Promoting Green Urban Development in Africa:
Enhancing the relationship between urbanization, environmental assets and ecosystem services

PART II: EVALUATING THE POTENTIAL RETURNS TO INVESTING IN GREEN URBAN DEVELOPMENT IN DURBAN
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This study forms one of the case studies of a larger study on Green Urban Development commissioned by the World Bank and co-funded by The Nature Conservancy. Anchor Environmental Consultants (Anchor) was subcontracted by AECOM to undertake case studies in three cities: Kampala, Uganda; Dar es Salaam, Tanzania; and Durban, South Africa. Each city was consulted as to the focus of the case study. In the case of Durban, the city requested a study to evaluate Durban’s natural capital and its role in Green Urban Development (GUD). The study is made up of two parts. The first part consists of providing an updated, spatial estimate of the value of natural capital in the eThekwini Municipal Area and the second part involves undertaking a scenario analysis to evaluate the potential returns to investing in GUD with a focus on the role of natural systems. This study builds on the preparation of an Environmental Profile for eThekwini Municipality by AECOM.

The study was led by Dr Jane Turpie of Anchor Environmental Consultants. Dr Liz Day of Freshwater Consulting Group and Gwyn Letley of Anchor Environmental undertook the ecological and green urban design aspects of the study and associated costings. Dr Robynne Chrystal of CCS consulting undertook the hydrological modelling work under the guidance of Prof Derek Stretch, and Dr Stef Corbella of CCS Consulting prepared the infrastructure costing model.

We are grateful to the eThekwini municipal staff for their interest and support of this project, in particular to eThekwini Municipality to the eThekwini Environmental Planning and Climate Protection Department for providing relevant GIS data and associated explanations for the Durban Metropolitan Open Space System.

Thanks to Roland White and Chyi-Yun Huang of the World Bank and Diane Dale, Brian Goldberg and John Bachmann of AECOM, Dr Timm Kroeger of TNC, Jeff Wielgus and Mike Toman of the World Bank for the inputs into the study design and comments on an earlier draft.
EXECUTIVE SUMMARY

Introduction

Urbanisation is taking place at an unprecedented rate throughout the world, often outpacing plans and the capacity of city managers. As a result, natural open space areas in cities are being degraded and diminished, and problems such as flooding, air and water pollution are getting worse. The environmental problems associated with increased hardened surfaces and the loss of natural areas and ecosystem services are particularly acute in developing country cities, where a lack of regulation and resources has led to poor planning, the expansion of informal settlements in high risk, marginal areas, and the inability to adequately manage the quantity and quality of surface water flows. While conventional storm water conveyance measures contribute to reducing flooding impacts, they have not been able to keep ahead of the problem and have also contributed to pollution and degradation of downstream aquatic systems.

However, great strides have been made in the design of more sustainable engineering mechanisms to deal with urban flooding and water quality problems, and the management and planning of cities is increasingly focusing on a more holistic approach that includes the conservation of natural areas as part of a green urban development (GUD) strategy. A GUD strategy does not only focus on surface water issues but also involves the maintenance of natural open space areas for recreation which is essential for human health and wellbeing.

One of the challenges of green urban development will be to find the right balance between natural, semi-natural, innovative and conventional built infrastructure. Understanding the costs and benefits associated with the different types of measures is important and requires careful consideration of their potential benefits and cost effectiveness in managing urban environmental problems.

Durban, located within the eThekwini Municipality on the east coast of South Africa, is rich in biodiversity, but faces a number of environmental and developmental challenges. While green open space areas make up some 33% of the total area within the municipality, less than one third of this falls within the urban edge and only about 10% is formally protected and just under 7% is actively managed. Rapid urbanisation and the continued expansion of informal settlements contributes to the degradation and loss of natural systems and biodiversity. Key environmental issues include more frequent and intense flooding events, solid waste pollution, elevated flows and nutrients as a result of increases in wastewater outflows, erosion, poor air and water quality, overexploitation of natural resources, and the spread of alien invasive species. All of these issues contribute to rising infrastructure and human health costs as well as livelihood and property value losses which in turn affect municipal finances and GDP outputs.

Green urban development is an approach that aims to minimize the impacts of urbanization on the environment, and tackles the core problems of pollution and waste, the consumption of natural resources, the loss of urban open space and the degradation and loss of biodiversity, as well as mitigation of the urban contribution to climate change. In addition to a range of policy interventions, this involves investing in natural capital as well as use of green structural engineering and conventional grey infrastructure. Green urban development includes (1) sanitation services and regulations to minimise pollution, (2) applying “green engineering” approaches to urban problems such as stormwater management, (3) controlling consumption and carbon emissions, (4) protecting natural assets and (5) maintaining parks, street trees and gardens.

The aim of this study was to explore, using a case study and scenario-based approach, the potential costs and benefits of undertaking a green urban development approach to address some of the main environmental issues described above, and to explore the potential tradeoffs between different types of interventions, with an emphasis on assessing the desirable balance between engineered interventions and the conservation of natural open space areas. The study focuses on three elements of green urban development, all of which impact on ecosystems and biodiversity: sewage and solid waste management, active stormwater management and the conservation of natural systems and riparian corridors.

The study involved modelling current flooding and water quality in the Umhlatuzana-Umbilo catchment, and determining the change in water quality and flood hydrographs under a series of hypothetical scenarios in which the past development of the area had involved different combinations and extents of green urban development measures including better sanitation, stormwater management and conservation measures. The economic implications of these changes were assessed in terms of implications for aquatic ecosystem health as well as the infrastructure costs, and losses in property, tourism and fishery benefits that would have been avoided under these alternative scenarios. The relative costs and benefits of different scenarios were then evaluated using a cost benefit approach.

Study area: the Umhluluzana-Umbilo Catchment

The Umhluluzana-Umbilo catchment is situated in the centre of the eThekwini Municipal Area (EMA) and covers an area of approximately 272 km². It incorporates...
Durban’s city centre, it’s harbour (Durban Bay) and important industrial areas and has a significant formal residential population. The catchment is undulating with steep river valleys in the upper and middle reaches, the lower catchment is relatively flat. The catchment has a mean annual runoff (MAR) of 43.25 million m³ and the two main rivers are the Umhlatuzana River and the Umbilo River which flow into Durban Bay. The EMA has a subtropical climate with humid wet summers and mild dry winters. The mean annual precipitation is just over 1000 mm and most of the rain falls between September and March.

Much of the catchment has been developed and is dominated by urban settlement, commercial and industrial land use, with some agriculture in the upper parts. There are a number of informal settlements in the catchment and these tend to be located along steep river banks and in river floodplains. There are around 6000 ha of natural vegetation in the catchment, dominated by woodland and forest. Most of the intact forest is found along the steep river valleys in the upper and middle catchment. The North Park Nature Reserve, Kenneth Stainbank Nature Reserve and Bluff Nature Reserve provide some protection to these natural systems. Durban Bay is one of South Africa’s largest estuaries and has a high degree of conservation. The head of the estuary a small 15 ha pocket of mangroves are protected as part of the Bayhead Natural Heritage Site.

Water pollution and flooding are two of the main environmental issues associated with this catchment. Pollution comes from a number of different sources including non-point source pollution such as pesticides, fertilisers and industrial and residential runoff; stormwater outflows, point source pollution from industrial discharge points (factories) and urban infrastructure (WWTW) resulting in high nutrient concentrations, point source pollution from discharges from informal settlements, and the presence of alien invasive vegetation within the riparian zone resulting in erosion and sedimentation. Flooding in the catchment is exacerbated by the high levels of litter and dead vegetation which block culverts and drains causing rivers to overturn and burst their banks. An enormous amount of plastic litter washes into the rivers and out to the sea during high runoff events. Pollution and flooding has a major impact on the biodiversity and ecological functioning of the river systems.

Water quality in the middle and lower reaches of the Umhlatuzana and Umbilo Rivers was assessed by the National River Health Programme as Poor, due mainly to water quality conditions in the upper catchment on the Umbilo River, in particular, are considered acceptable – a result of the lower density of settlements and the presence of largely unmodified riparian buffers in this part of the catchment.

Conservation areas and riparian corridors

Among the most feasible options identified were the protection, restoration and/or enhancement of natural systems. The maximum possible extent of each of these options was determined on the basis of GIS information on land use, soils and slope.

Currently there are approximately 6000 ha of natural vegetation in the catchment as per the D’MOSS plan. Taking into account future planning as per municipal scheme development zonation plans, the amount of natural vegetation in the catchment is reduced to 2800 ha, or 11% of the total catchment area. It was determined that a total of 7000 ha would be required to meet conservation targets, accounting for approximately 28% of the catchment area.

Riparian buffer zones along waterways intercept sediments, nutrients, pesticides and litter in diffuse or sheet surface runoff thereby reducing the amount of pollutants entering rivers and streams. They may also provide habitat and wildlife corridors and can be important for reducing erosion, slowing down floodwaters by increasing roughness (and thus reducing downstream peaks) and providing river bank stabilisation. In this study, riparian buffers extended 15 m on either side for smaller rivers and streams, 30 m on either side of major rivers and on one side of canalised rivers (1900 ha).
Scenario setup

Each scenario consisted of a combination of the different interventions described above, applied to different extents in the catchment. Since GUD measures are unlikely to have much positive impact in the absence of adequate sanitation, it was decided to include full sanitation (as required by existing legislation) in most of the scenarios. A total of 15 scenarios were designed and analysed (Table I). All scenarios assumed that the catchment was fully developed (as per municipal scheme zonation plans, effective 2014), except that scenarios with medium or high levels of conservation meant that the development was more compact. All scenarios had the same number of households and the same amount of commercial and industrial activity.

Scenario 1 (BAU) had full development as planned, but with the same level of backlog of sanitation and solid waste services as at present. The total area of informal settlements remained the same, i.e. 3% of total catchment area. No green engineering measures were implemented and the amount of natural open space was reduced to the planned extent of 2800 ha. This was termed the “Baseline.” Note that the baseline is not the same as the present-day situation, which was used to develop and calibrate the models, and against which water quality estimates are also compared out of interest.

In Scenario 2 (GUD without sanitation), all the green engineering and conservation measures were implemented but the sanitation backlog was not addressed. This was to test whether the GUD measures designed to address water quality would still be effective if sanitation were not properly addressed.

Scenario 3 (“Clean Baseline”, BAU + SWM) was the same as Scenario 1 except that the sanitation backlog and litter problems were addressed (i.e. informal settlements were serviced and any growth in sewage output was balanced by recycling). A comparison of Scenario 3 to Scenario 1 allowed a test of the effect of sanitation alone on water quality. Scenario 2 was compared to Scenario 15, and showed that in this particular catchment the measures being tested would work with or without sanitation, given the relatively small area of unserviced informal settlements.

The remaining scenarios all included full sanitation and litter prevention programmes, so “+SWM” is implied in Scenarios 3-15. Scenario 3 effectively provided a “Clean Baseline” against which to evaluate the relative net benefits of different engineering and conservation measures applied to different extents. Scenarios 4-15 were compared with Scenario 3, under the prior assumption that adequate sanitation is both imperative and a prerequisite to GUD.

Scenarios 4 to 8 were set up to test the effects of different amounts of natural areas (conservation areas and river buffers) on flooding and water quality. Scenarios 9 to 12 were set up to test the effects of different combinations of green engineering interventions. Scenarios 13 to 15 were set up to explore the effects of implementing both green engineering and conservation measures to different extents.

Scenario modelling

Several models were used during the scenario analysis to determine the potential costs and benefits associated with using a green urban development approach to addressing environmental issues. Inputs into the models included the extent and quality of natural areas, the extent, design and performance of a range of GUD engineering solutions for flood attenuation and water quality amelioration, and the amount and design capacity of stormwater conveyance and waste water treatment infrastructure.

A hydrologic (hydrology + hydraulic) model was set up for the Umhlatuzana-Umbilo catchment using the PC-SWMM software. This model was set up to run design flood events in order to determine the influence of green urban development interventions on flood hydrographs at strategic points relating to the location of existing flood conveyance infrastructure. The flood hydrographs generated under baseline conditions (fully-developed catchment as planned, business as usual) were compared with hydrographs generated under each of the different GUD scenarios. This provides an indication of the impacts of GUD interventions and the difference can be construed as an estimation of the flood attenuation benefit obtained from implementing these interventions in the catchment. The additional flood volumes without these interventions that would occur under different return period flood events, would require larger drains, culverts, and other conveyance infrastructure, depending on the size of the event these constructed flood management assets are designed to deal with. Thus a second model was developed in order to estimate the capital costs of the structures required under the baseline versus GUD scenarios. The difference, together with associated differences in discounted annual maintenance costs, was the total life-cycle flood infrastructure cost saving from the GUD measures.

A sediment and nutrient model, also set up in PC-SWMM, produced water quality outputs in the form of Total Suspended Solids (TSS) and nutrient concentrations and loads at specific points of interest in the catchment. The pollutant washoff from a given landuse during periods of wet weather was characterized in the model by using a user-defined Event Mean Concentration (EMC). Model subcatchment parameters were derived by area-weighting the various land use parcels within each subcatchment. The modelled runoff flows were coupled with EMC values to estimate the concentration and total load of TSS, TN and TP. Modelled suspended sediment loads were multiplied by a factor of 1.25 in order to account for bed load.

By comparing the modelled sediment and nutrient outputs for each scenario versus the baseline, it was possible to estimate the difference made by GUD interventions to the sediment loads and nutrient concentrations and loads transported to Durban Bay.

The water quality data were used as inputs into a River Ecosystem Health assessment tool to evaluate river system changes, into an Estuarine Ecosystem Services model to estimate changes in the value of selected services, and into an assessment to determine harbour dredging costs avoided.

Changes in the quantity of green open space areas were used to determine changes in carbon storage. The carbon storage value for the EMA was used to determine a per hectare cost for D’MOSS which was then used to determine a carbon storage costs for the minimum, medium and maximum extents of conservation areas under each scenario.

Changes in the quantity and quality of green open space areas were used as inputs into a Tourism Value model and a Hedonic Pricing Model, which estimated differences in tourism and property values, respectively. The comprehensiveness of these models varied according to priorities, availability of potentially suitable modelling platforms and models, and data availability. The Estuary Ecosystem Services Model, Tourism Value Model and Hedonic Pricing Model built on models developed for the municipality-wide eThekwini ecosystem services valuation study (Turpie et al. 2017). A cost benefit analysis (CBA) was set up to assess the overall impacts and benefits associated with the GUD approach.

Impacts on sediments and water quality

Both green engineering and natural interventions significantly reduced sediment loads into the harbour. Conservation areas and riparian buffers (Scenarios 4 – 8) had a significant impact on reducing TSS loads into the harbour. An increase in conservation area from the minimum to medium and or maximum extent translated into 18% and 32% reductions in TSS loads, respectively. The addition of river buffers led to a further 31-36% reduction in the annual TSS loading, and with the maximum extent of natural interventions (Scenario 8) annual TSS loads entering the harbour were reduced by 63%. Source controls at detention basins each had a relatively low impact on TSS loads into the harbour. However their effect was noticeable at certain points higher in the catchment where they had significant impacts on reducing TSS loads by up to 90%. Avoided...
Interventions such as riparian buffers appeared to have been implemented across the catchment. Treatment wetlands in part to result from the fact that the measures are PES category. The dramatic improvement was assumed to account for most significant impacts, generally accounting for an increase in water quality compared to present. Recycling and sanitation had been unacceptably poor state (Category E or F on a scale of A to F). The present-day concentrations of water quality variables in the river systems generally follow expected patterns for urban environments, with the highest concentrations of TN and TP occurring in the dry season when dilution is lowest, and TN tending to be lowest in the dry season, when flows are too low to mobilise sediments. Phosphorus-based enrichment in the catchment is significant, with all but the upper reaches of the Umhlatuzana River being in an unacceptably poor state (Category E or F on a scale of A to F). TN concentrations were also bad, although none of the sites were in a worse category than Category E.

A BAU approach will result in worsening of water quality compared to present. Recycling and sanitation (Scenario 3) resulted in significant improvement in river condition, particularly in reaches previously affected by runoff from poorly serviced informal settlements. While riparian buffers and conservation areas (scenarios 4-8) yielded improvements in TN and TP levels, green engineering measures alone or in combination with conservation measures (Scenarios 9 – 15) achieved the most significant impacts, generally accounting for an improvement in water quality condition by at least one PES category. The dramatic improvement was assumed in part to result from the fact that the measures are implemented across the catchment. Treatment wetlands exerted significant effects on water quality in the reaches where they were implemented. Interventions such as riparian buffers appeared to have little effect on instream nutrient concentrations but had significant implications for TSS. Riparian buffers and conservation areas also played a major role in determining overall river habitat integrity, through the provision of longitudinal corridors for faunal movement important in an increasingly urban environment.

Impacts on flooding and infrastructure requirements

Takes on, green engineering measures were more efficient at reducing peak flows than traditional natural interventions, although the maximum extent of conservation and riparian areas was highly effective. Riparian buffers were the least effective intervention. However, the more compact development scenarios with bigger conservation areas had a significant impact on peak flows with an 8% reduction in the impervious surface area in the catchment translating to a 15% decrease in peak flows during a 2- and 5-year return period floods. When the ratio of conservation to developed area was increased in the upper catchment, a significant reduction in peak flows was seen. While there was a significant improvement from minimum to medium conservation, the difference between medium and maximum conservation scenarios was relatively small because much of the added conservation area was in the lower catchment.

On average the source control measures reduced peak flows by 10%. Soakaways in residential areas contributed the most to this reduction, which was expected given their large scale of implementation compared to other source controls. Detention basins were found to be more effective at reducing peak flows during small to medium return period floods than higher return period floods. During small to medium return period floods, peak flows at the bottom of the catchment were reduced by 9.35%. The reduction was higher at points in the upper catchment.

If all interventions were applied together, peak flows were reduced by 45 – 50% for the smaller return periods (0.5- and 1-year), 25 – 30% for the medium return periods (2- and 5-year) and by 15 – 20% for the high return periods (10- and 20-year). However, combining conservation areas and green engineering interventions has a small additional effect relative to other scenarios, which suggests that green engineering and conservation interventions (in combination with compact development) are largely substitutable in terms of their effects on flooding.

The different interventions reduced capital cost requirements for flood conveyance by R19 million (riparian buffers) to R226 million (all interventions). The relatively small saving of 0.5 – 6% compared to the percentage change in flood sizes is to some extent an artefact of the present tendency for overdesign of conveyance infrastructure (due to solid waste, etc.).

Gains in ecosystem values

The decrease of nutrient and sediment loads into Durban Bay led to gains in estuarine and marine fishery values ranging from 9% for Scenario 4 to 55% for Scenario 15, worth R0.6 - R3.5 million per annum.

The effect of a more compact but greener development approach on property value was estimated to be significant, with property premiums associated with natural vegetation in a good condition increasing from R887 million for the minimum extent to R1.8 billion for the medium conservation extent and R3 billion under the maximum conservation extent.

The annual nature-based tourism value associated with natural open space areas in the Umfocwane catchment was estimated to be R205 million under the minimum extent, R439 million for the medium extent and R512 million under the maximum conservation area scenarios. This translates into a net present value of R2.35, R5.04 and R8.77 billion for the minimum, medium and maximum extents of conservation areas, respectively. We did not estimate the effect of different scenarios on the very high tourism value associated with beaches. The management of the Umfocwane catchment is not expected to have a major impact on these values, but the management of several other eThekwini catchments would be expected to have this added effect.

Increased areas of land under conservation result in increased avoidance of climate change damages. Based on the extent of D’MOSS under each of the conservation extents, it was estimated that the damage costs avoided by retaining carbon stocks within the Umhlatuzana-Umfolozi catchment would be approximately R3.2 million, R2.7 million and R1.3 million per annum for the maximum, medium and minimum extents of conservation areas considered. This translates to a net present value of R37 million, R31 million and R15 million for carbon storage, respectively.

In addition to the above, retaining natural areas in the catchment also provides biodiversity benefits. Larger conservation areas retain more viable species populations and together with riparian corridors provide connectivity which is critical for the movement of organisms and the resultant flows of ecosystem services. Ecological connectivity is particularly important in areas where the location and distribution of green open space is critical for delivery of ecosystem services.

Cost benefit analysis

Costs and benefits were examined relative to the scenario of full development with adequate sanitation (Scenario 3, Table III), under the assumption that adequate waste management is both imperative and a prerequisite to GUD, and to specifically focus on the potential added benefits of the less conventional GUD measures. Scenarios 4 – 8 and Scenario 10 had positive net present values (NPV). NPVs increased with increasing conservation area from riparian buffers alone (Scenario 6) to riparian buffers in conjunction with the full area of natural open space required to meet conservation targets (Scenario 8), with the latter having a NPV of R5.9 billion (using a discount rate of 6% over 20 years). This was because maintaining natural areas had relatively low costs and high benefits. However, the estimates derived from this study suggest that scenarios that include the implementation of source control measures (Scenarios 9, 11-15) would have a negative NPV. This was due to the very high costs of these measures, particularly of soakaways in residential areas. Scenario 10 (detention basins only), had a positive NPV, of R180 million, due to the relatively low costs of implementing this measure. This scenario had a higher NPV than Scenario 6, the result of higher cost infrastructure savings.

The results suggested that the compact development options with larger proportions of green open space were far more effective than using engineering measures alone. The open space areas not only deliver ecosystem services relating to the primary stormwater management objectives but also directly provide amenity value that is translated into property and tourism values. It is acknowledged, nevertheless, that the latter benefits were more difficult to estimate than other benefits such as the savings arising from flood management and therefore have some degree of uncertainty. The most uncertain estimates were those of tourism value, for which we have used average values in the absence of reliable estimates of marginal changes in value associated with changes in the “green-ness” of Durban. Nevertheless, our estimates could be considered as conservative; firstly, the demand for conservation areas is likely to increase as the city grows and incomes rise. Secondly, the cost-benefit analysis does not take into account a range of other potential benefits of the GUD interventions such as air quality and the existence value of biodiversity.

To provide some perspective, the initial capital requirement associated with each scenario (Table III) was compared to the eThekwini Municipality capital budget of R6.73 billion for 2016/17 (eThekwini Municipality 2016). Scenarios 4 – 8 and Scenario 10 have a funding requirement that is less than 1% of the municipal capital budget. Scenarios 11 and 12 would require 13.8% and 11.4% of the capital budget respectively and scenario 15 would require 96.1% of the capital budget. The requirements for scenarios 9, 13, and 14 are all higher than the proposed capital budget for the municipality, however, it is expected that capital requirements for large-scale implementation would occur over several years (or decades) as an area develops.
## Evaluating the Potential Returns to Investing in Green Urban Development in Durban

### Scenario Comparison Table

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Total Present Value of Costs (R millions)</th>
<th>Total Present Value of Benefits (R millions)</th>
<th>NPV (R millions)</th>
<th>Initial Capital Requirement (R millions)</th>
<th>% of EM Capital Budget 2016/17</th>
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<tr>
<td>5. Cons3</td>
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<td>7. R + Cons2</td>
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<td>12. S2+D</td>
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<tr>
<td>15. S2+D+W+R+Cons3</td>
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<td>6 148</td>
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<td>6 454</td>
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</tbody>
</table>

### Conclusions

Under a business as usual scenario, the continued growth of urban areas in Africa will result in a further deterioration of the natural environment and living conditions, a loss of values associated with green open space areas, and increased costs in reducing risks to people that result from environmental problems. The notion of Green Urban Development is therefore highly attractive, as it allows cities to grow in a way that maintains their resilience and maintains standards of living and quality of life. However, few studies have investigated what following a more sustainable green urban development path will actually cost, and whether these costs can be justified. Moreover, what Green Urban Development should look like is also not well defined, in terms of the degree to which is includes the conservation of river buffers and other natural areas, the mimicking of natural processes through innovative engineering design or the protection of downstream areas through conventional engineering measures. In eThekwini Municipality, these issues have to be considered as plans for the growth of Durban are laid out. In this study, we tested the idea of green urban development by backcasting a range of scenarios for a well-developed catchment.

This study attempted to analyse a highly complex problem in a fairly large catchment area, and as such, a great deal more work will still be needed in order to narrow the potential error margin. Our study found a lack of empirical studies to inform modelling assumptions, which suggests that much benefit could be obtained from the implementation and monitoring of pilot programmes. Furthermore, there are few well-developed modelling platforms that are capable of estimating the impacts of these kinds of interventions at scale. Most previous studies have analysed these problems at a micro-catchment scale, making it difficult to assess the economic implications of a change in policy. Thus, while these are first-cut estimates which warrant further refinement, they provide a useful step towards the informing policies to guide the city’s sustainable development path.

The results showed that in a catchment with little unserviced informal settlement (1% of the area) recycling the equivalent of a third of sewage outputs along with complete sanitation services has the most significant impact on nutrient loads entering the rivers and harbour, and that treatment wetlands make a significant further impact. Sediment loads can be effectively dealt with using either natural interventions (particularly river buffers) or green engineering interventions (source controls and detention basins), and these appear to be substitutable to a large degree when the former is brought about through more compact development. Similarly, both natural and green engineering interventions were highly effective at reducing flood peaks, and were also substitutable to a large degree in terms of this function. This suggests that some sensible combination could be applied, with green engineering interventions plans for the growth of Durban are laid out within the catchment for maximum overall effect.

However, not all green engineering interventions are equally viable. Our estimates suggested that the large-scale application of low-impact stormwater management measures (i.e. source controls) is extremely costly at today’s prices, even when accounting for economies of scale. With the other hand, the simpler green engineering measures, such as detention basins for reducing peak flows and treatment wetlands for improving water quality, were shown to be highly cost-effective, viable interventions.

The retention of significant natural areas within the catchment, which may require more compact development, was not only found to be highly effective at reducing sedimentation and flooding problems, but has the added benefit of yielding high amenity value realised as property and tourism value as well as intangible and unknown values associated with maintaining biodiversity and ecological connectivity. Although riparian buffers have limited influence on water quality and flooding in urban environments, the value in maintaining biodiversity is also very high, as they are a critical for providing connectivity between terrestrial systems, rivers and estuaries.

Because conservation with compact development incurs very low costs in comparison to other interventions, the net benefits of this strategy far outweighed any other. Compact development coupled with the other interventions creates the greenest city, in terms of water quality and biodiversity conservation goals, and is an economically justifiable strategy in terms of overall costs and benefits. Maintaining large natural areas and riparian buffers should therefore be a primary strategy, along with the strategic positioning of cost-effective green engineering measures.
ACRONYMS AND ABBREVIATIONS

<table>
<thead>
<tr>
<th>BAU</th>
<th>Business as usual</th>
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<tbody>
<tr>
<td>BCDA</td>
<td>Black Communities Development Act</td>
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<tr>
<td>BMP</td>
<td>Best Management Practice</td>
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<td>BWSP</td>
<td>Basic Water and Sanitation Programme</td>
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<td>WWTW</td>
<td>Waste Water Treatment Works</td>
</tr>
</tbody>
</table>

TABLE OF CONTENTS

EXECUTIVE SUMMARY ................................................................. 1

ACRONYMS AND ABBREVIATIONS ............................................ X

I. INTRODUCTION ........................................................................ 1

1.1 Background ........................................................................ 1
1.2 Durban’s environmental issues ............................................ 2
1.3 Green urban development ................................................. 3
1.4 Study objectives ................................................................. 4
1.5 Study approach ................................................................. 4

II. THE UMHLATUZANA-UMBILO CATCHMENT AREA ........ 7

2.1 Location and extent ............................................................ 7
2.2 Geography and climate ....................................................... 8
2.3 Historical and current land cover ........................................ 9
2.4 Pollution and flooding ....................................................... 9
2.5 Water quality .................................................................... 12
2.6 River condition ................................................................. 12

III. DESIGN AND POTENTIAL EXTENT OF SELECTED GREEN URBAN DEVELOPMENT INTERVENTIONS FOR THE STUDY AREA 13

3.1 Sewage and solid waste management ................................ 13
3.1.1. Dealing with sewage ................................................. 13
3.1.2 Managing solid waste ................................................. 13
3.2 Active stormwater management (green engineering) .......... 13
3.2.1 Overview of stormwater management .......................... 13
3.2.2 Review and feasibility of green engineering measures ....... 16
3.2.3 Potential extent of selected interventions ....................... 17
3.3 Conservation of natural systems and biodiversity ............. 19
3.3.1 Riparian buffers ....................................................... 19
3.3.2 Conservation areas and compact development ............... 19

IV. SCENARIO SET-UP ............................................................... 23

4.1 Approach .......................................................................... 23
4.2 Scenario elements ............................................................ 23
4.3 Scenarios ......................................................................... 24
V. SCENARIO MODELLING AND RESULTS 27
5.1 Overview .................................................................................................................. 27
5.2 Water quality improvements and related benefits ................................................ 28
5.2.1 Impacts on sediment and nutrient concentrations and loads .......................... 28
5.2.2 Impacts on river condition ............................................................................... 32
5.2.3 Avoided costs due to sediment retention ......................................................... 37
5.2.4 Impacts on estuary condition and fishery values ............................................ 38
5.3 Flood attenuation benefits ................................................................................... 39
5.3.1 Impacts on flood peaks .................................................................................... 39
5.3.2 Avoided costs due to flood attenuation ............................................................ 47
5.4 Amenity benefits of increased conservation areas ................................................. 49
5.4.1 Amenity value to locals ...................................................................................... 49
5.4.2 Nature-based tourism value .............................................................................. 50
5.5 Avoided climate change costs .............................................................................. 51

VI. COST BENEFIT ANALYSIS 53
6.1 Framework ............................................................................................................. 53
6.2 Scenario costs ....................................................................................................... 53
6.3 Cost-benefit analysis ............................................................................................ 55
6.4 Sensitivity analysis ............................................................................................... 58

VII. CONCLUSIONS AND POLICY RECOMMENDATIONS 59

VIII. REFERENCES 61

APPENDIX 1: URBAN STORMWATER MANAGEMENT OPTIONS 65
A1.1 Overview ............................................................................................................. 65
A1.2 Passive engineering measures to improve conveyance ..................................... 65
A1.2.1 Drains and swales ............................................................................................ 65
A1.2.2 Enlargement of river channel/canalisation/levees/dredging ............................ 65
A1.2.3 Hydraulic bypass ............................................................................................ 66
A1.3 Active engineering measures to retard runoff ............................................... 66
A1.3.1 Permeable pavements ...................................................................................... 66
A1.3.2 Infiltration trenches ......................................................................................... 67
A1.3.3 Soilakways (sub-surface infiltration trenches) ............................................... 68
A1.3.4 Green roofs .................................................................................................... 69
A1.3.5 Rainwater harvesting ....................................................................................... 70
A1.3.6 Vegetated swales ............................................................................................. 71
A1.3.7 Filter strips ....................................................................................................... 72
A1.3.8 Sand filters ........................................................................................................ 72
A1.3.9 Bio-retention areas .......................................................................................... 73
A1.3.10 Detention basins ........................................................................................... 74
A1.3.11 Constructed treatment wetlands ................................................................. 75
A1.4 Non-structural interventions ............................................................................. 76
A1.4.1 Sweeping and solid waste management ......................................................... 76
A1.4.2 River cleaning and stewardship ...................................................................... 76
A1.4.3 Riparian buffers .............................................................................................. 77
A1.4.4 Catchment reforestation .................................................................................. 78
A1.5 Relative performance of different measures .................................................... 79
A1.5.1 Average cost effectiveness in terms of peak flow and volume reduction .......... 80
A1.5.2 Average cost effectiveness in terms of water quality amelioration ................. 80
A1.5.3 Overall effectiveness, cost-effectiveness and potential co-benefits .................. 82

APPENDIX 2. SCENARIO ASSUMPTIONS 83
A2.1 Sanitation measures ............................................................................................ 83
A2.1.1 Scenario 1-2 (sanitation backlog) ................................................................. 83
A2.1.2 Scenarios 3-15 (full sanitation) ..................................................................... 84
A2.2 Stormwater source controls ............................................................................ 84
A2.2.1 Design and extent of the different interventions .......................................... 84
A2.2.2 Cost assumptions ......................................................................................... 86
A2.3 Treatment wetlands ......................................................................................... 86
A2.4 PC_SWMM model assumptions .................................................................... 87
A2.4.1 Assumptions regarding untreated urban runoff quality ............................... 87
A2.4.2 Assumptions for stormwater management interventions ............................ 88

APPENDIX 3. FLOOD MODELLING 93
A3.1 Model setup ....................................................................................................... 93
A3.1.1 Baseline information, software and GIS layers ............................................ 93
A3.1.2 Subcatchment delineation and flow lines ..................................................... 94
A3.1.3 Point sources ................................................................................................ 96
A3.1.4 Hydraulic parameters .................................................................................. 96
A3.1.5 Soil infiltration ................................................................................................ 99
A3.1.6 Storm design events ..................................................................................... 101
A3.1.7 U60F model .................................................................................................. 101
A3.2 Points of interest for scenario analysis .............................................................. 102
A3.3 Model calibration ............................................................................................. 102
A3.3.1 Rainfall selection and application ................................................................. 102
A3.3.2 Design rainfall generation for U60F .................................................. 103
A3.3.3 Available measured data ................................................................. 103
A3.3.4 Calibration of flows and water levels ........................................... 103
A3.4 Assumptions and limitations ............................................................... 104
A3.4.1 The use of design rainfall ............................................................... 104
A3.4.2 Groundwater and baseflow ......................................................... 104
A3.4.3 Stormwater network data .............................................................. 104

APPENDIX 4: INFRASTRUCTURE COST ESTIMATE METHOD 105
A4.1 Overview .......................................................................................... 105
A4.2 Identifying existing infrastructure .................................................... 105
A4.3 Assigning rainfall return periods ...................................................... 105
A4.4 Cost estimate of the infrastructure .................................................. 105
A4.4.1 Bridges ....................................................................................... 105
A4.4.2 Culverts ..................................................................................... 105
A4.4.3 Canals ....................................................................................... 105
A4.4.4 Pipes ......................................................................................... 105
A4.5 Flow vs dimension relationship ....................................................... 106
A4.5.1 Pipe scaling ................................................................................ 106
A4.5.2 Culvert scaling ........................................................................... 106
A4.5.3 Estimating the flow type ............................................................... 106
A4.6 Cost comparison ............................................................................... 106
A4.7 Additional information ................................................................. 106

APPENDIX 5. SEDIMENT AND NUTRIENT MODELLING 109
A5.1 Model setup ....................................................................................... 109
A5.1.1 Rainfall ...................................................................................... 109
A5.2 Points of interest for scenario analysis ........................................... 110
A5.3 Model calibration ........................................................................... 110

APPENDIX 6: RIVER ECOSSYSTEM HEALTH ASSESSMENT 113
A6.1 Approach for assessing river condition ........................................... 113
A6.2 Model outcomes ............................................................................... 116

LIST OF FIGURES

Figure 1.1 Schematic representation of Green Urban Development and associated terminology (Source: authors own interpretation) .............. 1
Figure 1.2 Schematic diagram of key environmental issues in Durban (divided into "brown issues" and "green issues"), their causes and their consequences (Source: author’s own analysis) .............................................. 2
Figure 1.3 The main elements of a green urban development policy (Source: authors) .............................................................................. 3
Figure 2.1 The location of Umhlatuzana-Umbilo catchment in the DMA ................................................................. 7
Figure 2.2 Elevation map showing the main elevation bands as one moves from the upper catchment to the lower catchment .................. 8
Figure 2.3 Average monthly rainfall (mm) for Durban, 1961-2003 (Source: StatsSA 2005) .............................................................. 9
Figure 2.4 Map of the historical vegetation within the Umhlatuzana-Umbilo catchment ................................................................. 10
Figure 2.5 Current landcover in the Umhlatuzana-Umbilo catchment .................. 10
Figure 2.6 The Cato Manor informal settlement is situated along the banks of the Mkumbane River ................................................................. 10
Figure 2.7 Sewage and litter from the informal settlement ends up in the Mkumbane River (Source: Google Earth) ....................... 11
Figure 2.8 Photos taken of the Umhlatuzana River after a flood event in February 2016 showing the large amounts of plastic and other waste washed into the river ................................................................. 11
Figure 3.1 Different types of measures used in stormwater management (Source: Turpie et al. 2017). These measures are described in detail in Appendix 1 ................................................................. 14
Figure 3.2 Soil drainage rates in the Umhlatuzana-Umbilo catchment (Source: South African atlas of agrohydrology and climatology) .......... 17
Figure 3.3 The properties selected as suitable for application of source controls in the catchment (a) green roofs, (b) permeable paving, (c) infiltration trenches and (d) soakaway pits ................................................................. 18
Figure 3.4 The potential extent of riparian buffers in the Umhlatuzana-Umbilo catchment ................................................................. 20
Figure 3.5 The total area of transformed land and natural open space (OS) in the catchment under status quo, minimum conservation, medium conservation and maximum conservation ................................................. 20
Figure 3.6 The extent of (a) conservation areas that will remain under existing development plans, (b) current conservation areas and (c) conservation areas that would have met biodiversity targets in the catchment ........................................................................... 21
Figure 5.1 The approach used for the scenario analysis and determining the costs and benefits associated with green urban development. ................................................................. 27
Figure 5.2 Annual TSS load (tonnes) for different outfalls into Durban Harbour for all scenarios ................................................................. 29
Figure 5.3 The annual TSS loadings at different points along the Umbilo River (left) and the Umhlatuzana River (right). Refer to Figure A6.1 for the monitoring station locations in the catchment............................... 30
Figure 5.4 Annual TP and TN loads for different outfalls entering Durban Harbour for all scenarios ................................................................. 31
Figure 5.5 Effects of different modelled scenarios on concentrations of Total Phosphorus and Total Suspended Solids (TSS), respectively. Site locations as shown in Figure A6.1 ................................................................. 31
Figure 5.6 Effects of different modelled scenarios on total inorganic nitrogen (TIN) concentrations at different monitoring sites in the study area. Site locations as shown in Figure A6.1 ................................................................. 35
Figure 5.7 Schematic summary of the linkages from water quality parameters to ecosystem services for a case of deteriorating water quality ........................................................................... 38
Figure 5.8 SWAT model of the U60F catchment including flow paths (yellow and red lines), detention basins (green squares), WWTPs (larger black dots), water quality monitoring stations (smaller black dots), extent of source controls for commercial and industrial areas (grey shaded) and residential areas (purple shaded areas). The Umhlatuzana-Umbilo catchment, the Amanzimnyama Stream catchment and all other contributing catchments have been outlined ........................................................................... 41
Figure 5.9 Summary of the simulated peak flows for all scenarios and all return periods for the Umhlatuzana/Umbilo Canal outfall into the harbour ........................................................................... 42
Figure 5.10 Summary of the relative change in peak flows compared to the baseline for all scenarios and all return periods for the Umhlatuzana/Umbilo Canal outfall into the harbour ........................................................................... 42
Figure 5.11 Percent impervious surface area and associated relative change in peak flow for the conservation scenarios compared to the baseline ........................................................................... 43
Figure 5.12 Simulated peak flows for a 2- and 5-year rainfall return period for the Baseline and Scenarios 4 and 5 at sampling points (a) R. Mkumbane_01 and (b) R. Zama_35 ................................................................. 43
Figure 5.13 Hydrographs showing a 2-year rainfall return period flood for Scenarios 9, 11 and 12 at sampling points (a) Umbilo_22, (b) R. Mkumbane_05, (c) R. Cats_15 and (d) R. Zama_35. Note that time units are reporting time steps from the model with one time unit representing 5 minutes ........................................................................... 44
Figure 5.14 Simulated peak flows for a 2-, 5-, 10- and 20-year rainfall return period for Scenario 10 compared to the Baseline at sampling points (a) R. Zama_35, (b) R. Zama_28, (c) R. Zama_10 and (d) R. Mkumbane. Note that time units are reporting time steps from the model with one time unit representing 5 minutes ........................................................................... 45

PAGE XIV EVALUATING THE POTENTIAL RETURNS TO INVESTING IN GREEN URBAN DEVELOPMENT IN DURBAN EVALUATING THE POTENTIAL RETURNS TO INVESTING IN GREEN URBAN DEVELOPMENT IN DURBAN PAGE XV
EVALUATING THE POTENTIAL RETURNS TO INVESTING IN GREEN URBAN DEVELOPMENT IN DURBAN

LIST OF TABLES

Table 3.1 The rules and criteria applied to different active stormwater management measures based on soil drainage, slope and water table characteristics:.................................................................................................................16
Table 3.2 Annual Average Treatment Performance Capabilities for surface flow wetlands (Source: Kadlec & Knight 1995) assuming wetland influent is a “typical municipal effluent”. .................................................................................................................................19
Table 4.1 Summary of interventions considered in the scenarios: ...........................................................................................................................................................................................................24
Table 4.2 Scenarios used in the analysis. Levels of each intervention are described using symbols for ease of comparison: + = Stormwater, × = Detention, − = None, +/− = Optional .............................................................................................................................................................................................24
Table 5.1 Comparison of different systems for the categorisation of river health/condition data, simplified after DWA(2008). .........................................................................................................................................................................................32
Table 5.2 The total annual dredging cost for each scenario, and annual and NPV dredging costs (R millions) for each scenario when compared to the baseline.................................38
Table 5.3 Estimated gains in estuarine and marine fishery values value due to a reduction in TSS and nutrients for scenarios 4-15 when compared to Scenario 3 as the baseline.................................39
Table 5.4 Stormwater infrastructure cost savings (R millions) for scenarios 4-15, when compared to the Baseline.................................................................48
Table 5.5 The property premium associated with natural vegetation in a good condition and the nature-based tourism value for minimum, medium and maximum conservation extents in the catchment for each scenario: ..................................................................................................................51
Table 6.1 Summary of the construction and maintenance costs (R millions) associated with GUD interventions for each scenario, excluding sanitation costs. Time frame of 20 years and a discount rate of 6% used ........................................................................................................................................................................................................32
Table 6.2 Present value of costs and benefits (R millions) for all scenarios (2015 Rand, 6% discount rate, 20 years) ..................................................................................................................56
Table 6.3 Total present value of costs and benefits and NPV (R millions) for all scenarios (2015 Rand, 6% discount rate, 20 years). Initial capital requirement and the capital requirement as a percentage of the annual capital budget for each scenario ..................................................................................................................65
Table 6.4 The impact of soakaways on NPVs for Scenarios 9, 12, 14 and 15 (R millions, 6%, 20 yrs.) ..........................................................................................................................58
Table A1.1 Measured pollutant removal capacities of selected stormwater management options and technologies (Source: Armitage et al. 2013): ..................................................................................................................81
Table A1.2 Relative merits (indicated by number of ‘+’) of different measures for stormwater and flood risk management, based on the literature. Measures considered in this study area are marked with an asterisk. ..................................................................................................................................................................................82
Table A2.1 Sewage output generated in the newly developed areas ........................................................................................................................................................................................................83
Table A2.2 General Effluent Limits .................................................................................................................................................................................................................................................84

Figure 5.15 Aerial screenshot of the Pinetown industrial region for the comparison of scenario 10 (with detention basins) and scenario 11 (detention basins and source controls). The noticeable difference is that the southern combat system (red lines) flows via a detention basin (green box) before joining with the northern stormwater system (yellow lines) on the lower right hand side. ..........................................................46
Figure 5.16 Simulated peak flows for a 2-, 5-, 10- and 20-year rainfall period return for Scenario 10 and at points (a) CI4, 55Umb (red line in Figure 5.15 with detention basin and source controls) and (b) CI5, 55Umb (yellow line in Figure 5.15 with only source controls upstream). Note that time units are reporting time steps from the model and one time unit represents 5 minutes .................................................................................................................................................46
Figure 5.17 Infrastructure capital cost saving (R million) for scenarios 4 – 15 when compared to the Baseline ............................................................................................................................................................................................................49
Figure A1.1 A schematic representation of leaves at two side of the watercourse ..................................................................................................................................................................................................................66
Figure A1.2 Schematic representation of a hydraulic berm ..........................................................................................................................................................................................................................................................66
Figure A1.3 Permeable paving allows water to soak into the gravel sub-base, temporarily holding the water before it soaks into the ground, or passes to an outlet (Source: susdrain, www.susdrain.org) ..............................................................................................................................................................................................................................................67
Figure A1.4 Soakaways are square or circular excavations either filled with rubble or other aggregate fill that are able to attenuate and treat significant amounts of stormwater runoff. They can be grouped and linked together to drain large areas such as highways and industrial areas. .................................................................................................................................................................68
Figure A1.5 Green roofs achieve runoff treatment and infiltration through the construction of vegetative cover on roofs which increases storage, evapotranspiration and attenuation (Source: susdrain, www.susdrain.org) ..................................................................................................................................................................................................................................................69
Figure A1.6 Diagram of a rainwater harvesting system. The first picture shows high stormwater runoff with none of the rain being collected whereas the second picture shows how rainfall is trapped and collected from the roofs in tanks and the amount of runoff entering streams and rivers is significantly reduced ..........................................................................................................................70
Figure A1.7 Swales are shallow grassed or vegetated channels used to collect and/or move water (Source: susdrain, www.susdrain.org) ..........................................................71
Figure A1.8 Filter strips are maintained grassed areas of land that are used to manage shallow overland storm runoff through several filtration processes. They are usually located as strips adjacent to development areas, roads, and waterways. ........................................................................................................................................................................72
Figure A1.9 Bio-retention areas are landscaped depressions employed to manage runoff by passing it through several natural processes. Rain gardens are an example of a bio-retention area. (Source: susdrain, www.susdrain.org) ........................................................................................................................................................................................................................................73
Figure A1.10 (a) Lamination effect due to the flood plain storage and (b) Example of flood plain storage in San Paulo, Brasil (Giugni et al. 2012). ..............................................................................74
Figure A1.11 Constructed treatment wetlands are man-made systems designed to mimic natural wetland systems (Source: susdrain, www.susdrain.org) ................................................................................................................................................................................................................................................75
Figure A1.12 Riparian buffers are located adjacent to streams and river channels. They can either be made up of grasses and smaller plants as in picture (a) or they can be densely vegetated with trees and bushes as in picture (b) (Source: susdrain, www.susdrain.org) .........................................................................................................................................................................................................................77
Figure A1.13 The effect of neovolatization on discharge upstream and downstream of the Murrumbidgee in Australia (Source: Rutherford et al. 2007). .....................................................................................................................................................................................................................78
Figure A1.14 Catchment reforestation will aid in runoff infiltration reducing the overall amount of stormwater reaching rivers and streams. Reforestation will also aid in removing sediments and nutrients ........................................................................................................................................................................................................................................................79
Figure A1.15 Comparison of average cost per unit volume of runoff reduction for various stormwater management options, based on data in the literature ...........................................................................................................................................................................................................80
Figure A1.16 Comparison of cost per unit mass of pollutant/nutrient reduction for various stormwater management options ................................................................................................................................................................................................................................................81
Figure A2.1 Applying source controls to a subcatchment in PC-SWMM ................................................................................................................................................................................................................89
Figure A2.2 Profile of a detention basin showing the berm and the outlet pipe ...........................................................................................................................................................................................................................................89
Figure A2.3 Layout of modelled detention basins, shown as green squares, within the UGOF quiescent upland catchment ................................................................................................................................................................................................................................89
Figure A2.4 Example of in-situ detention basin constructed by the EM in the Hilfrost region of the UGOF subcatchment ...........................................................................................................................................................................................................................................................................90
Figure A3.1 Landuse Categories and D’MOSS subcategories for all Conservation Areas within the EMA .................................................................................................................................................................................94
Figure A3.2 Information required to delineate subcatchments: topographical aerial survey, DEM and river centre lines based on river flow paths ................................................................................................................................................................................................................................................95
Figure A3.3 Current available stormwater shapefile (the red lines represent the flow paths, yellow lines are stormwater conduits and blue dots represent stormwater junctions) ..................................................................................................................................................................................................................................................................95
Figure A3.4 Newly available stormwater network shapefiles from the EM’S SMS audit ..................................................................................................................................................................................................................................................96
Figure A3.5 Percent impervious area for two different areas of contrasting landuse. The top value represents the Nilmper using approach 1 and the bottom value represents the Nilmper using approach 2 ..................................................................................................................................................................................................................................................98
Figure A3.6 Map of Green-Ampt Parameters developed by UKRIN (Source: Smicur 2013). ........................................................................................................................................................................................................................................100
Figure A3.7 SCI 24-hour rainfall distributions (not to scale) (Source: SCS (1984)) ........................................................................................................................................................................................................................................101
Figure A3.8 Snapshot of the PC-SWMM model for catchment UGOF ........................................................................................................................................................................................................................................102
Figure A3.9 Aerial image of all the Durban Harbour outfalls (red triangles). The stormwater network is shown by the yellow lines ..............................................................................................................102
Figure A3.10 Thiessen polygons determined for the available rain gauges relevant to the UGOF catchment ................................................................................................................................................................................................................................................103
Figure A5.1 Measure rainfall and simulated flow, depth; P, TIN, TSS concentrations for monitoring station (R_2ANA_10) on the Umbilitha River ....................................................................................................................................................................................................................................111
Figure A5.2 Measured rainfall and simulated flow, depth; P, TIN, TSS concentrations for monitoring station (R_UMKBOI_13) on the Umbilo River ........................................................................112
Figure A5.3 Measured water quality from water sampling stations on the Umbilo and Umhlatuzana Rivers at the same locations as the simulations. ........................................................................................................................................................................................................................................112
Figure A6.1 Location of water quality sampling sites for which data have been used in the hydrological model ...........................................................................................................................................................................................................................116
Figure A6.2 Effects of different modelled scenarios on total phosphorus concentrations at different monitoring sites in the study area ........................................................................................................................................................................................................................................116
Figure A6.2.1 (contd) Effects of different modelled scenarios on total phosphorus concentrations at different monitoring sites in the study area ................................................................................................................................................................................................................................................................116
Figure A6.3 Effects of different modelled scenarios on total suspended solids (TSS) concentrations at different monitoring sites in the study area ................................................................................................................................................................................................................................................................117
Figure A6.3.1 (contd) Effects of different modelled scenarios on total suspended solids (TSS) concentrations at different monitoring sites in the study area ................................................................................................................................................................................................................................................................118
Figure A6.4 Effects of different modelled scenarios on total inorganic nitrogen (TIN) concentrations at different monitoring sites in the study area ................................................................................................................................................................................................................................................................120
Figure A6.4.1 (contd) Effects of different modelled scenarios on total inorganic nitrogen (TIN) concentrations at different monitoring sites in the study area ................................................................................................................................................................................................................................................................121
Figure A6.4.2 (contd) Effects of different modelled scenarios on total inorganic nitrogen (TIN) concentrations at different monitoring sites in the study area ................................................................................................................................................................................................................................................................122
Figure A6.4.3 (contd) Effects of different modelled scenarios on total inorganic nitrogen (TIN) concentrations at different monitoring sites in the study area ................................................................................................................................................................................................................................................................123
1. INTRODUCTION

1.1 Background

Urbanisation is taking place at an unprecedented rate throughout the world, often outpacing plans and the capacity of city managers to provide the necessary services. As a result, urban ecosystems are being degraded and lost, and problems such as flooding, air and water pollution are becoming worse. This has led to negative impacts on health, income, productivity and quality of life, as well as stretching local and national government finances. These environmental problems are particularly acute in developing country cities, where a lack of resources and regulation has led to poor planning and the expansion of informal settlements, often in high risk areas.

Because urbanisation leads to the hardening of surfaces, the importation of water to supply urban inhabitants and the production of wastewater and sewage, managing the quantity and quality of surface water flows is one of the most important challenges for city planners and engineers. While conventional measures have involved “end-of-pipe” interventions to convey these problems away, these measures have often not been able to keep ahead of the problems, and have also contributed to the pollution and degradation of aquatic systems within and downstream of urban areas. This together with the encroachment of developments into the natural habitats within urban areas and at their margins, has led to the loss of biodiversity and ecosystem services.

Great strides have been made in the design of more sustainable engineering mechanisms to deal with urban problems, including innovative water retention measures such as porous pavements, green roofs and bio-swales that help to ameliorate the effects of urbanization on flooding and water quality closer to the source of the problem. In addition, management and planning of cities is increasingly taking a holistic approach that includes the use and conservation of semi-natural and natural areas within cities as part of a green urban development strategy. This not only contributes to solving surface water problems but also maintains areas for recreation which is essential for human health and wellbeing. All of this aligns well with the concept of “green urban development”, the essence of which is development that minimises impacts on and/or enhances the value of the natural environment.

Addressing urban environmental issues requires a combination of engineering, spatial planning, environmental management and other interventions. One of the challenges of achieving green urban development will be to shift the focus from reliance on conventional grey infrastructure and “end of pipe” measures, and find the right balance between ecological and green or engineered infrastructure (Figure 1.1) to tackle problems closer to source and maintain healthier, more vibrant and more resilient cities. This includes the strategic protection of natural habitats within cities for biodiversity protection and the delivery of ecosystem services. However, there is very little understanding of the costs and benefits of creating or protecting these different types of green infrastructure, especially in developing countries. It is also important to understand to what extent it would be more cost effective to rely on green rather than grey infrastructure to solve key environmental problems.

Figure 1.1 Schematic representation of Green Urban Development and associated terminology (Source: authors own interpretation)
Durban’s key environmental issues and their causes and consequences are summarised in Figure 1.2. The “brown issues” relate to environmental quality (air and water) and flooding. During the summer rainfall months, the city has to deal with frequent floods. While Durban has a relatively well-developed drainage system, flooding problems are exacerbated by the increased hard surfaces and the solid waste that accumulates in storm water conduits, particularly plastic bottles. Beachfront development and sea level rise also contribute to increasing risks of flooding in coastal areas. Another factor contributing to high flows and flooding is the importation of water to supply city inhabitants. In formal areas, the resulting waste water makes its way to sewage treatment works, which then discharge their wastes into the drainage systems. Combined with the effects of hardened surfaces, these elevated flows and nutrient levels lead to erosion of river banks and have an impact on estuarine ecology and functioning. Very little of this waste water is recycled. Yet, ironically, the EMA faces major water shortages as the supply of potable water from the surrounding catchments is outsourced by growing demand. Currently, water is supplied primarily by the uMgeni catchment to the city but it is expected that water from other catchments will soon be needed to meet growing demands. Water is also becoming more expensive as local resources are depleted and more water is imported into the city from greater distances away.

Poor air and water quality is caused by traffic and industrial emissions, effluents and polluted runoff especially from informal settlements where there is a sanitation backlog. The unplanned expansion of informal settlements and the lack of sufficient sanitation services to these areas has resulted in the direct discharge of effluents into rivers, dams and wetland areas. Approximately 72% of informal settlements lack formal sanitation infrastructure, contributing significantly to the degradation of freshwater ecosystems across the study area. The release of untreated or poorly treated effluent from waste water treatment works directly into rivers as a result of lack of capacity or overflow during storm events contributes to ever increasing pollution levels in freshwater systems. The groundwater has also become polluted as a result of poor waste disposal sites, pit latrines and septic tanks being used across the city. The increased pollution loads in freshwater systems are not only a human health hazard but also lead to the eutrophication of rivers and estuaries.

The unplanned expansion of informal settlements and planned expansion of formal settlements, agriculture, overexploitation of natural resources, and alien invasive species have led to the loss and degradation of natural habitats within and around the urban area. This exacerbates the “brown issues” referred to above (Figure 1.2). For example, illegal sand mining activities along or in some of the river channels intensifies the problem of bank erosion, and the loss of natural vegetation cover leads to sedimentation which clogs drainage channels. The degradation and loss of natural habitats and biodiversity, or “green issues”, also leads to the loss of amenity, natural resources and carbon. These impacts will be further impacted by increasing poverty and lack of economic growth, continued rapid urbanisation and the impacts of climate change. Climate change is predicted to change temperature, sea levels, rainfall patterns and storm events in a way that will both exacerbate water supply problems and flooding, and which will have direct and indirect impacts on ecosystems and biodiversity within the EMA. Therefore just dealing with the current set of problems will be an important step towards developing resilience against these future threats.

1.3 Green urban development

Green urban development is an approach that aims to minimize the impacts of urbanization on the environment and enhance environmental values (OECD 2013). The approach is advocated to increase, rather than limit, the development potential of cities. Given the degree to which global population and economic productivity is increasingly urbanized, it is also vital for global welfare.

We define green urban development as a range of actions that tackle the core problems of pollution and waste, the consumption of natural resources, the loss of urban open space and the degradation and loss of biodiversity, as well as mitigation of the urban contribution to climate change (Figure 1.3). This requires a combination of indirect and direct interventions that will serve synergistically to develop vibrant, resilient cities that are both greener in appearance and greener in terms of their local, regional and global...
Tackling water and energy consumption. The former is securing the protection, restoration or rehabilitation of selected natural areas in order to maintain biodiversity and valuable ecosystem services. Natural systems within cities contribute to livelihoods through the provision of natural resources, contribute to human health and wellbeing, property value and tourism through the provision of aesthetic and recreational amenity value, and contribute ecosystem services such as flood control, sediment retention, air and water quality amelioration, carbon storage, pollination of crops and provision of nursery areas for marine fisheries. As cities grow the remaining natural areas within them become increasingly important as refugia for biodiversity. All of these functions are lost however, if they are excessively degraded and fragmented. Thus cities need to plan and manage a system of natural open space areas within them and also take care to minimise the damages to aquatic ecosystems downstream.

1.4 Study objectives

The aim of this study was to explore, using a case study and scenario-based approach, the potential costs and benefits of undertaking a green urban development approach to address some of the main environmental issues described above, and to explore the potential trade-offs between different types of interventions, with emphasis on assessing the desirable balance between engineered interventions and the conservation of natural open space areas. The study focuses on three elements of green urban development, all of which impact on ecosystems and biodiversity: sewage and solid waste management, active stormwater management and the conservation of natural systems and riparian corridors.

The study aimed to provide a proof of concept, based on high-level exploratory analysis and simple scenarios in order to facilitate and promote dialogue rather than providing a blueprint for action. It is hoped that the study will provide a useful step towards the preparation of a Strategic Environmental Assessment to guide the city’s sustainable development path.

1.5 Study approach

The overall approach was to model current flooding and water quality in the Umhlathuze – Umbilo catchment and to determine the potential change in water quality and flood hydrographs at selected points in the catchment after implementation of a range of green urban development measures including sanitation, stormwater management and conservation measures. The relative effectiveness and cost-effectiveness of different types of measures were then evaluated.

Because of the strong linkages of GUD to catchment hydrology, the case study was for a selected catchment area, rather than a selected administrative area of Durban. A back-casting approach was used, for a catchment that is already developed, rather than designing alternative development scenarios in one of the prospective development nodes in the EMA. This was to allow the investigation of the potential costs and benefits of alternative policy measures while keeping other factors constant (industries, households, inhabitants, etc.). The Umhlathuze – Umbilo catchment was selected because it is one of the most developed catchment areas in the EMA. Nevertheless, this catchment still contains significant undeveloped areas that are zoned for future development. Therefore our approach had to include some assumptions regarding future development for these areas following a “business as usual” approach. This was done based on densities from comparable urban typologies in the area.

The study required the development of a hydrological model of the catchment area to model the effects of the interventions on storm flows and water quality. Modelling was carried out using the PC-SWMM modelling system which was set up at a fine resolution for event-based flood modelling and a coarser resolution for continuous water quality modelling. The current status quo was modelled and calibrated using existing data on flows and water quality. Following this, a new baseline was set up for the fully developed catchment. All scenarios involved interventions to be compared with the fully developed baseline, as if the catchment had been planned and developed differently from the outset. A total of 15 scenarios was run to compare the costs and outcomes of different types of interventions.

The interventions under consideration included (a) meeting sanitation needs, (b) various stormwater and effluent management measures and (c) conservation areas in conjunction with more compact development (so as to be able to support the same number of people and industry in the catchment). In order to inform the choice of stormwater management measures, a review was carried out on their efficacy, costs and the necessary or suitable conditions for their implementation. Based on this, and available GIS data on land cover, slope and soils of the catchment, the long list of possible measures was reduced to a set of measures that had both a high feasibility of implementation in the study area and that would be complementary in terms of their effects on flood risk and water quality amelioration. The potential extent of their implementation was then estimated and mapped. Finally, a set of scenarios was devised which included the full combination and various subsets of these measures.

The implications of the different scenarios were assessed based on the costs of the interventions, the cost savings due to reduced flood risk, ecosystem health and the avoided losses of ecosystem services. The cost savings due to reduced flood risk were modelled based on changes in the required design specifications for the existing type of stormwater conveyance infrastructure in the study area, as a result of changes in the size of the relevant return-period floods. Changes in ecosystem health were estimated based on changes in nutrient loads and concentrations in relation to current status quo. Changes in the value of ecosystem services was based on the changes in ecosystem size and quality, and models of the relationship between these and their value which were developed as part of the accompanying study of the value of eThekwini’s ecosystem services (Turpie et al. 2017).

A total of 15 scenarios was run to compare the costs and outcomes of different types of interventions.
II. THE UMHLATUZANA-UMBILO CATCHMENT AREA

2.1 Location and extent

The Umhlatuzana-Umbilo catchment (quaternary catchment U60F) is located in the centre of the EMA (Figure 2.1), incorporating the city centre, harbour, and a number of commercial and industrial areas which are situated both in the lower and middle catchment. The catchment covers an area of approximately 272 km².

Figure 2.1  The location of Umhlatuzana-Umbilo catchment in the EMA
2.3 Historical and current land cover
Historically, the vegetation in the catchment was dominated by coastal belt grassland, sandstone sourveld and coastal belt thornveld (Figure 2.4). Coastal forest and scarp forest was mostly found along the river valleys and steep gorges, with scarp forest generally restricted to higher elevations (Figure 2.4). Figure 2.5 shows the extent to which landcover has changed within the catchment and the amount of natural open space areas that remain, mostly in fragmented patches. Most of the catchment has been transformed and is dominated by formal and informal urban settlement, and commercial and industrial land (Figure 2.5). In the upper catchment there is a relatively large amount of agricultural land (Figure 2.5).

There are a number of informal settlements such as Cato Manor in the lower catchment, as well as peri-urban settlements such as Tshelimnyama in the upper catchment. The informal settlement at Cato Manor is located along the Mkumbane River, a tributary of the Umbilo River. The informal structures have been erected along the steep river banks and in the flood plain (Figure 2.6).

Currently there are just over 6000 ha of natural vegetation in the Umhlatuzana-Umbilo catchment, with 42% being woodland, 35% forest, 14% grassland, and 9% thicket. Most of the intact forest is located along the steep river valleys in the upper and middle catchment. The North Park Nature Reserve, Kenneth Stainbank Nature Reserve and Bluff Nature Reserve are located in the catchment providing some protection to these natural systems. Durban Bay Harbour is one of South Africa’s larger estuaries which in spite of a high degree of transformation is still of conservation importance. At the head of the estuary a small 15 ha pocket of mangroves are protected as part of the Bayhead Natural Heritage Site.

2.4 Pollution and flooding
Water pollution and flooding are two of the main environmental issues associated with the Umhlatuzana-Umbilo catchment. Pollution comes from a number of different sources including industrial, residential and agricultural runoff, stormwater outflows, solid waste and effluent from various waste water treatment works (WWTWs), with three major WWTWs (the Hillcrest WWTW, Umhlatuzana WWTW and Umbilo WWTW) located on the two main rivers. These pollution sources together have a major impact on the biodiversity and ecological functioning of the river systems (DWA 2013) as well as Durban Bay. Within the catchment...
study area there are a number of informal settlements without adequate sanitation, such as Cato Manor informal settlement which is situated on the banks of the Mkumbane River, a tributary of the Umbilo River. Without adequate sanitation raw sewage, litter and other pollutants end up in the river (Figure 2.7).

Flooding in the catchment is exacerbated by the high levels of litter and dead vegetation which block culverts and drains causing rivers and streams to overtop and burst their banks (Figure 2.8). An enormous amount of plastic litter washes into the rivers and out to sea during high rainfall events. Some of this ends up on Durban’s main beaches. Not only does this have impacts on the aesthetic (and by implication the tourism) value of the beaches themselves but there is also increasing concern about the impacts of plastic litter on marine ecosystems (Bergmann et al. 2015), particularly with regard to entanglement and plastic ingestion (e.g. Ryan 1990).
2.5 Water quality

The middle and lower reaches of the Umbilo and Umhlatuzana river catchments are highly impacted and water quality in both of these rivers is considered poor (RHP 2002, DWA 2013). However, water quality conditions in the upper catchment of the Umhlatuzana River, in particular, are considered “acceptable” (DWA 2013), in part because of the low density of settlements and the presence of extensive areas of largely unmodified riparian buffers in this part of the catchment.

In addition, Moodley (2014) analysed heavy metal concentrations at 17 sites in total in the Umhlatuzana, Umbilo and Amanzimyana Rivers during the 2011-2012 wet- and dry seasons, and found the following:

- The Umhlatuzana River upstream of its confluence with the Umbilo River had copper, aluminium and nickel at concentrations above DWAF (1996) target thresholds during the dry season (suggesting effluent outputs);
- The Umbilo, Amanzimyana and Umhlatuzana River downstream of its confluence with the Umbilo River had elevated concentrations of mercury, vanadium, lead and chromium at all sites during the dry season (suggesting industrial effluent releases);
- Copper, aluminium and lead were problematic in these sites during the wet season as well, albeit at lower concentrations (presumably as a result of dilution);
- Ammonia-nitrogen was above guideline concentrations at all sites in all systems, in both the wet and dry season;
- Orthophosphate was elevated above DWAF (1996’s) threshold for hypertrophic conditions in all systems during the wet season, suggesting possible surface runoff influences rather than effluent inflows; and
- Sites downstream of nature reserves on the Umbilo and Umhlatuzana Rivers showed a clear reduction in ammonia-nitrogen, orthophosphate and sulphur concentrations in river water.

Human health concerns as a result of bacterial or other pathogen contamination centre on both the Umbilo and Umhlatuzana Rivers (DWA 2013), with high *Escherichia coli* counts recorded in the Umbilo River, at Paradise Valley Nature Reserve and below the Umbilo WWTW, along with high nutrient loading and potentially toxic levels of unionised ammonia (DWA 2013). The Umhlatuzana River shows high *E.coli* counts at Kenneth Stainbank Nature Reserve (DWA 2013). Sources of bacterial loading are assumed to include periodic pulses of poorly-treated sewage effluent from waste-water treatment works, sewer overflows or leaks, point source and diffuse runoff from poorly serviced informal settlements and runoff from areas such as bus stations, informal markets and general street runoff, contaminated by human and other animal waste (e.g. dogs).

2.6 River condition

South Africa’s National River Health Programme (RHP 2002) rated the the Umhlatuzana and Umbilo Rivers as associated in a Fair overall condition – this rating considers the riparian and instream condition of the rivers. It is however derived from several components, as follows:

- In the Umhlatuzana River:
  - aquatic macroinvertebrate communities are rated as in Fair health;
  - fish communities are also rated in a Fair condition in the upper and middle reaches of the catchment but are considered in a Poor condition in the lower reaches, where riparian habitat quality has also deteriorated to Poor;
  - water quality in the middle and lower reaches of the river is Poor (due mainly to urban impacts).
- In the Umbilo River:
  - habitat integrity is rated as in Good condition in the middle reaches and Poor condition in the lower reaches;
  - water quality is considered Poor in the middle and lower reaches of the River, again due mainly to urban impacts;
  - invertebrates and fish populations are rated as in a Poor category, as a result of the heavy pollution load.
III. DESIGN AND POTENTIAL EXTENT OF SELECTED GREEN URBAN DEVELOPMENT INTERVENTIONS FOR THE STUDY AREA

3.1 Sewage and solid waste management

3.1.1 Dealing with sewage

Under green urban development, informal settlements would be provided with urine diversion dehydration toilets (UDDTs) and adequate services as a minimum requirement. Growing formal residential areas also provide a potential problem in that they lead to an increase in the output of treated sewage effluent. Under a green urban development policy it is assumed that the these potential effects are neutralised by recycling an equivalent amount of sewage effluent (see Appendix 2 for more detail). These innovative technologies are very much a part of green urban development thinking, which also addresses water and energy supply and demand.

3.1.2 Managing solid waste

Sediments and litter accumulate until they are either manually removed or are transported by the wind and/or stormwater runoff into the drainage system. Once in the drainage system, they can contribute to blockages and increased flood risk, as well as providing health risks. This is a significant and ongoing problem in the study area (Figure 2.8).

Solid waste problems have escalated in the last half century with the advent of plastic packaging and throw-away consumerism and business strategies, and are also inadequately managed in most African cities, including Durban. Addressing this problem is not only a critical component of stormwater management, but is also justifiable in terms of reducing impacts on the amenity value of green open spaces and the devastating impacts on freshwater and ocean environments and biodiversity.

Measures to address this include bans, taxes and refund systems on packaging and community-based river cleaning programmes as well as the more traditional measures of street sweeping and municipal waste collection. Community stewardship programs can have multi-sectoral impacts as they generate employment opportunities, provide awareness, safeguard communities and provide city-wide services such as functioning river systems that are clean and clear of litter. Sections of rivers are maintained by cooperatives which are responsible for removing alien vegetation, rubble and any solid waste blocking the free flow of water down the stream or river. They are also responsible for maintaining the grass and other vegetation along the banks of the waterway. The cooperatives generally consist of members of the community that are unemployed and vulnerable and the project focuses on raising awareness and generating employment. In Durban, the Sihlanzimvelo Stream Cleaning Project has been very successful in areas of the municipality where a number of rivers were considered critical in terms of health and functioning. It was assumed that a program similar to this was implemented in the catchment.

A multi-faceted solid waste programme is required to eliminate or at least drastically reduce the loads of solid waste entering the river systems in the study area. This would require not only localised action, but broader municipal-level strategies (such as by-laws, incentive measures and compulsory recycling and linked servicing) and even national strategies (legislation and taxation).

3.2 Active stormwater management

3.2.1 Overview of stormwater management

The increases in impermeable surfaces within urban areas prevent infiltration and cause higher levels of surface runoff during storm events than would have happened naturally, creating flooding problems in downstream areas (Armitage et al. 2013). This problem is exacerbated by the fact that urban stormwater runoff generally contains litter, debris, and sediments which lead to blockages of the systems designed to convey water. They also contain bacteria, heavy metals and nutrients, which means that floodwaters can become a pollution hazard. All of this can have negative impacts on property, urban infrastructure and downstream natural habitats, as well as urban inhabitants. With an increase in urbanisation worldwide and the associated impact of increasing stormwater runoff on aquatic ecosystems, the management of urban drainage has become a critically important challenge (Fletcher et al. 2015).

Various stormwater management measures have been designed that address flooding, water quality problems, or both (see Appendix 1 for a detailed review). These approaches are increasingly being applied in development planning in South Africa, and their inclusion (in any form) has recently become mandatory for new developments in the City of Cape Town and in Durban with the aim that the urbanisation effects of new developments are effectively “neutralised”. In this study, a review of alternative measures was carried out and their potential applicability to the study area was evaluated in order to inform the development of feasible scenarios for the analysis.
Stormwater management measures are classified into structural and non-structural measures, with structural measures being further subdivided into passive and active measures (Figure 3.1).

- **Passive structural measures** aim to convey water and protect areas from flooding. Examples are levees, increasing the channel capacity by clearing of debris or increasing its cross-section, and constructing hydraulic bypasses (waterways) to divert high flows.

- **Active structural measures** aim to modify the hydrograph (i.e. reduce flood peak and volume) and address water quality by retarding water movement, increasing its cross-section, and constructing hydraulic bypasses (waterways) to divert high flows.

- **Non-structural measures** do not involve physical construction but use knowledge, practice or agreements to reduce risks and impacts through behavioral changes, in particular through policies, agreements to reduce risks and impacts through behavioral changes, in particular through public awareness raising, training and education (Kundzewicz 2002). These include flood warning systems, land use regulations such as development setbacks which identify where development can and cannot occur, or to what elevation structures should locate their lowest habitable floor to; regulations that require flood proofing and retrofitting of buildings may increase the strength against flood actions; elevation of buildings may avoid completely the inundation. Flood insurance and relocations also belong to this typology of measures.

Although sanitation might be categorised as a non-structural measure in the context of stormwater management, there is a significant element of traditional built infrastructure required to address sewage reticulation and treatment. Where sanitation measures are inadequate, as is the case in a large proportion of African cities, this leads to water quality problems that are too severe to be treated by the green engineering measures incorporated in sustainable urban drainage systems. This reality is not emphasised in the literature because SUDS have largely been developed in higher income countries and cities. Investment in effective sanitation systems can therefore be seen as a fundamental imperative for green urban development, and something that has to be addressed first in most African cities.

The active structures or “green” engineering measures tend to be grouped as either source, local or regional controls (Thampapillai & Musgrave 1985, Kundzewicz 2002, Armitage et al. 2013; Figure 3.1 and Box 3.1, see Appendix 1 for details):

- **Source controls** tend to be used to manage stormwater runoff as close to the source as possible, generally within the boundaries of the property and include measures such as green roofs, soakaways and permeable paving.
- **Local controls** are usually used to manage runoff as a second line of defence typically in public areas, along roadways and adjacent to parks such as filter strips and swales.
- **Regional controls** are used to manage runoff as the last line of defence and are generally large-scale interventions constructed on municipal land such as detention ponds and wetlands (Armitage et al. 2013). Measures that retard flows generally also contribute towards improving water quality, and vegetated areas further contribute to water quality amelioration where flows are slow enough. The various stormwater management measures are described in more detail in Appendix 1.

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3.2.2 Review and feasibility of green engineering measures

The design requirements and limitations of green engineering measures described in the literature, such as slope, depth to groundwater and soil drainage characteristics, were obtained from the most recent and comprehensive studies (see Armitage et al. 2013, Morales Torres et al. 2015) as well as expert opinion (Table 3.1). Based on GIS data for the study area, the long list of possible measures was reduced to a set of measures that had both a high feasibility of implementation in the study area and that would be complementary in terms of their effects on the environment. The potential extent of each of the selected measures was then estimated and mapped.

Table 3.1 The rules and criteria applied to different active stormwater management measures based on soil drainage, slope and water table characteristics

<table>
<thead>
<tr>
<th>Source controls</th>
<th>Intervention</th>
<th>Soil drainage</th>
<th>Slope (%)</th>
<th>Water Table (m)</th>
<th>Selected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainwater harvesting</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>&lt;4%</td>
<td>No</td>
</tr>
<tr>
<td>Infiltration trenches</td>
<td>0.25-0.5 (medium)</td>
<td>&lt;15%</td>
<td>&gt;5m (low)</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Soakaway/subsurface infiltration beds</td>
<td>&gt;0.5 (well drained)</td>
<td>&gt;15%</td>
<td>&gt;5m (low)</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Permeable/porous pavements</td>
<td>&gt;0.5 (well drained)</td>
<td>n/a</td>
<td>&gt;5m (low)</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Green roofs</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>Yes</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Local controls</th>
<th>Bioretention areas, e.g. “raingardens”</th>
<th>&gt;0.5 (well drained)</th>
<th>&lt;12%</th>
<th>&gt;5m (low)</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand filters</td>
<td>&gt;0.5 (well drained)</td>
<td>&lt;6%</td>
<td>&gt;5m (low)</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Filter strips</td>
<td>&gt;0.5 (well drained)</td>
<td>2-6%</td>
<td>&gt;5m (low)</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Vegetated (grassed) swales</td>
<td>n/a</td>
<td>&lt;4%</td>
<td>n/a</td>
<td>No</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Regional controls</th>
<th>Detention basins</th>
<th>n/a</th>
<th>&lt;15%</th>
<th>&gt;5m (low)</th>
<th>Yes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment wetlands</td>
<td>n/a</td>
<td>0-0.5% (flat)</td>
<td>&gt;5m (low)</td>
<td>Yes</td>
<td></td>
</tr>
</tbody>
</table>

Rainwater harvesting tanks were not considered desirable on a large scale due to cost as well as the limited flood benefits, as tanks would fill up early in the rainy season and would not provide further storage. A better option would be to use measures that slowly release water, so that they are ready for the next high rainfall event, such as infiltration trenches, soakaways and detention basins.

A number of active structural measures were not feasible because of unsuitable soil drainage (Figure 3.2), high ground water levels, or the steepness of certain areas in the catchment. Many interventions require well-drained soils (i.e. high drainage rates), which are mostly in the lower catchment (Figure 3.2), where effectiveness of the intervention would be lower. Certain conveyance and engineering measures, such as vegetated swales, filter strips and bioretention areas are limited by slope and therefore their use on a large scale would not be possible because of the hilliness of the study area. Grassed swales, for example, were considered as a possible measure due their low construction and maintenance costs and their ability to improve water quality, attenuate peak flows and provide a “green” alternative to conventional gutter systems. However, it became clear that most of the roads in the middle and upper catchment fall outside of the criteria required for effective implementation of grassed swales (<4% slope).

It is necessary to consider localised measures that capture and/or slowly infiltrate runoff at source (i.e. on-site buildings, roofs, parking lots etc.) and regionally (i.e. off-site such as roads, walkways and other extensive paved areas). In doing so a “treatment train” can be created where runoff from local source areas is captured on site and runoff from larger areas is captured off site. Furthermore, at point-source pollution areas, such as WWTW, constructed wetlands could be designed to improve water quality.

Thus four types of source (on-site) control measures (green roofs, permeable paving, infiltration trenches and soakaway pits) and two types of regional control measures (detention basins, treatment wetlands) were considered as the feasible green engineering measures for implementation in the study area. Their design and potential extent is described further below.

3.2.3 Potential extent of selected interventions

3.2.3.1 Stormwater source controls

Source controls are on-site measures that are designed to reduce or neutralise the impact of hardened surfaces on runoff. There are a range of options that all contribute to this, and the mix of these options on a particular site may depend on physical limitations as well as the costs involved.

For each measure, we estimated the potential extent of implementation. In some cases, where costs were very high and full implementation unlikely to be feasible, the maximum extent considered in the analysis was less than the potential extent (see next section). The potential extent of each source control measure is shown in Figure 3.3 and the assumptions regarding extent, design and costs are discussed in more detail in Appendix 2. Technical details and assumptions relating to the implementation of source controls in the PC-SWMM model are also provided in Appendix 2.

3.2.3.2 Detention basins

Detention basins temporarily detain stormwater runoff from roads and other hardened surfaces, by capturing high flows and then releasing the stored water over a period of time. They are usually designed to fill and empty within 48 hours of a storm event. Whilst the other GUD measures capture runoff at the source, detention basins capture runoff off-site from larger public surface areas, such as roads.

The most effective location and the size of detention basins was determined based on the difference in runoff between pre-development (natural) and the post-development (fully-developed) scenarios within the catchment. This was estimated using the PC-SWMM model described in Appendix 2. Detention basins were positioned at the outlet of the subcatchments with the highest difference in volumes.

3.2.3.3 Treatment wetlands

 Constructed treatment wetlands are designed to improve polluted runoff and waste water effluent quality and provide some limited control of runoff volumes. Wetlands can be effective in terms of removal of low levels of pollutants (i.e. a polishing function) and also provide buffering functions, aesthetic value and wildlife habitat. Constructed wetlands are located as close to the source of pollution as possible so as to maximise the impact on improving water quality.

Rainfall event, such as infiltration trenches, soakaways and detention basins. A better option would be to use measures that slowly release water, so that they are ready for the next high rainfall event, such as infiltration trenches, soakaways and detention basins.

A number of active structural measures were not feasible because of unsuitable soil drainage (Figure 3.2), high ground water levels, or the steepness of certain areas in the catchment. Many interventions require well-drained soils (i.e. high drainage rates), which are mostly in the lower catchment (Figure 3.2), where effectiveness of the intervention would be lower. Certain conveyance and engineering measures, such as vegetated swales, filter strips and bioretention areas are limited by slope and therefore their use on a large scale would not be possible because of the hilliness of the study area. Grassed swales, for example, were considered as a possible measure due their low construction and maintenance costs and their ability to improve water quality, attenuate peak flows and provide a “green” alternative to conventional gutter systems. However, it became clear that most of the roads in the middle and upper catchment fall outside of the criteria required for effective implementation of grassed swales (<4% slope).

It is necessary to consider localised measures that capture and/or slowly infiltrate runoff at source (i.e. on-site buildings, roofs, parking lots etc.) and regionally (i.e. off-site such as roads, walkways and other extensive paved areas). In doing so a “treatment train” can be created where runoff from local source areas is captured on site and runoff from larger areas is captured off site. Furthermore, at point-source pollution areas, such as WWTW, constructed wetlands could be designed to improve water quality.

Thus four types of source (on-site) control measures (green roofs, permeable paving, infiltration trenches and soakaway pits) and two types of regional control measures (detention basins, treatment wetlands) were considered as the feasible green engineering measures for implementation in the study area. Their design and potential extent is described further below.

3.2.3 Potential extent of selected interventions

3.2.3.1 Stormwater source controls

Source controls are on-site measures that are designed to reduce or neutralise the impact of hardened surfaces on runoff. There are a range of options that all contribute to this, and the mix of these options on a particular site may depend on physical limitations as well as the costs involved.

For each measure, we estimated the potential extent of implementation. In some cases, where costs were very high and full implementation unlikely to be feasible, the maximum extent considered in the analysis was less than the potential extent (see next section). The potential extent of each source control measure is shown in Figure 3.3 and the assumptions regarding extent, design and costs are discussed in more detail in Appendix 2. Technical details and assumptions relating to the implementation of source controls in the PC-SWMM model are also provided in Appendix 2.

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Constructed treatment wetlands are designed to improve polluted runoff and waste water effluent quality and provide some limited control of runoff volumes. Wetlands can be effective in terms of removal of low levels of pollutants (i.e. a polishing function) and also provide buffering functions, aesthetic value and wildlife habitat. Constructed wetlands are located as close to the source of pollution as possible so as to maximise the impact on improving water quality.
The treatment wetlands were situated at point source pollution outlets in the study area; at the three existing WWTW. It was assumed that the runoff entering the wetlands was being treated to general standards and that the wetlands further treat runoff to specific standards (see Appendix 2).

In order to estimate the extent of the wetland for costing purposes, the removal rate was used to estimate the area required to meet the calculated concentrations based on the given efficiency (Table 3.2). Therefore the outflow from each WWTW was used in conjunction with nutrient and sediment concentrations to determine daily loads for nutrients and sediments. The removal rate and removal efficiency data provided in Table 3.2 was then used to calculate the area that would be required to treat these estimated daily loads. Based on these assumptions, the extent of the treatment wetlands ranged from 2 ha at the Hillcrest WWTW to 16 ha at the Umhlatuzana WWTW to 40 ha at the Umbilo WWTW. Technical details and assumptions relating to the implementation of treatment wetlands in the PC-SWMM model are given in Appendix 2.

### Table 3.2 Annual Average Treatment Performance Capabilities for Surface Flow Wetlands (Source: Kadlec & Knight 1995) assuming wetland influent is a “typical municipal effluent”

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Removal rate (% per ha/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOD</td>
<td>10.0</td>
</tr>
<tr>
<td>TSS</td>
<td>10.0</td>
</tr>
<tr>
<td>NH₃-N</td>
<td>4.7</td>
</tr>
<tr>
<td>TIN</td>
<td>6.9</td>
</tr>
<tr>
<td>TP</td>
<td>0.95</td>
</tr>
<tr>
<td>Metals</td>
<td>0.1</td>
</tr>
</tbody>
</table>

In this study, riparian buffers extended 15 m on either side for smaller rivers and streams, 30 m on either side of major rivers and on one side for rivers that have been canalised (Figure 3.4). These widths are broadly based on the 2014 Draft National River Buffer Guidelines (Macfarlane et al. 2014). This produces a total area of about 1900 ha. The buffers were clipped in GIS into the historical vegetation layer for the catchment to determine what vegetation would be located within the buffered areas.

### 3.3 Conservation of natural systems and biodiversity

Conservation of natural systems and biodiversity within urban areas includes the protection of viable areas containing representative habitats and biodiversity, ensuring that the layout of protected natural areas is conducive to allowing ecological processes such as the movements between systems, and ensuring that downstream aquatic ecosystems are protected from excessive degradation through changes in the quality or quantity of freshwater flows.

The latter is achieved in part through the interventions described above, and is considered one of the major objectives of this study. In addition, two types of conservation intervention were considered for the study area: the development of riparian buffer zones that protect a band of natural vegetation on either side of rivers and streams, and the retention of a representative amount of terrestrial natural open space that meets biodiversity targets for the catchment. These two interventions are ideally combined, with the riparian corridors providing connectivity between the protected terrestrial systems and other aquatic systems, including the estuary and ocean. The potential design and extent of these interventions is explored in more detail below.

#### 3.3.1 Riparian buffers

Riparian buffer zones along waterways intercept sediments, nutrients, pesticides and litter in diffuse or sheet surface runoff thereby reducing the amount of pollutants entering rivers and streams. They may also provide habitat and wildlife corridors and can be important for reducing erosion, slowing down floodwaters by increasing roughness (and thus reducing downstream peaks) and providing river bank stabilisation. They also provide space for river rehabilitation, reducing the need for future river lining. In combination, riparian buffers overlap with conservation areas.

In this study, riparian buffers extended 15 m on either side for smaller rivers and streams, 30 m on either side of major rivers and on one side for rivers that have been canalised (Figure 3.4). These widths are broadly based on the 2014 Draft National River Buffer Guidelines (Macfarlane et al. 2014). This produces a total area of about 1900 ha. The buffers were clipped in GIS into the historical vegetation layer for the catchment to determine what vegetation would be located within the buffered areas.

#### 3.3.2 Conservation areas and compact development

Currently there are approximately 6000 ha of natural vegetation (forest, woodland, thicket and grassland) in the catchment as per the D’MOSS plan (medium conservation; Figure 3.5). Most of the remaining natural open space areas are undevelopable. Taking into account future planning as per municipal scheme development zonation plans (effective 2014), the amount of natural vegetation in the catchment is reduced to 2800 ha, or 11% of the total catchment area (minimum conservation; Figure 3.6).

Based on conservation targets set out in the eThekwini Municipality Systematic Conservation Plan, a conservation plan was determined as if starting from the undeveloped catchment (historical vegetation), but selecting currently undeveloped areas first. Using targets for each vegetation type (forest, woodland, thicket and grassland) and the maximum remnant extent of each type of vegetation in the catchment, the additional amount and distribution of natural vegetation was estimated. Defining the additional conservation areas was done by following the current D’MOSS plan so as to retain connectivity and to identify nodes that could be...
further increased. Vegetation was also retained on steep slopes. Overall it was determined that a total of 7000 ha were required to meet conservation targets, accounting for approximately 28% of the catchment area (Figure 3.6).
The planned reduction in D’MOSS, current D’MOSS and ideal conservation plan were used in this study as alternative levels of conservation – minimum, medium and maximum - in the scenarios analysed. Figure 3.5 shows the difference between the conservation options in terms of how much natural open space in a good condition is conserved and how much land has been transformed into other land uses, while keeping other factors in the catchment constant (industries, households, inhabitants, etc.). The status quo represents the current situation in the catchment where parts of the D’MOSS have become degraded. Medium conservation represents the current status quo situation had all natural vegetation in the catchment not been degraded.
IV. SCENARIO SET-UP

4.1 Approach

This study aimed to evaluate the incorporation of various types of green measures in urban development, all of which contribute to stormwater management, protection of biodiversity and maintenance of ecosystem services. These measures include novel, green engineering solutions that mimic natural processes (active stormwater management) to complement the use of more traditional conveyance infrastructure that removes the flood and waste water beyond the urban environment, as well as conservation of riparian and terrestrial areas. These measures will vary in efficiency for different purposes (e.g. retarding stormflows), and from a stormwater management perspective may or may not have co-benefits (e.g. recreational amenity). In order to evaluate the relative investment that should be made in such alternative measures, this study has used a scenario evaluation approach.

It is important to note that the sanitation situation is usually the primary factor driving water quality in African cities. The influx of poor people into cities leads to the development of informal settlements and a backlog in the setting up of adequate sanitation systems which requires considerable investment. If drainage systems receive significant quantities of raw sewage, then measures to address water quality other than conventional conveyance (e.g. out to sea) are less likely to be effective as they might be overwhelmed. Therefore whether the sanitation backlog has been addressed is an important assumption that has to be made explicit in the scenarios. Since sanitation and solid waste management are existing obligations of all cities for health reasons alone, these do not form part of the economic analysis in this study. The study focuses on evaluation of different green urban development measures in the presence of adequate sanitation and solid waste management.

The scenario analysis used a backcasting approach in evaluating the alternatives. This involved assessing what the outcomes would have been, had a different development path been followed, but one that doesn’t change the amount of households or economic activities in the catchment. This approach avoided making a large amount of detailed (and probably wrong) planning assumptions as would have been required if scenarios were applied to greenfields areas earmarked for future development. The study is not about the costs and benefits of retrofitting these measures in the study area. Indeed, in some cases this would be impossible. Rather the study uses backcasting of an existing catchment to derive useful policy recommendations for the greenfields areas.

While the study area is the most developed catchment in the EMA, it is not yet fully developed as per the existing zonation plans. Thus it was still necessary to make some assumptions about the characteristics of the latter areas. These were taken as being the same as those of nearby developed zones of the same type.

In scenarios that included increased conservation area relative to full development (medium and maximum conservation scenarios), it was assumed that a compact development approach had been followed that used land more efficiently, incorporating taller buildings and more compact infrastructure. Passive structural stormwater management measures (drainage systems, culverts etc.) are assumed to be in place as at present.

4.2 Scenario elements

The green urban development interventions considered are described in detail in Chapter 3. These were grouped into seven types, with one of these (source controls) being comprised of four sub-types of interventions. The grouping of source controls was done because they all have the same basic aim to retard flows during storm events, and could be applied in any combination, depending on their relative costs. Different levels were considered for source controls and conservation areas.
4.3 Scenarios

A range of scenarios was then constructed. Each scenario consisted of a combination of the different interventions described above, applied to different extents in the catchment (Table 4.2). The possible number of combinations is very large, so these were chosen, not randomly, but with specific questions in mind. Since GUD measures are unlikely to have much positive impact in the absence of adequate sanitation, it was decided to include full sanitation (as required by existing legislation) in most of the scenarios. A total of 15 scenarios were designed and analysed (Table 4.2). All scenarios assumed that the catchment was fully developed (as per municipal scheme zonation plans, effective 2014), except that scenarios with medium or high levels of conservation meant that the development was more compact. All scenarios had the same number of households and the same amount of commercial and industrial activity.

Table 4.1 Summary of interventions considered in the scenarios.

<table>
<thead>
<tr>
<th>Intervention</th>
<th>Description</th>
<th>Possible extents if included</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sanitation</td>
<td>Sanitation measures implemented to meet existing needs and those associated with planned development. These include improved compliance and monitoring at existing WWTW, improved sanitation in informal settlement areas and adequate sanitation for the planned development areas. While the sanitation backlog and servicing planned development areas will generate further sewage outputs, it was assumed that at least an equivalent amount of wastewater would be recycled, resulting in no net increase in WWTW outputs.</td>
<td>Fully serviced</td>
</tr>
<tr>
<td>Litter removal</td>
<td>Measures to prevent and/or clean up solid waste (e.g. ban on plastic bags, bottles/compulsory refunds, community stewardship arrangements).</td>
<td>Fully dealt with</td>
</tr>
<tr>
<td>Source controls</td>
<td>On-site measures to reduce or neutralise the effects of built areas on runoff. The medium extent included the application of green roofs, permeable paving and infiltration trenches on all commercial and industrial buildings in the catchment. The maximum extent of implementation also included soakways on all residential buildings.</td>
<td>Medium = all non-residential properties Maximum = all properties</td>
</tr>
<tr>
<td>Detention basins</td>
<td>Applied at strategic points throughout the study area to reduce or neutralise the effects of built areas on runoff at a broader scale, and therefore also addressing increased runoff from roads, walkways and other hardened surfaces.</td>
<td>All sub-catchments</td>
</tr>
<tr>
<td>Treatment wetlands</td>
<td>Artificial wetlands constructed below waste water treatment works for polishing effluent and improving water quality.</td>
<td>All WWTWs</td>
</tr>
<tr>
<td>Riparian buffers</td>
<td>15-30 m of natural vegetation is maintained along streams and rivers in order to intercept and improve the quality of non-point source surface runoff from urban areas before it enters water courses as well as to provide a conservation corridor.</td>
<td>All streams and rivers (1300 ha)</td>
</tr>
<tr>
<td>Conservation areas (facilitated by compact development)</td>
<td>Compact development designed to retain significant conservation areas, to reduce hardened surface area and meet biodiversity conservation targets. This is fully achieved in the maximum conservation scenario, partly achieved in the medium conservation scenario (which retains the current extent) and minimally in the default scenario in which there is no compact development.</td>
<td>Minimum = 2800 ha as planned Medium = 6000 ha as at present Maximum = 7000 ha meeting conservation targets</td>
</tr>
</tbody>
</table>

Table 4.2 Scenarios used in the analysis. Levels of each intervention are described using symbols for ease of comparison. sw = stormwater.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Sanitation and waste management (SWM)</th>
<th>Green engineering (GE) / Active stormwater management</th>
<th>Conservation / Non-structural stormwater management</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Baseline: BAU (sanitation backlog)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2. GUD without sanitation</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3. Clean baseline: BAU + SWM</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>4. Cons2</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>5. Cons3</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>6. R</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>7. R + Cons2</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>8. R + Cons3</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>9. S2</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>10. D</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>11. S+D</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>12. S+D+R</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>13. S+Dr+R</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>14. S2+Dr+R+Cons2</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>15. S2+Dr+R+Cons3</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
</tbody>
</table>

Scenario 1 (BAU) had full development as planned, but with the same level of backlog of sanitation and solid waste services as at present. No green engineering measures were implemented and the amount of natural open space was reduced to the planned extent of 2800 ha. This was termed the “Baseline”. Note that the baseline is not the same as the present-day situation, which was used to develop and calibrate the models, and against which water quality estimates are also compared out of interest.

In Scenario 2 (GUD without sanitation), all the green engineering and conservation measures were implemented but the sanitation backlog was not addressed. This was to test the hypothesis that GUD measures designed to address water quality are not effective if sanitation is not properly addressed.

Scenario 3 (BAU + SWM) was the same as Scenario 1 except that the sanitation backlog and litter problems were addressed. A comparison of Scenario 3 to Scenario 1 allowed a test of the effect of sanitation alone on water quality.

The remaining scenarios all included full sanitation and litter prevention programmes, so “+SWM” is implied in Scenarios 3-15. Scenario 3 effectively provided a “Clean Baseline” against which to evaluate the relative net benefits of different engineering and conservation measures applied to different extents. Scenarios 4-15 were compared with Scenario 3, under the prior assumption that adequate sanitation is both imperative and a prerequisite to GUD.

Scenarios 4 to 8 were set up to test the effects of different amounts of natural areas (conservation areas and river buffers) on flooding and water quality. Scenarios 9 to 12 were set up to test the effects of different combinations of green engineering interventions. Scenarios 13 to 15 were set up to explore the effects of implementing both green engineering and conservation measures to different extents.
V. SCENARIO MODELLING AND RESULTS

5.1 Overview

A number of models were used during the scenario analysis to determine the potential benefits of different combinations and extents of green urban development interventions (Figure 5.1). Inputs into the models included the extent and quality of natural and semi-natural areas, the extent, design and performance of a range of green urban development engineering solutions for flood attenuation and water quality amelioration, and the amount and design capacity of conventional conveyance and waste water treatment infrastructure. In addition, assumptions were also made regarding the management of solid waste.

Figure 5.1 The approach used for the scenario analysis and determining the costs and benefits associated with green urban development.
A hydrologic (hydrology + hydraulic) model, carried out using PC-SWMM, produced flood hydrographs at specific points in the catchment and a sediment and nutrient model, also carried out in PC-SWMM, produced water quality outputs in the form of total suspended solids (TSS) and nutrient concentrations and loads at specific points of interest in the catchment. The comprehensiveness of these models varied according to priorities, availability of values, respectively. The water quality data were inputs into a River Ecosystem Health assessment tool to evaluate river system changes, into an Estuarine Ecosystem Services model to estimate changes in the value of those services, and were also used to estimate reductions in dredging costs. Changes in the quantity and quality of green open space areas (and beaches) were inputs into a Tourism Value model and a Hedonic Pricing Model, which estimated resultant changes in the tourism and property values, respectively. The comprehensiveness of these models varied according to priorities, availability of potentially suitable modelling platforms and models, and data availability. Some of the models built on models developed for the municipality-wide eThekwini ecosystem services valuation study (Turpie et al. 2017).

The possibility of also developing a dispersion model to estimate water quality impacts on surrounding beach areas was considered but was not included in the study due to the expected low level of impact in this case. It should be noted that this might be highly relevant for other catchment areas in the EMA, particularly the uMngeni catchment.

5.2 Water quality improvements and related benefits

5.2.1 Impacts on sediment and nutrient concentrations and loads

Annual sediment and nutrient loads were estimated by simulating the total suspended sediment (TSS), total phosphorous (TP) and total inorganic nitrogen (TIN) loads using the PC-SWMM model (see Box S.1). By comparing the modelled sediment and nutrient outputs for each scenario, it was possible to estimate the difference made by GUD interventions to the sediment and nutrient loads transported into Durban Bay.

Annual sediment and nutrient loads were estimated by simulating the TSS, TP and TIN loads using the PC-SWMM model described in detail in Appendix 5. TSS, TP and TIN loads were simulated for one year from August 2013 to August 2014 (total annual precipitation of 572 mm for the Durban city area, lower than MAP). The pollutant washoff from a given landuse during periods of wet weather was characterized in the model by using a user defined Event Mean Concentration (EMC). The Event Mean Concentration is a case of Rating Curve Washoff where the exponent is 1.0 and the coefficient represents the washoff pollutant concentration in mg/L. In each case build-up is continuously depleted as washoff proceeds, and washoff ceases when there is no more build-up available. The EMCs for TSS, TP and TIN were derived from literature and applied to the different landuse categories. Model subcatchment parameters were derived by area weighting the various land use parcels within each subcatchment. The modelled runoff flows were coupled with EMC values to estimate the concentration and total load of TSS and nutrients at different points in the catchment. The data can also be applied in PC-SWMM to determine the water quality volume to be catered for in stormwater management devices, such as source controls and detention basins. The percentage contribution of bed load and suspended sediments to the total sediment load is different for each catchment. For this study suspended sediment loads were multiplied by a factor of 1.25 in order to account for bed load. This is the factor generally applied in South Africa (Msadala et al. 2010, after Rooseboom 1992).

The uMngeni catchment and the Umbilo Rivers and other stormwater outfalls within the U6OF catchment discharge directly into Durban Harbour. In the PC-SWMM model, there were 79 harbour outfalls in total. In addition to the outfalls, polluted loads were simulated at a number of water quality monitoring stations situated throughout the catchment. A total of five monitoring stations on the uMngeni River, three stations on the Umbilo River, and one station on the Mkumbaan River were included as points of interest. Monthly water quality data collected by the eThekwini Water and Sanitation Department were used for calibration and validation of the model. Simulations were run for a one-week period from the 1 – 7 July 2014 at a two second time interval, and the simulated values were within reasonable range of the measured values. The assumptions regarding untreated urban runoff quality, and the effects of stormwater interventions are outlined in Appendix 2.

Recycling of wastewater and improved sanitation had the greatest impact on reducing nutrient loads into the harbour. Simulated TSS loads were highest under the BAU scenario with a total of just over 13 000 tonnes entering the harbour each year (Figure 5.2). This was reduced to 11 845 tonnes under the Clean Baseline, a result of improved sanitation in the catchment and the reduction in WWTP discharges to present-day levels due to recycling. Note that this change is significant, but relatively small compared to what it might be in a typical African city catchment with a much higher proportion of unserviced informal settlements. Also, much of the change in this case comes from the reduction in WWTP discharges.

Both source controls and conservation measures improved on the Clean Baseline situation. Source controls and detention basins, when implemented independently (Scenarios 9 and 10), were not as effective at reducing sediment loads when compared to the conservation scenarios, and a combination of these interventions produced the best result (Figure 5.2 and Figure 5.3). The total capacity of detention basins within the subcatchment was approximately 450 000 m³, whereas the combined attenuation capacity of source controls was orders of magnitude higher. Considering that the reductions of TSS loads were similar for Scenario 9 and 10, it implies that detention basins are more effective at reducing TSS loadings than source controls. Conservation areas and riparian buffers (Scenarios 4 – 8) had a significant impact on reducing TSS loads into the harbour (Figure 5.3). The increase in conservation area (medium and maximum extent) corresponds to an increase in the proportion of D’MOSS area by about 14 and 17% and a decrease in TSS loads by about 18 and 32% respectively. The establishment of river buffers corresponded to a further 7% increase in conservation area and a further 31-36% reduction in the annual TSS loading. The implementation of river buffers had a two-fold effect in terms of the modelling, i.e. the change in landuse alters the hydraulic parameters and the inclusion of treatment nodes (first-order decay equations) reduce TSS loads along the flow path. Scenario 8 had the largest impact of the non-structural interventions, reducing annual TSS loads by 63% (Figure 5.2 and Figure 5.3).
The accumulation of TIN and TP in the catchment is predominantly derived from discharges from WWTWs. For Scenarios 3 to 5, discharges from WWTWs accounted for 65-70% of the total annual TP loading into the harbour and about 50-60% of the total TIN loading. The implementation of treatment wetlands was therefore most efficient at reducing nutrient loadings into the harbour (Scenarios 14 and 15). Source controls, detention basins and river buffers only helped to reduce the total TP and TIN loading generated from surface washoff by a maximum of 15 and 20% respectively.

Figure 5.4 Annual TP and TIN loads for different outfalls entering Durban Harbour for all scenarios.

Source controls (Scenario 9) and detention basins (Scenario 10), when implemented on their own, had a low impact on TSS loads with decreases of 22% and 19% respectively. Detention basins were most effective when water is allowed to pond and sediments can settle. The efficacy of the detention basins diminished towards the lower ends of the catchment, where fewer were implemented and/or where flows were higher. The efficiency of the detention basins could be improved if their capacity in the lower reaches was increased or if more were implemented.

Overall, the source controls had a similar effect to the detention basins, reducing TSS loads into the harbour by approximately 22% suggesting that these measures are largely substitutable. The simulated results for Scenarios 11 and 12 show that the inclusion of soakaways in residential areas with other source controls (i.e. permeable paving, green roofs and infiltration trenches) reduce TSS loads by an additional 8%. Source controls were most effective at removing TSS when used in combination with detention basins. The implementation of a treatment train approach (multiple measures) was extremely efficient at reducing TSS loads, even with higher WWTW inputs. The accumulation of TSS in the catchment is predominantly derived from surface washoff. The contribution from WWTWs is significantly lower (Figure 5.3). The introduction of sanitation measures have a more significant impact on TSS loads in the Umbhlatuzana River due to a higher reduction in WWTW discharges (BAU compared to the Baseline). The addition of treatment wetlands reduce the TSS load from the WWTWs by about 68%, but only reduce the total TSS load into the harbour by less than 10% overall. The results indicate that river buffers (Scenarios 6 – 8) were also effective at reducing TSS loads. The most notable outcome of these simulations, however, is that the preservation of the maximum extent of D’MOSS areas with river buffers has similar effects as implementing a full treatment train approach.

The annual nutrient loading results have shown that just by improving sanitation in the catchment (BAU compared to the Clean Baseline) there is a 30% reduction in total nitrogen (TIN) loads and a 35% reduction in total phosphorous (TP) loads entering the harbour each year (Figure 5.4). With sanitation backlogs taken care of, neither natural areas nor green engineering measures implemented on their own had much additional effect (Figure 5.4), although significant localised effects were seen. The addition of treatment wetlands (Scenarios 14 and 15) resulted in the largest reduction in TIN and TP, with Scenario 15 reducing TIN by 63% and TP by 53%.

While conservation areas and riparian buffers have shown to be particularly effective at reducing TSS loads into the harbour and attenuating peak flows during small to medium flood events, these interventions (Scenarios 4 – 8) were less effective at reducing TIN and TP. Scenario 8 reduces TIN loads by 19% and TP loads by 14%. Results suggested that source controls and detention basins, when implemented on their own (Scenario 9 and 10), are also not very effective at reducing nutrient loads. The implementation of a treatment train was most effective at reducing nutrient loads into the harbour.

Figure 5.3 The annual TSS loadings at different points along the Umbilo River (left) and the Umbhlatuzana River (right). Refer to Figure A6.1 for the monitoring station locations in the catchment.
5.2.2 Impacts on river condition

Changes in river condition associated with each of the different scenarios were assessed quantitatively (see Box 5.2, Appendix 6), in terms of modelled instream water quality, and qualitatively, in terms of some of the broad parameters considered in assessments of ecosystem health (see Section 2.6).

Box 5.2 Summary of river ecosystem health assessment approach (details in Appendix 6)

The quantitative assessments used modelled concentrations of the three parameters included in the hydrological and water quality model, namely total phosphorous (TP), total suspended solids (TSS) and Total Inorganic Nitrogen (TIN). Modelled hourly concentrations of these parameters were available for the 10 sites shown in Figure 5.8 for a one-year period. The time series dataset was simplified to mean daily concentrations. These were presented in terms of different river health or condition categories, as recommended in South African (national) draft guidelines (DWAF 2008) and interpreted in Table 5.1. The range and/or threshold values for the variables considered in this study were also taken from DWAF (2008), using the ranges defined for each River Health Category (see Appendix 6 for more detail).

Table 5.1 Comparison of different systems for the categorisation of river health/condition data, simplified after DWAF (2008).

<table>
<thead>
<tr>
<th>Difference from natural</th>
<th>Category</th>
<th>Natural to poor category</th>
</tr>
</thead>
<tbody>
<tr>
<td>No change</td>
<td>A</td>
<td>Natural</td>
</tr>
<tr>
<td>Small change</td>
<td>B</td>
<td>Good</td>
</tr>
<tr>
<td>Moderate change</td>
<td>C</td>
<td>Fair</td>
</tr>
<tr>
<td>Large change</td>
<td>D</td>
<td>Poor</td>
</tr>
<tr>
<td>Serious change</td>
<td>E</td>
<td>Poor</td>
</tr>
<tr>
<td>Extreme change</td>
<td>F</td>
<td>Poor</td>
</tr>
</tbody>
</table>

Total suspended solids (TSS) data could not be interpreted in this manner. DWAF (2008) does not in fact quantify TSS concentrations for different health rating values, on the basis that these data are not routinely measured by the Department of Water and Sanitation (DWS). Existing water quality guidelines for TSS are limited. Even when Reference (“Natural”) Condition TSS data are available for a particular system, their value is often restricted. This is because of the tight links between sediment transport and flow velocity, and the largescale differences in sediment transport depending on discharge. In the current situation, therefore, while modelled TSS concentrations allowed comparison between different scenarios, and some comment on likely removal rates of other parameters expected to be associated with inorganic sediments (e.g. heavy metals and total phosphorus) they could not be used to infer absolute erosion and sedimentation rates. Guidelines for the interpretation of links between turbidity and river health (after DWAF 2008) were also drawn on in this regard.

The qualitative assessments carried out in this project considered the metrics used in Present Ecological State (PES) assessments of turbidity (for which TSS is considered a surrogate value, see Appendix 6) to infer qualitative change in river condition as a result of scenarios involving attenuation of runoff and the provision of riparian corridors and buffers. Changes in TSS data produced by the model were used to infer (but not quantitatively) changes in sediment transport and erosion.

In addition to limitations in the applicability of TSS data in inferring catchment-scale erosion and sediment processes, the following limitations must also be considered with regard to the approach taken to assess the impact of the different scenarios on river condition, and in particular, on river water quality, in this study, namely:

- The assessments are limited to TP, TSS and TIN and do not take account of other variables such as ammonia-nitrogen, various heavy metal concentrations; bacteria, salinity;
- The lack of data for other important water quality parameters means that interacting parameters are not considered (e.g. the influences of dissolved oxygen, pH, temperature and (in the case of some heavy metals) water hardness);
- The lack of data regarding the organic component of TSS and the proportions of total ammonia and orthophosphate comprising TIN and TP respectively.

All threshold values, guidelines, metrics and assumptions used to assess river ecosystem health are outlined in Appendix 6.

Changes in modelled water quality at the ten monitoring sites in the catchment (Figure A6.1) were interpreted with regard to the river health categories for water quality outlined above (see Box 5.2 and Appendix 6).

Figure 5.5 and Figure 5.6 show concentration ranges for different river reaches, and where rehabilitation of river water quality above a certain minimum condition may be required.

The Present Day concentrations of water quality variables in the river systems generally followed expected patterns for urban environments, with the highest concentrations of TIN and TP occurring in the dry season (winter), when dilution as a result of surface runoff is lowest, and TSS tending to be lowest in the dry season, when flows are assumed to be too low to mobilise high sediment loads (Figure 5.5 and Figure 5.6).

When individual sites were assessed (refer to Appendix 6), the exception to the above was seen to be the least-impacted upper reaches of the Umhlatuzana River (ZANA_35), where dry season TP concentrations were generally much lower than in the wet season. The reason for this may be that most of the phosphorus in the river water in these reaches is attached to sediments and/or is in a particulate form, rather than being orthophosphate derived. The site lies upstream of any waste water treatment works, and sources of orthophosphate into the system appear to be limited. During the dry season, mobilisation of sediments was also generally reduced and this might explain the low measured dry season total phosphorus concentrations in data from this site.

Phosphorus-based enrichment in the catchment is significant, with no sites under Present Day conditions being better than a Category D with regard to this nutrient, and most sites (with the exception of ZANA_35, which ranges between Category D and E for phosphorus) being in a Category F for most of the time (see Figure A6.2). The implication of this is that for meaningful rehabilitation of water quality to be achieved, a substantial reduction in instream phosphorus concentrations is necessary. Since “sustainable” aquatic ecosystems are assumed to lie in a condition of Category D or better (Kleyhans et al. 2005), this implies that achievement of PES ratings better than Category E with regard to total phosphorus should be a prerequisite of future management strategies and the scenarios were evaluated with this in mind.

Although concentrations of TIN were higher than for phosphorus, the ecological implications of nitrogen nutrients are less severe, with data for sites in the catchment (see Figure A6.4) showing that Present Day TIN concentrations were never in a worse category than Category E, and in a Category B to C in the upper reaches of the Umhlatuzana River (ZANA_35).
Scenario 1 (BAU) outputs indicated that in most cases, a BAU approach would result in worsening of water quality compared to present (and largely unsustainable conditions, below PES Category D), thus providing motivation for implementation of GUD approaches. Under the GUD scenarios, the modelled data need to be assessed with regard to where GUD structures are actually placed, taking into account river character / condition in different reaches and the existing known sources and types of water quality impairment. Assessment of the upper sites on the Umhlatuzana River, for example (ZANA_35) show that implementation of basic sanitation measures (Scenario 3) as well as the addition of basic GUD measures would have little impact on dry season water quality and only a slight impact on wet season water quality. This is because most of the proposed measures had little application in this part of the catchment, which is least affected by poor sanitation issues. Moreover, TSS concentrations at the downstream site (ZANA_34), downstream of the Hillcrest WWTW, were potentially negatively affected compared to BAU concentrations (see modelled TSS in Figure A6.3). This is assumed to be the result of upstream detention of less-impacted water flows (see Appendix 2), and as a result, increased concentrations downstream (Figure A2.3 shows the locations of modelled instream detention ponds, with ponds located upstream of the Hillcrest WWTW).

The addition of sanitation without any other GUD measures (Scenario 3 – Clean Baseline) resulted in some improvement in river water quality compared to Scenario 1 (BAU), and even compared to the Present Day. The impact on a site-by-site basis is not dramatic, however, and reflects the fact that while the water quality impacts of informal settlements on downstream (estuary) loading may be profound, their actual impacts at a river level are localised, affecting their receiving rivers and the downstream reaches only. Thus the implementation of improved sanitation measures would affect only those areas currently affected by informal settlements – e.g. the middle reaches of the Umhlatuzana River and the lower (Cato Manor) reaches.

Figure 5.5 Effects of different modelled scenarios on concentrations of Total Phosphorus and Total Suspended Solids (TSS), respectively. Site locations as shown in Figure A6.1.

Figure 5.6 Effects of different modelled scenarios on total inorganic nitrogen (TIN) concentrations at different monitoring sites in the study area. Site locations as shown in Figure A6.1.
of the Umbilo River (see Figure 2.6). In catchments where informal settlements comprise a significant proportion of landuse, changes in water quality as a result of informal sanitation would obviously be more pronounced. It must be stressed in this regard, moreover, that the modelled data indicate only patterns of major nutrient concentrations. The potentially more significant effects of informal sanitation on river water quality and its fitness for human or other use has not been explored in this study.

The modelled data shown in Appendix 6, Figure 5.5 and Figure 5.6 generally show that while improved sanitation affects phosphorus concentrations to some extent, as do the implementation of riparian buffers and conservation areas (scenarios 4–8) it is in fact the implementation of source control measures (see scenario 9) as well as the implementation of typical GUD measures (scenarios 10–15) that assert broad, significant impacts on total phosphorus concentrations. Almost throughout the study area, these measures are responsible for reducing modelled phosphorus concentrations by at least one PES category. Nevertheless, these figures need to be interpreted with some caution. To some degree, the dramatic reduction in instream concentrations of phosphorus is the result of the more generic application of source control measures at the catchment level, compared to the site specific application of measures such as improved sanitation, of relevance only to areas affected by informal settlement.

The results suggested that the application of detention ponds (scenario 10) was by far the most significant intervention with regard to bringing about an improvement in instream water quality nutrient concentrations, although not with regard to TSS reduction (see Figure A6.3, Appendix 6). The modelled effects of the detention ponds were, however, slightly problematic in that all of the sediment ponds were assumed to be located along water courses. In practice, this is unlikely to be ecologically sanctioned in significant areas, as a result of the ecological implications, and the catchment-scale impacts of TSS removal from the system in Scenario 10 are assumed to be over-emphasized by the model. Associated with TSS removal would, moreover, be the removal of total phosphorus, with Campbell (2001) for example estimating that some 70% percent of total phosphorus from informal settlements is transported in sedimentation with approaches such as the use of treatment wetlands clearly has the most impact on reaches downstream of the WWTWs where they are implemented – thus total phosphorus concentrations are most impacted by scenarios involving these measures (scenarios 14 and 15) at sites downstream of WWTWs (i.e. ZANA_34; ZANA_28 and Umbilo_04).

Interventions such as riparian buffers (scenarios 6–8) and conservation areas (varying between scenarios) had little effect on instream nutrient concentrations. They did, however, have significant implications for TSS, highlighting the modelled assumption that these factors play a significant role in reducing erosion of the stream banks and bed (thus decreasing downstream sediment load) as well as actively trapping sediment in diffuse runoff and thus reducing sediment concentrations. At the same time, however, it is noted that interventions such as detention basins would also play a role in sediment removal, thus explaining the significant effect of Scenario 10 on all aspects of water quality. Of interest, however, is the modelled effect of Scenario 10 on dry season flows throughout the study area, showing a marked increase in TSS concentrations at this time, out of keeping with the assumed role of detention ponds in terms of sediment trapping loads in rivers systems is complex, and this pattern is assumed to reflect problems with the model rather than real patterns of elevated sedimentation. To some extent, however, the absence of riparian buffers and conservation areas from Scenario 10 means that sediment availability in terms of the model was also elevated at all times in the catchment under this scenario.

While interventions such as riparian buffers and conservation areas may have little measurable effect on other aspects of water quality (e.g. phosphorus or nitrogen nutrient concentrations) they do play a major role in determining overall river habitat integrity or condition, through the provision of belt or ribbon of longitudinal corridors for faunal movement (important in an increasingly urban environment) as well as areas in which indigenous riparian vegetation can be established and allowed to spread into downstream reaches, improving reaigenous habitat quality and function. While such attributes do not add to water quality PES Category, they do add significantly to overall habitat quality, and should thus be regarded as playing a more substantial role in catchment ecosystem function than suggested by the data under current consideration.

The modelled data included sites at the downstream ends of the catchment, notably sites OF1 and OF2. Total phosphorus data were not available for these sites. TSS and TIN data showed a marked decrease in TSS and TIN downstream from both OF1 and OF2 in Scenario 10. 4 respectively indicated similar effects of the different scenarios on river condition at OF2_UMB at the inflow estuary to those discussed generally above. However, the results for OF1_UMB at the downstream end of the small Umbilaluzana system, just upstream of OF2_UMB, showed no clear patterns in TSS or TIN concentrations in scenarios 10–15. Scenario 10 interventions, suggesting that landuse in the catchment of this small system (a highly industrialised urban area) may not respond to the scenarios as developed in this study. For example, the system was not included in the development of significant riparian corridors along the larger major rivers. Moreover, important effects of the implementation of GUD measures such as removal of heavy metals from urban runoff that might be applicable to this system were not considered in the model.

From a strategic perspective, the above findings need to be considered in terms of the main objectives of improving GUD interventions in a particular catchment management strategy. From a sustainable practice perspective, all aquatic ecosystems should be managed so as to fall within a Category D or better. The modelled water quality data indicate that this would be readily achievable in terms of nitrogen nutrients throughout the catchment, and generally but not always achievable in terms of phosphorus. The modelled scenario results provided that the full suite of GUD measures was implemented. This means that sustainable management of the affected river systems requires more than simple application of existing legislation with regard to water quality and quantity, and by implication should require increased effort to offset such impacts. However, while the main objective of GUD measures is simply to protect downstream ecosystems (e.g. the estuary), the design and spatial layout of GUD measures can be more strategic, allowing a focus on loading rather than concentration of variables. This should, however, still be considered with regard to South Africa’s own legislation, which requires the maintenance of minimum sustainable (i.e. Category D) water quality standards for all aquatic ecosystems. This said, it is also acknowledged that river condition is a composite of many variables, including water quality, and that achievement of minimum standards with regard to alien plant clearing and indigenous plant restoration may be as important for restoring sustainable riverine ecosystems as improvement of water quality.

The application of detention basins in the model is one of the earliest modelled modelling and assessment period would probably be useful. The detention basins have been modelled as instream systems – a practice that would not be ecologically defendable in systems for which actual or desired ecological integrity exists. Moreover, in practice, SUDS approaches commonly incorporate many small off-channel detention basins, that would not have the implications for flow rates and associated water quality that appear to characterise the modelled scenarios involving the use of detention ponds, and Scenario 10 in particular.

5.2.3 Avoided costs due to sediment retention

The avoided sedimentation was taken as the difference in annual sediment yield from the catchment between the modelled scenarios. The avoided costs were estimated using dredging data provided by Transnet for Durban Harbour for the period 1 April 2015 – 31 March 2016. Maintenance dredging involves the removal of sediments from channels, basins and berths within the harbour. Dredging of channels and basins costs R85 per m$^3$ on average and dredging of berths costs R63 per m$^3$. A total of just under 182 000 m$^3$ of sediment was dredged from the harbour over the period 2015/16, an overall average cost of R22 per m$^3$ (Transnet NPA). However, most of the sediment removed from the harbour through maintenance dredging is not derived from river inputs but is from existing estuarine sediments that are shifted by the movement of large ships through the harbour (Transnet NPA). The “silt canal” at the top end of the estuary is not dredged on a regular basis and it is estimated that less than 5% of the annual volume of dredged sediment is of fluvial origin (Clive Greylings, Transnet NPA pers. comm.). This corresponds to the modelled current TSS load for the uLwapho catchment which represents 4% of the annual volume of dredged sediment. The proportion of total sediment due to the bedload was included in the estimation of mean annual sediment loads. The bedload is generally thought to constitute about 20% (by mass) of the total sediment yield from rivers. It also represents the coarser fraction of the sediment yield spectrum. Misadala et al. (2010), used a factor of 1.25 to cater for bedload and non-uniformity in suspended sediment concentrations in order to estimate the mean annual sediment load (after Rooseboom et al. 1992).

The annual TSS loads generated under different scenarios were compared to Scenario 3 as the baseline. The annual TSS loads were converted from kg to m$^3$ using a sediment density of 1350 kg/m$^3$ (Rooseboom 1992) and multiplied by a factor of 1.25 to cater for bedload and non-uniformity in suspended sediment concentrations. The mean annual sediment load was then multiplied by the annual average dredging cost with the difference in costs between the scenarios representing the costs avoided for dredging of Durban harbour.

A decrease in TSS loads into the harbour resulted in a decrease in annual maintenance dredging costs associated with maintenance dredging depths in the harbour. The modelled scenario results suggest that the annual dredging costs avoided range from R0.46 million for Scenario 4 to R1.75 million for Scenario 15 (Table 5.2) as a result of decreased sediment loads into the harbour. This equates to a net present value for dredging costs avoided of R5.3 million to R20.1 million (Table 5.2).
Table 5.2 The total annual dredging cost for each scenario, and annual and NPV dredging costs avoided (R millions) for each scenario when compared to the baseline.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Total annual dredging cost (R millions)</th>
<th>% decrease in TSS loads</th>
<th>Annual dredging costs avoided (R millions)</th>
<th>NPV dredging costs avoided (20 yrs., 6%, R millions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3. Clean Baseline</td>
<td>2.51</td>
<td></td>
<td></td>
<td>5.3</td>
</tr>
<tr>
<td>4. Cons2</td>
<td>2.05</td>
<td>18%</td>
<td>0.46</td>
<td>5.9</td>
</tr>
<tr>
<td>5. Cons3</td>
<td>1.70</td>
<td>32%</td>
<td>0.81</td>
<td>9.3</td>
</tr>
<tr>
<td>6. R</td>
<td>1.36</td>
<td>46%</td>
<td>1.02</td>
<td>13.2</td>
</tr>
<tr>
<td>7. R+Cons2</td>
<td>1.15</td>
<td>54%</td>
<td>1.36</td>
<td>15.6</td>
</tr>
<tr>
<td>8. R+Cons3</td>
<td>0.92</td>
<td>63%</td>
<td>1.59</td>
<td>18.2</td>
</tr>
<tr>
<td>9. S2</td>
<td>1.95</td>
<td>22%</td>
<td>0.56</td>
<td>6.5</td>
</tr>
<tr>
<td>10. D</td>
<td>2.04</td>
<td>19%</td>
<td>0.47</td>
<td>5.4</td>
</tr>
<tr>
<td>11. S+D</td>
<td>1.43</td>
<td>43%</td>
<td>1.08</td>
<td>12.4</td>
</tr>
<tr>
<td>12. S2+D</td>
<td>1.22</td>
<td>51%</td>
<td>1.29</td>
<td>14.8</td>
</tr>
<tr>
<td>13. S1+D+R</td>
<td>1.15</td>
<td>54%</td>
<td>1.36</td>
<td>15.7</td>
</tr>
<tr>
<td>14. S1+D2+R+Cons2</td>
<td>0.97</td>
<td>61%</td>
<td>1.54</td>
<td>17.7</td>
</tr>
<tr>
<td>15. S2+D2+R+Cons3</td>
<td>0.76</td>
<td>70%</td>
<td>1.27</td>
<td>20.1</td>
</tr>
</tbody>
</table>

5.2.4 Impacts on estuary condition and fishery values

A loss of natural system function and integrity in the catchment results in a loss in estuary functioning as nutrients and TSS loads increase. This has an impact on estuary condition and changes the values and outputs associated with different ecosystem services – such as tourism and recreation, nursery value and fishery outputs.

A deterioration of water quality in estuaries as a result of increases in nutrient and suspended sediment loads would lead to impacts on fish stocks, estuarine fishery values and the export of fish to marine fisheries (Figure 5.7). Water quality improvements, such as reduced nutrient and TSS loads, will have the reverse effect with increased fish exports to the marine environment as a result of improved estuary condition.

The relationships between water quality and fish abundance have been well studied in KwaZulu-Natal (Cyrus et al. 1987, 1988). Expert understanding of these and other relationships is used in the quantification of estuarine responses to changes in the quantity and quality of freshwater inflows to estuaries. A substantial amount of work has also been carried out by groups of estuarine specialist scientists to describe the present status of estuaries throughout South Africa, following standardised methods of describing estuarine health developed for the setting of environmental flow requirements as well as for estuary management more generally (Turpie et al. 1999, 2012). These require the description and scoring of all the abiotic and biotic components of estuaries, including water quality variables and fish communities. These scores have been collated and summarised for the most recent National Biodiversity Assessment of estuaries (van Nierkerk & Turpie 2012). The relationships between input loads and water quality, and between water quality and fish abundance determined in the Durban ESV study (Turpie et al. 2017) were used to estimate the potential improvements in the fishery and nursery value of Durban Bay as a result of the GUD interventions.

Increased fish exports to the marine environment and improvements in the estuarine fishery value as a result of improved estuary condition were assessed by comparing the effect of water quality improvements, i.e. a reduction in nutrient and TSS loads between scenarios. The gain in estuarine and marine fishery values as a result of decreased nutrient and sediment loads into Durban Bay when compared to Scenario 3 are shown in Table 5.3. The percentage gain in estuarine and marine fishery values compared to the baseline ranged from 9% for Scenario 4 to 55% for Scenario 15, translating into an annual gain of R0.6 - R3.5 million and a net present value of R6.8 – R40.2 million.

Table 5.3 Estimated gains in estuarine and marine fishery values due to a reduction in TSS and nutrients for scenarios 4-15 when compared to Scenario 3 as the baseline.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>% gain in estuarine &amp; marine fishery values (compared to the baseline)</th>
<th>Annual value gained (R millions)</th>
<th>NPV (20 yrs., 6%, R millions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4. San+MCons</td>
<td>18%</td>
<td>1.24</td>
<td>13.04</td>
</tr>
<tr>
<td>5. San+MCns</td>
<td>18%</td>
<td>1.24</td>
<td>13.04</td>
</tr>
<tr>
<td>6. San+Rip</td>
<td>28%</td>
<td>1.79</td>
<td>20.57</td>
</tr>
<tr>
<td>7. San+Rip+MCns</td>
<td>36%</td>
<td>2.29</td>
<td>26.27</td>
</tr>
<tr>
<td>8. San+RipHCns</td>
<td>46%</td>
<td>2.94</td>
<td>33.73</td>
</tr>
<tr>
<td>9. San+SC2</td>
<td>12%</td>
<td>0.74</td>
<td>8.53</td>
</tr>
<tr>
<td>10. San+DB</td>
<td>10%</td>
<td>0.61</td>
<td>7.03</td>
</tr>
<tr>
<td>11. San+SC+DB</td>
<td>26%</td>
<td>1.65</td>
<td>18.97</td>
</tr>
<tr>
<td>12. San+SC+DB</td>
<td>33%</td>
<td>2.22</td>
<td>24.32</td>
</tr>
<tr>
<td>13. San+SC+DB+R</td>
<td>46%</td>
<td>2.80</td>
<td>26.35</td>
</tr>
<tr>
<td>14. AIGUD1</td>
<td>44%</td>
<td>2.79</td>
<td>31.98</td>
</tr>
<tr>
<td>15. AIGUD2</td>
<td>55%</td>
<td>3.50</td>
<td>40.19</td>
</tr>
</tbody>
</table>

5.3 Flood attenuation benefits

5.3.1 Impacts on flood peaks

Urbanisation and its associated increase in impervious surface area are synonymous with increases in flood peaks. Urban stormwater systems are designed to effectively drain a catchment and reduce the impacts of development on flood flows, thereby altering catchment hydrology. Traditionally, urban stormwater systems drain frequent (minor) storms and associated runoff from properties to natural watercourses. During severe storm events, open spaces and road systems are considered acceptable drainage components of major stormwater systems.

Hydrological modelling of the Umhlatuzana-Umbilo catchment was performed in the US-EPA SWMM5/MMS hydrology and hydraulics engine, using the PC-SWMM software interface (see Box 5.3). The main aim of the hydrological modelling for the scenario analysis included investigating the effects of the implementation of various types and/or combinations of green urban development measures, such as source controls, detention basins, riparian buffers and conservation areas on flood hydrographs at selected points within the Umhlatuzana-Umbilo catchment.

The PC-SWMM model for the Umhlatuzana-Umbilo catchment, which includes flow paths, the location of detention basins, WWTWs, water quality monitoring stations and the extent of source controls in commercial, industrial and residential areas is shown in Figure 5.8.
SWMM is an integrated, physically-based model that was selected for this purpose based on a review of a range of possible modelling options and discussions with eThekwini Municipality’s Catchment, Stormwater and Coastal Management (CSCM) department. CSCM had recently completed the migration of completed HEC-RAS hydrologic models of the EMA to SWMM.

GIS subcatchment data available for this project from the eThekwini Municipality (EM) flood studies were in the order of 1 km$^2$ and larger. The subcatchments were further discretised into smaller subcatchments, in the order of 0.2 km$^2$, within the U60F catchment. A spatial analysis tool was used to process the flow paths, watershed boundaries, and river centre lines. The outlet points for the model were then identified and selected; i.e. estuaries and stormwater infrastructure.

EM flood models, based on geometric HecRAS files, were imported into the PC-SWMM model. The stormwater network shapfile for the catchment was incomplete and contained numerous errors and inconsistencies. These networks were amended where possible. A Stormwater Management System audit (visual inspection and assessment) of all stormwater infrastructure, recently carried out by the eThekwini Municipality, produced a number of new shapfiles that were imported into the model and connected to existing stormwater networks and flow paths. was included where available. The original stormwater shapfile was merged with the new SMS shapfiles and both were connected to the HECRAS and WDT flow paths.

Available current GIS landuse files (e.g. zoning files, D’Moss) were collated and reviewed. These files were concatenated into one consistent landuse polygon shapfile and the landuse classifications were reviewed and summarised into a common set of landuse conventions. The resulting shapfile was ‘groundtruthed’ using aerial imagery for the U60F catchment. A number of input parameters are required for SWMMs. These include hydraulic parameters, soil infiltration properties, rainfall and water quality parameters. The determination of the catchment characteristics was estimated using a spatial analyst tool for zonal statistics. Raster files were generated to represent the information required for the hydraulic and hydrological models, with reference to each subcatchment. The most significant input hydraulic parameter is the percentage of impervious area (Imperv. %). The hydraulic parameters were assigned to each landuse classification based on literature. The largest proportion of rainfall losses over pervious areas generally occur due to soil infiltration. The Green-Ampt method was adopted for this study. This method provides a soil memory as opposed to a brush broad coefficient approach. Three user-defined soil parameters were used; i.e. capillary suction head, saturated hydraulic conductivity, and the maximum available moisture deficit. Average daily abstractions and return flows/discharges were added as point sources at the appropriate junctions.

A user-defined hyetograph was used as the precipitation input into the model. The hyetograph was created using the total daily mean-areal precipitation depths derived by Smithers & Schulze (2000) for a 24-hour event. Unfortunately, the original stormwater model did not include the Umhlatuzana-Umbilo Canal and other surrounding stormwater systems. The original stormwater network in this model was used as a base for the model setup. A Stormwater Management System audit (visual inspection and assessment) of all stormwater infrastructure, recently carried out by the eThekwini Municipality, produced a number of new shapfiles that were imported into the model and connected to existing stormwater networks and flow paths. was included where available. The original stormwater shapfile was merged with the new SMS shapfiles and both were connected to the HECRAS and WDT flow paths.

The Umhlatuzana-Umbilo Canal is the main stormwater outfall that discharges into Durban Harbour. Simulated peak flows for the Canal, under different return periods, are shown in Figure 5.9 and the relative change from the baseline is shown in Figure 5.10. These results suggest that structural GUD measures, in combination with conservation areas, can have a significant impact on reducing peak flows, especially at lower flood return periods.

As expected, Scenarios 14 and 15 have the most significant impact on peak flows across the different flood return periods (Figure 5.9, Figure 5.10). Conservation areas and riparian buffers (Scenario 7 and Scenario 8) have an impact on reducing peak flows, especially at the medium return periods (2- and 5-year) when compared to other scenarios that include only structural interventions. When the structural GUD interventions are applied independently, such as in Scenario 9, where only source controls, their impact is significantly reduced, or in Scenario 10 (detention basins) where the impact on low flood return periods is significant but declines at high return periods (Figure 5.10). This demonstrates the importance of applying a treatment train approach which includes a mixture of structural GUD interventions in conjunction with conservation measures. Furthermore, the treatment train approach (i.e. Scenarios 14 and 15) is the most effective at reducing peak flows during higher return periods.

It is important to consider two key points when interpreting these results:

1. For low flow events (0.5- and 1-year return period), caution should be applied when interpreting what constitutes a significant change in peak flows as numerical instabilities in the model may appear to be relatively large in this regime (i.e. a 1 m$^3$/s variation may be represented by a 10% difference). It is therefore more appropriate to consider the absolute change rather than the relative change; and

2. Stormwater networks are generally designed to manage flows caused by lower rainfall return periods (i.e. the EM stormwater management design policy is based on a 2- to 5-year return period). Once flows exceed the capacity of the stormwater network (i.e. during high return periods), surcharges occur in the stormwater system and water tends to flow along the surface. The model was setup to include continuity in the total flows, but if a junction is surcharged, the peak flow will be underestimated. Although this does not provide a relative change in peak flows in this regime, this is what realistically occurs in-situ.
Impervious surfaces reduce infiltration and increase surface runoff, leading to higher peak flows and reduced runoff response times. The results show that as the amount of conservation area in the catchment increases and the percentage of impervious surface area decreases, the relative change in peak flows increases (Figure 5.11). In fact, an 8% reduction in the impervious surface area of the catchment (from the baseline to Scenario 4) corresponds to about a 15% decrease in peak flows. However, the distribution of D’MOSS areas within the catchment also had an influence on peak flows, as illustrated by the relative change between Scenarios 4 and 5. Although conservation areas covered a larger extent under Scenario 5, this only corresponded to a 1% increase in impervious area. The location of the conservation areas within the catchment is therefore important. Examples of this can be seen when peak flows are assessed at different sampling points, rather than as an overall impact at the outfall into the harbour.

At a sampling station which drains from an area north-east of the Umbilo River (R_Mkumbaan_01, refer Figure 5.8) peak flows increase from Scenario 4 to 5 (Figure 5.12a), due to the changes in the amount and location of conservation area under each scenario. However, in the upper catchment above the Hillcrest WWTW where the amount of conservation area is increased from Scenario 4 to Scenario 5, the reduction in peak flow was found to be more significant for Scenario 5 (Figure 5.12b).

While the implementation of river buffers (Scenarios 6 – 8) generally reduced peak flows, their impact was relatively minor when compared to other measures (Figure 5.11). Source control measures implemented alone (Scenario 9) reduced overall peak flows by about 10%. Soakaways in residential areas were more effective at attenuating peak flows when compared with other source controls implemented in commercial and industrial areas only (i.e. permeable paving, green roofs and infiltration trenches). This was partly explained by the fact that the soakaways were implemented on a larger scale, and so had a larger storage capacity.

The effect of different measures at attenuating peak flows varies spatially throughout the catchment and as such there is rationale for isolating the effectiveness of source controls and detention basins at a higher resolution within the catchment. When considering the peak flows downstream in isolation, the effectiveness of each intervention can be undetectable due to the overall impacts of the catchment.

The impact of different source control measures on reducing peak flows was assessed by examining the hydrographs for specific points in the catchment (Figure 5.13). For some points where there was no detention basin situated upstream, the peak flows were equal for Scenarios 9 and 12 (see R_Chats_15, Figure 5.13), and only a small difference was seen between Scenario 11 and 12. At other points, where detention basins were implemented upstream, their impact was noticeable, especially their ability to reduce initial runoff (as shown by the orange line of Scenario 9 in Figure 5.13 for the Umbilo and Mkumbaan points). The change in peak flows for stations situated in the highest parts of the catchment were found to much lower due to fewer source controls being implemented in these areas. The difference in peak flows observed for Scenario 11 and 12 highlight the effectiveness of soakaways, which were implemented in Scenario 12 but not in Scenario 11.
Another example, further illustrating the effect of source control measures at isolated points in the catchment, is shown in Figure 5.15 and Figure 5.16. This area represents the Pinetown industrial region of the catchment. There are two main stormwater systems that manage the runoff in this area, connecting at the lower right corner of the image. The purpose of a detention basin is to extend the time of concentration and thus regulate the flow downstream.

Figure 5.14  Simulated peak flows for a 2-, 5-, 10- and 20-year rainfall return period for Scenario 10 compared to the Baseline at sampling points (a) R_Zana_35, (b) R_Zana_29, (c) R_Zana_10 and (d) R_Mkumbaan. Note that time units are reporting time steps from the model with one time unit representing 5 minutes.

Detention basins (Scenario 10) were found to be more effective at reducing peak flows during small to medium return periods than during large flood events (Figure 5.14). The observed difference is much larger in the smaller return periods and is reduced during higher return period flows, especially above the 500m³/s regime. This is largely due to the capacity of the detention basins which is rapidly exceeded during higher flood return periods resulting in overflow. The simulation plots and results confirm the source controls have no effect at higher return periods, whilst the combination of source controls and detention basin continue to reduce peak flows for all return periods. This is illustrated in Figure 5.16.

Another example, further illustrating the effect of source control measures at isolated points in the catchment, is shown in Figure 5.15 and Figure 5.16. This area represents the Pinetown industrial region of the catchment. There are two main stormwater systems that manage the runoff in this area, connecting at the lower right corner of the image. The region incorporates both source controls and detention basins, however the point chosen on the northern system (conduit CIS_55Um) does not have a detention basin upstream. The simulation plots and results confirm the source controls have no effect at higher return periods, whilst the combination of source controls and detention basin continue to reduce peak flows for all return periods. This is illustrated in Figure 5.16.
5.3.2 Avoided costs due to flood attenuation

The reduced flood volumes that would occur under different return period flood events (e.g. 1:10 years), would have required smaller drains, culverts, etc., depending on the size of the event they are designed to deal with. Thus a second model was developed in order to estimate the capital costs of the structures required under the present versus the GUD scenarios (see Box 5.4, Appendix 4). The difference, together with associated differences in maintenance costs, is the total life-cycle cost avoided.

Box 5.4 Summary of the method used to estimate infrastructure cost savings (details in Appendix 4)

An analysis was undertaken to determine the difference in the replacement cost of stormwater infrastructure (including both conveyance and storage) between the existing stormwater infrastructure in the EMA and infrastructure that would be designed to different specifications depending on the amount of natural vegetation within the EMA.

The adopted methodology for this analysis focused on estimating the cost difference of the infrastructure with and without natural undeveloped areas in the EMA. The relationship between cost and flow for the status quo was established and used to estimate the cost of infrastructure based on changes caused to the flow as a result of having natural areas within the EMA developed into the average land use, i.e. what happens to the flows if the current D’MOSS is replaced with the average land use type within that catchment?

The methodology used to determine stormwater infrastructure engineering costs is outlined as follows:

1. Identify all stormwater infrastructure within the study area
2. Divide the infrastructure into four major categories (bridges, canals, culverts and pipes)
3. Determine the dimensions of all infrastructure in the study area
4. Estimate the costs of the existing infrastructure based on these dimensions
5. Assign rainfall design return periods to each category of infrastructure
6. Calculate the maximum open channel flow from the Manning’s equation (i.e. the threshold flow)
7. Estimate a scaling relationship between infrastructure dimensions and flow using theoretical uniform flows
8. Simulate the design rainfall return periods and estimate the maximum design flows for each scenario (status quo versus average land use)
9. Use the maximum flows, the existing infrastructure dimensions and the threshold flows to scale the existing infrastructure to required infrastructure dimensions under each scenario
10. Use the new infrastructure dimensions to estimate the cost of the scaled infrastructure
11. Compare the cost of the existing infrastructure to the cost of the scenario infrastructure

Because much of the flood conveyance infrastructure is oversdesigned for various reasons including the problems of blockages by litter, the estimation initially yielded a small cost to increase the size of the structures to deal with the difference in flows. Since this is clearly downward biased, a correction was then applied to adjust for this overdesign and produce a more comparable estimate from which to derive the realistic difference in value.
The savings in the capital cost requirements for flood conveyance were estimated to range from R19 million for scenario 6 to R226 million for scenario 15 when compared to the baseline (Table 5.4). This represents a 0.5% - 6% capital cost saving in stormwater infrastructure. Including an estimated 6% of capital costs as an annual repair and maintenance cost (eThekwini Municipality 2015), this suggests that the cost savings associated with the scenarios have a net present value ranging from R33 – R382 million (Table 5.4).

The inclusion of 23 detention basins in the subcatchment (Scenario 10) provides a cost saving of R194 million, whereas the implementation of all source controls (Scenario 9) provides a higher cost saving of R278 million. Soakaways in residential areas were more efficient at attenuating peak flows when compared with implementing source controls in commercial and industrial areas only (Scenario 9 compared with Scenario 11 and 12) and therefore, provide a higher cost saving when included (Table 5.4).

The conservation of natural areas (Scenario 8), the full extent of source controls (Scenario 9 and 12) and the combination of all GUD measures with conservation measures (Scenario 14 and 15) represent the highest infrastructure cost savings (Figure 5.17). The total cost saving, or flood attenuation value, associated with the implementation of Scenario 15 is R382 million and for Scenario 8 is R234 million. Therefore the contribution of large areas of natural vegetation and riparian buffers (Scenario 8), or compact development, have a significant impact on reducing peak flows, however the addition of structural GUD measures (i.e. full extent source controls and detention basins; Scenario 13, 14 and 15) would provide additional cost savings of R82 million, R102 million, and R146 million, respectively, in terms of stormwater infrastructure cost savings (Table 5.4, Figure 5.17).

### Table 5.4

Stormwater infrastructure cost savings (R millions) for scenarios 4 – 15 when compared to the Baseline.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Total capital costs (R millions)</th>
<th>Capital cost saving (R millions)</th>
<th>Maintenance Cost (NPV 20 yrs., 6%)</th>
<th>Total cost saving (R millions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3. Clean Baseline</td>
<td>3 392</td>
<td>3 781</td>
<td>58</td>
<td>143</td>
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<tr>
<td>4. Cons2</td>
<td>3 836</td>
<td>3 901</td>
<td>61</td>
<td>104</td>
</tr>
<tr>
<td>5. Cons3</td>
<td>3 859</td>
<td>3 836</td>
<td>42</td>
<td>104</td>
</tr>
<tr>
<td>6. R</td>
<td>3 901</td>
<td>3 781</td>
<td>13</td>
<td>33</td>
</tr>
<tr>
<td>7. R + Cons2</td>
<td>3 832</td>
<td>3 781</td>
<td>61</td>
<td>149</td>
</tr>
<tr>
<td>8. R + Cons3</td>
<td>3 781</td>
<td>3 755</td>
<td>95</td>
<td>234</td>
</tr>
<tr>
<td>9. S2</td>
<td>3 755</td>
<td>3 805</td>
<td>113</td>
<td>278</td>
</tr>
<tr>
<td>10. D</td>
<td>3 805</td>
<td>3 802</td>
<td>79</td>
<td>194</td>
</tr>
<tr>
<td>11. S+D</td>
<td>3 802</td>
<td>3 753</td>
<td>58</td>
<td>231</td>
</tr>
<tr>
<td>12. S+D</td>
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<td>3 742</td>
<td>129</td>
<td>316</td>
</tr>
<tr>
<td>13. S2+D</td>
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<td>3 727</td>
<td>56</td>
<td>354</td>
</tr>
<tr>
<td>14. S2+D+Hr+Cons2</td>
<td>3 727</td>
<td>3 694</td>
<td>140</td>
<td>341</td>
</tr>
<tr>
<td>15. S2+D+Hr+Cons3</td>
<td>3 694</td>
<td>3 920</td>
<td>156</td>
<td>382</td>
</tr>
</tbody>
</table>

Figure 5.17 Infrastructure capital cost saving (R million) for scenarios 4 – 15 when compared to the Baseline.

#### 5.4 Amenity benefits of increased conservation areas

Amenity values included the tourism value generated by expenditure by domestic and foreign visitors to Durban, and the value of green open space areas to residents of Durban. These values are mutually exclusive and can be added.

#### 5.4.1 Amenity value to locals

The hedonic analysis that formed part of the accompanying study of the value of eThekwini’s ecosystem services (Turpie et al. 2017; Letley & Turpie 2016) was used to determine the avoided losses of property value under different scenarios. The hedonic study found that both the amount and condition of natural open space areas in the EMA have significant positive impacts on property values. Therefore an increase in the amount of natural vegetation in a good condition within the catchment would have a positive impact on property price premiums. Overall property values were therefore expected to increase with the medium and maximum conservation interventions and decrease with the minimum conservation intervention.

The hedonic model was used to calculate the property price premiums attached to the conservation areas in the U60F catchment under different scenarios. The medium extent of conservation area represents the current D’MOSS which was used to develop the hedonic model. Therefore it was assumed that the areas of natural vegetation for the medium conservation extent were all in a good condition and from this the model results for the properties within the catchment could be used to calculate the associated premiums. To estimate the premiums that would be associated with the maximum conservation extent, it was assumed that the extra 1000 ha gained from the medium to maximum conservation area was managed in a good condition. Based on this assumption, a ratio was used to increase the amount of natural vegetation in a good condition surrounding each of the properties included in the model. For the minimum conservation extent, which is just less than half of the area of the medium conservation extent, it was assumed that the amount of natural vegetation in a good condition surrounding each property would be half that of the natural vegetation surrounding properties under the medium conservation extent.

The properties in the catchment were grouped by census sub-place. For sub-places that did not fall completely within the boundary of the catchment, the number of properties within the study area was estimated based on the percentage area of the sub-place within the catchment. The eThekwini Municipality planning scheme documents were used to estimate the increase in the...
number of properties in the catchment that would occur under the full development scenario. It was assumed that the proposed new development areas in the catchment have on average one dwelling unit per 650 m$^2$ based on an average taken from the central and outer-west scheme planning reports for general and special residential units. The total area of new development in the catchment was then divided by 650 m$^2$ to get the estimated number of new properties in the catchment to include in the analysis. This equated to 26 000 new properties, roughly 36% of the current total in the catchment. This percentage increase was then used to estimate the average property premium associated with natural open space in a good condition for each sub-place.

The effect of natural open space in a good condition on property values was obtained from the estimated model coefficients, which provide the percentage change in property value given a unit change in the value of natural open space in a good condition, given all other things being equal. The aggregate effect of open space in the catchment for minimum, medium and maximum conservation extent was then estimated by applying the regression results to the entire stock of residential houses within each sub-place as explained above. The sub-place premiums were summed to get a total premium for the catchment for each conservation area extent.

It should be noted that the latter value estimate is only a partial estimate of the amenity value to locals, in that it only included the value reflected in premiums paid for properties. It does not include values to locals who do not live in proximity to open space areas but who make use of them.

Based on the hedonic analysis that formed part of the accompanying study of the value of eThekwini’s ecosystem services (Turpie et al. 2017), the total premium associated with natural vegetation in a good condition under the maximum conservation extent was estimated to be R3 billion. It was estimated to be R1.8 billion for the medium conservation extent, and R887 million for the minimum extent. The extent of conservation areas and the total premium associated with these areas for each scenario are shown in Table 5.5.

5.4.2 Nature-based tourism value

The tourism model used geo-tagged Google Earth Panoramo photographs to determine the overall leisure tourism value in the EMA and formed part of the accompanying study of the value of eThekwini’s ecosystem services (Turpie et al. 2017). This approach was used to determine the changes in tourism value under different scenarios in catchment U60F. Using GIS the average R/ha values for natural open space areas in the U60F catchment were multiplied by the area of natural open space within each polygon to get a total nature-based tourism value for the current D’MOSS in the catchment, representative of the medium conservation extent in this study. The percentage change in conservation extent from medium to maximum and medium to minimum was then used to infer changes in tourism value. It was assumed that the change in tourism value was consistent across the conservation areas, irrespective of location in the catchment. In the absence of a dedicated choice-experiment study, this approach provides a ball-park estimate of the potential differences in the nature-based tourism value associated with natural systems under different scenarios.

The nature-based annual tourism value associated with natural open space areas in the U60F catchment was estimated to be R439 million for the medium extent conservation area (Table 5.5). This value was based on the number of photographic uploads associated with natural areas and the amount of natural open space in the catchment. This annual value increased to R512 million under the maximum conservation area and decreased to R205 million under the minimum extent. This translates into a net present value of R2.35 billion, R3 billion and R1.75 billion for the medium extent conservation area, irrespective of location in the catchment. The nature-based annual tourism value for the current D’MOSS in the catchment was then divided by 650 m$^2$ to get the annual value of R457 per ha.

5.5 Avoided climate change costs

The carbon storage analysis that formed part of the accompanying study of the value of eThekwini’s ecosystem services (Turpie et al. 2017) was used to determine the damages avoided of carbon storage under different scenarios. The damage costs to South Africa resulting from a loss of the carbon stocks within the EMA was estimated to be approximately R34.3 million per annum. This equates to a rough estimate of R457 per ha of D’MOSS within the EMA. Using the amount of D’MOSS area found within each conservation area (minimum, medium and maximum) the total carbon storage value for each conservation extent could be estimated.

Based on the extent of D’MOSS under each of the conservation extents, it was estimated that the damage costs resulting from a loss of the carbon stocks within the Umhlatuzane-Umbilo catchment would be approximately R3.2 million, R2.7 million and R1.3 million per annum for the maximum, medium and minimum extents of conservation areas. This translates to a net present value of R37 million, R31 million and R15 million, respectively.

**Table 5.5** The property premium associated with natural vegetation in a good condition and the nature-based tourism value for minimum, medium and maximum conservation extents in the catchment for each scenario.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Extent of conservation areas (min, med, max)</th>
<th>Total property premium (R million)</th>
<th>Annual nature-based tourism value (R million)</th>
<th>NPV nature-based tourism value (R million, 20 yrs., 6%)</th>
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<tr>
<td>1. Clean Baseline</td>
<td>*</td>
<td>887</td>
<td>205</td>
<td>2 351</td>
</tr>
<tr>
<td>2. Cons2</td>
<td>**</td>
<td>1 750</td>
<td>439</td>
<td>5 035</td>
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<td>3. Cons3</td>
<td>***</td>
<td>4 051</td>
<td>512</td>
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<td>4. R</td>
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</tr>
<tr>
<td>10. D+W+R+Cons2</td>
<td>**</td>
<td>1 750</td>
<td>439</td>
<td>5 035</td>
</tr>
</tbody>
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VI. COST BENEFIT ANALYSIS

6.1 Framework
A cost-benefit analysis was undertaken to evaluate the potential economic viability of implementing different green urban development measures to address some of the main environmental issues, such as water quality and flooding, in the Umhlatuzana-Umbilo catchment.

Cost-benefit analysis is a conceptual framework and tool used to evaluate the viability and desirability of projects and policies based on costs and benefits accumulating over time (Hanley & Spash 1993, Pearce et al. 2006). It involves the adjustment of future benefits and costs to their present value equivalent through the process of discounting at a rate which reflects the potential rate of return on alternative investments or the pure rate of time preference. For a project to be considered economically viable, the net present value (NPV) must be positive. This places greater weight on values occurring closer to the present, which means that the future benefits of restoration projects will be down-weighted compared with the upfront investment costs, and therefore have to be relatively larger (in current value terms) in order for a project to generate a positive net present value. Projects can also be evaluated by estimating the internal rate of return (IRR), which is the discount rate at which the total net present value of the project falls to zero.

The implicit assumption of the above is that the costs and benefits of a project can be determined with certainty. In reality however, accurately estimating all variables in a cost-benefit analysis becomes a challenge as a result of the way in which estimates are assessed and forecast (EAI 2006). Studies are limited by availability of data and resources, as well as uncertainty in the consideration of changes in factors such as land use, climate, household incomes and urbanisation (EAI 2006). It is therefore important to incorporate some form of sensitivity analysis so as to adequately assess the robustness of the estimates.

We applied a time frame of 20 years and discount rate of 6%, and sensitivity analysis using alternative discount rates of 3% and 9%.

6.2 Scenario costs
Determining the overall implementation costs of stormwater management interventions is difficult as there are a number of factors that affect costing. These factors are discussed in more detail in Box 6.1.

Construction costs of the different green engineering and conservation measures were obtained from the literature. The unit costs for the source control measures were adjusted based on the information provided in Box 6.1 taking into account the evidence for significantly reduced unit costs as a result of economies of scale. The source controls implemented in the catchment cover vast areas; significantly more than the 500 properties and 15 ha described as large scale in other studies (see Box 6.1). It was therefore assumed that the unit costs for green roofs and soakaways, the two interventions implemented at the largest scale in the catchment, would be reduced by up to 80% and the unit costs for permeable paving and infiltration trenches would be reduced by 50%.
6.3 Cost-benefit analysis

Costs and benefits of GUD scenarios were examined relative to the baseline scenario of full development with adequate sanitation (Scenario 3), under the assumption that adequate sanitation is both imperative and a prerequisite to GUD. Both the total costs and total benefits varied considerably across the different scenarios (Table 6.2, Figure 6.1). Scenarios 4 – 8 and Scenario 10 have positive net present values, with the benefits significantly outweighing the costs. Net present values increased with increasing conservation area from riparian buffers alone (Scenario 6) to riparian buffers in conjunction with the full extent of source control required to meet biodiversity targets (Scenario 8), with the latter having a net present value of R5.9 billion. This was because maintaining natural areas had relatively low costs and high benefits. However, the municipally an average of R50 000 per ha of land can be used (Richard Boon, pers. comm.). For this analysis the amount of land under conservation for the medium and maximum extents were costs, with the difference between these and the Baseline representing the opportunity cost of conservation.

A summary of the GUD construction costs, maintenance costs, conservation management costs, and the opportunity costs of conservation associated with each scenario are shown in Table 6.1. The source controls cover an extensive area and the scenarios that include these interventions therefore have the highest overall costs, in particular, those scenarios that include the full extent of source control implementation (i.e. Scenario 9, 12, 14 and 15). It is the implementation of soakaways in all residential areas that exaggerates these costs compared to other scenarios. For example, the difference in GUD construction costs between Scenario 11 and Scenario 12 is R8 billion, the result of soakaways being included in Scenario 12 but not in Scenario 11.

The most important factors are scale and whether the interventions are implemented as part of a new build or are retrofitted. Larger sites offer the opportunity for economies of scale to be realised (Shaffer et al. 2009, Committee on Climate Change 2012). Economies of scale refers to the reduction of per-unit costs through an increase in production volume. The materials and construction costs associated with SUDS such as green roofs and permeable paving decrease considerably over time as a result of increased take up, economies of scale, and greater competition between suppliers and installers (Shaffer et al. 2009). A review of available case studies on the costs of SUDS schemes in the U.K. was undertaken by DEFRA (2009), Committee on Climate Change (2012) and McKibbin (2015). These studies confirmed that the unit costs associated with SUDS decrease with development size as well as with higher density developments. In fact, SUDS capital costs decreased by up to 80% per property as well as per ha when the scale of the project increased from less than 100 properties to more than 500 properties, and from less than 1 ha to more than 15 ha. Shaffer et al. (2009) reported that the prices of permeable construction materials had fallen considerably over time as a result of improved technologies and increased demand for SUDS. A cost-benefit analysis of green roofs in urban areas in Helsinki by Nurmi et al. (2013) found that private benefits associated with small scale (property-level) implementation are in most cases not high enough to justify the investment in green roofs. However, they found that with a higher rate of implementation (at the city wide scale, 50% of all buildings with flat roofs) the unit costs decreased by up to 50% and significant public benefits emerged, such as air quality improvements and amenity values. The same study highlighted the importance of implementing incentive or regulation based supportive policies as well as investment in research and development to allow for lower cost green roof installation to encourage large scale implementation.

In addition to economies of scale, the cost of installing SUDS solutions into an existing development (i.e. retrofitting) involves higher costs compared to one designed as part of a new development. A number of DEFRA reports have found that project savings could have been far greater if the SUDS layout had been considered earlier, or upfront, in the development process. It is assumed that for this study the source control interventions were designed and implemented in the catchment as part of new build developments, i.e. it was assumed that when the buildings and parking areas were developed the source controls were part of the design process and were and not retrofitted, thereby reducing unit costs.

It should be noted that estimating the costs for such a large scale project is difficult and as a result the costs provided for the stormwater management interventions are not formal estimates, but are preliminary in order to obtain a ball-park estimate.

The cost of managing riparian buffers and conservation areas was based on conservation management costs taken from James et al. (1999) and Frazee et al. (2003). The average cost of managing the conservation areas was estimated to be R755/ha (2015 Rands). Based on a total extent of 1900 ha the total annual management costs associated with riparian buffers was R1.4 million. The annual cost of managing the conservation areas was estimated to be R2.1 million for the minimum extent, R4.5 million for the medium extent and R5.3 million for the maximum extent.

The opportunity costs of conservation, in the form of the amount of land acquisition costs, were also included in the analysis. Opportunity costs of conservation are the costs associated with foregone opportunities to convert the land into other profitable uses. In the area of the eThekwini Municipality, land acquisition is regarded as an important method for securing environmentally important areas and has been used successfully in protecting biodiversity in the EMA (Boon et al. 2016). Over the last decade, approximately 610 ha of priority biodiversity land has been acquired (Boon et al. 2016). The cost of acquiring land varies and is costed based on the amount of developable land (outside of flood zones, not on steep slopes) within the land zoning parcel. However, based on the past experiences of the
The results suggest that the compact development options that allow for a higher proportion of green open space are far more effective than using engineering measures alone. This is because the open space areas not only deliver ecosystem services relating to the primary stormwater management objectives but also directly provide amenity value that is translated into property values and tourism values. It is acknowledged, nevertheless, that the latter benefits were more difficult to estimate than other benefits such as the engineering cost savings, and therefore have some degree of uncertainty. The most uncertain estimates were those of tourism value, for which we have used average values in the absence of reliable estimates of marginal changes in value associated with changes in the green-ness of Durban. Nevertheless, our estimates could be considered as conservative. Firstly, the tourism/recreational benefits associated with conservation areas are likely to underestimate future values of these benefits, which are expected to increase as the city develops further, becomes larger and incomes rise. Secondly, the cost-benefit analysis does not take into account a range of other potential benefits of the GUD interventions. These include improvements in air quality, as well as intangible benefits such as the existence value of biodiversity.

To provide some perspective, the initial capital requirement associated with each scenario (Figure 6.1, Table 6.3) was compared to the eThekwini Municipality capital budget of R6.73 billion for 2016/17 (eThekwini Municipality 2015). Scenarios 4 – 8 and scenario 10 have a funding requirement that is less than 1% of the municipal capital budget. Scenarios 11 and 12 would require 13.8% and 11.4% of the capital budget respectively and scenario 15 would require 96.1% of the budget. The requirements for scenarios 9, 13, and 14 are all higher than the proposed capital budget for the municipality, however, it is expected that capital requirements for large-scale implementation would occur over several years (or decades) as an area develops.

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Table 6.3  Total present value of costs and benefits and NPV (R millions) for all scenarios (2015 Rand, 6% discount rate, 20 years), initial capital requirement and the capital requirement as a percentage of the annual capital budget for each scenario.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Total present value of costs (R millions)</th>
<th>Total present value of benefits (R millions)</th>
<th>NPV (R millions)</th>
<th>Initial capital requirement (R millions)</th>
<th>% of EM capital budget 2016/17</th>
</tr>
</thead>
<tbody>
<tr>
<td>4. Cons2</td>
<td>323</td>
<td>3 718</td>
<td>3 394</td>
<td>2</td>
<td>0.0%</td>
</tr>
<tr>
<td>5. Cons3</td>
<td>246</td>
<td>5 832</td>
<td>5 586</td>
<td>3</td>
<td>0.0%</td>
</tr>
<tr>
<td>6. R</td>
<td>16</td>
<td>67</td>
<td>50</td>
<td>1</td>
<td>0.0%</td>
</tr>
<tr>
<td>7. R + Cons2</td>
<td>204</td>
<td>3 754</td>
<td>3 550</td>
<td>4</td>
<td>0.1%</td>
</tr>
<tr>
<td>8. R + Cons3</td>
<td>262</td>
<td>5 992</td>
<td>5 730</td>
<td>5</td>
<td>0.1%</td>
</tr>
<tr>
<td>9. S2</td>
<td>12 344</td>
<td>293</td>
<td>-12 052</td>
<td>8 960</td>
<td>133.1%</td>
</tr>
<tr>
<td>10. D</td>
<td>27</td>
<td>207</td>
<td>179</td>
<td>22</td>
<td>0.3%</td>
</tr>
<tr>
<td>11. S+D</td>
<td>1 546</td>
<td>231</td>
<td>-1 315</td>
<td>928</td>
<td>13.8%</td>
</tr>
<tr>
<td>12. S2+D</td>
<td>12 372</td>
<td>355</td>
<td>-12 016</td>
<td>8 982</td>
<td>133.5%</td>
</tr>
<tr>
<td>13. S+D+R</td>
<td>1 284</td>
<td>277</td>
<td>-1 008</td>
<td>765</td>
<td>11.4%</td>
</tr>
<tr>
<td>14. S2+D+W+R+Cons2</td>
<td>9 888</td>
<td>3 955</td>
<td>-5 933</td>
<td>7 035</td>
<td>104.5%</td>
</tr>
<tr>
<td>15. S2+D+W+R+Cons3</td>
<td>9 181</td>
<td>6 148</td>
<td>-3 033</td>
<td>6 464</td>
<td>96.0%</td>
</tr>
</tbody>
</table>

6.4 Sensitivity analysis

The results were further tested under varying discount rates and assumptions of costs and benefits for one GUD intervention. Costs and benefits were varied for soakaway implementation as this intervention had the largest influence on NPV. Alternative discount rates of 3% and 9% were applied to the NPV calculations. The alternative discount rates did not have a significant impact on NPV calculations, with the NPV remaining negative at discount rates of 3% and 9% for Scenarios 9 and 11-15 and positive for Scenarios 4-8 and Scenario 10. Again, this highlights the significant influence of soakaway implementation costs on the overall NPV for these scenarios.

Comparing Scenarios 11 and 12 provides an indication into the costs and benefits associated with soakaways, as the only difference between the two is the implementation of soakaways in residential areas. The difference in benefits between these two scenarios is R124 million, with R116 million of this being stormwater infrastructure cost savings. Soakaways represent 80% of the cost for Scenario 15 and 89% of the cost for Scenario 14 but contribute approximately R124 million in benefits. This suggests that if soakaways were not implemented but all other source controls were still included then the NPV for Scenario 15 would be approximately R4.6 billion and for Scenario 14 would be R2.4 billion (Table 6.4). Or if the unit cost of soakaways was reduced by 8% as a result of economies of scale, competition and improved technologies then the NPV for Scenario 15 would be positive at R7 million. However, the NPV associated with other source control scenarios would remain negative (Table 6.4).

The table results suggest that the implementation of source controls is only feasible if incorporated in conjunction with conservation areas, riparian buffers and regional controls (detention basins and treatment wetlands) to maximise benefits associated with these measures. Detention basins alone have a positive NPV, as do riparian buffers. This result is encouraging. The sensitivity analysis has shown that a more conservative approach to source control implementation is needed, especially with regards to soakaways in residential areas.

The main findings from the CBA suggest that source control measures are costly, particularly the implementation of soakaways in residential areas. Detention basins and treatment wetlands are the most affordable engineering measures, with positive net benefits. Retaining natural areas in the catchment has the highest net benefits, due to the significant co-benefits associated with amenity values.

Table 6.4  The impact of soakaways on NPV for Scenarios 9, 12, 14 and 15 (R millions, 6%, 20 yrs.)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>NPV Base Case</td>
<td>-12 052</td>
<td>-12 016</td>
<td>-5 933</td>
<td>-3 033</td>
</tr>
<tr>
<td>NPV Soakaway unit costs reduced by a further 8%</td>
<td>-7 721</td>
<td>-7 686</td>
<td>-2 594</td>
<td>7</td>
</tr>
<tr>
<td>NPV Soakaways not included</td>
<td>-1 226</td>
<td>-1 190</td>
<td>2 415</td>
<td>4 568</td>
</tr>
</tbody>
</table>
VII. CONCLUSIONS AND POLICY RECOMMENDATIONS

Under a business as usual scenario, the continued growth of urban areas in Africa will result in a further deterioration of the natural environment and living conditions, a loss of values associated with green open space areas, and increased costs in reducing risks to people that result from environmental problems. The notion of Green Urban Development is therefore highly attractive, as it allows cities to grow in a way that maintains their resilience and maintains standards of living and quality of life. However, few studies have investigated what following a more sustainable green urban development path will actually cost, and whether these costs can be justified. Moreover, what Green Urban Development should look like is also not well defined, in terms of the degree to which it includes the conservation of river buffers and other natural areas, the mimicking of natural processes through innovative engineering design or the protection of downstream areas through conventional engineering measures. In eThekwini Municipality, these issues have to be considered as plans for the growth of Durban are laid out. In this study, we tested the idea of green urban development by backcasting a range of scenarios for a well-developed catchment.

This study attempted to analyse a highly complex problem in a fairly large catchment area, and as such, a great deal more work will still be needed in order to narrow the potential error margin. Our study found a lack of empirical studies to inform modelling assumptions, which suggests that much benefit could be obtained from the implementation and monitoring of pilot programmes. Furthermore, there are few well-developed modelling platforms that are capable of estimating the impacts of these kinds of interventions at scale. Most previous studies have analysed these problems at a micro-catchment scale, making it difficult to assess the economic implications of a change in policy. Thus, while these are first-cut estimates which warrant further refinement, they provide a useful step towards the informing policies to guide the city’s sustainable development path.

The results showed that in a catchment with little unserviced informal settlement (1% of the area) recycling the equivalent of a third of sewage outputs along with complete sanitation services has the most significant impact on nutrient loads entering the rivers and harbour, and that treatment wetlands make a significant further impact. Sediment loads can be effectively dealt with using either natural interventions (particularly river buffers) or green engineering interventions (source controls and detention basins), and these appear to be substitutable to a large degree when the former is brought about through more compact development. Similarly, both natural and green engineering interventions were highly effective at reducing flood peaks, and were also substitutable to a large degree in terms of this function. This suggests that some sensible combination could be applied, with green engineering interventions being strategically located within the catchment for maximum overall effect.

However, not all green engineering interventions are equally viable. Our estimates suggested that the large-scale application of low-impact stormwater management measures (i.e. source controls) is extremely costly at today’s prices, even when accounting for economies of scale. On the other hand, the simpler green engineering measures, such as detention basins for reducing peak flows and treatment wetlands for improving water quality, were shown to be highly cost-effective, viable interventions.

The retention of significant natural areas within the catchment, which may require more compact development, was not only found to be highly effective at reducing sedimentation and flooding problems, but has the added benefit of yielding high amenity value realised as property and tourism value as well as intangible and unknown values associated with maintaining biodiversity and ecological connectivity. Although riparian buffers have limited influence on water quality and flooding in urban environments, the value in maintaining biodiversity is also very high, as they are critical for providing connectivity between terrestrial systems, rivers and estuaries.

Because conservation with compact development incurs very low costs in comparison to other interventions, the net benefits of this strategy far outweighed any other. Compact development coupled with the other interventions creates the greenest city, in terms of water quality and biodiversity conservation goals, and is an economically justifiable strategy in terms of overall costs and benefits. Maintaining large natural areas and riparian buffers should therefore be a primary strategy, along with the strategic positioning of cost-effective green engineering measures.
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APPENDIX 1: URBAN STORMWATER MANAGEMENT OPTIONS

A1.1 Overview
Within urban areas, rain that falls onto impermeable surfaces such as streets, parking lots, pavements and roofs is unable to infiltrate into the ground as it would normally do in undeveloped areas, leading to higher levels of surface runoff during storm events than would have happened naturally and creating flooding problems in downstream areas (Armitage et al. 2013). This problem is exacerbated by the fact that urban stormwater runoff generally contains litter, debris, and sediments which lead to blockages of the systems designed to convey water, and they also contain bacteria, heavy metals and nutrients, which means that floodwaters can become a pollution hazard. All of this can have negative impacts on property, urban infrastructure and natural habitats, as well as urban inhabitants. With an increase in urbanisation worldwide and the associated impact of increasing stormwater runoff on aquatic ecosystems, the management of urban drainage has become a critically important challenge (Fletcher et al. 2015).

Urban drainage management has changed significantly over the last few decades, from a conventional ‘rapid disposal’ approach to a more integrated and sustainable ‘design with nature’ approach (Fletcher et al. 2015). The early traditional attitudes towards urban drainage management focused on trying to dispose of stormwater in the fastest way possible with not much consideration for surrounding ecosystems or for downstream water quality impacts. In the 1980s and 1990s a new focus on urban stormwater runoff and water quality developed around the world, which concentrated on a more catchment-wide management and restoration approach to urban drainage as opposed to the standard end-of-catchment solution (Fletcher et al. 2015). This embodied a more holistic approach which treats stormwater runoff problems at source and minimises environmental degradation, while delivering environmental, economic and social benefits. This rapid development in the field of urban drainage saw a number of terms being used to define similar concepts (Fletcher et al. 2015). Terms such as “Water Sensitive Urban Design” (WSUD), “Low Impact Development” (LID), “Sustainable Urban Drainage Systems” (SUDS), “Integrated Urban Water Management” (IUWM) and “Best Management Practices” (BMPs) were first used by professionals in countries such as Australia, New Zealand, United States, England and Scotland to describe this new approach to urban drainage and are all essentially synonymous. “Green infrastructure” is another term commonly used in this context, and tends to refer to any environmentally-friendly stormwater management structures, natural and semi-natural systems used in stormwater management. Storm water management measures now tend to be designed to address both flooding and water quality problems, with many measures addressing both of these. Both WSUD and SUDS approaches are increasingly being applied in development planning in South Africa, and their inclusion is mandatory for new developments in the City of Cape Town and in Durban. The results from this study provide the opportunity to understand more about the impact that GUD interventions can have on future development in Durban, adding to the already relevant and important policies that are in place.

A1.2 Passive engineering measures to improve conveyance
These measures are designed to protect areas from flooding by avoiding or mitigating the water flow off stream over the riverbanks, or accommodating the flood adjusting the riverbed carrying out channel improvement. Therefore, these kinds of measures try to constrain the inundation without modification of the hydrograph. Examples are levees, cleaning from debris or increasing of section of the riverbed, and hydraulic bypass, also known as waterways. They involve physical construction to reduce or avoid possible impacts of hazards, or application of engineering techniques to achieve hazard-resistance and resilience in structures or systems. These kind of measures alter the streamflow of rivers and channels, resulting in the reduction of the frequency and severity of floods. For example, reservoirs reduce peak flows; levees and flood walls confine flows within predetermined channels; improvements to channels reduce the peak stages; and flood ways help divert excess flow.

A1.2.1 Drains and swales
These convey flows from built-up areas via small channels, and can generally deal with small floods of 1-2 year return period.

A1.2.2 Enlargement of river channel/canalisation/levees/dredging
Excavation of a river channel involves either deepening or widening the channel to increase flood control capacity. A river can be made to carry larger discharges by improving the hydraulic condition of the channel through measures such as dredging. Similarly, levees (embankments) can be built to increase the conveyance capacity of the channel.
Levees are generally built as an embankment (i.e., earthwork). In the urban context, if there is not enough land area to build such earth structures, then they are constructed with reinforced concrete or masonry walls. The levees location is designed according to the inundation analyses; their scope is to prevent the inundation of floodplain. Their height is designed to prevent the inundation associated to a specific return period. Once the height is defined, their design will follow geotechnical rules if they are made with earth, or structural rules if they are concrete walls. To analyse the efficiency of such structures, they are modelled in the hydraulic routine as a modification of the digital elevation model.

A1.2.3 Hydraulic bypass

A hydraulic bypass is a new channel built to laminate the peak discharge crossing the floodable area in the urban context. The new channel takes part of the discharge and brings it to the final destination through an alternative path. Construction of a hydraulic bypass is very expensive and requires the identification of the alternative path for the new channel.

A1.3 Active engineering measures to retard runoff

The active structural measures are to modify the hydrograph by reducing and delaying the maximum peak discharge. Examples include floodplain storage (in-line or off-line) that stores the flood volume temporarily in an adequate upstream capacity, leading to flood attenuation as a result of the discharge being gradually released (Topa et al. 2014). When the discharge falls below the maximum allowable flow, the flood volume is released back to the river (De Martino et al. 2012). Off-stream floodplain storages are often used since they do not interfere with the natural drainage pattern between the stream and the floodplain, and only an outlet structure is needed to regulate the outflow discharge.

A1.3.1 Permeable pavements

Permeable pavements refer to pavements that are constructed in such a way that they promote the infiltration of stormwater runoff through the surface into the sub-layers or underlying substrata (Armitage et al. 2013). Permeable paving provides a surface that is suitable for pedestrian and/or vehicular traffic while allowing rainwater to infiltrate through the surface. There are a number of different alternatives for the surface material, including brick pavers, porous concrete, porous asphalt, stone chip, and permeable concrete block pavers (Armitage et al. 2013). Permeable paving is usually constructed on top of a coarse gravel base which creates the temporary storage facilities and allows stormwater runoff to infiltrate into the substratum, ultimately promoting the recharge of the groundwater table. The stored rainwater can also be reused for a number of purposes such as watering gardens and lawns (Armitage et al. 2013).

Permeable pavements generally do not remove litter and other debris from stormwater runoff as it tends to remain on the surface as the water infiltrates. Soluble pollutants, however, do pass through the permeable layer and surfaces that have an aggregate sub-base can provide good water treatment. Permeable paving can be used in a variety of locations, such as parking lots, private and public roads, industrial storage and loading areas, bike lanes, walkways and terraces (Armitage et al. 2013). The use of this paving is however restricted to slopes that are less than 5%, or ideally flat, as the high velocity stormwater from steep slopes does not have sufficient time to infiltrate before being washed away.

To ensure the long term effectiveness of permeable pavements, regular inspections and maintenance are recommended. Blockage of the fine stone aggregate can sometimes be an issue and requires cleaning or replacing if this does occur. This fine aggregate in the joints and slots is known to trap the most pollutants, including heavy metals. While clogging may be a maintenance concern, the often enormous infiltration capacity of permeable pavement systems means that considerable clogging can be tolerated (Armitage et al. 2013). Permeable pavements are relatively expensive to construct and can have high maintenance costs. However, they are incredibly efficient at reducing peak flows and reducing runoff volume as well as reducing pollutants. They remove approximately 60-95% of TSS, 70-90% of hydrocarbons, 50-80% of total phosphorous, 65-80% of total nitrogen and 60-95% of heavy metals (Armitage et al. 2013). Permeable pavements do not provide any amenity, social or ecological benefits.

Permeable pavements are relatively expensive to invest in and there are some constraints.

Advantages

- Significantly reduce stormwater discharge rates and volumes from impervious areas
- Reduce peak flows to watercourses reducing the risk of flooding downstream and reduce the effects of pollution in runoff on the environment
- Flexible and tailored solution that can suit the proposed usage and design life
- Allows for dual use of space, so there is no additional land take. They increase the ’usable’ area by utilizing roadways, driveways and parking lots as stormwater drainage areas
- Good community acceptability
- Stormwater runoff that is stored can be used to recharge the groundwater table and also be used for several domestic purposes
- Used permeable pavement systems can be utilised where foundation or soil conditions limit infiltration processes

Limitations

- Cannot be used where large sediment loads may be washed or carried onto the surface of the paving
- The implementation is generally limited to sites with slopes less than 5%
- Risk of long-term clogging and weed growth if poorly maintained
- Not normally suitable for high traffic volumes and speeds greater than about 50 km/hr, or for usage by heavy vehicles and/or high load purposes
- The pollutant removal ability of permeable pavements is lower than most other SuDS options.

Applications

Permeable pavements can be used in a variety of locations, such as parking lots, private and public roads, industrial storage and loading areas, bike lanes, walkways and terraces (Armitage et al. 2013). They can be used in a variety of locations, such as parking lots, private and public roads, industrial storage and loading areas, bike lanes, walkways and terraces (Armitage et al. 2013). Permeable pavements are relatively expensive to construct and can have high maintenance costs. However, they are incredibly efficient at reducing peak flows and reducing runoff volume as well as reducing pollutants. They remove approximately 60-95% of TSS, 70-90% of hydrocarbons, 50-80% of total phosphorous, 65-80% of total nitrogen and 60-95% of heavy metals (Armitage et al. 2013). Permeable pavements do not provide any amenity, social or ecological benefits.

A1.3.2 Infiltration trenches

Infiltration trenches are excavated trenches which are lined with geotextile and filled with rock, or other granular materials, and are designed to receive stormwater runoff from contiguous properties in urban areas (Armitage et al. 2013). They create temporary subsurface storage of stormwater runoff thereby enhancing the natural capacity of the ground to store and drain water. Infiltration trenches allow water to infiltrate into the surrounding soils from the bottom sides of the trench. They usually have a rectangular vertical cross-section and are designed to receive stormwater runoff from adjacent properties and transportation links such as asphalt roads and footpaths (Armitage et al. 2013). The amount of water that can be disposed of by an infiltration trench within a specified time is dependent on the infiltration potential of the surrounding soil, the size of the trench, and the bulk density of the fill material. Stormwater runoff is treated by physical filtration to remove solids, adsorption onto the material in the trench and biochemical reactions involving micro-organisms in the soil.

Advantages

- Increases stormwater infiltration and corresponding groundwater recharge
- Decrease the frequency and extent of flooding
- Effective in removing suspended particulates from stormwater
- Due to their relatively narrow cross section, they can be utilised in most urban areas
- Negligible visual impact as they are generally below ground

Limitations

- If situated in coarse soil strata, groundwater contamination is a possibility
- Restricted to areas with permeable soils
- Not appropriate on unstable or uneven land, or on steep slopes
- Prone to failure if sediment, debris and/or other pollutants are able to clog the gravel surface and/or
- Backfilled aggregate material

In the first year of construction maintenance is important, especially after the first large rainfall event. The trench needs to be assessed for performance and any sediment and debris build up which can cause clogging (Armitage et al. 2013). Removal and cleaning of stone may be necessary.
The construction costs associated with infiltration trenches are not very high, making them one of the more cost effective options in terms of their ability to reduce runoff volume and treat pollutants. Their maintenance costs can be higher than other interventions, especially in areas that have fine grained soils. Infiltration trenches remove approximately 70-80% of TSS, 60-90% of total phosphorous, 25-60% of total nitrogen, and 60-90% of heavy metals (Armitage et al. 2013). Their amenity and conservation value is poor, however they are generally constructed under the ground and so the aesthetic impact is negligible.

**A1.3.3 Soakaways (sub-surface infiltration trenches)**

Soakaways usually comprise an underground storage area that is packed with coarse aggregate or other porous media that gradually discharges stormwater into the surrounding soil (Armitage et al. 2013). Soakaways are similar to infiltration trenches in their operation and are also known as sub-surface infiltration beds or sub-surface infiltration trenches. They usually handle roof runoff from single buildings, such as large industrial buildings. Multiple soakaways can be linked to each other to drain larger areas such as parking lots or major roadways. The type of aggregate material used determines the infiltration characteristics of the device. Modular geo-cellular structures provide relatively high stormwater treatment and rates of groundwater recharge (Armitage et al. 2013).

The size of the soakaway is dependent on the porosity of the aggregate used to fill the excavated pit. The soakaway empties either by percolation of the stormwater directly to the underlying soil or via perforated sub-drains installed within the pit. Soakaways are usually designed to store the entire volume of a storm event and be able to infiltrate at least half of this volume within 24 hours to create further capacity for the runoff from subsequent rainfall events (Armitage et al. 2013). A single soakaway can serve an area of roughly 1000 m² but groups of soakaways can serve areas as large as 100 000 m² (Armitage et al. 2013). They range in depth from between 1 – 4 metres but are usually approximately 1.5 metres in depth when serving a single building.

The basic construction costs include clearing and removing of topsoil, surface preparation, pit excavation, supplying and laying filter fabric or geotextile, supplying and laying of aggregate fill or porous media, supplying and laying of building sand, supplying and laying of slotted pipes, topsoiling of verged areas, and grassing of surface area.

**Advantages**

- Have reasonable design lives of up to 20 years if maintained properly and relatively easy to construct
- Significantly decrease stormwater runoff volume, peak flow and rate
- Particularly effective in removing particulate and suspended stormwater runoff pollutants
- Reduce downstream erosion and flooding
- Minimal net land take

**Limitations**

- Usually limited to relatively small connected areas
- They do not function well when constructed on steep slopes or in unstable areas
- Sub-drain piping systems must be utilised
- When soakaways are implemented in very fine silt and clay stratum because of the low infiltration rates
- Sedimentation within the collection chambers will cause a gradual reduction in the storage capacity
- Ecological and amenity value is poor

The amount of water disposed of by soakaways depends on the infiltration potential of the surrounding soil, the size of the pit and the bulk density of the fill material. The amount of water retained by a soakaway is based on the roof area of the building and the peak rainfall event (mm) during the flood season. Soakaways are estimated to be retain 70-80% of TSS, 25-60% of total nitrogen, 60-80% of total phosphorous, 60-90% of E.coli and 60-90% of heavy metals. Soakaways are relatively cost-effective in terms of runoff reduction as well as in terms of their ability to remove suspended solids.

Green roofs are particularly effective when constructed on roofs with large surface areas such as commercial or industrial buildings or large residential blocks. Irrigation may be required to keep the roof green during particularly dry periods.

There are three main types of green roofs, namely:

- Extensive green roofs, intensive green roofs and simple intensive green roofs (Armitage et al. 2013). Extensive green roofs generally incorporate low growing and low maintenance vegetation that covers the whole roof surface. The roof is only accessed for maintenance purposes. Usually indigenous vegetation such as mosses, herbs and grasses are used as they are relatively self-sustaining. Intensive green roofs incorporate planters and trees and tend to have a high level of accessibility (Armitage et al. 2013). Rainwater harvesting interventions are often used as the primary irrigation source for intensive green roof flora. These roof systems require more intensive and frequent maintenance. Simple intensive green roofs are a combination of both extensive and intensive green roofs, having both larger plants as well as low lying ground cover. These roofs generally require high levels of maintenance such as cutting, fertilizing and watering – which requires increased accessibility (Armitage et al. 2013).

**Advantages**

- Good removal capability of atmospherically deposited urban pollutants
- Can be designed to closely mimic the pre-development state of buildings
- Ecological, aesthetic and amenity benefits
- Can be constructed on both new and already existing buildings
- Help to insulate and regulate buildings against temperature extremes
- Can be applied to high density urban areas
- May improve air quality
- No additional land take

**Limitations**

- More costly than conventional roof runoff practices due to their added structural, vegetative and professional requirements (professionals are required to ensure implementation of the waterproofing and plant requirements)
- Opportunities for retrofitting may be limited by roof structure (size, strength etc.)
- Not appropriate for steep roofs
- Detention of water within roof storage layer may result in leakage to the surrounding earth or basement (may require drainage to prevent leakage)
- Plant varieties may be quite limited. Using indigenous vegetation is best

Maintenance of green roofs include irrigation during establishment of vegetation, inspection for bare patches, weeds and plants that require replacement. Leaf litter removal may be required for certain systems and any possible stresses related to the roof and building structure need to be checked.

Green roofs are expensive to construct and are one of the least cost-effective options in terms of the cost per unit reduction of runoff volume or pollutant loads. Green roofs remove approximately 60-95% of TSS and 55-60% of heavy metals (Armitage et al. 2013). They provide a number of social and aesthetic benefits such as air quality improvement in urban areas, temperature control, and amenity value.
A1.3.5 Rainwater harvesting

Rainwater harvesting systems collect and store rainwater from hardened surfaces for later use. With minimal treatment the water that is collected could be used to supplement the potable water supply and can be used for a number of activities such as toilet flushing and irrigating crops and gardens (Armitage et al. 2013). Storage of runoff from roofs and other elevated impervious surfaces is provided by rainwater tanks, barrels, cisterns or other storage structures until the water is required (Armitage et al. 2013). The utilisation of stormwater as a water source not only saves potable water but it also significantly reduces the stormwater discharge from roofs. Rainwater harvesting systems are known to be particularly useful during extreme rainfall events as they help to protect receiving streams and rivers by reducing the initial runoff volumes and the associated polluted (Armitage et al. 2013).

There are two types of stormwater collection and reuse systems that are generally applicable to residential, commercial and industrial uses; namely the pumped supply system and the gravity supply system. The water collected in the tank from the rooftop is then gravity fed into specified application points in and around the building. The harvesting system could just involve the collection of rainwater from rooftops via gutters into a storage tank where water can then be collected for use. One large tank could be connected to and supply a number of houses.

There are a number of different types of stormwater collection and storage systems that are commercially available. An effective system will include strategically placed rooftop gutters and pipes, a filter sock to catch leaves/debris, a rainwater storage facility such as a tank or barrel, and a UV disinfection device. Storage facilities that are child proof, insect and vector proof should be given preference during the selection process, especially if the systems are to be placed in residential areas (Armitage et al. 2013). The following water balance equation is often used to calculate the volume of usable rainfall or the annual collectable rainfall:

\[ V = R \times A \times C \times FE \]

Where:
- \( V \) = volume of usable rainwater (l)
- \( R \) = average rainfall over a period (mm)
- \( A \) = Area contributing to runoff (m\(^2\))
- \( C \) = runoff coefficient (0-1)
- \( FE \) = filter efficiency (0-1)

For a standard flat roof the runoff coefficient is 0.4 and the filter efficiency is generally recommended to be 0.9 as a conservative estimate (Armitage et al. 2013).

The initial construction costs associated with the rainwater harvesting system are relatively expensive with the tank constituting the most significant cost of the system.

A1.3.6 Vegetated swales

Swales are shallow vegetated channels with flat and sloped sides that are designed to store and convey runoff as well as remove pollutants. Although swales are usually lined with grass, a variety of different types of vegetation can be used to suit the specific site (Armitage et al. 2013). Swales serve as an alternative option to the more typical roadside kerb or gutter and generally have a larger stormwater storage capacity so they help to reduce runoff volumes and peak stormwater flows (Armitage et al. 2013). Their ability to store and convey significant volumes means that they require relatively large surface areas in order to function effectively.

Swales are commonly used in combination with other systems, such as buffers and bio-retention interventions, to form a treatment train. In doing so runoff is retained and dissolved pollutants in stormwater runoff are also removed. The combination of infiltration and bio-infiltration removes the dissolved pollutants and the larger particles are filtered by the vegetation (Armitage et al. 2013). A swale that has been well designed should provide reduction in impervious cover, pronouncement of the surrounding natural landscape and multiple aesthetic enhancements, and they should be designed to meet flow conveyance requirements and effective stormwater pre-treatment (Armitage et al. 2013).

They are usually suitable for road medians, verges, car parking runoff areas, park and recreational edges.

The effective design life of a swale is directly related to the standard of maintenance, particularly in the first two years during the period of plant establishment which often requires frequent weed control and replanting.

Vegetated swales have low capital costs and are cost-effective in their ability to reduce peak flows and runoff volumes and to reduce pollutants. They have medium to good amenity potential in that they provide a green alternative to grey infrastructure in urban environments. Vegetated swales remove approximately 60-90% of TSS, 70-90% of hydrocarbons, 25-50% of total phosphorous, 30-50% of total nitrogen and 40-90% of heavy metals.
A1.3.7 Filter strips
Filter strips are maintained grassed areas of land that are used to manage shallow overland stormwater runoff through several filtration processes in a very similar manner to buffer strips (Armitage et al. 2013). Filter strips are usually gently sloping and provide opportunities for slow conveyance and infiltration. They therefore help to attenuate floods peaks and retain pollutants. They are commonly designed to accept runoff from upstream development and are usually located between hard-surfaced areas and a receiving stream, surface water collection or treatment system. They may also be used downstream of agricultural land to infiltrate and intercept runoff from these areas.

Filter strips use vegetative filtering as a primary means of stormwater runoff pollutant removal and if properly designed are able to remove most sediment and other settleable solids such as hydrocarbons (Armitage et al. 2013). Soluble nutrients and heavy metals, however, are often not adequately removed. The pollutant removal and water retention characteristics of filter strips is determined by the relationship between the length, width, slope and soil permeability compared to the stormwater runoff rate and velocity (Armitage et al. 2013).

Figure A1.8 Filter strips are maintained grassed areas of land that are used to manage shallow overland stormwater runoff through several filtration processes. They are usually located as strips adjacent to development areas, roads and waterways.

Advantages
- Installation and maintenance costs are relatively low and layout and design is flexible
- Significant removal of suspended solids and hydrocarbons. They trap the pollutants close to source
- Infiltration of stormwater runoff helps to attenuate flood peaks
- Integrate well within the natural landscape and can provide open space areas for recreation as well as amenity value

Limitations
- Clogging of subsurface drainage media can occur if maintenance is poor
- Limited potential for the removal of fine sediments and dissolved pollutants
- Stormwater runoff needs to be spread out in order for the strips to operate optimally
- Minimal stormwater storage capacity and not good at treating high flow velocities. They are not suitable for steep slopes.

Filter strips are designed specifically to control for nutrients and pollution more so than water quantity and are therefore more efficient at trapping and reducing TSS and pollutants than they are at reducing stormwater runoff. Grass filter strips remove approximately 50-85% of TSS, 70-90% of hydrocarbons, 10-20% of total phosphorous, 10-20% of total nitrogen and 25-40% of heavy metals.

A1.3.8 Sand filters
There are many different forms of sand filters. They usually comprise of a sedimentation chamber that is linked to an underground filtration chamber comprising sand or other media through which stormwater runoff can pass (Armitage et al. 2013). The sedimentation chamber facilitates the removal of suspended particulates and heavy metals, whilst the filtration chamber removes smaller particulate pollutants. The removal mechanism is partly through filtration by the sand bed and partly through microbial action within the media (Armitage et al. 2013). Sand filters tend to be installed for use in impervious areas that are less than 800mm but may be designed to manage runoff from larger areas too.

Sand filters are similar to bio-retention areas and other bio-retention systems, with the only difference being that stormwater runoff passes through a linear filter medium without vegetation (Armitage et al. 2013). The primary objective for sand filters is water quality improvement and they are particularly effective in the removal of hydrocarbons. They are also used extensively to remove sediment and other particulate pollutants from the first flush (Armitage et al. 2013).

Sand filters can be expensive to construct and often require regular maintenance, making them a less cost-effective option. They are highly efficient at removing suspended solids and pollutants. They remove approximately 80-90% of TSS, 50-80% of hydrocarbons, 50-80% of total phosphorous, 25-40% of total nitrogen, 40-50% of E. coli and 50-80% of heavy metals from stormwater runoff (Armitage et al. 2013).

Advantages
- Particularly effective in removing suspended solids (TSS)
- Efficient stormwater management technologies in areas with limited space as they can be implemented
- Beneath impervious surfaces
- They manage stormwater runoff effectively on relatively flat terrains with high ground water tables where bio-retention systems are inappropriate
- The filtered effluent can be reused for most non-potable domestic water uses including: toilet flushing, dish washing and garden watering; and
- May be retrofitted with relative ease into existing impervious developments, constrained urban locations or in series with conventional stormwater management systems

Limitations
- Generally ineffective in controlling stormwater peak discharges
- Premature clogging is likely to occur in sand filters if they receive excessive sediment carrying runoff, especially from construction sites and areas with open soil patches
- Large sand filters are not generally attractive, especially if they are not covered with grass or other vegetation
- Sand filters are expensive to implement and maintain relative to most other options technologies
- If designed and/or implemented incorrectly, they may fail, resulting in standing pools of water which have the potential to attract nuisances such as mosquitos and midges.

A1.3.9 Bio-retention areas
Bio-retention areas, sometimes referred to as ‘rain gardens’ are landscaped depressions which are typically under drained and rely on engineered soils, enhanced vegetation and filtration to reduce pollutant and reduce runoff downstream (Armitage et al. 2013). They are usually employed to manage the runoff from the first 25mm of rainfall by passing runoff through a number of natural processes such as filtration, absorption, biological uptake, sedimentation, infiltration and detention. These areas tend to include a number of different smaller stormwater interventions such as filter strips, temporary pond areas, sand beds, mulch layers and a wide variety of vegetation (Armitage et al. 2013). They are particularly effective at managing stormwater runoff from minor and more frequent rainfall events.

Bio-retention areas can manage stormwater runoff on a number of sites, such as between residential plots, alongside parking lots, adjoining roadways and within large landscaped impervious areas. The engineered soil media and the different varieties of vegetation are managed to capture and treat a specified water quality volume of stormwater runoff and in doing so they reduce runoff quantities and rates whilst improving the quality of stormwater entering watercourses further downstream (Armitage et al. 2013).

Advantages
- Reduces runoff volumes and rates, and attenuates flood peaks effectively
- Flexible application means these areas are easily incorporated into a wide variety of landscapes
- Very effective at the removal of most stormwater runoff pollutants
- Well suited for installation in high impervious areas, provided the system is well-engineered and adequate space is made available
- Good retrofit capability
- Aesthetically pleasing

Limitations
- Not suited to areas where the water table is shallower than 1.8m
- Requires frequent landscaping and maintenance to remain aesthetically pleasing
- Susceptible to clogging if surrounding landscape is not managed
- Not suitable for areas with steep slopes
- Construction costs can be high
Routine inspections and maintenance are required to ensure that bio-retention areas function effectively. The design life of these areas, as with most interventions, is directly related to the quality and frequency in maintenance (Armitage et al. 2013). Maintenance includes regular inspections, litter and debris removal, replacement of mulch areas, vegetation management and sediment removal.

Bio-retention areas can have high initial construction costs, making them less cost-effective in terms of cost per unit reduction of runoff volumes and pollutant loads. They remove approximately 50-80% of TSS, 5-80% of hydrocarbons, 50-60% of total phosphorous, 40-50% total nitrogen and 50-90% of heavy metals (Armitage et al. 2013). Their amenity potential is good.

A1.3.10 Detention basins

Detention basins or detention ponds are temporary storage facilities that are usually dry but are designed so that they are able to store stormwater runoff for short periods after high rainfall events (Armitage et al. 2013). The captured stormwater either infiltrates into the underlying soil layers or is drained into the downstream watercourse at a predetermined rate. Therefore they are effective at regulating the flow in downstream watercourses. Generally detention basins are designed to temporarily store as much water as possible for 24 – 72 hours whilst aiming to provide a safe and secure public environment (Armitage et al. 2013).

Detention basins are typically lined with grass and are designed to be multifunctional in that they provide access to recreational area when dry. They are surface storage basins that provide flow control through the attenuation of stormwater runoff and also facilitate some settling of particular pollutants. Detention basins tend to be located towards the end of the stormwater management train so are used if the extended treatment of runoff is required. The pollutant removal capability of a detention basin can be improved through the construction of a sediment trap at the entrance to the basin (Armitage et al. 2013). The hydraulic and pollution removal performance of detention basins depends on good maintenance. Regular inspections are needed to check if the clearing of accumulated sediment is necessary, especially if the basin is being used as a field or common (Armitage et al. 2013). Other maintenance includes the management of vegetation, inspections after high rainfall events, and possible de-silting.

Advantages

- Able to temporarily store large volumes of stormwater thus attenuating downstream flood peaks
- Relatively inexpensive to construct and easy to maintain
- Serve multiple purposes during drier seasons, particularly as sports fields, play parks or common
- If managed regularly, they can add aesthetic value to adjoining residential properties as well as presenting fewer safety hazards than wet ponds due to the absence of a permanent pool of water

Limitations

- Not very good at removing dissolved pollutants and fine material
- Generally not as effective in removing pathogens as constructed wetlands
- Siltation can be a problem and the floors of detention ponds can become swampy for some time after major rainfall
- Not very suitable in areas with a relatively high water table, or where the soil is very coarse and there is a risk of groundwater contamination

Detention basins are relatively inexpensive to construct and have low maintenance costs, making them cost-effective options for control runoff. Detention basins remove approximately 45-90% of suspended solids, 30-60% of hydrocarbons, 20-70% total phosphorous, 20-60% total nitrogen, 50-70% E.coli and 40-90% of heavy metals (Armitage et al. 2013).

The strategic positioning of such storage areas in urban areas can enrich the urban environment and facilitate maintenance operations. In fact, such areas, given their dimensions, can be easily used as social and recreation areas, such as play grounds or football fields, or for agriculture. There is a good example of this in San Paolo, Brazil, where floodplain storage has been applied to mitigate the flood risk from the Tamanduatei River, as shown in Figure A1.10b (Giugni et al. 2012).

A1.3.11 Constructed treatment wetlands

Wetlands are generally marshy areas of shallow water that are either partially or completely covered in aquatic vegetation. Wetlands provide habitat for a wide variety of fauna and flora and provide aesthetic appeal, especially in urban areas where green open space is limited. Constructed wetlands are man-made systems that are designed to mimic the natural wetland systems in areas where they were not previously found (Armitage et al. 2013).

They are able to serve larger catchment areas and are very useful at removing nutrients and suspended solids from stormwater runoff from residential areas. The most common stormwater pollutant treatment processes that wetlands provide are sedimentation, fine particulate filtration and biological nutrient and pathogen removal (Armitage et al. 2013). The percentage removal of pathogens and nutrients depends largely on the pollution concentration of the inflow, the rate at which the water is flowing through the wetland, the pollution saturation level of the wetland and the degree to which the nutrients and pathogens adhere to other particles and sediments (Armitage et al. 2013).

Constructed wetlands usually include four distinct zones (Armitage et al. 2013):

- The inlet zone which includes a sediment forebay for the removal of the more coarse sediments and litter entering the system;
- The macrophyte zone which is usually shallow and heavily vegetated and facilitates the removal of finer particles and the uptake of soluble nutrients such as nitrogen and phosphorous;
- The macrophyte outlet zone which channels cleaner stormwater runoff downstream; and
- The high flow bypass channel which protects the inlet, outlet and vegetative zones from damage and scour during abnormally high flow events.

Other considerations include litter traps or trash racks at the inlet to the wetland which prevents litter, debris, coarse sediment and other pollutants from entering the macrophyte zone and from being carried further downstream. The selection of the vegetation to be used in the wetland is important and a number of selection criteria should be considered, such as the speed at which the vegetation establishes itself and grows, the disease or weed risk associated with vegetation, the suitability of the vegetation for the local climate, the tolerance of vegetation to becoming water-logged and the pollutant removal capacity of the various vegetation types (Armitage et al. 2013).

![Figure A1.10](image-url) (a) Lamination effect due to the flood plain storage and (b) Example of flood plain storage in San Paolo, Brazil (Giugni et al. 2012).

![Figure A1.11](image-url) Constructed treatment wetlands are man-made systems designed to mimic natural wetland systems (Source: susdrain, www.susdrain.org).
Advantages

- Highly efficient at removing pollutants from stormwater runoff
- May attenuate peak stormwater flows depending on location and design of wetland
- Good community acceptability and provides amenity value in urban environments

Limitations

- Wetlands could potentially attract mosquitoes and birds whose faeces can increase the amount of phosphorous in the water
- Limited to relatively flat land
- Limited depth range for flow attenuation and little reduction in run volume
- Flooding of the wetland may result in water logging of the plants which may result in die off and a loss in treatment efficiency

Inspection and maintenance of constructed wetlands can be frequent and costly, however can be reduced through effective pre-treatment such as litter traps, trash racks and sediment forebays at the inlet to the wetland (Armitage et al. 2013). Maintaining healthy vegetation and adequate flow conditions is essential to the efficient functioning of the constructed wetland and this requires harvesting of the vegetation, such as papyrus or reeds. Once harvested the vegetation can be composted and re-used.

Wetland construction costs can be high when compared to other interventions, however their ability and efficiency in removing pollutants and nutrients makes them relatively cost-effective. They also have the added benefit of providing amenity value. Construction costs per hectare of wetland are exponential, meaning the cost per hectare decreases the larger the wetland. Constructed wetlands are estimated to remove approximately 80-90% of suspended solids, 50-70% of total nitrogen, 50-70% of total phosphorus, and 70-90% of dissolved oxygen. These include metals (Armitage et al. 2009).

A1.4 Non-structural interventions

Non-structural measures do not involve physical construction but use knowledge, practice or action to reduce risks and impacts, in particular through policies and laws, public awareness raising, training and education (Kundzewicz 2002). These include flood warning systems, land use regulations such as development setbacks which identify where development can and cannot occur, or to what elevation structures should locate their lowest habitable floor to; flood proofing and retrofitting of buildings may increase the strength against flood actions; elevation of buildings may avoid completely the inundation. Flood insurance and relocation also belongs to this typology of measure. Some of these measures are described in more detail below.

A1.4.1 Sweeping and solid waste management

Interventions such as street sweeping and proper removal and disposal of solid waste help to reduce sediment (and hence pollution) loads entering the drainage system, and help to prevent solid waste from blocking culverts and reducing the efficiency of the conveyance system.

A1.4.2 River cleaning and stewardship

One approach to keeping rivers clear of litter and debris and maintaining a healthy river system is to involve communities that live alongside rivers and streams. Community involvement projects can have multi-sectoral impacts as they generate employment opportunities, provide awareness, safeguard communities and provide city-wide services such as functioning river systems that are clean and clear of litter. Sections of rivers or streams are maintained by cooperatives which are responsible for removing alien vegetation, rubble and any solid waste blocking the free flow of water down the stream or river. They are also responsible for maintaining the grass and other vegetation along the banks of the waterway. The cooperatives generally consist of members of the community that are unemployed and vulnerable and the project focuses on raising awareness and generating employment. Two examples of such projects include the Sihlanzimvelo Stream Cleaning Project in Durban and the Malakula River Restoration Project in Dar es Salaam:

- In Durban, the Sihlanzimvelo Stream Cleaning Project has been very successful in areas of the municipality where a number of rivers were considered critical in terms of health and functioning. Approximately 470km of degraded river systems were identified and pilot study areas were initiated. Residents of the four communities formed part of the initial pilot study. They were employed to clean and maintain sections of the river adjacent to where they live. This includes unblocking of culverts and the removal of litter and alien vegetation. Grass and vegetation along the riverbed is maintained to a certain height. The results have been impressive and rivers have become cleaner, the risk of flooding has reduced through the removal of litter and debris and the communities feel safer as the areas became more accessible and crime has decreased. Through the project, residents have become more aware of the benefits that are derived from healthy river systems and have an incentive to keep it clean. The Sihlanzimvelo Rivers Cleaning Project is funded by the eThekwini Municipality and the South African government’s Expanded Public Works Programme (EPWP) and includes a contractor development component. The budget for the project is R45 million (approximately US$53 million). Over the course of the project a total of 732 job opportunities have since been created.

- In Dar es Salaam, the Malakula River Restoration Project was initiated in 2012 and is a multi-stakeholder partnership that has focused on implementing measures that enhance healthy living conditions of the riverine communities, and prevent further pollution on a sustained basis. The Malakula River originates from the Mzanga and Kizinga Rivers and drains into Masesani Bay in Kinondoni Municipality. The restoration project forms part of the International Water Stewardship Programme (IWSIP), an international programme for water security managed by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ). Project activities include physical clean-up of the Malakula River, the establishment of sustainable solid waste and wastewater management systems, such as introducing private waste collectors and developing new recycling centres, building capacity of service providers, raising awareness in communities, improving household sanitation, and implementing effective law enforcement measures. Project partners include the Wami River Basin Water Board (WRBBW), National Environment Management Council (NEMC), the local Kinondoni Municipal Council (KMC), Coca-Cola Kwanza, NабаkiAfrica, Nipe Fagio, the Bremen Overseas Research and Development Association (BORDA), and GIZ. Donor funding for the initial phase of the project was approximately EUR 400 000. In April 2016 the multi-stakeholder project came to an end with the project being handed over to the Malakula Community Change groups which will continue on with improving the health of the river.

A1.4.3 Riparian buffers

A riparian buffer is a vegetated area, or buffer strip, that is located adjacent to a stream or river channel and is usually forested, which helps to shade and partially protect the waterway from the impacts of adjacent land uses. Riparian buffers play an important role in improving water quality as well as providing stormwater infiltration benefits and conservation value. Riparian buffers are similar to filter strips but differ in that they are generally forested and always occur adjacent to river channels. Filter strips tend to be located in urban areas adjacent to development.

Riparian buffers reduce excess amounts of sediments, organic material, nutrients and pesticides in surface runoff and reduce excess nutrients and other chemicals in shallow ground water flow (Wadier et al. 2009). They are also known to reduce pesticide drift entering the water body. With the use of suitable indigenous vegetation, riparian buffers have the potential to provide a habitat corridor for wildlife (Armitage et al. 2013).

Advantages

- Relatively low costs involved in planting and establishing buffer zones
- Significantly improve water quality of streams and rivers
- Infiltration of stormwater runoff helps to attenuate flood peaks
- Natural intervention that provides amenity and conservation value.

Limitations

- Relatively limited potential for the removal dissolved nutrients

Riparian buffers can be cost-effective in that they require no major engineering or construction. The costs are associated with the purchasing of seedlings and the labour required to plant them. Riparian buffers are efficient at removing suspended solids, hydrocarbons and other pollutants. They are less effective at removing dissolved nutrients such as nitrogen and phosphorus. They contribute to the infiltration of stormwater runoff and therefore attenuate flood peaks.

Figure A1.12

Riparian buffers are located adjacent to streams and river channels. They can either be made up of grasses and smaller plants as in picture (a) or they can be densely vegetated with trees and bushes as in picture (b). They provide a buffer between adjacent land uses such as agriculture and residential areas and waterways.
Catchment reforestation is an important intervention that does not differ much from the riparian buffer intervention. Catchment reforestation focuses on planting indigenous trees and shrubs within the greater catchment area, in particular in areas that were previously forested. By increasing the number of larger trees and shrubs in the catchment the amount of runoff entering streams and rivers in reduced through trapping and infiltration. Forested areas are well known for their ability to reduce runoff as well as reduce nutrient and pollutant loads entering waterways. Reforestation in the catchment also increases conservation value and amenity value.

Advantages
- Relatively low costs involved in planting and re-establishing forested areas
- Significantly improve water quality of streams and rivers
- Infiltration of stormwater runoff helps to attenuate flood peaks
- Natural intervention that provides amenity and conservation value

Limitations
- Relatively limited potential for the removal dissolved nutrients

The capital costs involved in catchment reforestation are relatively low when compared to other interventions. This is because the intervention involves no engineering or construction work and is based solely on the planting of trees and shrubs. Costs include the buying of seedlings and the labour involved in planting them. Catchment reforestation provides numerous benefits such as amenity and conservation value as well as contributes to providing clean water. Trees absorb rainfall, slow down flow velocity, disperse surface runoff, offset water discharge, filter pollutants, and reduce excess nutrient and sediment loads into the rivers and streams (Rutherford et al. 2007, Ouyang et al. 2013, Opperman 2014). Therefore land cover change, such as deforestation, increases nutrient and sediment loads entering waterways, alters infiltration rates, elevates greenhouse gas emissions and leads to changes in regional and local hydrological cycles (Ouyang et al. 2013). The latter results in a significant reduction in floodwater retention and an associated loss of flood control (Ouyang et al. 2013). Therefore reforestation and the development of forested floodplain buffers in a catchment can reduce the water discharge and sediment load into the rivers and streams and enhance flood attenuation based on catchment characteristics (Ouyang et al. 2013). Vegetation can have numerous impacts on the amount of rainfall that becomes runoff and can generally affect flooding in three specific ways: by affecting the size and shape of the stream channel (geomorphology), by altering the amount of water that reaches the stream channel (hydrology), and by altering the resistance to flow (hydraulics) (Rutherford et al. 2007, Opperman 2014).

River channels that are forested have a higher roughness which means that the flood arrives later and that the peak flow is attenuated when compared to channels cleared of vegetation. The response to larger floods generally differs from smaller floods with smaller attenuation of the peak observed in the case of the small flood (Rutherford et al. 2007). Revegetating the riparian zone in the Murray-Darling catchment in Australia had a considerable effect on the size and timing of the flood peak reaching different outlets (Figure A1.14; Rutherford et al. 2007). At the upstream site (C) the peak is attenuated by 18% and at the larger outlet (A) the peak is attenuated by 29% (Figure A1.14).

A1.5 Relative performance of different measures

Generally a combination of stormwater management measures would be applied. There are usually trade-offs among the interventions and finding the correct balance can be a complex task. The active structural measures, such as floodplain storage interventions will reduce the need for extensive passive measures such as levees or the widening of channels. However, active measures alone often will be unable to eliminate flooding problems completely and thus generally will need to be implemented in conjunction with some conveyance infrastructure. Generally, the ‘softer’ the intervention the less efficient it tends to be in terms of m^3 reduction per unit of space. However, the softer interventions tend to have greater benefits in terms of amenity and social value. Therefore it is necessary to develop a sound methodology for evaluating the interventions based on cost-effectiveness, efficiency in removing peak flows, reducing runoff volume and water quality amelioration, and providing amenity, conservation and social benefits. These are discussed in more detail below.

When developing a proposed plan for managing stormwater it is important to link together the various interventions and the benefits that they provide with the greatest possible efficiency. That is, identify the combination of interventions for a specific project site that will achieve the outlined objective in the most cost-effective way. This involves determining the cost effectiveness of different interventions, i.e. a cost per unit reduction of runoff volume (m^3) or cost per unit reduction in pollutant loads (kg), depending on what the proposed project is trying to achieve. Outside of cost-effectiveness, interventions need to be assessed in terms of any other benefits that they may provide, such as conservation value, amenity value or social benefits such as increased water supply. The interventions need to be realistic in terms of what is feasible and practical within the designated project area.

Numerous studies have examined the relative ability of different interventions to reduce pollutant loads, flow volumes and attenuate peak flows during storm events, and their cost-effectiveness. Estimates for cost-effectiveness in terms of cost per unit runoff reduction ($/m^3) and cost per unit reduction in pollutant loads ($/kg) were collated from a wide range of stormwater management literature. These estimates tend to be site specific and based on local costs but nonetheless provide a clear indication of which interventions are generally more cost-effective in terms of their ability to reduce peak runoff and remove pollutants.
A1.5.1 Average cost effectiveness in terms of peak flow and volume reduction

Cost-effectiveness in terms of runoff reduction ($/m³) is shown in Figure A1.15. These estimates are based on reviews and examples from the stormwater management literature (Joksimovic & Alam 2014, Liu et al. 2015, Jiang et al. 2015, Committee for Climate Change 2012, Xiao & McPherson 2002, McPherson et al. 1999). From the examples it is clear that green roofs and permeable pavements are the least cost-effective, even though they are efficient at reducing runoff, due to their higher capital and maintenance costs compared to other options. Soakaways and infiltration trenches are the most cost-effective of the structural engineering methods as they are cheaper to construct and maintain. Constructed wetlands, sand filters, bioretention areas, detention basins, filter strips and swales generally are all relatively cost-effective. They are however less efficient at trapping or attenuating peak flows after a large storm. Riparian buffers and catchment reforestation represent the most cost-effective option in that they do contribute significantly to rainwater infiltration, but they also do not trap or attenuate peak flows (which is not captured in the $/m³ assessment). The structural engineering options are more efficient in this regard.

A1.5.2 Average cost effectiveness in terms of water quality amelioration

A number of interventions are designed to specifically control and improve the quality of stormwater runoff. Generally their performance is assessed based on their pollutant removal capabilities. Some interventions may be more efficient at removing suspended solids and hydrocarbons, whereas others may be particularly efficient at removing soluble nutrients such as phosphorus. Often this means that a number of interventions are required to achieve a specified outcome. The capacity for pollutant removal of different interventions is summarised in Table A1.1.

Detailed information provided in Armitage et al. (2013) (Table A1.1) was used to assess the water quality amelioration performance of the various interventions. These data were combined with cost data to estimate relative cost-effectiveness for a selected range of interventions (Figure A1.16).

The most cost-effective options in terms of TSS removal are filter strips, swales, sand filters and detention basins. Riparian buffers and catchment reforestation are also cost-effective options. Constructed wetlands and bioretention areas are among the least cost-effective for all three pollutants/nutrients, but they do have higher amenity values when compared to the other options.

![Figure A1.15](image-url) Comparison of average cost per unit volume of runoff reduction for various stormwater management options, based on data in the literature

<table>
<thead>
<tr>
<th>Option/Technology</th>
<th>TSS</th>
<th>Hydrocarbons</th>
<th>TP</th>
<th>TN</th>
<th>Faecal Coliforms</th>
<th>Heavy Metals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source Controls</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Green roofs</td>
<td>60-90</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>50-90</td>
</tr>
<tr>
<td>Sand filters</td>
<td>80-90</td>
<td>50-80</td>
<td>50-80</td>
<td>25-40</td>
<td>40-50</td>
<td>50-80</td>
</tr>
<tr>
<td>Underground sand filters</td>
<td>75-90</td>
<td>-</td>
<td>30-60</td>
<td>30-50</td>
<td>40-70</td>
<td>40-80</td>
</tr>
<tr>
<td>Surface sand filters</td>
<td>80-90</td>
<td>-</td>
<td>50-60</td>
<td>30-40</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Filter drains</td>
<td>50-85</td>
<td>30-70</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>50-80</td>
</tr>
<tr>
<td>Soakaways</td>
<td>70-80</td>
<td>-</td>
<td>60-80</td>
<td>25-60</td>
<td>60-90</td>
<td>60-90</td>
</tr>
<tr>
<td>Oil and grit separators</td>
<td>0-40</td>
<td>40-90</td>
<td>0-5</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Modular geocellular structures</td>
<td>P5</td>
<td>P5</td>
<td>P5</td>
<td>P5</td>
<td>P5</td>
<td>P5</td>
</tr>
<tr>
<td>Stormwater collection and reuse</td>
<td>P5</td>
<td>P5</td>
<td>P5</td>
<td>P5</td>
<td>P5</td>
<td>P5</td>
</tr>
<tr>
<td>Local controls</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bioretention areas</td>
<td>50-80</td>
<td>50-80</td>
<td>50-60</td>
<td>40-50</td>
<td>-</td>
<td>50-90</td>
</tr>
<tr>
<td>Filter strips</td>
<td>50-85</td>
<td>70-90</td>
<td>10-20</td>
<td>30-20</td>
<td>25-40</td>
<td>25-40</td>
</tr>
<tr>
<td>Infiltration trenches</td>
<td>70-80</td>
<td>-</td>
<td>60-80</td>
<td>25-60</td>
<td>60-90</td>
<td>60-90</td>
</tr>
<tr>
<td>Permeable pavements</td>
<td>60-95</td>
<td>70-90</td>
<td>50-80</td>
<td>50-60</td>
<td>85-60</td>
<td>-</td>
</tr>
<tr>
<td>Swales</td>
<td>60-90</td>
<td>70-90</td>
<td>25-80</td>
<td>30-90</td>
<td>-</td>
<td>40-90</td>
</tr>
<tr>
<td>Enhanced dry swales</td>
<td>70-90</td>
<td>70-90</td>
<td>30-80</td>
<td>50-90</td>
<td>-</td>
<td>80-90</td>
</tr>
<tr>
<td>Wet swales</td>
<td>60-80</td>
<td>70-90</td>
<td>25-35</td>
<td>30-40</td>
<td>-</td>
<td>40-70</td>
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<tr>
<td>Vegetated buffers*</td>
<td>50-85</td>
<td>70-90</td>
<td>10-20</td>
<td>10-20</td>
<td>-</td>
<td>25-40</td>
</tr>
<tr>
<td>Regional controls</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constructed wetlands</td>
<td>80-90</td>
<td>50-80</td>
<td>30-40</td>
<td>30-60</td>
<td>50-70</td>
<td>50-60</td>
</tr>
<tr>
<td>Extended detention shallow wetland</td>
<td>60-70</td>
<td>-</td>
<td>30-40</td>
<td>50-60</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Pocket wetland*</td>
<td>80-90</td>
<td>50-80</td>
<td>30-40</td>
<td>30-60</td>
<td>50-70</td>
<td>50-60</td>
</tr>
<tr>
<td>Submerged gravel wetland</td>
<td>80-90</td>
<td>60-70</td>
<td>50-60</td>
<td>50-60</td>
<td>85-90</td>
<td></td>
</tr>
<tr>
<td>Detention ponds*</td>
<td>45-90</td>
<td>30-60</td>
<td>20-70</td>
<td>20-40</td>
<td>50-70</td>
<td>40-90</td>
</tr>
<tr>
<td>Extended detention ponds</td>
<td>65-90</td>
<td>30-60</td>
<td>20-50</td>
<td>20-30</td>
<td>50-70</td>
<td>40-90</td>
</tr>
<tr>
<td>Infiltration basins</td>
<td>45-75</td>
<td>-</td>
<td>60-70</td>
<td>55-60</td>
<td>-</td>
<td>85-90</td>
</tr>
<tr>
<td>Retention ponds</td>
<td>75-90</td>
<td>30-60</td>
<td>30-50</td>
<td>30-50</td>
<td>50-70</td>
<td>50-80</td>
</tr>
</tbody>
</table>

*Estimated values based on similar stormwater technologies

TSS – Total Suspended Solids, TP = Total Phosphorous, TN = Total Nitrogen

![Figure A1.16](image-url) Comparison of cost per unit mass of pollutant/nutrient reduction for various stormwater management options

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**Table A1.1** Measured pollutant removal capacities of selected stormwater management options and technologies (Source: Armitage et al. 2013)
A1.5.3 Overall effectiveness, cost-effectiveness and potential co-benefits

The relative effectiveness of different interventions in terms of flood and water quality amelioration, their cost-effectiveness, and other potential benefits are summarised in qualitative terms in Table A1.2. This suggests that while conveyance measures are highly effective for reducing flood exposure/risk, they make little contribution to water quality amelioration, they vary in terms of cost-effectiveness and have relatively little in the way of co-benefits. Indeed, they are more likely to lead to externalities such as damage to aquatic ecosystems or acerbation of flooding further downstream. Of the conveyance measures, detention basins are potentially beneficial in terms of providing opportunities for amenity, such as sunken sports fields.

The “green” engineering measures are generally less efficient in flood protection, but are important for water quality. Effective flood protection will require these measures to be implemented in combination and/or at scale. Green engineering measures also vary in their cost-effectiveness and may not always compete with conveyance measures. They do however, also present much greater opportunities for delivering co-benefits, such as water supply and the provision of recreational areas. The latter is particularly the case for the vegetated options which have greater aesthetic appeal.

The protection or restoration of natural systems in catchment areas contributes to the reduction and retardation of flows and to water quality amelioration. Within the flood prone areas, riparian buffers and functional floodplain areas reduce the exposure to flooding, and further contribute to water quality amelioration. In all cases, these areas have the potential to contribute significantly in terms of other co-benefits.

Table A1.2 Relative merits (indicated by number of “X”) of different measures for stormwater and flood risk management, based on the literature. Measures considered in this study area are marked with an asterisk.

<table>
<thead>
<tr>
<th>Option/technology</th>
<th>Conveyance/Reduction of exposure</th>
<th>Flood attenuation/Reduction of flood risk</th>
<th>Water quality amelioration</th>
<th>Cost-effectiveness</th>
<th>Water supply</th>
<th>Amenity potential</th>
<th>Conservation value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Conveyance measures (lower catchment)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swales/drains</td>
<td>X</td>
<td>XX</td>
<td>XX</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Channel enlargement/canalisation/levees</td>
<td>XXX</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydraulic bypass</td>
<td>XXX</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>“Green” engineering measures (mid-upper catchment)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Infiltration trenches</td>
<td>XXX</td>
<td>XX</td>
<td>XX</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soakaways</td>
<td>XXX</td>
<td>XX</td>
<td>XX</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Permeable pavements*</td>
<td>XXX</td>
<td>XXX</td>
<td>XX</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rainwater harvesting</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>XXX</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bio-retention areas</td>
<td>XX</td>
<td>XXX</td>
<td>XX</td>
<td>X</td>
<td></td>
<td>XX</td>
<td>XX</td>
</tr>
<tr>
<td>Sand filters</td>
<td>XX</td>
<td>XXX</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Green roofs*</td>
<td>XX</td>
<td>XXX</td>
<td>X</td>
<td></td>
<td></td>
<td>XX</td>
<td>XX</td>
</tr>
<tr>
<td>Filter strips</td>
<td>XX</td>
<td>XXX</td>
<td>XXX</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vegetated swales</td>
<td>XX</td>
<td>XXX</td>
<td>XXX</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constructed wetlands*</td>
<td>XX</td>
<td>XXX</td>
<td>XX</td>
<td>XXX</td>
<td></td>
<td>X</td>
<td></td>
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<tr>
<td>Detention basins*</td>
<td>XXX</td>
<td>XXX</td>
<td>X</td>
<td></td>
<td></td>
<td>XXX</td>
<td>XXX</td>
</tr>
<tr>
<td><strong>Non-structural measures</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Development setbacks</td>
<td>X</td>
<td></td>
<td>XXX</td>
<td>XX</td>
<td>XX</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conventional solid waste management*</td>
<td>XX</td>
<td>X</td>
<td>XX</td>
<td>XX</td>
<td>XX</td>
<td>XX</td>
<td>XX</td>
</tr>
<tr>
<td>River cleaning programmes*</td>
<td>X</td>
<td>X</td>
<td>XXX</td>
<td>XX</td>
<td>XX</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Protection/restoration of catchment forests + wetlands*</td>
<td>XX</td>
<td>XXX</td>
<td>XXX</td>
<td>XX</td>
<td>XX</td>
<td>XXX</td>
<td>XXX</td>
</tr>
<tr>
<td>Protection/restoration of riparian areas, floodplains*</td>
<td>X</td>
<td>XX</td>
<td>XXX</td>
<td>XXX</td>
<td>XX</td>
<td>XXX</td>
<td>XXX</td>
</tr>
</tbody>
</table>

APPENDIX 2. SCENARIO ASSUMPTIONS

A2.1 Sanitation measures

A2.1.1 Scenario 1-2 (sanitation backlog)

For Scenarios 1 and 2 an adjustment to sanitation had to be made to incorporate the changes associated with increased development in the catchment. It was assumed that undeveloped land was developed as per the eThekwini Scheme Zonation Plans with all other areas remaining the same. As a result, sanitation had to be adjusted to include developed areas. Non-point source pollutants in these new areas were changed to the associated land use as described in the zonation plans. It was also assumed that the newly developed residential areas generated additional point source throughput to the existing WWTWs.

Based on information from the zonation reports it was assumed that land zoned for general multi-unit residential use would have a density of 25 dwelling units per ha. With an average household size of 3.2 in the EMA, this equates to a population density of 80 people per ha. Where land was zoned under the less formal township establishment act (LFTEA) or the black communities development act (BCDA), the assumption of 250 dwelling units and 800 people per ha was applied. Based on information provided by sanitation professionals, an average of 150 litres of sewage per person per day was assumed in order to calculate the total extra throughput to WWTW from the newly developed areas. It was assumed that two thirds of households in the LFTEA and BCDA areas received urine diversion dehydration toilets\(^1\) and one third received access to waterborne sewage. The extra throughput, a total of 28.6 ML, was added as additional output to the already existing WWTW based on the location of each newly developed area in relation to these WWTW in the U60F catchment (Table A2. 1).

### Table A2.1 Sewage output generated in the newly developed areas

<table>
<thead>
<tr>
<th>Existing WWTW in U60F</th>
<th>Additional output (ML per day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hillcrest</td>
<td>4.5</td>
</tr>
<tr>
<td>Umbilo</td>
<td>7.5</td>
</tr>
<tr>
<td>Umhlataluzana</td>
<td>16.7</td>
</tr>
<tr>
<td>TOTAL</td>
<td>28.6</td>
</tr>
</tbody>
</table>

1. Urine diversion dehydration toilets are dry toilets that collect urine and faeces separately and include a special toilet seat or pan. The faeces are collected in two collection vaults for extended storage in order to dehydrate the faeces for treatment and safe handling (Rieck & von Muench 2011)

The assumptions for scenarios 1 and 2 were as follows:

- Non-point source runoff from newly developed areas will change to be the same as the new landuse type as stipulated in zonation plans;
- All newly developed residential areas were provided with either waterborne sewage or with urine diversion dehydration toilets as per dwelling densities provided in zonation reports and average household size for the EMA;
- The extra sewage generated from the addition of newly developed residential areas will be treated at existing WWTW in the catchment;
- Treated effluent will be discharged into the sub-catchment from where it is taken;
- All effluent at WWTWs will be treated to within General Effluent Limits as defined in national guidelines (Table A2. 2);
- Servicing and maintenance of existing WWTW and wastewater infrastructure will be conducted to meet the above limits on an ongoing basis; and
- Sanitation in informal settlements remains the same.
Table A2.2: General Effluent Limits

<table>
<thead>
<tr>
<th>Substance/Parameter</th>
<th>General Limit</th>
<th>Substance/Parameter</th>
<th>General Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fecal Coliforms (per 100ml)</td>
<td>1 000</td>
<td>Cadmium and its compounds (mg/l)</td>
<td>0.005</td>
</tr>
<tr>
<td>Chemical Oxygen Demand (mg/l)</td>
<td>75</td>
<td>Dissolved Chromium (VI) (mg/l)</td>
<td>0.05</td>
</tr>
<tr>
<td>pH</td>
<td>5.5-9.5</td>
<td>Dissolved Copper (mg/l)</td>
<td>0.01</td>
</tr>
<tr>
<td>Total Ammonia (ionised and un-ionised) as Nitrogen (mg/l)</td>
<td>3</td>
<td>Dissolved Cyanide (mg/l)</td>
<td>0.02</td>
</tr>
<tr>
<td>Nitrate/Nitrite as Nitrogen (mg/l)</td>
<td>15</td>
<td>Dissolved Iron (mg/l)</td>
<td>0.30</td>
</tr>
<tr>
<td>Chlorine as Free Chlorine (mg/l)</td>
<td>0.25</td>
<td>Dissolved Lead (mg/l)</td>
<td>0.01</td>
</tr>
<tr>
<td>Suspended Solids (mg/l)</td>
<td>25</td>
<td>Dissolved Manganese (mg/l)</td>
<td>0.1</td>
</tr>
<tr>
<td>Electrical Conductivity (mS/m) above intake</td>
<td>70 to 150 mS/m</td>
<td>Mercury and its compounds (mg/l)</td>
<td>0.005</td>
</tr>
<tr>
<td>Ortho-Phosphate as phosphorus (mg/l)</td>
<td>10</td>
<td>Dissolved Selenium (mg/l)</td>
<td>0.02</td>
</tr>
<tr>
<td>Fluoride (mg/l)</td>
<td>1</td>
<td>Dissolved Zinc (mg/l)</td>
<td>0.1</td>
</tr>
<tr>
<td>Soap, oil or grease (mg/l)</td>
<td>2.5</td>
<td>Boron (mg/l)</td>
<td>1</td>
</tr>
<tr>
<td>Dissolved Arsenic (mg/l)</td>
<td>0.02</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A2.1.2 Scenarios 3-15 (full sanitation)

The scenarios with full sanitation assumed that informal settlement areas and newly developed areas receive the required access to sanitation which results in zero net increase in WWTW outputs. In other words, the wastewater generated in these areas is assumed to be removed and recycled using “green” sanitation measures such as urine diversion dehydration toilets and the recycling of wastewater, with WWTW outputs not augmented. This approach forms part of the green urban development strategy and is important to consider, especially given Durban’s current water shortages. Under the full sanitation scenarios the augmented WWTW outputs included in scenarios 3 and 2, as described above, are removed. Full sanitation scenarios also assumed that the compliance and monitoring of current WWTW and associated infrastructure is improved. Additionally, the full sanitation scenarios were improved further with the placement of treatment wetlands to polish runoff from the existing WWTW.

The assumptions for scenarios 3-15 were as follows:

- All households in the catchment, including informal settlements, have access to improved sanitation;
- Non-point source runoff from informal settlement areas will change to be of the same quality as runoff from formal residential areas;
- Non-point source runoff from newly developed areas will change to be of the same as the new landuse type as stipulated in zonation plans;
- There will be a zero net increase in WWTW outputs;
- Human wastes will be dealt with from informal settlements and newly developed residential areas using green sanitation measures such as wastewater recycling and urine diversion dehydration toilets; and
- The equivalent of treated sewage is recycled if any human wastes are treated using waterborne sewage.

Neither sanitation nor wastewater recycling were costed in this study, as these are imperatives that are not under scrutiny here. Our study focuses on the added value gains of investing in further green urban development measures.

A2.2 Stormwater source controls

A2.2.1 Design and extent of the different interventions

For each measure, we estimated the potential extent of implementation. In some cases, where costs were very high and full implementation unlikely to be feasible, the maximum extent considers in the analysis was less than the potential extent. The potential extent of each source control measure is shown in Figure 3.3.

Green roofs can be installed on large flat roof surfaces compatible with commercial/retail and industrial areas. Green roofs could be implemented on the commercial/retail and industrial erf areas in the catchment. The total extent of green roofs varied under each scenario. If green roofs were implemented in conjunction with the maximum conservation intervention, for example, then the total area suitable for green roofs was less than under the minimum conservation intervention due to the more compact development required under the maximum conservation scenario. For industrial and commercial buildings, it was assumed that the total roof area was equal to 40% of the erf area (eThekwini Municipality 2008). For the scenario analysis, it was assumed that the intervention would be implemented on half of the total roof area. It was assumed that the green roofs would be constructed to include a light layer of vegetation with waterproof membrane, filter membrane and drainage, and would be maintained on an ongoing basis.

Porous paving can be placed in commercial/retail and industrial areas. The potential maximum extent was determined based on the criteria for soil drainage, slope and depth to water table (see Table 3.1). There are numerous designs for porous paving and these could be considered further – e.g. it could be used at a local scale in business premises/shopping centres where site levelling allows for changes in natural topography and other factors such as drainage. The extent of the porous paving was based on the assumption that 15% of the total erf area for commercial/retail and industrial areas is paved.

Infiltration trenches need to be located close to the source of contamination, typically in industrial and commercial/retail areas. They are installed around parking areas and office blocks where permeable paving is not an option because of space limitations or because of soil and infiltration limitations. Figure 3.3 shows the potential maximum extent of the erf areas that infiltration trenches can be implemented in the catchment. These are the erf areas that could not be serviced by porous paving. Infiltration trenches vary in their size based on substrate and size of source runoff area. The assumption is that infiltration trenches slowly infiltrate water received from adjacent hardened surfaces which was assumed to be 15% of the total erf area.

Soakaway pits can be used to infiltrate runoff from roofs in residential areas. They collect stormwater and allow it to infiltrate into the surrounding soil, much like infiltration trenches. However, while infiltration trenches tend to be long and narrow at the surface, soakaways are vertical holes dug into the ground. The maximum potential extent in the study area is therefore the total residential area (i.e. urban settlement) within the catchment (Figure 3.3) and it is assumed that the maximum extent of soakaways installed at the individual property level would collect 40% of the erf runoff, as used by the eThekwini Municipality (eThekwini Municipality 2008). However due to the high cost of this measure, the maximum extent was taken to be half of the treated erf area (20%). The volume of the soakaway was calculated by multiplying the area treated by a two metre depth for each pit.

There were three levels of extent for the implementation of source controls in the catchment; none, medium or maximum (Table A2.3).

The total area of the application of the different source controls varied under each scenario depending on the overall extent of other GUD interventions being implemented. For example, scenarios with minimum conservation areas and no riparian buffers had larger areas of source control application as more buildings were available for implementation compared to scenarios with medium or maximum conservation areas. The total area of source controls was therefore less under the compact development scenarios (Table A2.4). The implementation of green roofs ranged from 385 – 474 ha and the maximum area of permeable paving was 70 ha (Table A2.4). Infiltration trenches were constructed in commercial and industrial areas where permeable paving was not feasible and had a maximum volume of 0.31 million m³ under scenarios 9, 11 and 13 (Table A2.4). The application of soakaways in residential areas resulted in extensive volumes, with the maximum volume reaching almost 52 million m³.

Table A2.3: The extent of implementation of source controls

<table>
<thead>
<tr>
<th>Source control</th>
<th>Type of building</th>
<th>Medium extent</th>
<th>Maximum extent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green roofs</td>
<td>Commercial &amp; Industrial</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Permeable paving</td>
<td>Commercial &amp; Industrial</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Infiltration trenches</td>
<td>Commercial &amp; Industrial</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Soakaways</td>
<td>Residential</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

Table A2.4: The total area and volume (ha, m³) of each source control intervention for each of the source control scenarios

<table>
<thead>
<tr>
<th>Scenarios with source control intervention</th>
<th>Green roofs</th>
<th>Permeable paving (ha)</th>
<th>Infiltration trenches (million m³)</th>
<th>Soakaway pits (million m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 9</td>
<td>474</td>
<td>70</td>
<td>0.31</td>
<td>51.63</td>
</tr>
<tr>
<td>Scenario 11</td>
<td>474</td>
<td>70</td>
<td>0.31</td>
<td>-</td>
</tr>
<tr>
<td>Scenario 12</td>
<td>386</td>
<td>60</td>
<td>0.24</td>
<td>-</td>
</tr>
<tr>
<td>Scenario 13</td>
<td>474</td>
<td>70</td>
<td>0.31</td>
<td>51.63</td>
</tr>
<tr>
<td>Scenario 14</td>
<td>385</td>
<td>68</td>
<td>0.22</td>
<td>39.81</td>
</tr>
<tr>
<td>Scenario 15</td>
<td>386</td>
<td>60</td>
<td>0.24</td>
<td>36.25</td>
</tr>
</tbody>
</table>
A2.3 Treatment wetlands

Constrained treatment wetlands are designed to improve polluted runoff and waste water effluent quality and provide some limited control of runoff volumes. Wetlands can be effective in terms of removal of low levels of pollutants (i.e. a polishing function) and also provide buffering functions, aesthetic value and wildlife habitat. Constructed wetlands are located as close to the source of pollution as possible so as to maximise the impact on improving water quality.

The treatment wetlands were situated at point source pollution outlets in the study area; at the three existing WWTW. It was assumed that the runoff entering the wetlands was being treated to general standards and that the wetlands further treat runoff to a specific standard. Table A2.7 and Table A2.8 include the annual average treatment performance capabilities for surface flow wetlands assuming that the wetlands further treat runoff to a specific standard.

A2.4 PC_SWM model assumptions

Runoff from impermeable surfaces are key contributors of sediments and pollutants to rivers and oceans. Characterisation of the untreated runoff quality is necessary for determining total nutrient and sediment loads flowing into the rivers in the catchment from different land use types and is necessary for guiding the selection of effective and efficient stormwater management options.

Event Mean Concentration (EMC) data used in water quality modelling includes Event Mean Concentrations (EMCs), derived from literature and applied in South Africa to the Salt River Stormwater Master Plan study for the 1.0-5 day, 5 mm return interval storm, with data for informal/poorly serviced high density urban settlements collected during storm event sampling on the Diep River catchment (Cape Town) and reported in Cerdonkey & Day (2010). These data can be applied to landuse across the catchment, to derive a fully developed catchment that accounts for stormwater runoff from different landuse types.

Table A2.7. Annual Average Treatment Performance Capacities for surface flow wetlands (Source: Kadlec & Knight 1995) assuming wetland influent is a “typical municipal effluent” (see Table A2.8).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Removal rate (% per ha/day)</th>
<th>Efficiency (% per ha/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOD</td>
<td>10</td>
<td>67</td>
</tr>
<tr>
<td>TSS</td>
<td>10</td>
<td>67</td>
</tr>
<tr>
<td>NH4-N</td>
<td>4.7</td>
<td>62</td>
</tr>
<tr>
<td>TIN</td>
<td>6.9</td>
<td>69</td>
</tr>
<tr>
<td>TP</td>
<td>0.95</td>
<td>48</td>
</tr>
<tr>
<td>Metals</td>
<td>0.1</td>
<td>50</td>
</tr>
</tbody>
</table>

It was assumed that economies of scale had been realised for the construction of treatment wetlands. The unit costs were therefore staggered and decreased with the size of the wetland being constructed. The cost of constructing the 2 ha wetland was set at 100% of standard unit costs (R225 per m²), the 16 ha wetland at 50% unit cost, and for the 40 ha wetland at 20% of unit costs. Annual maintenance costs were assumed to be 2% of construction costs. Based on the total area of 2, 16 and 40 ha for treatment wetlands, the overall construction cost was estimated to be R41 million.

A2.4.1 Assumptions regarding untreated urban runoff quality

On the basis of design criteria provided in Georgia (2003), and assuming interventions sized as specified for the relevant volumes, the following stormwater treatment interventions would be expected to remove the following proportions of the anticipated load – with load being calculated based on landuse type (Table A2.10). Removal efficiencies of LIDS measures were
not suitable for larger return periods and therefore water quality treatment first-order decay equations were applied to the GUD measures rather than a simple BMP efficiency. The nutrient removal efficiency of the different BMP measure was estimated in terms of the hydraulic residence time. A higher hydraulic residence time or ‘contact time’ is experienced during low flows (i.e. at the beginning and the end of the hydrograph) and will result in a higher removal rate.

Table A2.10  Assumed pollutant reduction based on a 0.5 year event (Source: Georgia 2001)

<table>
<thead>
<tr>
<th>Approach</th>
<th>TSS</th>
<th>TN</th>
<th>TP</th>
<th>Metals</th>
<th>Pathogens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry detention basins</td>
<td>60</td>
<td>30</td>
<td>10</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Dry enhanced swales</td>
<td>80</td>
<td>50</td>
<td>50</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>Wet enhanced swales</td>
<td>80</td>
<td>40</td>
<td>25</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Grass channel</td>
<td>50</td>
<td>20</td>
<td>25</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Gravity oil / grit separator (industrial areas)</td>
<td>40</td>
<td>54</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Permeable paving</td>
<td>80</td>
<td>50</td>
<td>50</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>Stormwater pond</td>
<td>80</td>
<td>30</td>
<td>50</td>
<td>50</td>
<td>70</td>
</tr>
<tr>
<td>Revegetation / reforestation</td>
<td>80</td>
<td>25</td>
<td>50</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>Vegetated filter strip</td>
<td>60</td>
<td>20</td>
<td>20</td>
<td>40</td>
<td></td>
</tr>
</tbody>
</table>

The water quality treatment first-order decay equations adopted for TIN and P were:

\[ TIN_{\text{out}} = TIN \times \exp(k \times HRT) \]
\[ P_{\text{out}} = P \times \exp(k \times HRT) \]

where \(TIN_{\text{out}}\) and \(P_{\text{out}}\) are the outlet concentrations, \(TIN\) and \(P\) are the inlet concentrations, \(k\) is a fitting parameter related to the settling velocity, water depth and time, \(HRT\) is the hydraulic residence time (seconds).

The TSS concentration depends on a number of factors including the settling velocity, water depth and time.

\[ TSS_{\text{out}} = TSS \times \exp(k \times \Delta T) \]

Where \(TSS_{\text{in}}\) is the outlet concentration, \(TSS\) is the inlet concentration, \(k\) is a fitting parameter related to the settling velocity and is equal to -0.001 m/s, \(\Delta T\) is the time step and \(\Delta T\) is the water depth (SWMM, 2009).

A SWMM model of flows under the ‘natural’ (original) land cover for the whole catchment area was executed in order to estimate ‘pre-development’ flows. Ideally each detention basin would be sized based on pre- and post-development flows at each point. Each detention basin was incorporated into the SWMM model by adding a storage node (i.e. converting a junction to a storage node) with a standardised capacity of 18 000 m$^3$. A 0.2 m diameter outlet pipe was added to allow for the detention pond to drain and for low flows to flow through. The berm height was set at 3m, allowing very high flows to overtop this (Figure A2.2). The above parameters were assumed based on information from the Catchment Management Department at the eThekwini Municipality, and a recently designed dry detention pond that was constructed in the EMA.

A total of 23 detention ponds were placed at various locations within the study area (Figure A2.3). In practice, detention basins are strategically placed to make use of the natural landscape to minimise construction costs. An example of this is the detention basin constructed by the EM in the Hillcrest area, as shown in Figure A2.4.

A2.4.2.2 Detention basins

A2.4.2 Assumptions for stormwater management interventions

A2.4.2.1 Source controls

The general approach for setting up source controls in PC-SWMM is to define a new landuse that is used exclusively for a source control subcatchment and has a specific BMP removal efficiency/treatment. The process of defining the extent of source controls was difficult without the exact erf areas and in order to define, for example, just the roof area or permeable paving area, the data files had to be accessed and changed to include the relevant source control and then imported back into the model. The source control was therefore represented by its own subcatchment. For commercial/retail and industrial areas and where these source controls were specified, it was assumed that 20% of the area within each subcatchment was assigned to green roofs and 15% to either permeable paving or infiltration trenches (all depending on the allocated placement). For residential areas, 20% of the impervious area was treated using soakaway pits. After source control placement the “percent impervious” and “width” properties of the altered subcatchments were adjusted to compensate for the amount of the original subcatchment area that was replaced by source controls (see Figure A2.1). Both surface and drain outflows from the source controls were routed to the same outlet location assigned to the parent subcatchment.

Infiltration trenches and porous paving were treated as pervious surfaces and the Green-Ampt infiltration equations were applied. The dimensions of soakaway pits, green- roofs and infiltration trenches were taken from SWMM (2009), van Niekerk (2011) and Armitage et al. (2013).
A2.4.2.3 Treatment wetlands

Treatment wetlands were located at the outlets of each of the three WWTWs in order to improve the quality of WWTW effluents entering the river systems. It was assumed that effluent flow from the WWTWs all passed through the treatment wetland. Evaporative loss was not taken into account as it was not expected to have a significant effect on the model results.

In the scenarios “with sanitation” it was assumed that the WWTW effluent entering the wetlands had been treated to DWS general standards (see Table A2.11). Measured effluent concentrations generally complied with general effluent limits, except for TSS concentrations measured at Hillcrest WWTW. The latter was reduced in the “with sanitation” scenarios from the mean of 48 to 30 mg/L to meet the general effluent limits. The efficiency ratio was applied to estimate the pollutant concentration below the treatment wetland (Table A2.11) and the new value was applied at each point source.

Table A2.11: Assumed treated pollutant concentrations of wetland effluent based on removal efficiencies given in Table 3.2

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Removal rate (kg/ha/day)</th>
<th>Efficiency (%)</th>
<th>General Effluent Limit (mg/L)</th>
<th>WWTWs Mean Effluent Concentrations (mg/L)</th>
<th>Wetland Effluent Concentrations (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Umbilo</td>
<td>Umhlatuzana</td>
<td>Hillcrest</td>
</tr>
<tr>
<td>TSS</td>
<td>10</td>
<td>67</td>
<td>30</td>
<td>21</td>
<td>7</td>
</tr>
<tr>
<td>TIN</td>
<td>6.9</td>
<td>69</td>
<td>18</td>
<td>7.9</td>
<td>7.3</td>
</tr>
<tr>
<td>TP</td>
<td>0.95</td>
<td>48</td>
<td>10</td>
<td>3.4</td>
<td>2.1</td>
</tr>
</tbody>
</table>

A2.4.2.4 River buffers

The dynamics of sediment and nutrient reduction through the use of river buffers are not fully understood and are complex to model. In order to achieve the most realistic representation of introducing river buffers into the model for the required scenarios discharge outlet points for each subcatchment were linked to nodes in the drainage systems flowpaths. Generally, overland flow (sheet flow) converges to become channel flow fairly rapidly before entering the main flowpath. Therefore, the treatment equations for TSS, TIN and P, as provided in section A2.4.1, were applied to the flowpath nodes, in order to account for pollutant reduction associated with river buffers. In addition, the hydraulic, soil and water quality parameters were altered to account for the change in landuse. This approach may overestimate the reduction due to an accumulative effect, but the implementation of river buffers would result in the encroachment of vegetation within the river and therefore increased contact area with streamflow. Therefore, this approach is assumed to best account for the overall objective of assessing the impacts of river buffers.
APPENDIX 3. FLOOD MODELLING

A3.1 Model setup

A3.1.1 Baseline information, software and GIS layers

The modelling of landuse change in the catchment required developing a comprehensive complex hydraulic surface runoff model. The integration of several GIS layers and post-processing for the hydraulic model input parameters was required for the setup of the model. A summary of the baseline information, software and GIS landuse layers used in developing the model is provided below.

Baseline information:
- Various GIS datasets from the eThekwini Municipality, including: 0.5m Rasta .IMG files for surface elevation, 2m Contour, Landuse Zonal, Durban Metro Open Space System (D’MOSS), High resolution Aerial imagery;
- Shuttle Radar Topography Mission (SRTM) 30m resolution surface elevation data;
- Soil type classification maps;
- Geometric HecRAS hydraulic files for EMA rivers (where available);
- Stormwater networks (where available);
- Relevant point source data (e.g. WWTW);
- Design Rainfall Estimation (HydroRisk, http://ukzn-iis-02.ukzn.ac.za/unp/beeh/hydrorisk);
- eThekwini Design Rainfall (Smithers 2002); and
- Water quality parameters and landuse change shapefiles.

Software:
- QGIS;
- US-EPA SWMM5 interfaced by the PCSWMM GUI;
- HecRAS, Hec-Geo-RAS; and
- Anaconda – Spyder – Python 2.7 – Data Analysis/Management.

GIS landuse layers:
- GIS landuse files (e.g. zoning files, landcover and D’MOSS) collated and reviewed, and concatenated into one consistent landuse polygon shapefile
- Post-processing was conducted to dissolve descriptions into a common set of landuse conventions. The final shapefile was ground truthed using aerial imagery for the EMA
- Original landuse descriptions from the D’MOSS landuse file were maintained throughout the landuse description process and were classified as “Nature and Conservation Areas” (Figure A3. 1)
- The D’MOSS classifications were further discretised to provide an indication of the hydraulic parameters required for the hydraulic model, i.e. grassland could be described as ‘open_grass’ or ‘open_grass_soil’ which indicates a higher soil erodibility (Figure A3. 1)
A3.1.2 Subcatchment delineation and flow lines

The study area was divided into subcatchments and the outlet points were identified (subcatchment runoff is routed to a single discharge point). Outlet points can be defined as nodes of the drainage system or they can be routed to other subcatchments. The GIS subcatchment (watershed basins) data derived from EM flood studies and are in the order of 1km$^2$ and larger. Although appropriate for flood studies, the information relevant to this scope of works required discretisation into smaller, more appropriate subcatchments, in the order of 0.2km$^2$ (Figure A3.2). These new subcatchments were processed from high resolution, .IMG raster files (DEM files). The raster files were converted to .flt float files which can be used as a TIN (Triangulated Irregular Network). A spatial analysis tool was then used to process out the flow paths, watershed boundaries, and river centre lines.

The flood models, based on geometric HecRAS files, were imported into the PCSWMM model. These files contained some stormwater infrastructure (e.g. culverts and bridges), but they did not include the stormwater network. Flow paths simulated using a watershed delineation tool (WDT) were appended to the HecRAS files in order to represent the required study area. A shapefile of the stormwater networks was provided by the eThekwini Municipality. The current available stormwater shapefile was incomplete and contained numerous errors and inconsistencies (see Figure A3.3). Invert levels and pipe sizes were often missing and connections were incorrect and/or missing. Available networks were amended where possible, i.e. a standard circular pipe size of 0.375m was allocated to pipes with missing geometry and tools were applied to either fill in missing invert levels (from the DEM) or to apply slopes within the network. Where necessary, main pipelines were added to these networks. The pipe profiles were later checked to ensure reasonable slope gradients and the continuity of flows.
A3.1.3 Point sources

Average daily abstractions and return flows/discharges were added as point sources at the appropriate junctions. A list of the wastewater treatment works (WWTWs) located within the catchment are given in Table A3. 1.

Table A3.1 WWTWs located within the study area.

<table>
<thead>
<tr>
<th>WWTW Name</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Design Capacity (Ml/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Umhlatuzana</td>
<td>-29.87713</td>
<td>30.884036</td>
<td>14.8</td>
</tr>
<tr>
<td>Umbilo</td>
<td>-29.84561</td>
<td>30.891653</td>
<td>23.2</td>
</tr>
<tr>
<td>Hillcrest</td>
<td>-29.79410</td>
<td>30.75635</td>
<td>1.2</td>
</tr>
</tbody>
</table>

A3.1.4 Hydraulic parameters

The determination of the catchment characteristics were estimated using a spatial analyst tool for zonal statistics. Raster files were generated to represent the following information required for the hydraulic and hydrological models, with reference to each subcatchment. These were used to estimate the many runoff characteristics outlined in Table A3. 2.

Table A3.2 Hydraulic input properties required for each subcatchment

<table>
<thead>
<tr>
<th>Hydraulic Parameter</th>
<th>Description</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area (ha)</td>
<td>Area of subcatchment</td>
<td>GIS tool</td>
</tr>
<tr>
<td>Width (m)</td>
<td>Width of overland flow path</td>
<td>GIS tool</td>
</tr>
<tr>
<td>Flow Length (m)</td>
<td>Length of overland sheet flow</td>
<td>GIS tool</td>
</tr>
<tr>
<td>Slope (%)</td>
<td>Average slope along the pathway of overland flow to inlet locations</td>
<td>GIS tool</td>
</tr>
<tr>
<td>Imperv. (%)</td>
<td>Percent impervious area</td>
<td>RGB colour extraction</td>
</tr>
<tr>
<td>N Imperv</td>
<td>Manning's roughness coefficient, N, for overland flow for impervious area</td>
<td>Rossman 2015 (Table 5)</td>
</tr>
<tr>
<td>N Perv</td>
<td>Manning's roughness coefficient, N, for overland flow for pervious area</td>
<td>Rossman 2015 (Table 5)</td>
</tr>
<tr>
<td>Dstore Imperv (mm)</td>
<td>Depth of depression storage on impervious areas</td>
<td>ASCE 1992 (Table 4)</td>
</tr>
<tr>
<td>Dstore Perv (mm)</td>
<td>Depth of depression storage on pervious areas</td>
<td>ASCE 1992 (Table 4)</td>
</tr>
<tr>
<td>Zero Imperv (%)</td>
<td>Percent of impervious area with no depression storage</td>
<td>SWMM default setting of 25% based on literature</td>
</tr>
<tr>
<td>Percent Routed (%)</td>
<td>Percent of runoff routed between sub-areas</td>
<td>Outfalls</td>
</tr>
</tbody>
</table>

Subcatchment areas were measured and the width of the subcatchment defined as the physical width of the overland flow. In an idealised, rectangular catchment, the total width would be twice the length of the drainage channel (assuming both sides of the subcatchment were symmetrical).

The most significant input hydraulic parameter is the percentage of impervious area (Imperv. %). There are a number of methods that can be employed to estimate the percent imperviousness of a subcatchment. Ideally the percent imperviousness could be measured accurately from aerial photos or land use maps, however, this can be tedious for large study areas. Two approaches were investigated: 1) a percent impervious area associated with each land use category based on standard values for different land uses found in the literature and 2) RGB colour extraction tool applied to differentiate between impervious and pervious areas based on aerial imagery (in the EMA) and Google Earth images (outside of the EMA). The first approach was used for this study. Figure A3. 5 shows sections of two different areas of contrasting land use i.e. residential and industrial. The top value represents the %Imperv using approach 1 and the bottom value represents the %Imperv using approach 2. The estimation using approach 2 was reasonable except where the colour spectrum was a mixture of green and brown, for example, recently harvest sugarcane and rural sandy areas.

Estimates of Manning’s roughness coefficient (N values) for overland flow, imperviousness and perviousness were taken from literature. A summary from three different sources are given in Table A3. 3.

Figure A3.4 Newly available stormwater network shapefiles from the EM’s SMS audit.
A3.1.5 Soil Infiltration

The largest proportion of rainfall losses over pervious areas generally occur due to soil infiltration. Theoretically, the Richards equation is the most representative, however its highly nonlinear partial differential equations make it unsuitable for continuous long-term simulations. Simple algebraic infiltration models have been developed that represent the dependence of infiltration capacity on soil characteristics and the present soil capacity during a storm event. There are five options that can be used in SWMM, namely Horton’s method, the modified Horton method, the Green-Ampt method, the modified Green-Ampt method and the Curve Number method. With all of these models, the parameters depend on the type and condition of the soil of interest.

It is worth noting that the Flood Line Delineation studies for EM use the Soil Curve Number (SCN) to represent the runoff coefficient for catchment routing. Although suitable for flood studies (as a conservative approach), this investigation will use the Green-Ampt method. This method provides a soil memory as opposed to a broad brush coefficient approach.

For the Green-Ampt infiltration method, the model requires three soil parameters that the user must specify for each of the subcatchments:

1. Capillary suction head, \( \Psi_s \) (mm);
2. Saturated hydraulic conductivity, \( K_s \) (mm/hr); and
3. The maximum available moisture deficit, \( \theta_{\text{max}} \) (volume of dry voids per volume of soil).

The depression storage is the volume that must be filled prior to the occurrence of runoff on both pervious and impervious areas. Values for depression storage were taken from the SWMM Manual (EPS 2015 after ASCE, 2015; Table A3.4). In SWMM, depression storage may be treated as a calibration parameter, particularly to adjust runoff volumes. Therefore obtaining accurate values in the setup may be unnecessary as these values may change during calibration. Depression storage is most sensitive for small storms; as the depth increases it becomes a smaller component of the water budget (EPA, 2015).

The depression storage is the volume that must be filled prior to the occurrence of runoff on both pervious and impervious areas. Values for depression storage were taken from the SWMM Manual (EPS 2015 after ASCE, 2015; Table A3.4). In SWMM, depression storage may be treated as a calibration parameter, particularly to adjust runoff volumes. Therefore obtaining accurate values in the setup may be unnecessary as these values may change during calibration. Depression storage is most sensitive for small storms; as the depth increases it becomes a smaller component of the water budget (EPA, 2015).

Table A3.3 Estimates of Manning’s roughness coefficient (n values) for overland flow. A summary from three different sources (Source: Rosman 2015)

<table>
<thead>
<tr>
<th>Source</th>
<th>Ground Cover</th>
<th>n</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crawford and Linley (1946)*</td>
<td>Smooth asphalt</td>
<td>0.01</td>
<td>0.01–0.04</td>
</tr>
<tr>
<td></td>
<td>Asphalt and concrete paving</td>
<td>0.014</td>
<td>0.01–0.019</td>
</tr>
<tr>
<td></td>
<td>Packed clay</td>
<td>0.03</td>
<td>0.02–0.04</td>
</tr>
<tr>
<td></td>
<td>Light turf</td>
<td>0.20</td>
<td>0.18–0.25</td>
</tr>
<tr>
<td></td>
<td>Dense turf</td>
<td>0.35</td>
<td>0.30–0.40</td>
</tr>
<tr>
<td></td>
<td>Dense shrubbery and forest litter</td>
<td>0.4</td>
<td>0.35–0.45</td>
</tr>
<tr>
<td>Engman (1986)*</td>
<td>Concrete or asphalt</td>
<td>0.011</td>
<td>0.010–0.012</td>
</tr>
<tr>
<td></td>
<td>Bare sand</td>
<td>0.010</td>
<td>0.009–0.011</td>
</tr>
<tr>
<td></td>
<td>Gravelled surface</td>
<td>0.02</td>
<td>0.018–0.023</td>
</tr>
<tr>
<td></td>
<td>Bare clay-loam, (cracked)</td>
<td>0.02</td>
<td>0.020–0.025</td>
</tr>
<tr>
<td></td>
<td>Range (natural)</td>
<td>0.13</td>
<td>0.12–0.15</td>
</tr>
<tr>
<td></td>
<td>Bluegrass sod</td>
<td>0.45</td>
<td>0.39–0.63</td>
</tr>
<tr>
<td></td>
<td>Short grass prairie</td>
<td>0.15</td>
<td>0.10–0.20</td>
</tr>
<tr>
<td></td>
<td>Bermuda grass</td>
<td>0.41</td>
<td>0.30–0.48</td>
</tr>
<tr>
<td>Yan (2001)*</td>
<td>Smooth asphalt pavement</td>
<td>0.012</td>
<td>0.010–0.015</td>
</tr>
<tr>
<td></td>
<td>Smooth impervious surface</td>
<td>0.013</td>
<td>0.011–0.015</td>
</tr>
<tr>
<td></td>
<td>Tar and sand pavement</td>
<td>0.014</td>
<td>0.012–0.016</td>
</tr>
<tr>
<td></td>
<td>Concrete pavement</td>
<td>0.017</td>
<td>0.014–0.020</td>
</tr>
<tr>
<td></td>
<td>Rough impervious surface</td>
<td>0.019</td>
<td>0.015–0.023</td>
</tr>
<tr>
<td></td>
<td>Smooth bare packed soil</td>
<td>0.021</td>
<td>0.017–0.025</td>
</tr>
<tr>
<td></td>
<td>Moderate bare packed soil</td>
<td>0.030</td>
<td>0.025–0.035</td>
</tr>
<tr>
<td></td>
<td>Rough bare packed soil</td>
<td>0.038</td>
<td>0.032–0.045</td>
</tr>
<tr>
<td></td>
<td>Gravel soil</td>
<td>0.032</td>
<td>0.025–0.045</td>
</tr>
<tr>
<td></td>
<td>Mowed poor grass</td>
<td>0.038</td>
<td>0.030–0.045</td>
</tr>
<tr>
<td></td>
<td>Average grass, closely clipped soil</td>
<td>0.050</td>
<td>0.040–0.060</td>
</tr>
<tr>
<td></td>
<td>Pasture</td>
<td>0.055</td>
<td>0.040–0.070</td>
</tr>
<tr>
<td></td>
<td>Timberland</td>
<td>0.090</td>
<td>0.060–0.120</td>
</tr>
<tr>
<td></td>
<td>Dense grass</td>
<td>0.090</td>
<td>0.060–0.120</td>
</tr>
<tr>
<td></td>
<td>Shrub and bushes</td>
<td>0.120</td>
<td>0.080–0.180</td>
</tr>
<tr>
<td></td>
<td>Business landuse</td>
<td>0.022</td>
<td>0.020–0.035</td>
</tr>
<tr>
<td></td>
<td>Semi-business land use</td>
<td>0.035</td>
<td>0.022–0.050</td>
</tr>
<tr>
<td></td>
<td>Industrial land use</td>
<td>0.035</td>
<td>0.020–0.050</td>
</tr>
<tr>
<td></td>
<td>Dense residential land use</td>
<td>0.040</td>
<td>0.025–0.060</td>
</tr>
<tr>
<td></td>
<td>Suburban residential land use</td>
<td>0.055</td>
<td>0.030–0.080</td>
</tr>
<tr>
<td></td>
<td>Parks and lawns</td>
<td>0.075</td>
<td>0.040–0.120</td>
</tr>
</tbody>
</table>

The maximum available moisture deficit, \( \theta_{\text{max}} \) (volume of dry voids per volume of soil).
A3.1.6 Storm design events

The eThekwini Municipality’s Design Storm Generator was used to determine the distribution of rainfall for different return periods, i.e. a 2-year, 5-year, 10-year and 20-year design storm. The EM Design Storm Generator uses a SCS Type II distribution (Figure A3.7) based on historical rainfall data (approximately 20 years) to generate a synthetic time distribution of rainfall intensity. The EM procedure of using a 24-hour rainfall depth for selected return periods was followed. The resultant design rainfall hyetograph was input into the SWMM models using a specified 5-minute interval.

A3.1.7 U60F model

The final model for catchment U60F is shown in Figure A3.8. Note the denser flowpaths where stormwater network data were available. The given HEC-RAS model and stormwater networks are shown in yellow and additional tributaries (in red and green) were added in using the watershed delineation tool.
A3.2 Points of interest for scenario analysis
The Umhlatuzana and Umbilo Rivers and other stormwater outfalls within the U60F subcatchment discharge directly into Durban Harbour. In the SWMM model, there are 79 outfalls in total (Figure A3.9). The peak flows and flow volume were estimated for each scenario for a 2, 5, 10 and 20-year return period. The effectiveness of GUD measures was not estimated for floods above a 20-year return period, as it is known that GUD interventions have little impact on larger floods.

A3.3 Model calibration

Real-time data were used for model calibration and validation. This was done using the data and methods outlined below. While river flows within the EMA tend to be relatively well monitored, there was no flow data available for the U60F quaternary catchment.

A3.3.1 Rainfall selection and application
Phase 1 of the calibration and validation was focused on the hydraulic flows and volumes. Real-time rainfall data for the EMA were obtained from the EM database. The Thiessen polygon method was applied to the rainfall stations in and around the U60F subcatchment and each rain gauge was assigned to a certain area (Figure A3.10).

A3.3.2 Design rainfall generation for U60F
The eThekwini Municipality’s Design Storm Generator was used to determine the distribution of rainfall for different return periods, i.e. a 2-year, 5-year, 10-year and 20-year design storm. The EM Design Storm Generator uses a SCS Type II distribution based on historical rainfall data (approximately 20 years) to generate a synthetic time distribution of rainfall intensity. The EM procedure of using a 24-hour rainfall depth for selected return periods was followed. The resultant design rainfall hyetograph was input into the SWMM models using a specified 5-minute interval.

A3.3.3 Available measured data
The efficacy of calibration depends entirely on the availability of measured data. Flow and/or water level data are most useful for the calibration of the hydraulic. Several real-time rainfall data sets were applied in order to calibrate the models.

A3.3.4 Calibration of flows and water levels
There are currently no measured flow or water level data available for the Umbilo and Umhlatuzana Rivers. Emphasis was, therefore, placed on setting up the model as accurately as possible. Peak flows were compared with peak flows estimated by Jezewski et al. (1984) and Makwananzi & Pegram (2004) who used a HEC-HMS model (Table A3.6). The peak flows estimated in the current study differ to those estimated by Makwananzi and Pegram (2004). Various methods to decrease the flood peaks were employed, however without measured data this was approached with caution. It is important to note that due to time constraints for this study, the time allocation for calibration was limited.

Table A3.6 Data used for calibration of flows and water levels

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>River</td>
<td>Area (km²)</td>
<td>Tc (h)</td>
<td>Peak Discharge (m³/s) for each return period</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2yr</td>
</tr>
<tr>
<td>Durban Bay</td>
<td>342</td>
<td>6.1</td>
<td></td>
</tr>
<tr>
<td>Umbilo</td>
<td>80</td>
<td>79</td>
<td>198</td>
</tr>
<tr>
<td>Umhlatuzana</td>
<td>118</td>
<td>127</td>
<td>244</td>
</tr>
</tbody>
</table>
The EM recently deployed a number of water sensors in the U60F catchment (in the Umhlatuzana and Umbilo Rivers) over two separate time periods. However, unusually heavy rainfall was experienced during both periods (including an almost 100-year flood) and most of the sensors were washed away. Two sensors were retrieved - one in the Umbilo River and one in the Umhlatuzana River. This data provided an indication of baseflows which helped to validate the accuracy of abstractions and return flows in these rivers. The sensitivity of the model to various hydraulic parameters was tested using the SRTC tool on PC-SWMM. The sensitivity of the results was tested for the various parameters (Table A3.7). The results were most sensitive to changes in the depression storage and % imperviousness.

Table A3.7  Sensitivity of runoff volume and peak flow to surface runoff parameters (EPA, 2015).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Typical effect on hydrograph</th>
<th>Effect of increase on runoff volume</th>
<th>Effect of increase on runoff peak</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>Significant</td>
<td>Increase</td>
<td>Increase</td>
<td>Less effect for a highly porous catchment</td>
</tr>
<tr>
<td>Imperviousness</td>
<td>Significant</td>
<td>Increase</td>
<td>Increase</td>
<td>Less effect when pervious areas have low infiltration capacity</td>
</tr>
<tr>
<td>Width</td>
<td>Affects shape</td>
<td>Decrease</td>
<td>Increase</td>
<td>For storms of varying intensity, increasing the width tends to produce higher and earlier hydrograph peaks, a generally faster response. Only affects volume to the extent that reduced width on pervious areas provides more time for infiltration.</td>
</tr>
<tr>
<td>Slope</td>
<td>Affects shape</td>
<td>Decrease</td>
<td>Increase</td>
<td>Same as for width, but less sensitive, since flow is proportional to square root of slope.</td>
</tr>
<tr>
<td>Roughness</td>
<td>Affects shape</td>
<td>Increase</td>
<td>Decrease</td>
<td>Inverse effects as for width.</td>
</tr>
<tr>
<td>Depression storage</td>
<td>Moderate</td>
<td>Decrease</td>
<td>Decrease</td>
<td>Significant effect only for low-depth storms.</td>
</tr>
</tbody>
</table>

A3.4  Assumptions and limitations
A number of assumptions were made during the setup of the SWMM model where input data were either insufficient or unreliable. These assumptions may be regarded as limitations of the model and therefore should be considered when analysing the results.

A3.4.1  The use of design rainfall
Note that design rainfall assumes that rainfall is equally distributed over the whole catchment at the same time. Realistically, a specific design rainfall does not imply an equal design runoff, however this is general practice when performing flood studies.

A3.4.2  Groundwater and baseflows
Groundwater was not included in the modelling. Insufficient data were available to incorporate any accurate representation of groundwater flows. Therefore, measured flow/water level data was used to infer the groundwater as baseflow. Groundwater inputs vary seasonally, therefore the ‘baseflow’ was estimated during summer and winter periods and incorporated into the model as a time series where possible.

A3.4.3  Stormwater network data
The current stormwater network data were inconsistent and incomplete. Only certain areas of the current SMS audit have been completed and were included in the model, however inconsistencies and errors were also found in these networks. Missing data were entered based on the following assumptions:

- pipe sizes: a default value of 0.375 m
- invert levels: levels were taken from the DEM and the profile was altered in order to acquire a reasonable slope

The model was run numerous times in order to resolve flooding and continuity issues resulting from problems with these data. Invert levels were manually adjusted in order to correct negative slopes.
APPENDIX 4: INFRASTRUCTURE COST ESTIMATE METHOD

A4.1 Overview
This section describes the cost estimation method. The method estimates the existing infrastructure costs from their dimensions. It then uses a scaling relationship between flow and the infrastructure dimensions to estimate the stormwater requirements under the different land use scenarios. The infrastructure required to satisfy the various scenarios are then costed. The cost difference between the existing infrastructure and the scenario infrastructure is indicative of the value of the natural areas.

A4.2 Identifying existing infrastructure
An inventory of all the stormwater infrastructure is identified and categorised into four major categories: bridges; canals; culverts and pipe networks. The bridges are divided into a further two subcategories: bridge culverts and bridge pipes. The bridge category excludes major bridges as their size is insensitive to flows.

A4.3 Assigning rainfall return periods
Each infrastructure category is assigned a design return period based on the eThekwini Design Guidelines (eThekwini Municipality 2008). Table A4. 1 shows the return periods associated with the relevant infrastructure category. The design rainfalls are then modelled to estimate the peak flows for each structure.

<table>
<thead>
<tr>
<th>Category</th>
<th>Return Period (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bridges</td>
<td></td>
</tr>
<tr>
<td>Bridges Culverts</td>
<td>20</td>
</tr>
<tr>
<td>Bridges Pipes</td>
<td>20</td>
</tr>
<tr>
<td>Canals</td>
<td>10</td>
</tr>
<tr>
<td>Culverts</td>
<td>5</td>
</tr>
<tr>
<td>Pipes</td>
<td>2</td>
</tr>
</tbody>
</table>

A4.4 Cost estimate of the infrastructure
Costs are estimated for each of the four categories as each contains different assumptions. Material costs are based on 2016 prices with delivery to central Durban. All prices include a 10% mark-up and exclude value added tax (VAT). Labour rates are legislated for the Civil Construction industry and were taken as R27/hr. All infrastructure was assumed to be under road ways and the reinstatement was estimated to be R420/m2. Excavation was taken as R90/m3, selected backfill as R80/m3 and backfill at R60/m3. The supply and placing of concrete was estimate at R2400/m3, shuttering was assumed to be R650/m2 and the supplying and fixing of steel was taken as R1200/t. Concrete blinding was estimated as R1600/m3. A 10-20% allowance on the total cost was provided for preliminary and general items (P&G) such as site establishment and supervision. The individual rates for each infrastructure category are summarised in additional information.

A4.4.1 Bridges
Bridges have two subcategories: bridge culverts and pipe culverts. Bridges differ from the culvert and pipe categories as they are positioned within watercourses. To allow for the complications of dealing with water the P&G was set to 20%. With the exception of not having manholes the bridge culverts and the pipe bridges are priced the same as the culverts and the pipes respectively.

A4.4.2 Culverts
Culverts are defined as any non-circular structure not acting as a bridge. The culvert costs are estimated from the cross-sectional area and the length. It is assumed that all the culverts are constructed from 0.3 m thick insitu reinforced concrete with steel reinforcing attributing to 4% of the total volume. It is assumed that all the ground conditions are the same and that the structures are founded on 200 mm of concrete blinding. Excavation quantities are based on 600 mm of cover and a payment width as defined in Clause 5.2 of SANS 1200DB. Manholes were priced as R25 000 each and one was assumed every 60 m.

A4.4.3 Canals
Canals are priced the same as culverts except there are no roof slabs, cover material or manholes.

A4.4.4 Pipes
The pipe costs are calculated similarly to the culvert costs. It is assumed that all the ground conditions are the same and that a Class B bedding (Drawing LB-1, SANS 1200LB) is used throughout. Excavation quantities are based on 600 mm of cover and a payment width as defined in Clause 5.2 of SANS 1200DB. Manholes were priced as R25 000 each and one was assumed every 60 m.
A4.5 Flow vs dimension relationship

To estimate the changes in cost relationship between flow and the infrastructure dimensions needs to be established. These flow relationships can be established theoretically for diameter and area from uniform flow conditions. The relationship is then used to scale the infrastructure dimensions for the different scenario flows. A scaling relationship exists for open channel flows and pressurised flows. Both of these flow types are estimated for each flow scenario.

A4.5.1 Pipe scaling

The scaling relationship for pipe diameters in open channel flow is

\[ D = D_0 \left( \frac{Q}{Q_0} \right)^{\frac{1}{2}} \]

and the scaling relationship for pressurised flows is

\[ D = D_0 \left( \frac{Q}{Q_0} \right)^{\frac{1}{3}} \]

where \( D \) is the scaled diameter, \( D_0 \) is the existing pipe diameter, \( Q \) is the scenario flow and \( Q_0 \) is the flow under the existing conditions (status quo).

A4.5.2 Culvert scaling

The scaling relationship for culvert area in open channel flow is

\[ A = A_0 \left( \frac{Q}{Q_0} \right)^{\frac{3}{2}} \]

and the scaling relationship for pressurised flows is

\[ A = A_0 \left( \frac{Q}{Q_0} \right)^{\frac{1}{3}} \]

where \( A \) is the scaled area, \( A_0 \) is the existing culvert area, \( Q \) is the scenario flow and \( Q_0 \) is the flow under the existing conditions (status quo). The culvert width is then determined by dividing the scaled area, \( A \), by the culverts original height.

A4.5.3 Estimating the flow type

To determine which scaling relationship is to be used the flow type needs to be estimated. The flow type is estimated by calculating the infrastructure’s maximum open channel flow from the Manning’s equation. This flow is referred to as the threshold flow and it is calculated from

\[ Q_{\text{threshold}} = \frac{1}{n} \left( \frac{A}{S_p} \right)^{\frac{5}{3}} \]

where \( n \), the Manning’s roughness, is assumed to represent concrete at a value of 0.015, \( A \) is the cross-sectional area, \( P \) is the perimeter and \( S_p \) is the slope of the infrastructure.

If the scenario flow, \( Q_c \), is less than the threshold flow the open channel scaling is used. If the scenario flow exceeds the threshold flow then the pressurised scaling is used.

Two other conditions are included to ensure that the scaling does not artifically inflate the benefit of the natural areas. If the scenario flow does not exceed the threshold flow and the existing flow then no scaling is applied. If the scenario flow exceeds the threshold flow but does not exceed the existing flow then the open channel scaling is applied. These conditions ensure that scenario flows that are larger than the existing flows but that do not require larger infrastructure are not scaled. This means that artificial benefits are not attributed to the natural areas. It also ensures that the cost of over design and future capacity are not penalised.

The followings is a summary of all the conditions relevant to the scaling:

1. If \( Q > Q_{\text{threshold}} \)
   then \( D = D_0 \left( \frac{Q}{Q_0} \right)^{\frac{1}{2}} \) or \( A = A_0 \left( \frac{Q}{Q_0} \right)^{\frac{3}{2}} \)

2. If \( Q < Q_{\text{threshold}} \) and \( Q < Q_0 \)
   then \( D = D_0 \left( \frac{Q}{Q_0} \right)^{\frac{1}{2}} \) or \( A = A_0 \left( \frac{Q}{Q_0} \right)^{\frac{1}{3}} \)

3. If \( Q < Q_{\text{threshold}} \) and \( Q \geq Q_0 \)
   then \( D = D_0 \) or \( A = A_0 \)

A4.6 Cost comparison

The difference between the existing infrastructure costs and the scenario infrastructure costs are the indicative value of the natural areas.

A4.7 Additional information

The items included for the costing of each category are shown in Table A4.2, Table A4.3, Table A4.4, Table A4.5. Table A4.6 shows the linear meter cost of concrete stormwater pipes.
APPENDIX 5. SEDIMENT AND NUTRIENT MODELLING

A5.1 Model setup
The water quality parameters assessed during the scenario analysis were nitrogen, phosphorous and total suspended solids (TSS). The landuses that generate these pollutants were defined and the pollutant build-up, pollutant washoff and street cleaning parameters were assigned to each landuse. The pollutant removal functions for nodes within the drainage system that contain storage/treatment facilities were also defined. The input parameters for each pollutant are as follows:

- the pollutant name;
- the concentration units (i.e. mg/L, μg/L, counts/l);
- concentration in rainfall;
- concentration in groundwater;
- concentration in direct infiltration/inflow; and
- first-order decay coefficient.

Note that no data was available to estimate the pollutant build-up and street cleaning parameters and therefore these features were not considered. The pollutant washoff from a given land use occurs during periods of wet weather and can be characterized in SWMM5 by either using an exponential or rating curve relationship. The Event Mean Concentration is a case of Rating Curve Washoff where the exponent is 1.0 and the coefficient represents the washoff pollutant concentration in mg/L. In each case build-up is continuously depleted as washoff proceeds, and washoff ceases when there is no more build-up available. The EMCs were derived from the literature (Table A5.1). These data were applied to the different landuse categories across the study area. The data below can be applied in determining the water quality volume to be catered for in stormwater management devices (e.g. source controls).

The TSS load estimated in PC-SWMM accounts for the total suspended sediments generated due to catchment runoff and does not account for the proportion of sediment transport activated from the river bed (i.e. the bedload). While bedload transport is the dominant mode for low velocity flows and/or large grain sizes, suspended load transport is the dominant mode for high velocity and/or fine grain sizes (Chadwick et al., 2013). In South Africa, a factor of 1.25 is generally applied to cater for bed load and non-uniformity in suspended sediment concentrations in order to estimate the mean annual sediment load (Msadala et al. 2010, after Rooseboom 1992). Cooper (1993) referenced estimates of the proportion of bedload in KwaZulu-Natal rivers from other studies to range from 12 to 50%.

A5.1.1 Rainfall
Real-time rainfall data was applied to the models. The simulations were run from 1 August 2013 until 30 July 2014. Note that sediment yields vary spatially and temporally and therefore a one year simulation is not indicative of the mean annual sediment yield. The annual rainfall (572 mm for Durban city central) experienced during this period was below the MAP of Durban (1000 mm) and therefore simulated results are conservative. Note that Rooseboom & Lotriet (1992) suggest that six years of continuous monitoring is required to obtain a reasonable estimate of the average sediment load of a typical South African river.

<table>
<thead>
<tr>
<th>Landuse Description</th>
<th>TSS (mg/l)</th>
<th>BOD (mg/l)</th>
<th>TIN (mg/l)</th>
<th>P (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Settlement - urban</td>
<td>100</td>
<td>15</td>
<td>3.41</td>
<td>0.79</td>
</tr>
<tr>
<td>Commercial / retail / Institutional</td>
<td>166</td>
<td>9</td>
<td>2.1</td>
<td>0.37</td>
</tr>
<tr>
<td>Industrial / road and rail</td>
<td>166</td>
<td>9</td>
<td>2.1</td>
<td>0.37</td>
</tr>
<tr>
<td>Extractive / utility</td>
<td>166</td>
<td>9</td>
<td>2.1</td>
<td>0.37</td>
</tr>
<tr>
<td>Farming / plantations and woodlots</td>
<td>201</td>
<td>4</td>
<td>1.56</td>
<td>0.36</td>
</tr>
<tr>
<td>Recreational open space</td>
<td>201</td>
<td>4</td>
<td>1.56</td>
<td>0.36</td>
</tr>
<tr>
<td>Settlement - rural</td>
<td>201</td>
<td>4</td>
<td>1.56</td>
<td>0.36</td>
</tr>
<tr>
<td>Natural vegetation (D’MOSS)</td>
<td>70</td>
<td>6</td>
<td>1.51</td>
<td>0.12</td>
</tr>
<tr>
<td>Settlement - informal</td>
<td>497</td>
<td>22</td>
<td>6.7</td>
<td></td>
</tr>
</tbody>
</table>
A5.2 Points of interest for scenario analysis

The Umhlatuzana and Umbilo Rivers and other stormwater outfalls within the U60F subcatchment discharge directly into Durban Harbour. As a result, Durban Harbour is synonymous with poor water quality.

In the SWMM model, there are 79 outfalls in total. The annual loadings for TIN, TSS and P were simulated over a 1-year period (July 2013 to June 2014). In addition to the outfalls, pollutant load and maximum flows were simulated at a number of water quality monitoring stations situated in catchment U60F (Table A5. 2, Figure 5.8). Note that these are the monitoring stations that monitor nutrients as well as the physico-chemical parameters.

<table>
<thead>
<tr>
<th>Sampling station</th>
<th>River</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>R_Zana_10</td>
<td>Umhlatuzana</td>
<td>Before the Umhlatuzana River meets the Umbilo river</td>
</tr>
<tr>
<td>R_Zana_20</td>
<td>Umhlatuzana</td>
<td>Umbhlatuzana River, upstream of the Umhlatuzana WWTWs</td>
</tr>
<tr>
<td>R_Zana_24</td>
<td>Umhlatuzana</td>
<td>Umbhlatuzana River, downstream of the Umbhlatuzana WWTWs</td>
</tr>
<tr>
<td>R_Zana_34</td>
<td>Umbhlatuzana</td>
<td>Umbhlatuzana River, downstream of the Hillcrest WWTWs</td>
</tr>
<tr>
<td>R_Zana_35</td>
<td>Umbhlatuzana</td>
<td>Umbhlatuzana River, upstream of the Hillcrest WWTWs</td>
</tr>
<tr>
<td>R_Umbilo_04</td>
<td>Umbilo</td>
<td>On the Umbilo River at Bellair Road – upstream of the Umbilo WWTWs</td>
</tr>
<tr>
<td>R_Umbilo_13</td>
<td>Umbilo</td>
<td>Before the Umbilo river meets the Umhlatuzana River</td>
</tr>
<tr>
<td>R_Umbilo_27</td>
<td>Umbilo</td>
<td>On the Umbilo River at Stapleton Road – upstream of the Umbilo WWTWs</td>
</tr>
<tr>
<td>R_Mkumbaan_01</td>
<td>Mkumbaan</td>
<td>On the Mkumbaan River which is a tributary of the Umbilo River</td>
</tr>
</tbody>
</table>

A5.3 Model calibration

Monthly water quality data collected by the eThekwini Water and Sanitation Department were used for calibration and validation of the model. Most of the rivers within the EMA are monitored. Table A5. 2 provides a summary of the sampling stations in the catchment used for calibration of the model. The water quality measured at the outfalls of the WWTWs were analysed (Table A5. 3). These values were significantly lower than those provided in the General Effluent Limits. Therefore the values were replaced with the average TIN, P and TSS values measured at each outfall of the WWTWs.

Simulations were run for a one-week period from the 1 – 7 July 2014 at a two second time interval. This period was chosen because there was one rainfall event experienced throughout the subcatchment. The results from these simulations are given in Figure A5. 1 and Figure A5. 2. The corresponding water quality parameters measured at the same points are provided in Figure A5. 3. Note that the simulated values are within reasonable range of the measured values.

The assumptions and limitations associated with model calibration include the following:

- The water quality monitoring program takes measurements on a monthly basis. This data therefore provides a snapshot of the water quality at a point at a specific time. TSS concentrations were inferred from turbidity data collected by the EM. The relationship between TSS and turbidity was taken from data collected by Newman (2015) in the Durban Bay, which has a high salinity. TSS concentrations are temporally and spatially dependant and therefore this is not a true representation of actual TSS concentrations. We recognise that this a major limitation in the estimation of measured TSS loads used for calibration;

- TIN, P and TSS concentrations from the WWTWs were averaged and added into the model as a point source at the outfall site of the relevant WWTWs. The discharge rates were assumed to be equal to the design capacity and is therefore not a true representation of actual discharge rates and quality; and

- Generalised event mean concentrations (EMC) were based on values derived in the United States.
Figure A5.2  Measured rainfall and simulated flow, depth, P, TIN, TSS concentrations for monitoring station (R_UMBilo_13) on the Umbilo River.

Figure A5.3  Measured water quality from water sampling stations on the Umbilo and Umhlatuzana Rivers at the same locations as the simulations.
A6.1 Approach for assessing river condition

Changes in river condition associated with each of the different scenarios were assessed quantitatively, in terms of modelled instream water quality, and qualitatively, in terms of some of the broad parameters included in considerations of ecosystem health.

The quantitative assessments used modelled concentrations of the three parameters included in the hydrological and water quality model namely total phosphorous (TP), total suspended solids (TSS) and Total Inorganic Nitrogen (TIN). Modelled hourly concentrations of these parameters were available for the 10 sites shown in Figure A6.1. Location of water quality sampling sites for which data have been used in the hydrological model for a one-year period. The time series dataset was simplified to mean daily concentrations. These were presented in terms of different river health or condition categories, as recommended in South African (national) draft guidelines (DWAF 2008) and interpreted in Table A6.1. The range and/or threshold values were also taken from (DWAF 2008), as presented in Table A6.2. Note that these values include orthophosphate (PO$_4$-P) thresholds rather than total phosphorus. Since only total phosphorus data were available for this study, this means that interpretation of data will tend to exaggerate phosphorus enrichment slightly in some cases, although orthophosphate tends to comprise by far the largest portion of total phosphorus in riverine systems.

Figure A6.1  Location of water quality sampling sites for which data have been used in the hydrological model
The importance and relevance of TSS in assessing water quality impacts on ecosystems

TSS is an important measure of water quality and river ecosystem health. It may be used to approximate turbidity, and thus provide an understanding of water clarity – of importance particularly in open water systems such as lakes and (in the present case) the harbour, as water clarity often determines dominance of the shallow water environment either by aquatic macrophytes or phytoplankton. In addition to its links with water clarity and plant growth, suspended inorganic material carries an electric charge, and thus provides adsorption sites for nutrients (phosphorus and nitrogen) as well as trace metals and various organic biocides. Suspended materials that settle out may smother and abrade riverine plants and animals. Community composition may change, depending on which organisms are best able to cope with this alteration in habitat. Predator-prey interactions can also be affected by the impairment of visibility for predators that hunt by sight.

The qualitative assessments carried out in this project considered the metrics used in Present Ecological State (PES) assessments of turbidity (see Table A6.3) for which TSS is considered a surrogate value to infer qualitative change in river condition as a result of scenarios involving attenuation of runoff and the provision of riparian corridors and buffers. Comment on the assumed relative influence of different scenarios on these issues was provided, with changes in TSS data produced by the model also used to infer (but not quantify) changes in sediment transport and erosion. In addition to limitations in the applicability of TSS data in inferring catchment-scale erosion and sediment processes, the following limitations must also be considered with regard to the approach taken to assessment of the impact of the different scenarios on river condition (Table A6.4), and in particular, on river water quality, in this study, namely:

- The assessments are limited to TP, TSS and DIN and do not take account of other variables such as ammonia-nitrogen, various heavy metal concentrations, bacteria, salinity;
- The lack of data for other important water quality parameters means that interacting parameters are not considered (e.g. the influences of dissolved oxygen, pH, temperature and [in the case of some heavy metals] water hardness); and
- The lack of data regarding the organic component of TSS and the proportions of total ammonia and orthophosphate comprising TIN and TP respectively.

### Table A6.1
Comparison of different systems for the categorisation of river health/condition data, after DWAF (2008). National guidelines for the determination of the ecological reserve with regard to water quality recommend the use of numeric ratings 0-1.

<table>
<thead>
<tr>
<th>Rating</th>
<th>Deviation from reference conditions</th>
<th>A-F Categories</th>
<th>Natural-Poor categories</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No change</td>
<td>A</td>
<td>Natural</td>
</tr>
<tr>
<td>1</td>
<td>Small change</td>
<td>B/C</td>
<td>Poor</td>
</tr>
<tr>
<td>2</td>
<td>Moderate change</td>
<td>C/D</td>
<td>Fair</td>
</tr>
<tr>
<td>3</td>
<td>Large change</td>
<td>D/E</td>
<td>Good</td>
</tr>
<tr>
<td>4</td>
<td>Serious change</td>
<td>E/F</td>
<td>Good</td>
</tr>
<tr>
<td>5</td>
<td>Extreme change</td>
<td>F</td>
<td>Good</td>
</tr>
</tbody>
</table>

### Table A6.2
Threshold values for variables considered in this study, using ranges defined for each River Health Category (see Table 5.15). The values shown in each row represent the upper threshold value of that category.

<table>
<thead>
<tr>
<th>Category</th>
<th>A-F</th>
<th>0-5</th>
<th>PO₄-P (mg P/L)</th>
<th>TIN (mg N/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>&lt;0.005</td>
<td>&lt;0.25</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>&lt;0.015</td>
<td>&lt;0.25</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>2</td>
<td>&lt;0.025</td>
<td>&lt;0.35</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>3</td>
<td>&lt;0.125</td>
<td>&lt;1</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>4</td>
<td>&lt;1</td>
<td>&lt;10</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>5</td>
<td>≥1</td>
<td>≥10</td>
<td></td>
</tr>
</tbody>
</table>

Total suspended solid (TSS) data could not be interpreted in this manner. DWAF (2008) does not in fact quantify TSS concentrations for different health rating values, on the basis that these data are not routinely measured by the Department of Water and Sanitation (DWS). Existing water quality guidelines for TSS are also limited, with target ranges for South African aquatic ecosystems being specified by DWAF (1996) as limited to a 10% increase in background TSS concentrations at a particular site and time, although DWAF (2008) notes the high natural variability between systems, making definition of degrees of change difficult in practice. Even when Reference ("Natural") Condition TSS data are available for a particular system, their value is often limited. This is because of the tight links between sediment transport and flow velocity, and the large differences in sediment transport depending on discharge. In the current situation, therefore, while modelled TSS concentrations allowed comparison between different scenarios, and some comment on likely removal rates of other parameters likely to be associated with inorganic sediments (e.g. heavy metals and total phosphorus) they could not be used to infer absolute erosion and sedimentation rates. Guidelines for the interpretation of links between turbidity and river health, as provided in Table A6.3 (after DWAF 2008) were also drawn on in this regard.

### Table A6.3
Guidelines to inform Present Ecological State ratings for turbidity/clarity (after DWAF 2008)

<table>
<thead>
<tr>
<th>Rating</th>
<th>Deviation from reference condition</th>
<th>Environmental clues about the turbidity status</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No change</td>
<td>Pristine river, no known man-made modifications of the catchment, no known concerns about turbidity, changes in turbidity appears to be natural and related to natural catchment processes such as rainfall runoff.</td>
</tr>
<tr>
<td>1</td>
<td>Small change</td>
<td>Some minor man-made modifications to the catchment, changes in turbidity appear to be largely natural and related to natural catchment processes such as rainfall runoff. Very minor effects of altering of habitats, of temporary nature and natural river processes clearly newly deposited silt soon after the event</td>
</tr>
<tr>
<td>2</td>
<td>Moderate change</td>
<td>Moderate changes to the catchment land-use have resulted in unnaturally high sediment loads and high turbidity during runoff events. The impacts are however temporary.</td>
</tr>
<tr>
<td>3</td>
<td>Large change</td>
<td>Erosion and/or river runoff processes is a known cause of unnaturally large increases in sediment loads and turbidity, habitat often silted but it is cleared from time to time. Low amounts of periphyton algae or phytoplankton are present.</td>
</tr>
<tr>
<td>4</td>
<td>Serious change</td>
<td>The catchment is known to have serious erosion problems, increased turbidity levels are present most of the time, large silt loads are deposited leading to a serious reduction in habitat. Low amounts of periphyton algae or phytoplankton are present.</td>
</tr>
<tr>
<td>5</td>
<td>Extreme change</td>
<td>The catchment is known to have serious erosion problems, increased turbidity levels are present most of the time, large silt loads are deposited leading to a total loss of habitat, silt loads are so high that fish kills have been attributed to it.</td>
</tr>
</tbody>
</table>

### Table A6.4
Present Ecological State (PES) metrics and explanations after (DWA 2013), and used in this study to infer qualitative change in river condition as a result of scenarios involving attenuation of runoff and the provision of riparian corridors and buffers.

<table>
<thead>
<tr>
<th>Metrics</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potential instream habitat continuity modification</td>
<td>Modifications that indicate the potential that instream connectivity may have changed from the reference. Indicators: Physical obstructions (e.g. dams, weirs, causeways). Flow modifications (e.g. low flows, artificially high velocities, physico-chemical &quot;barriers&quot;).</td>
</tr>
<tr>
<td>Potential riparian/wetland habitat continuity modification</td>
<td>Modifications that indicate the potential that riparian/wetland connectivity may have been changed. Indicators: Physical fragmentation, e.g. inundation by weirs, dams, physical removal for farming, mining, etc.</td>
</tr>
<tr>
<td>Potential instream habitat modification activities.</td>
<td>Modifications that indicate the potential of instream habitats that may have been changed from the reference. Includes consideration of the functioning of instream habitats and processes, as well as habitat for instream biota specifically. Indicators: Derived likelihood that instream habitat types (runs, rapids, riffles, pools) may have changed in frequency (temporal and spatial). Assessment is based on flow regulation, physical modification and sediment changes, land use/land cover (erosion, sedimentation), abstraction etc. may indicate the likelihood of habitat modification. The presence of weirs and dams are possible indicators of causes of instream habitat change. Certain introduced biota (e.g. carp, crucianaceae and mollusca) may also cause habitat modification. Eutrophication and resulting algal growth as well as macrophytes may also result in substantial changes in habitat availability.</td>
</tr>
<tr>
<td>Potential riparian/wetland zone Modifications</td>
<td>Modifications that indicate the potential that riparian/wetland zones may have been changed from the reference in terms of structure and processes occurring in the zones. Also refers to these zones as habitat for biota. Indicators: Derived likelihoods that riparian/wetland zones may have changed in occurrence and structure due to flow modification and physical changes due to agriculture, mining, urbanisation, inundation etc. Based on land cover/land use information. The presence and impact of alien vegetation is also included.</td>
</tr>
<tr>
<td>Potential flow modification</td>
<td>Modifications that indicate the potential that flow and flow regimes have been changed from the reference. Indicators: Derived likelihood that flow and flow regimes have changed. Assessment based on land cover/land use information (urban areas, interbasin transfers), presence of weirs, dams, water abstraction, agricultural return flows, sewage releases, etc.</td>
</tr>
<tr>
<td>Potential physico-chemical modification activities</td>
<td>Activities that indicate the potential of physico-chemical conditions that may have changed from the reference. Indicators: Presence of land cover/land use that implies the likelihood of a change of physico-chemical conditions away from the reference. Activities such as burning, cultivation, irrigation (i.e. agricultural return flows), sewage works, urban areas, industries, etc. are useful indicators. Algal growth and macrophytes may also be useful response indicators.</td>
</tr>
</tbody>
</table>
A6.2 Model outcomes

The figures below reflect the modelled concentrations of TSS, total phosphorus and TIN under different scenarios, at key water quality monitoring sites in the catchment (see Figure A6.1. Location of water quality sampling sites for which data have been used in the hydrological model).

Figure A6.2 Effects of different modelled scenarios on total phosphorus concentrations at different monitoring sites in the study area.

Figure A6.2 (cond.) Effects of different modelled scenarios on total phosphorus concentrations at different monitoring sites in the study area.
Figure A6.3 Effects of different modelled scenarios on total suspended solids (TSS) concentrations at different monitoring sites in the study area.
Figure A6.3 (cond) Effects of different modelled scenarios on total suspended solids (TSS) concentrations at different monitoring sites in the study area

Figure A6.4 Effects of different modelled scenarios on total inorganic nitrogen (TIN) concentrations at different monitoring sites in the study area
Figure A6.4 (cond.) Effects of different modelled scenarios on total inorganic nitrogen (TIN) concentrations at different monitoring sites in the study area.

**Zonke_28**

**Zonke_10**

**Umbilo_13**

**Amazimnyanya_OF11UMB**

**Combined outfall_OF21UMB**