

**GIS-BASED RISK MAPPING OF ILLICIT DISCHARGES INTO STORMWATER
DRAINAGE SYSTEMS IN CAPE TOWN**

by

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Thesis submitted to the Faculty of Engineering and the Built Environment
Department of Civil Engineering and Surveying
in fulfilment of the requirements for the degree of
Master of Technology: CARTOGRAPHY at

Cape Peninsula University of Technology

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**Bellville
September 2020**

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DECLARATION

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ABSTRACT

Migration into urban areas is driven by a diverse range of factors, such as opportunities to find employment and operate businesses, access to healthcare and educational facilities, and peace and stability. Although the effects have been felt throughout South Africa, Cape Town is a particularly popular destination. The phenomenon has increased pressure on available resources and infrastructure that was not designed to cope with dramatic increases in the size of the population. A myriad of problems have resulted as a direct consequence, including illicit discharges into stormwater drainage systems from all land uses. As local governments are faced with severe budgetary constraints, cost-effective methods need to be developed to mitigate pollution, which necessitates the conducting of appropriate research to understand the spatial distribution and extent of the problem, in order to identify and prioritise specific concerns for the deployment of limited resources and to provide solutions for the containment of pollution. Consequently, it was necessary to conduct a cost-effective desktop assessment study to map areas that are at high risk of illicit discharges in the city.

The aim of this research is to develop a reliable geographic information systems (GIS) desktop methodology for mapping areas in the urban catchments that are at risk of illicit discharges into stormwater systems. Among the specific objectives is to perform a spatial analysis of the hydraulic, hydrological, and land use datasets to classify and identify areas with high illicit discharge potential and to develop effective procedures for risk mapping illicit discharge potential (IDP).

The methodology entailed the use of datasets pertaining to twelve risk factors, namely, population density, development age, outfall density, ageing sanitary infrastructure, drainage density, generating site density, infrastructure access density, on-site sanitation, percentage impervious surface, and commercial, residential, and industrial land uses as indicators of the likelihood of illicit discharges into stormwater drainage systems. The study commenced with the collecting and compiling of data to transform datasets for individual risk factors into spatial data. Risk factors were then scored to determine thresholds in order to evaluate catchments on the basis of their IDP and to classify areas as being at low, medium, or high risk in relation to individual risk factors. A spatial overlay and analysis of past discharge records were performed to rank the influence of risk factors in relation to their ability to predict locations of illicit discharges. The past discharge records were categorised as pertaining to the water, wastewater, greywater, solid waste, and all/combined pathway groups. The five groups were then overlaid and analysed separately. A multi-criteria evaluation was performed to quantify risk factors as weights. The final step entailed the generating of composite maps to prioritise catchment areas as having low, medium, or high IDP.

The findings of the research study revealed that many land use, hydraulic, and hydrologic characteristics influenced the locations of illicit discharges. It also emerged that two principal risk factors, namely, residential land use and percentage impervious surface, were most crucial to predicting the locations of illicit discharges. The percentages of high-risk areas in the study area were found to vary from 25% and 32% for different discharge pathway groups. It is abundantly evident from the findings of this study that municipalities should avail themselves of risk mapping as a highly effective means of facilitating the structuring of the implementation of illicit discharge detection and elimination (IDDE) programmes. Risk mapping makes it possible for municipalities to follow a structured approach to formulate appropriate priorities for inspections of facilities, public education, investigations of outfalls and drainage areas, and projects to improve infrastructure.

Although the findings of the study are promising, further study is still recommended in the study area, in order to develop a truly comprehensive appraisal of the risk of illicit discharges. The inclusion of agricultural land use as a risk factor is recommended, as there is a great deal of agricultural activity in the area. It is also recommended that the most up-to-date data should be used at all times, in order to maximise the accuracy of findings.

Keywords: analytical hierarchy process, illicit discharge potential, multi-criteria evaluation, risk factors, risk mapping, stormwater, sub-catchments

ACKNOWLEDGEMENTS

I would like to begin by expressing my sincere gratitude to my supervisor, Dr Yaw Owusu-Asante, for the patience and enthusiasm which he displayed at all times during the conducting of my study. His guidance and support exceeded the call of duty. I could not have completed the study successfully were it not for his mentorship.

I would like to thank John Holmes, the then Managing Director of Umvoto Africa (Pty) Ltd, for allowing me to use the resources of the company for the duration of my studies and for the invaluable and continuous support which he provided at the most difficult times.

I would also like to acknowledge my beautiful and supportive wife, Tawanda, for her support and patience. I dedicate this work to her, and our angels, Anesu, Alicia, and Andrew.

I would also like to thank my brothers, Aleck and Nisbert, and my friends, Jonathan, Sam, Mahlatsi, Phenias, Shingi, Itumeleng, and Mlamli for their constant encouragement and for reviewing my work.

Although I wish to acknowledge the financial assistance which I received from the Water Research Commission to conduct this research, I feel that it is necessary to add that the opinions which are expressed in this thesis and the conclusions which I reached are my own, and do not necessarily reflect the standpoints of the Water Research Commission.

Finally, I give all glory to God, for none of this work would have been possible were it not for His blessings.

DEDICATION

I dedicate this thesis to my beautiful wife, Tawanda, and our three angels, Anesu, Alicia, and Andrew, and also to my late grandmother and my late parents.

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LIST OF ABBREVIATIONS AND ACRONYMS

AHP	Analytic hierarchy process
ArcGIS	A geographic information system (GIS) for working with maps and geographic information
CMA	Catchment management agency
CoCT	City of Cape Town
DEM	Digital elevation model
GIS	Geographic information system
IDDE	Illicit discharge detection and elimination
IDP	Illegal discharge potential
MCE	Multi-criteria evaluation
OWC	Open water course
PDCR	Past discharge complaint records
PHA	Philippi Horticultural Area
RV	Recreational vehicle
WWTW	Wastewater treatment works

GLOSSARY OF TERMS

Term	Description
Dry-weather flow	Flow in a stormwater drain or drainage ditch which occurs in the absence of stormflow.
Illicit discharge	An illegal connection to a storm sewer. Facilitating the disposal of any materials other than stormwater by means of a storm drain is illegal and considered to be an illicit discharge.
Informal settlement	For the purposes of this study, an informal settlement is a housing area in which dwellings have been erected illegally on municipal land.
Multiple-criteria decision analysis	A procedure which entails evaluating several different conflicting criteria in order to arrive at an optimal decision on the basis of the available options.
Outfall	A point at which a stormwater drainage system discharges to receiving waters.
Pollutant	Any material in water or wastewater which interferes with or precludes its intended beneficial disposal.
Risk factor	A spatial dataset which is used to estimate the likely risk of an illicit discharge occurring.
Sewer	A pipe, conduit, or drain, which is usually closed and not required to flow at full capacity for carrying flows of sanitary, industrial, and commercial wastewater.
Stormwater	Water from precipitation, which infiltrates the ground, collects in reservoirs or puddles, runs freely on the surface, or is captured by storm drainage systems.
Catchment	An area from which rainfall drains into a watercourse, watercourses, or a part of a watercourse, as a result of surface runoff, to a common point or common points.
Watercourse	A river or a natural channel in which water flows regularly or intermittently.

CHAPTER ONE: INTRODUCTION

1.1 Introduction

As increasing numbers of people are migrating to other countries, the populations of the countries of the world are becoming increasingly cosmopolitan. Patterns of migration are influenced by many different factors, such as opportunities to run businesses or obtain employment, the desire to obtain access to health and educational facilities, or the pursuit of peace and stability. Owing to the prospects that it offers immigrants, post-apartheid South Africa has seen a consistently large influx of people and Cape Town is perceived by many as a highly desirable city to adopt as a new home. As increasing numbers of people are attracted to Cape Town, pressure on available resources and infrastructure which had not been designed to cope with the increased numbers inevitably increases accordingly. According to Currie et al. (2017), the population of Cape Town was estimated to be 3 852 187 in 2014, which represented an increase of 3% since 2011. As the increasing population has overburdened the sewer and water infrastructure system, it poses risks to both the health of the population and the environment.

The pressure on available infrastructure has resulted in a multiplicity of problems, one of the most significant of which concerns illicit discharges into stormwater drainage systems from residential areas and informal settlements that are not served by formal sewer systems. Illegal stormwater connections and the dumping of inappropriate materials in sewer systems have had severe repercussions for the budgets of local governments. Consequently, the conducting of relevant research has become a necessity, in order to understand the spatial distribution and the extent of the problem, and also to determine how limited resources could most effectively be allocated to combat the problem and formulate solutions for its containment. Accordingly, a cost-effective desktop assessment needs to be carried out to determine the areas of the city that are at the highest risk of illicit discharges. This study takes the form of a GIS-based risk mapping, which is a procedure for evaluating the factors that could either affect or destroy a system, and ultimately provides a means of understanding the causes and possible consequences of the risks which are associated with the phenomenon under investigation.

Figure 1.1 provides a schematic summary of the contents of Chapter 1. The introduction is followed by a general background to the study, after which a definition of illicit discharges is provided, before the discussion proceeds to an elucidation of the research problem, the research question, and the aim and objectives of the study. The significance of the study is assessed in detail, after which the chapter concludes with a delineation of the structure of the thesis and a general conclusion.

1.2 Background to the study

Dry-weather flows which discharge from drainage systems into receiving bodies of water contaminate them with pollutants. The consequences of contamination can include any of a diverse range of undesirable phenomena, such as severely impaired or destroyed ecosystems, decimated fish populations, and severe threats to public health.

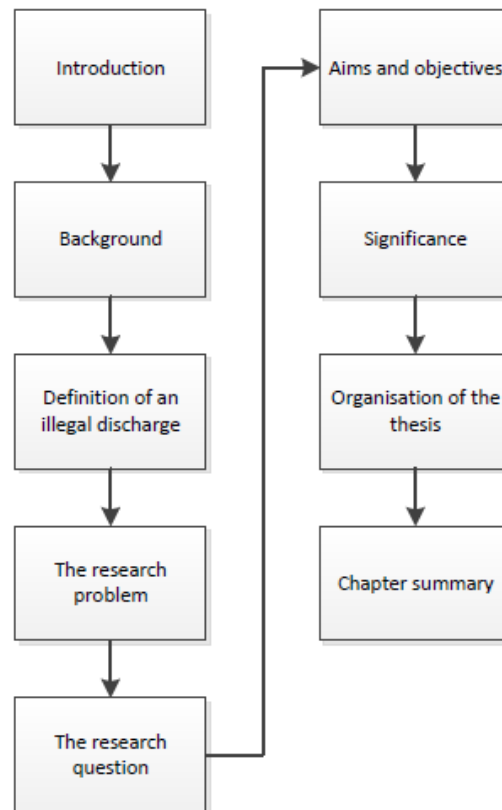


Figure 1.1: Flow chart for Chapter One

Accordingly, the ability to detect illicit discharges is crucial to restoring urban sub-catchments. Illicit discharges can also result in the closures of beaches, owing primarily to bacterial contamination and loss of aesthetic value. In addition, the continued pollution of waterbodies will result in falling values of waterfront homes, the cessation or restriction of fishing activities, and declining tourism. Apart from the adverse consequences for public health and the local economy that are associated with illicit discharges, the debilitating consequences for aquatic life and wildlife have already been recorded. There have been numerous instances of fish being killed and the loss of other aquatic life in sub-catchments as a result of illegal or accidental dumping and spills, which have resulted in lethal concentrations of pollutants in receiving waters (Brown et al., 2004).

Suburbanisation, which is manifested as urban sprawl, owing to rapidly increasing urban populations, has been one of the main causes of pollution in urban watercourses and the impairment of ecosystems. A combination of ageing and overburdened sewer and

stormwater systems in urban areas has also played a significant role. The findings of studies by Gaffield et al. (2003) and Swann (2001) have revealed that the resulting increased public health hazards have included the contamination of supplies of drinking water and recreational waters by bacteria, pathogens, and heavy metals, as a consequence of the interactions between ageing wastewater and stormwater infrastructure systems which both drain into the natural water environment.

The Big Lotus River Canal in Cape Town runs from the N2 freeway through a number of suburbs, townships, and informal settlements, until it reaches Zeekoevlei. On its course it receives inflows from several different industries and types of domestic waste, which vary from greywater, solid waste, and sewerage overflows. They enter the stream as it runs through the Cape Flats to the wetland of the vlei or marsh, which serves several different purposes, one of which is recreational. The level of contamination in the canal poses a serious health hazard for those who reside along its banks and further downstream, including the riparian habitat or ecosystem. Consequently, it is incumbent on the municipality to take appropriate measures to curb inappropriate discharges, in order to restore and protect this urban sub-catchment.

1.2.1 Definition of an illicit discharge

Most dry-weather discharges result from illegal connections, illegal dumping, or spills, all of which are referred to as illicit discharges for the purposes of this study. An opposite characterisation defines an illicit discharge as “*any non-stormwater (dry-weather) flow entering a storm drain, with some exceptions, including firefighting and those deemed an insignificant source of pollution to the local waterway*” (USEPA, 1999; 2010). They have a unique frequency, composition or type, and mode of entry. They are produced from what could be termed “generating sites” at residential, commercial, and industrial locales and can be characterised according to three principal attributes, namely:

- Discharge frequency, which can be continuous, intermittent, or transitory.
- Discharge categories, such as pathogenic or toxicant, nuisance and threatening to aquatic life, and clean water.
- Mode of entry, either direct or indirect, into a storm drainage system.

Illicit dry-weather flows originate from many different sources and can result from illegal dumping practices, broken sanitary sewer lines, cross-connections, connecting floor drains to storm sewers, overflows of sanitary sewers, inflow and infiltration, straight-pipe sewer discharges, improper disposal of waste from recreational vehicles (RVs), failing septic systems, and malfunctioning pumping stations (Brown et al., 2004). The principal sources typically include flows of sanitary wastewater or industrial and commercial

pollutants, failing septic tank systems, and vehicle maintenance activities (Brown et al., 2004). Inappropriate discharges must of necessity be considered unlawful or illegal because storm sewer systems, unlike sanitary sewer systems, are not designed to accept, treat, or discharge non-stormwater wastes.

Illegal connections are pipes that are improperly connected to a stormwater drainage network and represent fixed locations at which sewage, wash water, types of industrial waste, and other pollutants are able to enter it. Illegal dumping entails inappropriately disposing of substances in storm drains and is a common, but antisocial practice for disposing of substances such as paint, spent motor vehicle fluids, and similar types of waste (Bender et al., 2017). Spills occur when discharges reach storm drainage networks unintentionally, often as a consequence of vehicular accidents or owing to poor pollution management at business or construction sites. Unlike illegal connections, illegal dumping and spills are often intermittent or solitary occurrences and not confined to particular geographic locations. Conversely, individual people and employees of businesses who dump materials are highly likely to repeat the offence. As most illicit discharges tend to take place during spells of dry weather, evidence of them is often found by inspecting stormwater infrastructure for dry-weather flows. Among the most destructive potential consequences of illicit discharges are the degradation of the quality of water in downstream waterways, which limits their ability to be used as they had been intended to be used, and the destruction of aquatic ecosystems.

1.3 The research problem

The findings of studies that have been conducted in a great many countries, including South Africa, have demonstrated quite conclusively that the main source of high pollutant loads in receiving waters are dry-weather flows which discharge from storm drainage systems (RHP, 2005; GLA, 1983; Duke, 1997; Pitt & McLean, 1986; Grobicki, 2001; Pillay & Buckley, 2001; Quibell et al., 2003; Schoeman & MacKay, 1995; Van Ginkel, 1996; Van Veelen & DWAF, 1994a, b). As it has already been emphasised, eliminating or controlling inappropriate discharges have a crucial role to play in restoring urban sub-catchments.

The clearly evident lack of a comprehensive risk mapping procedure for potential illicit discharges in South Africa appears to be one of the principal contributory factors to the slow responses to the problem by local authorities. Consequently, a desktop risk mapping guide needs to be developed to provide the means for assessing areas which have the greatest potential for facilitating the entry of materials other than stormwater into the stormwater system. A comprehensive review of existing risk analysis techniques

(Tuomari et al., 1995; Johnson & Tuomari, 1998; Pitt & Rittenhouse, 2001; Zielinski & Brown, 2003; Brown et al., 2004; Tuomari & Thompson, 2003; Irvine et al., 2011; Versar, Inc., 2014a,b,c; Dymond, Aguilar, Bender, & Hodges, 2015a,b) suggests that a core set of risk factors have not been adopted (Owusu-Asante, 2019). For the purposes of this study, a risk factor refers to a spatial dataset that permits an assessment to be made of the risk of an occurrence of an illegal discharge. The approaches to risk analysis which are adopted at present are often based on either professional judgements or expert knowledge which is pooled in workshop situations (Owusu-Asante, 2019). A caveat of a risk analysis that is based on a professional judgement is that the judgement can affect or bias the eventual outcome. In addition, the accuracy of these judgements and their effects on the outcomes of analyses are not assessed. After performing a risk analysis in a study of water pollution in Cape Town, Nel et al. (2013) identified the following limitations:

- The workshop had been time-consuming.
- Agreeing on points which were allocated for each prioritisation criterion had been an obstacle.
- The accuracy of the analysis which the 'expert knowledge' had generated had not been assessed (Owusu-Asante, 2019).

Accordingly, it is necessary to arrive at an optimised risk analysis which permits the effects of all relevant land, hydraulic, hydrological, and environmental risk factors on the locations or occurrences of illicit discharges to be evaluated and the uncertainty pertaining to the accuracy with which the factors have been identified and evaluated to be determined.

1.4 The research question

The overall purpose of this research study was to develop GIS-based procedures to identify the areas in Cape Town that have the greatest potential for illicit discharges, to serve as a guide for the city authorities. Accordingly, the main research question is: Which are the areas of the urban sub-catchment that are at the risk of being polluted by illicit discharges into watercourses in the City of Cape Town Metro?

1.5 Aims and objectives of the study

The aim of this study was to develop desktop procedures for identifying areas in which illicit discharges into urban sub-catchments could potentially occur, on the basis of assessments of their low-, medium-, and high-risk levels.

The following objectives were set to achieve the aim of the study:

- To perform a spatial analysis of hydraulic, hydrological and land-use datasets to classify and identify high-risk areas with respect to illicit discharge potential (IDP).
- To develop procedures for risk mapping to determine IDP.

1.6 Significance of the study

The significance of this study is predicated on the following specific objectives:

- **To empower affected communities:** The polluting of water as a consequence of illicit discharges has extremely adverse implications for the health and environments of communities that are located near affected watercourses. The identification of high-risk areas, through GIS-based risk mapping, will facilitate the controlling of illicit discharges, thereby enabling communities to have potable water to drink and hazard-free water for recreational activities and fishing.
- **To contribute to the formulation of solutions for sustainable development:** Identifying areas which are at a high risk of illicit discharges represents a vital means of sustainably managing the scarce water resources of the nation and protecting its natural environment.
- **To inform policy and decision-making:** The National Water Act 36 of 1998 of South Africa requires Catchment Management Agencies (CMA) to set specific objectives with respect to monitoring the quality of water resources and to ensure that it is adequate for purposes such as swimming, fishing, and drinking. CMAs are also required to regulate discharges of pollutants. The act is intended to legislate against actions that compromise the quality of water as a consequence of pollution which occurs at both point and nonpoint sources, by criminalising the discharging of any potential pollutant into watercourses without a valid permit to do so. Developing cost-effective desktop procedures for allocating priority to urban areas on the basis of a low, medium, or high risk of illicit discharges into their sub-catchments would be of great value to municipalities, as a means of enabling them to implement the provisions of the act.
- **To develop innovative procedures which would be replicable in other communities:** Although the findings of the study are intended specifically to benefit the Cape Town Metro area, they also stand to benefit other communities with populations of a similar size and similar risks with respect to the hazards that accompany illicit discharges in South Africa and also in other countries.

1.7 Structure of the thesis

As it is depicted schematically in Figure 1.2, the thesis comprises five chapters.

Chapter One: The first chapter introduces the research topic, provides a formal statement of the research problem, and articulates the aim and objectives of the study and the research question that was formulated to guide it. The significance of the research is explained and the chapter concludes with a summary of the structure of the thesis.

Chapter Two: The literature review takes the form of an in-depth survey of the relevant literature pertaining to GIS-based risk mapping of illicit discharges into stormwater systems. A breakdown of mapping of sub-catchments and their assessment is provided, which is followed by reviews of risk mapping of sub-catchments in the state of Virginia in the United States and Cape Town in South Africa. A summary of the literature review is provided before the discussion proceeds to a detailed description of the area in which the study was conducted.

Chapter Three: The third chapter is devoted to a comprehensive discussion of the methods that were used to collect and analyse the data. Each risk factor is discussed individually, before the discussion proceeds to an explanation of how they were classified as low, medium, or high IDP. The spatial analysis, multi-criteria evaluation, and composite map production are also discussed in detail.

Chapter Four: The next chapter takes the form of a presentation of the findings and an interpretation of them in relation to individual risk factors. The results of the spatial analysis, multi-criteria evaluation, and composite map production are also presented and interpreted.

Chapter Five: The final chapter is devoted to a summary of the principal findings of the study, a discussion of the conclusions that were drawn from them, and a presentation of the recommendations that are made on the basis of the conclusions.

1.8 Conclusion

This chapter has provided a comprehensive overview of the research topic. The following chapter takes the form of an in-depth review of the relevant available literature which was consulted, in order to develop the research methodology that was employed to conduct the study.

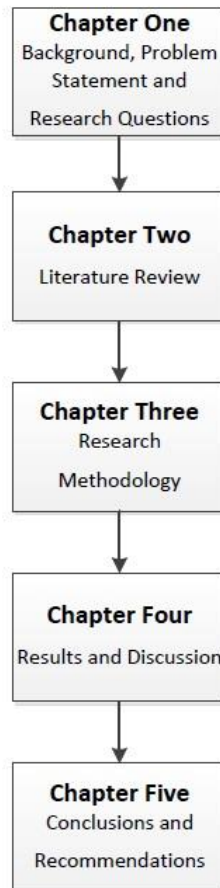


Figure 1.2: Structure of the thesis

CHAPTER TWO: LITERATURE REVIEW

Figure 2.1 provides a schematic depiction of the structure of the review of the relevant literature concerning risk mapping methods that are used in South Africa and other countries, which are discussed in the sections which follow. The objective of the review was to evaluate systematically the work that has been done in the domain in South Africa and abroad, in order to produce an accurate and comprehensive appraisal which includes achievements, unresolved problems and considerations that have not received due attention, and considerations pertaining to the assessment illicit discharges from which present and future needs will be assessed and met in an optimal manner for South African contexts. Although the number of studies that have been reviewed does not make the review an exhaustive one, it can nonetheless be considered to be an adequate one. The discussion commences with a general overview of mapping and assessing sub-catchments, which is followed by reviews of risk mapping sub-catchments in Virginia in the United States and Cape Town. The salient information that was gleaned from the literature is summarised, before the discussion moves on to a detailed description of the area in which the study was conducted.

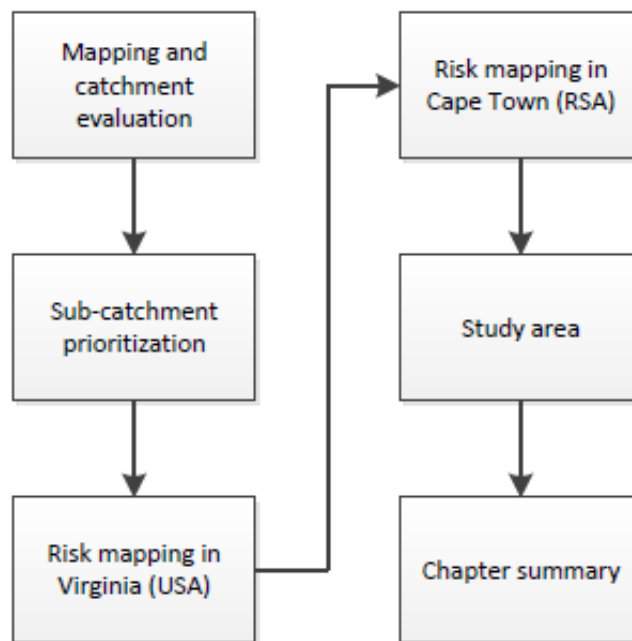


Figure 2.1: The flow chart for Chapter Two

2.1 Mapping and catchment evaluation

The work of Brown et al. (2004) has resulted in the development of a method for mapping and evaluating catchments that entails initially delineating designated areas into sub-drainage catchments. Data is then collected for each sub-drainage catchment, analysed, and clipped to match the extents of the sub-catchments. This procedure allows a GIS

analysis to screen areas, assess the degree of risk to which particular areas are exposed on the basis of data pertaining to their sub-catchments, and provide a basis for allocating priority to areas according to their potential to precipitate illicit discharges into the storm drainage system (Brown et al., 2004). This method is particularly applicable as a starting point for assessments in areas for which there is no existing data. In these cases, the data that is collected becomes the basis for subsequent more detailed investigations. A vital objective of these mapping activities is to identify the locations of all of the stormwater outfalls, the drainage area for each outfall, the land uses for each outfall drainage area, and significant hydrological, hydraulic, and environmental features. The maps that result contain complete descriptions of the drainage areas, including outfall locations, details of specific land uses, drainage boundaries for each outfall, and also delineate city limits, main streets, and other features, such as streams. From the evaluation of the catchment datasets and assessments of the quality of water and the degree of degradation that ecosystems have undergone, investigators are able to classify drainage areas with respect to their potential for precipitating illicit discharges, without needing to perform a classical risk analysis. In the survey that Zielinski and Brown (2003) carried out, almost all jurisdictions reported using either paper or digital maps, or both in some instances, to track outfalls and discharge data. Many of these communities used sub-watershed data to prioritise outfalls and other sites for inspections or dye-testing. More than 80% of the jurisdictions that were surveyed made use of GIS analyses to track outfalls and record site data.

2.2 Sub-catchment prioritisation with risk analysis and risk mapping

Although this method is similar to the one that was covered in section 2.1, prioritisation is based on classical risk analysis. In this instance, most of the datasets, or mapping data, or both, may already be available, either on paper or in electronic form, in many cases from GIS assessments. This information is analysed and a risk analysis is performed to prioritise sub-catchments. It emerged from a more recent survey by Lilly (2015) that 41% of the 29 respondents used a form of desktop geographic information system (GIS) assessment and 28% monitored the quality of water to prioritise sub-catchments or set objectives for their programmes. Mapping and risk analysis methods have been reviewed in several publications (Tuomari et al., 1995; Johnson & Tuomari, 1998; Pitt & Rittenhouse, 2001; Brown et al., 2004; Versar, Inc., 2014a; Lilly, 2015). Performing risk analyses for illicit discharge potential (IDP) at the sub-catchment level entails selecting a group of risk factors that are most applicable to the area in question and assign them a relative weight. Next, points are assigned for each sub-catchment, on the basis of defined scoring criteria for each risk factor. The total score for all of the risk factors is then used to designate whether a particular sub-catchment is at a low, medium,

or high risk of precipitating illicit discharges. A typical example is provided by Brown et al. (2004) and assessments are usually carried out in stakeholder workshops.

2.3 Risk mapping in Virginia in the United States

Bender (2016:10) conducted a study to facilitate the “*development of effective procedures for illicit discharge risk mapping*”. The objectives of the study were “(1) *Determine the IDDE methods currently in use or development through review of current literature and discussions with select Virginia Phase I and Phase II MS4s; (2) investigate potential spatial relationships and interactions among land use, hydraulic, and hydrologic characteristics and the occurrence of illicit discharges; (3) evaluate the sensitivity of an illicit discharge risk mapping tool to changes in relative weighting; (4) describe the uncertainty associated with different land use, hydraulic, and hydrologic risk factors used to calculate illicit discharge potential; and (5) develop recommendations for effective illicit discharge risk mapping for Phase II MS4s to utilize this tool during prioritization of outfall reconnaissance and other illicit discharge operations*”.

The limitations of this study, which the researcher endeavoured to overcome in the present study, were as follows:

- Bender’s (2016) study did not make use of multi-criteria evaluation (MCE), but rather relied on expert knowledge of local conditions to derive weighting schemes.
- The mapping unit of analysis for five risk factors was a political boundary that was independent of the hydrology of the catchment. Bender (2016:48) noted this shortcoming and explained that the “*unit of analysis was a political boundary independent of hydrology, and watersheds on the fringes of the study area were clipped to this boundary. As the five risk factors analysed over watersheds were linked to hydrologic conditions, clipping the fringe watersheds to political boundaries produced partial datasets, reflecting an incomplete analysis and leading to significant over- and underestimation of risk*”. Of the thirteen risk factors that Bender (2016) used, only eight or 62% were evaluated over sub-catchment areas. Consequently, it is possible that 38% of the datasets that were evaluated over political boundaries could have resulted in either overestimated or underestimated risks of illicit discharges. To overcome this shortcoming in the present study, nine of the twelve risk factors were evaluated over sub-catchment areas and the remainder were evaluated as computed raster surfaces, by using the kernel density function.
- As 23% of the risk factors which Bender (2016) used were not in a GIS format, it was necessary to translate the data into a spatial environment. The poor

quality of tabular data often results in the partial transferring of datasets to GIS, thereby compromising the quality of input data and increasing uncertainty. To improve the quality of spatial analysis, all of the data needs to be available in a spatial format, which was the case in this study, as all twelve of the risk factors were already in GIS format.

2.4 Risk mapping in Cape Town, South Africa

Owusu-Asante (2019) conducted a study to facilitate the “*analysis and determination of optimum risk factors to prioritise illegal discharge potential in urban catchments*”. The study was conducted in the Diep and Kuils Rivers catchments, both of which fall within the boundaries of the City of Cape Town Metropolitan Municipality. The limitations of the study of Owusu-Asante (2019), which the researcher endeavoured to overcome in this study, were as follows:

- In his study, Owusu-Asante considered two additional risk factors, namely, percentage of impervious surface and on-site sanitation. An impervious layer has been defined as “*the proportion of area that is covered by impervious surfaces such as concrete or rooftops, evaluated over individual watersheds*” (Bender, 2016:123). Bender (2016) also explains that percentage of impervious surface is an accurate indicator of development and has a direct influence on watershed hydrology, as development results in the creation of additional potential surfaces for the accumulation and washing off of pollutants. Bender (2016:51) lists percentage of impervious surface as being among the handful of risk factors that he considers to be most significant for determining the potential for illicit discharges in urban and suburban areas. Conversely, on-site sanitation, which refers to the number of public toilet facilities in a designated area, is a significant risk factor; it is an indicator of a lack of adequate sanitation facilities in an area, which is a highly prevalent social problem in Cape Town. As many, if not all, informal settlements in Cape Town lack access to basic municipal services, in a bid to resolve the problem of inadequate sanitation, the City of Cape Town supplied nearly 27 000 toilet units. Subsequent investigations have revealed that a great many of these toilets are either blocked, unclean, or broken and not used. As a direct consequence, residents resort to using buckets as toilets in their houses and disposing of the contents in stormwater systems. Accordingly, both percentage of impervious surface and on-site sanitation are crucial factors for risk mapping the potential for illicit discharges in the Cape Town Metro.
- Owusu-Asante (2019) used the statistical frequency analysis theorem to classify his data into low, medium, and high risk with respect to IDP, whereas in this

study the researcher adopted Bender's (2016) approach by using the Jenks Natural Breaks Method. Although frequency analysis is a highly effective means of defining thresholds for high risk, it is a considerably less effective means of defining thresholds for medium risk levels. By contrast, the Jenks Natural Break algorithm permits the accurate defining or classifying of all risk levels. It enables data to be classified on the basis of groupings that are inherent in the data and is recommended for mapping values which are not evenly distributed on a histogram.

2.5 The area in which the study was conducted

The project was confined to the City of Cape Town Metro. The population of Cape Town was estimated to be 3 852 187 in 2014 (Stats SA, 2014a). The metropole covers an administrative area of 2 461 square kilometres (City of Cape Town, 2016a) and is subdivided into some 190 suburbs (City of Cape Town, 2011). It is situated at the northern end of the Cape Peninsula. Figure 2.2 illustrates the distribution of population densities in Cape Town and the densely populated areas are shaded in bright red. Most of the densely populated areas are informal settlements and include Philippi, Nyanga, Gugulethu, Du Noon, Hout Bay, Masiphumelele, and Khayelitsha. It is estimated that the informal settlements number approximately 378 (Housing Development Agency, 2013) and contain an estimated 141 765 dwellings, thereby comprising nearly 13% of all households in Cape Town (please see Figure 2.2). The rate of urbanisation, which has been driven mainly by low-income migrants from rural areas, has contributed significantly to the expansion of informal settlements (Govender et al., 2012). Many recipients of low-cost housing allow shacks to be built on the spaces that are allocated to them, for which they charge rent. This practice has resulted in dramatic increases in local populations and inevitably added to pressure on water and sanitation systems. The increased numbers also result in unusually high volumes of solid waste, which is normally dumped in the streets as a matter of course. There is a severe shortage of wheelie bins and, in most cases, municipal refuse removal vehicles seldom enter informal settlements to collect refuse, which also encourages residents to resort to dumping their waste. Consequently, residents are exposed to the risk of disease as a result of unsanitary conditions and if the solid waste is washed away, it is highly likely to block stormwater systems. Figures 2.3a and 2.3b provide views from different angles of a makeshift solid waste dumping site in the Masiphumelele informal settlement.

Figures 2.4a and 2.4b provide gruesome testimony to the fate of most of the nearly 27 000 toilet units that the City of Cape Town supplied in an attempt to improve the inadequate sanitation facilities in informal settlements. Figure 2.4a is a photograph of a

blocked full flush toilet in the Masiphumelele informal settlement on the outskirts of Fish Hoek towards Kommetjie, while Figure 2.4b is a photograph of another blocked full flush toilet, in the Overcome informal settlement on the outskirts of Muizenberg, along the M5 expressway. The locations of the toilets also create environments that are ideal for enabling criminals to pounce on potential victims. Some full flush toilets were erected along the N2 in the township of Khayelitsha. As the toilets are located at the edge of the township, many residents are afraid to walk to them during the night, for fear of being raped or robbed. Consequently, most residents opt to use buckets as toilets during the night and to empty the contents of the buckets into stormwater systems in the morning, thereby further adding to the pollution of waterbodies. Accordingly, Govender et al. (2011:1) maintains that *“problems of environmental pollution of living space and of domestic hygiene are almost always related to poverty and sanitation”*.

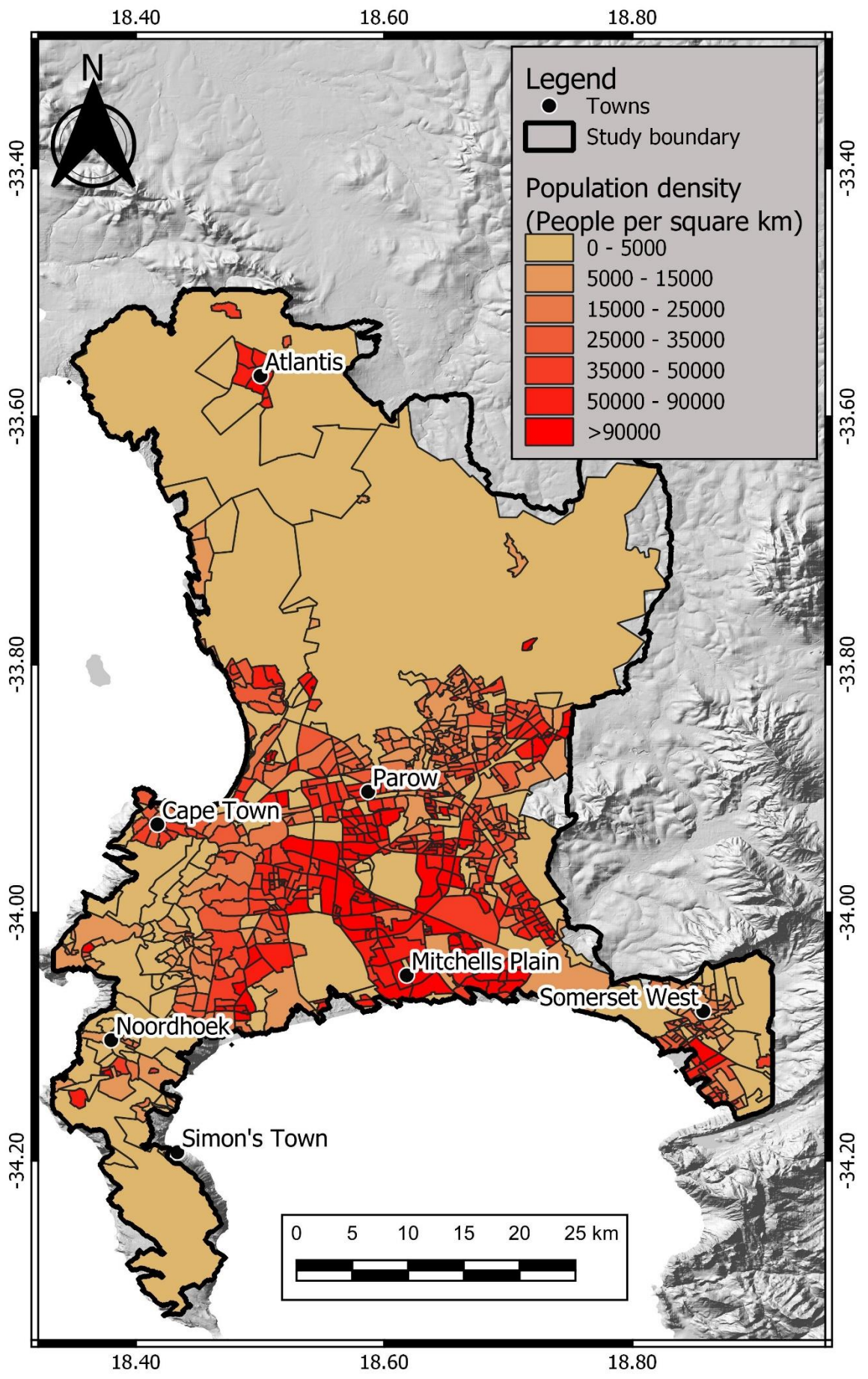


Figure 2.2: Population density map of the area in which the study was conducted (data supplied by the City of Cape Town Metropolitan Municipality)

It also emerged from the findings of their study that as some of the occupants of informal settlements who participated in the study did not have adequate facilities for disposing of wastewater and sewage, in many cases wastewater and untreated sewage was dispersed in their yards, thereby creating potential hazards in relation to illicit discharges into stormwater drainage systems. The publication in 2016 of the updated Diep River Estuarine Management Plan by a group that was headed by Koos Retief as the City of Cape Town Biodiversity Area Manager (2016) revealed that it had been found that informal settlements and low-cost housing areas were among the principal sources of the pollutants that entered the Diep River. The report confirmed that stormwater from the Du Noon area discharged into the river, while settlements of Joe Slovo and Phoenix also discharged into the Diep River, through the Erica Road stormwater drain.



Figure 2.3: Solid waste dumping site in Masiphumelele: (a) north-facing view; (b) west-facing view



Figure 2.4: Full flush toilets: (a) captured in the Masiphumelele informal settlement and (b) captured in the Overcome informal settlement

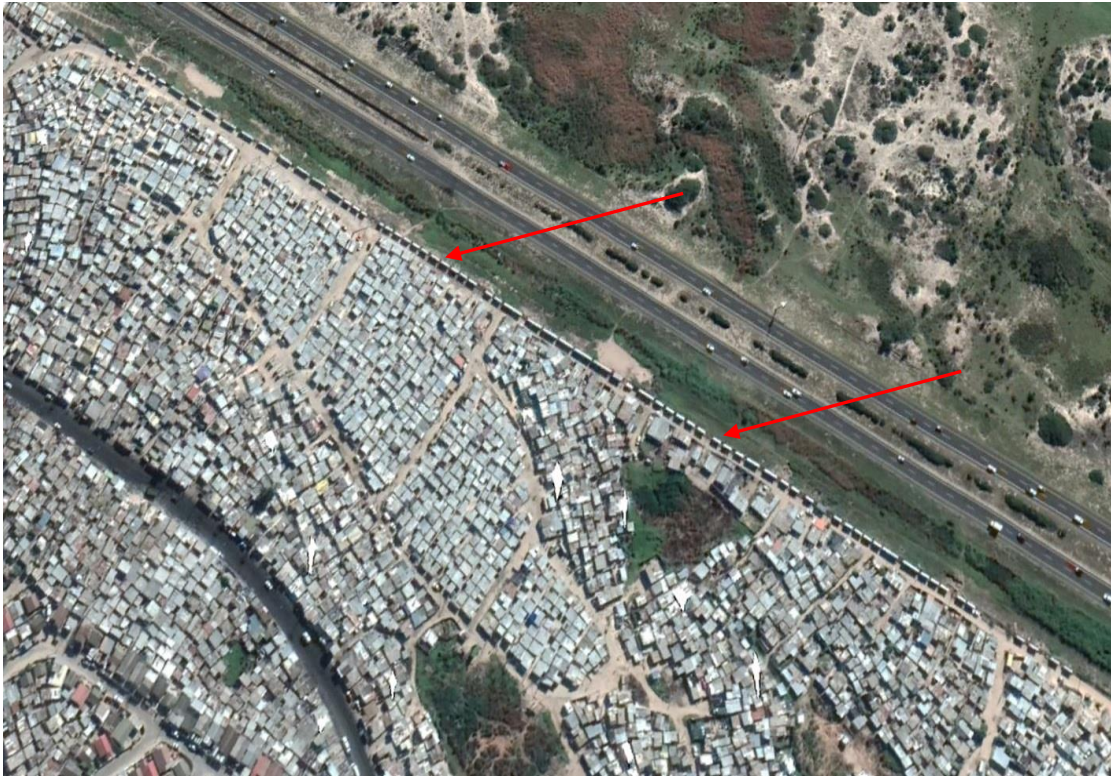


Figure 2.5: Google earth image of a section of Khayelitsha in Cape Town, depicting an informal settlement with a row of full flush toilets at the edge of the settlement (right) along the N2 freeway (source: Google Earth).

2.5.1 Land use

For the purposes of this study, land use refers to the characterisation of land cover on the basis of the activities in which people participate on particular parcels of land to produce crops or manufacture goods, or to change or maintain the land. Accordingly, land use provides a more accurate indication of the types of activities which occur on particular parcels of land and the potential pollution that may result from them than land cover classifications. As it can be seen in the distribution of land use in the City of Cape Town Metropolitan Municipality in Figure 2.6, the area is used mainly for residential and agricultural purposes. The central part of the area consists almost entirely of formal and informal residential areas, which include the some of the northern, southern, and western suburbs. Agriculture is the predominant activity in the northern part of the area, to the south-east of Atlantis, where some of the grain-producing farms in the metro are to be found. The Philippi Horticultural Area (PHA), which lies to the east of Mitchells Plain, is farmed by a group of small-scale farmers who make use of the local fertile soil. They produce vegetables that are supplied to most parts of the city and are able to farm throughout the year, through the use of irrigation.

Industrial areas are located mainly in the vicinity of Parow area and an industrial belt stretches towards Cape Town, encompassing the environs of the Cape Town

International Airport. The area that surrounds Cape Town is dominated by the commercial activities of corporate companies, which prefer to be based in the heart of the city. Spatial data that the researcher downloaded from the City of Cape Town open data portal (<https://web1.capetown.gov.za/web1/OpenDataPortal/AllDatasets>) reveals that there are twenty-four wastewater treatment sites in the area in which the study was conducted (please refer to the green square blocks in Figure 2.6). The ten that are located very close to the coastline are the Camps Bay Sea, Cape Flats, Green Point Sea, Hout Bay Sea, Llandudno, Macassar, Millers Point, Mitchells Plain, Ouderkraal, and Simonstown wastewater treatment sites. The remainder, namely, the Athlone, Bellville, Borchard's Quarry, Gordons Bay, Kraaifontein, Kuils River, Melkbosstrand, Parow, Scottsdene, Wesfleur, and Zandvleit wastewater treatment sites are located inland. There are also seventy-four dump sites, which are depicted as red squares in Figure 2.6, of which twenty-six are in use at present, two are in private use, and forty-six are no longer in use. The dumpsites that are in use include the Athlone, Atlantis, Belhar, Delft, Hout Bay, Wynberg, and Woodstock drop-off sites. Of the nineteen landfill sites in the area, which are depicted as black stars in Figure 2.6, six are closed, two are planned, two are proposed sites, and nine are active. The active landfill sites are the Kraaifontein, Coastal Park, Bellville, Vissershok South, Swartklip, Athlone, Vissershok North, Bellville, and Vissershok North leachate plants.

The land-use activities that have potential for precipitating illicit discharges into stormwater drainage systems include:

- The disposal of greywater and solid waste in residential areas.
- Faecal pollution from livestock farming and the possibility of fertilisers being deposited into stormwater systems as a consequence of agricultural activities.
- The oils and industrial waste products that have been reported to have been dumped into stormwater systems in industrial areas.
- The discharging of wastewater into stormwater systems by wastewater treatment plants.

2.5.2 Rivers and wetlands

The metro has a network of rivers, canals, and wetlands, which has been adversely affected by pollution. Not only does the city have a large industrial sector, but it now has more than 500 informal settlements, most of which lack adequate sanitary infrastructure. In 2019, the Zandvlei water area was temporarily closed owing to high levels of *E. coli*. According to the Water Outlook Report (City of Cape Town Department of Water and Sanitation, 2018:7), "*the water from the Cape Flats Aquifer is not suitable for immediate human consumption and must be treated to potable standards before it enters the*

reticulation system". The report goes on to explain that "a number of studies of the aquifer, dating back to 2006, indicate the pollution comes from landfill sites, wastewater treatment works, stormwater runoff, informal settlements, agricultural run-off, and cemeteries". The findings of a separate study of the Bottelary River in Cape Town that Feng (2016) conducted identified the sources of pollutants in the river as agricultural runoff, urban runoff, and treated sewage effluent from the Scottsdene Wastewater Treatment Works (WWTW). The major rivers (please see Figure 2.7) of the Cape Metro as they are listed by the City of Cape Town Water Services and the Cape Town Urban Water Cycle report which was published in August 2018 are as follows:

- The Great and Little Lotus Rivers, which flow into Zeekoevlei.
- The Diep, Zand, Keyzers, and Westlake Rivers, which flow into Zandvlei in Muizenberg.
- The Silvermine River, which enters the sea at Fish Hoek.
- The Lourens and Sir Lowry's Pass Rivers near Somerset West.
- The Steenbras River, which feeds the Steenbras Dams.
- The Eerste and Kuils Rivers, which flow into False Bay near Macassar.
- The Salt River and its tributaries, including the Liesbeek, Black, and Elsieskraal Rivers.
- The Disa River in Hout Bay, which provides water to the Kloof Nek Water Treatment Works.
- The Diep River, which drains the Malmesbury area and feeds Rietvlei near Table View, before it reaches the sea at Woodbridge Island in Milnerton.

2.6 Chapter summary

There are notable similarities between the risk mapping studies that were carried out by Brown (2004), Bender (2016), and Owusu-Asante (2019). They follow a similar procedure, namely:

- Delineate sub-catchments by using digital elevation models.
- Compile mapping layers and data pertaining to sub-catchments.
- Compute screening factors that influence discharges.
- Characterise the potential for illicit discharges across sub-catchment areas on the basis of defined scoring criteria.
- Generate maps to support field investigations.

The limitations of the study that Bender (2016) conducted were covered in sections 2.3 and 2.4 and were reduced significantly by Owusu-Asante (2019) in a study of two catchments in Cape Town in South Africa. He made use of the multi-criteria evaluation (MCE) method to assign weights to the relevant risk factors, as opposed to Bender's

(2016) study, in which weights were assigned on the basis of expert knowledge of local conditions. The respects in which the study of Owusu-Asante (2019) represented a significant improvement were the addition of percentage impervious surface and on-site sanitation as risk factors and the use that he made of the Jenks Natural Breaks method to classify the sub-catchments into low, medium, and high risk with respect to IDP.

The findings that emerged from the review of the relevant available literature suggested that there was a need for a research study in which:

- Sub-catchments are the mapping unit of analysis.
- MCE is used to assign weights, rather than professional judgement, which can be biased.
- The Jenks Natural Breaks Method is used to classify data into low, medium, and high risk with respect to IDP.

A study in which these three considerations are prioritised would provide an effective and cost-effective procedure for mapping risk with respect to IDP, in a manner that is not only replicable, but also permits the risk factors that are indicators of illegal discharges into stormwater systems to be documented. The sources of pollution into stormwater drainage systems in the City of Cape Town Metropolitan Municipality which were covered in section 2.5 provide ample justification for conducting a case study in the area.

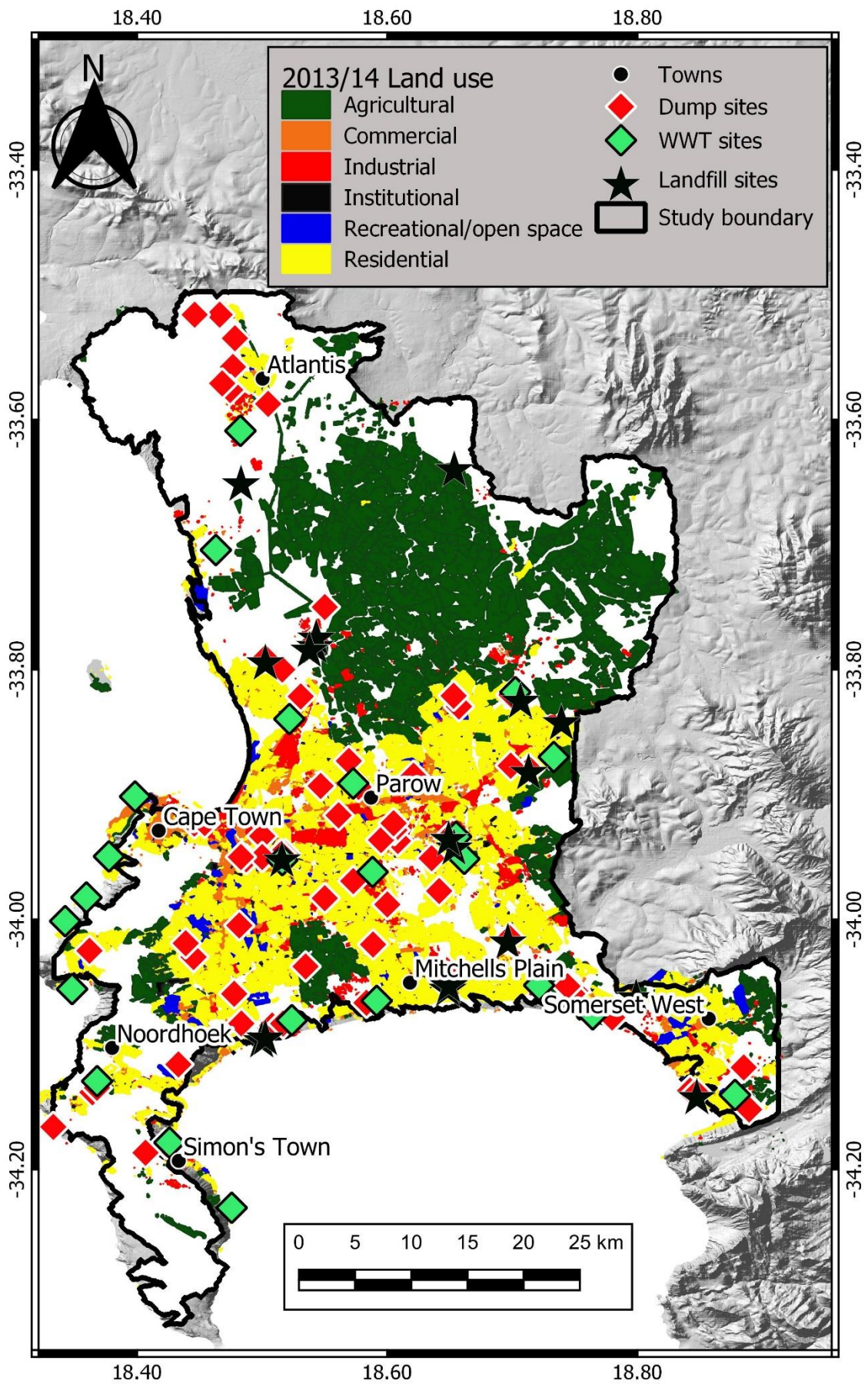


Figure 2.6: Map depicting distributions of land use in the Cape Town Metropolitan Municipality. Based on the 2013-14 national land cover dataset supplied by the City of Cape Town Metropolitan Municipality

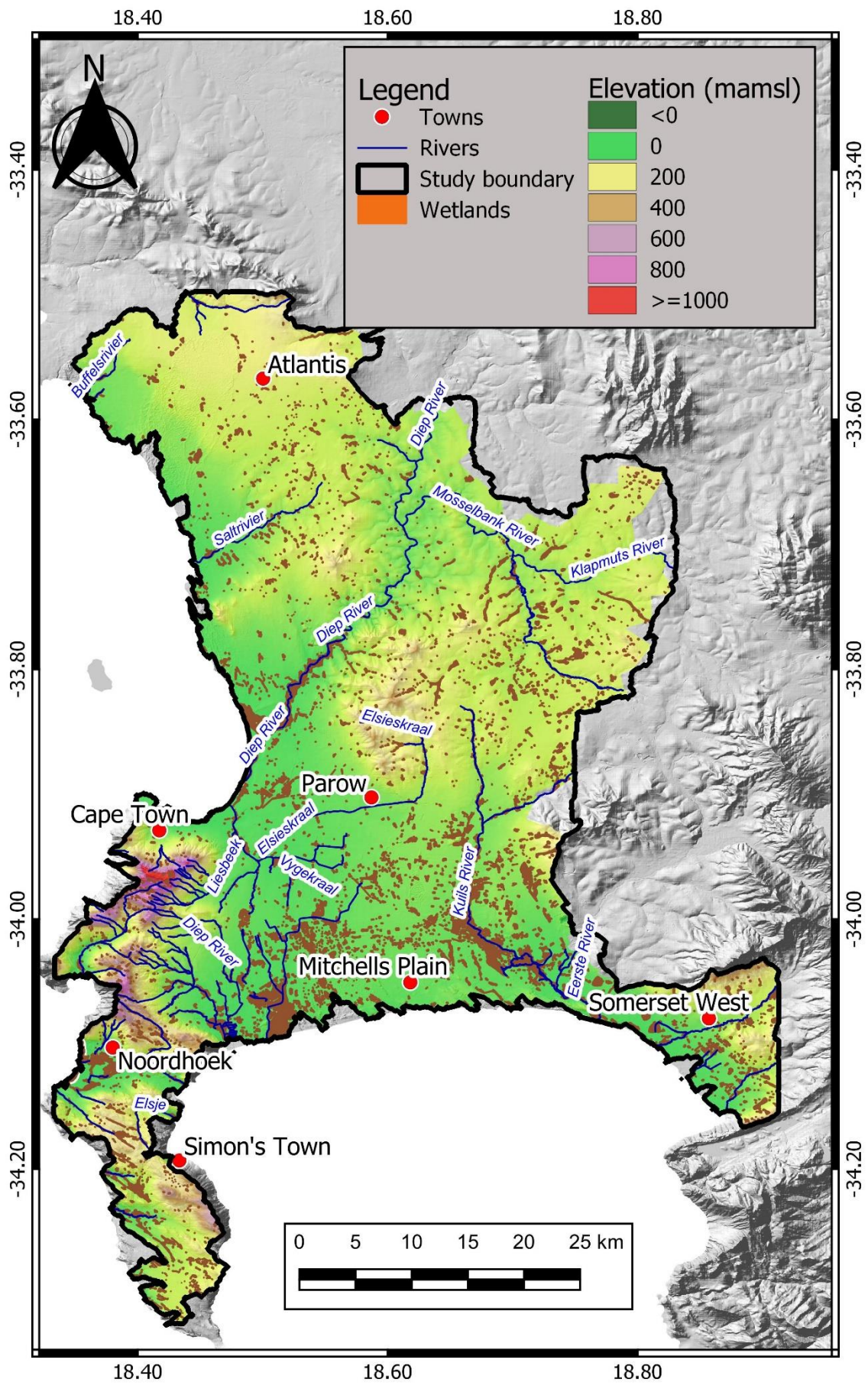


Figure 2.7: Map depicting the major rivers of the Cape Town Metropolitan Municipality

CHAPTER THREE: RESEARCH METHODOLOGY

This chapter is devoted to a detailed discussion of the use of spatial data to determine the potential severity of illicit discharges within the City of Cape Town Metropolitan Municipality and to identify the sub-catchments that require immediate attention. Brown et al. (2004) recommends the use of desktop assessments for mapping IDP by using background data to characterise sub-catchments in relation to IDP. As illicit discharge detection and elimination (IDDE) programmes to prevent or limit pollution to urban water systems require substantial investments of local resources to be made (Brown et al., 2004), it is necessary that the methods that are used are sufficiently cost-effective to enable municipalities to implement them. Consequently, as municipalities in developing countries are often required to contend with shortages of resources and skilled personnel and a lack of funds, they are unlikely to invest in IDDE programmes if they are costly. By eliminating the costs that field operations would incur, GIS-based risk mapping to determine IDP that draws on existing background data becomes a viable option for making cost-effective assessments. Figure 3.1 depicts a flow chart of the sequence of stages of the research study that are described in Chapter 3.

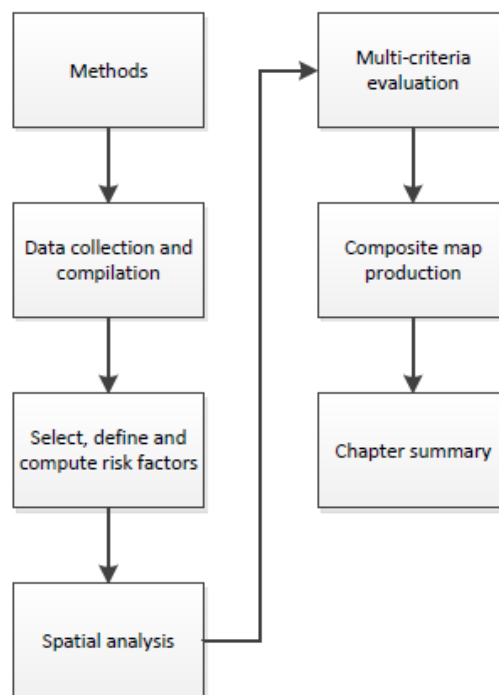


Figure 3.1 Flow chart for Chapter Three

As it emerged from the literature review, risk mapping techniques that are reliant on expert knowledge or professional judgement can bias the findings of studies. It was also pointed out that the accuracy of professional judgements and the effects that they have on the findings are not assessed. These considerations underscore the need to formulate a GIS-based risk mapping procedure for IDP that permits the investigation of the effects of hydraulic, hydrological, and environmental risk factors and factors pertaining to land

use on potentials for illicit discharges at specific locations (Owusu-Asante, 2019). Data from the City of Cape Town Metropolitan Municipality was used both to characterise IDP for individual sub-catchments within the area and to investigate the potential spatial relationships among risk factors and illicit discharges.

3.1 Research methods

Figure 3.2 depicts the five major tasks of which the research methodology was comprised.

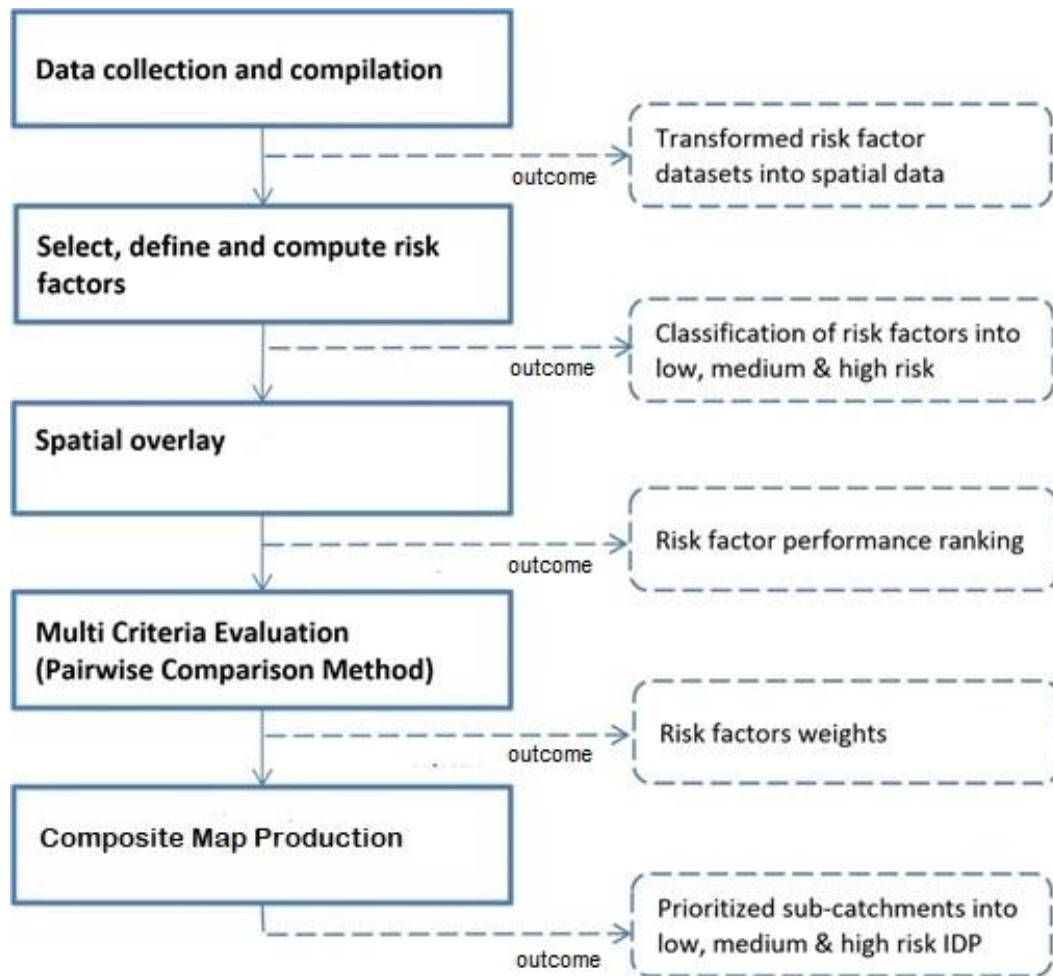


Figure 3.2: Flow chart depicting the steps of the desktop study (Owusu-Asante, 2019)

3.2 Collection and compilation of the data

All the datasets that were used in this research project were obtained from the City of Cape Town Metropolitan Municipality, which maintains a large public database of GIS data to manage the programmes that are implemented and the services that are provided in the municipal area. The types of data include:

- Hydrological data pertaining to catchment boundaries, rivers, streams, and canals.
- Data pertaining to land use, zoning, land parcels, and streets.

- Population data.
- Data pertaining to generating sites (Standard Industrial Classification codes for industries and commercial sites) (Owusu-Asante, 2019).

It was necessary to obtain additional datasets from relevant municipal departments, including those pertaining to sub-drainage watersheds from the twenty-five-metre digital elevation model (DEM), the stormwater drainage system and sanitary infrastructure, septic field locations, and detailed records of illicit discharges (Owusu-Asante, 2019). The datasets were compiled by means of a geographic information system, with ArcGIS version 10.1 being the software that was used most to clean and process the data and generate risk factors. All spatial graphics were produced by making use of QGIS.

Once the collecting of the data had been completed, all datasets were checked for topographical errors, which were subsequently corrected. All polygons were checked to identify any unclosed polygons. Sliver polygons occur as a consequence of spatial overlays of GIS layers. The sub-drainage catchments dataset contained 110 sliver polygons, which were deleted. As the sub-drainage catchments did not cover the entire area that falls under the City of Cape Town Metropolitan Municipality on the western side of Somerset West, their polygons were dissolved to form a study boundary and all datasets were clipped accordingly. Consequently, the dissolved polygons delineated the actual area that the study covered, which is enclosed by a black outline, the study boundary, in all of the figures in this study.

3.3 Select, define, and compute risk factors

Owing to the unavailability of local studies, with the exception of that of Owusu-Asante (2019), the researcher adopted the definitions and derivations of risk factors that were recommended by Brown et al. (2004) and Bender (2016). Accordingly, it was accepted on the basis of the findings of those studies that the risk factors were credible indicators of IDP. The remainder of the risk factors that were used in this study were selected in accordance with the findings of other studies in the literature review and the background information pertaining to the area in which the study was covered, which was presented in section 2.5.

The Jenks Natural Breaks method was used to classify the risk factors by means of a GIS software into low-, medium-, and high-risk with respect to IDP. Chen et al., (2013:49) characterise the method as “*a data classification method designed to determine the best arrangement of values into different classes*”. Breakpoints for all risk factors were obtained by using the method and were calibrated by overlaying past discharge-related complaints, in order to ensure that the high-risk areas included clusters of past

complaints. The two risk factors that were in point format, namely, infrastructure access density and on-site sanitation, were converted to a raster layer by using the kernel density function in a GIS software. Kernel density estimation is an estimation approach that takes the value of data assigned to a specific point and spreads it across a predefined area (Spencer et al., 2007). This was done to estimate the infrastructure access density and on-site sanitation values across the study area. Nine of the risk factors (development age, outfall density, ageing sanitary infrastructure, drainage density, generating site density, percentage impervious surface, land-use industrial, land-use commercial, and land-use residential) were evaluated within sub-catchments throughout the study area and the overall risk classes for IDP were based on the values per risk factor that were obtained for each sub-catchment. Population density was evaluated from census blocks that were developed by Statistics South Africa. Table 3.1 provides a summary of all of the risk factors that were used in this study and brief descriptions of what they denote. All of the raster layers had a resolution of 30m x 30m.

Table 3.1 Definitions of risk factors identified as indicators of IDP

Number	Dataset	Definition
1	Population density	Number of residents per square kilometre, measured over groups of census blocks
2	Development age	Average age of development or stormwater infrastructure in each sub-catchment area
3	Outfall density	Average number of outfalls per kilometre of stream in a watershed
4	Ageing sanitary infrastructure	Average age of sewer network in each sub-catchment area
5	Drainage density	Kilometres of pipes and open watercourse per square kilometre of sub-catchment area
6	Generating site density	Number of generating sites per sub-catchment area
7	Infrastructure access density	Number of storm drain inlets/outlets per square kilometre
8	On-site sanitation	Number of on-site sanitation facilities in informal settlements per square kilometre
9	Percentage impervious surface	Area of sub-catchment whose surface is impervious
10	LU commercial	Area of sub-catchment whose land-use is classified as commercial
11	LU residential	Area of sub-catchment whose land-use is classified as residential
12	LU industrial	Area of sub-catchment whose land-use is classified as industrial

3.3.1 Population density

Bender (2016:123) defines population density as “*the total number of people per square kilometre, measured within block groups (polygons), which was the smallest census unit*”

for which population data was available". The population layer vector file was loaded into a GIS software and a new field Pop_Density was created, which was populated by running a compute process, multiplying the population field by 1 000 000, and dividing the product by the shape area of the corresponding polygon. The resulting data was saved in a new field, Pop_Density, and was further classified into three risk levels by using the Jenks Natural Breaks method. A new field (Risk_index) was created, to be populated with the risk classes that had been derived from the Jenks Natural Breaks classification. The breakpoints between the risk levels were noted and the risk level for the highest population density was assigned a value of 3 in the Risk_index field. The risk level for an average population density was assigned a value of 2 and that for a low population density a value of 1. Past discharge complaint records (PDCRs) for all five pathways were overlaid and the breakpoints between the three risk levels were calibrated against the PDCRs. Once this step had been accomplished, the new breakpoints for all risk levels were noted and the file was reclassified into three risk levels, again with the areas with high population densities being assigned a value of 3, those with medium densities 2, and those with low densities 1 in the Risk_index field. The vector file was converted to decimal raster with a resolution of 30 metres and the pixel values were assigned the values of the Risk index field. A value of 3 represented high IDP, 2 medium IDP, and 1 low IDP. The output raster file was clipped to the boundaries of the dissolved sub-catchments and saved as the final population density IDP file. A detailed risk mapping procedure for population density is provided in section 1 of Appendix A.

3.3.2 Development age or the age of stormwater infrastructure

The age of development in a catchment can predict the potential for occurrences of illicit discharges. Owusu-Asante (2019:89) explains that "*a catchment with [a] development age of more than 100 years is likely to have a higher risk of IDP because of deterioration in the pipes and connections and also substandard, old construction materials, codes, and inspections*". Bender (2016:124) defines the age of development "*as the number of years since a structure was built on a parcel*". Accordingly, the ages of the land parcels concerned were aggregated to determine their average age (Owusu-Asante, 2019).

A stormwater infrastructure shapefile was loaded into a GIS software. The INFRSTAGE column contained the year and date of installation in the format YYYY/MM/DD. The year was extracted by using a script in the compute field properties and an age field was added to the attribute table. The age field was subsequently populated by using the compute field process again and subtracting the year value that had been extracted from the INFRSTAGE column from 2019. A total of 18 567 null values were extracted from

the main dataset and saved in a separate shapefile. The extracted null dataset values were then deleted from the original dataset. *“In 2006, CoCT assigned categories for Age of Infrastructure by a spatial-join to associate the ages of sewer, water, and the general plan polygons layers to the stormwater pipes layer, as historic records for age of infrastructure was (sic) not available”* (Kane, pers. Comm., 2017) and a similar approach was followed in this study. The shapefile containing null values was displayed, together with a planning dataset shapefile that had been supplied by the City of Cape Town Metropolitan Municipality. The planning shapefile contained the proposed development of infrastructure. A 50-metre buffer was run on the planning dataset and all line segments that fell within the buffer zone in the null file were selected. They were then assigned the age of infrastructure that was in the planning shapefile. This procedure was repeated using 100-metre and 200-metre buffer zones. Once this step had been completed, all of the line segments in the null dataset contained age values.

The null dataset was then merged back with the stormwater infrastructure file, to form an updated stormwater file that contained age values for all line segments. A spatial join process was run between the updated stormwater infrastructure file and the sub-catchments, using the average function. This step enabled the average age of all stormwater segments within each sub-catchment to be calculated and an outcome to be assigned to it. The Jenks Natural Breaks Method was run to categorise the file using the age column that had been obtained from the spatial join process into three risk levels. A new field (Risk_index) was created, to be populated with the risk classes that had been derived from the Jenks Natural Breaks classification. The breakpoints between the risk levels were noted and the risk level that contained the highest average stormwater infrastructure age was assigned a value of 3 in the Risk_index field. Conversely, the risk level for the stormwater infrastructure with the lowest age was assigned a value of 1, while that for infrastructure whose age was midway between the previous two classifications was assigned a value of 2.

Past discharge complaint records (PDCRs) for all pathways were overlaid and the breakpoints between the three risk levels were calibrated against the PDCRs. The new breakpoints for all risk levels were noted and the file was reclassified into three risk levels, again with the areas whose stormwater infrastructure was oldest being assigned a value of 3, those whose infrastructure fell between the oldest and the most recent a value of 2, and those whose infrastructure was most recent a value of 1 in the Risk_index field. The vector file was converted to decimal raster with a resolution of 30 metres and the pixel values were assigned the values of the Risk_index field. A value of 3 represented high IDP, 2 medium IDP, and 1 low IDP. The output raster file was clipped to the extents of

the dissolved sub-catchments and saved as the final stormwater infrastructure age IDP file. A detailed risk mapping procedure for development age is provided in section 2 of Appendix A.

3.3.3 Outfall density

The density of outfalls in a sub-catchment is a significant screening factor for assessing the potential for illicit discharges and is expressed in terms of numbers of outfalls from the storm drainage networks into particular sub-catchment waters or streams. In many instances, the higher the outfall density, the more connections there are between the storm drainage network and the stream, which can be indicative of a dense stormwater drainage network with many sub-catchments (Owusu-Asante, 2019). Outfalls that discharge into the open watercourses (OWCs) and waterbodies such as ponds and wetlands were also included in the analysis.

A watercourse layer that covered the study area was displayed in a GIS software, together with the study area boundary. The watercourse layer was clipped to the extents of the study area. The resulting clipped watercourses layer was used to generate a 50-metre buffer and saved as a separate file. The buffered file was displayed together with the outfalls and all outfalls were clipped, using the buffered watercourse shapefile. The clipped outfall densities were saved as a separate shapefile. A spatial join process was carried out between the clipped outfall densities shapefile and the sub-catchments. This step enabled the sum of all outfalls in a sub-catchment to be calculated and the outcome to be saved in a new field that was designated as 'count'. The Jenks Natural Breaks method was run to categorise the file using the 'count field' into three risk levels. A new field (Risk_index) was created, to be populated with the risk classes that had been derived from the Jenks Natural Breaks classification. The breakpoints between the risk levels were noted, with the risk level for the greatest number of outfalls being assigned a value of 3 in the Risk_index field, that for the smallest number of outfalls a value of 1, and that for the midpoint for the greatest and the smallest a value of 2. Past discharge complaint records (PDCRs) for all pathways were overlaid and the breakpoints between the three risk levels were calibrated against the PDCRs. The new breakpoints for all risk levels were noted and the file was reclassified into three risk levels, again with the areas with the greatest numbers of outfalls being assigned a value of 3 in the Risk_index field, those with the smallest numbers a value of 1, and those with numbers that lay between the two a value of 2. The vector file was converted to decimal raster with a resolution of 30 metres and the pixel values were assigned the values of the Risk_index field. A value of 3 represented high IDP, 2 medium IDP, and 1 low IDP. The output raster file was clipped to the extents of the dissolved sub-catchments and saved as the final outfall

density IDP file. A detailed risk mapping procedure for outfall density is provided in section 3 of Appendix A.

3.3.4 Ageing sanitary infrastructure

Brown et al. (2004) defines the risk factor of ageing sanitary infrastructure as the age and condition of a sub-catchment sewer network. The factor is used to evaluate the condition of the sanitary sewer network and the potential for a sanitary sewer system to contribute to incidences of illicit discharges to the drainage area through leaks, overflows, or illegal connections (Owusu-Asante, 2019). High IDP is predicated on the age of a sanitary sewer system exceeding the design life of the materials that were used to construct it and also becomes evident when clusters of pipe breaks, spills, and overflows are reported by sewer authorities (Owusu-Asante, 2019).

The sewer age file was displayed in a GIS software and a new field (Final_age) was added to the attribute table, which was populated by calculating the difference between 2019 and the figure in the Year column using the computed function. The sub-catchments were also added to a GIS software and a spatial join was carried out between the sewer age file and the sub-catchment to compute the average age of the sewer network in each sub-catchment. The Jenks Natural Breaks Method was run to enable the Final_age column in the file to be subdivided into three risk levels. A new field (Risk_index) was created, to be populated with the risk classes that had been derived from the Jenks Natural Breaks classification. The breakpoints between the three risk levels were noted, with the risk level for the greatest average age of sewer systems being assigned a value of 3 in the Risk_index field, while that for the average age was assigned a value of 2, and that for the lowest age a value of 1. Past discharge complaint records (PDCRs) for all pathways were overlaid and the breakpoints between the three risk levels were calibrated against the PDCRs. The new breakpoints for all three risk levels were noted and the file was reclassified into three risk levels again, with the areas whose sanitary infrastructure was oldest being assigned a value of 3 in the Risk_index field, while those whose infrastructure was of average age were assigned a value of 2, and those whose infrastructure was newest a value of 1. The vector file was converted to decimal raster with a resolution of 30 metres and the pixel values were assigned the values of the Risk_index field. A value of 3 represented high IDP, 2 medium IDP, and 1 low IDP. The output raster file was clipped to the extents of the dissolved sub-catchments and saved as the final sewer age IDP file. A detailed risk mapping procedure for ageing sanitary infrastructure is provided in section 4 of Appendix A.

3.3.5 Drainage density

Although drainage density is typically defined as the length of stream channels divided by the catchment or sub-catchment drainage area, the definition was modified in this study to apply specifically to urban drainage networks. The amended definition was the length of drainage conveyances divided by the sub-catchment area. The drainage infrastructure was used to provide a qualitative assessment of the development of drainage networks in the area in which the study was conducted. The more developed a drainage network is, the greater is its drainage density in kilometres of conveyances per square kilometre and the more quickly a sub-catchment will drain to its outlet (Owusu-Asante, 2019).

A conduits shapefile was overlaid in a GIS software, together with the sub-catchment shapefile. A spatial join was performed between the two using the sum option, to obtain the sum of all drainage channels in a sub-catchment, and the result was saved separately. A new field was created in the resulting shapefile and was populated by dividing the sum of the lengths of the conduits by the shape area to calculate the drainage density. The Jenks Natural Breaks Method was run to categorise the file, using the new field that had been computed into three risk levels. A new field (Risk_index) was created, to be populated with the risk classes that had been derived from the Jenks Natural Breaks classification. The breakpoints were noted, with the risk level for the highest drainage density being assigned a value of 3 in the Risk_index field, that with medium drainage density a value of 2, and that with the least drainage density a value of 1. Past discharge complaint records (PDCRs) for all pathways were overlaid and the breakpoints between the three risk levels were calibrated against the PDCRs. The new breakpoints for all risk levels were noted and the file was reclassified into three risk levels, again with the areas with the highest drainage density being assigned a value of 3 in the Risk_index field, while those with medium drainage density were assigned a value of 2, and those with the least a value of 1. The vector file was converted to decimal raster with a resolution of 30 metres, with the pixel values being assigned the values of the Risk_index field. A value of 3 represented high IDP, 2 medium IDP, and 1 low IDP. The output raster file was clipped to the extents of the dissolved sub-catchments and saved as the final drainage density IDP file. A detailed risk mapping procedure for drainage density is provided in section 5 of Appendix A.

3.3.6 Generating site density

Bender (2016:127) defines the generating site density risk factor as “*the number of potential generating sites per sub-catchment, where potential generating sites are facilities ranging from fuel stations to restaurants to industrial plants which inherently carry the risk of contributing illegal discharges of various pollutants to the sub-*

catchment". The findings of research by Brown et al. (2004) suggest that the risks of spills, leaks, or illicit discharges and becoming potential sources of pollutant loads for some land uses (residential, commercial, industrial, institutional, or municipal) are likely to be higher than they are for others. The activities that produce discharges in specific land uses are summarised in Table 3.2.

Table 3.2 Land uses and activities that produce indirect discharges (Brown et al., 2004)

Land use	Generating site	Activities that contribute to discharges
Residential	<ul style="list-style-type: none"> • Apartments • Multi-family residential dwellings • Single-family detached dwellings 	<ul style="list-style-type: none"> • Car washing • Driveway cleaning • Dumping/spills • Washing down of equipment • Watering gardens and lawns • Maintenance to septic systems • Swimming pool discharges
Commercial	<ul style="list-style-type: none"> • Campgrounds/RV parks • Car dealers/ Car rental companies • Car washes • Commercial laundries/ Dry cleaning agencies • Petrol stations/Auto repair shops • Marinas • Nurseries and garden centres • Oil change shops • Restaurants • Swimming pools 	<ul style="list-style-type: none"> • Building maintenance (power washing) • Dumping/spills • Care of grounds and lawns (irrigation) • Outdoor storage of fluids • Maintenance of parking lots • Fuelling of vehicles • Maintenance and repairs to vehicles • Washing of vehicles • Washing down of greasy equipment and grease traps
Industrial	<ul style="list-style-type: none"> • Auto recyclers • Beverages and brewing • Washing out facilities for construction vehicles • Distribution centres • Food processing • Washing out facilities for refuse removal trucks • Marinas, boat building and repair operations • Metal plating operations • Manufacturers of paper and wood products 	<ul style="list-style-type: none"> • All commercial activities • Industrial process water or rinse water • Washing down of loading and unloading areas • Outdoor storage of fluids

Land use	Generating site	Activities that contribute to discharges
	<ul style="list-style-type: none"> • Petroleum storage and refining facilities • Printing 	
Institutional	<ul style="list-style-type: none"> • Cemeteries • Churches • Corporate campuses • Hospitals • Schools and universities 	<ul style="list-style-type: none"> • Maintenance of buildings (e.g. power washing) • Dumping/spills • Care of grounds and lawns (irrigation) • Maintenance of parking lots (power washing) • Washing of vehicles
Municipal	<ul style="list-style-type: none"> • Airports • Landfills • Maintenance depots • Municipal fleet storage areas • Ports • Public works yards • Streets and highways 	<ul style="list-style-type: none"> • Maintenance of buildings (power washing) • Dumping/spills • Care of grounds and lawns (irrigation) • Outdoor storage of fluids • Maintenance of parking lots (power washing) • Maintenance of roads • Prevention of and responses to spills • Fuelling of vehicles • Maintenance and repairing of vehicles • Washing of vehicles

A generating site density shapefile was displayed in a GIS software, together with the sub-catchments. The generating site density shapefile was converted to a point file from a polygon file by using the centroid coordinates of the polygons. A spatial join was then carried out between the sub-catchments and the points shapefile, using the count function to obtain the number of generating sites within each sub-catchment and the results were saved in a new field. The Jenks Natural Breaks Method was run to categorise the new field that had been computed into three risk levels. A new field (Risk_index) was created, to be populated with the risk classes that had been derived from the Jenks Natural Breaks classification. The breakpoints between the risk levels were noted, with the risk level for the most generating sites being assigned a value of 3 in the Risk_index field, while that for the least generating sites was assigned a value of 1 and that for an average number of generating sites a value of 2. Past discharge complaint records (PDCRs) for all pathways were overlaid and the breakpoints between the three risk levels were calibrated against the PDCRs. The new breakpoints for all risk levels were noted and the file was reclassified into three risk levels, again with the areas with the most generating sites being assigned a value of 3 in the Risk_index field, while

those with the least sites were assigned a value of 1 and those with average numbers of sites a value of 2. The vector file was converted to decimal raster with a resolution of 30 metres and the pixel values were assigned the values of the Risk_index field. A value of 3 represented high IDP, 2 medium IDP, and 1 low IDP. The output raster file was clipped to the extents of the dissolved sub-catchments and saved as the final generating site density IDP file. A detailed risk mapping procedure for generating site density is provided in section 6 of Appendix A.

3.3.7 Infrastructure access density

Infrastructure access density can be defined as the number of access points to storm drain networks per square kilometre, while access points are defined as catch basins, pond outlet structures, pipe ends, inlets or outlets, and other features that are open to the atmosphere, thereby allowing materials to enter storm drain networks (Owusu-Asante, 2019).

The input layer was the stormwater inlet and the outlet point file dated February 2017 was supplied by the City of Cape Town Metropolitan Municipality. The point shapefile was loaded into a GIS software and converted into a raster file using the kernel density function. The resulting raster file was converted back to a vector file and the Jenks Natural Breaks Method was run to categorise the outlet point file into three risk levels. A new field (Risk_index) was created, to be populated with the risk classes that were derived from the Jenks Natural Breaks classification. The breakpoints were noted, with the risk level for the highest infrastructure access density being assigned a value of 3 in the Risk_index field, while that for a medium level of infrastructure access density was assigned a value of 2 and that for the lowest infrastructure access density was assigned a value of 1. Past discharge complaint records (PDCRs) for all pathways were overlaid and the breakpoints between the three risk levels were calibrated against the PDCRs. The new breakpoints for all risk levels were noted and the file was reclassified into three risk levels, again with the risk level for the most infrastructure access density being assigned a value of 3, a medium level a value of 2, and the lowest a value of 1 in the Risk_index field. The vector file was converted to decimal raster with a resolution of 30 metres and the pixel values were assigned the values of the Risk_index field. A value 3 represented high IDP, 2 medium IDP, and 1 low IDP. The output raster file was clipped to the extents of the dissolved sub-catchments and saved as the final infrastructure density IDP file. A detailed risk mapping procedure for infrastructure access density is provided in section 7 of Appendix A.

3.3.8 On-site sanitation

On-site sanitation refers to the number of publicly available sanitation facilities in informal settlements. Informal settlements still lack adequate functioning flush toilets and in those instances in which they are available, they are often situated at their fringes. Owing to high incidences of criminal assaults in informal settlements, most of the families use buckets in their homes to relieve themselves during the night, which are often emptied into stormwater systems the following morning.

The input layer was a toilets point shapefile which was supplied by the City of Cape Town Metropolitan Municipality. The point shapefile was loaded into a GIS software and converted into a raster file by using the kernel density function. The resulting raster file was converted back to a vector file and the Jenks Natural Breaks Method was run to categorise the toilets point shapefile into three risk levels. A new Risk_index field was created, to be populated with the risk classes that had been derived from the Jenks Natural Breaks classification. The breakpoints were noted, with the risk level for the most on-site sanitation facilities being assigned a value of 3 in the Risk_index field, while that for the least was assigned a value of 1 and that for an average number of facilities was assigned a value of 2. Past discharge complaint records (PDCRs) for all pathways were overlaid and the breakpoints between the three risk levels were calibrated against the PDCRs. The new breakpoints for all risk levels were noted and the file was reclassified into three risk levels, again with the risk level for the most on-site sanitation facilities being assigned a value of 3 in the Risk_index field, which that for an average number of facilities was assigned a value of 2 and that for the least number a value of 1. The vector file was converted to decimal raster with a resolution of 30 metres and the pixel values were assigned the values of the Risk_index field. A value of 3 represented high IDP, 2 medium IDP, and 1 low IDP. The output raster file was clipped to the extents of the dissolved sub-catchments and saved as the final on-site sanitation IDP file. A detailed risk mapping procedure for on-site sanitation is provided in section 8 of Appendix A.

3.3.9 Percentage impervious surface

Percentage impervious surface has been defined as the area of impervious surfaces such as tarred roads, concrete, or rooftops in a sub-catchment, expressed as a percentage (Bender, 2016). Impervious surfaces increase the potential for the accumulation and washing off of pollutants into stormwater systems. The input file was a percentage impervious surface polygon shapefile, which was supplied by the City of Cape Town Metropolitan Municipality.

The percentage impervious surface polygon shapefile was displayed in a GIS software. The sub-catchments were also loaded onto the GIS software and a spatial join between

the percentage impervious file and the sub-catchments was carried out to compute the total sum of the impervious surfaces in each sub-catchment. The Jenks Natural Breaks Method was used to categorise the area column of the file into three risk levels. A new Risk_index file was created, to be populated with the risk classes that had been derived from the Jenks Natural Breaks classification. The breakpoints were noted, with the risk level for the greatest total sum of areas of impervious surface being assigned a value of 3 in the Risk_index field, while the smallest sum was assigned a value of 1 and an average sum was assigned a value of 2. Past discharge complaint records (PDCRs) for all pathways were overlaid and the breakpoints between the three risk levels were calibrated against the PDCRs. The new breakpoints for all three risk levels were noted and the file was reclassified into three risk levels, again with the areas containing the greatest total sum being assigned a value of 3, medium 2 and the lowest total sum a value of 1 in the Risk_index field. The vector file was converted to decimal raster with a resolution of 30 metres and the pixel values were assigned the values of the Risk_index field. A value of 3 represented high IDP, 2 medium IDP, and 1 low IDP. The output raster file was clipped to the extents of the dissolved sub-catchments and saved as the final percentage impervious surface IDP file. A detailed risk mapping procedure for percentage impervious surface is provided in section 9 of Appendix A.

3.3.10 Commercial, residential, and industrial land use

Land use in this study refers to the characterisation of land cover on the basis of the activities in which people engage on a land parcel to develop, change, or maintain it. The input file was a raster of the national land cover dataset that covered 2013-14. This raster file contained 72 classes of land cover, which were reclassified into six classes, namely, commercial, residential, industrial, recreational or open space, institutional, and agricultural classifications. The reclassification entailed merging some of the classes of land cover classes into single classes to arrive at the following classifications:

- The urban commercial class was classified as class number 1 (commercial).
- All urban informal areas, urban residential areas, urban township areas, urban village areas, and urban built-up areas were classified as class number 2 (residential).
- Bare, semi-bare, water seasonal, and water permanent mines, mine buildings, and urban industrial areas were classified as class number 3 (industrial).
- Urban sports grounds and facilities were classified as class number 4 (recreational open space).
- Urban schools and their sports grounds were classified as class number 5 (institutional).

- Cultivated commercial fields, cultivated commercial pivots, cultivated orchards, cultivated vines, cultivated subsistence farming areas, cultivated cane pivots, and all plantations and woodlots were classified as class number 6 (agricultural).

A new field was created and commercial, residential, and industrial classes were assigned a value of 3, as they have particularly high IDP, owing to the nature of the activities that occur on their land parcels and the waste that they generate. The recreational open space and institutional classes were assigned a value of 2, as they have moderate IDP and the agricultural class was assigned a value of 1, as it has low IDP. Only the commercial, residential, and industrial classes were of interest for the purposes of this study and saved in a separate file.

The commercial land use file was converted to a shapefile and a spatial join was run between the converted commercial shapefile and sub-catchments to calculate the sum of commercial areas within each sub-catchment. The Jenks Natural Breaks Method was used to categorise the area column of the file into three risk levels. A new Risk_index field was created, to be populated with the risk classes that had been derived from the Jenks Natural Breaks classification. The breakpoints were noted, with the highest risk level for commercial land use with respect to the greatest commercial presence being assigned a value of 3 in the Risk_index field, while that for moderate risk was assigned a value of 2 and that for the lowest risk was assigned a value of 1. Past discharge complaint records (PDCRs) for all pathways were overlaid and the breakpoints between the three risk levels were calibrated against the PDCRs. The new breakpoints for all three risk levels were noted and the file was reclassified into three risk levels, again with the areas in which the total sum of commercial land use was highest being assigned a value of 3, those for which the sum had an average value a value of 2, and those in which the total sum was lowest a value of 1 in the Risk_index field. The vector file was converted to decimal raster with a resolution of 30 metres and the pixel values were assigned the values of the Risk_index field. A value of 3 represented high IDP, 2 medium IDP, and 1 low IDP. The output raster file was clipped to the extents of the dissolved sub-catchments and saved as the final land-use commercial IDP file. A detailed risk mapping procedure for commercial land use is provided in section 10 of Appendix A, while procedures for residential and industrial land uses are provided in sections 11 and 12 respectively of Appendix A.

The dataset was derived from the National Land Cover Database for 2013-2014, which covered the whole of South Africa and was released by the Department of Environmental

Affairs. The age of the datasets introduces a degree of uncertainty, as there have been numerous changes with respect to land use in the area in which the study was conducted. Consequently, using this dataset could have resulted in a significant underestimation of the potential risk that this risk factor represented in certain sub-catchments.

3.4 Spatial analysis

Past discharge complaints records (PDCRs) of illicit discharge were obtained from the notification database of the City of Cape Town Metropolitan Municipality. Before the spatial analysis was performed, the PDCRs for four discharge pathways, namely, wastewater, water, greywater, and solid waste were selected and grouped (please see Table 3.3), as it was hypothesised that some risk factors could be associated with illicit discharges from these sources (Owusu-Asante, 2019). All complaints that concerned discharges from sewers, manholes, or toilets were grouped as pertaining to wastewater pathways, as they concerned the sanitary sewer network.

All complaints that had been submitted as a result of water pipe leaks, pipe bursts, water runoff, and flooding were grouped as pertaining to the water pathway. Similarly, all complaints that resulted from blocked gullies in informal settlements, blocked manholes, and water pollution were grouped as pertaining to the greywater pathway, while all complaints concerning the illegal dumping of solid waste, uncollected refuse, and a lack of litter bins were grouped as pertaining to the solid waste pathway. Finally, all four pathways (wastewater, water, greywater, and solid waste) were combined as the ALL pathway as it was necessary to consider a pathway that receives and delivers all waste streams.

After each complaint had been assigned to a discharge pathway group, the complaints were spatially overlaid on top of risk factor layers in a GIS software, one pathway at a time. An illicit discharge was considered to be 'captured' by a risk factor if it fell within the high-risk overlay for that factor (Bender, 2016), which is class number 3 of the Risk_Index field in this study. Statistical methods, in the form of an online chi-square calculator (<http://vassarstats.net/odds2x2.html>), were used to compare the respective influence of individual risk factors. In addition, the statistical methods were also used with the aim of arriving at a relative ranking that describes the ability of individual risk factors to predict overall IDP (Owusu-Asante, 2019).

A chi-square test with $\alpha = 0.05$ was used to determine if there was a significant difference in the influence which was exerted by any two risk factors (Owusu-Asante, 2019). The

influence was measured by the proportion of captured records in a discharge pathway group. The chi-square analyses and captured proportions were then used to rank risk factors in sub-catchments, according to their ability to predict occurrences and/or locations of discharges in each discharge pathway (Owusu-Asante, 2019). The chi-square results are provided in Appendices D1 to D5.

3.5 Multi-criteria evaluation (Risk factor weightings)

Weights are used to rate risk factors as a means of predicting the risk of IDP. The analytic hierarchy process (AHP), which is a decision-making framework for solving multi-criteria problems by assessing alternatives against an array of diverse objectives, was used to determine the weights. Although Owusu-Asante (2019) provides a detailed mathematical background of the AHP, the general procedure is as follows:

- Identify and define the problem and specify the solution that is desired.
- Structure the problem in a hierarchy.
- Construct a pairwise comparison matrix of the relevant contribution or impact of each element or risk factor. Each risk factor is compared with the other risk factors (2 at a time), to develop a 12 by 12 comparison matrix.
- Normalise the resulting matrix.
- Average the values in each row to determine the corresponding weights.
- Evaluate the consistency for the entire hierarchy by multiplying each consistency index by the priority of the corresponding criterion.

For each pathway, the results from the spatial analysis were used to construct a pairwise comparison by comparing the captured values of the risk factors against each other, using the Saaty table (Table 3.4). A 'subjective approach' was used to link the percentage capture rates of risk factors to Saaty's scale of comparison. Two risk factors were considered to be of equal importance if the difference between their percentage capture rates was less than 5%. Weak or slight importance was assigned if the difference between the capture rates was between 6 and 10%. For differences in capture rates that were 11-20, 21-30, 31-40, 41-50, 51-60, 61-75, and 76-100 the following were respectively assigned: moderate importance, moderate plus importance, strong importance, strong plus importance, very strong importance, very very strong importance, and extreme importance (Owusu-Asante, 2019). The difference between the capture rates for population density and development age was 32 (49-17), with population density being assigned an importance value of 5 and development age an importance value of 1/5. A matrix of order 12 (as 12 risk factors were considered for this study) was then generated for each pairwise table by using this procedure and the values were captured in an Excel matrix. Once the pairwise comparison of all 12 risk factors

was complete, column totals were calculated for each risk factor and the assigned importance values were normalised by dividing the importance value by the column total. The sum of each normalised matrix is 1. The weights were then calculated by averaging the normalised values in each row. The calculation for the first row in for the water pathway (please refer to Table E1, Appendix E) is: $[0.203 + 0.176 + 0.14 + 0.167 + 0.154 + 0.227 + 0.149 + 0.203 + 0.282 + 0.182 + 0.18 + 0.182]/12 = 0.187$, while those for the remaining eleven rows generated values of 0.039, 0.022, 0.034, 0.024, 0.122, 0.029, 0.116, 0.148, 0.056, 0.168, and 0.056 respectively.

The advantage of the AHP method is that it allows the consistency of the comparisons to be evaluated. The next step was to calculate λ_{max} , in order to determine the consistency index (CI) and consistency ratio (CR). The procedure entailed first multiplying each row in the original pairwise comparison matrix by the weight vector, in order to obtain a new vector. Each value in the new vector was then divided by the weight in the corresponding row to obtain a consistency measure vector. The values in the consistency measure vector were then averaged to obtain a lambda (λ_{max}) value. The calculation for the first row in the consistency measure vector for the water pathway was as follows: $1*0.187 + 5*0.039 + 6*0.022 + 5*0.034 + 6*0.024 + 2*0.122 + 5*0.029 + 2*0.116 + 2*0.148 + 4*0.056 + 1*0.168 + 4*0.056]/0.187 = 12.582$ and the remaining eleven rows yielded 12.114, 12.251, 12.232, 12.227, 12.598, 12.118, 12.598, 12.683, 12.324, 12.599, and 12.324 respectively. The mean of these values was 12.3874023, which was the estimate for λ_{max} . If any of the estimates for λ_{max} were to be less than n, or 12 in this case, it would indicate an error in the calculations.

The CI for a matrix is calculated from $(\lambda_{max}-n)/(n-1)$ and, as $n=12$ for this matrix, the CI was 0.0352. The final step was to calculate the CR, which was obtained by dividing the CI by the randomness index, which is set to 1.54 when $n=12$. For the water pathway, the CR was $0.0352/1.54=0.0223$, which was acceptable, as Saaty maintains that a CR value of 0.1 or less indicates that the judgements are consistent (Owusu-Asante, 2019). The weights, detailed pairwise comparison matrix, normalised matrix, CI, RI, and CR for all of the pathways are provided in Appendices E1 to E5.

Table 3.3 Historical complaints records grouped under four discharge pathways

Pathways	Description of discharge
Wastewater: (sanitary sewer source)	Sewer pump station: faulty
	Sewer pump station: overflow
	Sewer spillage
	Sewer: blocked/overflow
	Sewer: pipe broken

Pathways	Description of discharge
	Sewer: line blocked
	Manhole blocked
	Toilet blocked
Water: (leaks and runoffs from bursts, defective infrastructure, firefighters, etc.)	Flooding: roads, property, informal areas
	Main leak
	Meter leak
	Pipe burst
	Tap defective
	Tap missing
	Tap stolen
Greywater/sullage: (Including all pollution incidents)	Gulley blocked (informal settlements)
	Gulley request (informal settlements)
	Gulley/manhole blockages (stormwater)
	Water pollution complaints/incidents
Solid waste	Dumping in/on stormwater infrastructure
	Gulley/manhole blockages (stormwater)
	Illegal dumping
	Illegal dumping offenders
	Litter bins not serviced
	Litter bins required
	Non-removal of refuse
	Non-collection of materials for recycling
	Stolen bins
Street sweeping (request)	

Table 3.4 The Saaty table

Intensity of importance	Definition	Explanation	Range or difference between capture rates for risk factors (%)
1	Equal importance	Two factors contribute equally to the occurrence	0-5
2	Weak or slight importance		6-10
3	Moderate importance	Experience and judgement slightly favour one over the other	11-20
4	Moderate plus importance		21-30
5	Strong importance	Experience and judgement strongly favour one over the other	31-40
6	Strong plus importance		41-50
7	Very strong importance	Experience and judgement very strongly favour one over the other and its importance is demonstrated in practice	51-60
8	Very very strong importance		61-75

Intensity of importance	Definition	Explanation	Range or difference between capture rates for risk factors (%)
9	Extreme importance	The evidence that favours one over the other is of the highest possible validity	76-100

3.6 Production of composite maps

A composite map is a map in which multiple risk factor layers are combined to form a single layer. Generating a composite map makes it possible to relate the risk factors to one another and identify similarities and differences between them. All risk factors were converted to a decimal raster format with a pixel resolution of 30m x 30m. The decimal raster files were clipped using the study boundary in ArcGIS to make certain that they were all clipped to the same extents. The risk factors were displayed in ArcGIS and an overlay process was run. Each risk factor classification score was multiplied by its corresponding weight for each pathway to produce five composite maps for the wastewater, water, greywater, and solid waste pathways. All of the PDCRs were merged for the 'all-pathway' group and a composite map for this group was produced by following the same procedure as had been followed in the case of the previous maps. The five composite maps were each reclassified using the Jenks Natural Breaks Method into the three risk levels: low risk was indicated through the use of green, medium risk was represented in yellow, and high risk in red.

3.7 Chapter summary

This chapter has provided a detailed methodology for risk mapping. It has enumerated the steps in great detail, by commencing with the methods that were used to collect and compile the data to transform datasets for specific risk factors into spatial data. The methods that were used to score risk factors in order to classify them into low, medium, and high risk were explained, before the discussion moved to methods for the spatial overlaying and analysis of past discharge records to rank the influence that individual risk factors exerted on illicit discharges. The past discharge records were then categorised into water, wastewater, greywater, solid waste, and all/combined pathway groups and a multi-criteria evaluation was performed to quantify the weights for individual risk factors. The final section covered the production of composite maps to generate final assessments that enabled catchment areas to be prioritised according to low, medium, or high risk with respect to IDP.

CHAPTER FOUR: PRESENTATION AND DISCUSSION OF THE FINDINGS

This chapter takes the form of a presentation, discussion, and analysis of the findings of the research study. Figure 4.1 provides a schematic overview of the structure of the chapter in the form of tables and maps that were developed to indicate the areas that are at the highest risk of IDP. The discussion begins with a presentation of the results of the risk mapping for the twelve risk factors, before the results of the spatial analysis are presented, followed by those of the multi-criteria evaluation and the production of composite maps. The chapter concludes with a discussion of the limitations of the study.

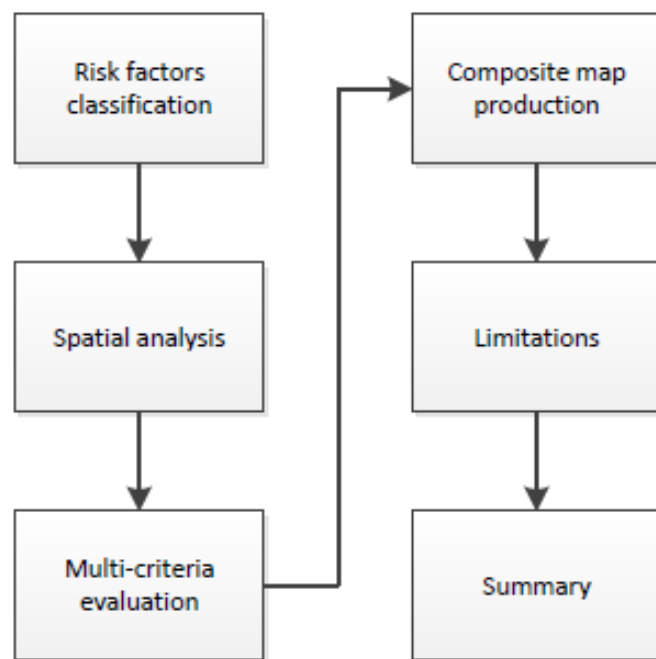


Figure 4.1 Flow chart for Chapter Four

4.1 Classification of risk factors

The classifications of each of the twelve risk factors are summarised in Table 4.1, which provides the risk mapping thresholds for low, medium, and high IDP for each factor in line with Bender's (2016) approach by using the Jenks Natural Breaks Method. Conversely, the percentages of the study area that were classified as having low, medium, or high IDP in relation to each risk factor are summarised in Table 4.2.

Table 4.1: Metric breakdown for each risk factor

No.	Risk Factor	Low (1)	Medium (2)	High (3)	Method used
1	Population density	<25000	25000-100000	>100000	Jenks Natural Breaks in ArcGIS
2	Development age (or age of stormwater infrastructure)	<20	20-40	>40	Jenks Natural Breaks in ArcGIS

No.	Risk Factor	Low (1)	Medium (2)	High (3)	Method used
3	Outfall density	<5	5-30	>30	Jenks Natural Breaks in ArcGIS
4	Ageing sanitary infrastructure	<25	25-50	>50	Jenks Natural Breaks in ArcGIS
5	Drainage density	<7.5	7.5-15	>15	Jenks Natural Breaks in ArcGIS
6	Generating site density	<10	10-75	>75	Jenks Natural Breaks in ArcGIS
7	Infrastructure access density	<4	4-12	>12	Jenks Natural Breaks in ArcGIS
8	On-site sanitation	<4	4-12	>12	Jenks Natural Breaks in ArcGIS
9	Percentage impervious surface	<25000	25000-50000	>50000	Jenks Natural Breaks in ArcGIS
10	Commercial land use	<15000	150000-750000	>750000	Jenks Natural Breaks in ArcGIS
11	Residential land use	<3524737	3524737-7500000	>7500000	Jenks Natural Breaks in ArcGIS
12	Industrial land use	<300000	300000-750000	>750000	Jenks Natural Breaks in ArcGIS

4.1.1 Population density risk classification

The calibrated thresholds for medium-risk and high-risk classifications were 25000 and 100000 people per square kilometre respectively (Table 4.1). A relatively small portion of the study area, comprised of 4.78%, was classified as being at high risk, while 30.62 % was classified as being at a medium level of risk and 64.6% was classified as being at low risk (refer to Table 4.2). Most of the areas that were classified as high-risk areas are either informal settlements or high-density areas (as is depicted in Figure B1 in Appendix B), which include sections of Nomzamo in Strand, Khayelitsha, Seawinds and Vrygrond just outside of Muizenberg, Imizamo Yethu in Hout Bay, Gugulethu, Nyanga, Crossroads, Bishop Lavis, Elsies River Wallacedene and Scottsdene to the east of Brackenfell Industrial, Du Noon, Mitchells Plain, Fisantekraal, and Masiphumelele. These areas are characterised by poor service delivery, most have little or no access to clean water, and nearly all of the inhabitants reside in informal dwellings or shacks (IIED, 2017). The medium risk areas were medium and low-density areas, such as Durbanville, Bellville, Tokai, Rondebosch, Sea Point, and Muizenberg. As these areas are not plagued by poor service delivery, there appears to be significantly less pressure on sanitary and water supply systems than there is in high-risk areas. The low-risk areas included agricultural areas, wine farms, and national parks. A graphic depiction of the distribution of risk in relation to IDP for population density is provided in Figure 4.2 and Figure B1 in Appendix B. These findings are corroborated by literature. Govender et al. (2011:1) postulated that “problems of environmental pollution of living space and of domestic hygiene are almost always related to poverty and sanitation. The same study also found out that some of the occupants of informal settlements who participated in the study did not have adequate facilities for disposing of wastewater and sewage, in many

cases wastewater and untreated sewage was dispersed in their yards, thereby creating potential hazards in relation to illicit discharges into stormwater drainage systems.

There were several sources of uncertainty in this dataset. In the firstly instance, there were 32 block groups (polygons) whose population was zero. Consequently, when the population density was computed, the result was also zero. It could not be ascertained whether these blocks were unpopulated or the figure of zero represented an error in the dataset. A degree of uncertainty also stemmed from the conversion of the shapefile to a raster, as some of the block groups were smaller than the 30-metre pixels and some were larger. Resolution was lost around the edges of these block groups, as a 30-metre grid could easily have spanned several block groups, thereby creating the possibility that some block groups could have been absorbed into values from adjoining blocks, which could have resulted in over- or underestimations of IDP in affected polygons.

Table 4.2 Percentages of the study area with low, medium, or high IDP for each risk factor

No.	Risk Factor	Low	Medium	High
1	Population density	64.6	30.62	4.78
2	Development age (or age of stormwater infrastructure)	50.09	26.79	23.12
3	Outfall density	85.77	7.41	6.85
4	Ageing sanitary infrastructure	55.1	30.95	13.95
5	Drainage density	33.35	55.81	10.84
6	Generating site density	82.77	8.45	8.78
7	Infrastructure access density	65.77	19.99	14.24
8	On-site sanitation	96.3	1.78	1.92
9	Percentage impervious surface	56.29	12.13	31.58
10	Commercial land use	65.06	20.72	14.22
11	Residential land use	58.27	13.42	28.31
12	Industrial land use	73.85	11.16	14.99

4.1.2 Development age risk classification

The calibrated thresholds for medium and high-risk classifications were 20 and 40 years respectively (please see Table 4.1). A significant 23.12% of the study area was classified as being at high risk, while 26.79 % was classified as being at a medium risk, and 50.09% was classified as being at low risk (please see Table 4.2). Most of the areas that were classified as high-risk areas are densely populated areas (as can be seen in Figure B2 in appendix B), which are mainly comprised of older developments, which include the

Somerset West area, Firgrove and Macassar, Fish Hoek, Tokai, Westlake, Steenberg, Lakeside, Muizenberg, Claremont, Kenilworth, Rondebosch, Mowbray, Cape Town, Summer Greens, Edgemoed, Milnerton, Melkbosstrand, Parrow, Durbanville, Blue Downs, and Atlantis. As these developments inevitably have ageing infrastructure, they are at a high risk of burst and leaking pipes, which, in turn, result in discharges into stormwater systems. The medium-risk areas appear to be comprised mainly of developments that are not as old, whose infrastructure is still within its intended lifespan, although increased pressure on infrastructure increases the likelihood of pipe bursts. The areas included the Woodlands area in Mitchells Plain, Bergvliet, the lakes in Noordhoek, and some parts of Goodwood. The low-risk areas included newer developments, agricultural areas, wine farms, and national parks, where the infrastructure is either new or non-existent, in the case of some farms and open areas, such as parks and recreational areas. The sub-catchments in areas in which infrastructure was either relatively new or did not exist were classified as having low IDP. The distribution of risk classifications for development age with respect to IDP is depicted in Figure B2 in Appendix B.

The principal source of uncertainty was the large number of null infrastructure age attributes. The file contained a total of 195 762 attributes, of which 18 567 had been assigned null values in the age column. Although the planning dataset was used to populate the null values, it could not be ascertained with complete certainty that the data pertaining to infrastructure in the planning dataset was necessarily sufficiently accurate.

4.1.3 Outfall density risk classification

The calibrated thresholds for medium- and high-risk classifications were 5 and 30 respectively (please see Table 4.1). A relatively small 6.82% of the study area was classified as being at high risk, while 7.41 % was classified as being at a medium risk, and 85.77% area was classified as being at a low risk (please see Table 4.2). Most of the areas that were classified as being at high risk were sub-catchment areas through which most of the rivers in the study area flow, which are comprised mainly of older developments. The sub-catchments in which the Diep, Liesbeek, Elsieskraal, and Bottelary Rivers flow were classified as high-risk areas during the risk mapping process (as is depicted in Figure B3 in Appendix B) something conforming to the 2016 Diep River Estuarine Management Plan. These are problematic areas, as several cases of pollution and contamination have been reported to the City of Cape Town Metropolitan Municipality, whose cause has been attributed to the dumping of solid waste. These sub-catchments also contain large numbers of outfalls, which increases the likelihood of

illegal connections to the rivers. The distribution of IDP classifications for outfall density is depicted in Figure B.3 in Appendix B.

Uncertainty in the assessment of the outfall density risk factor stemmed from the availability of little or no data pertaining to open watercourses for some sub-catchments. As a direct consequence, it is likely that IDP with respect to outfall density was underestimated for most sub-catchments. The lack of metadata for this dataset inevitably casts doubt on its accuracy.

4.1.4 Ageing sanitary infrastructure risk classification

The calibrated thresholds for medium and high-risk classifications were 25 and 50 respectively (please see Table 4.1). A significant 13.95% of the study area was classified as being at high risk, while 30.95 % was classified as being at a medium risk, and 55.1% was classified as being at a low risk (please see Table 4.2). Most of the areas that were classified as high-risk areas (as is depicted in Figure B4 in Appendix B) are densely populated areas, which are comprised mainly of older developments. Consequently, their ageing infrastructure places them at a high risk of pipe bursts and leaks, which, in turn, result in discharges into stormwater systems. The areas include Somerset West, Cape Town, Fish Hoek, Mowbray, Rondebosch, Athlone, Milnerton, Du Noon, and the Parow Industrial Area (Swilling, 2006). Although the medium risk areas tend to be comprised of less old developments whose infrastructure is still within its intended lifespan, increased pressure on infrastructure increases the likelihood of pipe bursts. Informal settlements that were classified as low-risk areas were likely to have relatively recently installed sanitary infrastructure networks and included parts of Mitchells Plain, Grassy Park, and Da Gama Park. Other low-risk areas were newer developments, agricultural areas, wine farms, and national parks. The distribution of IDP classifications in relation to development age is depicted in Figure B4 in Appendix B.

Sub-catchments were used as the unit of analysis, as the sub-catchment was the smallest available hydrologic unit in the study area. Using sub-catchments could have contributed to a degree of inaccuracy, as they are not delineated by subsurface infrastructure and, consequently, did not completely represent drainage areas into which leaking sewage would be dispersed. Although some sub-catchments were assigned low age values and classified as having low IDP, this assessment might not necessarily be accurate in all cases. While these areas might have newer infrastructure than others, in many instances, significant population influxes could contribute to overpopulation in those areas and result in increased pressure on the infrastructure. The increased

susceptibility of sewer pipes to bursts would, in turn, result in increased illicit discharges into stormwater systems.

4.1.5 Drainage density risk classification

The calibrated thresholds for medium- and high-risk classifications were 7.5 and 15 respectively (please see Table 4.1). While 10.8% of the study area was classified as being at high risk owing to drainage density, 55.81% was classified as being at a medium risk, and 33.35% was classified as being at a low risk (please see Table 4.2). Most of the areas that were classified as high-risk areas (as is depicted in Figure B5 in Appendix B) were pockets of densely populated urbanised areas. As these developments are comprised of several built-up areas that generate large volumes of surface runoff, they have a great need for adequate drainage infrastructure. Although the areas that were classified as being at a medium risk are also fairly densely populated, as they are not as built-up and urbanised as the high-risk areas, they have significantly less need of extensive drainage infrastructure. The low-risk areas were agricultural areas, wine farms, and national parks. As these areas are the least built up and also do not require extensive drainage infrastructure. Although Somerset West was classified as a low-risk area, its profile was significantly different from that of other low-risk areas. It is possible that the data for this risk factor emanated from the area. The distribution of IDP classifications in relation to drainage density is depicted in Figure B5 in Appendix B.

A great deal of uncertainty was inherent in the assessment of this risk factor. The sub-catchments that were used were generally not delineated to include the effects of subsurface infrastructure on sub-catchment boundaries. In addition, sub-catchments that were small in size, as a result of either clipping or their actual sizes, often yielded densities that were significantly skewed, in that they were projected as having either higher or lower drainage densities than they had in reality. In some cases, no data pertaining to infrastructure in sub-catchments was included in the dataset. These sources of uncertainty were further compounded when the map was converted to raster format, which resulted in a loss of resolution around the sub-catchment boundaries.

4.1.6 Generating site density risk classification

The calibrated thresholds for medium- and high-risk classifications were 10 and 75 respectively (please see Table 4.1). While 8.7% of the study area was classified as being at high risk, 8.45 % classified as being at a medium risk, and 82.77% was classified as being at a low risk (refer to Table 4.2). Most of the areas that were classified as high-risk areas (as is depicted in Figure B6 in Appendix B) are industrial and commercial areas, for example, the industrial areas of Parow and the City of Cape International Airport,

which are particularly likely to generate illicit discharges into stormwater systems. The medium risk areas were fairly densely populated areas in which there are pockets of commercial or industrial activities, such as fast-food outlets and car wash facilities. The low-risk areas were low-density settlements, agricultural areas, wine farms, and national parks, in which there are few, if any, registered commercial or industrial activities. The distribution of IDP classifications in relation to generating site density is depicted in Figure B6 in Appendix B.

The uncertainty pertaining to this dataset stems from the age of the data, as the file was generated from the 2013/2014 national land cover dataset. As the data is outdated, it is logical to assume that at present there are more generating sites than there were in 2014. The conversion of the polygons to points could have resulted in underestimating IDP in particular areas, as it could be possible that an industrial area in which several industrial companies were located would have been captured under one polygon, which would have been eventually counted as only one generating site, whereas there could have been several generating sites, each of which might have had a different IDP associated with its activities. As generating sites such as medical facilities, cemeteries, educational campuses, and municipal facilities that handle solid waste (landfill sites) were excluded, inaccuracies in the assessment of IDP for the sub-catchments on which these generating sites were located were inevitable. Although this dataset was derived from the national land cover dataset that was provided by the City of Cape Town Metropolitan Municipality, some of the zoning categories that were classified as generating sites are highly questionable. Although some polygons whose zoning was classified as either public open spaces or rural areas were classified as generating sites, it seems incorrect to do so, as the relevant literature does not characterise these zoning categories as generating sites. Consequently, IDP was overestimated for some sub-catchments in relation to generating site density.

4.1.7 Infrastructure access density risk classification

The calibrated thresholds for medium and high-risk classifications were 4 and 12 respectively (please see Table 4.1). While a significant 14.24% of the study area was classified as being at high risk, 19.99 % was classified as being at a medium risk, and 65.77% was classified as being at a low risk (please see Table 4.2). Most of the areas that were classified as high-risk areas (as is depicted in Figure B7 in Appendix B) are pockets of densely populated urbanised areas. As the built-up areas in them generate large volumes of surface runoff, there is a great need for extensive drainage infrastructure. Although the medium-risk areas are also highly populated areas, it can be assumed that they are not as built up and urbanised as the high-risk areas and

accordingly require less extensive drainage infrastructure. The low-risk areas were agricultural areas, wine farms, and national parks. Once again, Somerset West was an exception, as it was classified as a low-risk area although it is a built-up area, which suggests that the data that was used did not emanate from the area. The distribution of IDP classifications in relation to drainage density is depicted in Figure B7 in Appendix B.

Uncertainty concerning this dataset stemmed from its age. As it was last verified in February 2017, it is highly likely that assessments of IDP for some sub-catchment areas were underestimations, owing to a lack of credible updated data. The kernel density function was used to determine the density of infrastructure access points and a smooth surface was generated to represent density values. The continuous surface was broken when the reclassify tool was used to classify the continuous density variable into a set of risk levels, which were used in the development of the final map. The overlay was made by converting the raster to a vector format, using the raster to polygon tool. These procedures could have had some effect on the final data layers that were used to carry out the risk analysis.

4.1.8 On-site sanitation risk classification

The calibrated thresholds for medium and high-risk classifications were 4 and 12 respectively (please see Table 4.1). Only 1.92% of the study area was classified as being at high risk, while 1.78 % was classified as being at a medium risk, and 96.3% was classified as being at a low risk (please see Table 4.2). Most of the areas that were classified as high-risk areas (as is depicted in Figure B8 in Appendix B) were pockets of informal settlements which lack water and sanitation. A few isolated pockets were classified as being at a medium risk. As almost all were located on the fringes of high-risk areas, it is likely that they were newer settlements that were forming in relatively close proximity to the established ones. None of the low-risk areas appeared to house informal settlements. The distribution of IDP classifications in relation to on-site sanitation is depicted in Figure B8 in Appendix B.

Once again, uncertainty concerning this dataset stemmed from its age, as it was last updated in 2017. As there would have been a significant further proliferation of informal settlements in Cape Town during the intervening period, it is highly probable that data pertaining to on-site sanitation in recent settlements was not included in the dataset and that levels of IDP were underestimated in those areas as a direct consequence. The kernel density function was used to determine the density of stormwater infrastructure access points, and a smooth surface was generated to represent density values. The continuous surface was broken when the reclassify tool was used to classify the

continuous density variable into a set of risk levels, which were used in the development of the final map. The overlay was made by converting the raster to a vector format, using the raster to polygon tool. These procedures could have had some effect on the final data layers that were used to carry out the risk analysis.

4.1.9 Percentage impervious surface risk classification

The calibrated thresholds for medium and high-risk classifications were 25000 and 50000 square metres respectively (please see Table 4.1). A highly significant 31.58% of the study area was classified as being at high risk, while 12.13 % was classified as being at a medium risk, and the remaining 56.29% was classified as being at a low risk as indicated on the results table. Most of the areas that were classified as high-risk areas (as is shown in Figure B9 in Appendix B) were built-up developed areas. Complexes, parking lots, tarred surfaces, and the rooftops of buildings are among the features that are classified as impervious surfaces. Bender (2016) explained that percentage of impervious surface is an accurate indicator of development and has a direct influence on watershed hydrology, as development results in the creation of additional potential surfaces for the accumulation and washing off of pollutants. Accordingly, the more developed an area is, the higher the risk of illicit discharges resulting from impervious surfaces, as these surfaces generate high volumes of runoff, which, in turn increase the risk of pollutants entering stormwater systems. The areas that were classified as being at a medium risk were areas in which moderate development had taken place, while all of the low-risk areas were located on the outskirts of the city boundaries, such as agricultural areas and natural parks, which were not built up or urbanised. The distribution of IDP classifications in relation to percentage impervious surface is depicted in Figure B9 in Appendix B.

The dataset was derived from the National Land Cover Database for 2013-2014, which covered the whole of South Africa and was released by the Department of Environmental Affairs. The age of the data in the dataset introduces a degree of uncertainty, as the intervening period between the publication of the data and the present time would inevitably have witnessed substantial new developments in the form of the establishment of new settlements and commercial and industrial sites and the construction of new complexes. Accordingly, using this dataset would inevitably result in underestimating the potential risk of illicit discharges from runoff from impervious surfaces in some sub-catchments.

4.1.10 Commercial land use risk classification

The calibrated thresholds for medium and high-risk classifications were 150000 and 750000 square metres respectively (please see Table 4.1). While 14.22% of the study area was classified as being at high risk, 20.72 % was classified as being at a medium risk, and 65.06% was classified as being at a low risk (please see Table 4.2). Most of the areas that were classified as high-risk areas (as is depicted in Figure B10 in Appendix B) are built-up developed areas and are the commercial hubs of the city of Cape Town. The more commercial activity in a sub-catchment, the greater is the likelihood of illicit discharges into stormwater systems. Areas such as restaurants, car wash facilities, and shopping centres generate a great deal of solid waste. If it is not disposed of correctly, its ultimate destination is likely to be a stormwater system. In addition, as these areas continuously attract large crowds, the risk of people disposing of solid waste in stormwater systems is substantially increased. By contrast, as the areas that were classified as being at a medium risk were characterised by moderate levels of development, the correspondingly moderate levels of commercial activity are likely to result in a reduced risk of illicit discharges. All of the low-risk areas were located on the outskirts of the city boundaries and were agricultural areas and natural parks, where there is a minimal risk of illicit discharges. The distribution of IDP classifications in relation to commercial land use is depicted in Figure B10 in Appendix B.

As the dataset was derived from the South African National Land Cover Database for 2013-2014, which was released by the Department of Environmental Affairs, the age of the data introduced a considerable degree of uncertainty, as many parts of the study area have undergone significant changes with respect to land use. Accordingly, using the dataset inevitably resulted in a significant underestimation of the potential risk that commercial land use posed in some sub-catchments.

4.1.11 Residential land use risk classification

The calibrated thresholds for medium and high-risk classifications were 3524737 and 7500000 square metres respectively (please see Table 4.1). A significant 28.31% of the study area was classified as being at high risk, while 13.42 % was classified as being at a medium risk, and 58.27% was classified as being at a low risk (please see Table 4.2). Most of the areas that were classified as high-risk areas (as is depicted in Figure B11 in Appendix B) are the residential areas within the study boundary. They include the wealthy and affluent suburbs of Constantia, Tokai, and Hout Bay and the townships of the Cape Flats, such as Khayelitsha and Gugulethu. Among the prominent causes of the high risk of illicit discharges from residential areas are illegal connections, waste from car wash facilities, the dumping of solid waste, maintenance to septic systems, and

swimming pool discharges. This is supported by Armitage et al. (2015:181) who stated that “*nearly all solid waste pollution in the river systems of South Africa is derived from urban areas*”. Residential areas also produce greywater, wastewater and water discharges through car wash facilities, laundry, inadequate sanitation facilities and burst water pipes. The areas that were classified as being at a medium risk tended to be areas that contained isolated pockets of settlements, while the low-risk areas are agricultural areas and natural parks in which there were no residents. The distribution of IDP classifications in relation to residential land use is depicted in Figure B11 in Appendix B.

As the dataset was derived from the South African National Land Cover Database for 2013-2014, which was released by the Department of Environmental Affairs, the age of the data introduced a considerable degree of uncertainty, as many parts of the study area have undergone significant changes with respect to land use. Accordingly, using the dataset inevitably resulted in a significant underestimation of the potential risk that residential land use posed in some sub-catchments.

4.1.12 Industrial land use risk classification

The calibrated thresholds for medium and high-risk classifications were 300000 and 750000 square metres respectively (please see Table 4.1). While 14.99% of the study area was classified as being at high risk, 11.16 % was classified as being at a medium risk, and 73.85% was classified as being at a low risk (please see Table 4.2). The areas that were classified as high-risk areas (as depicted in Figure B2 in Appendix B) were the industrial hubs within the study boundary. The great risk of illicit discharges into stormwater systems that they pose stems from the high volumes of waste that they generate. The greater the number of industries in an area, the greater is the likelihood of illegal connections to stormwater systems being made. Some residential areas were classified as medium-risk areas, as there was evidence to suggest that there were sites that were characterised by industrial activities in them. The low-risk areas appeared to be devoid of any form of human activity. The distribution of IDP classifications in relation to industrial land use is depicted in Figure B12 in Appendix B. Industrial land-use was identified as a source of waste products that are deposited into sewers, rivers and wetlands by Musingafi (2014).

As the dataset was derived from the South African National Land Cover Database for 2013-2014 which was released by the Department of Environmental Affairs, the age of the data introduced a considerable degree of uncertainty, as many parts of the study area have undergone significant changes with respect to land use. Accordingly, using

the dataset inevitably resulted in a significant underestimation of the potential risk that industrial land use posed in some sub-catchments.

4.2 Spatial analysis

After the risk factors had been generated and the spatial overlay had been completed, Table 4.3 was compiled in order to express the discharge capture rate for each risk factor overlay as a percentage. An expanded table of detailed capture rates is provided in Table C1 in Appendix C. In order to carry out the spatial overlay, it was necessary to obtain the past discharge complaints records for the period from June 2011 to June 2012 from the City of Cape Town Metropolitan Municipality. The results of the spatial overlay for each risk factor are presented in Figures C1 to C12 in Appendix C. The results revealed that many illicit discharges are associated with the percentage impervious surface and residential land use risk factors in all pathway groups. Figure 4.3 depicts the percentage impervious surface risk map with grey water discharges overlaid. A very high number of the past discharge complaints were captured (902 of 1124) by this risk factor. Urbanised areas provide a great many opportunities for illicit discharges of all pathway types into stormwater systems as a result of generating particularly high volumes of surface runoff. The findings above correlate to Benders' (2016) who found that for one part of his study area most illicit discharges were concentrated in regions of medium to high intensity of development. Development age and residential land use were the other risk factors that had high capture rates for wastewater discharges. Residential areas always pose high risks of generating wastewater discharges as a result of blocked or leaking sewer systems. Population density, ageing sanitary infrastructure, industrial land use, generating site density, and infrastructure access density had capture rates of from 25% to 36% for the wastewater pathway group (spatial maps for these risk factors are provided in Figure C1, Figure C4, Figure C12, Figure C6, and Figure C7 respectively in Appendix C). The low capture rates for areas with high population densities can be attributed to the inadequate wastewater services to which they have access. As most of the areas are built illegally and without having building plans approved by the City of Cape Town Metropolitan Municipality, inadequate service provision is an almost inevitable consequence. In addition, as most generating sites in commercial and industrial areas do not operate continuously throughout 24-hour cycles, the likelihood of wastewater-related problems is relatively low, which would account for the low capture rates. However, findings from Owusu-Asante (2019) indicated that areas of high population densities provide more opportunities for illicit connections and dumping of solid waste. The differences in the findings can be attributed to the size and location of the study areas used. Owusu-Asantes'(2019) study only focussed on two drainage

catchments within the study area of this current project, namely the Diep and Kuils catchment areas.

For the water pathway group, population density, residential land use, percentage impervious surface, and generating site density had the highest capture rates, at 49%, 45%, 44%, and 40% respectively. This correlates to the findings of Owusu-Asante (2017) who concluded that for the water pathway drainage density and population density had high capture rates. Population density and residential land use both contribute significantly to incidences of illicit discharges, in that areas that are inhabited by people create environments in which overburdened infrastructure is likely to result in burst and leaking pipes and flooding. High percentages of impervious surfaces are equally likely to increase incidences of illicit discharges still further, by conveying water that has been generated, as a consequence of overburdened infrastructure, into stormwater systems.

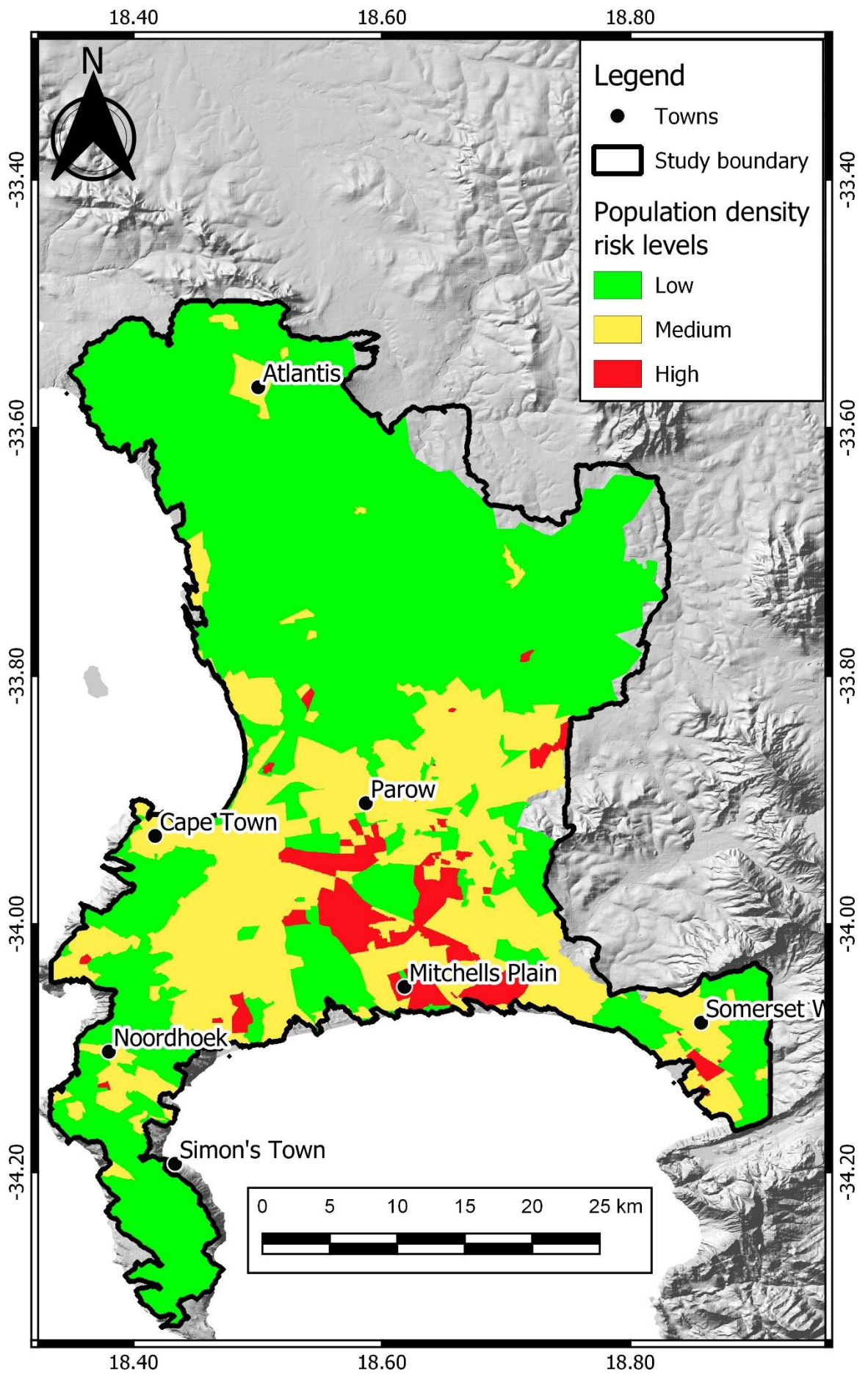


Figure 4.2: Population density risk map

Capture rates for on-site sanitation, commercial land use, and industrial land use, development age, ageing sanitary infrastructure, drainage density, and outfall density were very low, at from 4% to 39% (spatial maps for these risk factors are in Figure C8, Figure C10, Figure C12, Figure C2, Figure C4, Figure C5, and Figure C3 respectively in Appendix C). The finding that outfall density accounted for only 4% of the PDCRs for the water pathway could be attributed to incomplete coverage of the study area by water-related PDCRs. Recorded complaints emanated from sections of the study area only, as was also the case with PDCRs for solid waste (please see Figure 4.6). As a result, IDP was underestimated in areas that were not covered by the PDCRs, as no capture rates could be generated.

For the greywater pathway, percentage impervious surface and residential land use (spatial maps for these risk factors are depicted in Figures C9 and C11 respectively in Appendix C) generated very high capture rates for discharges. The built-up character of residential areas entails high percentages of impervious surface, although most discharges of greywater occur in these areas as a consequence of human activities. Several backyard activities, such as small-scale car wash facilities, result in the disposal of greywater in stormwater systems. Capture rates for population density, development age, generating site density, infrastructure access density, commercial land use, and industrial land use were moderate and ranged from 34% to 22%. Capture rates for outfall density, ageing sanitary infrastructure, infrastructure access density, and on-site sanitation were the lowest and ranged from 16% to 10%.

For the solid waste pathway, there were very high capture rates for percentage impervious surface and residential land use, which stood at 86% and 74% respectively. This finding stemmed from most cases of illegal dumping of solid waste, reports of failure to remove solid waste, and blockages as a result of solid waste having occurred in residential, commercial, or industrial areas. It was found from the attribute table of the solid waste PDCRs in GIS that only 285 of the 6313 recorded complaints were listed as not having emanated from residential areas. This is in contrast to Owusu-Asantes' (2019) study which showed land-use residential as having recorded low capture rates. The differences are as a result of the two catchments used as the study area by Owusu-Asante (2019) not covering the entire Cape Town area but just a portion of it, with the vast of the study area being farmland. Only the southern part of his study area was urbanized and as stated above, with only 285 records out of 6313 not emanating from residential areas, this automatically affected his capture rates. The influence of the built-up nature of residential areas on these findings was borne out by correlations in most, if not all, cases between residential land use and percentage impervious surface with

respect to the solid waste pathway. Capture rates for population density, development age, ageing sanitary infrastructure, generating site density, infrastructure access density, commercial land use, and industrial land use were moderate at from 37% to 24%. It is highly likely that the heavy fines that the city imposes on businesses in commercial and industrial areas for the illegal dumping of solid waste could be a contributory factor to these findings. Capture rates for outfall density, drainage density, and on-site sanitation were the lowest, at 5%, 9%, and 6% respectively. The on-site sanitation risk factor applied mainly to areas in which there were informal settlements. Although a great many severe problems concerning solid waste were evident, it was equally evident that they are seldom reported, as the culprits are inhabitants of informal settlements. While there were many outfalls in the sub-catchments within the study area, only outfalls within a 50-metre buffer zone in relation to watercourses were considered in the risk mapping in this study and the rest were disregarded. In addition, the watercourse layer that was used did not appear to pass through some catchments, which resulted in no outfalls being captured for those catchments during the buffering procedure, which ultimately affected the spatial analysis. As metadata was not provided for the watercourses file, the accuracy of the dataset is questionable.

Table 4.3: Discharge capture rates in the study area

RISK FACTORS	Percentage of group total captured by high risk factor overlay				
	PDCR: Wastewater	PDCR: Water	PDCR: Greywater	PDCR: Solid Waste	PDCR: All
Records in cluster	70120	1009	1124	6313	97419
Population density	33	49	29	24	29
Development age	46	17	34	37	44
Outfall density	11	4	10	5	11
Ageing sanitary infrastructure	36	14	16	26	32
Drainage density	14	7	12	9	14
Generating site density	25	40	22	24	24
Infrastructure access density	28	10	33	25	28
On-site sanitation	6	39	13	6	6
Percentage impervious surface	82	44	80	86	79
Commercial land use	35	21	23	30	33
Residential land use	68	45	75	74	67

RISK FACTORS	Percentage of group total captured by high risk factor overlay				
	PDCR: Wastewater	PDCR: Water	PDCR: Greywater	PDCR: Solid Waste	PDCR: All
Industrial land use	33	21	23	34	31

The chi-square test (with $\alpha=0.05$) was carried out to determine whether there was a significant difference in the ability of the risk factors to predict the occurrence of discharges in each pathway (Owusu-Asante, 2019). The chi-square test results are presented in Appendix D. For the water pathway, 18% of the chi-square test results were not statistically significant and these are highlighted in yellow (please see Table D1 in Appendix D). For the greywater pathway, 19% of the chi-square test results were not statistically significant and these are highlighted in yellow (please see Table D2 in Appendix D).

For the wastewater pathway, only one of the chi-square test results was not statistically significant and is highlighted in yellow (please see Table D2 in Appendix D). For the solid waste pathway, only two of the chi-square test results were not statistically significant and are highlighted in yellow (please see Table 4 in Appendix D). For the all/combined pathway, only two of the chi-square test results were not statistically significant and are highlighted in yellow (please see Table D5 in Appendix D).

4.3 Multi-criteria evaluation

The weights that were obtained from carrying out the AHP are summarised in Table 4.4. For the water pathway group, population density, generating site density, on-site sanitation, percentage impervious surface, and residential land use were the most dominant risk factors, each of which had a weight value greater than 0.1 (please refer to Table E1 in Appendix E for a detailed AHP matrix for the water pathway). The outfall density and drainage density risk factors had weight values of 0.022 and 0.024 respectively. It was determined from the results that for the water pathway, the population density, generating site density, on-site sanitation, percentage impervious surface, and residential land use risk factors were the most significant for predicting the overall IDP of sub-catchments in the study area. This correlates with Owusu-Asante (2019) who identified drainage density, population density, generating site density, land-use commercial and land-use industrial as being the most significant for predicting the overall IDP of the study area.

For the greywater pathway, the percentage impervious surface and residential land use risk factors were the most dominant and both had weight values greater than 0.2. Outfall density and drainage density were the least significant risk factors, with weight values of 0.021 and 0.022 respectively (please refer to Table E2 in Appendix E for a detailed AHP matrix for the greywater pathway). It was determined from the results that for the greywater pathway, percentage impervious surface and residential land use were the most significant risk factors for predicting the overall IDP of sub-catchments in the study area. For the wastewater pathway, residential land use, percentage impervious surface, and development age were the most dominant risk factors. The residential land use risk factor had a weight value of 0.209, the percentage impervious surface risk factor a value of 0.285, and the development age risk factor a value of 0.112 (please refer to Table E3 in Appendix E for a detailed AHP matrix for the waste water pathway). These risk factors are directly applicable to older developments that have ageing infrastructure that is susceptible to leaks and bursts. Increasing pressure on resources also increases the likelihood of bursts, while impervious surfaces facilitate the runoff of wastewater and discharging it into stormwater systems. For the solid waste and all pathways, the percentage impervious surface and residential land use risk factors were the most dominant and both had weight values above 0.2 (please refer to Tables E4 and E5 in appendix E for detailed AHP matrices for the solid waste and all/combined pathways respectively). In contrast, findings from Owusu-Asante (2019) indicated that drainage density and population density were the most significant risk factors for determining IDP for the solid waste and all pathways.

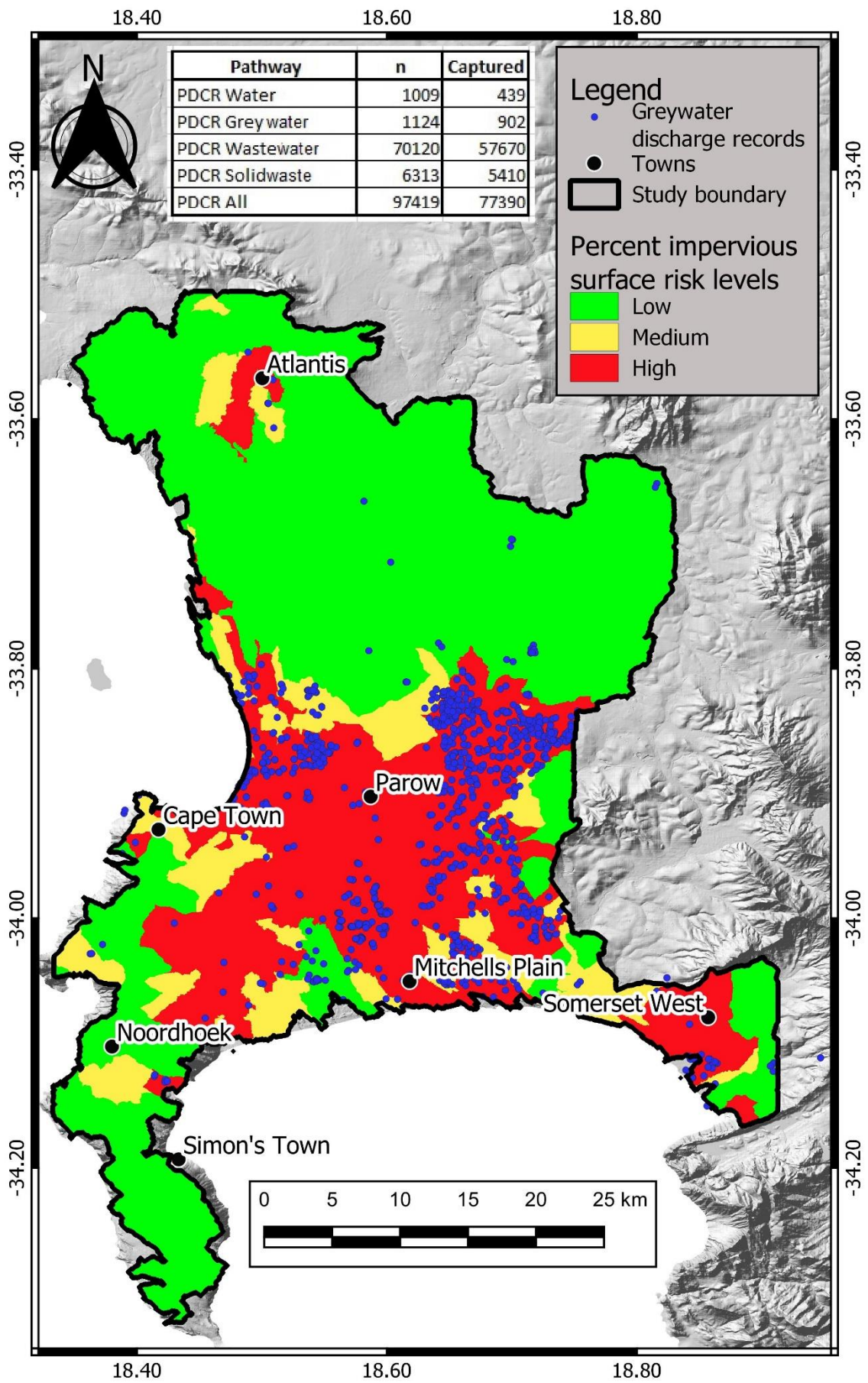


Figure 4.3: Example of a percentage impervious surface risk map with greywater discharge records

Table 4.4: AHP final weights

	Final weights (Water)	Final weights (Greywater)	Final weights (Wastewater)	Final weights (Solid waste)	Final weights (All)
Population density	0.187	0.065	0.056	0.043	0.055
Development age	0.039	0.077	0.112	0.092	0.108
Outfall density	0.022	0.021	0.021	0.018	0.020
Ageing sanitary infrastructure	0.034	0.027	0.077	0.047	0.051
Drainage density	0.024	0.022	0.026	0.019	0.037
Generating site density	0.122	0.042	0.039	0.043	0.039
Infrastructure access density	0.029	0.074	0.043	0.043	0.050
On-site sanitation	0.116	0.024	0.016	0.019	0.017
Percentage impervious surface	0.148	0.298	0.285	0.318	0.296
Commercial land use	0.056	0.045	0.058	0.064	0.061
Residential land use	0.168	0.250	0.209	0.224	0.211
Industrial land use	0.056	0.056	0.058	0.070	0.056

4.4 Production of composite maps

By using the weights in Table 4.4, all twelve of the risk factors were combined in the ArcGIS software to produce composite maps. As Owusu-Asante (2019:95) explains, “*the distribution of land area over the three risk levels in each composite map gives a numerical measure of qualitative sensitivity of the overall risk map to different weight schemes associated with the discharge pathway groups*”. Table 4.5 and the composite maps (in appendix F) indicate that the high-risk areas appear consistently across all of the pathways. To be more specific, 25% of the study area was mapped as an area with a high-risk of IDP for all of the five pathways. This area included all of the high-density settlements (Vrygrond, Steenberg, Retreat, Khayelitsha, Nyanga, Philippi, and Gugulethu), low-density settlements (Muizenberg, Lakeside, Tokai, Constantia, and Rondebosch), industrial areas (the airport area and Parow Industrial), and commercial areas in the study area.

As the results for all of the five pathways confirm, all developed or urbanised areas were classified as high-risk areas. The ‘all’ pathway had the highest percentage of high-risk area in the study area at 32.12%, in which 75.83% was urbanised (please see Figure 4.4 and Figure F5 in Appendix F). The solid waste pathway had the highest percentage area that was classified as being at low risk (52.17%) in the study area and only 5.26% of the area was urbanised (please see Figure F4 in appendix F). The water, wastewater,

and greywater pathways had high risk areas of 29.51%, 31.7%, and 31.06% respectively. The percentage of high-risk areas that is urbanised for the above-named pathways are 73.41%, 74.77% and 73.29% respectively (please see Figures F1, F2 and F3 respectively in Appendix F). A possible reason for the same areas being classified as high risk for all of the five pathways could be that the areas that have been classified as high risk resemble the high-risk areas in relation to both the percentage impervious surface and land-use residential risk factors. As these two risk factors had the highest weight value, it is possible that the two layers greatly influenced the outcome during the production of the composite maps by overshadowing the other risk factors.

Table 4.5 Percentages of high-risk areas per pathway for all composite maps

Risk category	Water	Wastewater	Solid waste	Greywater	All
Low	50.9 (3.61*)	50.92 (4.76*)	52.1 (5.26*)	51.27 (4.43*)	51.16 (4.52*)
Medium	19.59 (22.98*)	17.38 (20.47*)	17.42 (22.89*)	17.67 (22.26*)	16.72 (19.65*)
High	29.51 (69.42*)	31.7 (74.77*)	30.48 (71.85*)	31.06 (73.29*)	32.12 (75.83*)

(*) percentage over urbanised area only

In a similar study that Bender (2016) carried out, four different weight schemes were used in two catchments. The mapped high-risk area was approximately 27% of the total study area for all of the weight schemes that were used to produce the composite maps. The high-risk area varied from 26% to 39% in the second catchment. Owusu-Asante (2019) used the same five pathways as were used in the present study in the Diep and Kuils River catchments, which are located within the study area for this study, to arrive at a high-risk area of in the region of 12%.

4.5 Limitations of the research methods

The most significant limitation in the risk mapping stemmed from datasets that contributed to over- or underestimating the illegal discharge potential of areas. This limitation affected six of the nine datasets that were evaluated within sub-catchment areas, namely, development age, ageing sanitary infrastructure, percentage impervious surface, and commercial, residential, industrial land use. For the development age and ageing sanitary infrastructure risk factors, the average age of the existing infrastructure was used to categorise each entire sub-catchment as low-, medium-, or high risk with respect to IDP.

A complication that arose from using this approach stemmed from instances in which some infrastructure was old, but surrounded by newer infrastructure that had been developed during the construction of new developments. Averaging the ages of all of the infrastructure resulted in areas that contained both old settlements and newer

developments being classified as high-risk areas owing to the average age of the infrastructure of the entire sub-catchment under consideration. The converse was equally problematic, in that newer developments that were surrounded by older areas could potentially be classified as high-risk areas. The same limitation also applied to the percentage impervious surface and commercial, residential, and industrial land use risk factors. Categorising the sub-catchments on the basis of areas that were covered by particular categories of land use could have contributed over- or underestimating the IDP in some areas.

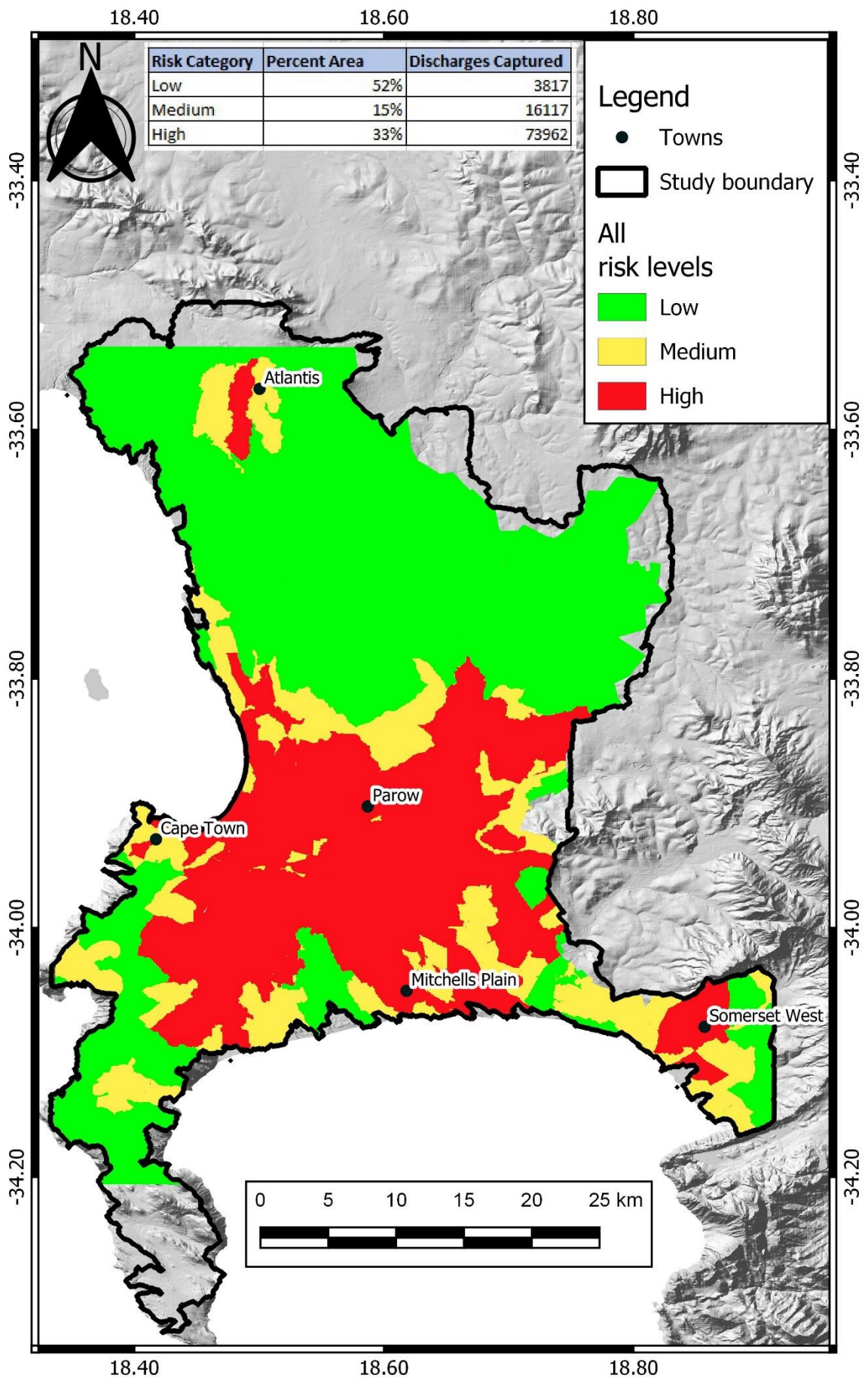


Figure 4.4: The All pathway composite risk map with captured records

Another limitation in the risk mapping stemmed from a great many uncertainties in the datasets. Uncertainty in the watercourse data stemmed from a lack of watercourse data for some sub-catchments, although this dataset was used to create a buffer and select all outfalls that fell within the buffer distance. As a result, the IDP of most sub-catchments would inevitably have been underestimated, as no outfalls were captured by the buffers of the watercourse layer for some sub-catchments. Using the sub-catchment as the unit of analysis for the ageing sanitary infrastructure risk factor resulted in a degree of inaccuracy, as the sub-catchments are not delineated by subsurface infrastructure and, consequently, did not completely represent drainage areas into which leaking sewage could disperse. Although some sub-catchments were assigned low age values and, accordingly, were classified as having low IDP, other factors could have contributed to far higher IDP. While the areas might have been characterised by newer infrastructure, significant population influxes could result in their becoming overpopulated, thereby increasing pressure on the infrastructure. The sewer pipes would then be susceptible to bursts, which, in turn, could result in illicit discharges into stormwater systems.

For the datasets that were derived from the National Land Cover Database for 2013/2014, the principal source of uncertainty was the age of the data. The affected datasets were those for the generating site density, percentage impervious surface, and the commercial, residential, and industrial land use risk factors. As the data is six years old, it can be safely assumed that it is outdated, as there have been numerous subsequent developments in the forms of new settlements being established and new commercial and industrial sites and new complexes being constructed. Consequently, using a dataset that had been derived from this data could contribute to significantly underestimating the potential risk that these risk factors pose in some sub-catchments. In addition, the data pertaining to the generating sites risk factor could have been affected by misclassification. Generating sites such as medical facilities, cemeteries, educational campuses, and municipal facilities that handle solid waste (landfill sites) were excluded and not regarded as generating sites, thereby contributing to potential inaccuracies in the assessments of IDP in the sub-catchments in which these generating sites are located. Conversely, some zoning categories that were classified as generating sites were highly questionable. Some polygons whose zoning was classified as either public open spaces or rural areas were classified as generating sites, which seems incorrect, as the relevant available literature does not characterise these zoning categories as generating sites. In these instances too, it would be possible to over- or underestimate IDP for some sub-catchments.

A degree of uncertainty was also introduced during the conversion of the shapefile to a raster. Some of the block groups were smaller than the 30-metre pixels for the raster, while others were larger. Resolution was lost around the edges of these block groups, as a 30-metre grid could easily have spanned several block groups, thereby creating the possibility that some block groups could have been absorbed into values from adjoining blocks. This limitation also could have contributed to over- or underestimated IDP in the affected polygons. For the point shapefiles it was necessary to use the kernel density function to convert the points to a raster. The continuous surface was broken when the reclassify tool was used to classify the continuous density variable into a set of risk levels, which were used for the final map. The overlay was made by converting the raster to a vector format by using the raster to polygon tool. These procedures could have affected the final data layers that were used to carry out the risk analysis. Clipping the data by using sub-catchments as the unit of analysis might have also distorted the data at the edges of the catchments. Nine datasets were clipped and evaluated over sub-catchments, namely, development age, outfall density, ageing sanitary infrastructure, drainage density, infrastructure access density, percentage impervious surface, and residential, commercial, and industrial land use.

4.5.1 Quality and age of the data

As several of the datasets that were used in the study lacked metadata, the data could be considered to be inadequate in several instances. In the assessment of the population density (which was based on the 2011 national census), the populations of 32 block groups (polygons) were captured as zero. Consequently, their computed population densities were also recorded as being zero. It could not be confirmed whether these polygons were not populated at the time of the conducting of the study or whether the zeros represented a capturing error. In addition, informal settlements have proliferated since 2011 and areas that were not classified as residential land use are now characterised by houses, complexes, and informal settlements. An informal settlement shapefile that was obtained among the data that had been requested from the City of Cape Town Metropolitan Municipality, during the conducting of the study, contained 640 informal settlements, almost double the 378 that the Housing Development Agency reported in 2013. Immigration and migration have also resulted in significantly increased population figures in some areas. The dataset for land use was derived from the National Land Cover Database for 2013-14 that was published by the Department of Environmental Affairs, which had subsequently become outdated in several instances. The data from the National Land Cover Dataset was used to derive five risk factors, namely, industrial, commercial, and residential land uses, generating site density, and percentage impervious surface, the datasets for all of which were affected by changes

in land use. Figures 4.5a and 4.5b provide an illustration of changed land use over time in Endlovini, an informal settlement that has mushroomed in Khayelitsha.

As the development age dataset had 18 567 null values in the age column, age values needed to be derived from a planning dataset. The accuracy of the planning dataset could not be ascertained, as metadata was unavailable. The past discharge complaints records were outdated, as they were based on records that covered 2011 and 2012 only. In addition, the discharge records that were supplied for the water and solid waste pathways covered only approximately two thirds of the study area, as is depicted in Figure 4.6. This limitation affected the weights of the risk factors, as the results of the spatial analysis were used as input for carrying out the AHP, which generated the final weights that were used for the composite maps. Risk factors that had low capture rates for the water and solid waste pathways could have had much higher capture rates had the PDCRs for the two pathways covered the entire study area.

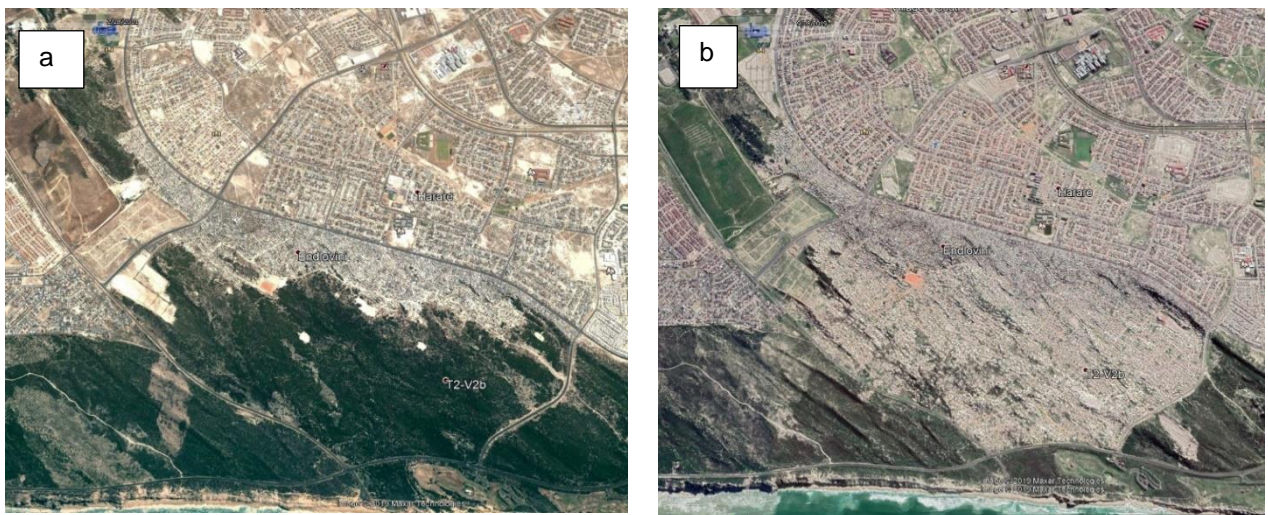


Figure 4.5 Land cover changes in Endlovini: (a) in 2011; (b) in 2019 (Google Earth)

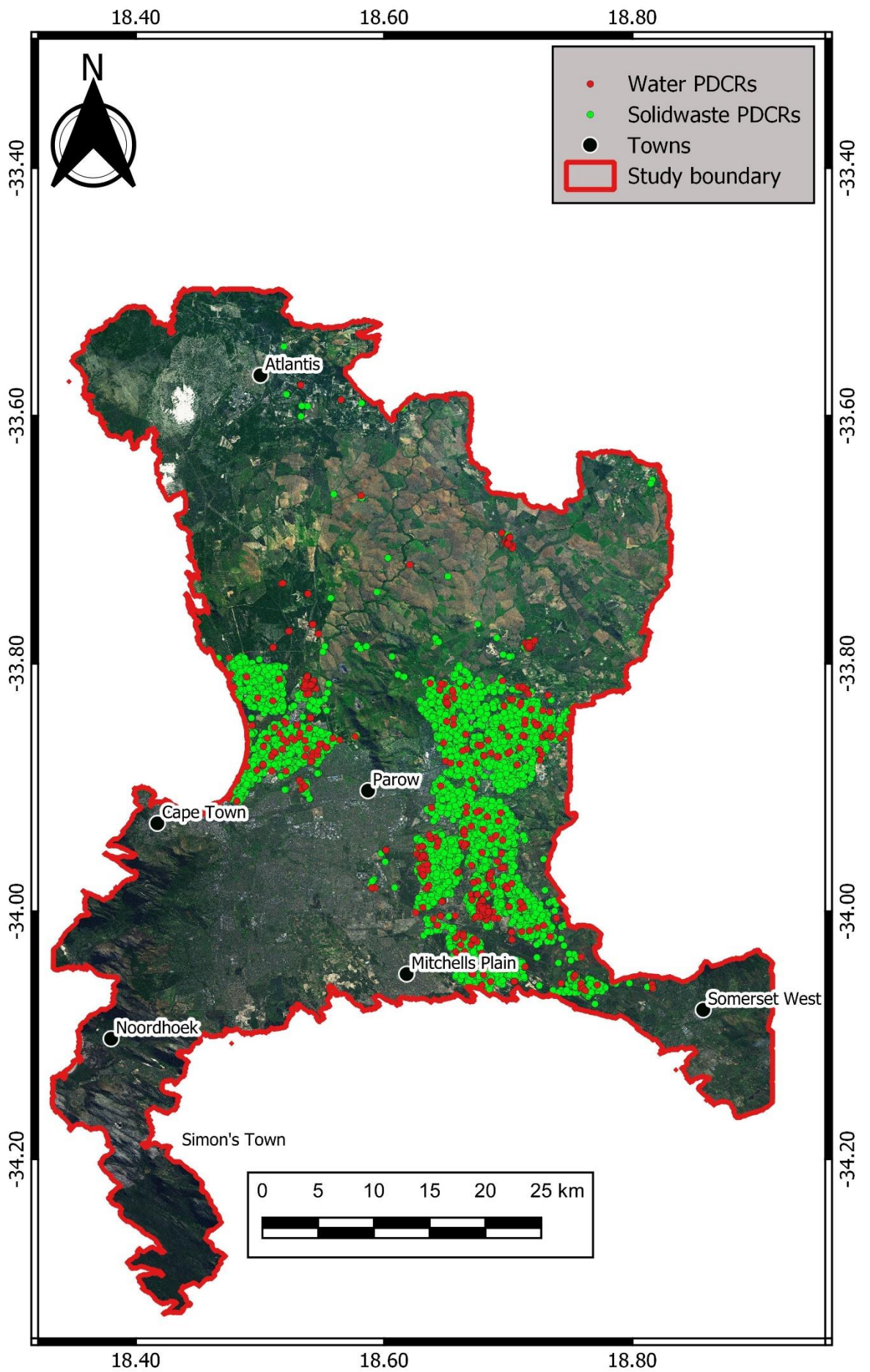


Figure 4.6: Areas covered by PCDRs for the water and solid waste pathways

4.6 Summary

The results of the classification of risk factors revealed that most of the areas that had been classified as having high IDP contained urbanised settlements. It emerged from the spatial analysis that the capture rates for the percentage impervious surface and residential land use were consistently high for all five pathways, while those for outfall density and on-site sanitation were low for all five pathways. The final weights revealed that population density, generating site density, on site sanitation, percentage impervious surface, and residential land use had weights greater than 0.1 for the water pathway, while only percentage impervious surface and residential land use had weights greater than 0.1 for greywater, with weight values of 0.295 and 0.250 respectively. For the wastewater pathway, the development age, percentage impervious surface, and residential land use risk factors had the highest weight values of 0.112, 0.285, and 0.209 respectively. For the solid waste pathway, the percentage impervious surface had the highest weight value of 0.315, which was followed by residential land use with a value of 0.224. For the all/combined pathway, development age had a weight value of 0.108, percentage impervious surface a value of 0.295, and residential a value of 0.211. The composite maps generated high-risk areas that ranged from 29.51% for the water pathway to 31.7% for the wastewater pathway. A significant 25% of the study area was consistently identified as being at high risk for all five pathways.

The results enabled the research question to be answered by demonstrating that urbanised areas are at a particularly high risk of illicit discharges into watercourses. In addition, they are also more prone to illegal connections and the dumping of solid waste than other areas. Most of the areas that were classified as having high IDP owing to population density are located in informal settlements in which the provision of basic sanitation services is inadequate. The finding that the percentage impervious surface and residential land use had very high capture rates for all five pathways confirmed that they were the most significant risk factors for identifying areas with high IDP.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

This chapter provides a summary of the principal findings of this study and also contains recommendations for future research in risk mapping to determine IDP. The conclusions that have been drawn from the findings are presented in the following section rest on the assumptions that the research problem has been adequately covered and the objectives of the study have been successfully achieved.

5.1 Conclusions

The objectives of this study were to identify areas of the urban sub-catchment that were at a high risk of illicit discharges into watercourses in the area of the City of Cape Town Metropolitan Municipality and to develop procedures for risk mapping to determine IDP. It can be seen in the composite maps that appear in Appendix F that urbanised areas are at a high risk of illicit discharges into watercourses. In addition, it is evident from the findings of this research study that many land use, hydraulic, and hydrologic characteristics influence the locations of illicit discharges (Owusu-Asante, 2019). Two risk factors, namely, residential land use and percentage impervious surface, have been found to be particularly significant for predicting the locations of illegal discharges. The spatial analysis yielded a ranking of the influence that individual risk factors exert, which indicated that the population density, development age, generating site density, and commercial and industrial land use factors were of the greatest significance for determining IDP in the study area. Accordingly, the City of Cape Town Metropolitan Municipality should prioritise analysing these risk factors, as many of the datasets are already in its database.

The risk mapping procedure that is explained in Appendix A provides a detailed desktop procedure which can be used to prioritise areas in which illicit discharges are most likely to occur in urban sub-catchments and also achieves the second objective of this study. The procedure is applicable to any study area and it is evident from the findings of the study that risk mapping represents a highly effective means for municipalities to structure the implementation of IDDE programmes (Owusu-Asante, 2019). The risk mapping procedure makes it possible for municipalities to follow a structured approach in order to determine priorities for facility inspections, public education, investigations of outfalls and drainage areas, and projects to improve infrastructure. In addition, it provides both local and district municipalities with opportunities to prioritise areas that have been identified as having the highest IDP for allocations of staff and resources. This strategy stands to reduce the costs of implanting programmes, while at the same time ensuring compliance with requirements pertaining to effluent discharge and ecological integrity.

As Bender (2016:50) explains, “a risk map made with high quality data will still only point to areas with discharge potential, meaning that it is more likely that discharges will occur in high-risk areas, but that discharges will likely still occur in areas with a very low perceived risk”. Conversely, Owusu-Asante (2019:96) maintains that “risk maps should not be used to eliminate regions for inspections or other control activities, but serve as a tool to focus or direct those activities towards larger high-risk areas to improve efficiency”.

In summary:

- The findings of this research study enabled the researcher to identify areas in the urban sub-catchment of the City of Cape Town Metropolitan Municipality that were at risk in relation to illicit discharges into stormwater systems. All of the areas that comprised 25% of the study area that were mapped as high-risk areas with respect to IDP were urbanised areas.
- This research study extended the remit of those that were conducted by Bender (2016) and Owusu-Asante (2019), in that
 - It used the MCE method instead of the professional judgement that Bender (2016) used, thereby reducing bias in the outcome.
 - It used the Jenks Natural Breaks Method to determine thresholds for risk classes.

5.2 Recommendations

While the findings of the study are promising, it is nonetheless recommended that its scope should be broadened in several respects. The findings of the study emerged from the use of twelve risk factors, namely, population density, development age, outfall density, ageing sanitary infrastructure, drainage density, generating site density, infrastructure access density, on-site sanitation, percentage impervious surface, and commercial, residential, and industrial land uses. Recommended additional risk factors are:

- Agricultural land use: A great deal of agricultural activity occurs within the study area, in locations such as the PHA area to the west of Mitchells Plain (please see Figure 2.5) and on small-scale farms to the north-east of Cape Town. Although the sub-catchments that were covered by this study were mainly urbanised areas, the areas in which agricultural activities occur were not taken into account. Agricultural land use should be included as a risk factor, as agriculture generates a great many contaminants in the form of fertilisers.
- Bender (2016) included dog licence density as a risk factor, which he defined as ‘the number of dogs per square kilometre’. It is a valid risk factor for

determining IDP owing to the high likelihood of the dog waste not being appropriately disposed of and posing a pollution risk to water bodies. There tend to be large numbers of stray dogs in informal settlements and it is highly unlikely that their waste is disposed of in a responsible manner. In some low-density suburbs such as Tokai, Muizenberg, and Durbanville it is customary to keep dogs as pets and in some high-density settlements they are kept to provide security. In areas such as the Cape Flats pit bulls are bred for illegal dog fighting. All categories of dogs contribute to high IDP through the improper disposal of or failure to dispose of their waste.

- Bender (2016) also used construction site density as a risk factor, which he defined as ‘the number of active construction sites per square kilometre’. Including this risk factor would also improve the accuracy of IDP mapping.
- It is also recommended that the effects of uncertainties on the results of risk mapping should be quantified and that the interactions of the risk factors that are used in risk mapping should be accounted for.

Improvements could also be made to the GIS risk mapping procedures that are used to analyse risk factors by including the effects of conditions in neighbouring sub-catchments. It is also recommended that up-to-date data should be used whenever it is possible to do so, in order to optimise the accuracy of assessments. In the production of composite maps in this study, the analytic hierarchy process was used to determine the relative weights of risk factors. As the AHP is one of several methods that is used in multi-criteria evaluation, it is recommended that other methods should be used in future studies, both to corroborate existing findings and also to evaluate the degree of accuracy that different methods permit.

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APPENDICES

APPENDIX A: RISK MAPPING PROCEDURE

Several spatial datasets were processed in the steps that follow to produce several risk maps. The datasets that were used were either in shapefile or raster format, while the output is in raster format only. All raster files were resampled to a resolution of 30 x30m pixels.

1. POPULATION DENSITY RISK FACTOR

- i. Input data is a polygon shapefile
(**Census2011_Population_Household_Density.shp**)
- ii. Add a field Pop_Density of type double
- iii. Open the attribute table and right click on the Pop_Density field. Choose calculate
"Pop_Density" = ("PLTN"*1000000)/"Shape_Area" to obtain the average population density (people/km²)
- iv. Symbolize by "Pop_Density" using Jenks Natural Breaks Method with 3 classes:
 - a. Class 1 (0- 80389.00872)
 - b. Class 2 (80389.00873 – 251477.639)
 - c. Class 3 (251477.639 – 871886.890601)
- v. Calibrate the breakdown classes by overlaying the past discharge records with the reclassified population density. The aim is to try to obtain a cluster of past discharge records in class 3. Edit the classes to:
 - a. Class 1 (0-25000)
 - b. Class 2 (25000 – 100000)
 - c. Class 3 (100000 – 871887)
- vi. Create a field Risk_index (and assign values 1-3) based on step v. with 1 being low risk, 2 medium risk, and 3 high risk
- vii. Overlay with past discharge records and calculate discharges captured
 - a. Using the population density shapefile, select high risk class (open attribute table>click on the dropdown icon top left>Select by attributes>Navigate to the Risk_Index column and double click on it>Double click on value 3 and click on apply)
 - b. Click on Selection in ArcMap Window >Select by location
 - i. Select features from choose past discharge complaints
 - ii. Source layer select PopulationDensity shapefile
 - iii. Spatial method select (all points completely within)
 - iv. Select apply

- v. Open past discharge complaints attribute table to count number of records captured
- viii. Convert result to raster using Risk_Index field (Conversion Tools.> To Raster > Polygon to Raster) based on "Risk_Index" field and save the file as **PopDensity.tif**.
- ix. Reclassify (Spatial Analyst > Reclass>Reclassify Tool) to ensure NoData values are mapped to zero and save the file as **PopDensity_Reclass.tif**.
- x. Copy Raster Tool (Data Management> Raster> Raster Dataset > Copy Raster) – convert risk-index raster to pixel type = 32_Bit_Float. This format enables raster calculator operations and save the file as **PopDensity_32Bit.tif**.
- xi. Clip Raster (Data Management > Raster > Raster Processing > Clip) to the geometric extents of the Jurisdictional Boundaries and save the output file as **1_PopDensity.tif**.

2. DEVELOPMENT AGE (STORMWATER INFRASTRUCTURE) RISK FACTOR

- i. Input data is a line shapefile (**swpipes_update_jul2005_spjn_water_sewer.shp**)
- ii. Created a new column Dev_Age
- iii. Calculate the age by using the calculate function (left(INFRSTAGEt,4))
- iv. This left 60568 blanks, which were populated using the AGE_INFRA column
- v. Using the select by attribute option (right click on attribute table>click on select by attribute>Use the Dev_Age column) and select all zeros and blanks. This will select all the lines that do not have an age assigned to them (18 567 records)
- vi. Click on the shapefile in the layer panel of ArcGIS and choose export
- vii. Navigate to the development age directory and save the file as **swpipes_blanks.shp**
- viii. Turn on the edit function in ArcGIS and repeat step iv above and delete all the selected lines. (NB these lines are being deleted as they will be fixed and merge together, hence the aim is to avoid having duplicate lines).
- ix. Add the **swpipes_blanks.shp** and the **swpipes plan.shp** to the display panel in ArcGIS
- x. Using **swpipes plan.shp** point file
 - a. Create the following buffers
 - i. 50m
 - ii. 100m
 - iii. 200m
 - b. Use select by location to select pipes within the above distances and assign age based on swpipes plan file. Click save when done.
- xi. Remove all layers from the panel and add **swpipes_blanks.shp** and **swpipes_update_jul2005_spjn_water_sewer.shp** .

- xii. Click the following (Geoprocessing>Merge) and select the add swpipes_blanks.shp and swpipes_update_jul2005_spjn_water_sewer.shp layers. Save the output as **swpipes_updated.shp**.
- xiii. Using the swpipes_updated.shp. Perform a spatial join (Analysis Tools>Overlay>Spatial join) and select **watersh_flow1_polyg.shp** as the target features and **swpipes_updated.shp** as Join features. This calculates the average age of the stormwater pipes in each sub catchment. Save the output as **DevelopmentAge_SubUnits.shp**.
- xiv. Symbolise the sub-catchments using the Jenks Natural Breaks Method (using Dev_Age) column
 - a. Class 1 (0-16)
 - b. Class 2 (16 - 55)
 - c. Class 3 (55- 113)
- xv. Calibrate the breakdown classes by overlaying the past discharge records with the reclassified development age. The aim is to try to obtain a cluster of past discharge records in class 3. Edit the classes toL
 - a. Class 1 (0-20)
 - b. Class 2 (20 – 40)
 - c. Class 3 (40 – 113)
- xvi. Create a field Risk_index (and assign values 1-3) based on step v. above with 1 being low risk, 2 being medium risk and 3 being high risk. Save the file as DevelopmentAge_RV.shp .
- xvii. Overlay with past discharge records and calculate discharges captured that fall unfrt high-risk areas
 - c. Using the development age shapefile, select high risk class (open attribute table>click on the dropdown icon top left>Select by attributes> Navigate to the Risk_Index column and double click on it> Double click on value 3 and click on apply)
 - d. Click on Selection in ArcMap Window>Select by Location
 - i. Select features from choose past discharge complaints
 - ii. Source layer select development age shapefile
 - iii. Spatial method select (all points completely within)
 - iv. Select apply
 - v. Open past discharge complaints attribute table to count number of records captured
- xviii. Convert to raster (Conversion Tools>To Raster >Polygon to Raster) based on “Risk_Index” field and save as Save the file as **DevelopmentAge_SubUnits.tif** .

- xix. Reclassify (Spatial Analyst >Reclass >Reclassify Tool) this raster to ensure NoData values are mapped to zero and save resulting file as **DevelopmentAge_Reclass.tif** .
- xx. Copy Raster Tool (Data Management >Raster> Raster Dataset > Copy Raster) – convert risk-index raster to pixel type = 32_Bit_Float. This format enables raster calculator operations and save the file as **DevelopmentAge_32Bit.tif**.
- xxi. Clip Raster (Data Management > Raster > Raster Processing > Clip) to the geometric extents of the study boundary and save the file as **2_DevelopmentAgeWGS84.tif** .

3. OUTFALL DENSITY RISK FACTOR

- i. Input data is a points shapefile (**Outfalls.shp**)
- ii. Display rivers covering the study area (**rivers.shp**) and the study area shapefile (**study_boundary.shp**)
- iii. Get the rivers line shapefile and clip to it using the study boundary file (Geoprocessing>Clip). Select **rivers.shp** as input features and **study_boundary.shp** as the clip features. On output features type **rivers_clipped.shp** and click on ok.
- iv. Display the clipped rivers and generate a 50m buffer around them (Geoprocessing>Buffer). Select **rivers_clipped.shp** as input, and put **rivers_50mBuffer.shp** as output. Make the linear unit under distance 50 metres and click on run.
- v. Display the buffered river file (**rivers_50mBuffer.shp**) and the outfalls file and run a clip process to only clip outfalls that fall within a 50m buffer of rivers (Geoprocessing>Clip). Select **Outfalls.shp** as input, **rivers_50mBuffer.shp** as the clip features. Name the output **outfalls_river_clip.shp**.
- vi. Perform a spatial join between the clipped outfalls and the sub-catchment areas (Analysis Tools>Overlay>Spatial join) and select **watersh_flow1_polyg.shp** as the target features and **outfalls_river_clip.shp** as Join features. This calculates the sum of all the outfall density points in each sub-catchment. Save the output as **OutfallDensity_SubUnits.shp**.
- vii. Symbolise with Jenks Natural Breaks Method, using the count field:
 - a. Class 1 (0-524)
 - b. Class 2 (25-106)
 - c. Class 3 (107-311)
- viii. Calibrate the breakdown classes by overlaying the past discharge records with the reclassified outfall density. The aim is to try to obtain a cluster of past discharge records in class 3. Edit the classes toL

- a. Class 1 (0-5)
 - b. Class 2 (6 – 30)
 - c. Class 3 (30 – 311)
- ix. Create a field Risk_index (and assign values 1-3) based on step viii. above with 1 being low risk, 2 medium risk, and 3 high risk and save as **OutfallDensity_RV.shp**.
- x. Overlay with past discharge records and calculate discharges captured that fall on high risk areas
 - a. Using the outfall density shapefile, select high risk class (open attribute table> click on the dropdown icon top left>Select by attributes> Navigate to the Risk_Index column and double click on it> Double click on value 3 and click on apply)
 - b. Click on Selection in ArcMap Window>Select by Location
 - i. Select features from choose past discharge complaints
 - ii. Source layer select outfall density shapefile
 - iii. Spatial method select (all points completely within)
 - iv. Select apply
 - v. Open past discharge complaints attribute table to count number of records captured
- xi. Convert to raster (Conversion Tools > To Raster > Polygon to Raster) based on “Risk_Index” field. Select **OutfallDensity_RV.shp** as input and set the output to **OutfallDensity_SubUnits.tif**
- xii. Reclassify (Spatial Analyst > Reclass > Reclassify Tool) this raster to ensure NoData values are mapped to zero. Use the **OutfallDensity_SubUnits.tif** as input and set the out to **OutfallDensity_Reclass.tif**
- xiii. Copy Raster Tool (Data Management > Raster > Raster Dataset > Copy Raster) – convert risk-index raster to pixel type = 32_Bit_Float. Use the **OutfallDensity_Reclass.tif** as input and set the output to **OutfallDensity_32BitFloat.tif**
- xiv. Clip Raster (Data Management > Raster > Raster Processing > Clip) to the geometric extents of the study boundary and name the output as **3_OutfallDensityWGS84_32Bit.tif**.

4. AGEING SANITARY INFRASTRUCTURE RISK FACTOR

- i. Input data is a line shapefile (**Stormwater_Sewer_Age.shp**).
- ii. Add field (Final_Age)
- iii. Calculate Age (2019-Year column)

- iv. Perform a spatial join between ageing sanitary infrastructure and the sub-catchment areas (Analysis Tools>Overlay>Spatial join) and select **watersh_flow1_polyg.shp** as the target features and **Stormwater_Sewer_Age.shp** as Join features. This calculates the average age of the sanitary infrastructure in each sub-catchment. Save the output as **AgeingSan_SubUnits.shp**
- v. Add column Risk_Index (based on age) and symbolize using Jenks (3 classes)
 - a. Class 1: 0- 15
 - b. Class 2: 16 – 37
 - c. Class 3: 38 – 99
- vi. Calibrate the breakdown classes by overlaying the past discharge records with the reclassified ageing sanitary density. The aim is to try to obtain a cluster of past discharge records in class 3. Edit the classes to:
 - a. Class 1: 0- 25
 - b. Class 2: 25 – 50
 - c. Class 3: 50 – 99
- iii. Create a field Risk_index (and assign values 1-3) based on step v. above with 1 being low risk, 2 medium risk, and 3 high risk and save the file as **AgeingSan_SubUnitsRV.shp**.
- vii. Overlay with past discharge records and calculate discharges captured that fall under high-risk areas
 - a. Using the ageing sanitary infrastructure shapefile, select high-risk class (open attribute table> click on the dropdown icon top left>Select by attributes> Navigate to the Risk_Index column and double click on it> Double click on value 3 and click on apply)
 - b. Click on Selection in ArcMap Window>Select by Location
 - i. Select features from choose past discharge complaints
 - ii. Source layer select ageing sanitary infrastructure shapefile
 - iii. Spatial method select (all points completely within)
 - iv. Select apply
 - v. Open past discharge complaints attribute table to count number of records captured
- viii. Convert to raster (Conversion Tools > To Raster > Polygon to Raster) based on “Risk_Index” field. Use **AgeingSan_SubUnitsRV.shp** as input and save the output as **AgeingSan_SubUnitsRV.tif**
- ix. Reclassify (Spatial Analyst > Reclass > Reclassify Tool) this raster to ensure NoData values are mapped to zero. Use the tif above as input and save the output as **AgeingSan_Reclass.tif**.

- x. Copy Raster Tool (Data Management > Raster > Raster Dataset > Copy Raster) – convert risk-index raster to pixel type = 32_Bit_Float. This format enables raster calculator operations. Use the raster above as input and save the output as **AgeingSan_32BitFloat.tif**.
- xi. Clip Raster (Data Management > Raster > Raster Processing > Clip) to the geometric extents of the study boundary. Save the output as **4_AgeingSanInfrastructureWGS84_32Bit.tif**.

5. DRAINAGE DENSITY RISK FACTOR

- i. Input data is a line shapefile (**Conduits.shp**)
- ii. Use the intersect tool to separate the lines which cross sub drainage catchments (Analysis>Tools>Overlay>Intersect).
- iii. Calculate the sum of conduits in each sub drainage catchment (Analysis Tools-Overlay-Spatial Join). Select the conduits and sub drainage units and save the output as **Conduits_Broken.shp**.
- iv. Perform a spatial join between the conduits and the sub-catchment areas (Analysis Tools>Overlay>Spatial join) and select **watersh_flow1_polyg.shp** as the target features and **Conduits_Broken.shp** as Join features. This calculates the average age of the sanitary infrastructure in each sub-catchment. Save the output as **Conduits_SubUnits.shp**
- v. Display the subunits from step iii above and add a field of type double called “Drainage_D”
- vi. Calculate values of this field by using the following formula $\text{Drainage_D} = \frac{\text{Shape_Leng} * 3281}{\text{Shape_Area}}$. This calculates the sum of conveyance kilometres in each sub catchment.
- vii. Add column Risk_Index and symbolise using Jenks (3 classes)
 - a. Class 1: 4.218703 – 12.343081
 - b. Class 2: 12.343081- 24.009863
 - c. Class 3: 24.009863 – 42.837624
- viii. Calibrate the breakdown classes by overlaying the past discharge records with the reclassified drainage density. The aim is to try to obtain a cluster of past discharge records in class 3. Edit the classes to:
 - a. Class 1: 4.218703 – 7.5
 - b. Class 2: 7.6 - 15
 - c. Class 3: 16 - 43
- ix. Create a field Risk_index (and assign values 1-3) based on step v. above, with 1 being low risk, 2 medium risk, and 3 high risk and save the file as **Conduits_RV.shp**.

- x. Overlay with past discharge records and calculate discharges captured that fall under high-risk areas
 - a. Using the drainage density shapefile, select high risk class (open attribute table>click on the dropdown icon top left>Select by attributes> Navigate to the Risk_Index column and double click on it> Double click on value 3 and click on apply)
 - b. Click on Selection in ArcMap Window>Select by Location
 - i. Select features from choose past discharge complaints
 - ii. Source layer select drainage density shapefile
 - iii. Spatial method select (all points completely within)
 - iv. Select apply
 - v. Open past discharge complaints attribute table to count number of records captured
- xi. Convert to raster (Conversion Tools >To Raster >Polygon to Raster) based on “Risk_Index” field. Select **Conduits_RV.shp** as input and save the raster as **Conduits_RV.tif**.
- xii. Reclassify (Spatial Analyst >Reclass>Reclassify Tool) this raster to ensure NoData values are mapped to zero. Use the raster from above as input and save the output as **Conduits_Reclass.tif**.
- xiii. Copy Raster Tool (Data Management > Raster > Raster Dataset >Copy Raster) – convert risk-index raster to pixel type = 32_Bit_Float. This format enables raster calculator operations. Use the reclassified raster as input and save the output as **Conduits_32BitFloat.shp**.
- xiv. Clip Raster (Data Management > Raster > Raster Processing >Clip) to the geometric extents of the study boundary and save the output as 5_DrainageDensity_32Bit.tif.

6. GENERATING SITE DENSITY RISK FACTOR

- i. Input data is a polygon shapefile (**Generating_Site_Density.shp**)
- ii. Convert the polygons to points using central coordinates and save the output as **CentroidsPoints.shp**.
- iii. Perform a spatial join between the centroid points and the sub catchment areas (Analysis Tools>Overlay>Spatial join) and select **watersh_flow1_polyg.shp** as the target features and **CentroidsPoints.shp** as Join features. This calculates the sum of the generating sites in each sub-catchment. Save the output as **GenSites_SubUnits.shp**
- iv. Symbolise using Jenks (3 classes):
 - a. Class 1: 0- 56

- b. Class 2: 57 - 195
 - c. Class 3: 196 -473
- v. Calibrate the breakdown classes by overlaying the past discharge records with the reclassified generating site density. The aim is to try to obtain a cluster of past discharge records in class 3. Edit the classes to:
 - a. Class 1: 0 - 10
 - b. Class 2: 11 - 75
 - c. Class 3: 76 - 473
- vi. Create a field Risk_index (and assign values 1-3) based on step v. above, with 1 being low risk, 2 medium risk, and 3 high risk and save the file as **GenSites_RV.shp**.
- vii. Overlay with past discharge records and calculate discharges captured that fall under high-risk areas
 - a. Using the drainage density shapefile, select high risk class (open attribute table> click on the dropdown icon top left>Select by attributes> Navigate to the Risk_Index column and double click on it> Double click on value 3 and click on apply)
 - b. Click on Selection in ArcMap Window>Select by Location
 - i. Select features from choose past discharge complaints
 - ii. Source layer select generating site density shapefile
 - iii. Spatial method select (all points completely within)
 - iv. Select apply
 - v. Open past discharge complaints attribute table to count number of records captured
- viii. Convert to raster (Conversion Tools >To Raster >Polygon to Raster) based on "Risk_Index" field. Use the shapefile **GenSites_RV.shp** as input and save the resulting raster as **GenSites_RV.tif**.
- ix. Reclassify (Spatial Analyst >Reclass > Reclassify Tool) this raster to ensure NoData values are mapped to zero. Use the raster from above and save the output as **GenSites_Reclassified.tif**.
- x. Copy Raster Tool (Data Management > Raster > Raster Dataset >Copy Raster) – convert risk-index raster to pixel type = 32_Bit_Float. This format enables raster calculator operations. Use the reclassified tiff as input and save the output as **GenSites_32BitFloat.tif**.
- xi. Clip Raster (Data Management > Raster > Raster Processing >Clip) to the geometric extents of the study boundary and save the output as **6_GeneratingSiteDensityWGS84_32Bit.tif**.

7. INFRASTRUCTURE ACCESS DENSITY RISK FACTOR

- i. Input data is a points shapefile (***Stormwater_Inlet-Outlet_derived_10feb17.shp***)
- ii. Create raster layer using the kernel density function (Spatial Analyst > Density > Kernel Density) and save the file as ***Kernel_InfraAccessDensity.tif***.
- iii. Run a vectorise conversion to convert the density tiff file to vector (Conversion Tools > From Raster > Raster To Polygon). Select the raster file from step ii as input and save the output as ***Kernel_InfraAccessDensity.shp***.
- iv. Symbolise using Jenks (3 classes):
 - a. Class 1: 0 – 4.966668791
 - b. Class 2: 4.966668792 – 16.8102636
 - c. Class 3: >16.8102636
- v. Calibrate the breakdown classes by overlaying the past discharge records with the reclassified infrastructure access density. The aim is to try to obtain a cluster of past discharge records in class 3. Edit the classes to:
 - a. Class 1: 0 - 4
 - b. Class 2: 4 - 12
 - c. Class 3: >12
- vi. Create a field Risk_index (and assign values 1-3) based on step v. above, with 1 being low risk, 2 medium risk, and 3 high risk and save the output as ***InfraAccessDensity_RV.shp***.
- vii. Overlay with past discharge records and calculate discharges captured that fall under high-risk areas
 - a. Using the drainage density shapefile, select high-risk class (open attribute table> click on the dropdown icon top left>Select by attributes> Navigate to the Risk_Index column and double click on it> Double click on value 3 and click on apply)
 - b. Click on Selection in ArcMap Window>Select by Location
 - i. Select features from choose past discharge complaints
 - ii. Source layer select infrastructure access density shapefile
 - iii. Spatial method select (all points completely within)
 - iv. Select apply
 - v. Open past discharge complaints attribute table to count number of records captured
- viii. Convert to raster (Conversion Tools >To Raster >Polygon to Raster) based on “Risk_Index” field. Use the shapefile ***InfraAccessDensity_RV.shp*** as input and save the resulting raster as ***InfraAccessDensity_RV.tif***.

- ix. Copy Raster Tool (Data Management > Raster > Raster Dataset >Copy Raster) – convert risk-index raster to pixel type = 32_Bit_Float. This format enables raster calculator operations.
- x. Clip Raster (Data Management >Raster > Raster Processing >Clip) to the geometric extents of the study boundary and save the output as **7_InfrastructureAccessDensityWGS84.tif**.

8. ON-SITE SANITATION RISK FACTOR

- i. Input file is a point shapefile (**Toilets_Merged_03102011_Proj.shp**)
- ii. Create raster layer using the kernel density function (Spatial Analyst >Density > Kernel Density) and save the output as **Kernel_OnSite.tif**
- iii. Run a vectorise conversion to convert the toilets file to vector (Conversion Tools > From Raster > Raster To Polygon). Select the raster file from step ii as input and save the output as **OnSiteSanitation.shp**.
- iv. Symbolise using Jenks (3 classes):
 - a. Class 1: 0 – 79.97322
 - b. Class 79.97323 – 297.500387
 - c. Class 3 > 297.500387
- v. Calibrate the breakdown classes by overlaying the past discharge records with the reclassified on-site sanitation. The aim is to try to obtain a cluster of past discharge records in class 3. Edit the classes to:
 - a. Class 1: 0 - 4
 - b. Class 2: 4 - 12
 - c. Class 3: >12
- vi. Create a field Risk_index (and assign values 1-3) based on step v. above with 1 being low risk, 2 medium risk, and 3 high risk and save the output as **OnSiteSanitation_RV.shp**.
- vii. Overlay with past discharge records and calculate discharges captured that fall under high-risk areas
 - a. Using the drainage density shapefile, select high risk class (open attribute table> click on the dropdown icon top left>Select by attributes> Navigate to the Risk_Index column and double click on it> Double click on value 3 and click on apply)
 - b. Click on Selection in ArcMap Window>Select by Location
 - i. Select features from choose past discharge complaints
 - ii. Source layer select toilets shapefile
 - iii. Spatial method select (all points completely within)

- iv. Select apply
- v. Open past discharge complaints attribute table to count number of records captured
- viii. Convert to raster (Conversion Tools >To Raster >Polygon to Raster) based on “Risk_Index” field. Use the shapefile ***OnSiteSanitation_RV.shp*** as input and save the resulting raster as ***OnSiteSanitation_RV.tif***.
- ix. Copy Raster Tool (Data Management > Raster > Raster Dataset >Copy Raster) – convert risk-index raster to pixel type = 32_Bit_Float. This format enables raster calculator operations and save the output as ***OnSiteSanitation_32BitFloat.shp***.
- x. Clip Raster (Data Management >Raster > Raster Processing >Clip) to the geometric extents the study boundary and save the output as ***8_OnSiteSanitationWGS4.tif***.

9. PERCENTAGE IMPERVIOUS SURFACE RISK FACTOR

- i. Input data is a polygon file containing impervious area (***Percent_Impervious.shp***)
- ii. Perform a spatial join between the centroid points and the sub catchment areas (Analysis Tools>Overlay>Spatial join) and select ***watersh_flow1_polyg.shp*** as the target features and ***Percent_Impervious.shp*** as Join features. This calculates the sum of the generating sites in each sub catchment. Save the output as ***PercentImpervious_SubUnits.shp***
- iii. Symbolise using the Jenks Natural Breaks Method using 3 classes of area:
 - a. Class 1: 0 – 402401.831027
 - b. Class 2: 402401.831028 - 3081766.1033
 - c. Class 3 > 3081766.1033
- iv. Calibrate the breakdown classes by overlaying the past discharge records with the reclassified on-site sanitation. The aim is to try to obtain a cluster of past discharge records in class 3. Edit the classes to:
 - a. Class 1: 0 - 25000
 - b. Class 2: 25000 - 50000
 - c. Class 3: >50000
- v. Create a field Risk_index (and assign values 1-3) based on step v above with 1 being low risk, 2 being medium risk and 3 being high risk and save the output as ***PercentImpervious_RV.shp***.
- vi. Overlay with past discharge records and calculate discharges captured that fall under high-risk areas
 - a. Using the drainage density shapefile, select high risk class (open attribute table> click on the dropdown icon top left>Select by attributes> Navigate to

- the Risk_Index column and double click on it> Double click on value 3 and click on apply)
- b. Click on Selection in ArcMap Window>Select by Location
 - i. Select features from choose past discharge complaints
 - ii. Source layer select percent impervious shapefile
 - iii. Spatial method select (all points completely within)
 - iv. Select apply
 - v. Open past discharge complaints attribute table to count number of records captured
 - vii. Convert to raster (Conversion Tools >To Raster >Polygon to Raster) based on "Risk_Index" field. Use the shapefile **PercentImpervious_RV.shp** as input and save the resulting raster as **PercentImpervious_RV.tif**.
 - viii. Reclassify (Spatial Analyst > Reclass > Reclassify Tool) this raster to ensure NoData values are mapped to zero and save the output as **PercentImpervious_Reclassified.tif**.
 - ix. Copy Raster Tool (Data Management > Raster > Raster Dataset > Copy Raster) – convert risk-index raster to pixel type = 32_Bit_Float. This format enables raster calculator operations and save the output as **PercentImpervious_32BitFloat.tif**.
 - x. Clip Raster (Data Management > Raster > Raster Processing > Clip) to the geometric extents of the study boundary and save the file as **9_PercentImpervious.tif**.

10. COMMERCIAL LAND USE RISK FACTOR

- i. Input data is a raster file Land cover 2013-2014 (**NLC2013-2014.tif**)
- ii. 72 classes reclassified into 6 classes using the following script in QGIS
 - 10- thru 34 = 6
 - 35-39 = 3
 - 42 = 1
 - 43 = 3
 - 44 thru-51 = 2
 - 52 = 5
 - 53 thru-56 = 6
 - 57 thru-60 = 4
 - 61 thru-72 = 2

Where

class 1 is commercial

class 2 is residential

- class 3 is industrial
 - class 4 is recreational/open space
 - class 5 is institutional
 - class 6 is agricultural
- iii. Assigned the following risk values to the raster layer
 - a. Class 1 – 3, class 2 – 3, class 3 – 3, class 4 – 2, class 5 – 2, class 6 – 1
 - iv. Convert to shapefile (Conversion Tools >From Raster >Raster to Polygon)
 - v. Select class 1 by attribute and export the highlighted polygons only (Commercial only) and save as **LU_Commercial.shp**
 - vi. Display the shapefile from above and open the attribute table. Add a column, area (type double) and calculate area of each commercial pocket
 - vii. Perform a spatial join between the centroid points and the sub catchment areas (Analysis Tools>Overlay>Spatial join) and select **watersh_flow1_polyg.shp** as the target features and **LU_Commercial.shp** as Join features. This calculates the sum of the generating sites in each sub catchment. Save the output as **LU_Commercial_SubUnits.shp**
 - viii. Symbolise the shapefile using the Jenks Natural Breaks Method:
 - a. Class 1: 0 – 392704.511599
 - b. Class 2: 392704.5116 – 1659438.34594
 - c. Class 3 > 1659438.345941
 - ix. Calibrate the breakdown classes by overlaying the past discharge records. The aim is to obtain a cluster of past discharge records in class 3. Edit the classes to:
 - a. Class 1: 0 – 150000
 - b. Class 2: 150000 - 750000
 - c. Class 3: > 750000
 - x. Create a field Risk_index (and assign values 1-3) based on step v above with 1 being low risk, 2 being medium risk and 3 being high risk and save the file as **LU_Commercial_RV.shp**
 - xi. Overlay with past discharge records and calculate discharges captured that fall under high-risk areas
 - a. Using the drainage density shapefile, select high risk class (open attribute table> click on the dropdown icon top left>Select by attributes> Navigate to the Risk_Index column and double click on it> Double click on value 3 and click on apply)
 - b. Click on Selection in ArcMap Window>Select by Location
 - i. Select features from choose past discharge complaints
 - ii. Source layer select landuse shapefile

- iii. Spatial method select (all points completely within)
 - iv. Select apply
 - v. Open Past discharge complaints attribute table to count number of records captured
- xii. Convert to raster (Conversion Tools >To Raster >Polygon to Raster) based on "Risk_Index" field. Use the shapefile **LU_Commercial_RV.shp** as input and save the resulting raster as **LU_Commercial_RV.tif**.
- xiii. Copy Raster Tool (Data Management > Raster > Raster Dataset >Copy Raster) – convert risk-index raster to pixel type = 32_Bit_Float. This format enables raster calculator operations and save the file as **LU_Commercial_32BitFloat.tif**.
- xiv. Reclassify (Spatial Analyst > Reclass > Reclassify Tool) to ensure NoData values are mapped to zero and save the file as **10_Commercial_Final.tif**.

11. RESIDENTIAL LAND USE RISK FACTOR

- i. Input data is a raster file Land cover 2013-2014 (**NLC2013-2014.tif**)
- ii. 72 classes reclassified into 6 classes using the following script in QGIS:
 - 10 thru-34 = 6
 - 35 thru-39 = 3
 - 42 = 1
 - 43 = 3
 - 44 thru-51 = 2
 - 52 = 5
 - 53 thru-56 = 6
 - 57 thru-60 = 4
 - 61 thru-72 = 2

Where

- class 1 is commercial
- class 2 is residential
- class 3 is industrial
- class 4 is recreational/open space
- class 5 is institutional
- class 6 is agricultural

- iii. Assign the following classes to the raster layer
 - a. Class 1 – 3, class 2 – 3, class 3 – 3, class 4 – 2, class 5 – 2, class 6 – 1
- iv. Convert to shapefile (Conversion Tools >From Raster >Raster to Polygon)
- v. Select class 2 by attribute and export the highlighted polygons only (Residential only) and save as **LU_Residential.shp**

- vi. Display the shapefile from above and open the attribute table. Add a column, area (type double) and calculate area of each commercial pocket
- vii. Perform a spatial join between the centroid points and the sub-catchment areas (Analysis Tools>Overlay>Spatial join) and select **watersh_flow1_polyg.shp** as the target features and **LU_Residential.shp** as Join features. This calculates the sum of the generating sites in each sub catchment. Save the output as **LU_Residential_SubUnits.shp**
- viii. Symbolise the shapefile using the Jenks Natural Breaks Method:
 - a. Class 1: 0 – 1659438.34594
 - b. Class 2: 1659438.34595– 2176275.77836
 - c. Class 3 > 2176275.77837
- ix. Calibrate the breakdown classes by overlaying the past discharge records. The aim is to obtain a cluster of past discharge records in class 3. Edit the classes to:
 - a. Class 1: 0 – 3524737
 - b. Class 2: 3524738 - 750000
 - c. Class 3: > 750000
- x. Create a field Risk_index (and assign values 1-3) based on step v. above, with 1 being low risk, 2 medium risk, and 3 high risk and save the file as **LU_Residential_RV.shp**
- xi. Overlay with past discharge records and calculate discharges captured that fall under high-risk areas
 - a. Using the drainage density shapefile, select high risk class (open attribute table> click on the dropdown icon top left>Select by attributes> Navigate to the Risk_Index column and double click on it> Double click on value 3 and click on apply)
 - b. Click on Selection in ArcMap Window>Select by Location
 - i. Select features from choose past discharge complaints
 - ii. Source layer select landuse shapefile
 - iii. Spatial method select (all points completely within)
 - iv. Select apply
 - v. Open past discharge complaints attribute table to count number of records captured
- xii. Convert to raster (Conversion Tools >To Raster >Polygon to Raster) based on “Risk_Index” field. Use the shapefile **LU_Residential_RV.shp** as input and save the resulting raster as **LU_Residential_RV.tif**.

- xiii. Copy Raster Tool (Data Management > Raster > Raster Dataset > Copy Raster) – convert risk-index raster to pixel type = 32_Bit_Float. This format enables raster calculator operations and save the file as ***LU_Residential_32BitFloat.tif***.
- xiv. Reclassify (Spatial Analyst > Reclass > Reclassify Tool) to ensure NoData values are mapped to zero and save the file as ***11_Residential_Final.tif***.

12. INDUSTRIAL LAND USE RISK FACTOR

- i. Input data is a raster file Land cover 2013-2014
- ii. 72 classes reclassified into 6 classes using the following script in QGIS:
 - 10 thru-34 = 6
 - 35 thru -39 = 3
 - 42 = 1
 - 43 = 3
 - 44 thru-51 = 2
 - 52 = 5
 - 53 thru -56 = 6
 - 57 thru -60 = 4
 - 61 thru-72 = 2

Where

 - class 1 is commercial
 - class 2 is residential
 - class 3 is industrial
 - class 4 is recreational/open space
 - class 5 is institutional
 - class 6 is agricultural
- iii. Classes then assigned the following risk values
 - a. Class 1 – 3, class 2 – 3, class 3 – 3, class 4 – 2, class 5 – 2, class 6 – 1
- iv. Convert to shapefile (Conversion Tools > From Raster > Raster to Polygon)
- v. Select class 3 by attribute and export the highlighted polygons only (Industrial only) and save as ***LU_Industrial.shp***
- vi. Display the shapefile from above and open the attribute table. Add a column, area (type double) and calculate area of each commercial pocket
- vii. Perform a spatial join between the centroid points and the sub catchment areas (Analysis Tools > Overlay > Spatial join) and select ***watersh_flow1_polyg.shp*** as the target features and ***LU_Industrial.shp*** as Join features. This calculates the sum of the generating sites in each sub catchment. Save the output as ***LU_Industrial_SubUnits.shp***

- viii. Symbolise the shapefile using the Jenks Natural Breaks method:
 - a. Class 1: 0 – 669876.978522
 - b. Class 2: 669876.978523 – 2616676.54119
 - c. Class 3 > 2616676.54119
- ix. Calibrate the breakdown classes by overlaying the past discharge records. The aim is to obtain a cluster of past discharge records in class 3. Edit the classes toL
 - a. Class 1: 0 – 300000
 - b. Class 2: 300000 - 750000
 - c. Class 3: > 750000
- x. Create a field Risk_index (and assign values 1-3) based on step v. above, with 1 being low risk, 2 medium risk, and 3 high risk and save the file as ***LU_Industrial_RV.shp***
- xi. Overlay with past discharge records and calculate discharges captured that fall on high risk areas
 - a. Using the drainage density shapefile, select high risk class (open attribute table> click on the dropdown icon top left>Select by attributes> Navigate to the Risk_Index column and double click on it> Double click on value 3 and click on apply)
 - b. Click on Selection in ArcMap Window>Select by Location
 - i. Select features from choose past discharge complaints
 - ii. Source layer select landuse shapefile
 - iii. Spatial method select (all points completely within)
 - iv. Select apply
 - v. Open Past discharge complaints attribute table to count number of records captured
- xii. Convert to raster (Conversion Tools >To Raster >Polygon to Raster) based on “Risk_Index” field. Use the shapefile ***LU_Industrial_RV.shp*** as input and save the resulting raster as ***LU_Industrial_RV.tif***.
- xiii. Copy Raster Tool (Data Management > Raster > Raster Dataset >Copy Raster) – convert risk-index raster to pixel type = 32_Bit_Float. This format enables raster calculator operations and save the file as ***LU_Industrial_32BitFloat.tif***.
- xiv. Reclassify (Spatial Analyst > Reclass > Reclassify Tool) to ensure NoData values are mapped to zero and save the file as ***12_Industrial_Final.tif***.

APPENDIX B: RISK MAPPING RESULTS

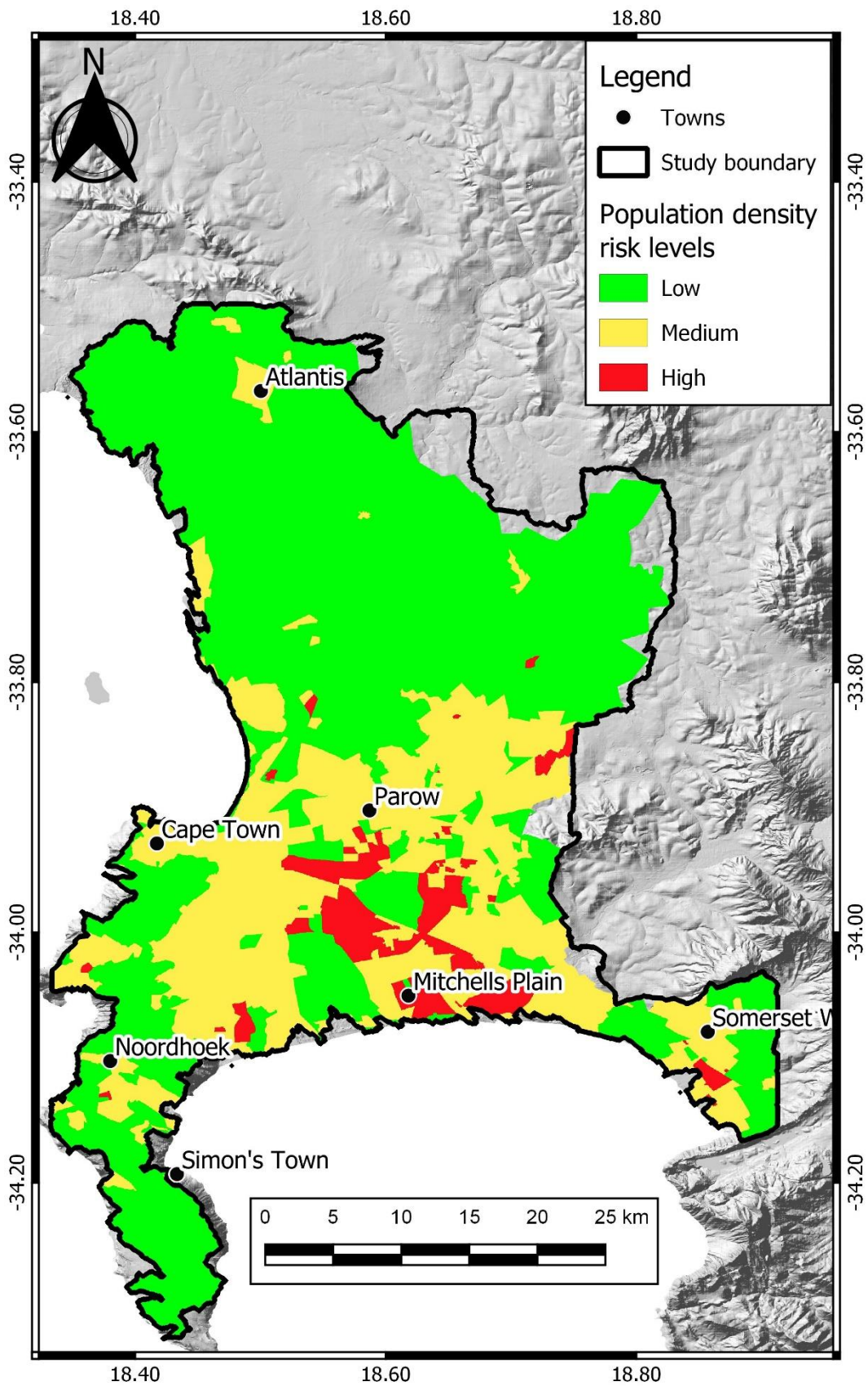


Figure B1: Population density risk map

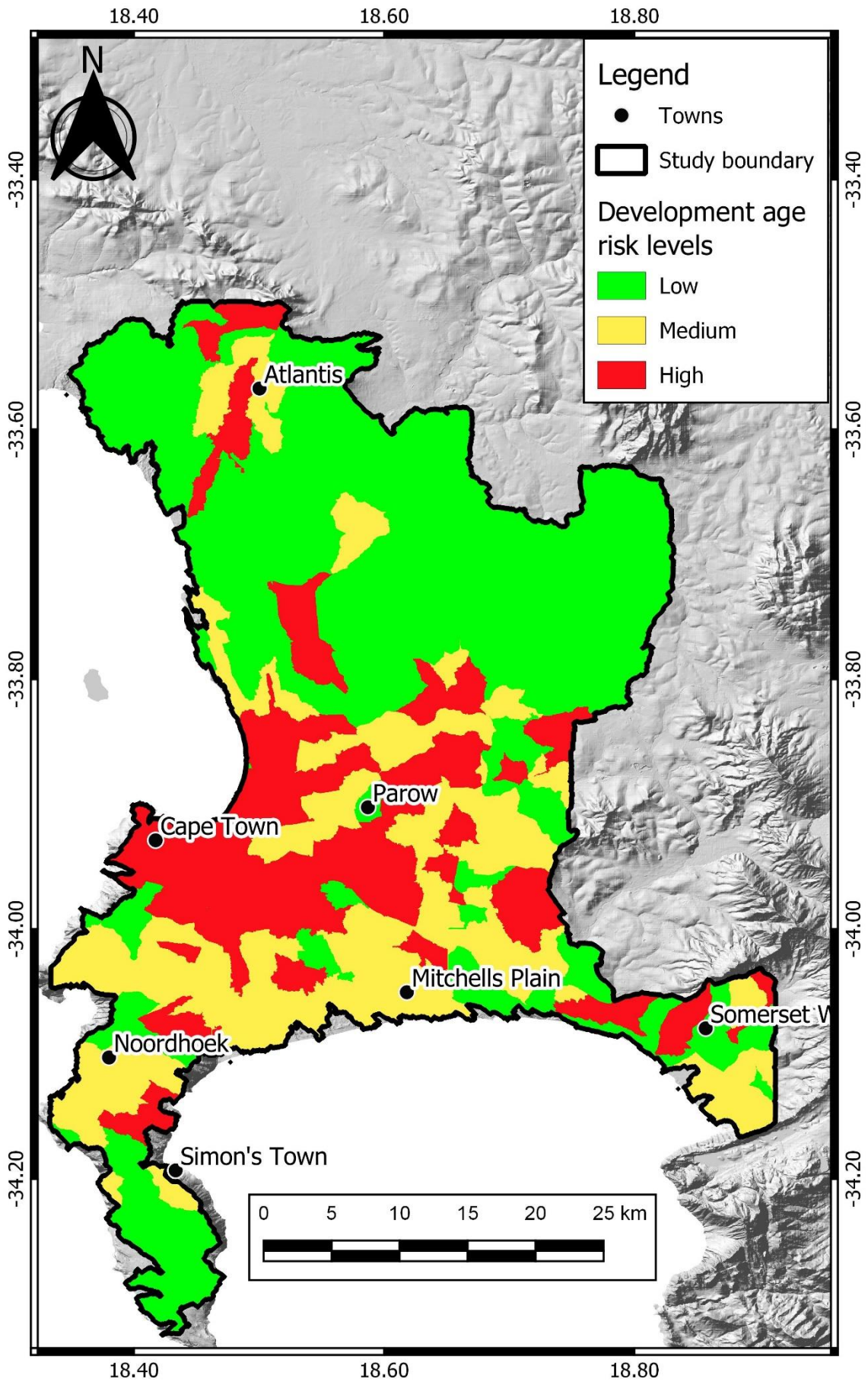


Figure B2: Development age risk map

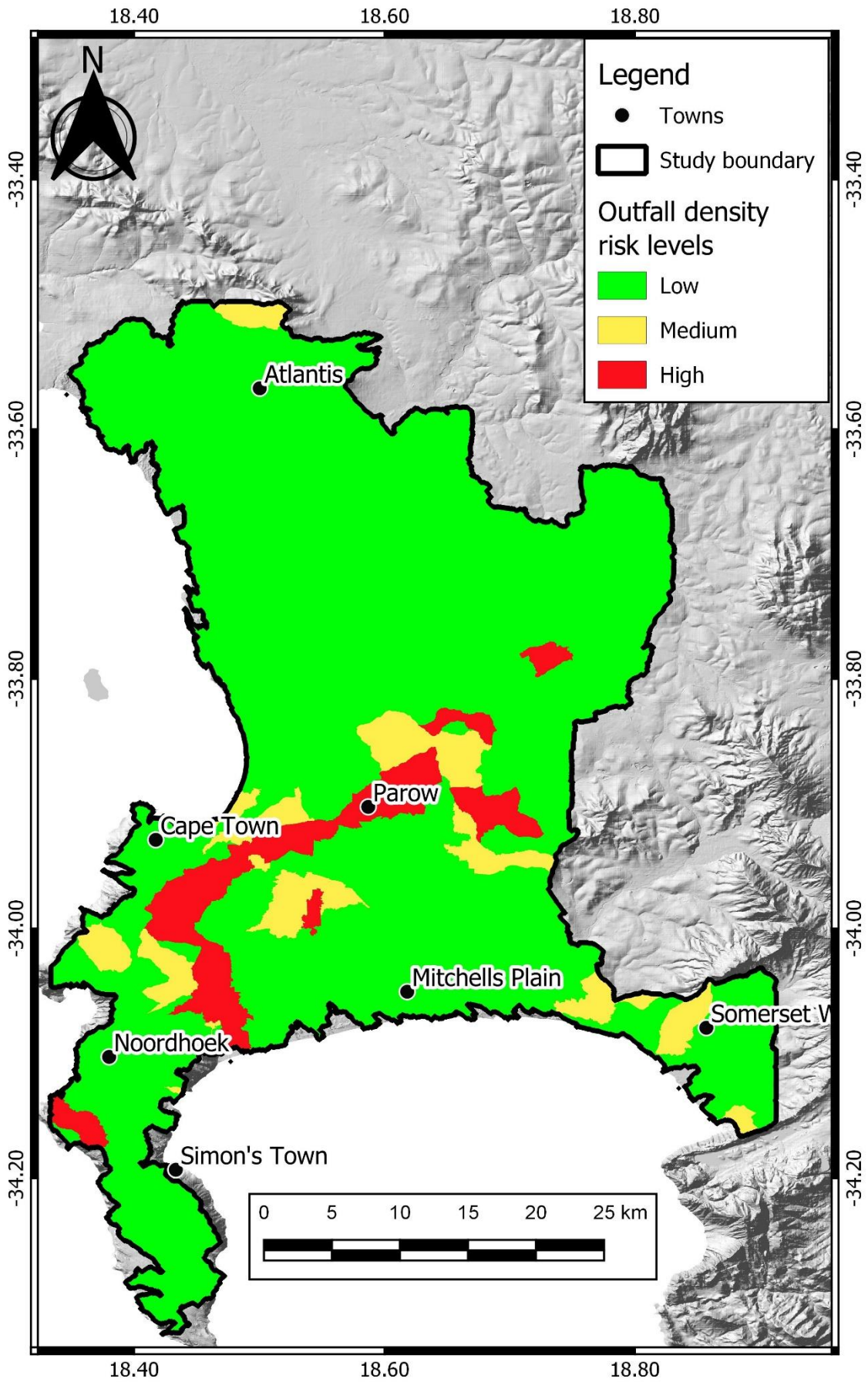


Figure B3: Outfall density risk map

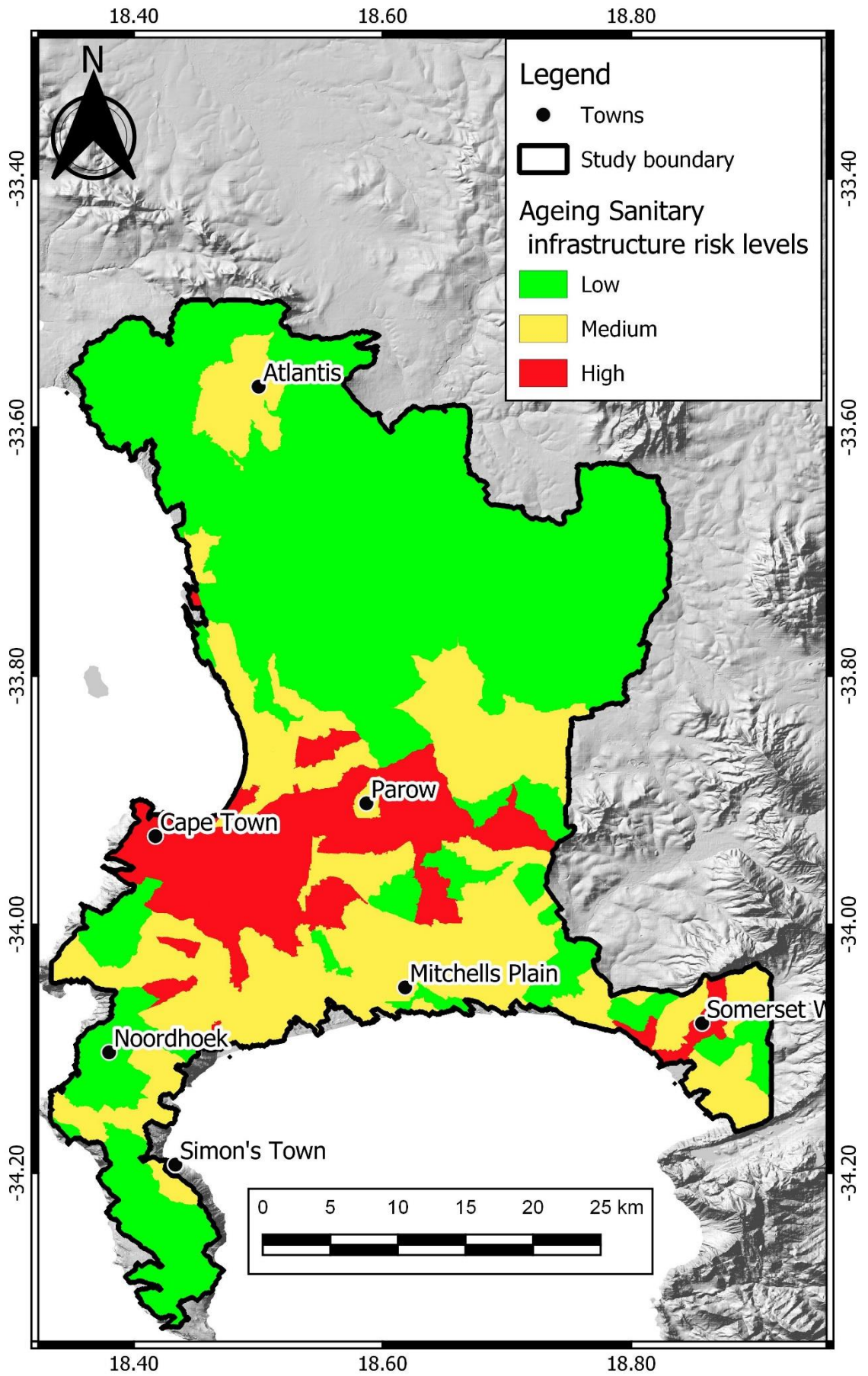


Figure B4: Ageing sanitary infrastructure risk map

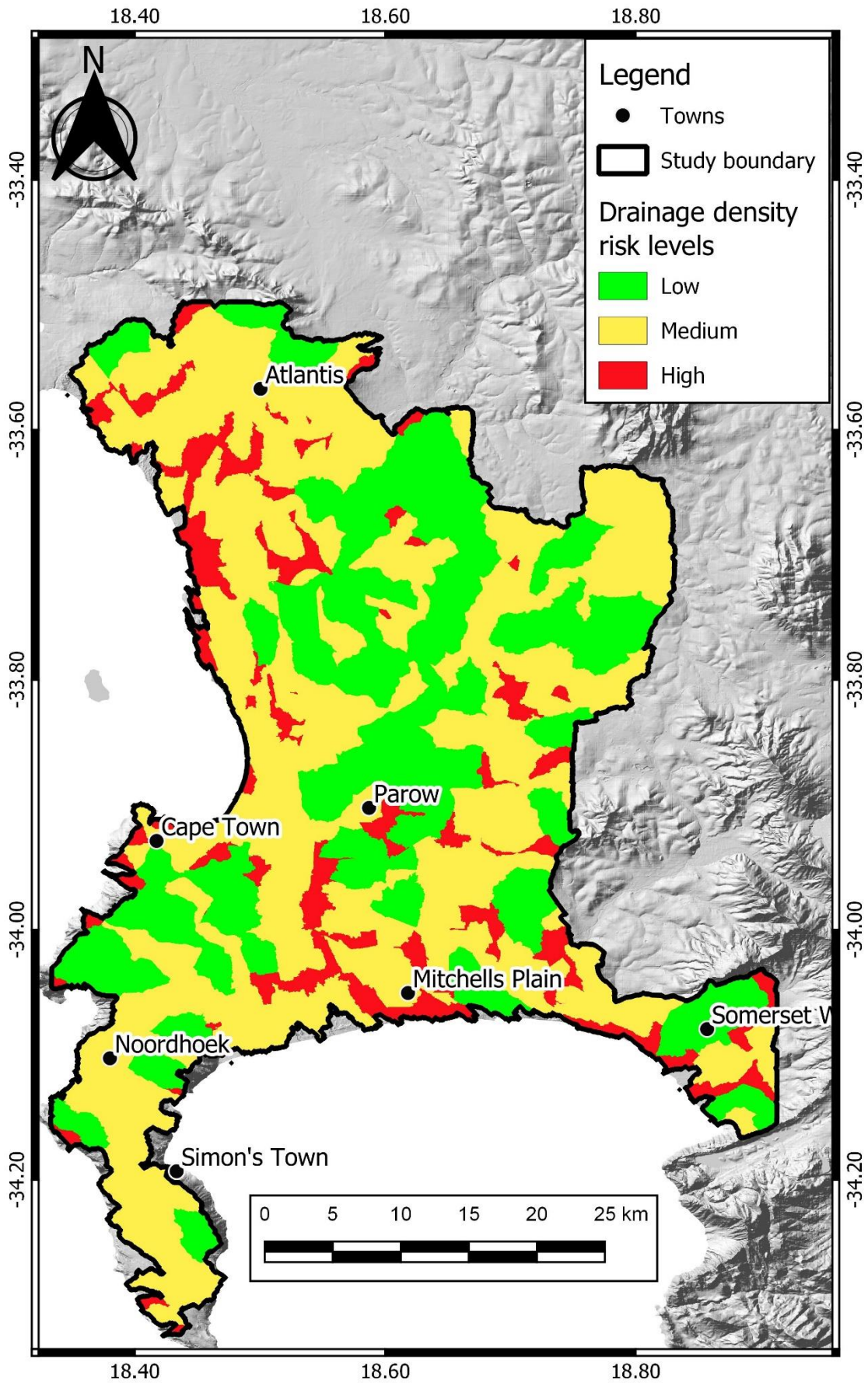


Figure B5: Drainage density risk map

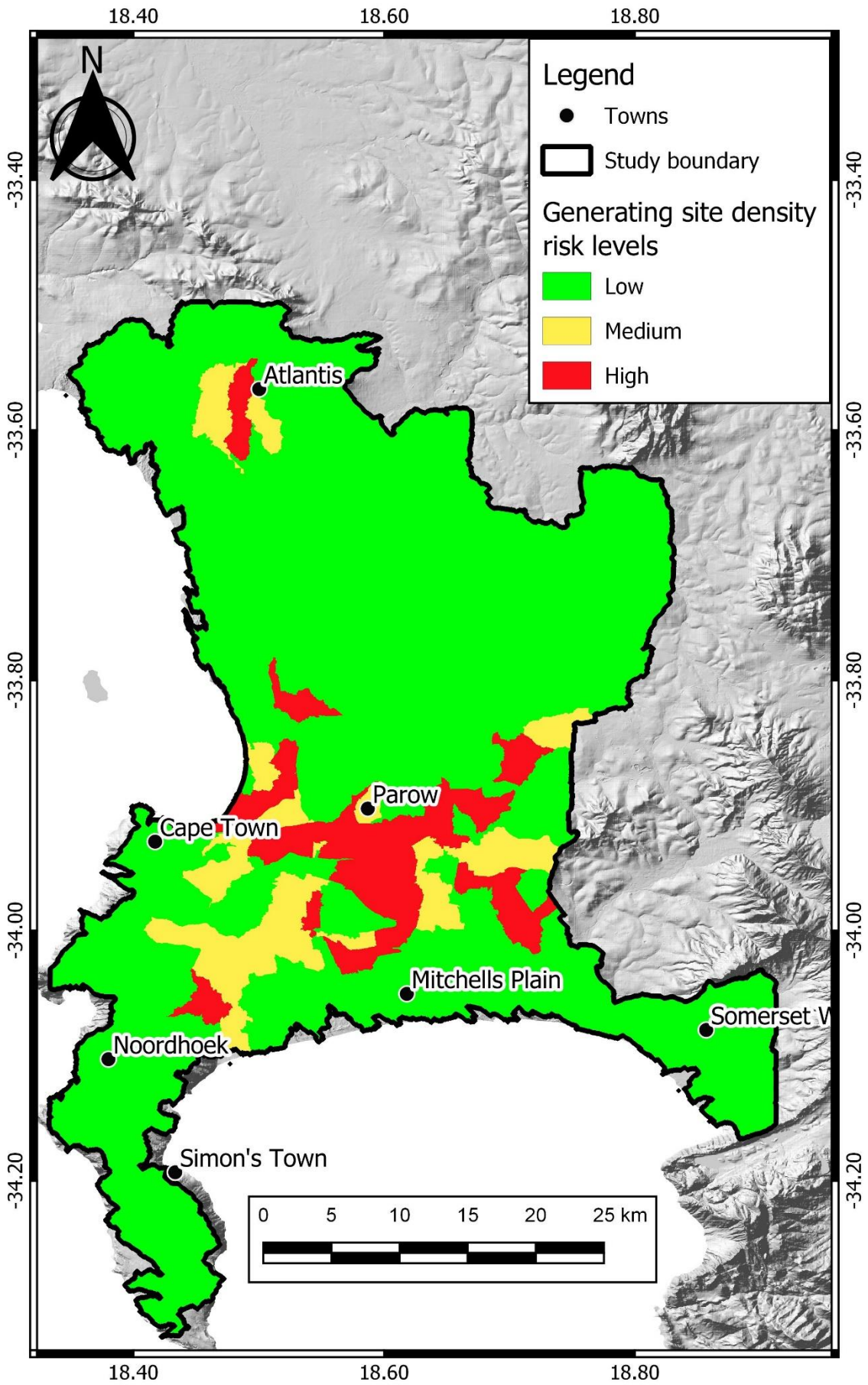


Figure B6: Generating site density risk map

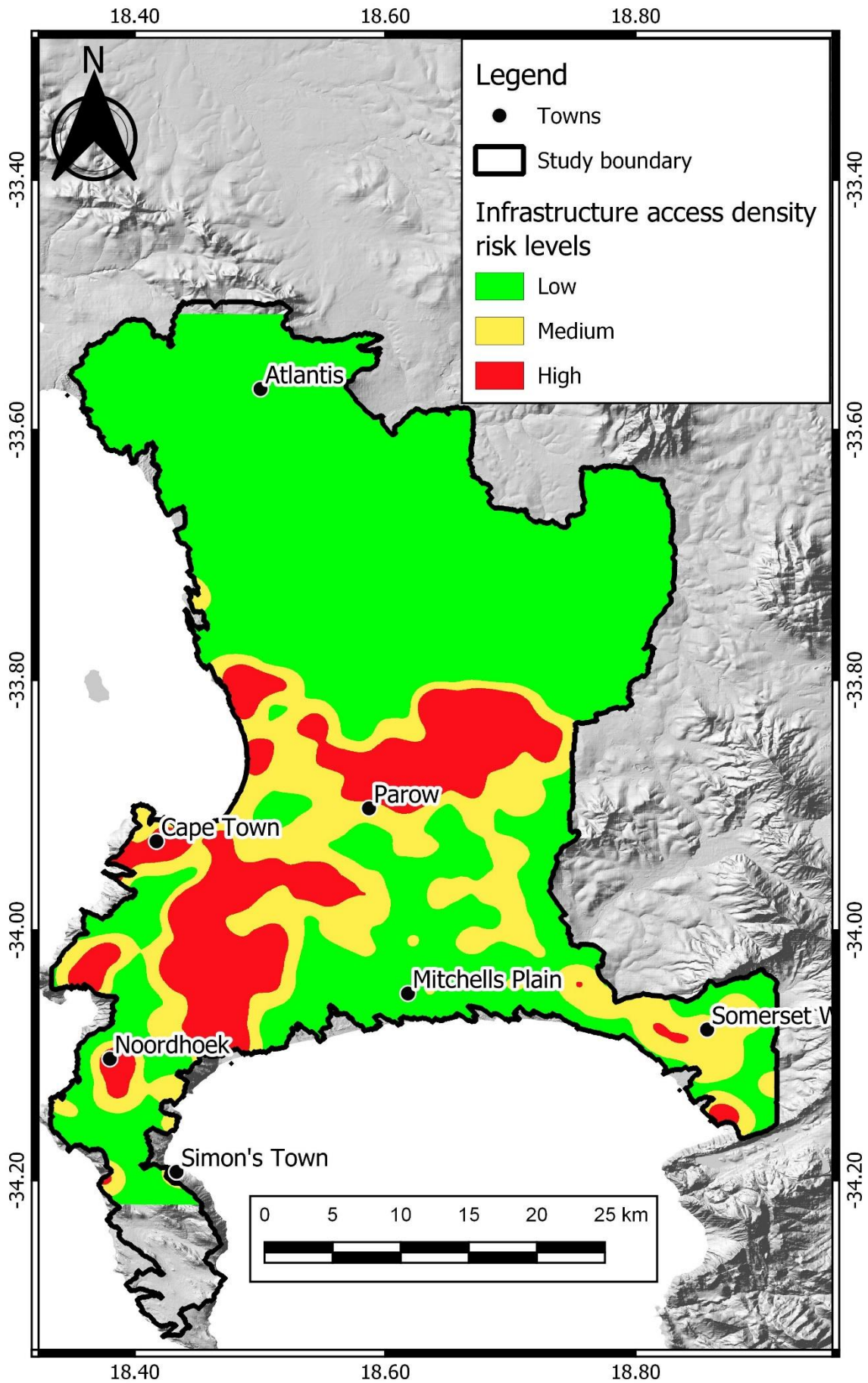


Figure B7: Infrastructure access density risk map

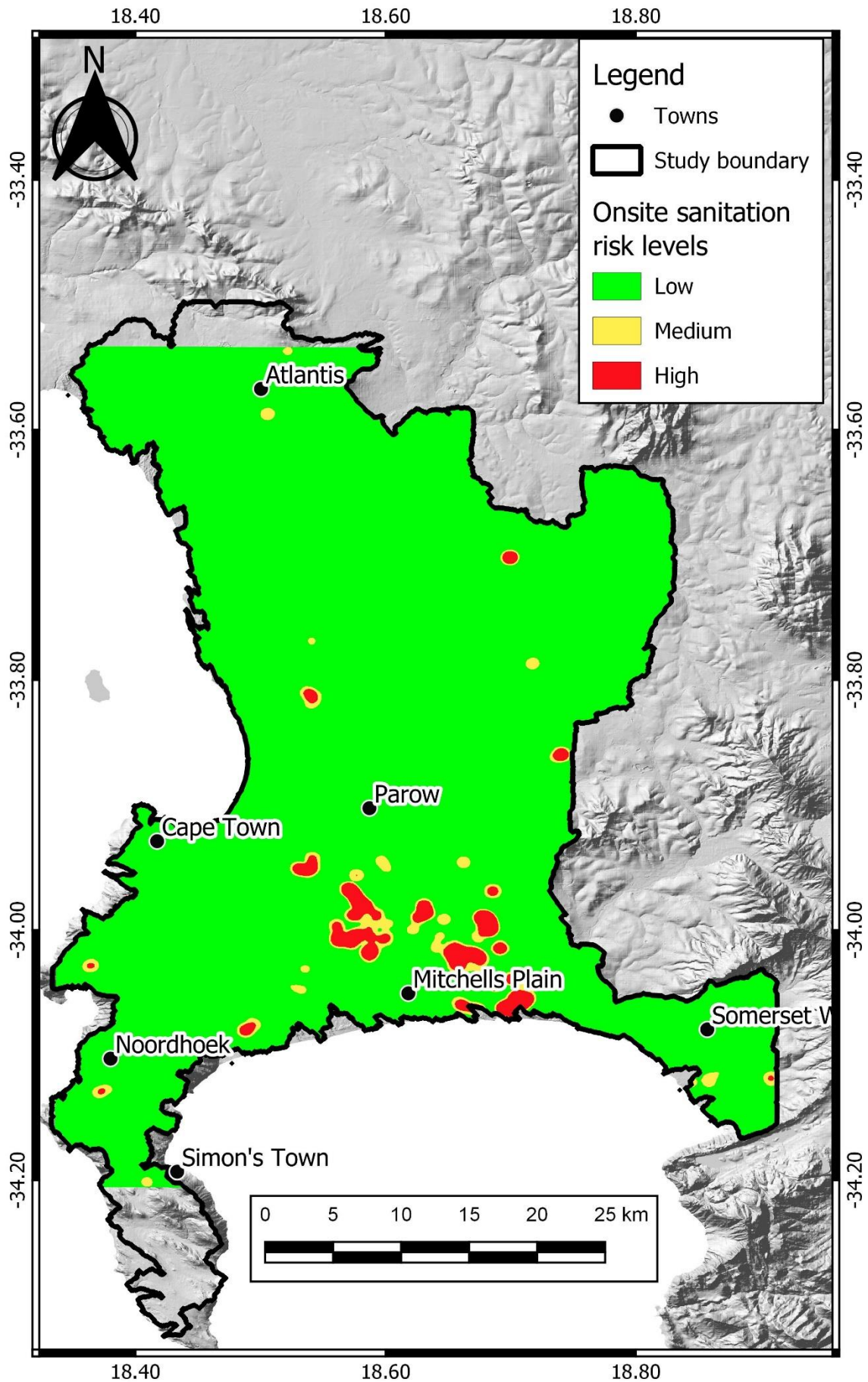


Figure B8: On-site sanitation risk map

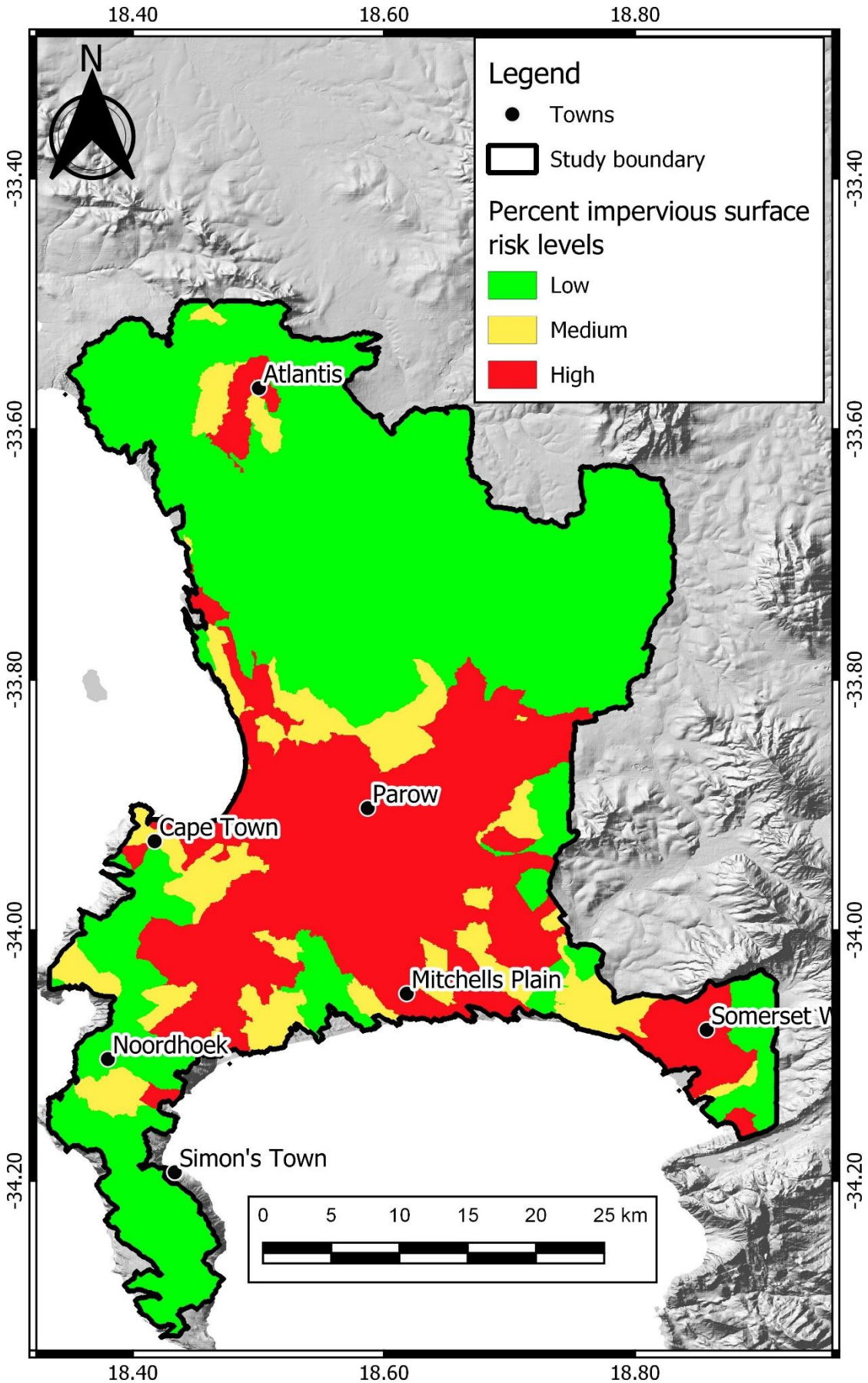


Figure B9: Percentage impervious surface risk map

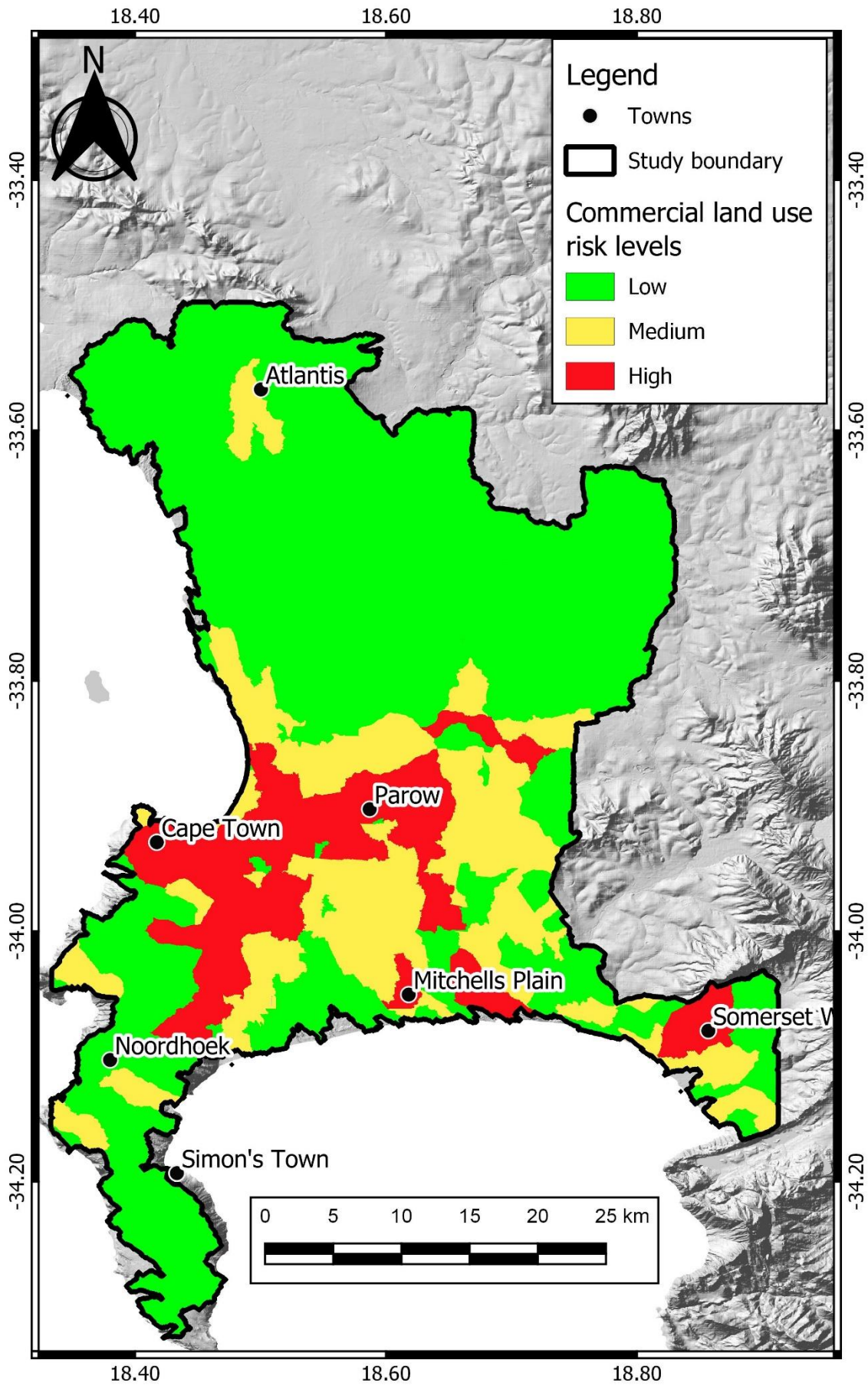


Figure B10: Commercial land use risk map

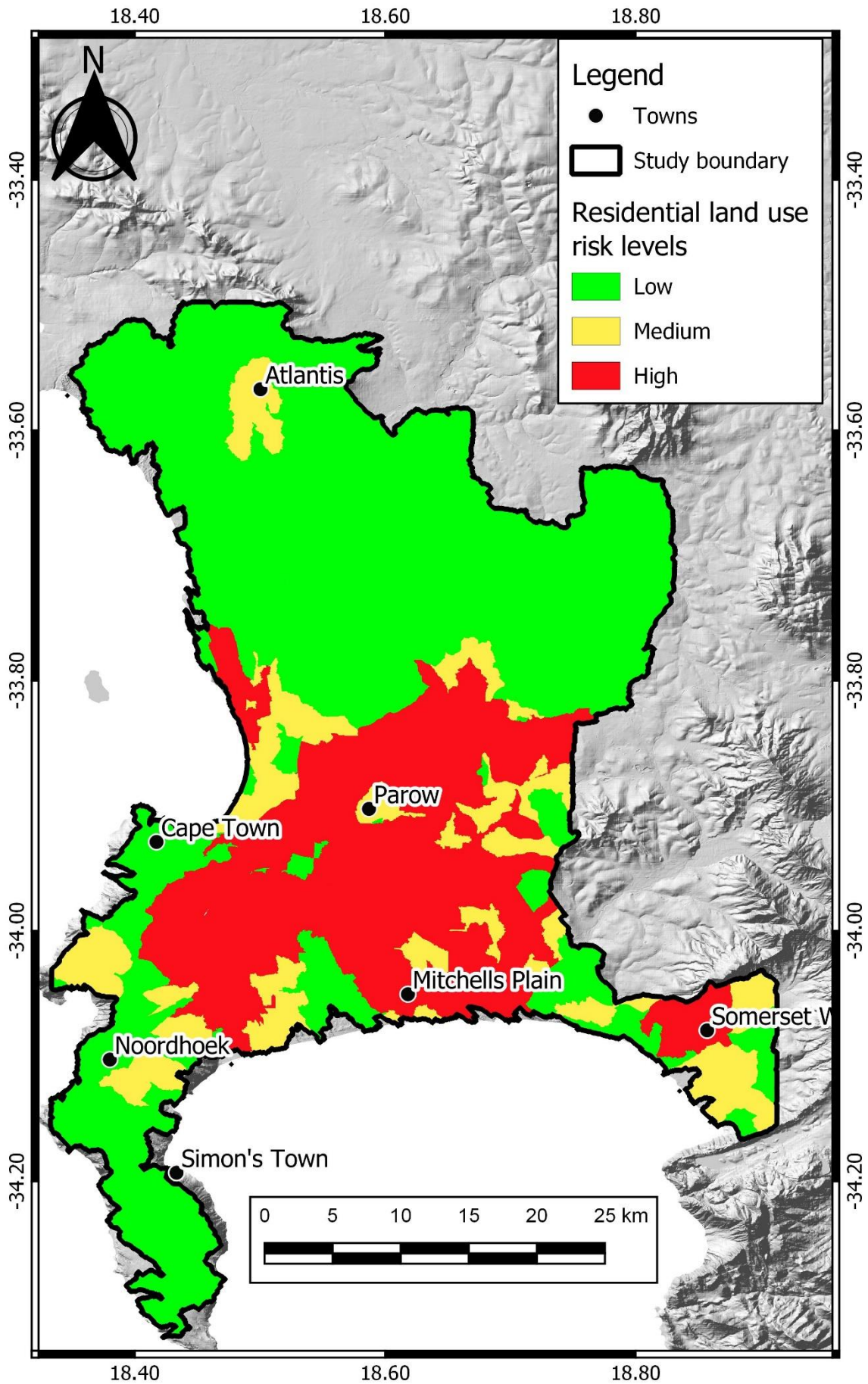


Figure B11: Residential land use risk map

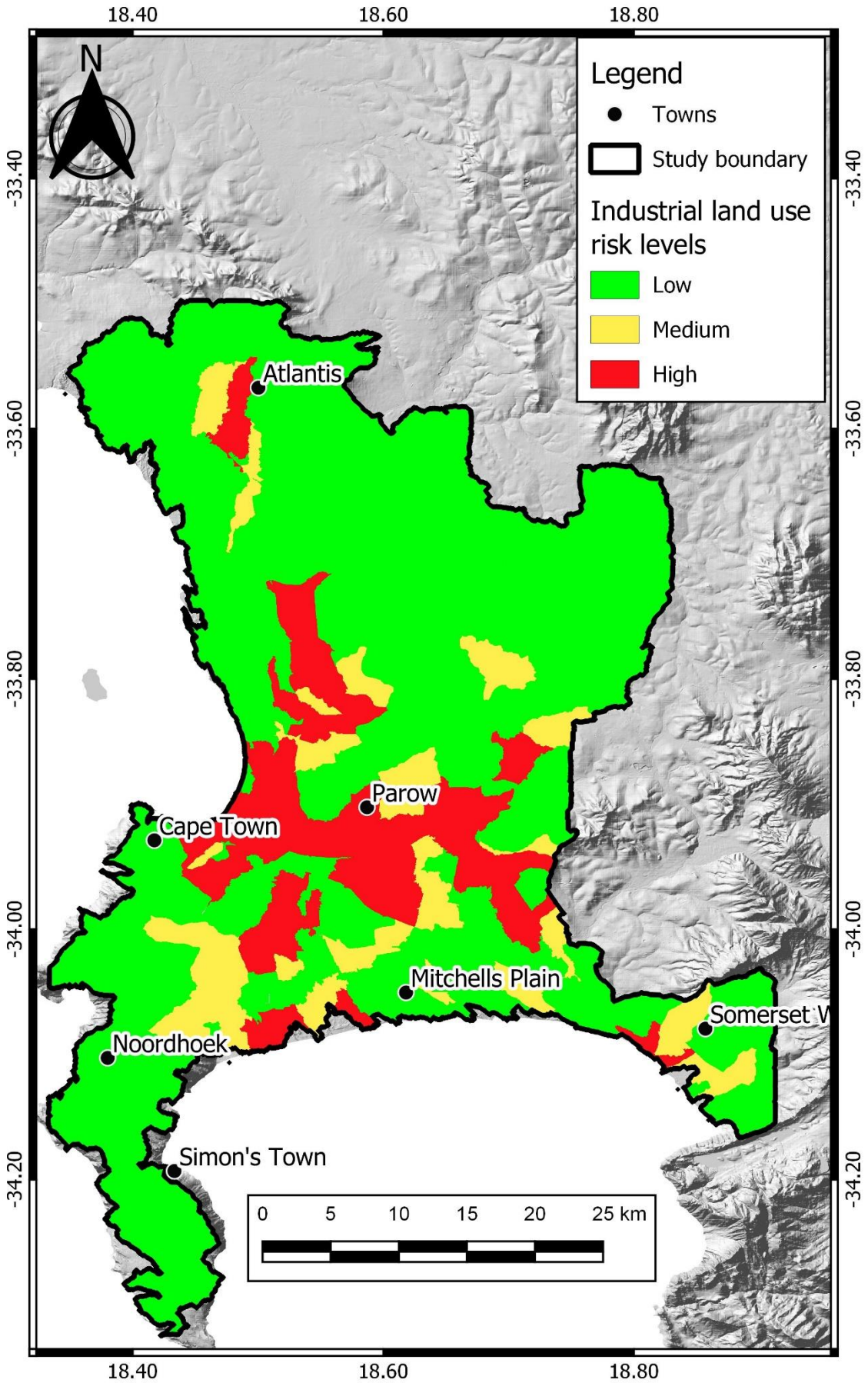


Figure B12: Industrial land use risk map

APPENDIX C: RISK MAPS WITH ALL DISCHARGE RECORDS OVERLAID

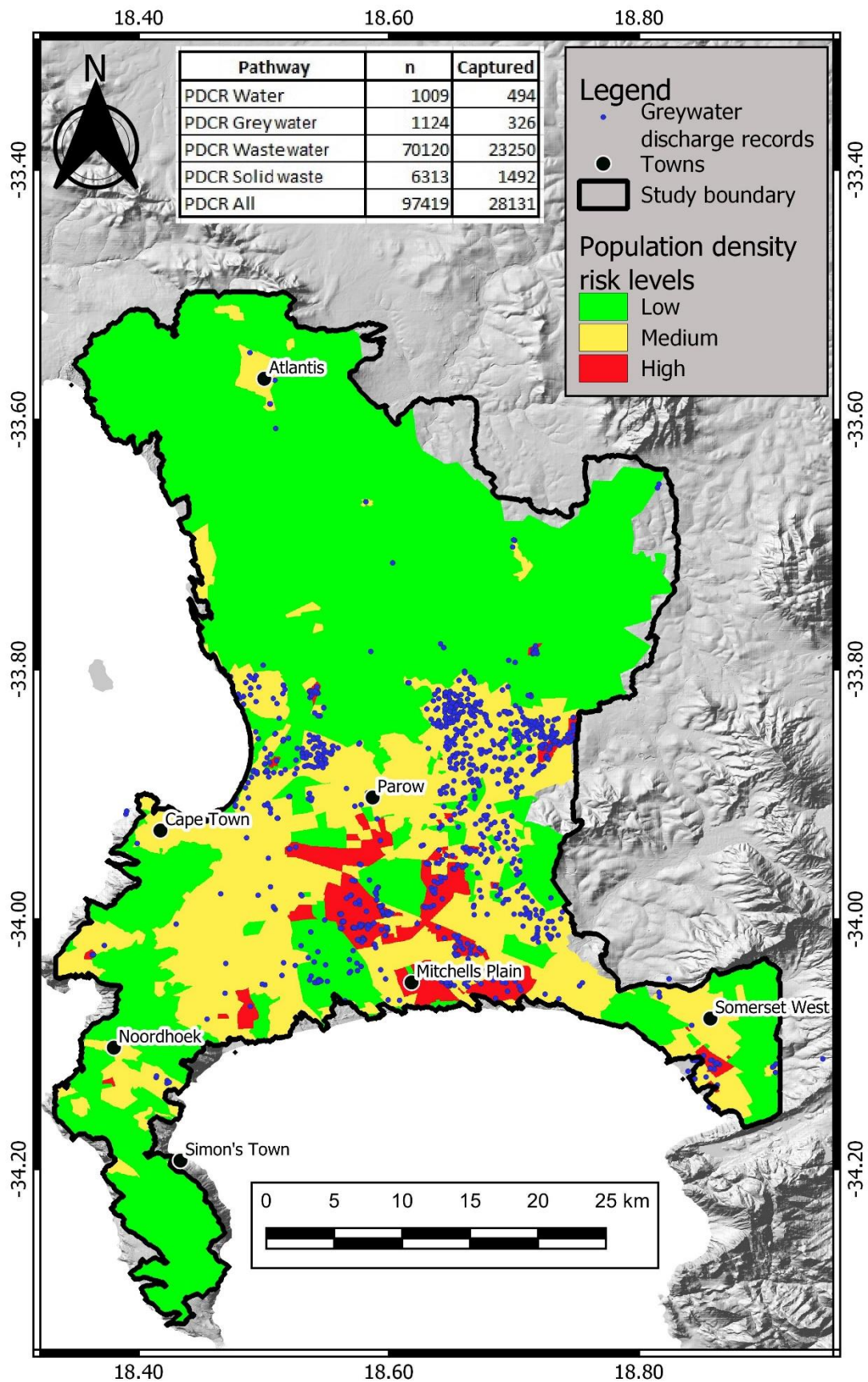


Figure C1: Population density risk map with greywater discharge records

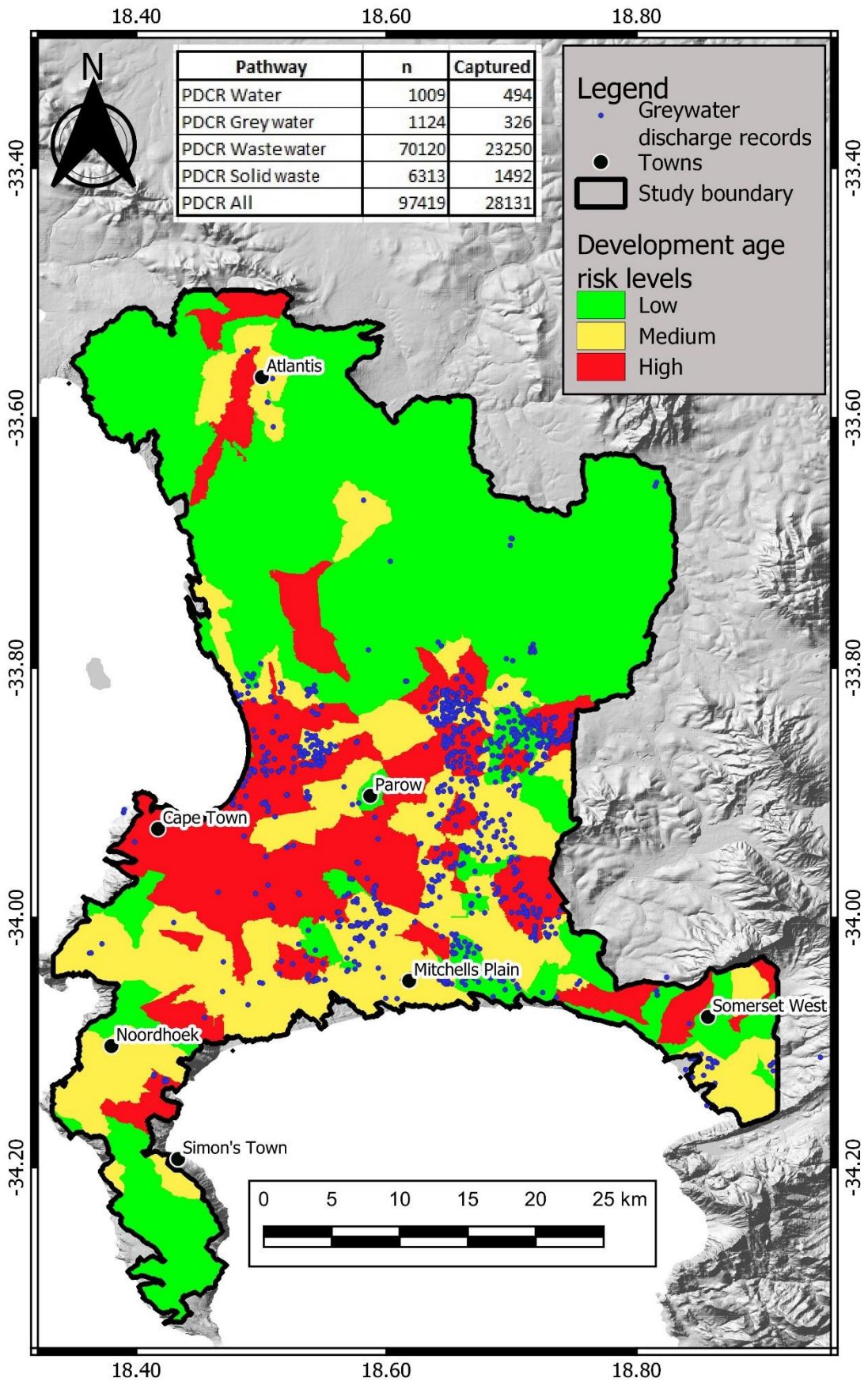


Figure C2: Development age risk map with greywater discharge records

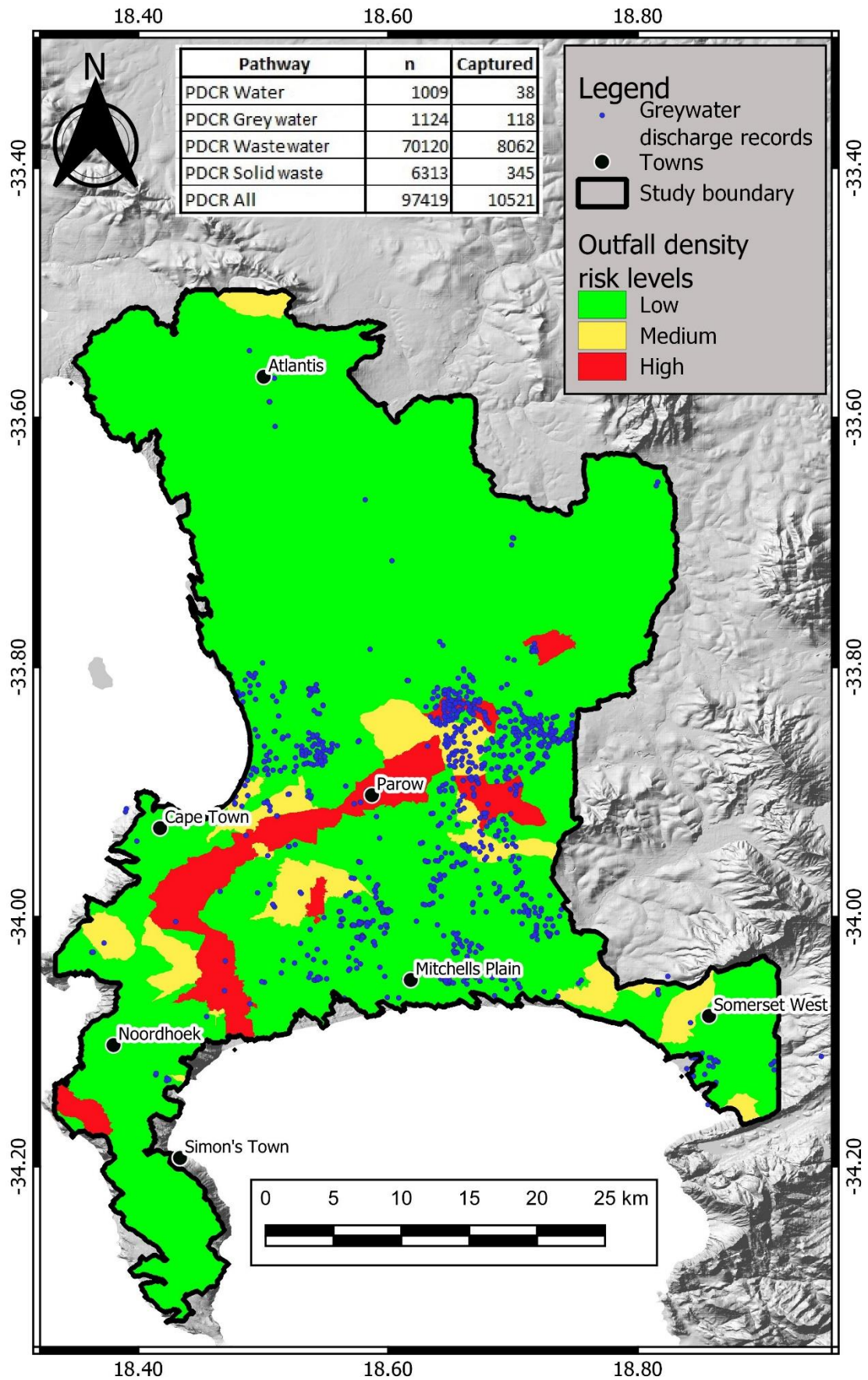


Figure C3: Outfall density risk map with greywater discharge records

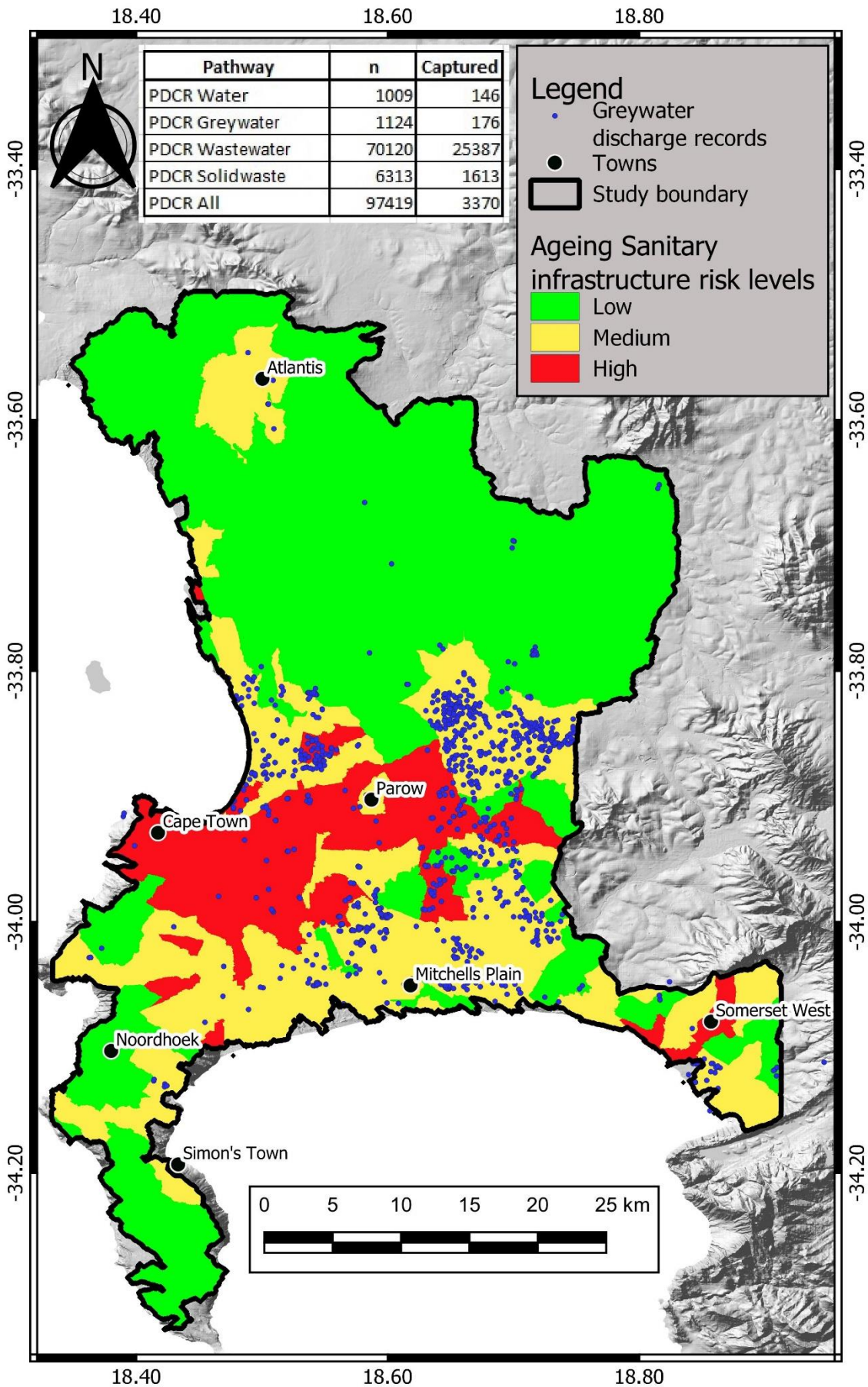


Figure C4: Ageing sanitary infrastructure risk map with greywater discharge records

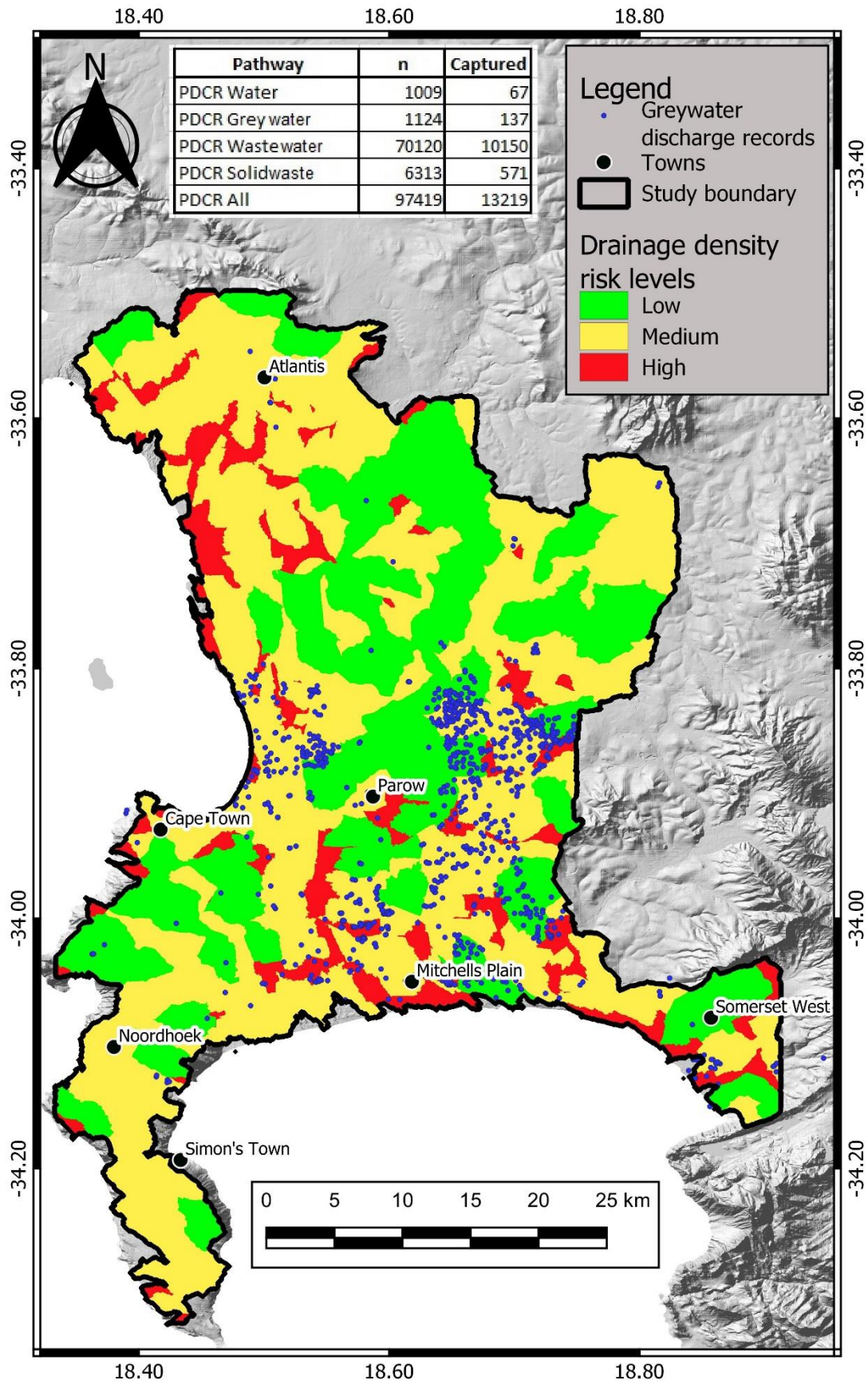


Figure C5: Drainage density risk map with greywater discharge records

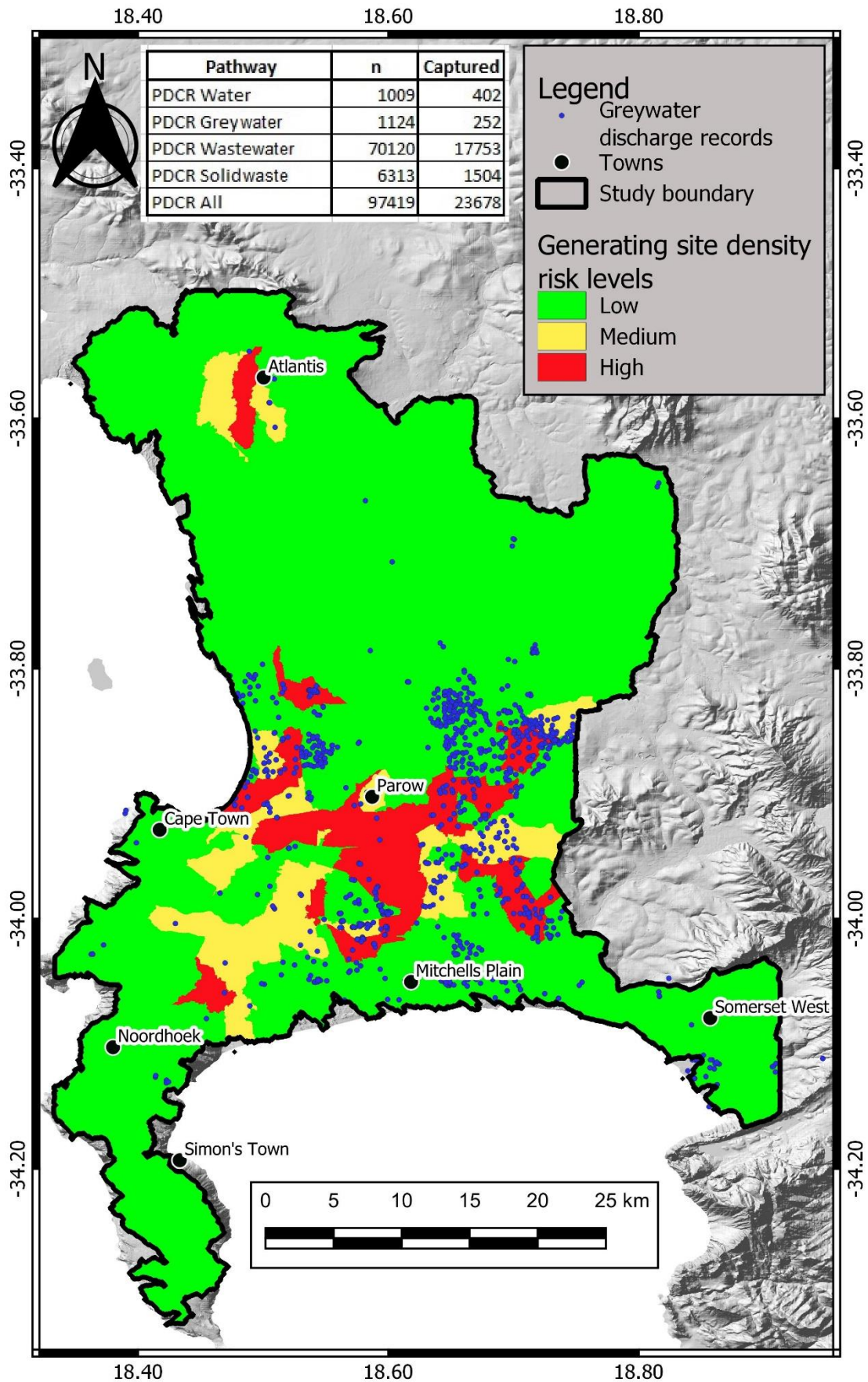


Figure C6: Generating site density risk map with greywater discharge records

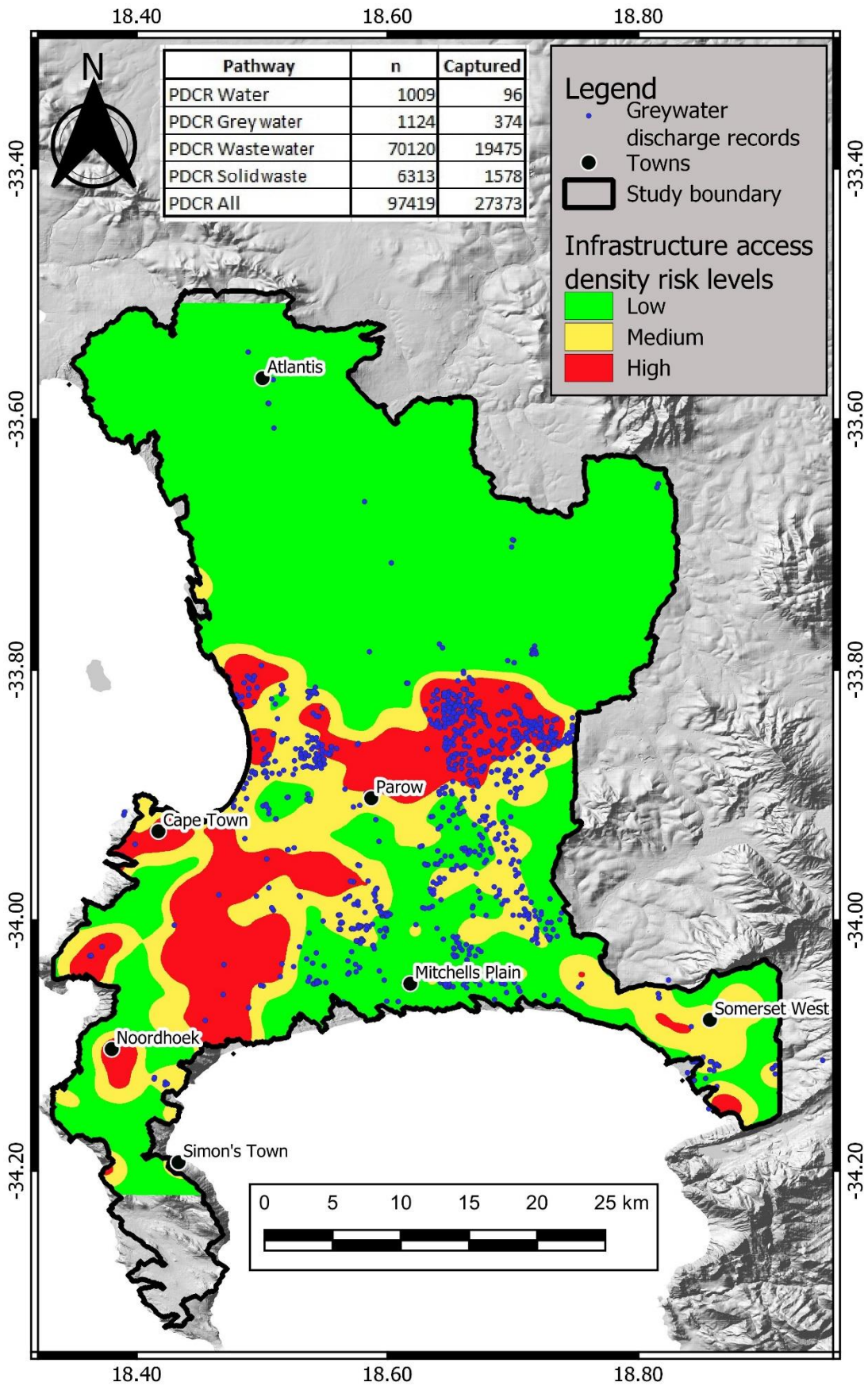


Figure C7: Infrastructure access density risk map with greywater discharge records

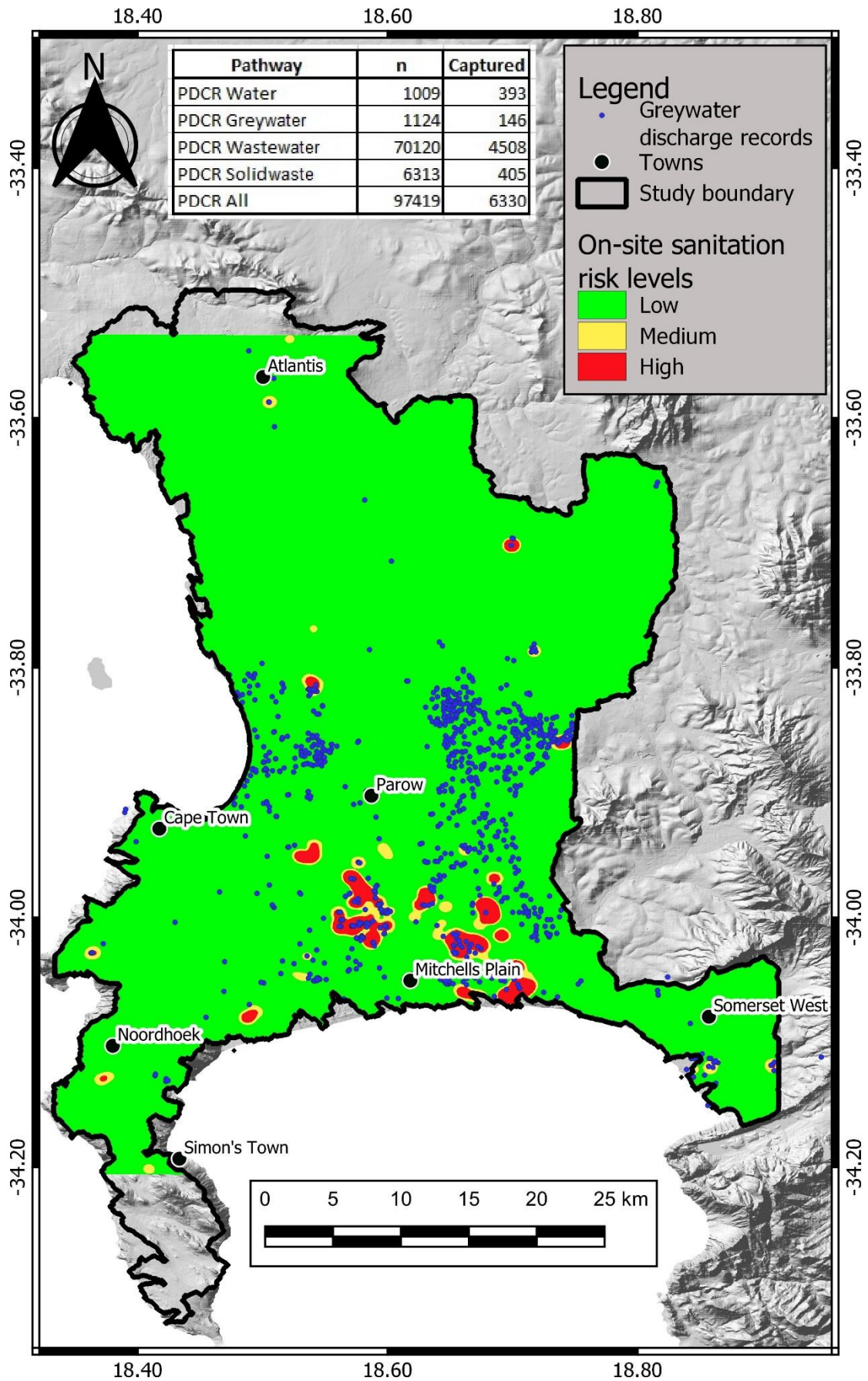


Figure C8: On-site sanitation risk map with greywater discharge records

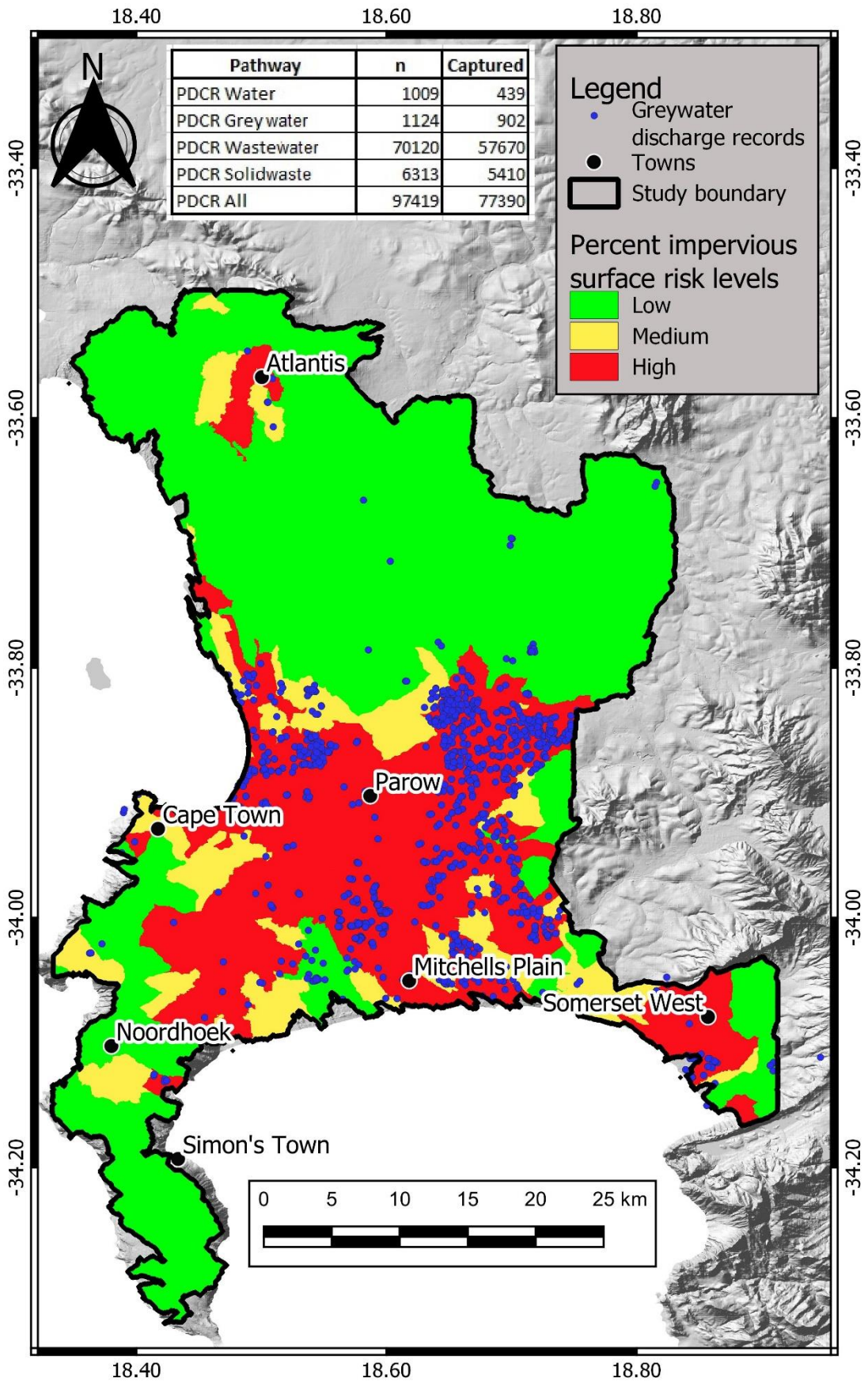


Figure C9: Percentage impervious surface risk map with greywater discharge records

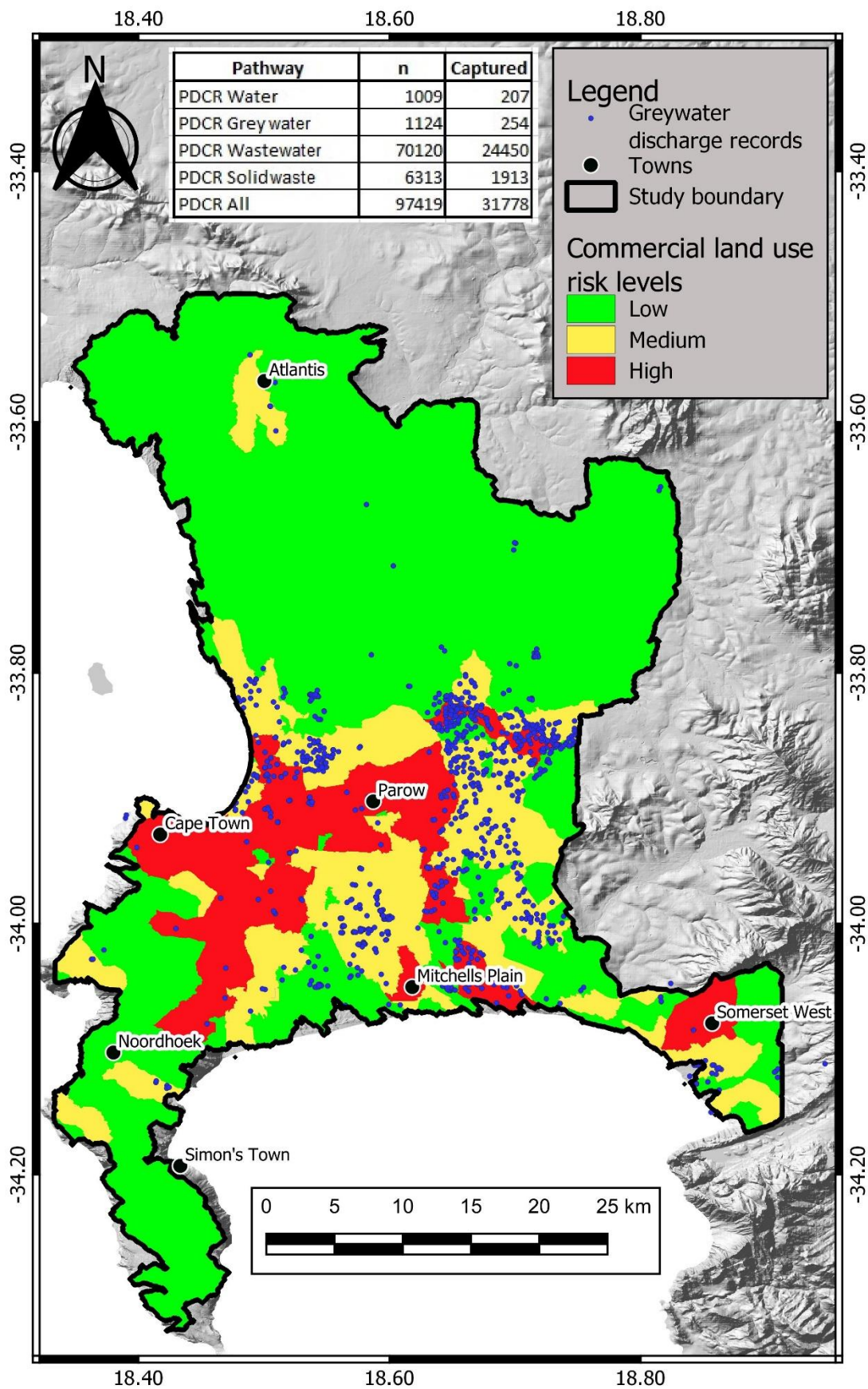


Figure C10: Commercial land use risk map with greywater discharge records

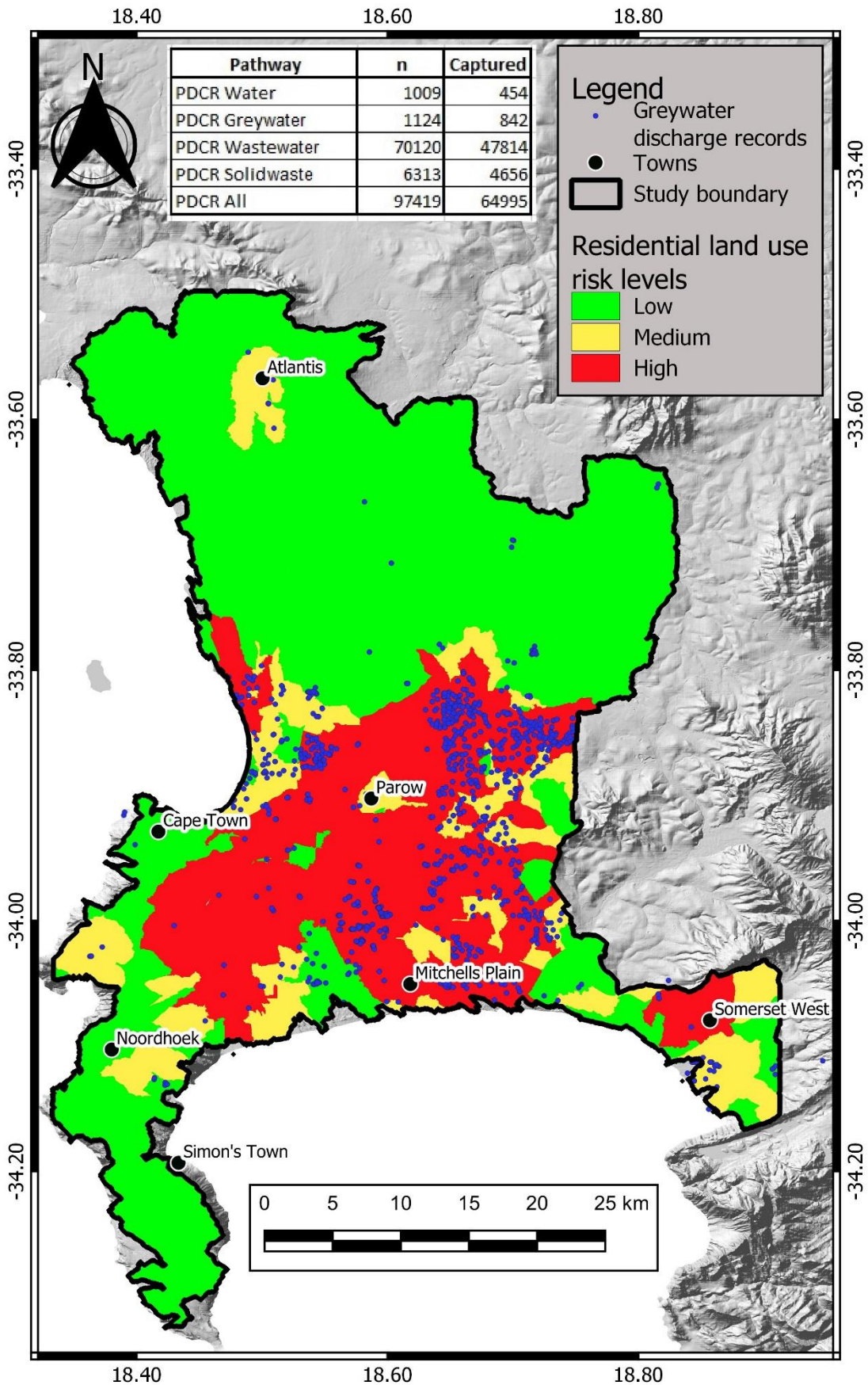


Figure C11: Residential land use risk map with greywater discharge records

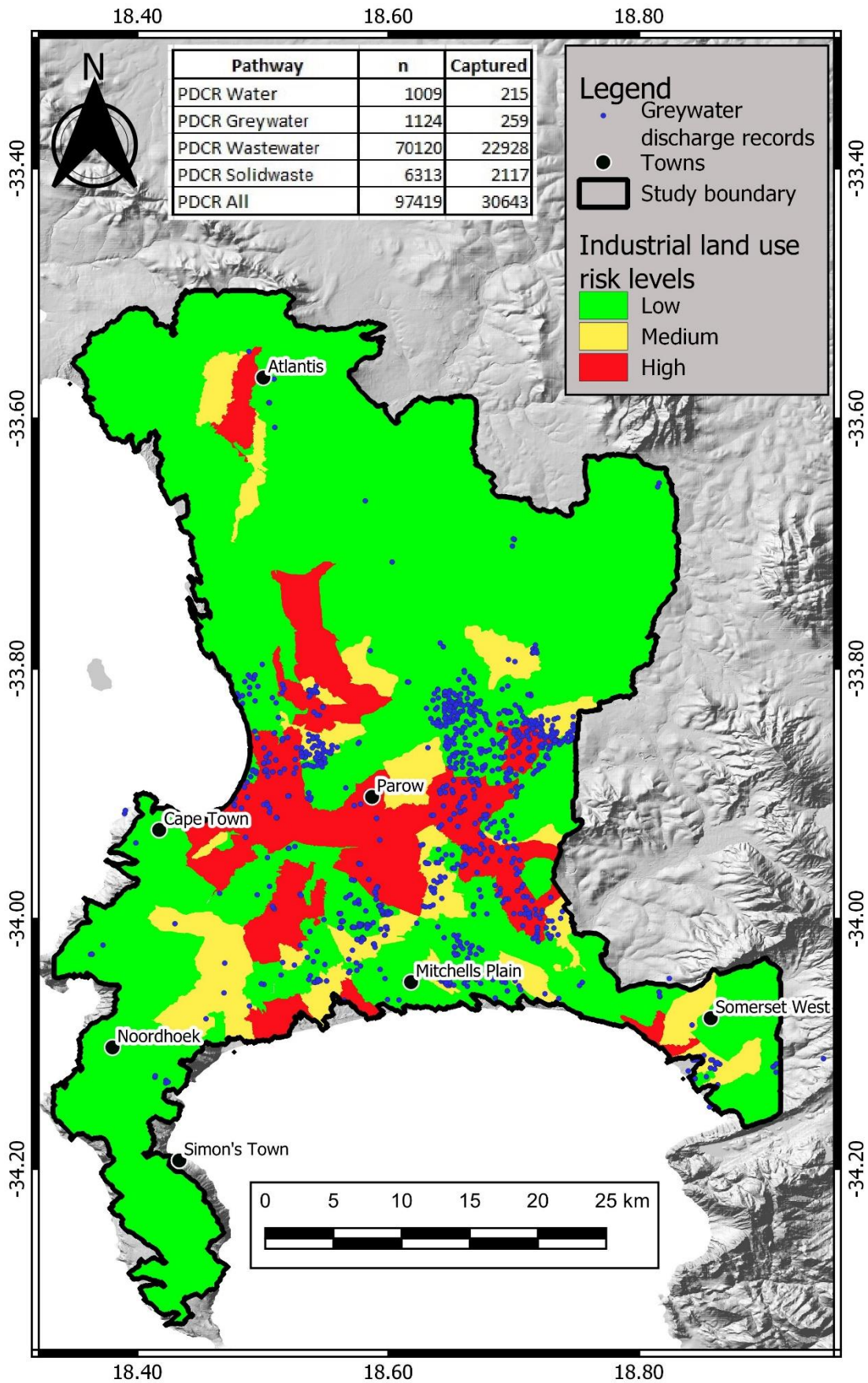


Figure C12: Industrial land use risk map with greywater discharge records

TABLE C1: DISCHARGES CAPTURED BY ALL RISK FACTORS FOR ALL DISCHARGE PATHWAYS

Number	Data	Discharge Type														
		Water (1009)			Greywater (1124)			Wastewater (70120)			Solidwaste (6313)			All		
		1009			1124			70120			6313			97419		
	Captured	Not Captured	Percentage Captured	Captured	Not Captured	Percentage Captured	Captured	Not Captured	Percentage Captured	Captured	Not Captured	Percentage Captured	Captured	Not Captured	Percentage Captured	
1	Population density	494	515	49	326	798	29	23250	46870	33	1492	4821	24	28131	69288	29
2	Development age	171	838	17	380	744	34	32113	38007	46	2344	3969	37	42448	54971	44
3	Outfall density	38	971	4	118	1006	10	8062	62058	11	345	5968	5	10521	86898	11
4	Aging sanitary infrastructure	146	863	14	176	948	16	25387	44733	36	1613	4700	26	31370	66049	32
5	Drainage density	67	942	7	137	987	12	10150	59970	14	571	5742	9	13219	84200	14
6	Generating site density	402	607	40	252	872	22	17753	52367	25	1504	4809	24	23678	73741	24
7	Infrastructure access density	96	913	10	374	750	33	19475	50645	28	1578	4735	25	27373	70046	28
8	On-site sanitation	393	616	39	146	978	13	4508	65612	6	405	5908	6	6330	91089	6
9	Percent impervious	439	570	44	902	222	80	57670	12450	82	5410	903	86	77390	20029	79
10	Commercial land use	207	802	21	254	870	23	24450	45670	35	1913	4400	30	31778	65641	33
11	Residential land use	454	555	45	842	282	75	47814	22306	68	4656	1657	74	64995	32424	67
12	Industrial land use	215	794	21	259	865	23	22928	47192	33	2117	4196	34	30643	66776	31
	Total	3122	8986		4166	9322		293560	547880		23948	51808		387876	681952	

APPENDIX D: CHI-SQUARE TEST RESULTS

TABLE D1: CHI-SQUARE TEST OUTPUT SHOWING P-VALUES FOR THE WATER PATHWAY

	Population density	Development age	Outfall density	Ageing sanitary infrastructure	Drainage density	Generating site density	Infrastructure access density	On-site sanitation	Percentage impervious surface	Commercial land use	Residential land use	Industrial land use
Population density	1	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.015935	<0.0001	<0.081738	<0.0001
Development age		1	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.045771	<0.0001	<0.01497
Outfall density			1	<0.0001	<0.004998	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Ageing sanitary infrastructure				1	<0.0001	<0.0001	<0.000788	<0.0001	<0.0001	<0.000439	<0.0001	<0.0001
Drainage density					1	<0.0001	<0.022201	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Generating site density						1	<0.0001	<0.718432	<0.104204	<0.0001	<0.0001	<0.0001
Infrastructure access density							1	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
On-site sanitation								1	<0.041881	<0.0001	<0.006819	<0.0001
Percentage impervious surface									1	<0.0001	<0.532299	<0.0001
Commercial land use										1	<0.0001	<0.698535
Residential land use											1	<0.0001
Industrial land use												1

TABLE D2: CHI-SQUARE TEST OUTPUT SHOWING P-VALUES FOR THE GREYWATER PATHWAY

	Population Density	Development age	Outfall density	Ageing sanitary infrastructure	Drainage density	Generating site density	Infrastructure access density	On-site sanitation	Percentage impervious surface	Commercial land use	Residential land use	Industrial land use
Population density	1	<0.016026	<0.0001	<0.0001	<0.0001	<0.000427	<0.032347	<0.0001	<0.0001	<0.000622	<0.0001	0.001507
Development age		1	<0.0001	<0.0001	<0.0001	<0.0001	<0.823063	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Outfall density			1	<0.000364	<0.231764	<0.0001	<0.0001	<0.076864	<0.0001	<0.0001	<0.0001	<0.0001
Ageing sanitary infrastructure				1	<0.020604	<0.0001	<0.0001	<0.080737	<0.0001	<0.0001	<0.0001	<0.0001
Drainage density					1	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Generating site density						1	<0.0001	<0.0001	<0.133614	1	<0.0001	<0.764177
Infrastructure access density							1	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
On-site sanitation								1	<0.0001	<0.0001	<0.0001	<0.0001
Percentage impervious surface									1	<0.0001	<0.002852	<0.0001
Commercial land use										1	<0.0001	<0.841481
Residential land use											1	<0.0001
Industrial land use												1

TABLE D3: CHI-SQUARE TEST OUTPUT SHOWING P-VALUES FOR THE WASTEWATER PATHWAY

	Population density	Development age	Outfall density	Ageing sanitary infrastructure	Drainage density	Generating site density	Infrastructure access density	On-site sanitation	Percentage impervious surface	Commercial land use	Residential land use	Industrial land use
Population density	1	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.068027
Development age		1	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Outfall density			1	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Ageing sanitary infrastructure				1	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Drainage density					1	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Generating site density						1	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Infrastructure access density							1	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
On-site sanitation								1	<0.0001	<0.0001	<0.0001	<0.0001
Percentage impervious surface									1	<0.0001	<0.0001	<0.0001
Commercial land use										1	<0.0001	<0.0001
Residential land use											1	<0.0001
Industrial land use												1

TABLE D4: CHI-SQUARE TEST OUTPUT SHOWING P-VALUES FOR THE SOLID WASTE PATHWAY

	Population density	Development age	Outfall density	Ageing sanitary infrastructure	Drainage density	Generating site density	Infra Access Density	On-site sanitation	Percentage impervious surface	Commercial land use	Residential land use	Industrial land use
Population density	1	<0.0001	<0.0001	<0.013141	<0.0001	<0.823063	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Development age		1	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Outfall density			1	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Ageing sanitary infrastructure				1	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Drainage density					1	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Generating site density						1	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Infrastructure access density							1	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Toilets								1	<0.0001	<0.0001	<0.0001	<0.0001
Percentage impervious surface									1	<0.0001	<0.0001	<0.0001
Commercial land use										1	<0.0001	<0.0001
Residential land use											1	<0.0001
Industrial land use												1

TABLE D5: CHI-SQUARE TEST OUTPUT SHOWING P-VALUES FOR THE ALL PATHWAY

	Population density	Development age	Outfall density	Ageing sanitary infrastructure	Drainage density	Generating site density	Infrastructure access density	On-site sanitation	Percentage impervious surface	Commercial land use	Residential land use	Industrial land use
Population density	1	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Development age		1	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Outfall density			1	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Ageing sanitary infrastructure				1	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.048865	<0.0001	<0.000414
Drainage density					1	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Generating site density						1	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Infrastructure access density							1	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
On-site sanitation								1	<0.0001	<0.0001	<0.0001	<0.0001
Percentage impervious surface									1	<0.0001	<0.0001	<0.0001
Commercial land use										1	<0.0001	<0.0001
Residential land use											1	<0.0001
Industrial land use												1

APPENDIX E: AHP VALUES FOR EACH PATHWAY

TABLE E1: AHP: WATER PATHWAY

Pairwise Comparison Matrix														
	Population density	Development age	Outfall density	Aging sanitary infrastructure	Drainage density	Generating site density	Infrastructure access density	On-site sanitation	Percent impervious	Commercial land use	Residential land use	Industrial land use	Consistency Measure	
Population density	1	5	6	5	6	2	5	2	2	4	1	4	12.58223101	
Development age	1/5	1	3	1	2	1/4	2	1/4	1/4	1/2	1/4	1/2	12.11374831	
Outfall density	1/6	1/3	1	1/2	1	1/5	1/2	1/5	1/5	1/3	1/6	1/3	12.25051949	
Aging sanitary infrastructure	1/5	1	2	1	2	1/4	1	1/4	1/4	1/2	1/5	1/2	12.23166645	
Drainage density	1/6	1/2	1	1/2	1	1/5	1	1/5	1/5	1/3	1/5	1/3	12.22715003	
Generating site density	1/2	4	5	4	5	1	4	1	1	3	1/2	3	12.59795038	
Infrastructure access density	1/5	1/2	2	1	1	1/4	1	1/4	1/5	1/3	1/4	1/3	12.11786667	
On-site sanitation	1/2	4	5	4	5	1	4	1	1/2	3	1/2	3	12.59820662	
Percent impervious	1/2	4	5	4	5	1	5	2	1	4	1	4	12.68338047	
Commercial land use	1/4	2	3	2	3	1/3	3	1/3	1/4	1	1/4	1	12.32371406	
Residential land use	1	4	6	5	5	2	4	2	1	4	1	4	12.5986601	
Industrial land use	1/4	2	3	2	3	1/3	3	1/3	1/4	1	1/4	1	12.32371406	
Column Totals =	4.9333333	28.33333	42	30	39	8.816666667	33.5	9.81667	7.1	22	5.56666667	22		
Normalized Matrix														
													Row Totals	WEIGHTS Average
Population density	0.2027027	0.17647059	0.14	0.16666667	0.1538462	0.2268431	0.149253731	0.2037351	0.281690141	0.18181818	0.17964072	0.1818182	2.247	0.187
Development age	0.04054054	0.03529412	0.071429	0.03333333	0.0512821	0.028355388	0.059701493	0.0254669	0.035211268	0.02272727	0.04491018	0.0227273	0.471	0.039
Outfall density	0.03378378	0.01176471	0.02381	0.01666667	0.025641	0.02268431	0.014925373	0.0203735	0.028169014	0.01515152	0.02994012	0.0151515	0.258	0.022
Aging sanitary infrastructure	0.04054054	0.03529412	0.047619	0.03333333	0.0512821	0.028355388	0.029850746	0.0254669	0.035211268	0.02272727	0.03592814	0.0227273	0.408	0.034
Drainage density	0.03378378	0.01764706	0.02381	0.01666667	0.025641	0.02268431	0.029850746	0.0203735	0.028169014	0.01515152	0.03592814	0.0151515	0.285	0.024
Generating site density	0.10135135	0.14117647	0.119048	0.13333333	0.1282051	0.11342155	0.119402985	0.1018676	0.14084507	0.13636364	0.08982036	0.1363636	1.461	0.122
Infrastructure access density	0.04054054	0.01764706	0.047619	0.03333333	0.025641	0.028355388	0.029850746	0.0254669	0.028169014	0.01515152	0.04491018	0.0151515	0.352	0.029
On-site sanitation	0.10135135	0.14117647	0.119048	0.13333333	0.1282051	0.11342155	0.119402985	0.1018676	0.070422535	0.13636364	0.08982036	0.1363636	1.391	0.116
Percent impervious	0.10135135	0.14117647	0.119048	0.13333333	0.1282051	0.11342155	0.149253731	0.2037351	0.14084507	0.18181818	0.17964072	0.1818182	1.774	0.148
Commercial land use	0.05067568	0.07058824	0.071429	0.06666667	0.0789231	0.037807183	0.089552239	0.0339559	0.035211268	0.04545455	0.04491018	0.0454545	0.669	0.056
Residential land use	0.2027027	0.14117647	0.142857	0.16666667	0.1282051	0.2268431	0.119402985	0.2037351	0.14084507	0.18181818	0.17964072	0.1818182	2.016	0.168
Industrial land use +	0.05067568	0.07058824	0.071429	0.06666667	0.0789231	0.037807183	0.089552239	0.0339559	0.035211268	0.04545455	0.04491018	0.0454545	0.669	0.056
													1.000	
													Lambda, λ_{max} = 12	
													Consistency Index, CI = 0	
													Randomness Index, RI = 2	
													Consistency Ratio, CR = 0	2.3%

TABLE E4: AHP: SOLID WASTE PATHWAY

Pairwise Comparison Matrix												
	Outfall density	Aging sanitary infrastructure	Drainage density	Generating site density	Infrastructure access density	On-site sanitation	Percent impervious	Commercial land use	Residential land use	Industrial land use	Consistency Measure	
Population density	3	1	3	1	1	3	1/8	1/2	1/6	1/2	12.19975324	
Development age	5	3	4	3	3	5	1/6	2	1/5	1	12.78017726	
Outfall density	1	1/4	1	1/3	1/3	1	1/9	1/4	1/8	1/4	12.35032124	
Aging sanitary infrastructure	4	1	3	1	1	3	1/7	1	1/6	1/2	12.23932977	
Drainage density	1	1/3	1	1/3	1/3	1	1/8	1/4	1/8	1/4	12.38486887	
Generating site density	3	1	3	1	1	3	1/8	1/2	1/6	1/2	12.19975324	
Infrastructure access density	3	1	3	1	1	3	1/8	1/2	1/6	1/2	12.19975324	
On-site sanitation	1	1/3	1	1/3	1/3	1	1/8	1/4	1/8	1/4	12.31818714	
Percent impervious	9	7	8	8	8	8	1	7	3	7	13.53682922	
Commercial land use	4	1	4	2	2	4	1/7	1	1/6	1	12.43509267	
Residential land use	8	6	8	6	6	8	0.33333333	6	1	5	13.51116085	
Industrial land use	4	2	4	2	2	4	1/7	1	1/5	1	12.685037	
Column Totals =												
	46	23.91666667	43	26	26	44	2.6646825	20.25	5.60833333	17.75		
Normalized Matrix												
	Row Totals	WEIGHTS										Consistency Measure
Population density	0.511	0.043										12.19975324
Development age	1.105	0.092										12.78017726
Outfall density	0.220	0.018										12.35032124
Aging sanitary infrastructure	0.565	0.047										12.23932977
Drainage density	0.232	0.019										12.38486887
Generating site density	0.511	0.043										12.19975324
Infrastructure access density	0.511	0.043										12.19975324
On-site sanitation	0.229	0.019										12.31818714
Percent impervious	3.817	0.318										13.53682922
Commercial land use	0.765	0.064										12.43509267
Residential land use	2.689	0.224										13.51116085
Industrial land use	0.845	0.070										12.685037
		1.000										
<p>Lambda, λ_{max} = 13</p> <p>Consistency Index, CI = 0</p> <p>Randomness Index, RI = 2</p> <p>Consistency Ratio, CR = 0 3.3%</p>												

TABLE E5: AHP: ALL/COMBINED PATHWAY

Pairwise Comparison Matrix												
	Aging sanitary infrastructure	Drainage density	Generating site density	Infrastructure access density	On-site sanitation	Percent impervious	Commercial land use	Residential land use	Industrial land use	Consistency Measure		
Population density	1	3	2	1	4	1/6	1	1/5	1	12.89800245		
Development age	3	4	3	3	5	1/5	3	1/4	2	13.26826002		
Outfall density	1/4	1/3	1/3	1/3	2	1/8	1/4	1/7	1/3	12.41542625		
Aging sanitary infrastructure	1	1/3	2	1	4	1/6	1	1/5	1	12.50597627		
Drainage density	3	1	1/2	1/3	2	1/8	1/3	1/7	1/3	12.87768201		
Generating site density	1/2	2	1	1	3	1/7	1/2	1/6	1/2	12.73608147		
Infrastructure access density	1	3	1	1	4	1/7	1/2	1/5	1	12.88052356		
On-site sanitation	1/4	1/2	1/3	1/4	1	1/8	1/4	1/8	1/4	12.76358095		
Percent impervious	6	8	7	7	8	1	6	3	6	13.54907452		
Commercial land use	1	3	2	2	4	1/6	1	1/5	1	12.87328586		
Residential land use	5	7	6	5	8	0.33333333	5	1	5	13.59949232		
Industrial land use	1	3	2	1	4	1/6	1	1/5	1	12.96825487		
Column Totals =	23	35.16667	27.166667	22.91666667	49	2.8607143	19.8333333	5.82738095	19.41667			
Normalized Matrix												
	Row Totals	WEIGHTS									Consistency Measure	
		Average										
Population density	0.043478261	0.085308	0.0736196	0.043636364	0.0816327	0.0582605	0.05042017	0.03432074	0.0515021	0.665	0.055	12.89800245
Development age	0.130434783	0.113744	0.1104294	0.130909091	0.1020408	0.0699126	0.15126050	0.04290092	0.1030043	1.292	0.108	13.26826002
Outfall density	0.010869565	0.009479	0.0122699	0.014545455	0.0408163	0.0436954	0.01260504	0.02451481	0.0171674	0.240	0.020	12.41542625
Aging sanitary infrastructure	0.043478261	0.009479	0.0736196	0.043636364	0.0816327	0.0582605	0.05042017	0.03432074	0.0515021	0.611	0.051	12.50597627
Drainage density	0.130434783	0.028436	0.0184049	0.014545455	0.0408163	0.0436954	0.01680672	0.02451481	0.0171674	0.438	0.037	12.87768201
Generating site density	0.02173913	0.056872	0.0368098	0.043636364	0.0612245	0.0499376	0.02521008	0.02860061	0.0257511	0.468	0.039	12.73608147
Infrastructure access density	0.043478261	0.085308	0.0368098	0.043636364	0.0816327	0.0499376	0.02521008	0.03432074	0.0515021	0.594	0.050	12.88052356
On-site sanitation	0.010869565	0.014218	0.0122699	0.010909091	0.0204082	0.0436954	0.01260504	0.02145046	0.0128755	0.198	0.017	12.76358095
Percent impervious	0.260869565	0.227488	0.2576687	0.305454545	0.1632653	0.349563	0.30252101	0.51481103	0.3090129	3.554	0.296	13.54907452
Commercial land use	0.043478261	0.085308	0.0736196	0.087272727	0.0816327	0.0582605	0.05042017	0.03432074	0.0515021	0.731	0.061	12.87328586
Residential land use	0.217391304	0.199052	0.2208589	0.218181818	0.1632653	0.116521	0.25210084	0.17160368	0.2575107	2.531	0.211	13.59949232
Industrial land use	0.043478261	0.085308	0.0736196	0.043636364	0.0816327	0.0582605	0.05042017	0.03432074	0.0515021	0.678	0.056	12.96825487
1.000												
Lambda, λ_{max} = 13												
Consistency Index, CI = 0												
Randomness Index, RI = 2												
Consistency Ratio, CR = 0 5.5%												

APPENDIX F: COMPOSITE MAPS

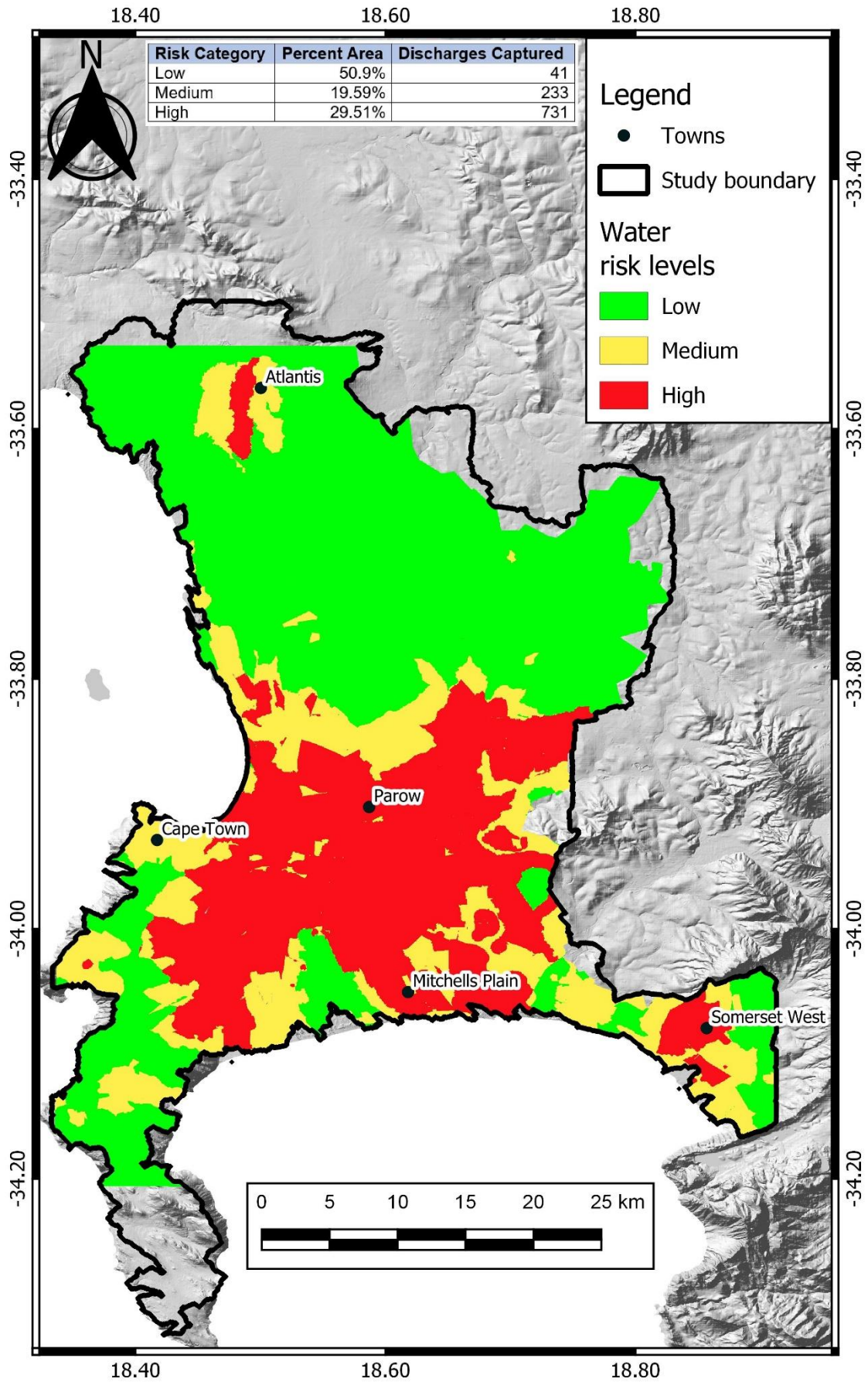


Figure F1: Water composite map

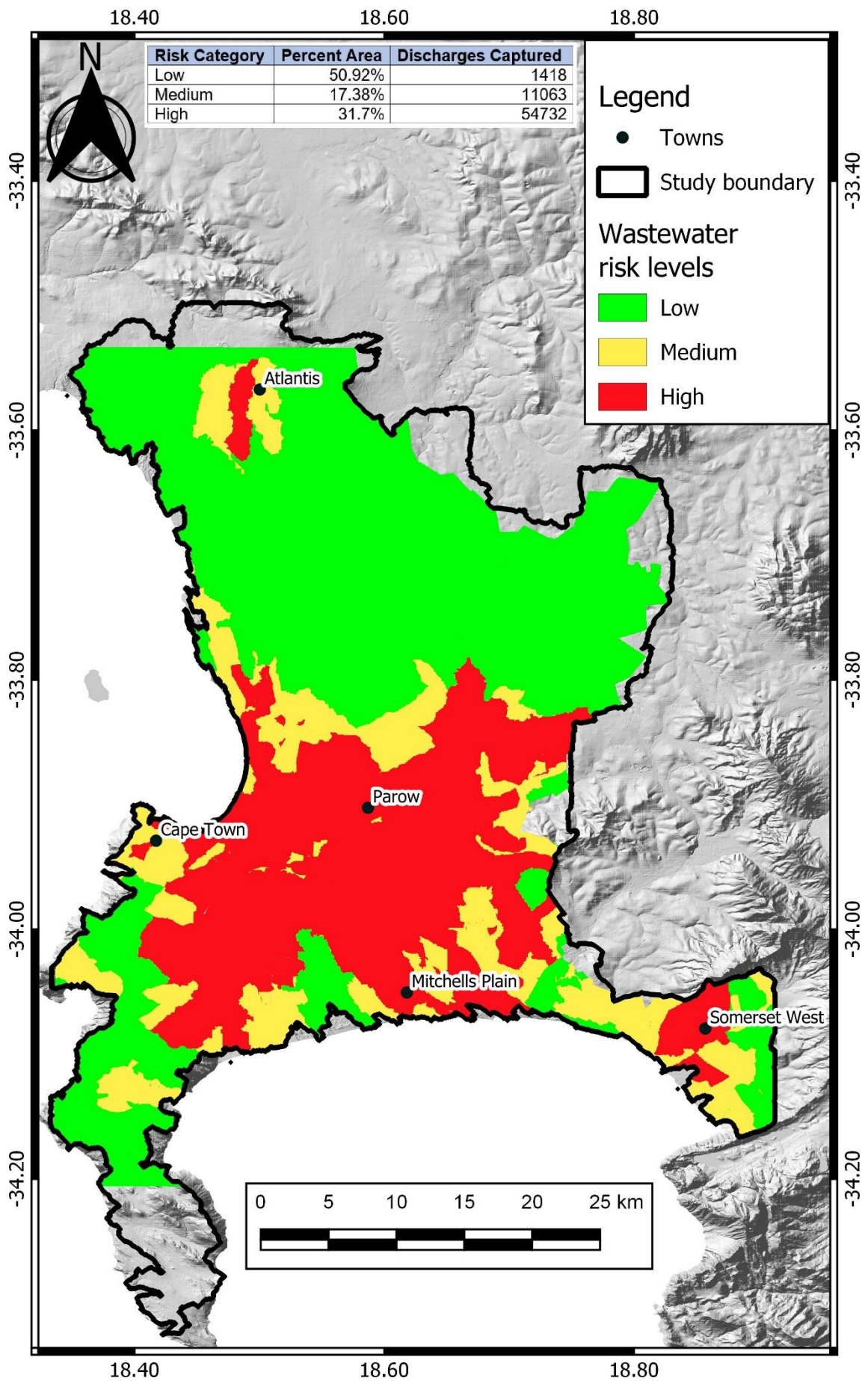


Figure F2: Wastewater composite map

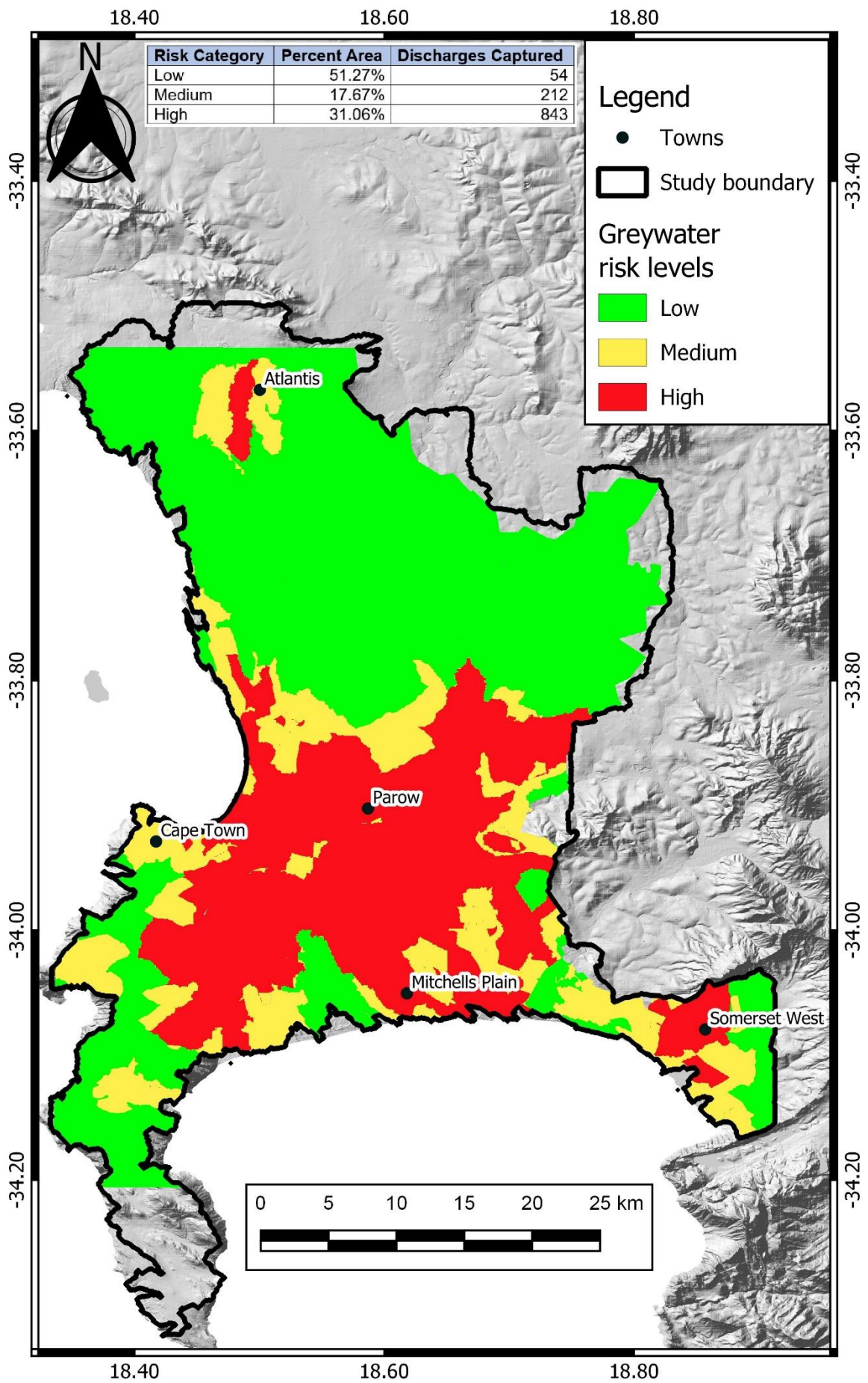


Figure F3: Greywater composite map

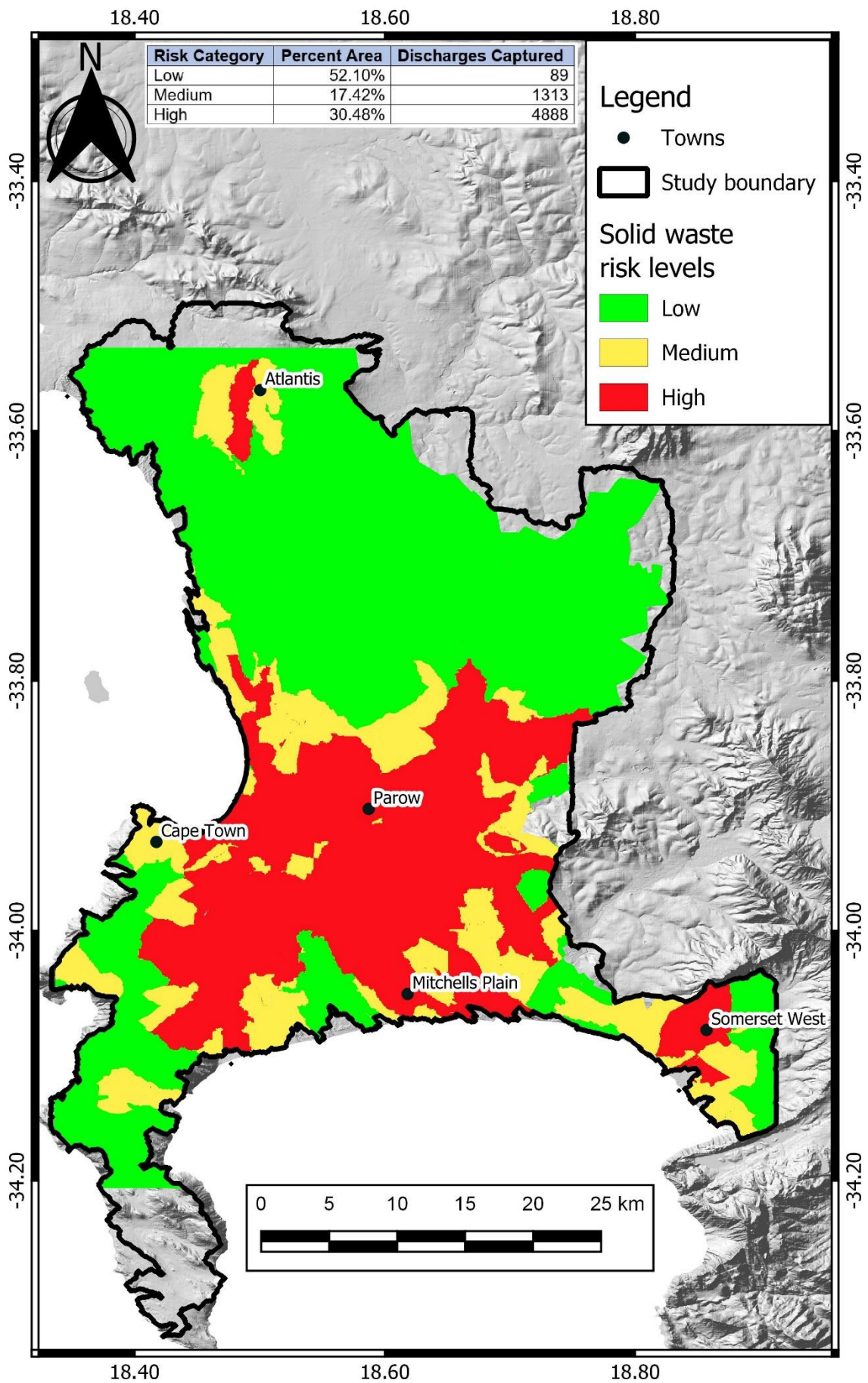


Figure F4: Solid waste composite map

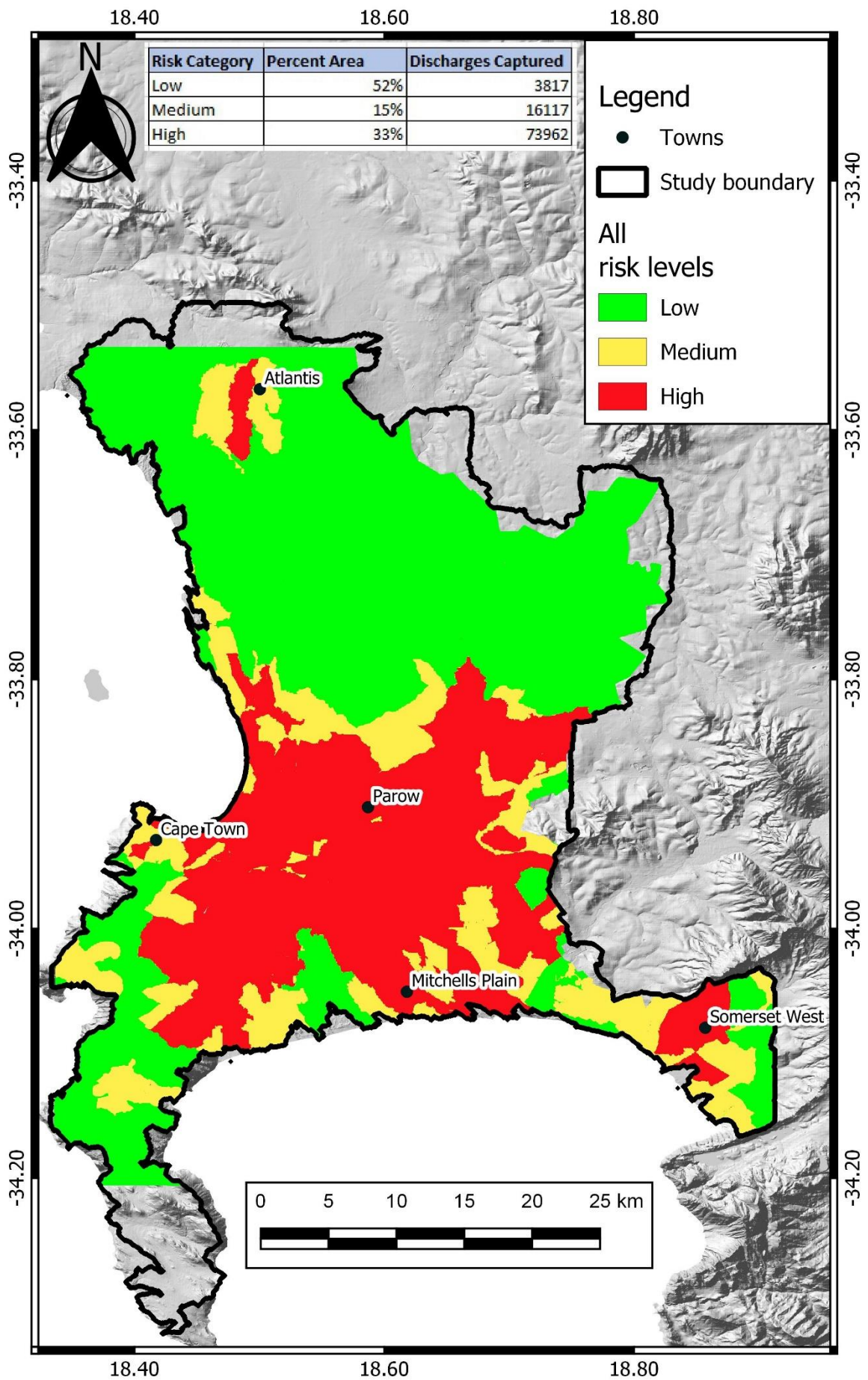


Figure F5: All/combined composite map