River Vulnerability Assessment for the eThekwini Municipality

Business Case for Durban's Transformative Riverine Management Programme

30 NOVEMBER 2020

C40 CITIES FINANCE FACILITY

Funding partners:

Federal Ministry for Economic Cooperation and Development
CIFF CHILDREN'S INVESTMENT FUND FOUNDATION
UK Government
USAID FROM THE AMERICAN PEOPLE

Implementing agencies:

giz Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH
C40 CITIES

ABOUT THE C40 CITIES FINANCE FACILITY

The C40 Cities Finance Facility (CFF) is a collaboration of the C40 Cities Climate Leadership Group and Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. The CFF supports cities in developing and emerging economies to develop finance-ready projects to reduce emissions to limit global temperature rise to 1.5°C and strengthen resilience against the impacts of a warming climate. The CFF is funded by the German Federal Ministry for Economic Cooperation and Development (BMZ), the Children's Investment Fund Foundation (CIFF), the Government of the United Kingdom and the United States Agency for International Development (USAID).

ACKNOWLEDGEMENTS

The contributions of the following eThekwini Municipality officials to the preparation of this report are appreciated: Geoff Tooley, Sean O'Donoghue, Joanne Douwes, Casandra Rajnarain, Zane Abdul and JP Calitz. In addition, grateful thanks to Shahid Solomon from GIZ for his commitment to and support of this study. Finally, thanks to Durban Solid Waste and eThekwini analytical laboratories for providing access to the relevant monitoring and water quality data.

Prepared by:

C40 Cities Finance Facility

Deutsche Gesellschaft für
Internationale Zusammenarbeit (GIZ) GmbH

Registered offices
Bonn and Eschborn, Germany

Potsdamer Platz 10
10785 Berlin, Germany

E contact@c40cff.org
W c40cff.org

Authors: Gary de Winnaar, Adrienne Louw, Mark Graham and Nicola Mander

www.groundtruth.co.za

www.futureworks.co.za

EXECUTIVE SUMMARY

Rivers globally, as well as within South Africa, are one of the most threatened ecosystem types. They play a vital role in delivering benefits to society through the provision of ecosystem goods and services. Rivers are recognised as being particularly vulnerable to the impacts of climate change and it is anticipated that their ability to deliver ecosystem goods and services may decline under a changing climate. Riverine vulnerability is driven by several factors, such as sedimentation and invasive alien plants (IAPs), which alter their ability to deliver ecosystem goods and services and thus, in turn, influence the vulnerability of the receptors dependent upon the supply of these ecosystem goods and services. In order to maintain the health of river systems, and thus the receptors dependent upon them, there is a need to improve their management, particularly within the eThekwini Municipality where approximately 95% of rivers are in a degraded condition. As such, GroundTruth in collaboration with FutureWorks has undertaken a Vulnerability Assessment to inform the climate change scenario of the Cost Benefit Analysis (CBA) and Business Case for upscaling investment in Durban's Transformative Riverine Management Programme (TRMP). The Vulnerability Assessment aimed to assess the exposure, sensitivity and adaptive capacity (i.e. the three components of climate change vulnerability) of three key receptors (i.e. vulnerability of city infrastructure to flooding, vulnerability of private infrastructure to flooding, and vulnerability of human health, aesthetics and recreation to pollution) that are linked to river systems in the eThekwini Municipality.

The river vulnerability modelling process was undertaken using four selected catchments, namely the Ohlanga, uMhlangane, Palmiet and iSipingo River systems. Modelling was done at a sub-catchment scale sized according to the management units adopted by the Sihlanzimvelo programme. A total of 12 sub-catchments were developed for the Ohlanga, 15 for the uMhlangane, 7 for the Palmiet and 5 for the iSipingo Catchments. The first step in the modelling process involved the mapping and delineation of four zones for each sub-catchment, namely the 1 in 100-year floodplain, extended river areas, a buffer of rivers and floodplains, and the remaining catchment areas. A spatial data analysis and weighting process was then undertaken to determine the spatial distribution of risks and receptors within each of the delineated river zones in each sub-catchment and thus obtain values for numerous variables such as the density of sewer manholes within each zone of a particular sub-catchment. All spatial analyses and mapping were undertaken using ArcGIS 10. Based on the defined river zones and obtained values for selected variables, spatial analysis and mapping of the exposure, sensitivity, and adaptive capacity for each of the three receptors was then undertaken. For the vulnerability of city infrastructure, the combined effects of exposure caused from flooding, sensitivity to flooding and the adaptive capacity of the river system to reduce flooding impacts were spatially modelled. Similarly, the vulnerability of private infrastructure, such as buildings associated with settlements, was spatially modelled as the combined effects of

exposure caused from flooding, sensitivity of private infrastructure to flooding and the adaptive capacity of the river system to reduce flooding impacts. Exposure of private infrastructure is the same as the exposure to city infrastructure, with exception of the added risk from debris that exacerbates risk of flooding for city infrastructure such as culverts and road crossings. Exposure to flooding for both city and private infrastructure was based a number of key drivers, including catchment slope and impervious areas. Human health, aesthetic, and recreational value vulnerability was modelled as the combined effects of exposure from pollution, sensitivity of various user groups that are exposed to pollution and adaptive capacity of the river systems to assimilate and/or ameliorate pollutants. Exposure to pollution was based on multiple key drivers, such as solid waste and sewer failures, whilst sensitivity was based on user groups dependent on river systems or areas connected with river systems. The exposure, sensitivity and adaptive capacity scores were summed for each catchment to obtain an overall vulnerability score for each sub-catchment, which were then averaged to establish the overall vulnerability of each of the four select catchments.

The spatial modelling process revealed that exposure to both flooding and pollution is highest within the iSipingo Catchment, followed by the uMhlangane, whilst sensitivity to flooding and pollution is generally highest within the Palmiet Catchment, followed by the uMhlangane. Adaptive capacity and resilience to flooding and pollution are highest within the uMhlangane Catchment, and lowest within the iSipingo. Overall, the iSipingo Catchment is the most vulnerable river system based on all three modelled key receptors, followed by the uMhlangane, Palmiet and Ohlanga respectively. Evidence from this study suggests that solid waste and sewage pollution place the greatest pressure on rivers that flow through the municipality.

The likely climate change scenario adopted for the Business Case assumes a 10% increase in daily rainfall, 20% increase in rainfall intensity and an average daily temperature increase of 2°C. However, it should be acknowledged that the vulnerability assessment of rivers and affected receptors is based on the *status quo* due to the complexity and uncertainty of modelling the anticipated future effects of climate change on exposure, sensitivity and adaptive capacity. Nevertheless, the hydrological modelling conducted by Schulze and Davis (2020) for the uMhlangane Catchment provides useful insights in terms of projected climate change impacts and the implications for river vulnerability. It is anticipated that there will be an increase in the frequency of 1 in 10 year floods, with a disproportionate increase in sediment yields within the catchment. Similar climatic impacts are anticipated for the rest of the municipality and these will likely exacerbate the threats and pressures currently facing eThekwini's river systems. It is thus anticipated that eThekwini's river systems will become increasingly vulnerable under a changing climate and that there is a need to manage the impacts on river systems if the future well-being of rivers and those dependent upon them are to be sustained and protected.

CONTENTS

About the C40 Cities Finance Facility 2

Acknowledgements 2

EXECUTIVE SUMMARY 3

1. INTRODUCTION 7
  1.1 Project Background 7
  1.2 Riverine Vulnerability and Vulnerability Assessments 7
  1.3 Drivers of River Vulnerability 8
    1.3.1 Invasive Alien Plants (IAPs) 9
    1.3.2 Sedimentation 9
    1.3.3 Sewage pollution 10
    1.3.4 Solid waste 10
    1.3.5 Flooding and flow alteration 10

2. BACKGROUND TO RIVERS OF ETHEKWINI 11
  2.1 Overview 11
  2.2 Health and Ecological State of Rivers 13
    2.2.1 eThekwini STATE OF RIVERS (2006 and 2007) 13
    2.2.2 The 2018 National Biodiversity Assessment (NBA) for rivers 13
    2.2.3 The 2017-2018 National State of Rivers (SoR) 14
  2.3 Threats to River Ecosystems 15
    2.3.1 Present land use and land cover 16
    2.3.2 Sewage pollution 18
    2.3.3 Solid waste 19
    2.3.4 Flooding and sedimentation 21
    2.3.5 Invasive Alien Plants (IAPs) 22

3. RIVER VULNERABILITY MODELLING 24
  3.1 Defining an Appropriate Catchment Scale for Analysis 24
  3.2 Selection of Ecosystem Services and Key Receptors 24
  3.3 Mapping and Delineation of River Areas 26
  3.4 Spatial Data Analysis 27
  3.5 Weighting Values from Input Variables 28
  3.6 Vulnerability of City Infrastructure 29
    3.6.1 Exposure of city infrastructure to flooding 30
    3.6.2 Sensitivity of city infrastructure to flooding 32
    3.6.3 Adaptive capacity for flooding 34

3.6.4 City infrastructure vulnerability ... 36
3.7 Vulnerability of Private Infrastructure ... 37
3.7.1 Exposure of private infrastructure to flooding ... 37
3.7.2 Sensitivity of private infrastructure to flooding ... 38
3.7.3 Adaptive capacity for flooding ... 39
3.7.4 Private infrastructure vulnerability ... 41
3.8 Human Health, Aesthetics, Recreation Vulnerability ... 42
3.8.1 Exposure to pollution ... 42
3.8.2 Sensitivity to pollution ... 43
3.8.3 Adaptive capacity of rivers to assimilate pollutants and trap waste ... 45
3.8.4 Vulnerability to human health, aesthetics, and recreation ... 47
3.9 River Vulnerability Summary ... 48
4. CLIMATE CHANGE IMPLICATIONS ... 50
3.1 Alien Vegetation ... 50
3.2 Flooding ... 51
3.3 Sedimentation ... 52
3.3. Pollution from sewerage and solid waste ... 52
5. REFERENCES ... 53

1. INTRODUCTION

1.1 Project Background

FutureWorks has been appointed to prepare a Business Case for upscaling investment in Durban's Transformative Riverine Management Programme (TRMP). The Business Case will be informed by a Cost Benefit Analysis (CBA) that compares a range of potential future investment scenarios for riverine management on municipal, private and traditional authority land in riverine areas. FutureWorks appointed GroundTruth to undertake a Vulnerability Assessment of river systems that forms an important component for developing the CBA and Business Case.

One of the scenarios to be modelled in the CBA is that of climate change. This scenario will seek to articulate how the costs and benefits of riverine corridor management may shift in response to climate change. The climate change scenario will be informed by a vulnerability assessment which will assess the exposure, sensitivity, and adaptive capacity of a number of key receptors linked to river systems, such as municipal infrastructure and human health, in order to determine their vulnerability to various risks associated with rivers, such as flooding and solid waste. The modelling of vulnerability is to be done using four catchments as proxies and assumptions from global climate change modelling.

1.2 Riverine Vulnerability and Vulnerability Assessments

River systems are recognized as being particularly vulnerable to the impacts of climate change. This is largely due to the fact that they are influenced, directly and indirectly, by changes in temperature and precipitation and often have a long history of degradation (Capon *et al.*, 2013; Friggens and Woodlief, 2015; Tickner *et al.*, 2020). Freshwater systems are known to provide a host of services to society and possess approximately 10% of all earth's species (Tickner *et al.*, 2020). These freshwater systems, and much of their associated biodiversity are at risk globally (Tickner *et al.*, 2020).

The Intergovernmental Panel on Climate Change (IPCC) identifies three components of climate change vulnerability: exposure, sensitivity, and adaptive capacity. These are defined as follows:

- ***Exposure*** the '*nature and degree to which a system is exposed to significant climatic variations*';
- ***Sensitivity*** the '*degree to which a system is affected, either adversely or beneficially, by climate-related stimuli*'; and
- ***Adaptive* capacity** the '*ability of the system to adjust to climate change, including climate variability and extremes, to moderate potential damages, to take advantage of opportunities, or to cope with the consequences*' (GIZ, 2014).

Vulnerability assessments are thus the process for "*assessing, measuring and/or characterizing the exposure, sensitivity, and adaptive capacity of systems to climate* *change*" (Nelitz *et al.*, 2013). The interdependence between the three vulnerability components is shown in **Figure 1**, as adapted from the IPCC by Petrie *et al.* (2014).

Understanding vulnerability, in terms of its distribution and drivers, provides crucial insights to help inform decision making regarding climate change. Riverine vulnerability assessments are a useful tool for identifying the key aspects of vulnerability and allow for the prioritization of adaptive management options and the development of robust adaptation measures. It is therefore evident that vulnerability assessments have the potential to play an important role in enhancing the sustainable management of rivers, particularly in the light of increased hydrological pressures related to climate change (Corobov *et al.*, 2013; Friggens and Woodlief, 2015; Gain *et al.*, 2012).

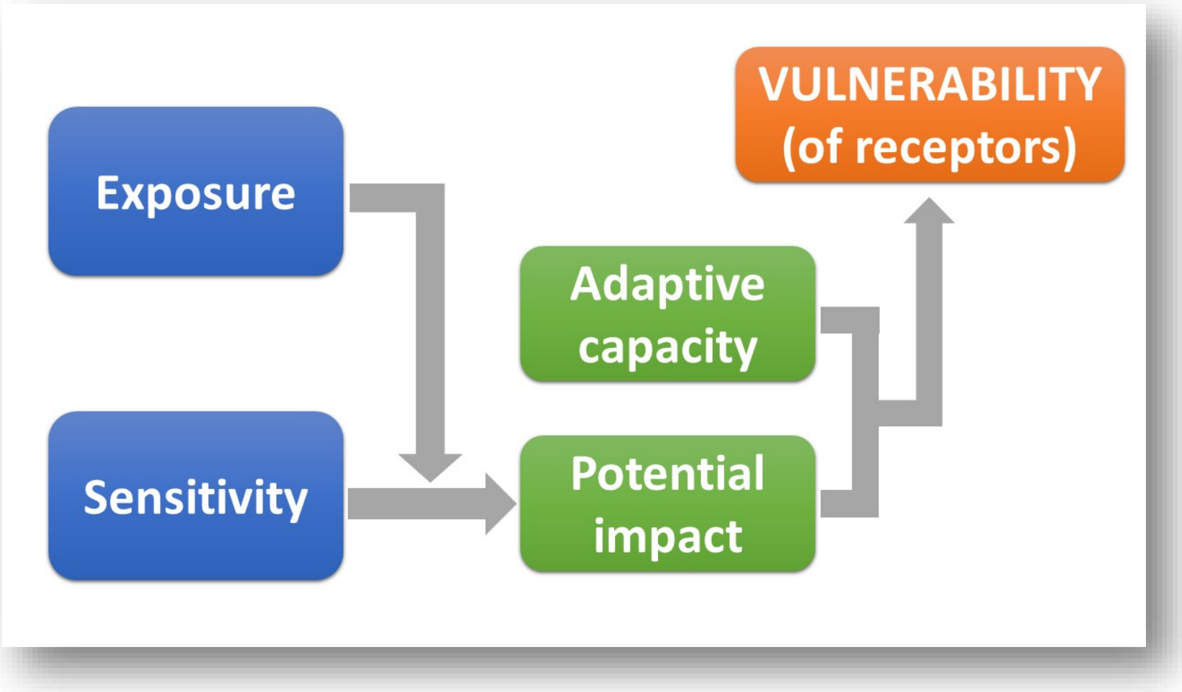

Figure 1: Key components of vulnerability assessment (after Petrie et al., 2014).

This study incorporates a detailed spatial modelling process of key and selected catchments in eThekwini to combine multiple variables of exposure, sensitivity and adaptive capacity (as per the components of **Figure 1**) to map and prioritise catchment areas based on the vulnerability of river systems to impacts from future climate change.

1.3 Drivers of River Vulnerability

Riverine vulnerability is driven by several factors that influence the vulnerability of the river system, as well as the vulnerability of the receptors dependent upon the ecosystem goods and services that these systems provide. Some of the key drivers of riverine vulnerability include invasive alien plants (IAPs), sedimentation, sewage pollution, and solid waste. The eThekwini Integrated Development Plan (IDP) identifies 11 main risks and impacts to eThekwini riverine systems. These are:

- IAPs
- Sediment control
- Catchment degradation
- Urban stormwater management
- Flood risk management
- Riverbank erosion and stabilisation
- Poor water quality
- Solid waste management
- Negative biodiversity impacts
- Sand mining

The impacts of these drivers, or risks, are likely to be exacerbated by a growing human population and changing climate. For example, warming temperatures and increased precipitation may result in an increase in IAP densities, whilst increased flooding events may result in an increase in the deposition of solid waste in river systems. For the purpose of this study five key vulnerabilities were identified, namely IAPs, sedimentation, sewage pollution, solid waste, and flooding and flow alteration. Each of these are discussed in further detail below.

1.3.1 Invasive Alien Plants (IAPs)

IAPs are of major concern, being recognised as one the main direct drivers of global biodiversity decline (Pyšek *et al.*, 2020). River ecosystems are particularly vulnerable to invasion by IAPs. This is largely due to their dynamic hydrology and frequent disturbance regime, and the fact they act as corridors for the dispersal of propagules (Richardson *et al.*, 2007; Tickner *et al.*, 2001). Flooding events often remove riparian vegetation, thereby creating a niche for the establishment of IAPs. These species are classic pioneer species and often establish rapidly and have a greater potential to rapidly respond to changing environmental conditions than indigenous vegetation, thus allowing them to outcompete indigenous vegetation (Capon *et al.*, 2013; Roger *et al.*, 2015). Increased temperatures and carbon dioxide (CO_2) levels under current and projected climate change are also likely to favour many of the IAPs. IAPs can have numerous negative impacts on river ecosystems, including a reduction in native biodiversity, a decline in the supply of ecosystem goods and services, increased risk of native species extinctions and an alteration of ecosystem productivity, nutrient cycling, hydrology, geomorphology and disturbance regimes (Downey and Richardson, 2016; Jia *et al.*, 2016; Pyšek *et al.*, 2020). IAPs pose an additional threat to municipal and private infrastructure as their proliferation in the riparian zone results in their accumulation as debris when scoured from riverbanks, and increases the blockage of, and damage to, infrastructure during flooding.

1.3.2 Sedimentation

The accumulation of sediment in rivers is a key driver of riverine vulnerability. Sedimentation is closely linked with erosion and sand mining, with an increase in erosion in catchments often leading to an increase in the sediment load in rivers. Thus, poor catchment management can significantly contribute to the sedimentation of river systems. Sedimentation alters the water quality of rivers (including water temperature), thus negatively influencing their ability to deliver ecosystem goods and services. In addition to the direct impacts to rivers, sedimentation also impacts the receptors of river systems in several ways. For example, the deposition of sediment in culverts may lead to blockages and, in turn, exacerbate the impacts of flooding (Furniss *et al.*, 1998; Gillespie *et al.*, 2014).

1.3.3 Sewage pollution

Sewage pollution of river systems is a major contributing factor to the vulnerability of these systems. It emanates from discharging manholes, poorly serviced and maintained infrastructure, and poorly functioning wastewater treatment works (WWTW). Sewage discharge into rivers leads to a deterioration in water quality, altering both the physico-chemical and microbiological aspects of the water (Seanego and Moyo, 2013). The most common effects associated with sewage discharge into rivers include oxygen depletion, an increase in nutrients, such as nitrogen and phosphorous, and faecal contamination (Seanego and Moyo, 2013). These effects may result in an array of problems for rivers, as well as the receptors of rivers, including 1) eutrophication, 2) harm to freshwater fauna and flora, and 3) negative impacts on human health (Mema, 2010; Seanego and Moyo, 2013).

1.3.4 Solid waste

As the human population continues to grow, solid waste generation is rapidly increasing. This generation of solid waste is one of the main drivers of riverine vulnerability, especially in developing countries. The accumulation of solid waste in river systems results in contamination of the water, which negatively impacts its physico-chemical and biological aspects (Nwaneri *et al.*, 2018). In addition to impacting the health of river systems, solid waste has numerous consequences for the receptors of river systems. For example, a decline in water quality in response to solid waste pollution negatively impacts the health of both human and animal populations that rely on these river systems. Additionally, solid waste can result in damage to private and municipal infrastructure by causing blockages of drainage systems, thus exacerbating the impacts of flooding.

1.3.5 Flooding and flow alteration

Urbanisation results in the transformation of catchment areas by a range of “hard” (e.g. roads, residential, educational, industrial, commercial, waste-water treatment, water supply, etc.) and “soft” (e.g. gardens, parks, recreation facilities, open spaces, etc.) land use activities. Depending on the extent and distribution of urban developments, these can have a significant impact on catchment hydrology and water flows. Most notable is flooding due to the increase in hardened, impervious surfaces that effectively convert rainfall to runoff. Surface runoff generated from these areas is often collected by stormwater infrastructure such as stormwater drains and reticulation systems, which eventually discharge stormwater into the environment, often in a concentrated and uncontrolled manner. In addition to floods, urbanisation can result in a change in the natural flow/hydrology (both increases and decreases) through dams and inter-basin transfers that are linked to bulk water supply and wastewater treatment facilities.

2. BACKGROUND TO RIVERS OF ETHEKWINI

2.1 Overview

The eThekwini Municipality covers an area of 2 556 km^2 and has a population of approximately 4 million people (eThekwini Municipality, 2020). Within the municipality there are over 7 000km of watercourses and 17 main river catchments flowing into 16 estuaries along the coast (**Figure 2**). The Umlaas River no longer has an estuary as the lower reaches are canalised directly into the sea. Other river systems, such as the Umbilo and uMhlatuzana, are also completely canalised in the lower reaches, but flow into the Durban Bay. The Municipality contains 97km of coastline, along which 8 beaches are either part of, or in the process of, being internationally recognised as Blue Flag beaches (Vetchies, Anstey's, North, South, uMhlanga Main, Umdloti Main, uShaka and Westbrook, with the Umgababa and Amanzimtoti beaches under pilot for the Blue Flag project). There are 27 wastewater treatment plants within the Municipality and approximately 8 790km of wastewater pipeline (Friedrich and Kretzinger, 2012), along with numerous point and diffuse sources of pollution into the river systems. Interestingly, the municipal wastewater pipeline infrastructure is longer than the river length in the municipality.

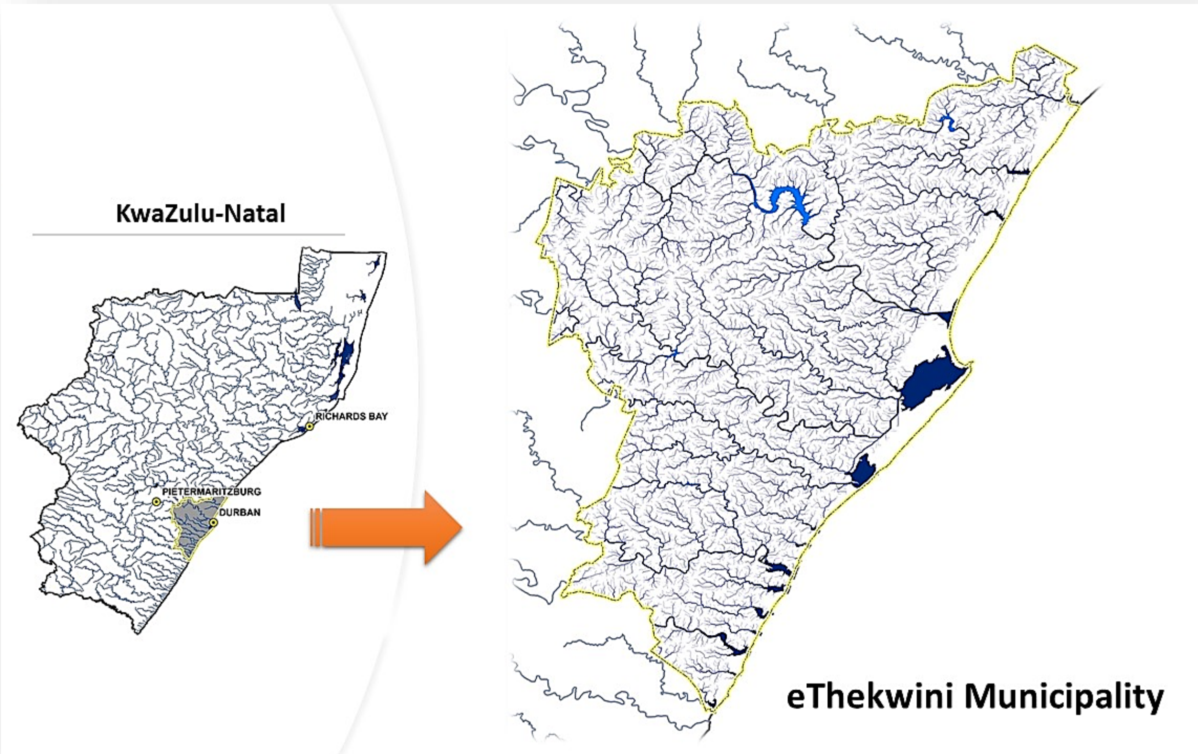

Figure 2: Overview of river systems that flow through the eThekwini Municipality (yellow boundary).

Figure 3 shows the main river catchments associated with the eThekwini Municipality The uMngeni River system is the largest catchment within the municipality, draining roughly 32% of the area, followed by the Umlaas (16%), Lovu (10%), and iSipingo/Mbokodweni (9%). Some of the smaller systems include the Little Manzimtoti, Msimbazi, Umgababa, and Ngane, all located south of Durban. A number of eThekwini's catchments, namely the uMngeni, Lovu, and Mkomazi, originate upstream of the municipality, and are thus impacted by activities occurring beyond the municipal boundary.

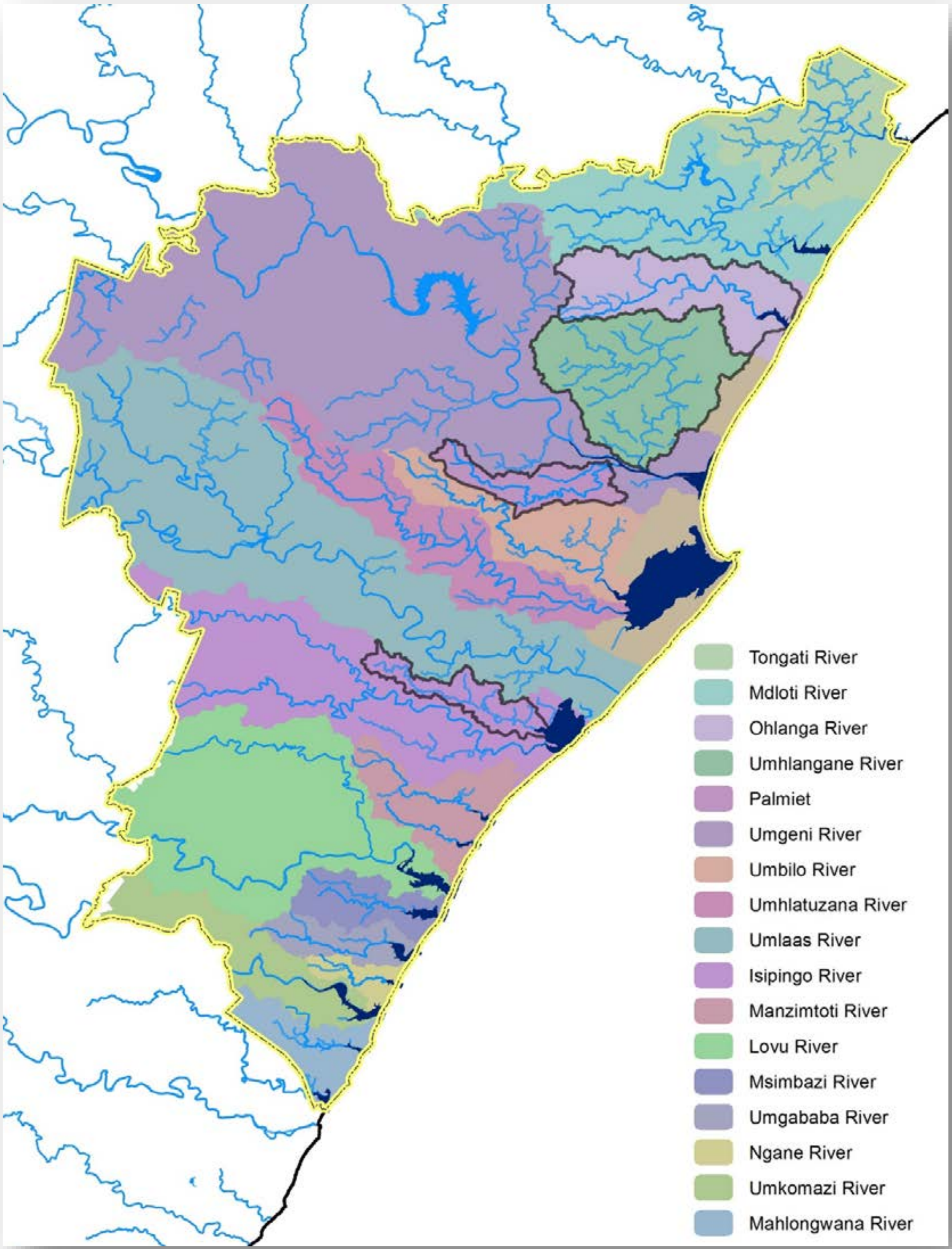

Figure 3: River catchments that are associated with the eThekwini Municipality. Catchments selected for the detailed river vulnerability assessment (Section 3) are designated by the grey lines.

2.2 Health and Ecological State of Rivers

2.2.1 eThekwini STATE OF RIVERS (2006 and 2007)

The most current State of Rivers (SoR) survey of the major rivers and tributaries in the eThekwini Municipal Area (EMA) was undertaken in 2006/2007 by GroundTruth. The purpose of this was to determine the state of health and integrity of rivers within eThekwini. Most of the sites surveyed in 2006 (some 61 sites covering 33 rivers and streams) were then resurveyed in 2007 in order to determine if any changes or trends in data between 2006 and 2007 were evident. The results of these two surveys are presented in **Table 1**.

Table 1 Summarised ecological integrity and/or health of rivers based on the high level assessment of river monitoring sites in eThekwini during the 2006 and 2007 SoR survey

Year	River Integrity / Health				
	Natural	Good	Fair	Poor	Not sampled
2006	3	20	17	21	0
2007	2	19	21	17	2

The 2006/2007 SoR surveys indicated a range of water qualities, river health conditions and impacts associated with the rivers flowing through the municipality. Between 2006 and 2007 the water quality for rivers within eThekwini was relatively consistent. The results of these surveys determined that water quality was reflective of the activities occurring upstream of the monitoring points. The SoR surveys indicated that the Aller, Mbokodweni, Isipingo, Ohlanga, Hlawe, Piesang, Mlazi, Umbilo, uMngeni and uMhlatuzana were the most polluted rivers in eThekwini. Central and northern rivers were found to be most polluted, with those in the south, and those in the upper reaches of the municipality, being less polluted. The most prevalent pollutants reported in rivers in eThekwini were *E. coli* and nutrients, namely ammonia, phosphorous and various nitrogenous compounds, usually occurring in conjunction with one another and often associated with sewerage infrastructure or treatment.

Of the 59 SoR sites sampled in 2007, 18 occur within Ngonyama Trust land – 55% of which were in a natural to good river health, 28% in a fair, and 17% in poor condition. The remaining 41 sites occur within the more urban areas. Of these, 29% were in a natural to good river health, 37% in a fair condition, and 34% in poor condition.

2.2.2 The 2018 National Biodiversity Assessment (NBA) for rivers

The 2018 National Biodiversity Assessment (NBA) seeks to:

1. Address the status of, and trends in, South Africa's biodiversity.
2. Determine whether biodiversity is being effectively managed and conserved; and
3. Ascertain how society is benefitting from biodiversity (NBA, 2018).

The 2018 NBA of rivers incorporates the 2014 DWS desktop assessment of the Present Ecological State (PES), Ecological Importance (EI) and Ecological Sensitivity

(ES) per sub-quaternary catchment (SQ4) and associated river reaches for all Secondary Catchments in South Africa (DWS, 2014). Overall, 67% of South Africa's rivers are degraded, with tributaries generally less heavily impacted than mainstream rivers (38% and 28% in a natural to near-natural condition respectively) (Van Deventer *et al.*, 2019). The 2018 NBA also reports that rivers are, in general, declining in condition.

Figure 4 summarises the PES of rivers that flow through the municipality based on the 2018 NBA. By comparison, 95% of the assessed rivers (i.e. the mainstem rivers covering 690km of the river length in the municipality) are degraded, with only the upper Mbokodweni and Mahlongwana Rivers reported to be in a good condition. No rivers are noted to be in a "natural" state and only 5% are in good condition.

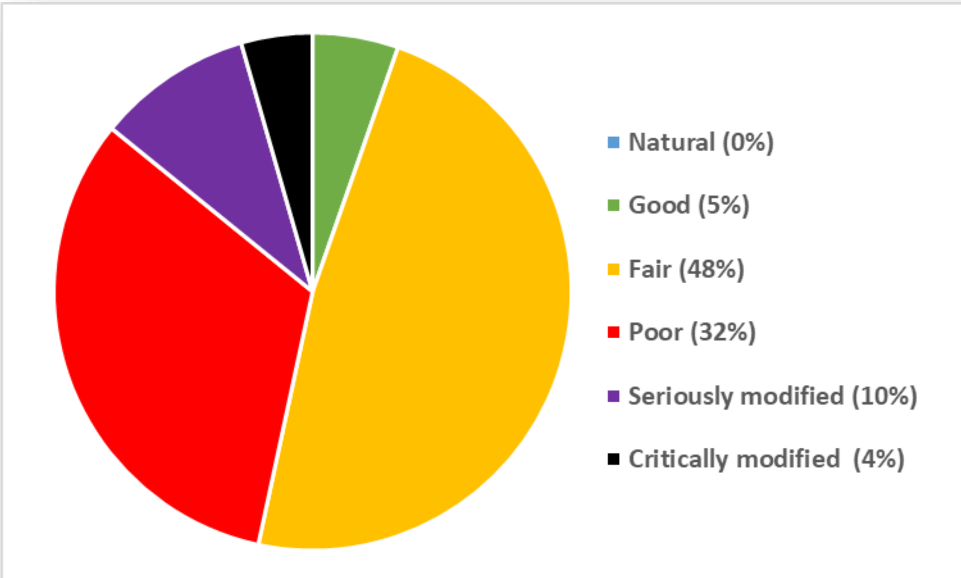

Figure 4: Present Ecological State (PES) of rivers in the eThekwini Municipal Area (2018 National Biodiversity Assessment)..

2.2.3 The 2017-2018 National State of Rivers (SoR)

In addition to the 2018 NBA, the River Ecostatus Monitoring Programme (REMP), also assesses the ecological condition of rivers at key monitoring sites across South Africa. These assessments are based only on aquatic macroinvertebrate communities, with limited sampling taking place within the municipality – only two sampling sites were surveyed in 2017, with an additional three sites surveyed in 2018. The results from the REMP for rivers within the municipality are as follows:

- the Tongati River, just upstream of the estuary, was largely to seriously modified (D/E) in 2017 with a slight improvement to largely modified (D) in 2018 – river health is most likely impacted by faecal pollution and contamination from fertilizers;
- Mdloti River, where it enters the municipality, was in a fair (C) condition in 2018;

- uMngeni River, downstream of Inanda Dam, was in a moderate condition (C) in 2017 with a slight improvement (B/C) in 2018 – impacts are largely due to flow regulation;
- Lovu River, just upstream of the estuary, was in a moderate condition (C) in 2018; and
- Mkomazi River was in a moderate condition (C) in 2018.

2.3 Threats to River Ecosystems

The 2018 NBA highlights that rivers, wetlands and estuaries are the most threatened ecosystems within South Africa. This is congruent with global trends (e.g. Tickner et al 2020). Rivers and wetlands are crucial ecological infrastructure for water security, often complementing built infrastructure such as dams and water supply schemes, but the benefits provided by these ecosystems through the provision of ecosystem services (e.g. water supply, flood regulation, water quality) are largely compromised by their poor ecological condition. The 2018 NBA also identifies five key pressures for rivers, namely:

- changes in the hydrological regime;
- water quality deterioration;
- loss and alteration of natural habitat;
- invasive alien species; and
- over-exploitation of species (Section 1.3 provides context to some of these pressures).

Currently, 64% of South Africa's 222 river ecosystem types are Threatened (i.e. they are either Critically Endangered, Endangered or Vulnerable) with only 13% considered Well Protected. Of the seven river ecosystem types that occur within the municipality, two are Critically Endangered and four are Endangered, but in terms of river length they make up 1% and 44% respectively out of the 690km of river assessed at the national scale (**Figure 5**). The remaining 55% of the rivers (or 380km) are classified as Least Threatened. However, when assessed specifically for the municipality using the condition and length of various river types all rivers are Critically Endangered. This alone highlights the necessity and importance of the TRMP currently being undertaken by the city and which is the genesis for the vulnerability assessment. Key threats that have been identified that continue to threaten the well-being of rivers within eThekwini are presented in the following sections, which form the basis for assessing river vulnerability.

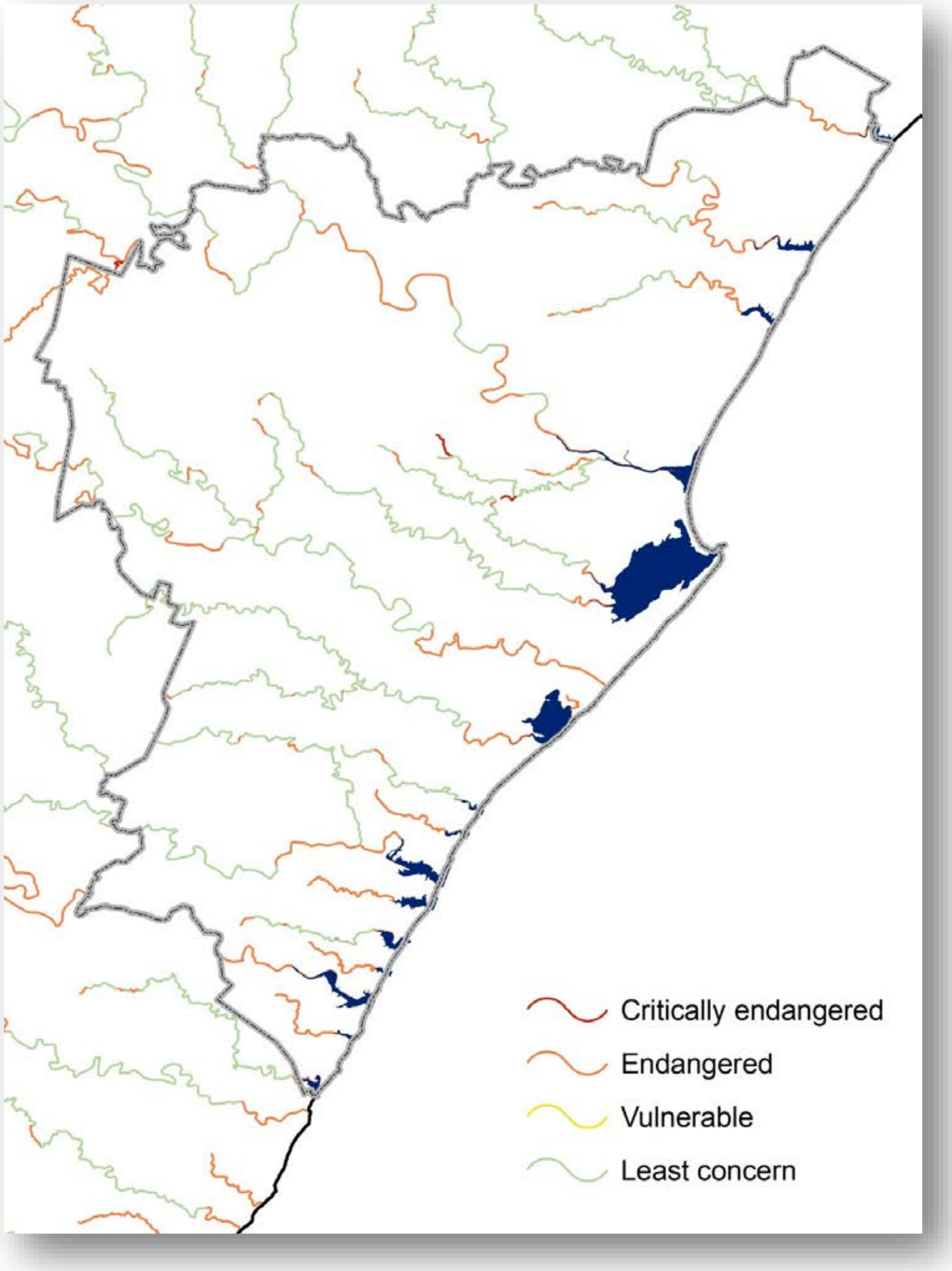

Figure 5: Threat status of rivers that flow through the eThekwini Municipality based on the 2018 National Biodiversity Assessment

2.3.1 Present land use and land cover

Roughly 42% of eThekwini's river corridors (defined here as the land 100m adjacent to rivers) are transformed. Transformation is largely in the form of urbanisation made up of formal residential (21%), industrial/commercial development (6%), and informal residential (3%) that is concentrated around the city of Durban. Agricultural production (predominantly sugarcane), rural areas, and dams make up a smaller portion of the transformed land (6%, 5%, and 4% respectively). The remaining 58% of the river corridors are comprised largely (40%) of woody vegetation as either forest, woodland, or thicket with varying degrees of disturbance and invasive alien plant infestations, while 16% comprises "grassy" vegetation.

The level of transformation of areas adjacent to rivers can significantly influence how resilient the river systems will be in response to system drivers and pressures (e.g. flooding, water quality impacts, solid waste pollution, etc.), particularly considering future climate change impacts. **Figure 6** illustrates the degree of transformation by making use of a transformation index calculated from the relative portion of river corridors and areas adjacent to river corridors that have been transformed by land use activities based on the South African National Land Cover (SANLC) dataset from 2018 (DEA, 2019). The river corridors for all of the main catchments within the municipality are noticeably more transformed than the catchment areas that are outside the river corridors (**Figure 6**). This highlights the underlying trend whereby river ecosystems are under increasing pressure, and which corroborates the trends and threats affecting rivers in the 2018 NBA.

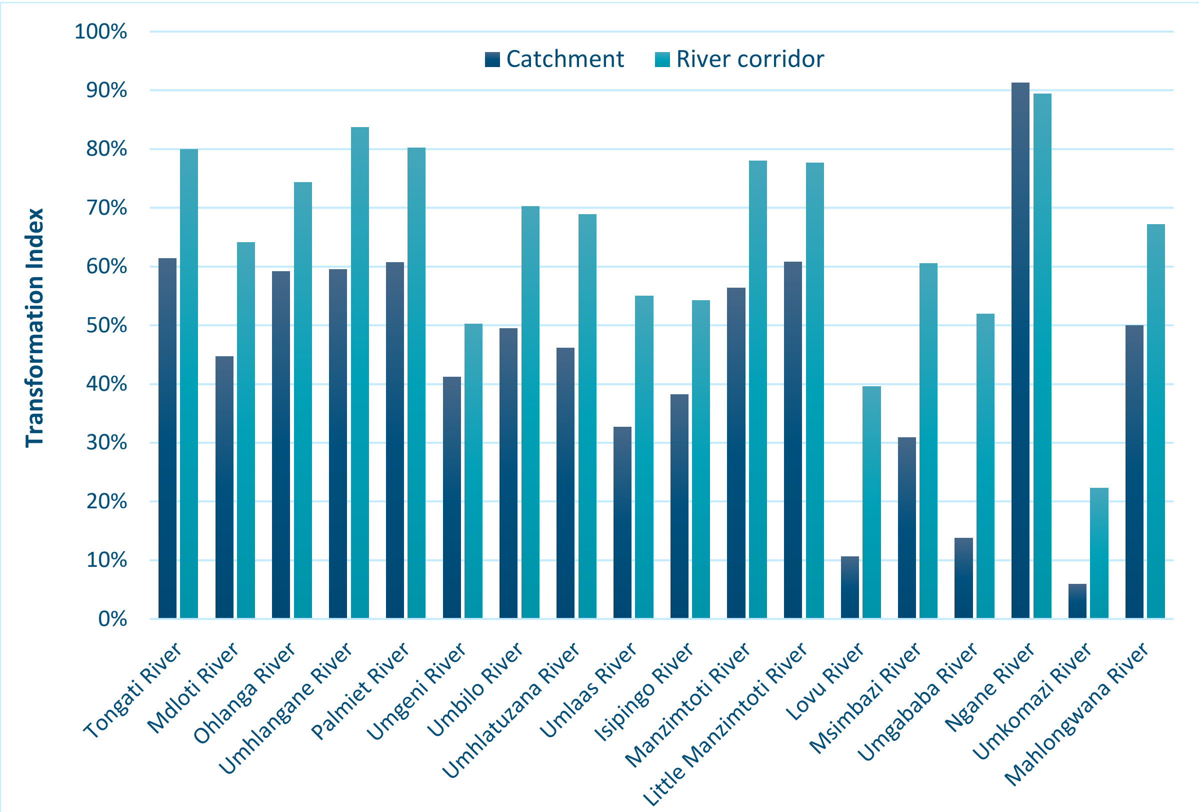

Figure 6: Relative transformation of river catchments and river corridors within the eThekwini Municipality

This situation of river corridor transformation varies across the municipality with some catchments, such as the Lovu, Umgababa and Umkomazi, being considered more resilient/better buffered from land use impacts. The small Ngane River Catchment (only around 1,500 ha) on the south coast on the other hand has been heavily transformed such that only 10% remains untransformed, both within the river corridor and broader catchment. Associated drivers and pressures emanating from land use activities that affect rivers system also varies across the municipality as presented in the following sections.

2.3.2 Sewage pollution

There are over 290 000 sewer manholes within the municipality that are linked to 8 450 kilometres of sewer pipes and over 280 pump stations that carry raw sewage to the 35 WWTWs. This infrastructure is constantly failing from a lack of maintenance, which is exacerbated by blockages caused from improper use by people and damage from flooding events. The combined effects of these pressures on the sewer systems is resulting in increasing leaks and surcharges, often raw sewage directly into rivers, largely because sewer infrastructure traverses the lowest points in the landscape (**Figure 7**), along with the rivers

Figure 7: Raw sewerage flowing directly into the Palmiet River (right) because of damaged sewer infrastructure (left)

An analysis of reports of sewer manhole data presents an alarming number of reported failures or issues throughout the municipality, with an increasing trend since 2016 (**Figure** 5 **8**). On average, there were between 80 and 93 reported failures over this period. Lamont, an average sized (403 ha) suburb in the Lamontville area south of Durban, consistently reported the highest number of failures, ranging from 788 in 2016 to 880 in 2019, with a spike in 2017 of 922 failures.

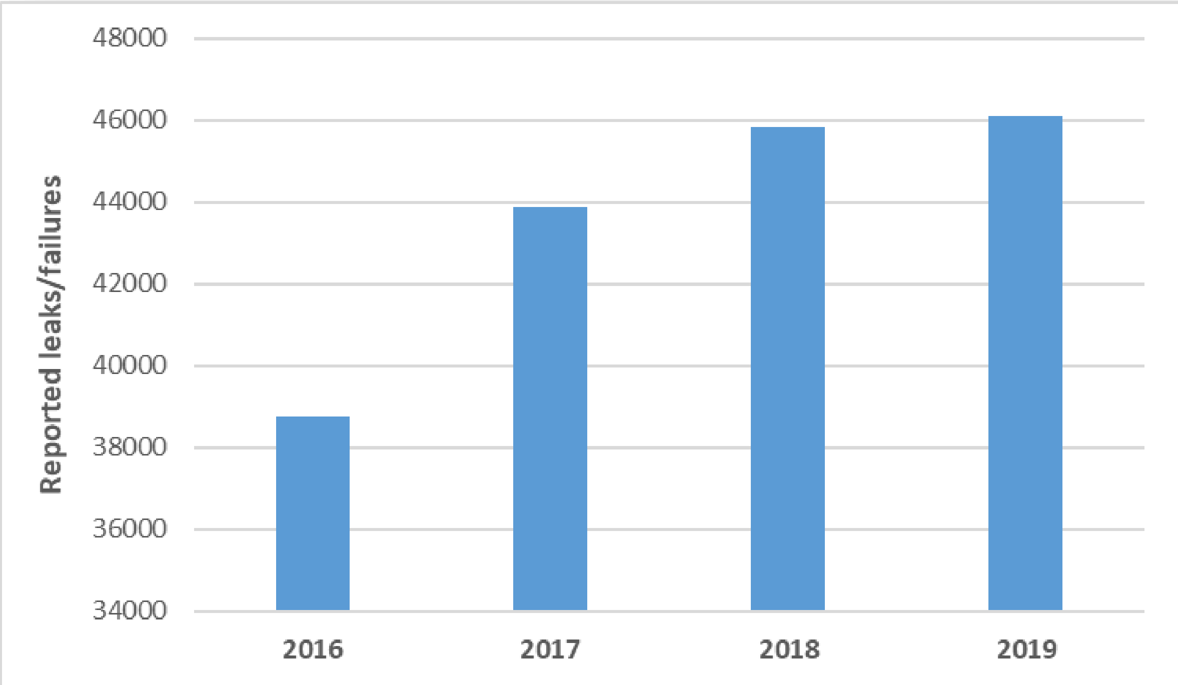

Figure 8: Total reported leaks and failures per annum in eThekwini

2.3.3 Solid waste

Globally, over 320 million tons of plastic are produced every year, of which an estimated 5% enters oceans (Jambeck *et al.*, 2015). South Africa is a significant contributor, and is ranked 15th in the world, producing up to 2 million tons of municipal solid waste every year. Urban centres such the City of Durban are obvious hotspots for solid waste pollution, hence the focussed study on plastic pollution as part of the recent source-to-sea study conducted in the lower uMngeni River system (NIRAS and GroundTruth, 2019).

Of the waste that is generated, significant amounts enter rivers that flow through the municipality. The recent flooding event in Durban was a case and point whereby massive volumes of solid waste was carried by flood waters down river systems only to be deposited along the beaches of Durban (NIRAS and GroundTruth, 2019).

These trends and pictures are becoming increasingly common occurrences in the municipality.

Figure 9: Scenes from the April 2019 floods in Durban where massive volumes of plastic waste was deposited along beaches (after NIRAS and GroundTruth, 2019)

Sources of solid waste originate mainly within the urban areas, particularly from informal townships where there is poor service delivery and ineffective waste collection systems, which occupy roughly 10% of the municipality, and illegal dumping sites (**Figure 10**). Solid waste is then carried along various flow paths or is blown by wind landing up within river systems, estuaries (including Durban Bay), and eventually the Indian Ocean. Stormwater drain outlets often collect solid waste carried by stormwater runoff from roads and other developed/hardened catchment areas, which eventually discharge (often in a direct manner) into the aquatic environment/rivers downstream, and ultimately into estuaries and the ocean. Road networks and river crossings not only provide concentration and channelling of solid waste flows into aquatic environments, but are also access points for illegal dumping, often associated with poorly serviced municipal areas and notably the traditional townships and informal housing.

Figure 10: Informal settlements are an obvious source for waste pollution entering into river due to poor solid waste management and ineffective waste collection systems (left) as are the numerous sites of illegal from dumping (right)

2.3.4 Flooding and sedimentation

Increased runoff from hardened areas within the eThekwini Municipality has amplified the flooding response of catchments. The effect on runoff is exacerbated within densely populated urban areas, especially when combined with the network of roads and stormwater infrastructure. Within the municipality there are approximately 12 650km of road, 3 500km of stormwater pipes and over 170 000 stormwater manholes that are largely concentrated within the urban areas. An analysis of impervious surfaces developed from remoted sensing by the city indicates that roughly 20% of the municipality comprises hardened surfaces made up by roofs, roads, parking areas, etc. Impacts from flooding are becoming more frequent, resulting in increased costs to the City as well as people living along river systems (**Figure 11**). Increased flooding also drives other secondary impacts such as a soil erosion, bank collapse, and sedimentation. These effects are in turn exacerbated by other system drivers such as infestation of riparian areas by IAPs, not to mention the added pressure on city infrastructure through sediment build-up upstream of river crossings (**Figure 11**). A major hydrological reset exists for the uMngeni River due to the presence of Inanda Dam, which effectively attenuates flooding in the uMngeni Catchment. This is repeated, to a lesser degree, by other impoundments on various other catchments, for example the Hazlemere Dam on the Mdloti River.

Figure 11: Increased flooding presents a risk to city infrastructure such as bridges and culverts, especially when flood waters are loaded with debris and solid waste (left). Flooding also poses a serious threat to informal settlements that often are positioned right of the edge of riverbanks (right)

2.3.5 Invasive Alien Plants (IAPs)

IAPs are a constant threat to the natural open spaces within the eThekwini Municipality, which has been subject to a long history of invasions. Infestations are potentially more problematic along river systems, which often are the only natural open spaces remaining in the landscape. In these situations, IAP thrive due to both natural and anthropogenic disturbances such as flooding, bank erosion/collapse, vegetation clearing, illegal dumping, etc. Furthermore, the reduction and fragmentation of natural open spaces within the municipality results in an increase in the ratio of edge to patch size (Mavimbela *et al.*, 2018). This means that open spaces are becoming increasingly disturbed around the edges, giving IAPs more of a competitive advantage over indigenous species.

Although it is well-known that IAPs are a serious problem in the municipality, knowledge of the extent and distribution of IAPs, as well as diversity and abundance of problematic species, is largely limited especially in relation to catchments and river systems. Recent assessment and mapping of IAPs within the Palmiet Catchment identified a number of different IAP species and infestation hotspots occurring along the Palmiet River (**Figure 12** and **Figure 13**). Most notable IAPs in terms of frequency of occurrence and abundance that were recorded included: Napier Grass (*Pennisetum purpureum*); Mexican Sunflower (*Tithonia diversifolia*); Saligna Gum (*Eucalyptus grandis*); Castor-oil Plant (*Ricinus communis*) and Syringa (*Melia azedarach*).

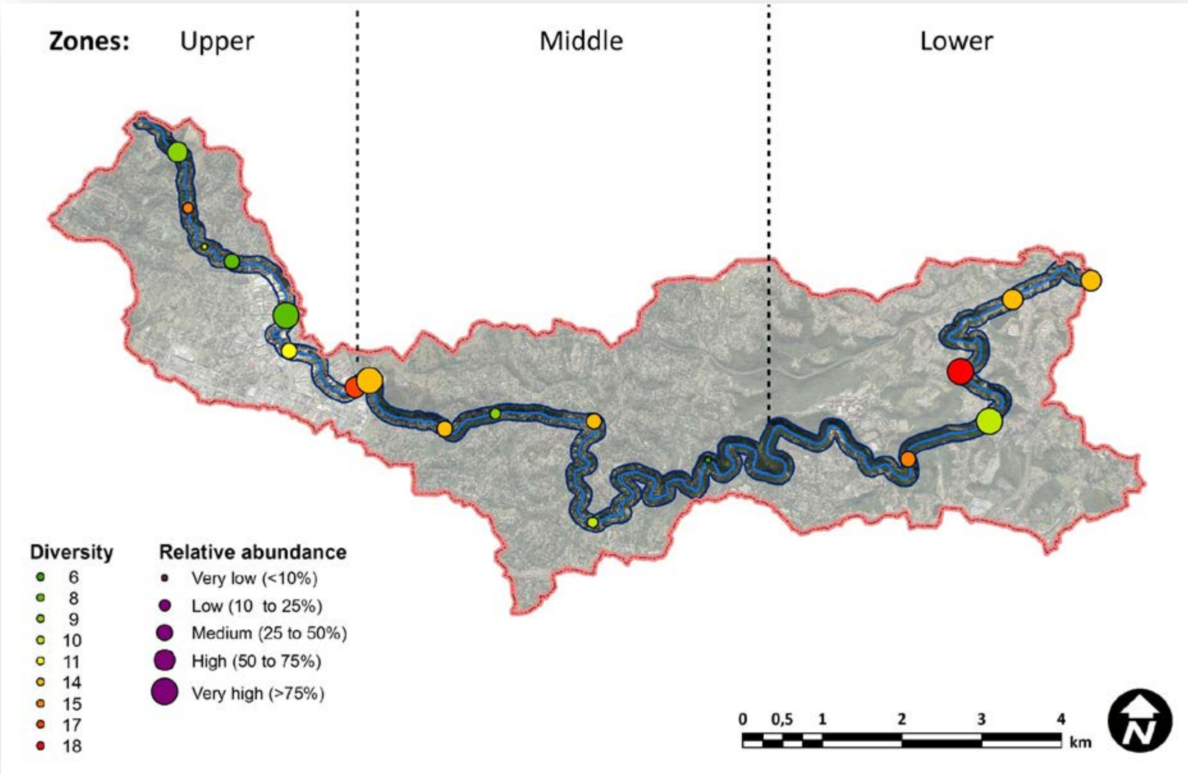

Figure 12: The Palmiet River system within the Pinetown area, dominated by invasive alien plants

Figure 13: The Palmiet River system within the Pinetown area, dominated by invasive alien plants

C40 CITIES FINANCE FACILITY

3. RIVER VULNERABILITY MODELLING

A river vulnerability modelling process was undertaken for the four selected catchments to assess the vulnerability of the key receptors based on the evaluation of the ecosystem services delivered by river systems (see Section 3.2). The modelling methodology is detailed below.

3.1 Defining an Appropriate Catchment Scale for Analysis

River systems in South Africa are typically categorised according to several primary catchments (22 in total). Nested within each primary catchment are smaller catchment units, namely secondary (148 in total), tertiary (278 in total) and quaternary catchments (1946 in total). Sub-quaternary (SQ4) catchments are the smallest spatial unit typically used in South Africa. Out of the total 9 433 SQ4 catchments in South Africa, 47 occur within the eThekwini Municipality. The municipality uses an even finer catchment scale resolutions – referred to as minor catchments, of which there are a total of 2 132 within the municipal area.

For this study, four selected river systems were chosen to assess their vulnerability, as well as to inform the overall business case within the broader TRMP. These catchments include the Ohlanga, uMhlangane, Palmiet and iSipingo (hereafter referred to as the "selected catchments" – see **Figure 2**). These catchments were considered largely on the basis that they have received significant attention in recent years, particularly through the development and implementation of various river management programmes such as the Sihlanzimvelo Stream Cleaning Project, the Palmiet River Rehabilitation Programme, and the Wise Wayz Water Care Project.

A total of 328 of the eThekwini's minor catchments occur within the selected catchments. These minor catchments were aggregated up to align more with the spatial scale adopted by the Sihlanzimvelo programme making up 12 for the Ohlanga, 15 for the uMhlangane, 7 for the Palmiet and 5 for the iSipingo Catchments (referred to hereafter as "sub-catchments"). These sub-catchments form the planning unit for this study to prioritise areas in terms of vulnerability and to provide focus for appropriate possible future interventions.

All spatial data obtained for the river vulnerability assessment was analysed using GIS and assigned to each sub-catchment for the four selected catchments.

3.2 Selection of Ecosystem Services and Key Receptors

It is widely recognized that river systems provide a range of ecosystem goods and services on which society is highly dependent (Gilvear *et al.*, 2013; Palmer *et al.*, 2009). The Millennium Ecosystem Assessment (2005) identifies a comprehensive suite of ecosystem goods and services derived from freshwater ecosystems and classifies these as being either regulating, provisioning, supporting or cultural. The ability of a river to provide goods and services is dependent upon its ecological condition which, in turn, is influenced by a number of factors, such as surrounding land use and climate change (Burkhard *et al.*, 2014; Grizzetti *et al.*, 2019). The generalized relationship between aquatic ecosystem ecological condition and the ability to supply ecosystem goods and services is illustrated in **Figure 14**.

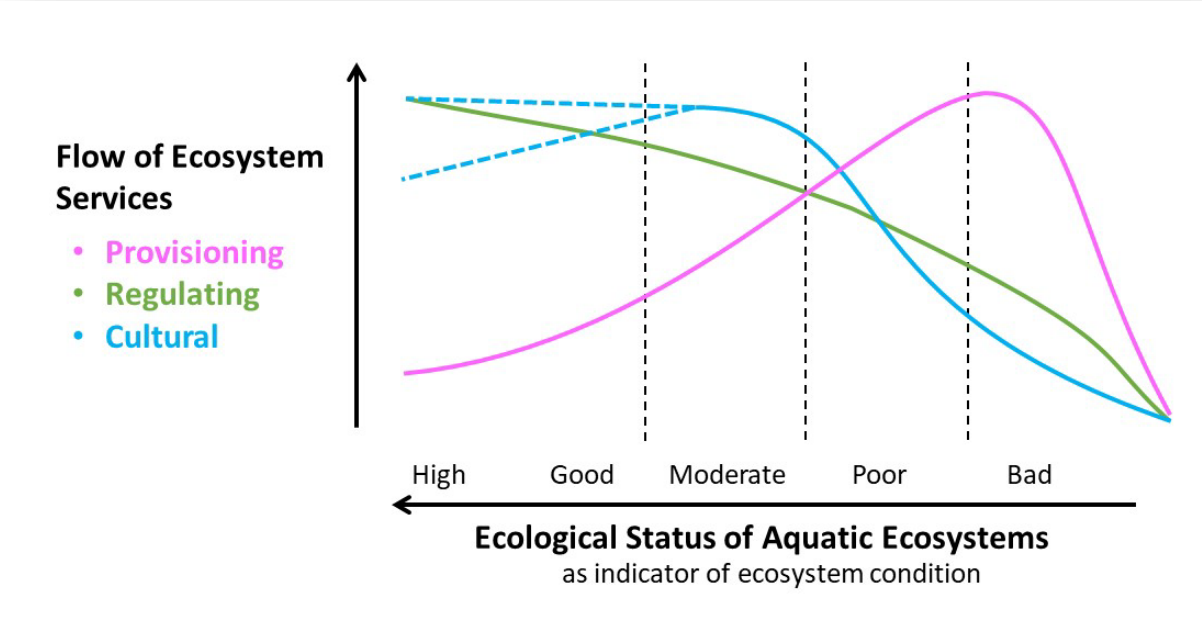

Figure 14: Modelled changes to ecosystem services in response to changes in ecological status of aquatic (riverine) ecosystems (after Grizzetti et al., 2019).

Although numerous ecosystem services are derived from river systems, not all of these are likely to be applicable in the context of the eThekwini Municipality. In order to identify those most relevant to the eThekwini Municipality, and that could be influenced by the implementation of riverine management programmes, the comprehensive list of ecosystem services was distilled to a subset of the most significant ones of greatest relevance to eThekwini, namely :

- Surface water supply
- Water quality maintenance
- Flood reduction
- Recreation
- Erosion control and sediment reduction

A change in supply or state of these services has numerous impacts on infrastructure, the health and well-being of dependent communities, and economic activities within the municipality. It is anticipated that climate change will exacerbate the risks already faced by rivers, such as through increased erosion and sedimentation, and reduce their ability to deliver ecosystem goods and services (Palmer *et al.*, 2009). Based on the ecosystem services identified as being relevant to the eThekwini Municipality, receptors within eThekwini that are likely to be impacted by, or vulnerable to, a change in supply of these services have been identified based on a first principles approach and through discussion with key stakeholders. It is anticipated that the following key receptors will be vulnerable to a change in the supply or state of the selected riverine ecosystem services:

- City infrastructure
- Private infrastructure
- Human health and recreational/aesthetic/spiritual value
- Crops and livestock

Within the resource constraints of the project, the crops and livestock receptor was not assessed on the basis that these are considered less important in terms of overall river vulnerability within eThekwini. **Table 2** below shows the key ecosystem services and their relationship (from week to strong) with the three selected receptors.

Table 2 Strength of the relationship between ecosystem se/service and receptors selected for the Vulnerability Assessment. Green indicates a strong relationship, orange a moderate relationship, and red a week/no relationship

Ecosystem Services	City infrastructure	Private infrastructure	Human health/ aesthetics/ recreation
Freshwater supply			
Crops			
Fodder and livestock			
Water purification & nutrient regulation			
Erosion prevention			
Flood protection			
Pest & disease control			
Waste regulation (e.g. solid waste)			
Recreation/tourism/ religious/ aesthetic			
Biodiversity (e.g. pollination)			

3.3 Mapping and Delineation of River Areas

Areas associated with the rivers draining the selected sub-catchments were mapped using the 1 in 100 year floodplain (polygon) and river (line) layers provided by the city. The rivers layer was classified into river orders according to the Strahler Stream Ordering method[1] (Strahler, 1957). River orders were also used to order, and then buffer the 1 in 100 year floodplains to provide a more extensive river management zone that can account for future climate change impacts. The buffers were applied to the ordered floodplains as follows: 5 m for second order, 10 m for third order, 20 m for fourth order; and 30 m for fifth order. In addition, rivers that extended beyond the floodplains (typically only rivers up to third order) were also buffered according to river order, i.e.: 5 m for first order; 10 m for second order; and 15 m for third order. The scale of these buffers were validated against aerial imagery. The buffered rivers and floodplains were merged into a single layer to represent the river management zone.

[1] First order rivers represent small, headwaters river systems located at the top of catchments. Where two first order rivers join they become second order rivers. River orders increase as more rivers of the same order number flow into each other (i.e. two, second order rivers produce a third order river). Where two rivers with different stream orders join, the river downstream is given the higher of the two order numbers.

A 50-metre buffer was added onto the river management zones, and merged with the sub-catchments to allow for modelling of system drivers and pressures in close proximity to the rivers, as opposed to broader catchment drivers/pressures. The resultant layer therefore contained four zones for each sub-catchment, namely the 1 in 100 year floodplain, extended river areas, a buffer of rivers and floodplains, and the remaining catchment areas (**Figure 15**).

Figure 15: Example of data analysis zones used in the river vulnerability modelling to represent proximity to river systems according to each catchment. Zones include the 1 in 100 year floodplain (light blue areas), extended river areas (blue lines), and 50-m buffer (green lines)

3.4 Spatial Data Analysis

Having defined the zones of influence, where and what might be affected within these zones requires assessment (i.e. where, what and how much will be vulnerable). All spatial data used for the river vulnerability modelling, which included a range of point, line, polygon and grid data layers, was analysed in ArcGIS 10 using the catchment and river zones based on proximity to river systems (as illustrated in **Figure 15**). The values obtained from each spatial layer was according to the respective zones. For example, the number of stormwater manholes occurring within floodplains or the area of informal settlement that occurs within the river management zones (i.e. floodplain and extended river areas). These values were area-weighted using the area of each zone within the respective sub-catchments to generate relative values. The relative values were also weighted in terms of proximity (i.e. impact on the feature) to the river system whereby floodplains were given the highest weighting (100), followed by the extended river area (75), 50-metre buffer (25), and surrounding catchment areas (1).

The processing of various spatial layers allowed values to be calculated for a particular variable (e.g. the number of culverts within floodplains) for each sub-catchment. The values generated also allowed multiple variables to be combined (e.g. city infrastructure represented by culverts, road crossings, manholes, and pipelines). This was achieved by calculating the relative proportion of each value against the maximum value (out of the 39 sub-catchments) for a particular variable resulting in discrete values ranging between 0 and 1. The normalised values for each variable were then summed together to calculate a total value. Generally, point data representing layers such as formal and informal houses, culverts, stormwater/sewer manholes, etc. were calculated as density values. Polygons on the other hand were used to calculate the relative proportion values using area in hectares (e.g. the percentage of impervious area within the floodplain of each sub-catchment).

3.5 Weighting Values from Input Variables

To determine and model which input parameters were likely to have the greatest impact on a receptor, requires weightings to be assigned. Weightings were generated using the pairwise comparison method, also known as Analytical Hierarchy Process (AHP; Saaty, 1980), for each step where multiple input variables were combined (**Table 3** and **Table 4**). The combination of different input variables (e.g. average slope, relief ratio, drainage density, impervious area, and stormwater manholes used to calculate flood risk) was done by summing together weighted variable values.

Table 3 Example of input values used to determine weightings for pollution exposure (Table 4) using the Saaty (1980) Analytical Hierarchy Process (AHP) pairwise comparison method

Variable	Sewer Leaks	Solid Waste	Industry	WWTWs
Sewer Leaks	1.0	2.0	4.0	4.0
Solid Waste	0.5	1.0	5.0	5.0
Industry	0.3	0.2	1.0	3.0
WWTWs	0.3	0.2	0.3	1.0

Table 4 Example of output data and weighting values obtained from the pairwise comparison representing exposure to pollution (Table 3)

Variable	Sewer Leaks	Solid Waste	Industry	WWTWs	Weight
Sewer Leaks	0.5	0.6	0.4	0.3	**0.45**
Solid Waste	0.3	0.3	0.5	0.4	**0.35**
Industry	0.1	0.1	0.1	0.2	**0.13**
WWTWs	0.1	0.1	0.0	0.1	**0.07**

3.6 Vulnerability of City Infrastructure

Vulnerability of city infrastructure is presented here as the combined effects of exposure caused from flooding, sensitivity of city infrastructure to flooding and the adaptive capacity of the river system to reduce flooding impacts to city-owned infrastructure. City infrastructure includes features that are closely associated with river systems such as road crossings/culverts, stormwater pipelines and manholes, and stormwater pipelines and manholes. **Figure 16** provides an example of the steps followed and input variables used to assess the overall vulnerability of city infrastructure to flooding based on exposure, sensitivity, and adaptive capacity.

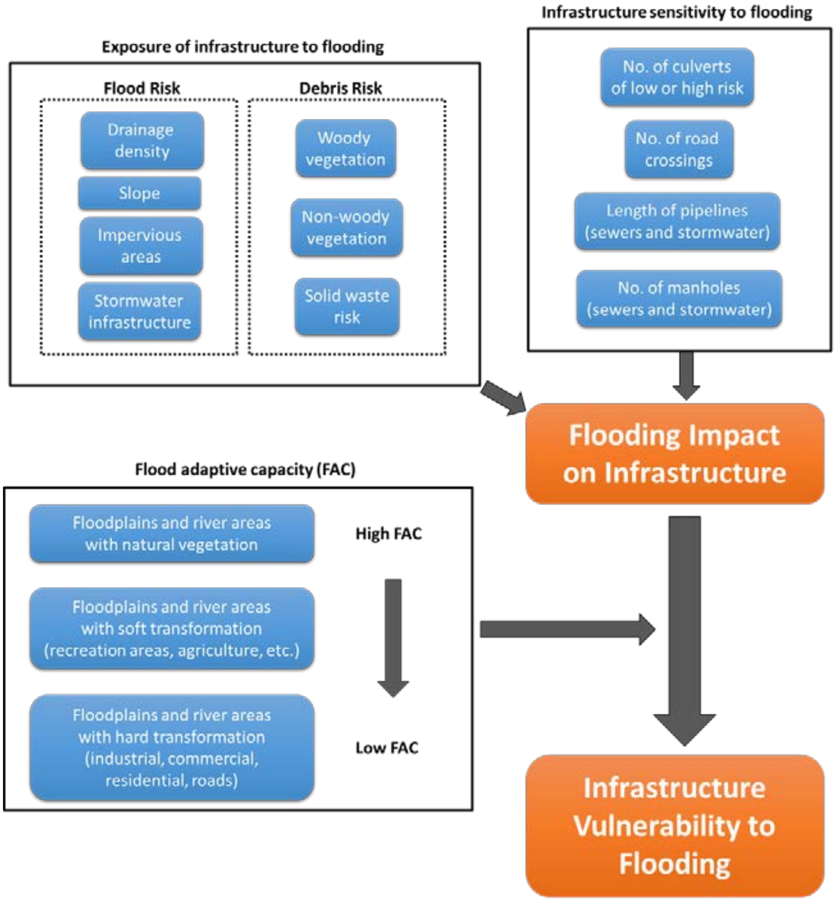

Figure 16: Input data layers and variables used to model the vulnerability of city infrastructure to flooding in relation to the key vulnerability assessment steps (i.e. exposure, sensitivity, adaptive capacity)

3.6.1 Exposure of city infrastructure to flooding

The approach used to spatially model the potential risk of flooding within the respective sub-catchments incorporated the following morphometric properties, which are known to be useful predictors of the flooding response of catchments (Aravinda and Balakrishna 2008, Bangira 2013, Diakakis 2011, Marchi *et al.* 2010, Romshoo *et al.* 2012):

- ***Catchment slope*** – a driver of the potential flooding response based on the relief of a catchment expressed as average slope. The higher the catchment's average slope, the higher the capacity to promote rapid concentration of runoff and hence flood risk (Marchi *et al.* 2010). A 0.12 weighting was applied to catchment slope scores.
- ***Relief ratio*** – a function of catchment steepness, and calculated as the ratio of the catchment's total relief (i.e. the difference between the highest and lowest catchment elevations) to the length of the longest river channel draining the catchment (Schumm 1956). The steeper the relief, the greater the flood risk. A 0.06 weighting was applied to relief ratio scores.
- ***Impervious areas*** – expressed as the proportion of catchment area comprising urbanised land cover owing to the high density of roads, rooves, and other hardened surfaces such as parking areas and walkways. Runoff is directly related to the proportion of area covered by hardened surfaces, thus increasing the flood peak generated during a storm event. The portion of impervious areas within each sub-catchment was calculated using the impervious areas grid obtained from the city combined with the surface area of roads as buffered using the city's road coverage. A 0.49 weighting was applied to the impervious area scores.
- ***Stream order*** – a driver of the potential flood magnitude, where the higher the stream order, the higher the flood volume that can be generated. Strahler's (1956) stream ordering method was used to calculate the stream orders of rivers draining the catchments. Stream orders were used to calculate drainage density.
- ***Drainage density*** – defined as the total length of all stream orders within a catchment and is calculated as the ratio of stream order lengths to bifurcation ratio[2] (Horton 1945). Drainage density is a function of the catchment's ability to efficiently remove surface runoff and is therefore proportionate to the peak discharge of a catchment. A 0.04 weighting was applied to the drainage density scores.
- ***Stormwater manholes*** – stormwater manholes form part of the stormwater infrastructure that is designed to effectively manage stormwater runoff generated from urban areas. The accumulation of this runoff is carried within the stormwater systems and eventually discharged into the downstream environment. Thus, the number of stormwater manholes within each sub-catchment that discharge directly into the environment was used to assess the

[2] Bifurcation ratio is the ratio of the number of the stream segments of given order 'nu' to the number of streams in the next higher order (nu+1) (Horton 1945).

potential contribution of stormwater infrastructure to the flooding response of each sub-the catchment. Combined with the impervious areas, stormwater infrastructure can significantly increase risk of flooding. A 0.29 weighting was applied to stormwater manhole scores.

Each input variable used to evaluate catchment morphometric properties was mapped and analysed using various tools and procedures in ArcGIS 10. The integration of all input layers within each individual sub-catchment was then cascaded within each of the four selected catchments to simulate the sequential downstream accumulation of flows down each river system based on the configuration of sub-catchments. This was achieved by taking the flood risk value for each sub-catchment and adding it to the average values from the sub-catchments positioned immediately upstream. The accumulated flood risk value of each sub-catchment then becomes one of the averaging values that is added to the next, downstream sub-catchment.

The accumulated flood risk values calculated according to the approach was then combined with debris risk to determine the overall flood exposure for each sub-catchment. Debris risk was calculated using the proportion of each sub-catchment that contains woody vegetation (i.e. trees and shrubs, including IAPs), non-woody vegetation (i.e. reeds, sedges, grasses, etc.), as well as solid waste (as derived in Section 3.8.1 for the human health, aesthetic, recreation receptor).

Figure 17 below shows the exposure risk (from low to high) from flooding to city infrastructure for the 39 focused sub-catchments. Results highlight that city infrastructure within the lowest three sub-catchments of the iSipingo River Catchment are at greatest risk of flooding, followed by the lower Palmiet Catchment.

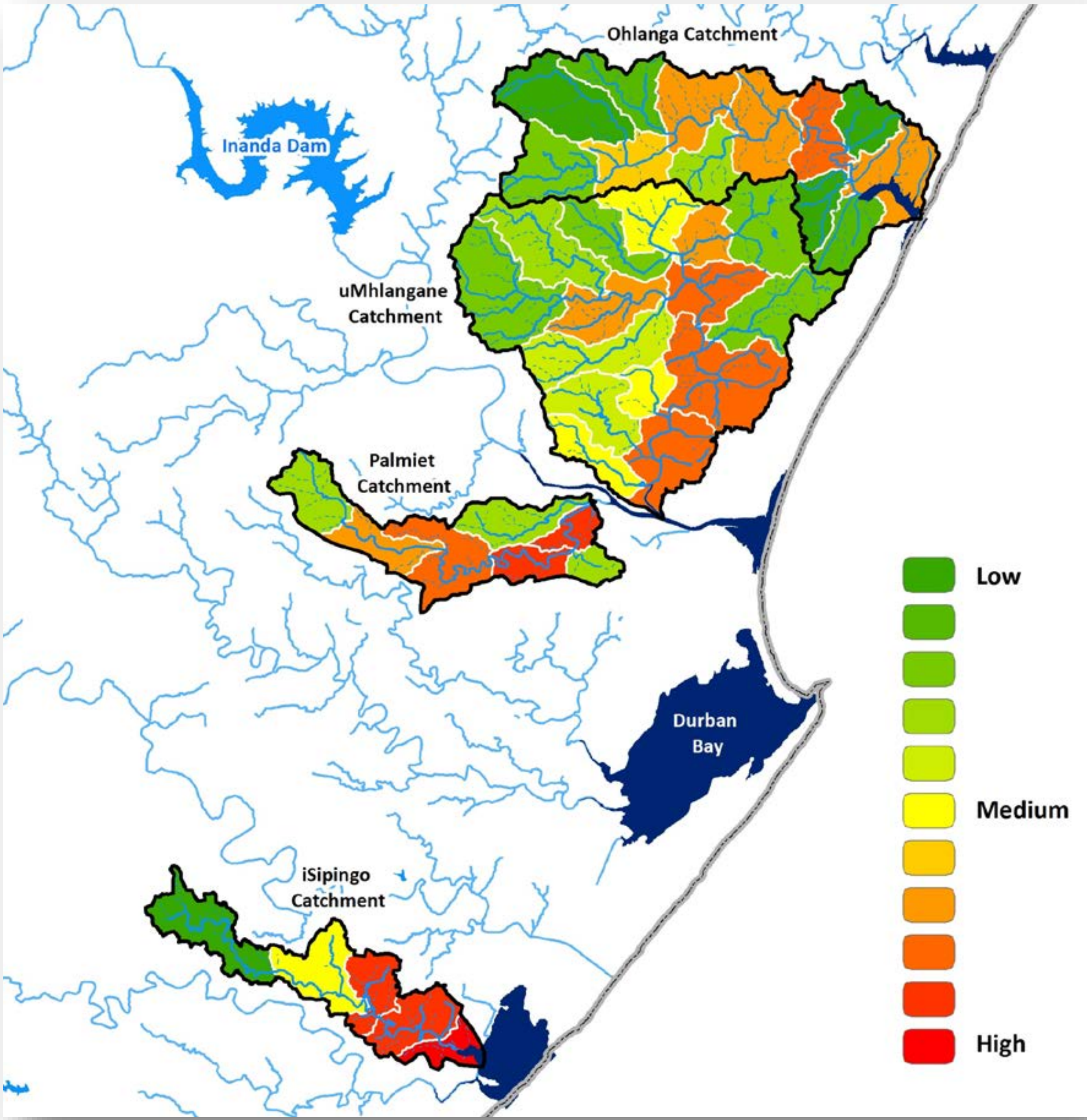

Figure 17: Exposure of city infrastructure such as culverts, roads, stormwater/sewer pipes and stormwater/sewer manholes from risks of flooding with exacerbated flood risk from debris (e.g. solid waste, woody vegetation, and grassy vegetation)

3.6.2 Sensitivity of city infrastructure to flooding

The sensitivity of city infrastructure to flooding is based on the presence of road crossings/culverts, pipelines and manholes within the river management area, with those occurring within the 1 in 100 year floodplain being most sensitive. The overall sensitivity score of each sub-catchment was calculated as follows:

- ***Culverts*** – the number of culverts within the river management area of each sub-catchment was used to determine the relative number of culverts within floodplains and extended river areas, and weighted higher for those occurring within floodplains. Specific culvert risk information (i.e. high flood risk versus low flood risk culverts) that was workshopped with the city as part of the broader CBA study was also used to further weight the relative culvert scores. A 0.63 weighting was applied to the final culvert scores.

- ***Roads*** – roads that cross over rivers and/or run alongside rivers are also at risk of being damaged by flooding events, and thus were add to the overall sensitivity of city infrastructure to flood damages. Roads were mapped using the total road length within the river management area of each sub-catchment, and weighted higher for those occurring within floodplains. A 0.24 weighting was applied to the road scores.
- ***Pipelines*** – the total length of sewer and stormwater pipes that occur within the river management area of each sub-catchment was used to determine the potential threat of these becoming damaged by floods but weighted higher for those occurring within floodplains. A 0.08 weighting was applied to the pipeline scores on the basis that replacement/repair costs are much lower than for culverts and roads.
- ***Manholes*** – the total number of sewer and stormwater manholes that occur within the river management area of each sub-catchment was used to determine the potential threat of these becoming damaged by floods, and also weighted higher for those occurring within floodplains. A 0.05 weighting was applied to the manhole scores.

Figure 18 below shows the level of sensitivity for each of the 39 sub-catchments based on the occurrence of city infrastructure within the river management area. The highest sensitivity is largely centred around several sub-catchments within the uMhlangane Catchment, but also the upper Palmiet Catchment (which includes Pinetown) and the sub-catchments that drains the suburbs of Caneside, Forest Haven, Woodview, and Shastri Park within the Ohlanga Catchment.

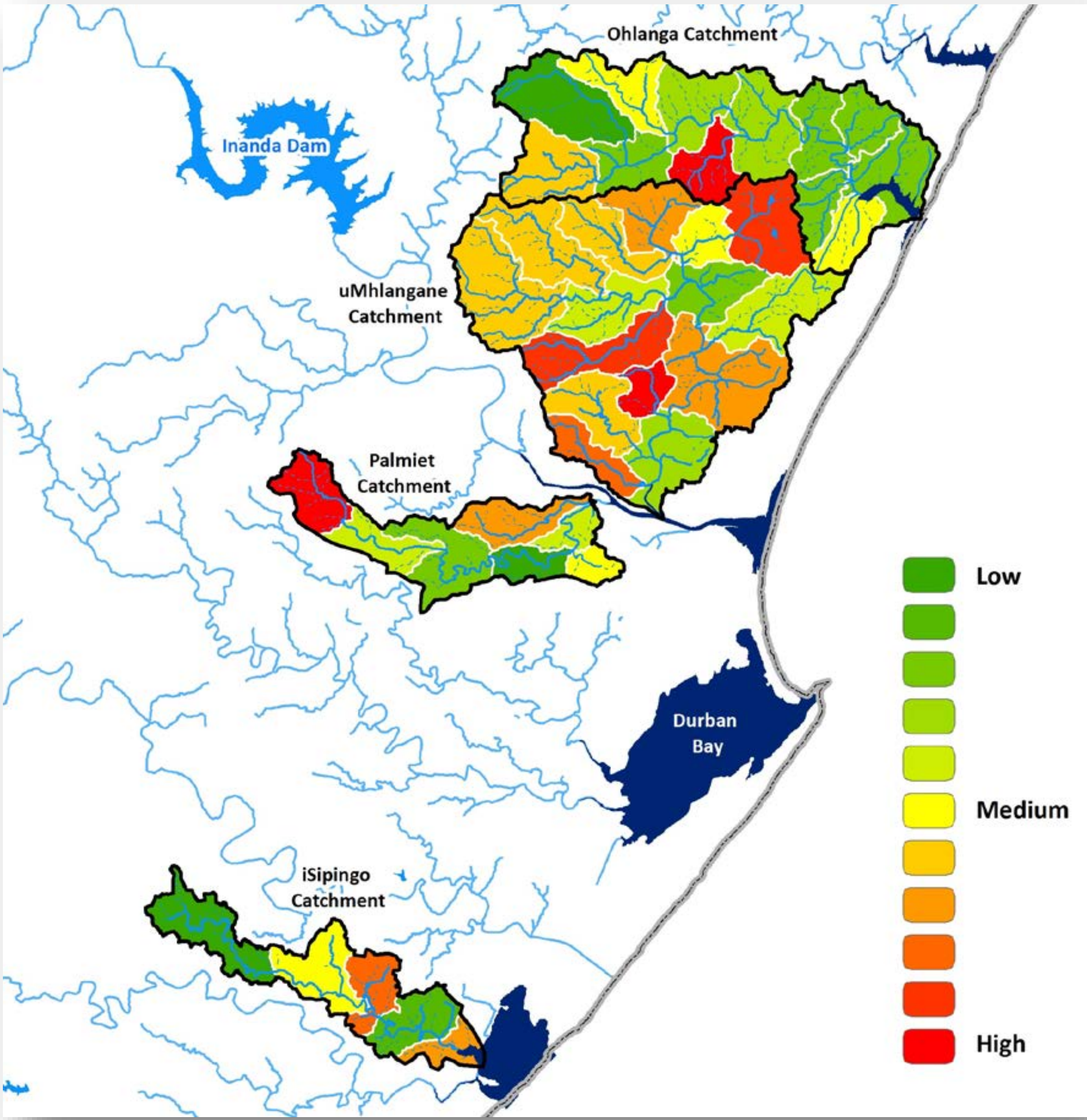

Figure 18: Sensitivity of city infrastructure (i.e. culverts, roads, and sewer/stormwater pipelines and manholes) to flooding

3.6.3 Adaptive capacity for flooding

This refers to the ability of an area to cope with or "absorb" a flood event and is influenced by the extent to which it has been transformed. The adaptive capacity of rivers for flooding is based on the present composition (using the 2018 national land cover data) and extent of the river management area within each sub-catchment. The ability of the 1 in 100 year floodplains and extended river areas to receive and attenuate floods was determined by the proportion of each zone that is made up of either vegetation, "soft" transformed developments (such as recreation areas, sports fields, agricultural lands, etc.), and "hard" transformed developments (such as roads, settlements, industrial areas and commercial areas). Thus, floodplains that are largely natural, and which occupy a high proportion of the catchment area have the greatest capacity to attenuate floods, whether based on the existing composition of vegetation cover and soft/hard transformation or through implementation of additional flood attenuation interventions (e.g. creation of natural flood terraces, off-channel levees, etc.).

Figure 19 illustrates the adaptive capacity of rivers that flow through the selected catchments. The Ohlanga Catchment has the greatest adaptive capacity for receiving and managing floods, followed by the uMhlangane, which has some capacity in the eastern headwaters (i.e. the upper uMhlangane and Glen Anil Rivers). The iSipingo Catchment generally has the least opportunity as the whole system has little adaptive capacity.

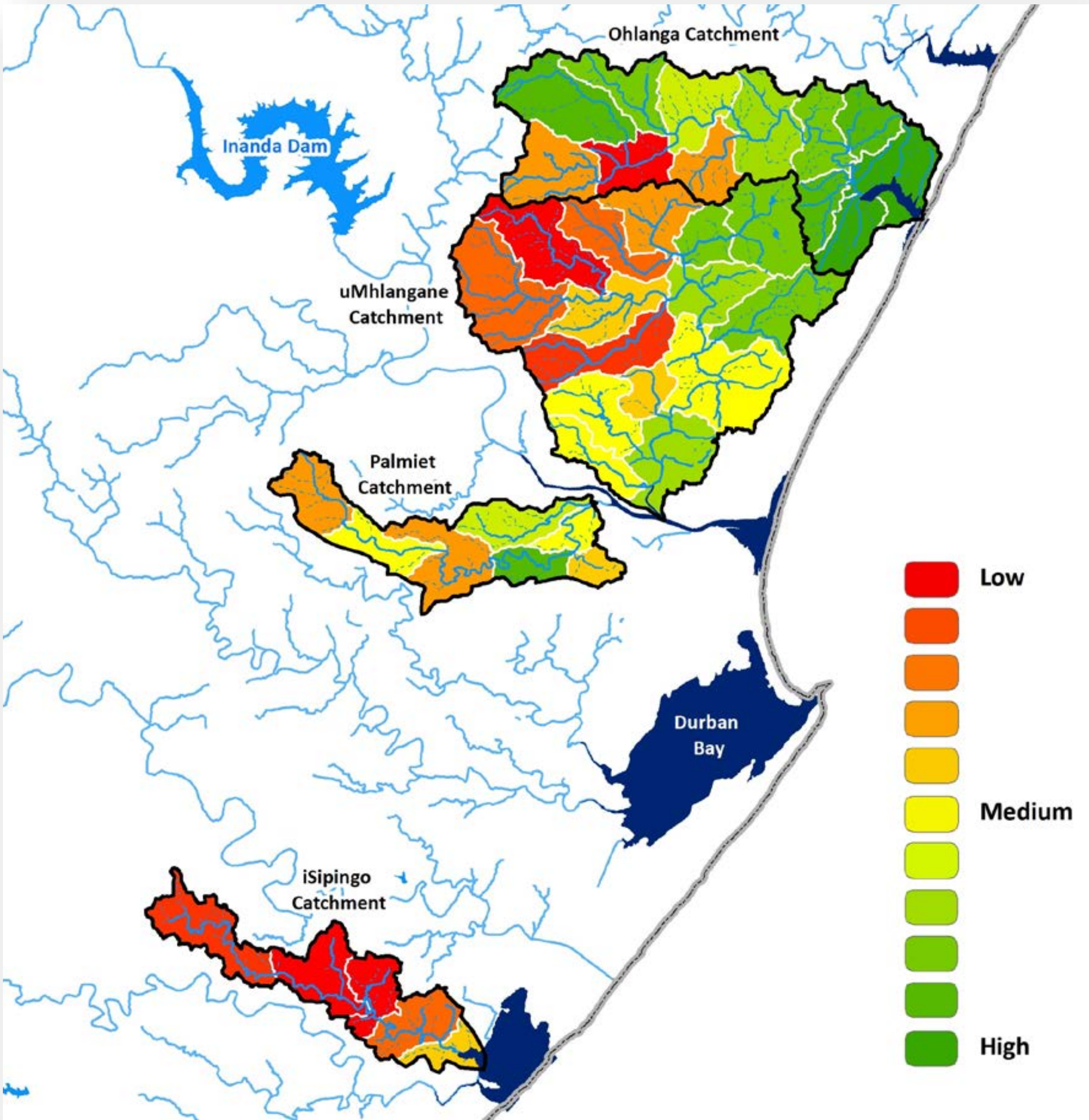

Figure 19: Adaptive capacity of river systems for receiving and attenuating floods based on the land cover composition within the 1 in 100 year floodplains and extended river areas

3.6.4 City infrastructure vulnerability

The overall vulnerability of city infrastructure to flooding was calculated for each sub-catchment based on flood exposure, sensitivity of city infrastructure, and the adaptive capacity of the river systems as detailed in previous sections. The lower iSipingo Catchment has highest level of vulnerability due to high exposure and sensitivity, and the very limited capacity for flood attenuation (**Figure 20**).

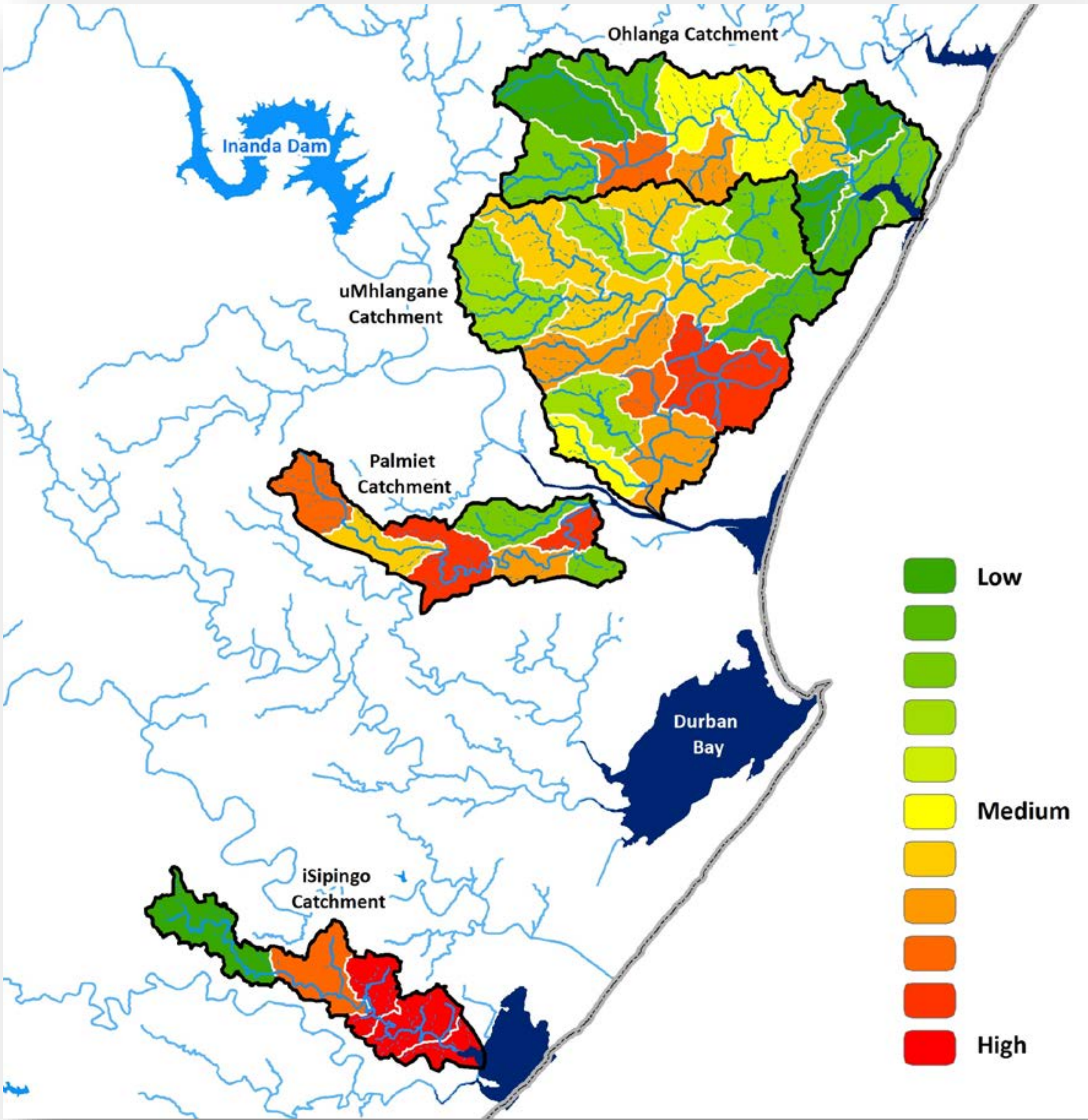

Figure 20: Overall vulnerability of city infrastructure to flooding for the Ohlanga, uMhlangane, Palmiet and iSipingo River systems

3.7 Vulnerability of Private Infrastructure

A similar process to the previous section was followed to determine vulnerability of private infrastructure. It is presented here as the combined effects of exposure caused from flooding, sensitivity of private infrastructure to flooding and the adaptive capacity of the river system to reduce flooding impacts. Private infrastructure includes buildings associated with informal settlements, formal settlements, commercial developments, and industrial developments.

3.7.1 Exposure of private infrastructure to flooding

Exposure of private infrastructure is the same as the exposure to city infrastructure, with exception of the added risk from debris that exacerbates risk of flooding for city infrastructure such as culverts and road crossings. Consequently, the exposure outputs for city infrastructure were used (see Section 2.3.1) with the risk from woody debris and solid waste excluded. **Figure 21** below illustrates the exposure risk (from low to high) for the 39 sub-catchments. The lowest sub-catchments in the iSipingo River Catchment are at greatest risk of flooding, followed by the lower Palmiet and uMhlangane Catchments. The Ohlanga Catchment is least at risk.

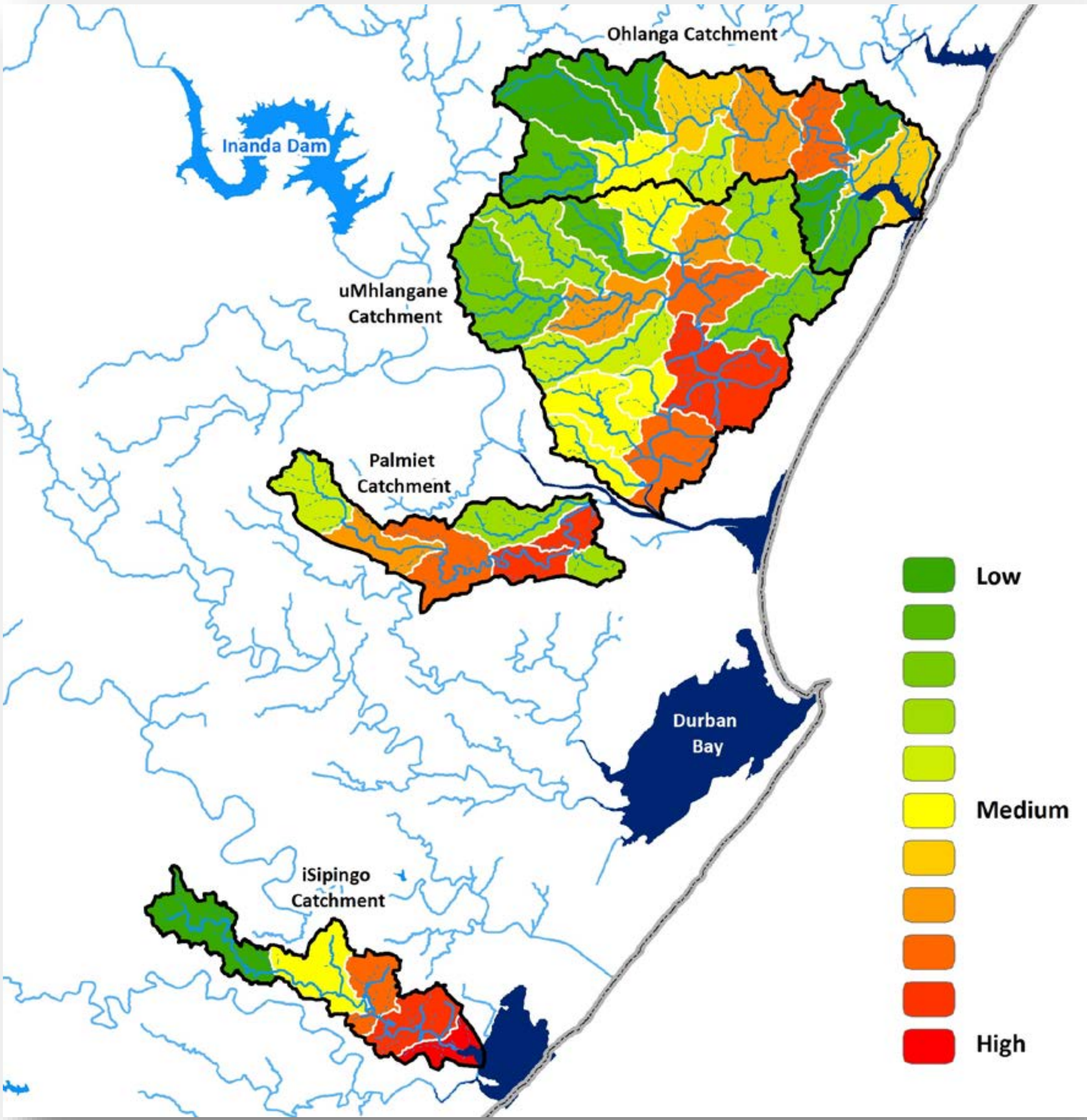

Figure 21: Exposure of private infrastructure (i.e. buildings/dwellings within informal settlements, formal settlements, and industrial/commercial areas) to flooding

3.7.2 Sensitivity of private infrastructure to flooding

The sensitivity of private infrastructure to flooding is based according to sector type (i.e. informal, formal, commercial, and industrial), and their level of sensitivity to flood impacts. For example, informal settlements are most sensitive as they potentially could lose everything, they own should their home be washed away during a flood event. Furthermore, they are financially more constrained (i.e. they have limited or no financial savings and/or insurance cover) to either mitigate flood risk (e.g. through building flood walls) or to replace losses and/or repair damages. On the other hand, commercial/industrial developments, and to a lesser degree formal development, are more resilient to flooding impacts. These groups are more likely to put structures in place to protect their infrastructure from flooding (e.g. berms, gabions, etc.). The sensitivity of each sub-catchment was calculated using the area of industrial/commercial land that falls within the 1 in 100 year floodplain or extended river area. Settlement sensitivity was calculated using the number of dwellings within informal and/or formal settlement areas that occur within the floodplain and/or river area. The number of dwellings within the formal settlement areas was further weighted using the relative portion of the formal settlement that is considered low-income. The following overall weightings were applied to each sector: informal settlement (0.69), formal settlement (0.23), and commercial/industrial (0.08). below shows the exposure risk (from low to high) for the 39 sub-catchments.

Figure 22 below shows the level of sensitivity for each of the 39 sub-catchments based on the occurrence of private infrastructure within the river management area. Rivers where private infrastructure is most sensitive to flooding include: the lower parts of the Mawothi River (of the upper Ohlanga Catchment), the Shembe River (of the upper uMhlangane Catchment), the tributary of the Palmiet River that drains the suburbs of Sherwood/Clare Hills, and the middle reaches of the iSipingo River (**Figure 22**).

3.7.3 Adaptive capacity for flooding

The adaptive capacity of rivers to help reduce the risk of flooding to private infrastructure is exactly the same as the adaptive capacity that was derived for city infrastructure (see Section 3.6.3 and **Figure 19**).

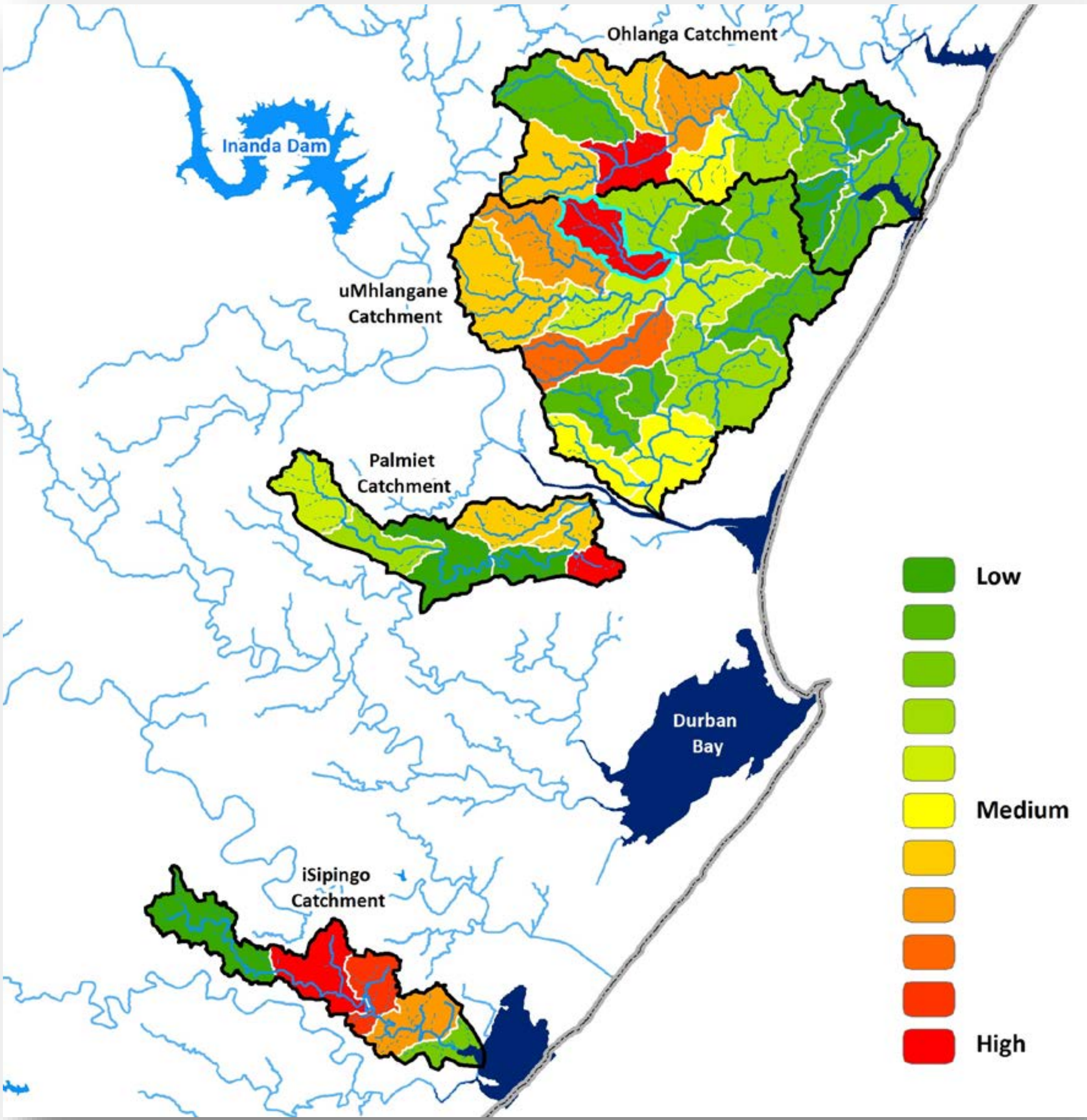

Figure 22: Sensitivity of private infrastructure (i.e. buildings/dwellings within informal settlements, formal settlements, and industrial/commercial areas) to flooding

3.7.4 Private infrastructure vulnerability

The overall vulnerability of private infrastructure was calculated for each sub-catchment using the outputs calculated for exposure, sensitivity, and adaptive capacity as per the aforementioned sections. The lower iSipingo Catchment has the highest level of vulnerability due to high exposure and sensitivity, and the very limited capacity for flood attenuation **Figure 23** below.

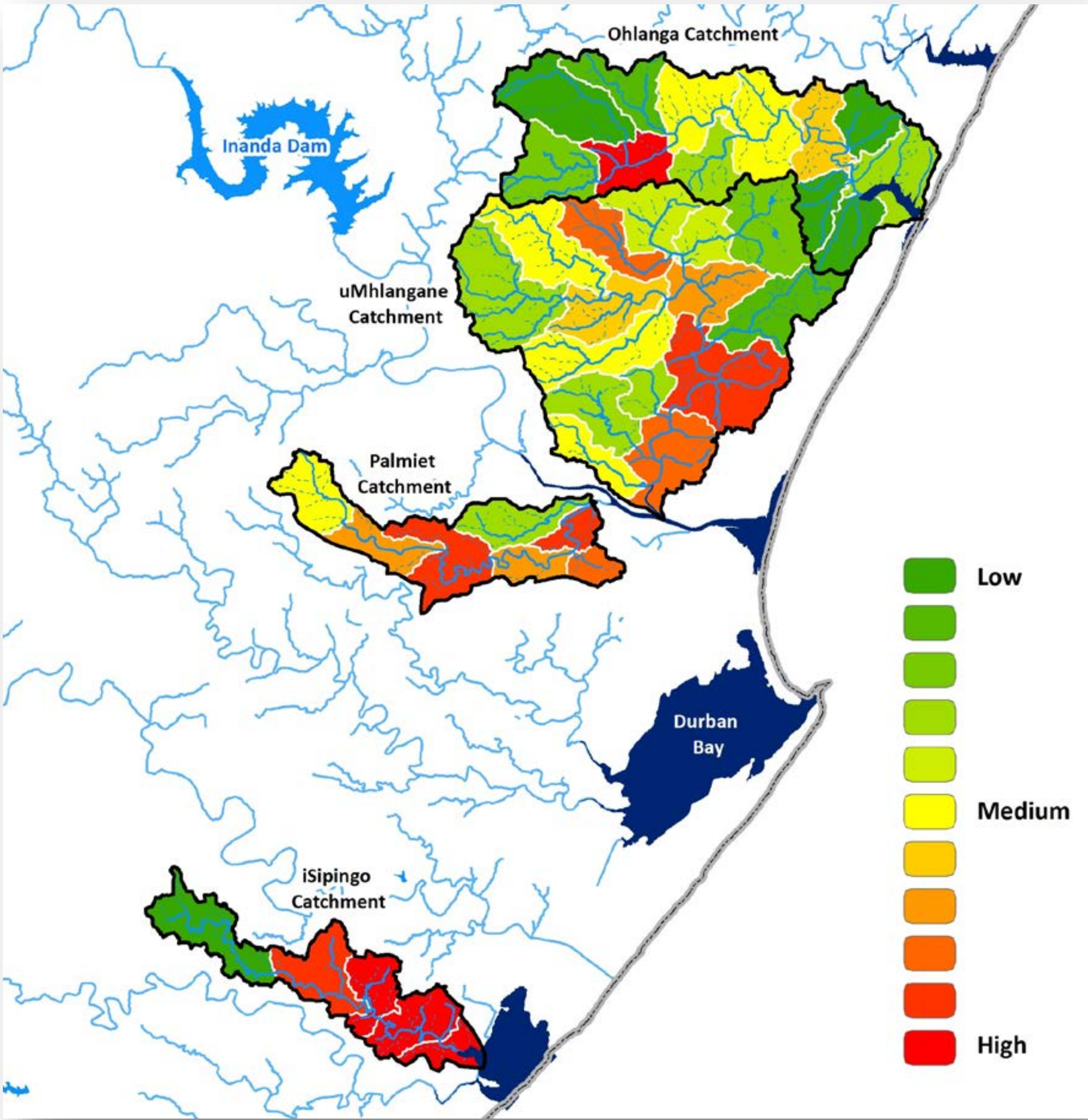

Figure 23: Overall vulnerability of private infrastructure to flooding for the Ohlanga, uMhlangane, Palmiet and iSipingo River systems

3.8 Human Health, Aesthetics, Recreation Vulnerability

Human health, aesthetic, and recreational value vulnerability of rivers is presented here as the combined effects of exposure from pollution, sensitivity of various user groups that are exposed to pollution and adaptive capacity of the river systems to assimilate and/or ameliorate pollutants (including trapping of solid waste).

3.8.1 Exposure to pollution

Exposure to pollution was based on the following key drivers: solid waste, sewer failures, WWTWs discharge, and industrial activities. These drivers are briefly described below in terms of acting as sources of pollution, whether as nutrients, chemicals, or solid waste:

- ***Solid waste –*** solid waste was modelled using surrogates that represent potential sources, namely: informal settlements, low-income settlements, formal settlements, industrial/commercial developments, stormwater manholes that discharge into the environment, and road crossings. Manholes and road crossings were incorporated as points in the landscape, whereas the other data layers were based on areas. Informal settlements and low-income settlements were considered as having the greatest potential to generate solid waste due to limited waste collection and services in these areas as compared to the more formalised and serviced areas in the city. A 0.35 weighting was applied to the solid waste scores.
- ***Sewer failures –*** these data (obtained from the city) represent reported or logged sewer leaks and failures from 196 suburbs that intersect the selected catchments. Data were provided by eThekwini for a four-year period (2016 to 2019), with the total number failures reported for each year within each suburb. The data was weighted using the relative number of sewer manholes within each suburb that occur within the respective sub-catchments. This was done to align the sewer failure data from the suburbs with the sub-catchments. The average number of reported failures from the four years of data was calculated and assigned to each catchment. A 0.45 weighting was applied to the sewer failure scores.
- ***Wastewater Treatment Works (WWTWs) discharge –*** A water quality index (WQI) was calculated for the WWTWs that occur within the study area (i.e. the uMhlanga, Northern, Phoenix, Kwamashu and iSipingo works). A WQI provides a numeric value that describes the overall quality of water based on a selection of parameters. The WQI from each WWTWs was assigned to their respective sub-catchments. WQI values were extrapolated for downstream sub-catchments using a 25% reduction of the WQI, while adding the WQI values from other sub-catchments. A 0.07 weighting was applied to the WWTWs WQI scores.
- ***Industrial developments –*** effluents generated from industrial processes can have a detrimental impact on aquatic ecosystems, particularly in terms of toxicity, but are considered difficult to generalise due to the complexity and diversity of commercial chemicals that are often used. Nevertheless, the array of industries was represented using the proportionate area of industrial

developments within the sub-catchments. A 0.13 weighting was applied to the industrial development scores.

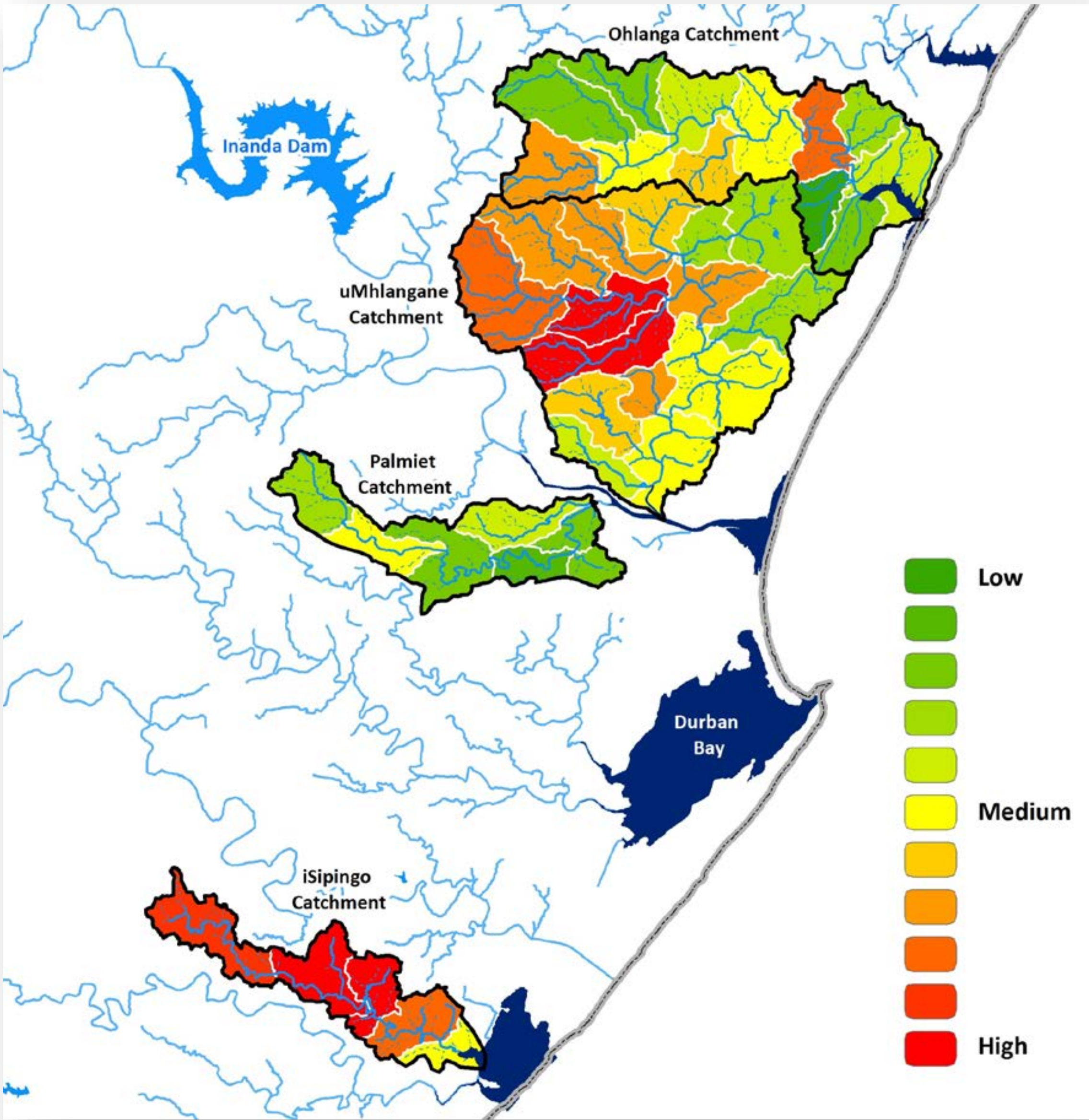

Figure 24: Exposure of pollution affecting human health, aesthetic, and recreational values of river systems

3.8.2 Sensitivity to pollution

The sensitivity of people to pollution and solid waste is based on user groups that are dependent on or who utilise rivers systems, as well as areas connected to the rivers such as estuaries and beaches. The most sensitive user group are informal settlements living along rivers that likely rely most heavily on river water for their well-being and recreation (e.g. subsistence crops/vegetable gardens, washing, swimming, etc.). Other, less sensitive user groups include people living along the rivers and those that frequent beaches and estuaries for recreational purposes. Each user group was incorporated into the river vulnerability modelling as follows:

- ***Informal settlements –*** the number of dwellings occurring within the riverine areas and comprising informal settlement areas based on the 2011 census was used to represent this user group. A 0.46 weighting was applied to the informal settlement sensitivity scores.
- ***Formal settlements –*** the number of dwellings occurring within riverine areas and comprising formal settlement areas was used to represent this user group. A 0.13 weighting was applied to the formal settlement sensitivity scores.
- ***Estuaries –*** the importance and sensitivity of the three estuaries (i.e. uMhlanga, uMngeni, iSipingo/iZimbokodo estuaries) that occur downstream of the selected catchments were assessed using the metrices from the 2018 NBA. This included the integration of the biodiversity importance ratings developed by Turpie *et al.* (2002) and Turpie and Clark (2009), the core set of national or provincial estuaries, and the DAFF fish nursery importance scores. The integrated estuarine sensitivity scores calculated were: 2.5 for the uMhlanga Estuary; 3.2 for the uMngeni Estuary; and 0.6 for the iSipingo/iZimbokodo Estuary complex. These sensitivity score were then moderated using the length of river that separates each sub-catchment and estuary on the premise that that further away a sub-catchment is from an estuary the lower the impact that sub-catchment has on the estuary. A 0.07 weighting was applied to the estuary sensitivity scores largely due to the lower dependence/utilisation by people.
- ***Beaches –*** in a similar manner to the estuaries, sensitivity scores were derived for each of the selected catchments, then moderated using the river lengths and shoreline distances that separate each sub-catchment from beaches. The sensitivity scores calculated for each system was derived from the shoreline distance to the nearest Blue Flag Beach, as well as the number of Blue Flag listed beaches occurring within 10km of the river mouth. A 0.34 weighting was applied to the beach sensitivity scores.

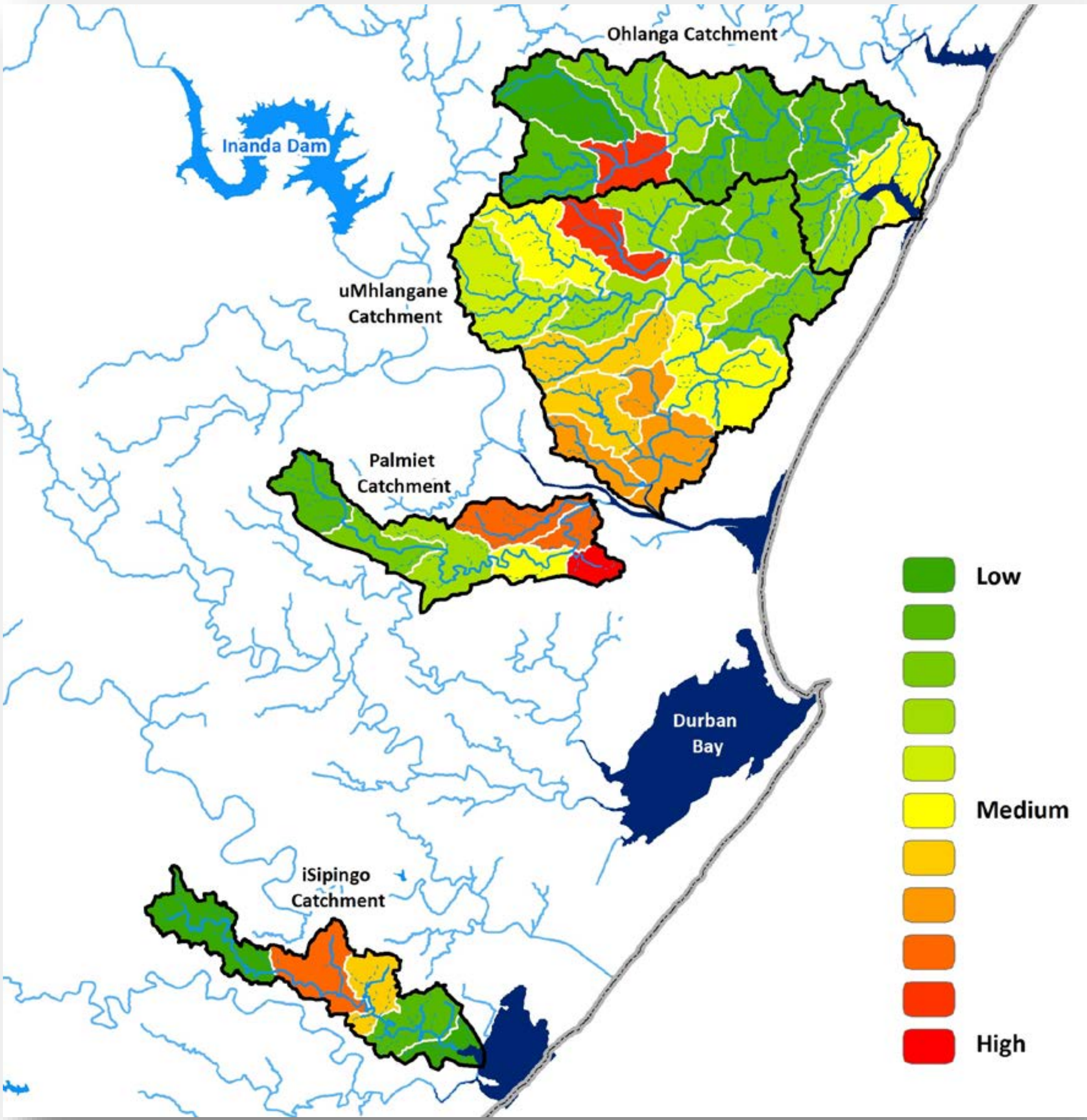

Figure 25: Sensitivity of people to river pollution due to effects on human health, aesthetics, and recreation systems

3.8.3 Adaptive capacity of rivers to assimilate pollutants and trap waste

The adaptive capacity of rivers to ameliorate the current water quality situation is dependent on several factors. This approach considers a number of key factors that are expected to have a positive effect on water quality, whether through the existing natural ecological functions of the rivers systems or from development of ecological and/or engineering interventions that can be implemented to address specific water quality problems. Factors modelled and influencing river adaptive capacity are as follows:

- ***River assimilative/trapping potential –*** the area of floodplain and extended river area that is untransformed was analysed for each sub-catchment.

Natural/vegetated areas along river help to absorb, assimilate, and breakdown a variety of contaminants (e.g. nutrients, sediments, organic chemicals) within the river substrates, by soil microbes (e.g. denitrification), and through plant uptake. In addition, these areas also help to trap solid waste that becomes entangled in vegetation or that is deposited on the banks following a flooding event. Similarly, “soft” transformed areas (e.g. sports fields, agricultural areas, etc.) along rivers also provide these services but to a lesser degree and were thus given a lower weighting. The relative proportion of the river management area that comprises vegetation and “soft” transformations was evaluated and weighted to score the assimilative/trapping potential of each sub-catchment. A 0.27 weighting was applied to the river assimilative/trapping scores.

- ***Protected areas –*** Formally protected areas that occur along rivers systems (e.g. the Palmiet Natural Reserve) act as “green” lungs in the landscape, and provide an opportunity for a river to recover from upstream impacts, thereby improving the health and condition of the river ecosystem. This offers maximum potential for the assimilation and trapping of pollution, and the greater the proportion of a river system that is protected, the greater this function will be. A 0.25 weighting was applied to the river protection scores.
- ***Area of wetland habitat –*** Wetlands are effective at providing a range of water quality functions. The wetland mapping (i.e. NWM5) from the 2018 NBA was used to characterise, select, and analyse wetlands within the selected catchments. Only the non-river type wetlands were analysed (i.e. seepage wetlands, depressions and unchanneled valley-bottom wetlands), and the proportion of these wetlands was calculated for each sub-catchment. A 0.27 weighting was applied to the wetland habitat scores.
- ***River dilution potential –*** dilution potential was represented using stream order as a proxy for river flow by taking the total length of each river order weighted by the order number (i.e. the bigger the river order the greater the dilution). A 0.10 weighting was applied to the river dilution scores.
- ***River topographic index –*** rivers that have flat and extensive floodplains or riparian areas offer space and opportunities for interventions to be implemented that can address specific water quality problems. Interventions can range from river rehabilitation and restoration to engineering solutions such as river groins that are effective at directing and concentrating solid waste to be deposited on the riverbanks in response to flood events. The river management area (i.e. inclusive of 1 in 100 year floodplains and extended river areas) was characterised based on slope, and a slope score was derived from the proportion of the river management area that is either very flat, moderately flat, moderately steep and steep. A 0.05 weighting was applied to the river topographic scores.
- ***Infrastructure –*** the presence of existing infrastructure within and along rivers (e.g. canals, culverts, stormwater drains, and road crossings) provide opportunities to adapt engineering designs to retrofit solid waste interventions. Interventions can include trash booms, litter socks, etc. Existing infrastructure was analysed using the length of canals, number of culverts and number of

road crossings occurring within each sub-catchment. A 0.06 weighting was applied to the river dilution scores.

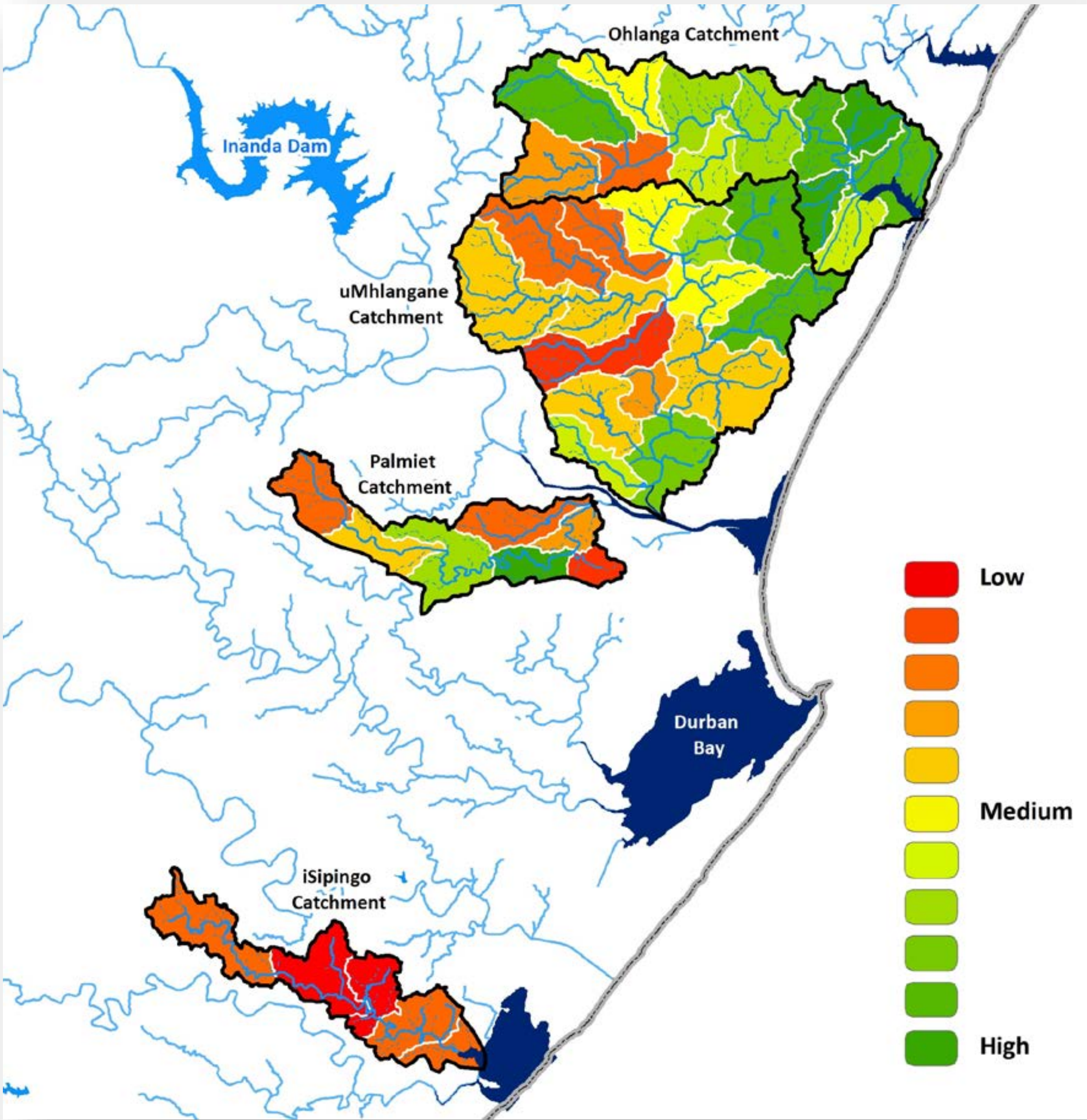

Figure 26: Adaptive capacity of river systems for assimilating and trapping pollution as a benefit to human health, aesthetics, and recreation

3.8.4 Vulnerability to human health, aesthetics, and recreation

The overall vulnerability of human health, aesthetic, and recreational value was calculated for each sub-catchment based on the exposure to pollution, sensitivity of people to pollution and solid waste, and the adaptive capacity of the river systems as discussed above. The results are presented in **Figure 27** below.

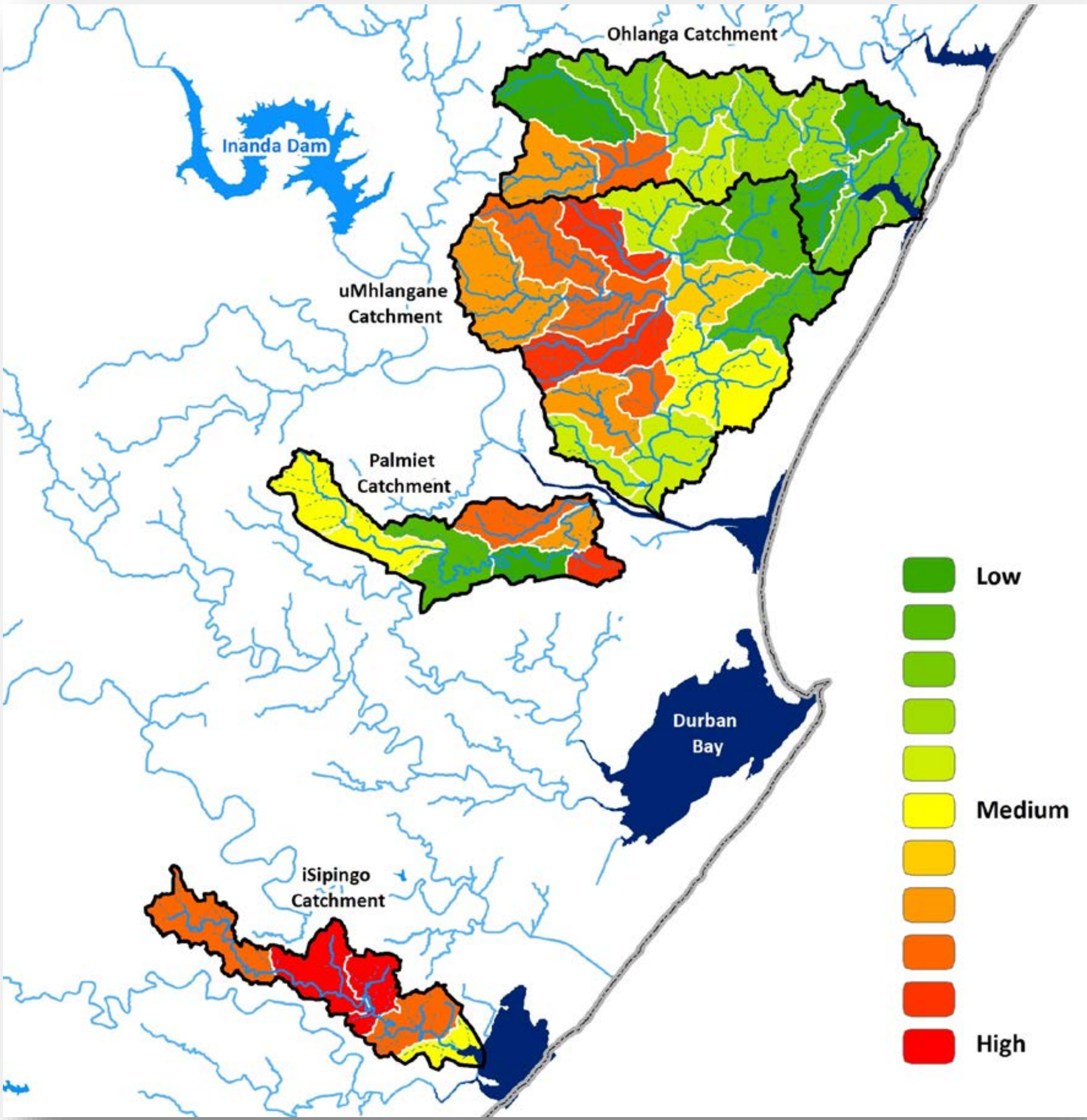

Figure 27: Overall vulnerability of human health, aesthetics, and recreation to flooding for the Ohlanga, uMhlangane, Palmiet and iSipingo River systems

3.9 River Vulnerability Summary

The synthesised results from the river vulnerability assessment are presented in Table 5 for the four selected catchments. Key headlines from that summary are: ***Exposure to flooding and pollution*** was consistently found to be the highest within the iSipingo Catchment, followed by the uMhlangane.

- ***Sensitivity to flooding and pollution*** was found to be generally highest within the Palmiet Catchment, followed by the uMhlangane.
- ***Adaptive capacity and resilience to flooding and pollution*** was consistently found to be the highest within the uMhlangane Catchment, and lowest within the iSipingo.

- Overall, the ***iSipingo Catchment is the most vulnerable*** river system based on all three of the modelled receptors, followed by the uMhlangane, Palmiet and Ohlanga (**Table 5**).

Table 5 Summary of scores obtained from the assessment of exposure, sensitivity and adaptive capacity for the selected catchments, which were used to calculate overall vulnerability

Catchment	Exposure	Sensitivity	Adaptive Capacity	Vulnerability
City Infrastructure Vulnerability to Flooding				
Ohlanga	0.72	0.26	**0.81**	**1.30**
Umhlangane	1.16	0.32	0.70	**2.14**
Palmiet	0.85	**0.39**	0.68	**1.83**
iSipingo	**1.61**	0.26	0.53	**3.48**
Private Infrastructure Vulnerability to Flooding				
Ohlanga	0.52	0.12	**0.81**	**0.86**
Umhlangane	0.91	0.16	0.70	**1.61**
Palmiet	0.68	0.12	0.68	**1.17**
iSipingo	**1.09**	**0.26**	0.53	**2.43**
Vulnerability to Human Health, Aesthetics and Recreation				
Ohlanga	0.44	0.21	**0.41**	**1.84**
Umhlangane	0.60	0.30	0.32	**3.13**
Palmiet	0.35	**0.38**	0.30	**3.01**
iSipingo	**0.80**	0.22	0.19	**5.82**

4. CLIMATE CHANGE IMPLICATIONS

Freshwater systems are particularly vulnerable to climate change (Dallas and Rivers-Moore, 2014). This is largely due to the fact that they are influenced, both directly and indirectly, by changes in temperature and precipitation and often have a long history of degradation (Capon *et al.*, 2013; Friggens and Woodlief, 2015; D.; Tickner *et al.*, 2020). Climate change is likely to impact both the physical habitat, water quality and primary productivity aspects of river systems, which will, in turn, alter their ability to deliver ecosystem goods and services and thus have numerous consequences for human societies and ecosystems (Dallas and Rivers-Moore, 2014).

Based on the recent hydrological modelling of the uMhlangane Catchment undertaken by Prof. Roland Schulze and Nicolas Davis suggests that flood magnitude (based on the 1 in 10 year event) will increase by approximately 15%. Thus, it can be expected that the frequency of a 1 in 10 year flood will increase. The modelling of the uMhlangane Catchment also highlights that sediment yields will increase significantly by around 30%. These results assume (as the likely Climate Change scenario) that daily rainfall will increase by 10%, rainfall intensity by 20% and average daily maximum and minimum temperatures by 2^{o}C.

Future impacts from climate change are thus expected to further amplify the drivers and pressures that currently affect river ecosystems within the municipality. The implications from climate change are therefore likely to increase river vulnerability throughout the municipality. Climate change implications are discussed based on alien vegetation, solid waste, flooding, and sedimentation.

3.1 Alien Vegetation

The impacts of climate change, namely elevated temperatures and atmospheric CO_2 levels, changes in precipitation and enhanced nitrogen deposition, are likely to influence alien plant invasion (Jia *et al.*, 2016). Specifically, changing climatic conditions are likely to impact the range, abundance, and impacts of IAPs (Beaury *et al.*, 2020). Different functional groups of alien plants are likely to have different responses to climate change. The following responses of alien vegetation to aspects of climate change are anticipated:

- **Warming temperatures**
    - The biomass of woody species is expected to increase more than that of herbaceous species in response to warming temperatures (Jia *et al.*, 2016).
    - C4 plants (i.e. warm season, drought-tolerant plants) may respond more positively to warming temperatures than C3 plants (cool season, drought intolerant plants) due to their higher drought tolerance (Jia *et al.*, 2016).
- **CO_2 enrichment**
    - Evidence suggests that IAPs respond positively to elevated levels of CO_2 (Thuiller *et al.*, 2008).
    - Faster-growing species benefit more than slow-growing species, especially for invasive woody species (Thuiller *et al.*, 2008).

- C4 plants are likely to respond more favourably to increased levels of CO_2 than C3 plants.
- **Flooding:**
  - Flooding events often strip indigenous vegetation from river banks and stress native ecosystems, creating ideal niches for colonization by IAPs (Beaury *et al.*, 2020; Thuiller *et al.*, 2008).

It is widely recognized that climate change is likely to enhance the ability of alien species to invade new areas, whilst simultaneously decreasing the ability of native ecosystems to resist invasion by disturbing the dynamic equilibrium maintaining them (Thuiller *et al.*, 2008). Under a changing climate it is thus anticipated that IAPs will increase in abundance, especially woody species and C4 alien plants, and have a higher potential for invasion (Jia *et al.*, 2016). Not only is an increase in the abundance of IAPs expected under climate change, but a new suite of IAPs is likely to develop as the ranges of species shift in response to changing climatic conditions (Roger *et al.*, 2015).

Increased infestations of IAPs pose a severe threat to river ecosystems through the loss of biodiversity patterns and process, as well as critical ecosystem services provided by rivers (see Section 3.2). This compromises the overall resilience of river ecosystems and increases vulnerability from flooding and pollution for the City and the people living within it.

3.2 Flooding

Changes in regional patterns of precipitation and temperature as a result of climate change are expected to alter natural flow regimes (Palmer *et al.*, 2009). Specifically, it is anticipated that flood events are likely to increase in frequency under a changing climate (Palmer *et al.*, 2009). This corroborates with the results from the hydrological modelling of the uMhlangane Catchment with the magnitude of floods expected to increase by around 15% (Prof. Roland Schulze and Nicolas Davis, pers. comm., 2020).

The issue of flooding is further exacerbated by a growing human population and the associated increase in urbanisation. Namely, an increase in urbanisation results in an increase in impermeable areas, which in turn, results in increased stormwater runoff and localised flooding.

Flooding is closely interlinked with, and frequently exacerbates, a number of other threats facing river ecosystems, such as erosion, sedimentation, alien vegetation establishment and declining water quality (Palmer *et al.*, 2009). For example, increased flooding results in increased erosion of riverbanks and thus increased sediment loads in rivers.

Thus, the overall impacts of increased flooding because of climate change will become pronounced. For the City this will involve increased costs to maintain, repair or even replace damaged infrastructure, especially given that debris risk is likely to increase because of IAP infestations and continued solid waste pollution. For the private sector and people living along rivers, the consequences could be dire, especially those living in informal settlements.

3.3 Sedimentation

Changes in precipitation in response to climate change are anticipated to result in increased erosion rates, and thus increased sedimentation within rivers (Capon *et al.*, 2013). The hydrological modelling of the uMhlangane Catchment indicates that sediment yield will be noticeably higher than flooding with sedimentation expected to increase by around 30% (Prof. Roland Schulze and Nicolas Davis, pers. comm., 2020).

Sedimentation is closely linked to several other aspects of river systems likely to be influenced by climate change. Namely, increased flooding events may result in riverbanks becoming denuded of vegetation. This therefore results in increased sedimentation as soils are no longer bound by vegetation, as well as a reduction in sediment trapping. In response to increased sediment yield, rivers will become more turbid, which in turn, elevates water temperatures. Given that water temperature is a major controller of aquatic life (Smith, 1972; Chapman, 1992; Week *et al.*, 1995; Allan, 1995), this will have a drastic effect on the ecological well-being of rivers. Furthermore, increased water temperatures will also encourage algal growth, resulting in further problems (e.g. eutrophication, deoxygenation, and water toxicity), and ultimately disrupting normal ecosystem functioning (Nazari-Sharabian *et al.*, 2018).

Increased sedimentation of rivers is likely to also affect ongoing maintenance of infrastructure such as culverts and road crossing due to sediment deposition and build-up upstream of infrastructure, which will also alter the ability of these structures to effectively manage stormwater flows and floods.

3.3. Pollution from sewerage and solid waste

Solid waste and sewerage pollution probably place the greatest pressure on rivers within the municipality, particularly when comparison is made between present land use activities and present ecological health of rivers. Without changing the way these impacts are managed, the future well-being of rivers will continue to decline while vulnerability to human health, aesthetics, and recreation will increase.

Water quality impacts are an ongoing challenge for the City that will require a broad range of strategies and actions covering multiple interventions (i.e. institutional, economic, social and biophysical) across all spheres of influence to include various stakeholders (i.e. primary, targeted, enabling, supporting, and external). Specific water quality actions should therefore be prioritised to address some of the more urgent problems such as failing sewer infrastructure and sewer blockages.

5. REFERENCES

Beaury, E.M., Fusco, E.J., Jackson, M.R., Laginhas, B.B., Morelli, T.L., Allen, J.M., Pasquarella, V.J., and Bradley, B.A. (2020). Incorporating climate change into invasive species management: Insights from managers. *Biological Invasions*, *22*(2), 233–252.

Burkhard, B., Kandziora, M., Hou, Y., and Müller, F. (2014). Ecosystem service potentials, flows and demands-concepts for spatial localisation, indication and quantification. *Landscape Online*, *34*, 1–32.

Capon, S.J., Chambers, L.E., Mac Nally, R., Naiman, R.J., Davies, P., Marshall, N., Pittock, J., Reid, M., Capon, T., and Douglas, M. (2013). Riparian ecosystems in the 21st century: Hotspots for climate change adaptation? *Ecosystems*, *16*(3), 359–381.

Corobov, R., Sîrodoev, I., Koeppel, S., Denisov, N., and Sîrodoev, G. (2013). Assessment of climate change vulnerability at the local level: A case study on the Dniester River Basin (Moldova). *The Scientific World Journal*, *2013*.

Dallas, H.F., and Rivers-Moore, N. (2014). Ecological consequences of global climate change for freshwater ecosystems in South Africa. *South African Journal of Science*, *110*(5–6), 01–11.

Downey, P.O., and Richardson, D. M. (2016). Alien plant invasions and native plant extinctions: A six-threshold framework. *AoB Plants*, *8*.

eThekwini Municipality. (2020). *Durban Strategic Environmental Assessment-Environmental Analysis Phase: Environmnetal Status Quo Report*. eThekwini Municipality.

Friedrich, E., and Kretzinger, D. (2012). Vulnerability of wastewater infrastructure of coastal cities to sea level rise: A South African case study. *Water Sa*, *38*(5), 755–764.

Friggens, M.M., and Woodlief, C.K. (2015). Synthesis of aquatic climate change vulnerability assessments for the Interior West. *Albuquerque, NM: US Department of Agriculture, Forest Service, Rocky Mountain Research Station. 67 p.*

Furniss, M.J., Ledwith, T.S., Love, M.A., McFadin, B.C., and Flanagan, S.A. (1998). *Response of Road–Stream Crossings to Large Flood Events in Washington, Oregon, and Northern California*. Publication.

Gain, A.K., Giupponi, C., and Renaud, F.G. (2012). Climate change adaptation and vulnerability assessment of water resources systems in developing countries: A generalized framework and a feasibility study in Bangladesh. *Water*, *4*(2), 345–366.

Gillespie, N., Unthank, A., Campbell, L., Anderson, P., Gubernick, R., Weinhold, M., Cenderelli, D., Austin, B., McKinley, D., and Wells, S. (2014). Flood effects on road–stream crossing infrastructure: Economic and ecological benefits of stream simulation designs. *Fisheries*, *39*(2), 62–76.

Gilvear, D.J., Spray, C.J., and Casas-Mulet, R. (2013). River rehabilitation for the delivery of multiple ecosystem services at the river network scale. *Journal of Environmental Management*, *126*, 30–43.

GIZ. (2014). *A framework for climate change vulnerability assessments*.

Grizzetti, B., Liquete, C., Pistocchi, A., Vigiak, O., Zulian, G., Bouraoui, F., De Roo, A., and Cardoso, A. (2019). Relationship between ecological condition and ecosystem services in European rivers, lakes and coastal waters. *Science of the Total Environment*, *671*, 452–465.

Jia, J., Dai, Z., Li, F., and Liu, Y. (2016). How will global environmental changes affect the growth of alien plants? *Frontiers in Plant Science*, *7*, 1623.

Mema, V. (2010). Impact of poorly maintained waste water and sewage treatment plants: Lessons from South Africa. *ReSource*, *12*(3), 60–61.

Nelitz, M., Boardley, S., and Smith, R. (2013). Tools for climate change vulnerability assessments for watersheds. *Prepared by ESSA Technologies Ltd. for the Canadian Council of Ministers of the Environment*.

NIRAS International Consulting and GroundTruth, South Africa (2019). Source to Sea: Screening study of pollution and flows in KwaZulu-Natal, South Africa. Report prepared for the Swedish Agency for Marine and Water Management (SwAM) and the South African Department of Environment, Foresty and Fisheries' (DEFF, previously DEA) Oceans and Coast branch. 1 October 2019.

Nwaneri, O., Nwachukwu, M., Ihua, N., and Nwankwo, C. (2018). The effect of solid waste disposal on Nworie river. *Journal of Environment and Biotechnology Research*, *7*(2), 23–29.

Palmer, M.A., Lettenmaier, D.P., Poff, N.L., Postel, S.L., Richter, B., and Warner, R. (2009). Climate change and river ecosystems: Protection and adaptation options. *Environmental Management*, *44*(6), 1053–1068.

Petrie, B., Chapman, A., Midgley, A.and Parker, R. (2014). Risk, Vulnerability and Resilience in the Limpopo River Basin System: Climate change, water and biodiversity – a synthesis. For the USAID Southern Africa “Resilience in the Limpopo River Basin” (RESILIM) Program. OneWorld Sustainable Investments, Cape Town, South Africa.

Pyšek, P., Hulme, P.E., Simberloff, D., Bacher, S., Blackburn, T.M., Carlton, J.T., Dawson, W., Essl, F., Foxcroft, L.C., and Genovesi, P. (2020). Scientists’ warning on invasive alien species. *Biological Reviews*.

Richardson, D.M., Holmes, P.M., Esler, K.J., Galatowitsch, S.M., Stromberg, J.C., Kirkman, S.P., Pyšek, P., and Hobbs, R. J. (2007). Riparian vegetation: Degradation, alien plant invasions, and restoration prospects. *Diversity and Distributions*, *13*(1), 126–139.

Roger, E., Duursma, D.E., Downey, P.O., Gallagher, R.V., Hughes, L., Steel, J., Johnson, S.B., and Leishman, M.R. (2015). A tool to assess potential for alien plant establishment and expansion under climate change. *Journal of Environmental Management*, *159*, 121–127.

Saaty, T.L. (1980). The Analytic Hierarchy Process: Planning, Priority Setting, and Resource Allocation. McGraw-Hill, New York. pp. 287.

Seanego, K., and Moyo, N. (2013). The effect of sewage effluent on the physico-chemical and biological characteristics of the Sand River, Limpopo, South Africa. *Physics and Chemistry of the Earth, Parts A/B/C*, *66*, 75–82.

Thuiller, W., Richardson, D.M., and Midgley, G.F. (2008). Will climate change promote alien plant invasions? In *Biological invasions* (pp. 197–211). Springer.

Tickner, D., Opperman, J.J., Abell, R., Acreman, M., Arthington, A.H., Bunn, S.E., Cooke, S.J., Dalton, J., Darwall, W., and Edwards, G. (2020). Bending the curve of global freshwater biodiversity loss: An emergency recovery plan. *Bioscience*, *70*(4), 330–342.

Tickner, D.P., Angold, P.G., Gurnell, A.M., and Mountford, J.O. (2001). Riparian plant invasions: Hydrogeomorphological control and ecological impacts. *Progress in Physical Geography*, *25*(1), 22–52.

Van Deventer, H., Smith-Adao, L., Collins, N.B., Grenfell, M., Grundling, A., Grundling, P-L., Impson, D., Job, N., Lötter, M., Ollis, D., Petersen, C., Scherman, P., Sieben, E., Snaddon, K., Tererai, F. and Van der Colff, D. (2019). South African National Biodiversity Assessment 2018: Technical Report. Volume 2b: Inland Aquatic (Freshwater) Realm. CSIR report number CSIR/NRE/ECOS/IR/2019/0004/A. South African National Biodiversity Institute, Pretoria.

C40 Cities Climate Leadership Group
3 Queen Victoria Street, City
London EC4N 4TQ
United Kingdom

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH
Potsdamer Platz 10
10785 Berlin
Germany

E contact@c40cff.org
W c40cff.org

Funding Partners:

Federal Ministry for Economic Cooperation and Development

Funded by UK Government

USAID FROM THE AMERICAN PEOPLE

Implementing agencies:

giz Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

C40 CITIES CLIMATE LEADERSHIP GROUP

Funding partners:

Federal Ministry for Economic Cooperation and Development

CIFF CHILDREN'S INVESTMENT FUND FOUNDATION