial waters). Protected areas at altitude are largely protected from pollution, yet unit area of polluted wastewater treatment work (threat impact-score 9), is equivalent to the unit area of potential pollution of perennial waters (threat impact-score of 2, at all altitudes including protected areas). In many cases better representations of threats are sought, and should vary with altitude or other appropriate gradient. These subtle differences are not relevant for the Area Approach to spatial threats (Landcover, Discrete or General Threat Indices, as they are indices based on a binary data input). The Cumulative and the Compounded Threat Indices however, do take degree of threat into account. The scale of a threat's effect may be species specific, but in many cases tolerance to threat may be the same or similar for the family or order. Since the threat-impact scores are independent of the probability of encountering that threat, the impact-score for all amphibians crossing a highway is 10 (10 for reptiles, 8 for mammals and perhaps 1 for birds), even though only one species may live near a highway. I suggest that the threat indices based on threat-impact scores need not be at the species-scale. If taxonomic, then at the order-scale. If ecologic, then at the life-history-strategy-scale. Variation in threat to respective distribution is largely due to a difference in said distribution and less so to the variable effects of the same threat to different species of the same genus, family or order.

Can the understanding of the spatial heterogeneity of threats result in directed management action for upland and lowland species?

Lowland species.

Amphibians are excluded from some areas within its extents of occurrence, by both lack of habitat and due to threats. A spatial analysis of threats (given a cumulative threat threshold) can approximate the area due to the latter. The four species that have a distribution in areas of high co-occurring threats are all lowland species. Table 2.3 shows that 27.7% to 45.9% of land has a threat impact score greater than 9 (Figure 2.4). This is an indication of the degree to which areas of occupancy are overestimated. A fifth lowland species, *X. gilli,* is largely protected in the Cape of Good Hope (section of TMNP) (de Villiers, 2004b; de Villiers, de Kock and Measey, 2016), its (percentage) distribution lost to threats are similar to upland species (Table 2.2).

The peninsula has one endemic lowland amphibian; *C. platys* has previously been considered of Least Concern (IUCN, 2013), but with changes to taxonomy (Channing *et al.,* 2013) will soon be assessed as Near Threatened. This species' spatial distribution (as well as *A. lightfooti*) is likely to be an underestimation of its extent (J. Measey, pers. comm.) because, as a small bodied species, records from many of their habitats are lacking. Yet a more comprehensive extent would not necessarily heighten its relative threat index score (Figure 2.5). The conservation status of the Cape Rain Frog (*Breviceps gibbosus*) is Near Threatened throughout its entire range; this is in contrast to the peninsula distribution's consistently high scores across all indices (Figure 2.5). This contrast shows that threats to, and conservation priority for peninsula populations are not necessarily indicated by respective Red List statuses. On the other hand, the high threat index for *M. capensis* on the Cape peninsula reflects its high threat status (Critically Endangered).

Mitigation of and responses to threats to one of the lowland species has an engaged and successful local conservation model. Coordinated by the Western Leopard Toad Conservation Committee, conservation efforts by the City and its partners, alongside citizens, focus on information and action campaigns that tries to ensure private properties and the urban landscape are less of a population-sink for individuals of *S. pantherina* (leopardtoad.co.za). Furthermore, the volunteers drive data-collection and citizen-science contributions, especially during breeding seasons. For lowland amphibian species, mitigation strategies are well understood: to prevent domestic pool drowning and predation (by pets and non-native vertebrates like fish and birds) (Rowe and Garcia, 2014), the restoration of wetlands (Petranka *et al.,* 2007), and facilitating dispersal, breeding success, connectivity (Hamer and McDonnell, 2008); implemented at a suburban and neighbourhood scale. However, because this mostly concerns private property in the City of Cape Town, initiatives are dependent on collaborations with property owners that volunteer to act (Measey *et al.,* 2014). Acts encouraged include providing an escape from property boundaries (e.g. by cutting escape-holes through solid barriers at ground-level) and from pools, uploading images and locations to iSpot (iSpotNature.org), and being wary of road-crossings (warning signage). Road deaths are further mitigated by temporally arresting migrating toads before they cross a road, and carrying them across during the breeding season. The conservation committee is a forum for debating and considering innovative solutions to threats (e.g. to mitigate road deaths, restore connectivity: use biodiversity bridges, like toad tunnels under temporary speed-humps). A similar volunteer-citizen approach may be appropriate for *B. gibbosus*, but not for all lowland species. Two lowland species, *X. gilli* (Endangered) and *M. capensis* (Critically Endangered) are not as exposed to the public and, much like upland species, need not (and should not) use citizens to spearhead conservation efforts. Competition between *Xenopus* species may be a greater threat for *X. gilli* conservation (Vogt *et al.*, 2017), than *Xenopus* hybridization (Furman *et al.*, 2017). Any threat due to a sympatric or congeneric dynamic was not picked up in the spatial threat assessment for two reasons: the invasion front of *X. laevis* is little recorded, and the water bodies that allow for invasion are small in size, yet large in influence (Picker, 1985).

The one known habitat on the Cape peninsula for *M. capensis* is Kenilworth racecourse, whose infield needs to be included in invasive plant clearing schedules, while the zonation of the infield properties needs to be protected from potential developments by granting it statutory protection. Alternatively or concurrently, populations can be established within TMNP (IUCN and Nature, Union internationale pour la conservation de la Group, 1998).

Greater opportunities for connections and protection (from fragmentation and habitat loss) in the distribution of lowland species is a priority for Table Mountain National Park and the City of Cape Town (Holmes *et al.,* 2012), my findings support this. Mitigation in the form of statutory protection of critical biodiversity areas (Holmes *et al.,* 2012), information campaigns that highlight domestic habits, landscaping, and precautions that aid conservation on private properties. Lowlands within TMNP coincide with conservation or rehabilitation efforts in Tokai, Cecelia, the Noordhoek Valley, and the renosterveld slopes of the City Bowl (e.g. Signal Hill). Lowland species may need to use uplands for dispersal between isolated areas, as coastal movement for frogs on the peninsula are very limited.

Upland species

Species at high altitude have a lower proportion of its distribution affected by habitat change as manifest in anthropogenic land-cover change, which most affects urban areas. The Landcover Threat Index and the Discrete Threat Index (seven threat classes, which exclude the areas representing fires and alien plants) reflect this reality for all upland species (Figure 2.5). However, two of the three upland species are Critically Endangered. This status is understandable, as the upland species are limited by, and isolated at altitude; their conservation status relates fundamentally to the extinction risk associated with a small distribution within an altered ecology, rather than the degree to which the distribution is under threat by direct anthropogenic means (e.g. urbanization). The threat to a small distribution is similar to that of an island or an area protected from development; landscape-scale threats (like fire frequency, system modifications, aliens) play a bigger role.

For the conservation of upland species a landscape-wide approach is warranted: invasive alien control (van Wilgen *et al.*, 2016), mimicking appropriate fire-regimes (Van Wilgen *et al.*, 2010; Bond and Van Wilgen, 2012), monitoring and the management of ecological process and ecosystem services for the benefit of wildlife (and thus society), also the obfuscation of exact breeding site locations on platforms like iSpot. Initiatives that are in place (e.g. for alien control) are rigid and regimented, while existing inter-governmental conservation efforts have a too narrow a focus (e.g. baboons). There is no multi-stakeholder committee considering innovative or strategic responses to a range of conservation issues and threats. Solutions to water supply and demand issues in the light of climate change is the obvious conservation focus for water security; related to both humans and to stream- and seasonal wetland species (e.g. *H. rosei* and *C. rosei*) at altitude (McDiarmid and Altig, 1999). While the mossy habitat-niche of the Peninsula Moss Frog (*A. lightfooti*) is highly specific and susceptible to drought and displacement by some invasive plants.

The Peninsula Dwarf Mountain Toadlet (*C. rosei*) population is seen to have more vitality following appropriate fire intervals and when (seasonally) excluding recreational disturbances (Cressey *et al.,* 2014, Becker, unpublished). This species has declined in TMNP enigmatically over the past 20 years, and will soon be assessed as Critically Endangered and as a peninsula endemic (Cressey, Measey and Tolley, 2014; Channing *et al.*, 2017). In this frog's case the critical status is due to it being both an isolated upland species and affected by local declines of speculative cause. I infer that population declines may be due to one of two factors: either the threat not assessed in this study (enigmatic) or the threats are present at past distributions (where species have been lost over the past 50 years). All threat-classes should be mapped, while potential and extinct distributions should be included in a spatial threat assessment. These factors represent two shortcomings with the spatial threat indices: they do not consider all threats that may influence a species, nor the extirpated distributions (where threats have proven to exclude the species).

The results (Figure 2.5) show that for Critically Endangered (CR) species the Cumulative Threat Index (STI, based on the sum of threat impact scores) is consistently above 0.9. But this index implies that the conservation status of *A. lightfooti,* and *C. platys* (all NT) underestimates their degree of threat. While for *B. gibbosus* (NT) the status underestimate the degree of threat faced on the Cape peninsula. Thus the Cumulative Threat Index (STI) is the ostensible index that represents cumulative threats. The Land-cover index and the Area index (of 7 threat classes) discount the threat-coverage representing alien plants and modifications (fire), such that these indices are comparable across the uplands and lowlands.

Expansion of a GIS threats database. There are ways to produce spatial representation of threats not represented. i) creating discrete spatial threat-data, derived from observations, local monitoring results, or inference (e.g. ozone depletion increases the threat of ultra-violet radiation damage to *C. rosei* (Blaustein *et al.*, 1994; Cressey, Measey and Tolley, 2014), ii) using other appropriate proxies (in relation to water, use catchments or rivers; in relation to ultra-violet threat, use altitude). I hypothesise that the cause of an enigmatic decline is the threat which may be present in extant distributions but is beyond a threshold where extirpated. A further function of any spatial threat index could be to better approximate that threshold. Identifying and mapping threats may be as simple as desktop assessment, but finding solutions in a complex socio-ecological system requires a structured yet adaptable approach (Folke *et al.*, 2005; Meffe *et al.*, 2012).

Mapping of threats has been attempted in relation to the distribution of amphibians. Often they are not comparable, as a study may focus on a narrow range of threats (e.g. Surasinghe et al., 2012), or is of too large a scale, too low spatial resolution (e.g. Hof *et al.,* 2011). With the major limitation being data availability (Joppa *et al.*, 2016). However, opportunities for conservation exist in cities (Elmqvist *et al.*, 2013): data of high spatial resolution. This method lends itself to be comparable between cities and the distribution of their respective biodiversity. Joppa *et al*. (2016) advocates for a ‘gold-standard’ of data, which should meet five requirements: available freely, of a minimum resolution, up to date, repeated, and assessed for accuracy. The data used in this study fails in one regard: it is not up to date. Shapefiles / spatial representations are true for the year and month the aerial image (used to stereographically trace features like agricultural and mine footprints) was taken; while an individual property’s zonation may be altered ad hoc, the zonation map may be produced only periodically. Tulloch *et al*. (2015) asks: Why are threats mapped? Their answer highlights the direction this threats-database must take: using a spatial information system (of threats) to inform a structured decision-making process for biodiversity threat mitigation.

2.5. Conclusion

A threat map is a tool that identifies spaces that conservation actions might have the greatest effect per unit effort. A threat index informs relative (comparative) threats to species' distributions. Land-cover derived from remote sensing provides a threat index and map of high temporal resolution (every 16 days), while threat types derived from property attributes and proxies to threats provides a threat index and map of high spatial resolution. The Cape Rain Frog (*Breviceps gibbosus*) is not assessed as being threatened, yet its distributions on the peninsula is shown to be threatened to a degree greater than that of some threatened species, and is consistently high for all indices.

2.6. Recommendations

City Parks and South African National Parks on the Cape peninsula are managed as urban parks, and should have a common strategy or approach to urban wildlife and ecosystem services conservation. For directed threat mitigation actions, residents of areas where Breviceps gibbosus are found need to be a focus for amphibian conservation information drives by both the City of Cape Town and Table Mountain National Park. The M. capensis population of the peninsula is found on private land. What is needed is a statutory commitment by the owners to conserve the land in perpetuity.

Spatial representations of threat-class ‘diseases’ (chytrid fungal disease), and ‘Climate Change’ are lacking, and if mapped, need to be produced at an appropriate scale for discrete spatial units (e.g. conditions per catchment, per unit altitude). I recommend monitoring the aliens, water, and temperature of stream habitats at plateau-altitude and wetland habitats of the lowlands.

Both upland and lowland strategies for threat mitigation relies on local collaborations to reach conservation goals on the Cape peninsula (Measey *et al.*, 2014), the most strategic and effective would be an inter-agency cooperative between SANBI / Kirstenbosch, SANParks, the Extended Public Works Programme, and the City of Cape Town. Urban biodiversity conservation and threat mitigation can be more successful if managed by a multi-stakeholder committee of biosphere stewards (Elmqvist *et al.*, 2013) with two main tools: structured decision-making and a database of mapped threats.

CHAPTER THREE. Mapping threats to Table Mountain Ghost Frog (*Heleophryne rosei*) tadpoles on slopes of the Table Mountain massif, using stratified stream-habitat monitoring results.

3.1. Introduction

Global amphibian decline was reported by herpetologists in the 1990s (Blaustein and Wake, 1990; Phillips, 1990; Corn, 1994; Pounds and Crump, 1994), initially as an enigmatic loss (Stuart *et al.*, 2008) particularly of mountain populations with aquatic eggs and larvae (e.g. Lips, 1998). Declines in populations have since been attributed to drivers of global change (Millennium Ecosystem Assessment, 2005). Over 31% of more than 6000 recognized species of extant amphibians are considered to be threatened, resulting in there being more threatened amphibians of conservation priority than any other class of vertebrate (Stuart *et al.*, 2008; Hoffmann *et al.*, 2010). The major threats to amphibians globally are (in order) habitat loss, pollution, disease, fire, and invasive species (Stuart *et al.*, 2004; Alford, 2011). However, there are population declines attributed to, as yet, unidentified drivers of change. These enigmatic declines can happen in seemingly pristine habitats, including within protected areas (e.g. Cressey *et al*., 2014).

Mediterranean climatic regions have a long history of human settlement and as a consequence watercourses and landscapes are altered and threatened (Cooper *et al.,* 2013; Sim 1907; Shaughnessy 1980; Rebelo *et al.,* 2011). Amphibians rely on both freshwater habitats (most notably during the larval stage) and terrestrial habitats during their biphasic lifecycle. Anthropogenic changes to water catchments include damming and abstraction, weirs, wells/boreholes, aqueducts, canals; altering or re-routing flow and delinking streams from their floodplain (Fagan, 2011). Indirect effects include the modification of riparian flora and fauna, and adjacent land-use activities (Dudgeon *et al.*, 2006). Anthropogenic changes such as these would have an effect on that catchment's aquatic habitat suitability, thus an index of habitat quality is based on which families of invertebrate larvae is extant (Chutter, 1994; Dickens and Graham, 2002). For mountain stream vertebrates and invertebrates the two main ecological requirements is sufficient water flow, and appropriate temperature and chemistry. Water temperature and water flow are variables known to influence amphibian processes and responses; that of metabolism and growth rates, emergence, fecundity, and ultimately survival (McDiarmid and Altig, 1999). These, together with other water chemistry variables, may be used to determine the suitability of stream conditions at the lower (altitudinal) limits of the Table Mountain Ghost Frog's tadpole habitat.

The south-western region of southern Africa is known as the phyto-geographically distinct Cape Floristic Region (Verboom *et al*., 2009; Colville *et al.*, 2014), and is a mega-diverse hotspot of biodiversity (Cowling *et al.*, 2003). This region's floral richness is mirrored by a high degree of faunal diversity and endemism, including insect clades (e.g. Procheş and Cowling 2006; Sole *et al*., 2013), freshwater fish (e.g. Darwall *et al*., 2009), reptiles (Bates *et al.*, 2014) and amphibians (Poynton, 1964; Holt *et al.*, 2013; Colville *et al.*, 2014). The Cape peninsula is an isolated sandstone and granite mountain ridge, one of the richer enclaves of the Cape Floristic Region (CFR), and is within a metropolitan area. Table Mountain National Park (TMNP) is an urban park, and was established to conserve the biodiversity, waterscape and landscapes of the Cape peninsula. This peninsula reflects the regional trends in diversity and endemism of the CFR, while surrounded by a city. Climate models of the region predict small amphibian habitat gains along with larger habitat losses. General range reductions are to be accompanied by a northward and westward (Botts, Erasmus and Alexander, 2015), or northward and eastward shift (Hannah *et al.*, 2005; Mokhatla, Rodder and Measey, 2015) of amphibian habitats. Such shifts away from the Cape peninsula are limited. The mountains of the Cape peninsula are isolated from the inland ranges by lowlands of Cape Flats Sand Fynbos and Cape Flats Dune Strandveld (Mucina and Rutherford, 2006), formed by ocean incursions, during inter-glacial periods (Compton, 2011). These natural isolations have been reinforced with an anthropogenic restriction associated with the urban and agricultural landscape of the City of Cape Town (hereafter referred to as the city). Home to over 3.7 million people (StatsSA 2011), the city's urban footprint increased six-fold between 1946 and 2002 (Rebelo *et al.,* 2011b). Lowland areas of the peninsula and the cape flats are largely transformed, while upland areas are protected from development and large-scale habitat transformation.

Threats are not necessarily excluded from Table Mountain National Park; as citizens and visitors have free access to many areas, with dogs, horses and bicycles permitted in certain zones. Skeleton Gorge is regularly used as a popular hiking track, and is the type-locality of the Ghost Frog genus and family: *Heleophryne rosei,* Heleophrynidae. Members of the family Heleophrynidae are endemic to cool, fast flowing mountain streams of southern and eastern South Africa (Channing, Boycott and Van Hensbergen, 1988) and consist of two genera and seven species. The main threats to Heleophrynidae are: afforestation and the spread of alien vegetation, damming of mountain rivers, water extraction, the introduction of predatory fish, fires, erosion and the siltation of streams (Minter *et al.*, 2004; South African Frog Re-assessment Group, (SA-FRoG), IUCN, 2010).

Heleophryne rosei dispersal pathways and dispersal ability has not been studied. The Table Mountain Ghost Frog is assumed to consist of one metapopulation because it has a small distribution and adults which can move between streams (Du Toit, 1934; Boycott and De Villiers, 1986). It is torrent adapted with a population source near the (cool, wet) cliffs and plateau, and population sinks at the lower limit of its range (warmer, drier, potentially higher predation rate). Even though aquatic and semi-aquatic communities in streams and wetlands of the Mediterranean climatic region are resilient and adapted to summer seasonal drought (Gasith and Resh, 1999), the environmental water requirements, health, connectedness, persistence, and resilience of aquatic communities using near-perennial rivers are of conservation concern.

Protected areas are mandated to conserve natural habitats and ecosystem processes from, and as a result of, anthropogenic changes. This is achieved through statutory protection, monitoring, research, adaptive management, and rehabilitation. South African National Parks has undertaken to monitor biodiversity (McGeoch *et al.*, 2011); and to collaborate with other conservation organizations so as to avoid duplication of effort. CapeNature, the provincial conservation authority, monitors *H. rosei* tadpoles through an annual (timed) tadpole-count (Measey *et al.*, 2011), during the driest season (end of summer); five streams on the lower (contour zone) reaches (as well as two streams on the plateau). CapeNature's monitoring sites were chosen based on surveys conducted by Boycott and De Villiers (1986). SANParks measures water temperature and chemistry in the middle reaches of twelve streams, seasonally.

Long-term monitoring would record changes over time. Changes beyond an ecological boundary, or threshold, are likely to be noticed soonest at the ecological margins of amphibian metapopulations. Metapopulations are fluid, but influenced by dispersal abilities, strong site fidelity, and degree of suitable habitat connectivity (Smith and Green, 2005). The latter abiotic influence varies in the landscape and can be monitored. Changes to permanence of water flow is abiotic, and for this species a threat to flow relates to a threat to suitable habitat connectivity for tadpoles of the metapopulation. This threat can be represented in two threat-classes as defined by Salafsky *et al*. (2008): i) Natural system modifications, including 'dams and water management / use' (threat sub-class #7.2), and ii) Climate Change, including 'habitat shifting and alteration' (threat sub-class #11.1), 'droughts' (threat sub-class #11.2), and 'temperature extremes' (threat sub-class #11.3). Monitoring water conditions, controlled for the presence or absence of *H. rosei* tadpoles, may show a threat or boundary which can be mapped at the catchment-scale. Alford *et al.* (2001) notes that global amphibian decline may not be as a result of global causes, but rather the "cumulative effects of local declines with local causes". The aim of this study is to determine which of the monitored water variables influence the presence or absence of tadpoles, and to propose a water chemistry niche that might apply to Table Mountain Ghost Frog tadpoles. I hypothesize that tadpole presence in the lower catchments of mountain streams is dependent on measurable water variables. A margin may be reached where water conditions are not viable as larval habitat, these conditions can be mapped as a threat. Cecelia and Platteklip streams no longer support tadpoles and may have reached unfavorable conditions, while Nursery stream could be approaching marginal conditions for *H. rosei* tadpoles (de Villiers, pers. comm.)

3.2. Methods and Materials

The Table Mountain massif constitutes the Northern Section of South Africa's Table Mountain National Park. Twelve streams flowing off Table Mountain were chosen for this study (Figure 3.1). I seasonally monitored selected water conditions therein, controlled for altitude. While CapeNature conducts its annual dry-season tadpole count (during Feb/March: the end of the southern summer) in five of these streams. CapeNature's data is used as the response variable in linear models using 'R' (R Core Team, 2013), while water temperature and water chemistry are determinate variables.

Site description

Until the latter 1800s, water engineering projects were limited to the lowlands of Cape Town (e.g. canalization and enclosing water courses (Brown and Magoba, 2009). The expansion and growth of Cape Town necessitated an ambitious water scheme on the Plateau of Table Mountain; starting with the Woodhead tunnel (1891) which diverts the waters of the Disa stream, via the Pipe Track, to the City Bowl's Moltino reservoir. Five reservoirs, which cumulatively store over 2.375 billion liters (Appendix 3.1), was built on the Plateau; its waters to be released (mostly) in the dry season, for residential use on the Atlantic seaboard from Constantia neck and Hout Bay to Signal Hill and the City Bowl. This system employs two inter-basin transfers; via Woodhead tunnel and via a bypass (Figure 3.1 and Appendix 3.1, the waters of Victoria and Alexander reservoirs originally flow eastward, but is diverted southwest to the De Villiers dam and then the Original Disa stream). The surface area flooded behind the dam walls is the magnitude of the direct loss of riverine and terrestrial habitat. This area is about 38 hectares (Appendix 3.1), and is the limit of habitat loss, as no new/future dam walls are to be constructed on Table Mountain. Downstream summer water temperatures are cooler after a dam or reservoir is built, while downstream winter temperatures are warmer than it was before the impoundment (Baxter, 1977). Potential downstream temperature regulation is limited to shading and controlling the depth from which water is released from reservoirs: either from the hypolimnion (from cool depths), or as overflow from the epilimnion (warmer surface layer).

Heleophryne rosei adults have been found in caves (Gow, 1963; Poynton, 1964), indicating they are able to move away from rivers, and possibly between catchments (Figure 3.1: map). Streams where tadpoles have been found: include in Platteklip Gorge (Du Toit, 1934); abundant (Boycott and De Villiers, 1986) in the two tributaries of Orangekloof, the Disa Gorge (flowing below Woodhead reservoir), and the original Disa Stream (flowing below DeVilliers reservoir); the east-flowing Window Gorge, Nursery Ravine, Cecilia Ravine; and the streams on the plateau, including above the Hely-Hutchinson reservoir. Boycott and De Villiers (1986) surveyed the Newlands, Fernwood, and Hiddingh streams; absences below the cliff-face (below 400m) were confirmed with their 1980s surveys and with this study. Similarly, the two largest catchments on the Atlantic seaboard, Blinkwaterskloof and Kasteelspoort streams have no record of occurrences below the plateau. The upper catchments of these twelve rivers (Table 3.1) constitute the Plateau of Table Mountain.

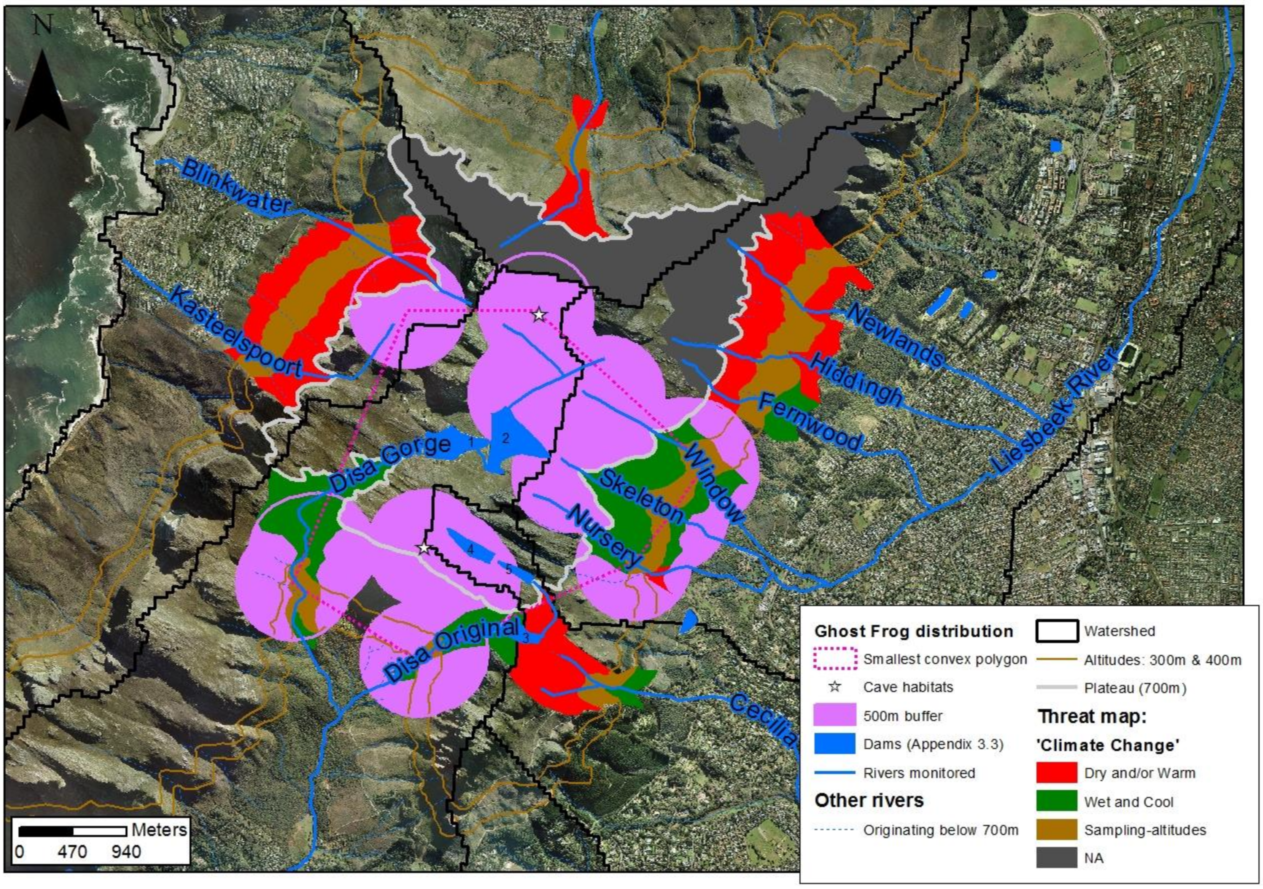


Figure 3.1: Water temperature and water flow results are mapped as Dry to represent 'Drought' and Warm to represent 'Temperature extremes' interpolated for 400m and above (to the plateau at 700m), and for 300m and below (to 200m). Green areas are favourable for tadpoles as water conditions are both below a summer mean temperature of 17.2°C and water flows during all four season. The red bands indicate where water conditions are either above a summer mean temperature of 17.2°C or water stops flowing during at least one season, or both: unfavourable for tadpoles. Also illustrated are 12 streams flowing off the Northern Section of TMNP, and where they interact the two water sampling altitudes (300m and 400m). The distribution of *Heleophryne rosei* is indicated using two methods: as produced for Chapter Two of this study (a 500m buffer around observations), and the smallest convex polygon around all records. The white star represents adult cave habitats (Gow, 1963; Poynton, 1964)**.**

Water chemistry monitoring

Water chemistry variables provide information about the health of streams and perhaps the suitability of these waters as a habitat for amphibian larvae. The area of interest for this study is at the lower altitudinal edges of occupancy: below the cliffs (around the 400m contour), and close to the species lower limit (around the 300m contour). These altitudes are where tadpoles are most evident as a result of path access and topography. Water chemistry variables of twelve streams have been monitored by SANParks seasonally (Appendix 3.2), for 2.5 years (ten seasons, including three summer and three autumn seasons), two sites on each stream. Some streams have short sections of no surface flow, even in the wettest of seasons. This is natural and not considered as a study site. Sites at which water flows on the surface, and are safe-to-access near the 300m and 400m contours were identified during the spring/summer of 2013/2014). Blinkwaterskloof stream has no surface flow for large sections of its profile, while the route up the Blinkwaterskloof is closed and restricted because TMNP deems it unsafe to transit. As a consequence it is represented at only one (the lower) altitude.

The survival of *H. rosei* larvae are relevant to two programmes within SANParks' Biodiversity Monitoring System: the Species of Special Concern Monitoring Programme, and the Freshwater and Estuarine Monitoring Programme (Russell *et al.,* 2012). The variables measured in this study are prescribed by the latter programme, and include dissolved oxygen, pH, salinity/conductivity, and temperature (Appendix 3.2). YSI (Yellow Springs Instrument, Yellow Spring, USA) probes were used; models ph100, DO200, EC300. These variables are cost effective and convenient to measure *in situ.* Measures of eutrophication (nitrates and phosphates) were not monitored as these variables would need to be quantified ex situ, and the area is protected from urban and agricultural runoff, thus there is no reason to suspect their levels to be anything other than natural. Habitat suitability for aquatic larvae is entirely dependent on water conditions. Larval metabolic and growth rates are influenced by water temperature (McDiarmid and Altig, 1999). Changing the pH of waters affects the ionic balance of organisms living therein. Small pH changes are generally not lethal, although growth rates of aquatic organisms can be impaired and fecundity reduced (Davies and Day, 1998). Dissolved oxygen is critically important to tadpoles (and other aquatic life), for respiration and gaseous exchange. Oxygen concentrations are not predicted to be a limiting factor in lotic streams (e.g. Viertel and Richter, 1999), as mountain streams are typically oxygen-rich. Electro-conductivity (EC) is a proxy measure of concentrations of dissolved salts and of evaporation (including evapotranspiration).

Methods of Statistical analysis.

A Stepwise linear regression was used to remove variables that do not explain the observed presence/absence. Linear Models are constructed in combinations of the retained explanatory or predictor variables called for by the stepwise regression. The binomial response variable (presence or absence) is tested for, while abundances are displayed in relation to the ecological boundary for the *H. rosei* tadpoles (Table 3.2). The log-likelihood of fifteen (both single and multi-variable) models was derived, and Akaike's information criterion (Akaike, 1973) was calculated. The Akaike Information Criterion (AIC) provides a means of model selection, as it measures the relative quality of each model for a given dataset. In this case, which model best explains the observed presence or absence of tadpoles. All analyses was conducted in R (R Core Team, 2013).

Sources of bias or error.

A lack of water readings in summers would bias the average reading (of water variables) to the conditions found during the cooler, wetter seasons. Altitudinal readings (Garmin GPS60) in crevices and valleys have a higher error (than outside of crevices – this is true for latitudinal and longitudinal error as well); while natural intermittent flow (not due to lack of water or drought, but rather due to the flow going subterranean) or unsafe conditions would shift the study site away from the exact 300m and 400m aimed for. Water sampling was conducted in 10 seasons; winter and spring (n=2), summer and autumn (n=3).

3.3. Results

The variables that best explain the observed presences of *Heleophryne rosei* tadpoles below the Table Mountain plateau are the interacting effects of: permanence of the stream's water flow and the mean temperature (Table 3.2). An ecological boundary for the average upper thermal limit can be considered (low temperatures are not considered limiting). Furthermore, the results show that electro-conductivity is not a significant predictor, while pH, and dissolved oxygen are not predictors of tadpole presence.

Four variables were retained (stepwise): the permanence of the stream flow, the mean water temperature, the mean electro-conductivity, and aspect. The top two models have a difference in AIC of less than 2, thus the model with the least parameters is preferred. Presence of tadpoles is best explained by temperature mean, electro-conductivity mean, and permanence of stream (Table 3.2). The lower the water temperature, the more likely tadpoles are present ($t = -0.302$). Permanent water flow is required by tadpoles ($t = 0.959$). With this model over 60% of the variance in the dataset is explained by three variables ($R^2 = 0.602$). Permanence of flow and the mean temperature are significant contributors to this and to the state of the dependent variable (i.e. the observed presences of *Heleophryne rosei* tadpoles) ($p = 0.0005$). Four of the five extant streams had flowing surface water during all study seasons (Table 3.1, where $n=10$), at both measured altitudes. Nursery Ravine, however, had no surface flow for large sections around the 300m contour during spring and summer.

Table 3.1 : The mean summer and annual temperatures, indicating permanence of flow (n=3 and n=10 respectively). The temperature identified as a putative temperature-extreme boundary is 17.2°C. Blue numbers are maximum mean temperatures for tadpole habitat, the summer mean proposed as a temperature threshold. Red numbers indicate parameters for which *H. rosei* tadpoles are absent (at and below the reference altitude). These limitations are mapped as the Climate Change threat-class in Figure 3.1. Underlined variables indicate conditions favourable for tadpoles. Tadpole annual abundance-data (n=10) courtesy of CapeNature, Atherton de Villiers.

Stream name	Tadpole presence/absence	Water use / management	Aspect	CapeNature: Relative abundance (n=10)	Site altitude	Annual mean temp (°C)		Summer mean (°C)	
Newlands	Absent	Limited / past use	East	NA	NL300	15.5	(n=10)	18.0	(n=3)
					NL400	12.8	(n=6)	16.4	(n=2)
Fernwood	Absent	Limited / past use	East	NA	FR300	14.6	(n=10)	16.4	(n=3)
					FR400	12.2	(n=5)	-	(n=0)
Hiddingh	Absent	Diversion	East	NA	HR300	14.9	(n=10)	17.9	(n=3)
					HR400	11.3	(n=1)	-	(n=0)
Kasteelspoort	Absent	Water input / IBT	West	NA	KS300	15.8	(n=9)	18.4	(n=2)
					KS400	14.3	(n=6)	-	(n=0)
Blinkwater	Absent	(Sub-surface flow assumed)	West	NA	BK300	15.8	(n=7)	19.9	(n=1)
					BK400	-	(n=0)	-	(n=0)
Platteklip	Absent (Historical)	Weirs (limited use)	North	NA	PG300	18.5	(n=10)	22.4	(n=3)
					PG400	16.6	(n=10)	18.8	(n=3)
Cecelia	Absent (Historical)	Abstraction / diversion	East	NA	CR300	14.4	(n=10)	17.0	(n=3)
					CR400	13.7	(n=7)	-	(n=0)
Nursery	**Present**	Abstractions	East	0.055	NR300	12	(n=4)	-	(n=0)
					NR400	13.5	**(n=10)**	16.6	(n=3)
Window	**Present**	Abstractions / by weir	East	0.748	WG300	13.6	**(n=10)**	16.8	(n=3)
					WG400	13.4	**(n=10)**	17.1	(n=3)
Skeleton	Present	Abstractions	East	0.902	SG300	13.9	**(n=10)**	16.9	(n=3)
					SG400	13.5	**(n=10)**	16.3	(n=3)
Disa original	**Present**	Dammed / IBT input	West	0.921	DO300	**14.1**	**(n=10)**	16.2	(n=3)
					DO400	**14.1**	**(n=10)**	16.8	(n=3)
Disa (gorge)	**Present**	Dammed / IBT abstracted	South	1.000	DS300	14.1	**(n=10)**	17.2	(n=3)
					DS400	13.9	**(n=10)**	17.1	(n=3)

A putative temperature niche.

Tadpoles are found in waters with an annual mean temperature of between 13.4°C and 14.1°C (n=10 consecutive seasons), raising to between 16.2°C and 17.2°C for the (mean) summer season only (n=3 consecutive summers).

Table 3.2 : Four variables were considered for Linear Models. The top model includes all four variables. The ΔAIC between the top two models is low (less than 2). The second model is preferred (as it has fewer parameters). The preferred model includes these three variables: Mean temperature, Electro-conductivity, and permanence of stream flow.

Model	Log likelihoods	Number of parameters	ΔAICs	Akaike weight
Mean temperature, Aspect, Mean electro-conductivity & Permanence of stream	-2.5784	8	0.00000	0.52693
Mean temperature, Mean electro-conductivity & Permanence of stream	**-5.9015**	**5**	**0.64620**	**0.38145**
Mean temperature & Permanence of stream	-8.9415	4	4.72615	0.04960
Mean temperature, Aspect & Permanence of stream	-6.1528	7	5.14883	0.04015
Permanence of stream	-14.6036	3	14.05050	0.00047
Aspect & Permanence of stream	-11.8493	6	14.54186	0.00037
Mean temperature	-15.1089	3	15.06099	0.00028
Permanence of stream & Mean electro-conductivity	-14.5558	4	15.95474	0.00018
Permanence of stream, Aspect, & Mean electro-conductivity	-11.8339	7	16.51099	0.00014
Mean temperature & Mean electro-conductivity	-15.1054	4	17.05392	0.00010
Aspect	-14.1983	5	17.23973	0.00010
Mean electro-conductivity	-16.2959	3	17.43499	0.00009
Aspect & Mean temperature	-13.9862	6	17.61188	0.00008
Mean electro-conductivity & Aspect	-13.9862	6	18.81569	0.00004
Mean temperature, Aspect, & Mean electro-conductivity	-13.3607	7	19.56459	0.00003

3.4. Discussion

Results suggest that permanence of water flow and water temperature are predictors of *Heleophryne rosei* tadpole's presence; more so than any of the water chemistry variables measured. This indicates that 'drought' and 'temperature extremes' can be reliably mapped using monitoring results controlled for altitude, but not 'habitat alteration' The results put a putative temperature envelope for *H. rosei* tadpoles at 17.2°C (summer mean) or below. The lower end of this species' temperature envelope cannot be measured *in situ* as it is not likely to be reached naturally. Thus if resources are a limiting factor for Park Management and if only one season is monitored, then that season should be summer. Water flow and water temperature are known to be influenced by land-use practices that affect adjacent riparian vegetation cover and fluvial connectivity (Zwick, 1992), it is also affected by water abstraction and water storage (Baxter, 1977; Bosch and Hewlett, 1982; Davies and Day, 1998; Cooper *et al.*, 2013).

The extent of an amphibian metapopulation expansion or contraction is due to three factors (Hanski, 1999; Smith and Green, 2005). Two are biological and may be species dependent (dispersal ability and site fidelity), while one is abiotic and observable in the landscape (habitat connectivity). *H. rosei* adult's ability to disperse is reasonably assumed to not be a limiting factor to metapopulation expansion, while site fidelity is unknown. For the Table Mountain Ghost Frog, two contractions of tadpole habitats (from Cecilia and Platteklip streams) are inferred based on the absence of contemporary sightings (Boycott and De Villiers, 1986). SANParks and TMNP now have a benchmark temperature below which conditions may allow for metapopulation expansion. Water flow (including flow impoundments) and temperature are now discussed; both in relation to mitigating threats, and rehabilitation potential.

Water flow

The data shows that if habitat connectivity (through water flow) is broken at 400m altitude, that stream is not a habitat for tadpoles at any altitude below 400m (Table 3.1), even though cool water may re-emerge downstream, at the water table. Nursery Ravine, Cecilia Ravine and Fernwood Gully each have one of two study-altitudes with favourable conditions for tadpoles. Nursery Ravine is the only that (sporadically) supports tadpoles. The observed difference between it and the two streams that do not have tadpoles present is the altitude at which flow is absent. The favourable conditions in Cecilia and Fernwood are at 300m, disconnected from the cliffs and plateau by a lack of flow at 400m. See Figure 3.1. The implication of this is the extent of the dendritic movement of larvae downstream is only so-far-as perennial flow allows.

Dams and Water management, Use. Dams transform and flood lotic stream habitats, and splits a once continuous river. Yet dams are seemingly an opportunity for cooler and larger flow volume downstream during summer. Dam infrastructure may allow for cooler summer water temperatures below the dam wall than if the dam were absent (Baxter, 1977) while supplementing summer flow when water is released for use downstream. The results indicate that the waters of the Disa Stream flow permanently, even though water is abstracted from above the study sites. However, the water diverted by the Woodhead tunnel to the Kasteelspoort stream does not seem to aid westward dispersal of tadpoles from the Disa catchment to the Kasteelspoort catchment. Waters that would have flowed east to reach the Cecelia (and Rooikat) ravine is dammed on the plateau (Victoria and Alexander reservoirs) and directed southwest via the De Villiers reservoir. Alexander Reservoir's excess waters may best be used for a restorative ecological experiment: returning waters to the Cecelia / Rooikat streams (Figure 3.1). The Kirstenbosch reservoir stores water abstracted from the Nursery, Skeleton and Window streams; the weir on Window Gorge siphons off all the summer flow, such that there is no tadpole habitat below the weir (as noted by CapeNature). If the *H. rosei* is a priority for conservation, water abstractions should be limited to below the habitat of this Critically Endangered species (i.e. below 240m altitude)

Pine plantations. The Table Mountain plateau was initially felled of pines in the 1970s and 1980s, in a phased eradication (Cowling *et al.,* 1976), and Table Mountain Ghost Frogs still breed there today even though remnant pines have germinated and are still present at lower densities. However, it cannot be said if tadpole numbers have improved since then, as CapeNature's *H. rosei* tadpole monitoring started only in 2003. TMNP is removing pine plantations piecemeal from mid and lower slopes at Tokai and Cecilia. Sections of Cecilia have been harvested since the 2000s, but *H. rosei* tadpoles not been observed since the 1980s (De Villiers 1997 / 1993). An increase in water yield would be a positive sign of habitat rehabilitation. Pine harvesting and alien removal are measures that ultimately increase water yield (Bosch and Hewlett, 1982). The re-colonisation of *H. rosei* tadpoles to the streams of Cecelia Ravine would represent a successful rehabilitation of that system; as it transitions from pine plantation to fynbos. This re-colonisation has not yet occurred, even though the average summer temperatures for Cecelia Ravine is 17.0°C (within the upper temperature niche). Cecelia stream is near-perennial. It is not known if Cecelia stream flowed during the summers prior to pine plantations and dam construction (see the bypass between dam #5 and dam #3 in Figure 3.1).

Mitigation and rehabilitation with regard to water flow are to maximize water inputs (promoting condensation by e.g. fog harvesting) and catchment water yield (e.g. by removing invasive plants, Appendix 3.3), while minimizing use and water abstraction where possible. In the context of climate change, drought, and water scarcity, innovative solutions must be sought and considered in partnership with local and national authorities. Nursery and Cecilia streams would benefit if water flow could be supplemented, with the aim of rehabilitating respective tadpole populations.

Fire, erosion, and siltation threat.

Fires do not occur frequently in *H. rosei* stream habitats, even though frequent fire is listed as a threat to *H. rosei* (South African Frog Re-assessment Group, (SA-FRoG), IUCN, 2010). At the study altitudes, fire is naturally excluded by Afromontane forest vegetation. The Disa valley at Orangekloof, and much of the back table and Table Mountain Plateau has not burned for over six decades (Masson and Moll, 1987; Pooley, 2014). TMNP, while in an urban setting, attempts to mimic natural fire cycles through prescribed burning of senescent vegetation, piecemeal. This prescription is often not permitted by the City, during the dry season, for health and safety reasons. Erosion and siltation (burying of rocky mountain streams) is a threat to Heleophrynidae (de Villiers, 2004a; Minter *et al.*, 2004). However, based on my observation that the stream with the highest anthropogenic sand-input hosts a viable population in Skeleton Gorge, I speculate that siltation of streams is an isolated and transient threat. Erosion and siltation monitoring can include fixed-point photography.

Temperature

Average summer temperatures higher than the observed ecological niche of 17.2°C could be a limiting factor for the Table Mountain Ghost Frog ($t = -0.302$); but temperatures below the lower margin are not considered limiting. The mean annual temperature for Platteklip and Kasteelspoort streams are not within the temperature niche, it is speculated that any movement of tadpoles off the plateau, downstream would be irregular; and limited to cooler, higher, or shaded conditions closer to the plateau (e.g. recorded by CapeNature in the Valley of the Red Gods in 2003). Another factor influencing water temperature may be the presence of dams. Both tributaries of the Disa River, Disa Stream (in Disa Gorge) and the Original Disa, flow from reservoirs. These two streams have the two highest mean temperatures for tadpole habitats (at 400m: 13.9°C and 14.1°C respectively). The highest mean summer temperature for tadpole habitats is measured in Disa Gorge, where water is abstracted above the study altitudes. The precautionary approach should apply in this regard: release of cooler (hypolimnion) waters is preferred, rather than the over-flow of warmer surface waters (from the epilimnion).

Land-cover changes, depletion of indigenous shading canopy. Riparian vegetation has a cooling effect on the water in the adjoining stream (Davies and Day, 1998). The Table Mountain Ghost Frog is associated with Afromontane forests. These forests have shrunk from their pre-colonial extents (Sim, 1907), and have rebounded in some places (e.g. Orangekloof (Poulsen and Hoffman, 2015)). This literature indicates that the indigenous forest canopy was significantly greater than their current extent, and the rebound is limited to the southern slopes of Table Mountain. Campbell and Moll (1977) show that Platteklip and Kasteelspoort streams flowed under the cover of indigenous trees (circa 1600s) for much of its length. Mitigation (with regard to temperature) is the reduction of energy (heat) inputs and/or the increase of indigenous cooling / heat-shading measures.

3.5. Conclusion

Lack of water flow in streams at 400m altitude and mean summer temperatures above 17.2°C may exclude *Heleophryne rosei* tadpoles from reaches below the cliffs of Table Mountain's plateau. However, lack of flow at 300m altitude is limiting to tadpoles below 300m only, as tadpoles can be found below the cliffs given perennial flow at 400m (i.e. Nursery stream). The extent of expansion of the Table Mountain Ghost Frog's reproductive metapopulations may be predicted based on suitable tadpole habitat. The monitoring results can be used to map threats (classes 'Climate Change' and 'Natural System Modifications') at a local catchment scale.

The environmental reserve (of water) is a legal obligation, but it has not been determined for most rivers in the study area. The lack of enough flow required for a Critically Endangered freshwater species may indicate insufficient flow for the environmental reserve, as indicated by streams from which the metapopulation has retreated or where recruitment is low. Nursery Ravine is the extant stream in which the observed presences are fewest (pers. comm.: Kirstenbosch staff and CapeNature staff). Environmental water (flow) requirements may not be met for *H. rosei* tadpoles of Cecilia Ravine, possibly due to the water bypass between the Alexander and DeVilliers dam (Figure 3.1 and Appendix 3.1); while for Nursery Ravine abstraction during the summer continues. Urban and human needs are often seen to oppose ecological needs, but for Cape Town and the waters of Table Mountain this is not necessarily the case. Recently the City of Cape Town undertook a feasibility study for fog harvesting on Table Mountain. If positioned opportunely the additional water yield can simultaneously supplement flow, and contribute to reservoirs. Two such positions are on the watershed between Nursery Ravine and Hely-Hutchensen reservoir, and on the watershed between Cecilia Ravine and DeVilliers reservoir.

3.6. Recommendations

In addition to existing measures (e.g. alien clearing), three actions to mitigate ‘climate change’ and ‘natural system modifications’ can be considered. i) Streams can be shaded by rehabilitated natural vegetation, ii) environmental water reserve should be determined, met and/or mitigated as there is occasional overflow of excess bulk water resources, iii) additional water inputs (to the upper catchment) should be considered in conjunction with limiting water abstractions to below a certain altitude. Measures need only address two basic issues: to keep waters cooler, and to supplement or retain stream flow. There is no forum currently to debate solutions. The City of Cape Town, CapeNature, Kirstenbosch Botanical Gardens, and SANParks (and perhaps the national and provincial authorities that issue water-use rights) need to be open to options and innovations regarding water resilience, and needs a forum to debate options for drought mitigation measures.

A peninsula freshwater conservation forum would be helpful to coordinate conservation and freshwater management. Not only for human needs but for freshwater biodiversity and ecosystem functionality. CapeNature and TMNP should conduct co-ordinated tadpole surveys and water chemistry monitoring twice a year: summer and autumn. Winter sampling is not necessary. Rooikat stream (north of Cecelia) should be added to the monitoring schedule as it also flows below a dam, Blinkwaterskloof stream need not be included due to limitations of access and safety. The increase of (indigenous) shading plants in the upper catchments should be considered. Supplementation as a mitigation measure is conceivable for Cecelia if some waters of the Victoria and Alexander dams is not diverted to the De Villiers dam, but rather left on its original course toward Cecelia and Rooikat ravines. Cecelia/Rooikat, Platteklip, and Nursery streams are the sources of three of Cape Town’s rivers. In this context, these three streams should be prioritized for water-course and Ghost Frog habitat rehabilitation; reservoir overflow diversion for environmental water requirements (Cecelia/Rooikat), shading plant establishment (Platteklip), and experimentation on catchment response to experimental and innovative solutions (e.g. fog harvesting above Nursery Ravine).

CHAPTER FOUR: A Conclusion

The study in Chapter Two produces a regional threat layer applicable to Anura in general. It shows that *Capensibufo rosei* (Bufonidae) and *Arthroleptella lightfooti* (Pyxicephalidae) on the uplands face similar threats, while *Microbatrachella capensis* (Pyxicephalidae) and *Breviceps gibbosus* (Brevicipitidae) on the lowlands face different set of similar threats. Taxa (Pyxicephalidae in this example) may not be the best delineator of the variably of threats faced. But habitat preference or breeding strategy may be. All seasonal wetland breeders are similarly impacted by threats to wetlands. The same threat would impact wetland plants and invertebrates. Anura react similarly to a threat, therefore using the same impact score for the five families represented is appropriate for this Order and scale. Calculating a threat index for all threatened taxa on the Cape peninsula (Rebelo *et al.,* 2011b) is a vast undertaking. Conducting spatial threat assessments using life-history characteristics would allow the assessment to include species with vastly different responses to the same threat, at the same time allowing all threatened taxa to be included in only a few categories. Threat indices may be computed for all threatened flora, vertebrates, and macro-invertebrate larvae from overlaying impact scores that vary per threat-class based on characteristics such as whether or not they migrate, are lentic or lotic, etc.

The advantage of one impact response is that only one threat surface is created from which species' distributions can be cut. The value of a fine scale threat assessment is that it highlights smaller patches of highly threatened areas, where mitigation measures and monitoring can be succinctly directed. The regional threat layer (figure 2.3 for uplands, figure 2.4 for lowlands) shows hotspots of threat above a given compounded threat impact score, using the PTI. Lowland threats are associated with roads and high-density dwellings or smaller residential properties, industrial and commercial nodes; as well as vacant land currently used for conservation, but zoned for development, military or communal use, or agriculture. For outside the urban edge (figure 2.3) this threat assessment highlights the eastern slopes of Table Mountain and the Constantiaberg for threat mitigation. These are the slopes associated with erosion potential (geological event), invasive alien plants, infrequent fires, and plantations (mainly pine) and other food agriculture (mainly vineyards), as well as recreational activities and all associated human intrusions. Table Mountain National Park management is committed to the rehabilitation of state land to indigenous lowland and mountain, granite and sandstone fynbos. Plantations are being harvested piecemeal (SANParks, 2009), alien plant eradication efforts are ongoing (Foxcroft *et al.*, 2017), fire regimes are adaptively managed for biodiversity (Van Wilgen *et al.*, 2011), and control measures against soil erosion are some threat mitigating actions on the Cape peninsula (SANParks, 2016). Agriculture (food) and human intrusions on the other hand are not directly managed or mitigated, and may increase without an understanding of environmental water requirements and capacity limitations. In this regard, the environmental (ecological) water requirements need to be calculated for the Cape peninsula.

Mapped representations of species-specific conditions related to climate and climate change can be extrapolated from the results of Chapter Three. Permanence of flow is shown to be important, yet tadpoles are not found where cool water flows permanently in Fernwood Gully. Thus I conclude that the location (altitude) of permanent flow is also important. Figure 4.1 is a hypothetical representation (unverified) of positive and negative ‘Drought’ and ‘Temperature extremes’ conditions for *Heleophryne rosei* tadpoles. It implies that where water flows perennially at 400m altitude and above, with a mean summer temperature less than 17.2°C, there tadpoles should be found.

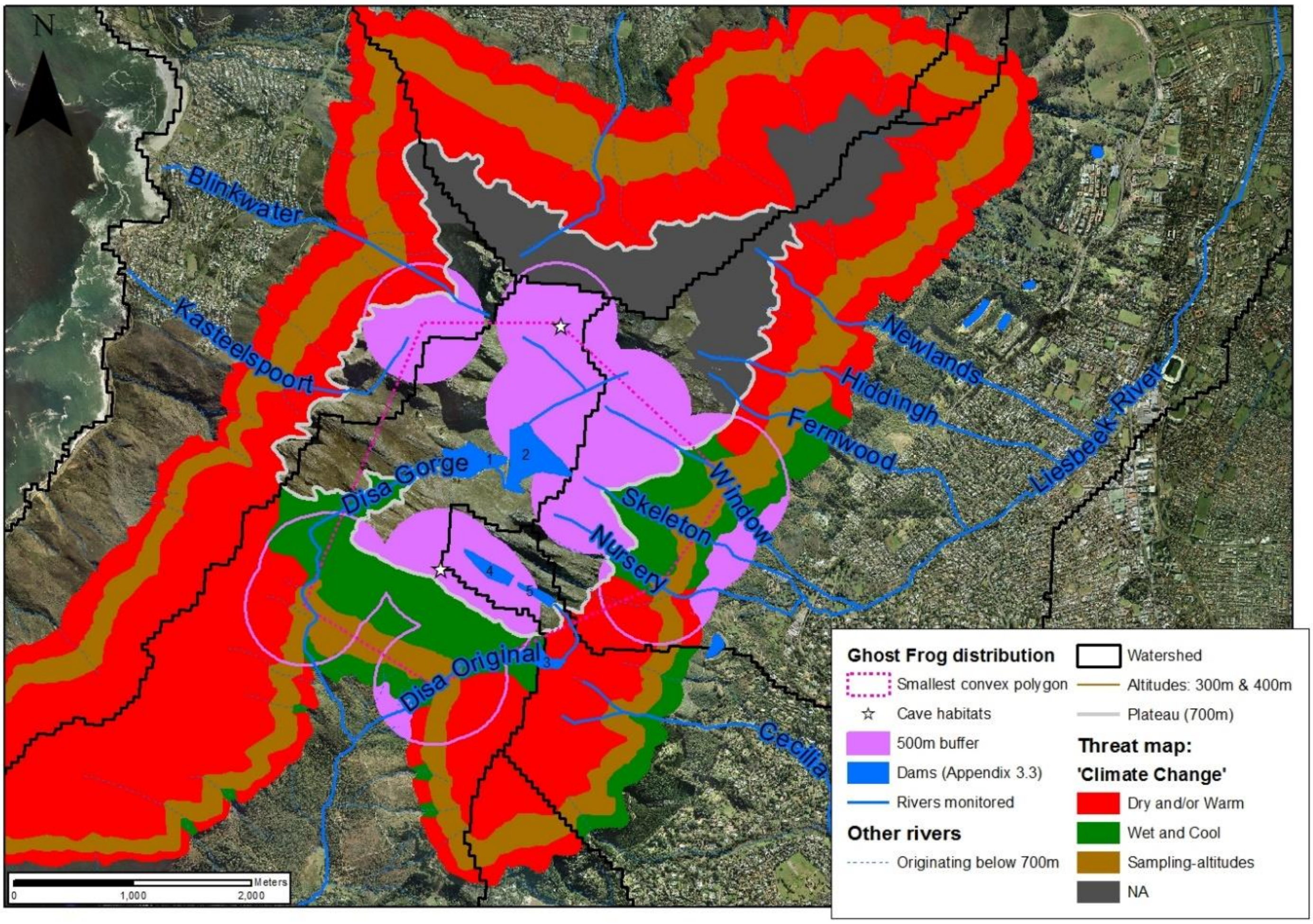


Figure 4.1: Favourable and unfavourable conditions for Table Mountain Ghost Frog (*Heleophryne rosei*) tadpoles. A representation of species-specific 'climate change' variables extrapolated from monitoring data

Such extrapolations are easily confirmed through dry season temperature and flow-monitoring. However, the temporal resolution of water temperature data is not ideal. Long-term monitoring should include records not only of daytime conditions months apart but should record circadian temperature. This was done in the study area by Dallas & Ketley (2011) for one stream (Window Gorge, Liesbeek river catchment). I recommend expanding this long-term monitoring to five catchments on four slope aspects: Platteklip northward, Nursery (instead of Window) eastward, Cecilia eastward, Disa southward, and Kasteelspoort westward.

As municipal property zonations and agricultural footprints (amongst other anthropogenic threat extents) change with time, so shapefiles representing them get updated. Representations of pollution include landfill dumps and wastewater treatment-works, but it also include the perenial streams and water bodies (Budzik *et al.,* 2014). This is based on the assumption that during the summer pollutants in these waters are most concentrated. However, the best means to assess pollution is through quantitative measurments where posible. For fine scale spatial analysis species should be represented by the core habitats and distributions (incuding alien invasive species). Similar to climate change and disease threats, prevalaince of invasive plants and animals can be mapped per catchement, controled for altitude (including in the urban and suburban environment) or a buffer around point localities. Representations of fire or lack of fire for the urban landscape will be difficult to represent.

The location and extent of protected areas does not necessarily inform its conservation efficacy (Chape *et al.*, 2005), with no metric that is globally established. A spatial threat assessment would, however, inform the relative threat of any distribution within the threat assessment, including the threat to the extent of a National Park and the surrounding landscape. This spatial threat assessment quantifies the threat to the underlying matrix of ecosystems that protected areas reply on to maintain populations, including residents of, and migrants (like *Sclerophrys pantherina*, figure 2.4) through the protected area.

Land-use is governed by legislation (City of Cape Town, 2015) related to property zonation (allowable land-use), which greatly influences a landscape’s vulnerabilities to anthropogenic threats and, consequently, this spatial threat assessment. A direct legislative solution to several threats lies in the governance of land through property zoning: to grant an official conservation status to selected properties of the Cape peninsula; especially those that are currently being used for conservation, without legal protection. This effectively dis-allows certain activities and developments. Urban expansion and developments are pushing ever closer to the borders of protected areas, resulting in ever harder boundaries and surfaces. Land protection status and conceptual biodiversity corridors are respective mitigation responses to arrest habitat change and fragmentation. But it is not enough. Synergistic threats need synergistic or holistic plans that monitor and address all types of threat, focusing on hotspots of both threat and biodiversity.

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APPENDICES

Appendix 2.1: Sources and format (scale) of data used to represent nine threat classes (Salafsky *et al.,* 2008). NGI data from their Mowbray offices, and SANParks data from their Planning Department. City of Cape Town shapefiles downloaded from an online portal: https://web1.capetown.gov.za/web1/OpenDataPortal/AllDatasets

Threat-class number	Threat Class	Shapefiles	Vector type / Raster cell-size	Source
1	Residential & commercial development	Property Zonation	Polygon	City of Cape Town (CoCT)
1	Residential & commercial development	TMNP infrastructure	Point (buffered)	SANParks
2	Agriculture	Pine	Polygon	National Geo-spatial Information (NGI)
2	Agriculture	Cultivated lands	Polygon	City of Cape Town
2	Agriculture	Vineyards	Polygon	National Geo-spatial Information (NGI)
2	Agriculture	Property Zonation	Polygon	City of Cape Town
3	Energy production or Mining	Mining (only)	Polygon	National Geo-spatial Information (NGI)
4	Transportation & service corridors □	Roads	Line (buffered)	National Geo-spatial Information (NGI)
4	Transportation & service corridors □	Railways	Line (buffered)	National Geo-spatial Information (NGI)
6	Human intrusions & disturbances	Recreational areas	Polygon	National Geo-spatial Information (NGI)
6	Human intrusions & disturbances	Military land	Polygon	Property cadastral (CoCT)
6	Human intrusions & disturbances	Gardens and Parks	Polygon	City of Cape Town
7	Natural system modifications	Dams	Polygon	National Geo-spatial Information (NGI)
7	Natural system modifications	Fire scars	Polygon / 100m cells	SANParks (limted to open landscapes)
8	Invasive & other problematic species…	Plant density estimation	Polygon	SANParks (limted to open landscapes)
9	Pollution	Perennial streams	Line (buffered)	National Geo-spatial Information (NGI)
9	Pollution	Perennial water bodies	Area	National Geo-spatial Information (NGI)
9	Pollution	Landfill sites	Area	National Geo-spatial Information (NGI)
9	Pollution	Waste-water Treatment	Area	National Geo-spatial Information (NGI)
10	Geological events	Slope angle	100m cells	Digital elevation model

Appendix 2.2: Extract of GIS database of threat impact scores, as attributed to representations of threats in nine threat classes (Salafsky *et al.*, 2008). Threat indices presented in this thesis are derived from attribute 'ImpactScore', the general threats impact score for amphibians. Species specific deviations of impact score are not shown here. * Numerical values in the 'ShortName' column represent erf size categories in square meters (m^2) of single dwelling, residential properties only. Each category includes the face-value (size quoted) and sizes smaller - down to, but excluding the previous category. This table is split onto three pages.

ShortName	Threat-Class	Threat Sub-Class	ImpactScore	Scope	Severity	Deviation	Rationale
General Residential 1 : G	Residential & commercial development	Housing & urban areas	9	Pervasive	Serious	None	Group housing, Security estates, multi-level appartments. Often high density, using m
General Residential 2	Residential & commercial development	Housing & urban areas	9	Pervasive	Serious	None	Group housing, Security estates, multi-level appartments. Often high density, using m
General Residential 3	Residential & commercial development	Housing & urban areas	9	Pervasive	Serious	None	Group housing, Security estates, multi-level appartments. Often high density, using m
General Residential 4	Residential & commercial development	Housing & urban areas	9	Pervasive	Serious	None	Group housing, Security estates, multi-level appartments. Often high density, using m
General Residential 5	Residential & commercial development	Housing & urban areas	9	Pervasive	Serious	None	Group housing, Security estates, multi-level appartments. Often high density, using m
General Residential 6	Residential & commercial development	Housing & urban areas	9	Pervasive	Serious	None	Group housing, Security estates, multi-level appartments. Often high density, using m
Community: Local	Residential & commercial development	Housing & urban areas	7	Large	Slight	None	Community funtions, like schools
Community: Regional	Residential & commercial development	Housing & urban areas	7	Large	Slight	None	Community funtions, like schools
10	Residential & commercial development	Housing & urban areas	10	Pervasive	Extreme	Breviceps gibbosus and Sclerophrus	Small properties tend to be close to 100% developed, and/or paved
50	Residential & commercial development	Housing & urban areas	10	Pervasive	Extreme	Breviceps gibbosus and Sclerophrus	Small properties tend to be close to 100% developed, and/or paved
100	Residential & commercial development	Housing & urban areas	9	Pervasive	Serious	Breviceps gibbosus and Sclerophrus	Small properties tend to be close to 100% developed, with some ground paved
200	Residential & commercial development	Housing & urban areas	8	Pervasive	Serious	Breviceps gibbosus and Sclerophrus	Small properties tend to be close to 100% developed, with a small proportion paved
300	Residential & commercial development	Housing & urban areas	8	Pervasive	Serious	Breviceps gibbosus and Sclerophrus	Small properties tend to be close to 100% developed, with a small proportion paved
400	Residential & commercial development	Housing & urban areas	7	Pervasive	Moderate	Breviceps gibbosus and Sclerophrus	Larger properties (middle income) allows for close to 50% garden space
500	Residential & commercial development	Housing & urban areas	6	Large	Moderate	Breviceps gibbosus	Larger properties (middle income) allows for over 50% garden space
600	Residential & commercial development	Housing & urban areas	5	Large	Slight	None	Large residential properties tend to have a large percentage as green lands
700	Residential & commercial development	Housing & urban areas	5	Large	Slight	None	Large residential properties tend to have a large percentage as green lands
800	Residential & commercial development	Housing & urban areas	4	Restricted	Slight	None	Large residential properties tend to have a large percentage as green lands
900	Residential & commercial development	Housing & urban areas	4	Restricted	Slight	None	Large residential properties tend to have a large percentage as green lands
1000	Residential & commercial development	Housing & urban areas	3	Restricted	Slight	None	Large residential properties tend to have a large percentage as green lands
5000	Residential & commercial development	Housing & urban areas	3	Restricted	Slight	None	Large residential properties tend to have a large percentage as green lands
10000	Residential & commercial development	Housing & urban areas	2	Restricted	Slight	None	Large residential properties tend to have a large percentage as green lands
50000	Residential & commercial development	Housing & urban areas	2	Restricted	Slight	None	Large residential properties tend to have a large percentage as green lands
100000	Residential & commercial development	Housing & urban areas	1	Restricted	Slight	None	Large residential properties tend to have a large percentage as green lands
500000	Residential & commercial development	Housing & urban areas	1	Restricted	Slight	None	Large residential properties tend to have a large percentage as green lands
1000000	Residential & commercial development	Housing & urban areas	1	Restricted	Slight	None	Large residential properties tend to have a large percentage as green lands
5000000	Residential & commercial development	Housing & urban areas	1	Restricted	Slight	None	Large residential properties tend to have a large percentage as green lands
Caravan Park	Residential & commercial development	Tourism & recreation areas	5	Small	Moderate	None	Caravan parks tend to not be paved
Clubhouse	Residential & commercial development	Tourism & recreation areas	8	Restricted	Extreme	None	Clubhouses are urban developments
Golf course	Residential & commercial development	Tourism & recreation areas	7	Restricted	Extreme	Sclerophrys	Mono-cultures that are mowed and fertilized. However, water features and the 'rough' a
Golf driving range	Residential & commercial development	Tourism & recreation areas	6	Restricted	Moderate	None	Lawns that are mowed
Holiday resort	Residential & commercial development	Tourism & recreation areas	8	Restricted	Extreme	None	Urban infrastructure
Shooting range	Residential & commercial development	Tourism & recreation areas	4	Small	Slight	None	Unpaved quarries
Sports field	Residential & commercial development	Tourism & recreation areas	6	Large	Moderate	None	Lawns that are mowed
Stadium	Residential & commercial development	Tourism & recreation areas	10	Restricted	Extreme	None	Stadia are developments that exclude natural vegetation, and the pitch is the only acc
Swimming pool	Residential & commercial development	Tourism & recreation areas	8	Small	Moderate	None	Chlorinated water
Tennis court	Residential & commercial development	Tourism & recreation areas	8	Restricted	Moderate	None	Hard surfaces
Urban park	Residential & commercial development	Tourism & recreation areas	2	Restricted	Slight	None	Minimal hard surfaces
Other	Residential & commercial development	Tourism & recreation areas	8	Large	Serious	None	Unknown

* Erf size catagories in square meters (m^2) of single dwelling, residential properties only. Each catagory includes the face-value (size quoted) and sizes smaller - down to, but excluding the previous catagory.

General Industrial 1	Residential & commercial development	Commercial & industrial areas	10	Restricted	Extreme	Sclerophrys	Industrial zones have no greenbelt, lawns or wetlands.
General Industrial 2	Residential & commercial development	Commercial & industrial areas	10	Restricted	Extreme	Sclerophrys	Industrial zones have no greenbelt, lawns or wetlands.
Risk Industry	Residential & commercial development	Commercial & industrial areas	10	Restricted	Extreme	Sclerophrys	Industrial zones have no greenbelt, lawns or wetlands.
Mixed Use 1	Residential & commercial development	Commercial & industrial areas	8	Restricted	Extreme	None	Commercial zones have no greenbelt or wetlands. Remnent vegetation may not be sui
Mixed Use 2	Residential & commercial development	Commercial & industrial areas	8	Restricted	Extreme	None	Commercial zones have no greenbelt or wetlands. Remnent vegetation may not be sui
Mixed Use 3	Residential & commercial development	Commercial & industrial areas	8	Restricted	Extreme	None	Commercial zones have no greenbelt or wetlands. Remnent vegetation may not be sui
Local Business 1 : Busine	Residential & commercial development	Commercial & industrial areas	8	Restricted	Extreme	None	Commercial zones have no greenbelt or wetlands. Remnent vegetation may not be sui
Local Business 2 : Local	Residential & commercial development	Commercial & industrial areas	8	Restricted	Extreme	None	Commercial zones have no greenbelt or wetlands. Remnent vegetation may not be sui
General Business 1	Residential & commercial development	Commercial & industrial areas	8	Restricted	Extreme	None	Commercial zones have no greenbelt or wetlands. Remnent vegetation may not be sui
General Business 2	Residential & commercial development	Commercial & industrial areas	8	Restricted	Extreme	None	Commercial zones have no greenbelt or wetlands. Remnent vegetation may not be sui
General Business 3	Residential & commercial development	Commercial & industrial areas	8	Restricted	Extreme	None	Commercial zones have no greenbelt or wetlands. Remnent vegetation may not be sui
General Business 4	Residential & commercial development	Commercial & industrial areas	8	Restricted	Extreme	None	Commercial zones have no greenbelt or wetlands. Remnent vegetation may not be sui
General Business 5	Residential & commercial development	Commercial & industrial areas	8	Restricted	Extreme	None	Commercial zones have no greenbelt or wetlands. Remnent vegetation may not be sui
General Business 6	Residential & commercial development	Commercial & industrial areas	8	Restricted	Extreme	None	Commercial zones have no greenbelt or wetlands. Remnent vegetation may not be sui
General Business 7	Residential & commercial development	Commercial & industrial areas	8	Restricted	Extreme	None	Commercial zones have no greenbelt or wetlands. Remnent vegetation may not be sui
Not zoned	Residential & commercial development	Housing & urban areas	2	Restricted	Unknown	None	Properties not zoned could be used without a known functionary, or unfavorablity zone
Park buildings	Residential & commercial development	Tourism & recreation areas	6	Large	Moderate	None	Generalized impact score of 6
Utilty	Residential & commercial development	Housing & urban areas	6	Restricted	Moderate	None	Generalized impact score of 6
Rural	Residential & commercial development	Housing & urban areas	3	Restricted	Slight	None	Small holdings with minimum development
Pine	Agriculture	Wood and pulp plantations	7	Restricted	Serious	Sclerophrys	Pine needles exclude many species. Evapotranspiration is higher (less water). Weste
Vineyard / fruit	Agriculture	non-timber crops	6	Restricted	Moderate	Sclerophrys	Grape vines allow for some biodiversity. Western Leopard Toad is noted to occure in s
Cultivated lands	Agriculture	non-timber crops	6	Restricted	Moderate	None	Cultivated lands allow for some biodiversity. Horticulture excluding viticulture
Zoned agriculture	Agriculture	Wood and pulp plantations	2	Restricted	Unknown	Microbatrachella and Sclerophrys	Immediately downslope of Horticulture and viticulture activities. The Micro Frog is espe
Digging	Energy production or Mining	Mining and Quarrying	10	Restricted	Extreme	None	Sand mining uses an open-cast method
Quarry	Energy production or Mining	Mining and Quarrying	4	Small	Moderate	None	Quarries are mostly decommissioned. These sites often form ponds
Excavation	Energy production or Mining	Mining and Quarrying	10	Restricted	Extreme	None	Excavations remove the topsoil (Open-cast)
Mine Dump	Energy production or Mining	Mining and Quarrying	8	Restricted	Extreme	None	Hostile environment for non-pioneer species, but with rehab potential
ArterialRoad	Transportation & service corridors □	Roads and Railroads	8	Large	Serious	None	Secondary, Main, and Arterial roads carry a high volume of traffic at speed
MainRoad	Transportation & service corridors □	Roads and Railroads	8	Large	Serious	None	Secondary, Main, and Arterial roads carry a high volume of traffic at speed
NationalFreeway	Transportation & service corridors □	Roads and Railroads	10	Large	Extreme	None	Freeways and National roads are most treacherous to amphibian (and many other) life
NationalRoad	Transportation & service corridors □	Roads and Railroads	10	Large	Extreme	None	Freeways and National roads are most treacherous to amphibian (and many other) life
On/OffRamp	Transportation & service corridors □	Roads and Railroads	6	Large	Moderate	None	On ramps and off ramps carry high volumes of traffic at a slower speed
OtherRoad	Transportation & service corridors □	Roads and Railroads	4	Restricted	Moderate	None	"Other" indicates informal roads. Untarred. Low volumes of traffic at slow speeds
SecondaryRoad	Transportation & service corridors □	Roads and Railroads	8	Large	Serious	None	Secondary, Main, and Arterial roads carry a high volume of traffic at speed
Street	Transportation & service corridors □	Roads and Railroads	6	Large	Moderate	None	Streets (Especially residential streets) do not carry I high volume of traffic
Footpath	Transportation & service corridors □	Roads and Railroads	1	Small	Unknown	None	Foot traffic can better avoid amphibians
Railway	Transportation & service corridors □	Roads and Railroads	4	Small	Slight	None	Train tracks have a narrow surface area on which amphibians need to be to suffer a m
Slipway	Transportation & service corridors □	Roads and Railroads	3	Small	Slight	None	Concrete
Station	Transportation & service corridors □	Roads and Railroads	7	Restricted	Moderate	None	Perhaps stations should be covered under urban-structures
Track	Transportation & service corridors □	Roads and Railroads	4	Restricted	Moderate	None	Informal roads. Untarred. Low volumes of traffic at slow speeds
Multi	Transportation & service corridors □	Roads and Railroads	10	Large	Extreme	None	Where two or more types of road (two or more categories) overlap. (Not the intersectio
Military	Human intrusions & disturbances	Military exercises	2	Small	Moderate	None	Access is restricted, and military land acts as conservation land.
Paths	Human intrusions & disturbances	Recreational activities	1	Small	Unknown	None	Foot traffic can better avoid amphibians (unlike road traffic)
Horse-race course	Human intrusions & disturbances	Recreational activities	7	Small	Extreme	None	Lawned surface (not hard)
Motor sport track	Human intrusions & disturbances	Recreational activities	10	Small	Extreme	None	Tared surfaces excludes most species
Botanical garden	Human intrusions & disturbances	Recreational activities	6	Small	Moderate	None	Indigenous, endemic species showcased alongside exotic (non-invasive) species, and
Parks	Human intrusions & disturbances	Recreational activities	6	Small	Moderate	None	Indigenous, endemic speciesused alongside exotic (non-invasive) species, and grasse

Dam	Natural system modifications	Dams & water management/use	9	Restricted	Moderate	Heleophryne, Capensibufo, Microbatr	Flooded riverine habitat and ajoining terrestrial areas
Closed Reservoir	Natural system modifications	Dams & water management/use	10	Restricted	Moderate	None	Flooded and artifitial. Closed
Open Reservoir	Natural system modifications	Dams & water management/use	9	Restricted	Moderate	None	Flooded and artifitial. Open
One fire	Natural system modifications	Fire & fire suppression	1	Restricted	Slight	None	Land that burns at an acceptable / normal / average frequency
Two fires	Natural system modifications	Fire & fire suppression	4	Restricted	Moderate	None	Land that has burned at a too frequent rate (for fynbos veg)
Three fires	Natural system modifications	Fire & fire suppression	5	Restricted	Moderate	None	Land that has burned at a too frequent rate (for fynbos veg)
Four fires	Natural system modifications	Fire & fire suppression	6	Restricted	Serious	None	Land that has burned at a too frequent rate (for fynbos veg)
Five fires	Natural system modifications	Fire & fire suppression	7	Restricted	Extreme	None	Land that has burned at a too frequent rate (for fynbos veg)
Zero fires	Natural system modifications	Fire & fire suppression	5	Restricted	Serious	Capensibufo rosei	Land that has not burned for a while
Six fires	Natural system modifications	Fire & fire suppression	8	Restricted	Extreme	None	Land that has burned at a too frequent rate (for fynbos veg)
Seven fires	Natural system modifications	Fire & fire suppression	9	Restricted	Extreme	None	Land that has burned at a too frequent rate (for fynbos veg)
Gutteral Toad	Invasive & other problematic species, ge	Problematic native species/disease	5	restricted	unknown	Congeneric	Sclerophrys invasive
Common Platanna	Invasive & other problematic species, ge	Problematic native species/disease	5	restricted	unknown	Congeneric	Xenpus invasive
Rare	Invasive & other problematic species, ge	Invasive non-native/alien species / c	2	restricted	slight	Athroleptella (IUCN impact score of 5	Density dependence effects
Scattered	Invasive & other problematic species, ge	Invasive non-native/alien species / c	4	restricted	slight	Athroleptella (IUCN impact score of 5	Density dependence effects
Medium	Invasive & other problematic species, ge	Invasive non-native/alien species / c	6	restricted	moderate	Athroleptella (IUCN impact score of 5	Density dependence effects
Occasional	Invasive & other problematic species, ge	Invasive non-native/alien species / c	2	restricted	slight	Athroleptella (IUCN impact score of 5	Density dependence effects
Unknown	Invasive & other problematic species, ge	Invasive non-native/alien species / c	1	restricted	slight	Athroleptella (IUCN impact score of 5	Density dependence effects
Very scattered	Invasive & other problematic species, ge	Invasive non-native/alien species / c	5	restricted	moderate	Athroleptella (IUCN impact score of 5	Density dependence effects
Closed	Invasive & other problematic species, ge	Invasive non-native/alien species / c	8	restricted	extreme	Athroleptella (IUCN impact score of 5	Density dependence effects
Dense	Invasive & other problematic species, ge	Invasive non-native/alien species / c	7	restricted	extreme	Athroleptella (IUCN impact score of 5	Density dependence effects
Sewage Works	Pollution	Domestic & urban waste water	8	Restricted	Serious	Sclerophrys	Eutrophic wetlands. The Western Leopard Toad can tolerate some eutrophication
Refuse Dump	Pollution	Garbage & solid waste	9	Small	Extreme	None	Landfills attract scavangers
Perennial waters	Pollution	Domestic & urban waste water	2	Restricted	Unknown	Sclerophrys	Water bodies are exposed to random spilages and runoff pollution. The Western Leopa
Angle 50-59	Geological events	Landslide	5	small	moderate	Heleophryne	Erosion and Trauma threat
Angle 60-69	Geological events	Landslide	6	small	Serious	Heleophryne	Erosion and Trauma threat

Appendix 3.1: Dams and Reservoirs that store water flowing from the Table Mountain massif of Table Mountain Nation Park. Managed by the municipality and a national botanical garden. Construction dates and capacity-data taken from the City of Cape Town website.

Dam vs. Reservoir	Name	Source	Surface area (Ha)	Date	Capacity (Mega litres), x 10^6
Dam 1	Woodhead	**Disa River**	9.8	1890-1897	954
Dam 2	Hely-Hutchinson	**Disa River**	16.9	1904	925
Dam 3	De Villiers	**Disa (Original)**	3.1	1910	243
Dam 4	Victoria	**Cecelia / Rooikat / Original Disa**	4.8	1896	128
Dam 5	Alexandra	**Cecelia / Rooikat / Original Disa**	2.6	1903	126
Reservoir	Kirstenbosch	**Window / Skeleton / Nursery**	2	1968	
Reservoir	Molteno	**Woodhead / Hely-Hutchinson via the Pipe Track & Kloof Neck**	2.8	1881	188

Appendix 3.2. The Cape Research Centre of the South African National Parks measured water variables at 300m and 400m on twelve streams flowing from Table Mountain. Measurement were taken, and observations were recorded for ten seasons, from 2014-2016; starting in summer, ending in autumn.

Variable	Tool	Method	Units
Number of Tadpoles	Observations by CapeNature	Annual timed counts	number
Aspect	Observation	Observation	Cardinal units (4)
Latitude (South)	Gamin GPS 60	GPS reading (5 decimals)	Degrees, decimal degrees
Longitude (East)	Gamin GPS 60	GPS reading (5 decimals)	Degrees, decimal degrees
Altitude (m)	Gamin GPS 60	GPS: meters above sea-level	Metres (m)
Date	Blackberry 9320	Observation	dd/mm/ccyy
Time of Day	Blackberry 9320	Observation	24h00
Temperature (°C)	YSI EC 300	Mid-stream temperature	Degrees Celsius
pH	YSI pH 100	Mid-stream pH	pH (Log scale)
Dissolved Oxygen	YSI DO 200	Record DO (ppm) of water in mid-stream	Convert ppm to mg/l
Electro-conductivity	YSI EC 300	Record EC (ųS) of water in mid-stream (@25°C)	Convert ųS or uS to mS/m
Total Dissolved Solids	YSI EC 300	Record TDS in water in mid-stream	Grams per litre
Substrate	Observation	In addition to Cobble - Sand, Gravel or Boulders	Categorical

Appendix 3.3: The species prioritized for invasive plant controlled in Table Mountain National Park. All species in this table do not necessarily affect the Table Mountain Ghost Frog (*Heleophryne rosei*). Clearing and invasive-control data collection and work done by Biodiversity Social Project (BSP) of the State's Extended Public Works Programme (EPWP). Source: Table 6 of Table Mountain National Park, Park Management Plan (2015-2025) (SANParks, 2016)**.**

Species	Common Name	NEMA:BA Category	CARA Category	Levels of Infestation
Acacia cyclops	Rooikrans	1b	2	Rare – medium
Acacia longifolia	Long Leaf Wattle	1b	1	Rare – dense
Acacia mearnsii	Black Wattle	2	2	Rare – dense
Acacia melanoxylon	Australian blackwood	2	2	Rare – dense
Acacia saligna	Pork Jackson	1b	2	Rare – closed
Eucalyptus conferruminata (ref. lehmannii)	Spider Gum	1b	1	Rare – closed
Hakea gibbosa	Rock hakea	1b	1	Rare – occasional
Hakea sericea	Silky hakea	1b	1	Rare
Leptospermum laevigatum	Australian myrtle	1b	1	Rare – closed
Paraserianthes lophantha	Stinkbean	1b	1	Rare – closed
Pinus pinaster	Cluster pine	1b	2	Rare - closed
Pinus radiata	Radiata pine	1b	2	Rare – closed
Pittosporum undulatum	Australian cheesewood	1b	1	Rare – medium