CIV5000Z MASTERS DISSERTATION: CIVIL ENGINEERING

Century City as a case study for Sustainable Drainage Systems (SuDS) in South Africa

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"Have we been equally ambitious in reinventing our role in shaping the future of rapid urbanisation worldwide? Will we remain leaders in lagging technologies – following the parade with brooms and shovels, cleaning up environmental damage and compensating for the impacts of economic development? There is clearly an opportunity for us to reinvent our role in the future of sustainable urban development. To help environmental decision-makers incorporate economic and social ends in their pursuit of environmental and public health protection. We cannot be accused of ignoring the environment. We may be guilty, however, of being isolated from the economic and social issues related to urbanisation and land use."

– P.R. Brown (Cities of the Future)

"Do you not know that in a race all the runners compete, but [only] one receives the prize? So run [your race] that you may lay hold [of the prize] and make it yours. Now every athlete who goes into training conducts himself temperately and restricts himself in all things. They do it to win a wreath that will soon wither, but we [do it to receive a crown of eternal blessedness] that cannot wither. Therefore I do not run uncertainly (without definite aim). I do not box like one beating the air and striking without an adversary. But [like a boxer] I buffet my body [handle it roughly, discipline it by hardships] and subdue it, for fear that after proclaiming to others the Gospel and things pertaining to it, I myself should become unfit [not stand the test, be unapproved and rejected as a counterfeit]."

– 1 Corinthians 9:24-27 (Amplified)

Declaration

This dissertation is prepared for the faculty of Engineering and Built Environment in partial fulfilment of the requirements for the degree of *Masters in Engineering in Civil Engineering*; as described in the Engineering and Built Environment Student Handbook (2011). This dissertation is a product of the Civil Engineering Department at the University of Cape Town.

I, Michael Alexander Pringle Vice, know the meaning of plagiarism and declare that all the work in this dissertation, barring that which I have properly acknowledged, is my own.

Signed: ________________________

Michael AP Vice

Date: ________________________

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Terms of Reference

On the 18th of January 2010, the Department of Civil Engineering at the University of Cape Town (UCT) commissioned Mr. Michael Vice with a dissertation entitled, "Century City as a case study for Sustainable Drainage Systems (SuDS) in South Africa", under the supervision of Associate Professor Neil Armitage. The dissertation, which is in partial fulfilment of the requirements for the degree of *MSc in Engineering in Civil Engineering*, is the sole requirement of the postgraduate course; CIV5000Z MASTERS DISSERTATION: CIVIL ENGINEERING. A number of items in the dissertation also form part of the Water Research Commission (WRC) deliverables for project *K5/1826: Alternative technology for stormwater management*. The requirements stipulated by UCT for the dissertation and associated dissertation preparation are recorded in the Faculty of Engineering and Built Environment (EBE) Handbook (2010 edition) as follows:

CIV5109Z DISSERTATION PREPARATION

DP requirement for entry to CIV5000Z.

Course outline: The aim of this course is to allow the student to undertake preparatory work for the Masters Dissertation. Work required includes literature searches and reviews; identification of the research problem, objectives and hypothesis; consideration of research methodology; planning for the active research phase; and ensuring that research infrastructure (e.g. apparatus etc.) is or will be in place. The student should maintain regular contact with his/her supervisor in order to show evidence of suitable progress towards these aims. The supervisor must indicate satisfactory fulfilment of the course aims prior to the student proceeding to the dissertation.

CIV5000Z MASTERS DISSERTATION: CIVIL ENGINEERING

120 NQF credits.

Prerequisites: CIV5109Z.

The WRC's requirements are recorded in the Water Research Commission's Solicited Research Proposal for K5/1826: Alternative technology for stormwater management (2008) and stipulate the following with respect to the South African Draft Guidelines for SuDS and associated technical report:

SuDS GUIDELINES

The SuDS guidelines will be directed to practitioners and will include, inter alia;

- The type of area where the technology is most applicable

- A description of the technology
- The operation and maintenance requirements
- The relative costs of the technologies and their efficiency in reducing stormwater flow rates and quantities, and improving water quality
- The advantages and disadvantages of alternative technology over traditional approaches
- Lessons learnt from the research
- An option selection matrix

TECHNICAL REPORT

The report (or reports) will present:

- The literature review
- Methodology
- Pilot studies
- Lessons learnt
- An evaluation of the various options (distinguishing between greenfield and retrofit, economic and sub-economic)
- The legal requirements
- The conclusions and recommendations.

The dissertation was formatted according to the standards displayed in, "Preparing a report in MS Word for Windows" (Armitage & Carden, 2004), and "Professional Communication" (English *et al.*, 2006), as instructed by A/Prof. Neil Armitage.

Abstract

South Africa's developing cities are experiencing rapid urbanisation, particularly in the major metropolises. Infrastructural development is a prominent component of the South African economy, and has been allocated hundreds of billions of Rands by the budgetary council in the present political term of office (2009-2014). In light of the harmful effects of anthropogenic emissions on the environment, the increasing scarcity of freshwater resources, and the speedy progression of the 'climate change' phenomenon, scholars largely suggest that prospective development should advance according to the ideals of 'sustainability' and take the form of 'sustainable development'. These discourses essentially promote the improvement of the quality of human life within the capacity of supporting ecosystems (WCU, 1991). They are relatively new in the South African development sector, and challenge the underlying principles of 'conventional' design and management practices.

There is a particularly ardent interest in the promotion of sustainable development in the management of stormwater runoff. The drainage of impervious urban development in South Africa is largely achieved using 'hard', conventional drainage infrastructure such as concrete lined gutters, cast iron catchpits, pipe and manhole networks, and canalisation. However, this causes an increase in stormwater runoff volumes, flows, and flood peaks downstream, leading to the deterioration of environmental assets and the goods and services they provide. In developed countries such as Australia, the USA, and the UK, an alternative form of urban drainage namely Sustainable Drainage Systems (SuDS) has been used as an alternative urban drainage practice for almost 25 years. The objective of SuDS is to manage surface water drainage holistically in line with the ideals of sustainable development by effectively managing stormwater runoff quantity, quality and the associated amenity and biodiversity. This can be achieved by mimicking the natural hydrological cycle through a number of sequential stormwater management interventions in the form of a 'treatment train'.

The purpose of this dissertation is to present Century City as a case study to assess the early implementation of SuDS in South Africa. The case study highlights several critical issues and practical obstacles that urban practitioners should consider in prospective SuDS schemes. Century City's stormwater management system is characterised by conventional drainage practices, isolated SuDS options, and SuDS options aligned in 'treatment train' configuration – termed a 'transitional drainage system', as it transitions between conventional and sustainable drainage practices. The findings of the case study include, *inter alia*, ineffective design approaches to SuDS options, disparities between the management approaches to conventional and sustainable stormwater systems, and problematic management interventions in the constructed wetland. Two items are included in the appendices as supplementary information to the case study, namely: (1) the South African Draft Guidelines for Sustainable Drainage Systems (SuDS), and (2) a SuDS Conceptual Design Poster. Both documents were drafted and compiled by the author as additional research objectives. The guidelines and poster can be used collectively to aid in the planning, design and management of SuDS schemes in South Africa.

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Glossary of Terms

This glossary contains stormwater management and engineering related terms that are used throughout this dissertation. Terms used differently from that stipulated in the glossary will be defined specifically in the context in which they are used. The sources utilised for the compilation of this glossary include: CSIR (2000a,b), Debo & Reese (2003), Roads and Stormwater Department (2009a,b), Wilson et al. (2004), Woods-Ballard et al. (2007).

Abstraction is the portion of rainfall that does not contribute to runoff, typically including, interception, infiltration and storage in local depressions.

Absorption refers to the taking up of one substance into the body of another. i.e. stormwater runoff taken up into a plant.

Accretion is a process of natural or artificial accumulation of silt, sand or other soil-type media, resulting in the development of additional land.

Aerobic is the state requiring or allowing the presence of free essential oxygen.

Anaerobic is the absence of free elemental oxygen, or a state not requiring or damaged by the absence of free elemental oxygen.

Annual exceedance frequency refers to the frequency that a particular flood level may be expected to occur each year.

Annual probability of exceedance is the statistical probability of a hydrological rainfall event of a given magnitude being equalled or exceeded in any given year.

Aquifer is a porous, water-logged subsurface geological formation, restricted to mediums capable of yielding a substantial supply of water.

Attenuation means the reduction of peak stormwater flow.

Authorised person is a person appointed or authorised by the Council of a Metropolis to perform orders of duty, under a specified stormwater management by-law.

Bioretention area is a depressed landscaping area that collects stormwater runoff so it infiltrates into the soil below the area into an underdrain, thus prompting pollutant removal.

Block paver is a precast concrete or clay brick sized flexible modular unit.

Brownfield means a site or land that is or was occupied by a permanent structure, which may have become vacant, under-used or derelict and has the potential for redevelopment.

Buffer strip is a vegetated area of gently sloping ground designed to drain water evenly off impermeable areas and filter out insoluble pollutants. It is also known as a filter strip.

Catchment means the area from which any rainfall will drain into a watercourse or wetland, through surface flow to a common point or common points.

Channel is a natural or artificial watercourse through which a body of water flows periodically or continuously or forms connecting links between other bodies of water.

Check dam is a low and fixed weir or dam that lies across a drainage channel to retard or reroute flow from a channel, ditch or canal, for the purpose of erosion or scour reduction.

Climate Change is a continuous phenomenon and refers to the change in global climatic conditions, e.g. as a result of temperature increases due to anthropogenic emissions.

Confined aquifer is an aquifer which is enclosed by formations that are less permeable or impermeable media.

Contamination refers to the introduction of microorganisms, factory produced chemicals, or wastewater in concentrations that deem water unsuitable for most human uses.

Critical duration is the length of rainfall event that typically results in the greatest rate of flow, flood volume or flood zone level at a specified location.

Degradation refers to the general and progressive lessening of stream or channel profiles, or earth's surface, due to long-term periods of water induced erosion and/or scour.

Depression storage refers to precipitation stored in surface depressions.

Design life probability of exceedance is the selected probability of exceedance of a particular event being equalled or exceeded for a drainage system or a component thereof.

Design period is usually the length of time a structure or asset will be expected to have a useful life, or the amortisation period if loans have been procured to finance the construction of the structure or asset.

Design storm encompasses the properties of a selected storm, which include the depth, spread and duration of the rainfall as well as variations in rainfall intensity in space and time over the catchment area during the storm.

Detention pond is a depression that is normally dry except following larger storm events when it stores stormwater on a temporary basis to attenuate flows. It may allow infiltration of stormwater into the ground.

Development means any man-made change to property, including but not limited to, construction or upgrading of buildings or other structures, paving, municipal services, etc.

Dominant logic is a belief system that individuals and/or companies advocate.

Drainage is commonly referred to as one of the following four; (1) the removal of excess groundwater or surface waters by gravity or pumping, (2) the behaviour in which waters are removed from an area, (3) the area from which water bodies are removed, or (4) the general flow of all liquids under the force of gravity.

Drainage area is that part of a catchment above a specified point that contributes to the runoff at that point.

Drainage corridor is an area usually extending on either side of the centerline of a watercourse along its longitudinal length, including; vleis, wetlands, dams or lakes, that can be linked to the conveyance of runoff.

Drainage system refers to the network comprising drains, hydraulic control structures, levees, and pumping mechanisms that drain land or protect it from potential flooding.

Drawdown is the lowering of the surface level of a water body as a result of the withdrawal of water, typically in the case of groundwater tables, ponds or wells.

Dry pond is a detention pond that remains dry during dry weather flow conditions.

Dry weather flow means flow occurring in a water course not attributable to a storm rainfall event. Dry weather flows do not fluctuate rapidly.

Effluent is generally wastewater that flows from a process or confined space that has been partially or completely treated.

Encroachment means the progressive advance of any man-made changes to property, including but not limited to any structure or activity such as mining, dredging, filling, grading, paving, excavation or drilling operations, or the progressive advancement of terrestrial or aquatic vegetation into a floodplain, drainage, or overland flood escape route.

Evapotranspiration means the evaporation from all water, soil, snow, ice, vegetation and other surfaces plus transpiration of moisture from the surface membranes of leaves and other plant surfaces.

Event probability is the probability of a particular threshold being equalled or exceeded in any particular rainfall event.

Fill means the placement of fill material such as natural sands, dirt, soil or rock and may include concrete, cement or other waste materials at a specified location to bring the ground surface up to a desired elevation.

Filtration, means the filtering of stormwater runoff pollutants that are conveyed with sediment by trapping these constituents on vegetative species, in the soil matrix or on geotextiles.

Flood means a temporary rise in water level, including ground water or overflow of water onto land not normally covered by water.

Floodplain means the area susceptible to inundation by larger rainfall events.

Floodplain fringe is that area in a river defined as being below the level reached by the regional maximum flood and above the level reached by normal flow.

Flood zone or floodway means the area inundated by the regional maximum flood (RMF).

Freeboard means the vertical distance from the regular water surface to the top of a confining structure, usually a wall and/or gate.

Gabion is a rectangular shaped steel wire basket that is generally filled with rock, for embankment protection and flood control.

Geotextile is a textile or plastic fabric designed to separate different fill materials, which is normally relatively permeable.

Greenfield means a site or land such as parkland, open space and agricultural land which has previously been undeveloped.

Green roof is roof on which plants and vegetation can grow. The vegetated surface provides a degree of retention, attenuation, temperature insulation and treatment of rainwater.

Gross pollutants are waste items generally larger than 10 mm in diameter, which typically include; plastics, cardboard packaging, metals, plastic and glass bottles, paper products, and organic material.

Hydrograph is a plot of discharge or runoff relative to time.

Hydrology refers to the physical, chemical and physiological sciences of the water bodies of the earth and the interaction to the life thereon, which includes: occurrence, distribution, circulation, precipitation, surface runoff, stream-flow, infiltration, storage and evaporation.

Hydraulic roughness is a composite of the physical characteristics that influence the flow of water across the ground, whether natural or channelized.

Impervious surface is land where water cannot infiltrate into the subsurface but is conducted by gravity on the surface as overland flow. Roads, parking lots, sidewalks and rooftops are examples of impervious surfaces in urban areas.

Infiltration is a complex process of allowing runoff to penetrate the Earth's surface and flow through the upper soil surface.

Infiltration device is a SuDS element designed to aid infiltration of surface water to the ground.

Infiltration trench is a trench that is usually filled with granular material, designed to promote infiltration of surface water to the ground.

Interception refers to precipitation stored on vegetation as opposed to rain stored in surface depressions (termed depression storage).

Levee is an embankment that is normally constructed horizontally along the highest bank of a watercourse to confine flow during relatively large rainfall events.

Long-term storage is the volumetric control of stormwater runoff in a specified infiltrating area that will drain very slowly.

Major drainage system is a stormwater drainage system which caters for severe, infrequent storm events, to prevent fatalities and minimise damage to property.

Minor drainage system is a stormwater drainage system which caters for frequent storms of a minor nature, to minimise inconveniences.

Non-structural measures are planning, institutional and pollution prevention practices designed to prevent or minimise pollutants from entering stormwater runoff and/or reduce the volume of stormwater requiring management.

Overland flood escape route means an area, as determined by Council, over which stormwater, which is in excess of the capacity of a stormwater system, will flow to safeguard property from flooding.

Owner means the person in whom is vested legal title to the immovable property.

Perennial stream is a watercourse that flows continuously for all or most periods of the year.

Permeability refers to the ability of a material to allow water to flow through when fully saturated and subjected to an unbalanced pressure.

Peak discharge (also known as 'peak flow') is the maximum rate of flow of water passing a given point during or after a rainfall event.

Photodegradation means the breakdown of organic pollutants in stormwater runoff through extended exposure to ultra-violet light.

Plant-uptake is the removal of stormwater runoff nutrients and metals through uptake by plants.

Polish means to provide additional treatment.

Porous asphalt is an asphalt surface that is used to make pavement layers pervious, with open voids to allow water to pass through.

Precipitation is the water received from atmospheric moisture as rainfall, hail, snow or sleet, normally measured in millimetres according to depth.

Rainwater harvesting is the direct capture of stormwater runoff, typically off rooftops, for supplementary water uses onsite.

Receiving waters are natural or man-made aquatic systems which receive stormwater runoff e.g. watercourses, wetlands, canals, estuaries, groundwater and coastal areas.

Recurrence interval or return period is the average interval between events exceeding a stated benchmark. The recurrence interval is usually expressed in years and is the reciprocal of the annual probability. That is, the event having an annual probability of occurrence of 2% (0.02) has a recurrence interval of 50 years. This does not imply that such an event will occur after every 50 years, or even that there will necessarily be one such event in every 50 years, but rather that over a much longer period (like a 1,000 year period) there will be approximately 20 events of equal or greater magnitude (1000/20 = 50 years).

Responsible person means the person whose act or omission caused, or contributed to, an emergency incident and, if the incident occurred in the course of that person's employment, his or her employer.

Retention pond is a pond-like structure where runoff is detained for a sufficient time to allow settlement and possibly biological treatment of some pollutants.

Retrofitting means the process of modification or installation of additional or alternative stormwater management devices or approaches in an existing developed area in order to achieve best management of stormwater.

Return period is the average time interval of hydrological event occurrences of a given or greater magnitude. The interval is normally expressed in years.

Riparian refers to anything that is situated next to or adjoining the embankment of a watercourse or other water bodies.

Riprap refers to stone or blocks, which are intentionally placed along the embankment of watercourses to minimise the potential for erosion.

Runoff generally refers to the excess water that flows after precipitation.

Scour refers to the movement of solid material due to the forces of flowing water.

Sedimentation is the deposition of soil particles that have been carried by flowing waters, typically during flood peaks, as a consequence of a decrease in the velocity of flow below the minimum transportation velocity.

Sheet flow is runoff over a relatively flat or flattened surface.

Soakaway is a subsurface structure that is designed to promote infiltration into the ground.

Source controls are non-structural or structural best management practices to minimise the generation of excessive strormwater runoff and/or pollution of stormwater at or near the source.

Spillway is a waterway adjoinging ponding areas or other hydraulic structures, used for the routing of excess water.

Stage is the elevation of the water surface above some specified elevation datum.

Stormwater is water resulting from natural precipitation and/or accumulation and includes rainwater, groundwater and spring water.

Stormwater attenuation pond is a facility which temporarily stores excess stormwater runoff with the intention of reducing the flood peak.

Stormwater outfall is the point at which runoff discharges from a conduit.

Stormwater runoff refers to the portion of rainfall which flows to the surface drainage system.

Stormwater system is constituted by both the constructed and natural facilities, including stormwater pipes, canals, culverts, overland escape routes, 'vleis', wetlands, dams, lakes, and other watercourses, whether over or under public or privately owned land, used or required for the management, collection, conveyance, temporary storage, control, monitoring, treatment, use and disposal of stormwater.

Structural measures/controls are permanent, engineered devices implemented to control, treat or prevent stormwater pollution and/or reduce the volume of stormwater that requires management.

Subdrain is generally a drain-type structure that is implemented beneath lined conduits such as sewers, stormwater networks, canals, or roadways, to manage groundwater flows in order to mitigate potential damage to property.

Subsurface runoff is the flow derived from water infiltrating the soil and flowing laterally in the upper soil strata. It usually reaches the receiving streams or bodies of water fairly soon after a rainfall event without joining the main body of groundwater (referred to as 'interflow').

SuDS is the abbreviation for sustainable drainage systems or sustainable (urban) drainage systems, which are individual or sequential management practices and/or control structures or technologies designed to drain surface water in a more sustainable manner than conventional techniques.

Surface runoff is that part of the runoff that travels over the ground surface and in channels to reach the receiving streams or bodies of water.

Sustainable development means development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

Swale is a shallow vegetated channel designed to conduct and retain water, but may also permit infiltration. The vegetation assists in filtering particulate matter.

Time of concentration is the time required for water to flow from the most hydraulically remote point of the basin to the point/location of analysis.

Treatment train is a combination of different methods implemented in sequence or concurrently to achieve best management of stormwater. These methods include source control, non-structural and structural measures.

Volatilisation is the conversion of stormwater runoff compounds to gas or vapour typically as a result of heat, chemical reaction, a reduction of pressure or a combination of these.

Watercourse means a river, stream, channel, canal or other visible topographic feature, whether natural or constructed, in which water flows regularly or intermittently and includes any associated storage and/or stormwater attenuation dams, natural vleis or wetland areas.

Watercourse edge means the top edge of a discernable bank or canal in the case of natural and constructed watercourses respectively. Where an edge is not readily discernable, the extremity of the area susceptible to inundation by the 1:2 year storm is deemed the watercourse edge.

Watershed is the upper boundary of a specified catchment area for rainfall that contributes to a given drainage area.

Water pollution incident means an unexpected occurrence, which has the potential of prejudicing the quality of water in the stormwater management system or threatening public health or safety.

Water quality volume is the volume of runoff which requires water quality treatment in order to reduce/remove a specified percentage of pollutants.

Water table is the upper most level of a zone of saturation below the Earth's surface, except where this surface is formed by an impermeable body.

Weir is a relatively small dam-type structure across a waterway used to divert flow, reduce erosion and/or measure flow volumes.

Wetland means land translational between terrestrial and aquatic systems where the water table is usually at or near the surface, or is periodically covered with shallow water, and which land in normal circumstances supports or would support vegetation typically adapted to life in saturated soil. This includes water bodies such as lakes, salt marshes, coastal lakes, estuaries, marshes, swamps, 'vleis', pools, ponds, pans and artificial impoundments.

Whole Life Cost means to estimate the present day value of total costs of a structure throughout its likely operating life.

Acronyms & Abbreviations

AADD	Annual Average Daily Demand
AAR	Average Annual Rainfall
AASHTO	American Association of State Highway Transportation Officials
ACR	Annual Collectable Rainfall
ANG	Australian National Guidelines
ARI	Average Recurrence Interval
BMP	Best Management Practice
CAR	Controlled Activities Regulations
CBP	Concrete Block Paver
CBR	Californian Bearing Ratio
CCPOA	Century City Property Owner's Association
CIRIA	Construction Industry Research and Information Association
CMOSS	Cape Metropolitan Open Space Strategy
CoCT	City of Cape Town
CSS	Centralised Supply System
CSRM	Catchment, Stormwater and River Management
CTSDF	Cape Town Spatial Development Framework
DCP	Development Control Plan
DEADP	Department of Environmental Affairs and Development Planning
DEAT	Department of Environmental Affairs and Tourism
DIMS	Distributed Information Monitoring System
DirSS	Direct Supply System
DPWID	Department of Public Works and Infrastructure Development
DSS	Decision Support System
DTI	Department of Trade and Industry
DWAF	Department of Water Affairs and Forestry
DWEA	Department of Water and Environmental Affairs
EBE	Engineering and the Built Environment
ECO	Environmental Control Officer
EIA	Environmental Impact Assessment
EPA	Environmental Protection Agency
EU	European Union
FOS	Factor of Safety
FRDS	Functional Regional Development Strategy
FTW	Floating Treatment Wetland
GBCSA	Green Building Council of South Africa
GBR	General Binding Rules
GIS	Geographic Information System

GSS	Gravity Supply System
HDPE	High Density Polyethylene
HRT	Hydraulic Residence Time
I&AP	Interested and Affected Party
IDP	Integrated Development Plan
ILLUDAS	Illinois Urban Drainage Area Simulation
IUWM	Integrated Urban Water Management
KIP	Key Performance Indicator
KS	Knowledge System
LASMD	Los Angeles Stormwater Management Division
LID	Low-Impact Development
LOP	Level of Protection
LOS	Level of Service
LRI	Land Resources International
LS	Language System
MAP	Mean Annual Precipitation
MAPS	Managed Aquatic Plant Systems
MAR	Mean Annual Rainfall
MBWCP	Moreton Bay Waterways and Catchments Partnerships
MCPP	Municipal Climate Protection Programme
MIC	Managed Impervious Catchment
MPBs	Modular Paving Blocks
MUSIC	Model for Urban Stormwater Improvement Conceptualisation
NCDWQ	North Carolina Division of Water Quality
NSDP	National Spatial Development Strategy
NWRS	National Water Resources Strategy
PCBP	Permeable Concrete Block Paving
PID	Partners in Development
PPS	Problem Processing System
PS	Presentation System
PRPB	Porous Rectangular Paving Blocks
RDP	Reconstruction and Development Programme
RI	Rainfall Intensity
RWHM	Rainwater Harvesting and Management
SAICE	South African Institute of Civil Engineering
SARCC	South African Rail Commuter Corporation
SCS	Soil Conservation Service
SDBIP	Service Delivery and Budget Implementation Plan
SDF	Spatial Development Framework
SEPA	Scottish Environmental Protection Agency
SI	Sustainability Index

SLAMM	Source Loading and Management Model
SS	Settleable Solids
SSDP	Simplified Site Development Process
STTAT	SUDS Treatment Train Assessment Tool
SuDS	Sustainable Drainage System
SWMM	Stormwater Management Model
SWMP	Stormwater Master Planning
TN	Total Nitrogen
TP	Total Phosphorous
TSS	Total Suspended Solids
UDM	Urban Drainage Modelling
UK	United Kingdom
UNEP	United Nations Environmental Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
USA	United States of America
USEPA	United States Environmental Protection Agency
UWM	Urban Water Management
WCED	World Commission on Environment and Development
WITS	University of Witwatersrand
WLC	Whole Life Costing
WQV	Water Quality Volume
WRC	Water Research Commission
WSDP	Water Services Development Plan
WSUD	Water Sensitive Urban Design
WWTW	Wastewater Treatment Works

1. Introduction

"Civil engineering is the business of working creatively and co-operatively with the natural world to deliver a sustainable constructed environment to enhance the quality of life for present and future generations" (Blockley, 2005).

1.1 Creating a sustainable constructed environment

Water is an essential element of the human make up; therefore it is vital that humans are good stewards of this valuable resource by managing it in a sustainable manner. Natural water resources should be managed sustainably to enhance the livelihoods of humans whilst preserving the environment (Pieterse, 2010). Urban design and management practitioners should endeavour to provide adequate and equitable urban water services whilst ensuring that future generations are the beneficiaries of these same water resources. It has become increasingly difficult to meet this challenge amidst rapid urbanisation over the past five decades. Failure to implement effective management controls and sustainable principles in urban development has lead to the steady demise of water systems in cities (Armitage, 2006). These failures typically result in unmanageable service delivery demands, the deterioration of water-related infrastructure, and the collapse of natural and ecological assets. In response to the labyrinth of complexity associated with rapid urbanisation, 'sustainability' and 'sustainable development' evolved as new concepts for overcoming widespread environmental challenges (World Conservation Union, 1991). It has been 24 years since these concepts rose to prominence following the publication of the World Commission on Environment and Development (WCED) report, "Our Common Future" (Mebratu, 1998). The WCED report, also referred to as the 'Brundtland Commission', defined 'sustainable development' as, *"development that meets the needs of the present without compromising the ability of future generations to meet their own needs"* (Brundtland, 1987).

'Sustainability' and 'sustainable development' are enjoying considerable prominence at present in most developed countries (Reed *et al.*, 2001; Armitage, 2009). In the case of South Africa, and the City of Cape Town in particular, these notions are being increasingly realised in urban development sectors in the form of policies, compliance-related manuals and municipal benchmarks (Murray, 2002). In terms of urban drainage, Sustainable Drainage Systems (SuDS) has of late been introduced in Cape Town in local policy documents as an alternative to conventional forms of urban drainage (Roads and Stormwater Department, 2011; Roads and Stormwater Department, 2009a,b). Conventional drainage systems comprise 'hard' and impervious infrastructure with the intention of collecting, conveying and discharging stormwater runoff into the nearest watercourses as quickly as is physically possible (SABS Construction Standards, 2010; CSIR, 2000b; Watson & Miles, 1982). Conventional drainage practices therefore focus largely on the 'quantity' management of stormwater runoff, and neglect the impacts of stormwater on biomass and biodiversity as well as the value of water-related amenity. Conversely, SuDS attempts to mimic natural, predevelopment hydrological conditions, by managing stormwater runoff ‘quantity’, ‘quality’, and ‘amenity and biodiversity’ (Woods-Ballard *et al.*, 2007). SuDS were developed as surface water drainage systems in line with the ideals of sustainable development, and promote the dematerialisation of conventional stormwater infrastructure with the use of natural drainage processes. SuDS schemes that are developed and managed properly have the potential to mitigate the adverse effects of urban stormwater runoff on immediate and receiving ecosystems (Wilson, *et al.* 2004). Notionally, SuDS is an element of Water Sensitive Urban Design (WSUD), which is a holistic approach to the planning and design of water-related infrastructure, with the principal objective of minimising the impacts of urban development on the natural water cycle (MBWCP, 2006; Melbourne Water, 2005).

These notions and principles partly inspired the implementation of sustainable and environmentally-oriented stormwater management initiatives in Century City, situated in the northern suburb of Milnerton in the City of Cape Town, South Africa. For fifteen years, managers at Century City have focused largely on creating a sustainable constructed environment that benefits both its human inhabitants and the environment (Liebenberg *et al.*, 2009; Liebenberg, 2011). Lems (2008) and Hjorth & Bagheri (2006) suggest that with equal consideration of the following dimensions: environment, society, economy, technology and politics, ‘sustainable development’ presents the basis upon which natural resources can be conserved and utilised effectively. The Century City case study partly reflects this hypothesis. Furthermore, the development of SuDS in Century City demonstrates that environmental services can assist in the improvement of livelihoods and income (CCPOA, 2011a,b).

1.2 Focus of research

This dissertation presents Century City as an example of the early implementation of SuDS in South Africa. Century City has the largest documented history of any such development in South Africa. The development’s managers attempted to meet the demand for a sustainable solution to stormwater management in a manner that added socioeconomic and environmental value to the development (Liebenberg *et al.*, 2009). The objective of the case study is to identify and describe the stormwater management processes within Century City as well as render practical assessments and analyses of the performance of selected SuDS options and treatment trains. Century City was selected as the focus of research out of a possible nineteen case studies carried out countrywide in 2009. This case study is divided into two parts. Part one investigates, in particular, three aspects of the development’s stormwater management system, namely: (1) planning, (2) implementation and modelling, and (3) operation, monitoring and maintenance; emphasising several implemented SuDS options. The SuDS options reviewed include, *inter alia*, rainwater harvesting, bio-retention areas, filter strips, infiltration basins, swales, a detention pond, and a constructed wetland; the benefits of which include a reduction in the likelihood of flash flooding, an improvement in water quality, and the enhancing of amenity, biomass and biodiversity. Part two assesses, analyses and discusses flawed thinking that led to dysfunctional systems, and the subsequent attempts by management to overcome them. This is demonstrated in an assessment of ineffective design approaches to selected local control SuDS, and in an analysis of the Century City constructed wetland using 'System Thinking' (ST) theory. The ST analysis of the constructed wetland proves, hypothetically, that failure to effectively initiate and apply sustainable drainage alternatives such as SuDS is rooted in a lack of understanding of environmental complexity and the management thereof.

The Century City case study has also provided a reference for the South African Draft Guidelines for SuDS, drafted by the author. A proposal was issued by the South African Water Research Commission (WRC) for the drafting of SuDS Guidelines to commence in April 2008, under the project *K5/1826: Alternative technology for stormwater management*. Some of the methods used in the investigation and analysis of Century City's stormwater management system and the drafting of the SuDS Guidelines are therefore linked. The following five principal methods were used to compile the case study: (1) comprehensive desk studies of the global applications of SuDS schemes, (2) identification and assessments of South African case studies, (3) integration of economic and botanical 'knowledge bases', (4) interdisciplinary feedback sessions, and (5) national SuDS workshops. The purpose of the SuDS Guidelines is to bridge the divide between the philosophy of SuDS and its practical application. The guidelines have been designed to be relevant and useful to all urban design and management practitioners countrywide. In addition, a stand-alone SuDS Conceptual Design Poster is presented to supplement the guidelines as a quick-referencing tool for the selection of appropriate SuDS options during the planning and conceptual design phases. The SuDS Guidelines and SuDS Conceptual Design Poster are presented in Appendix 1 and Appendix 2, respectively.

1.3 Chapter outline

The subsequent chapters of this dissertation include the following information:

Chapter 2 is a literature review that provides context for the development of SuDS in South Africa. It is a fundamental component of the dissertation and examines four main themes and/or concepts that are explored in subsequent chapters. These themes include: a historical overview of stormwater management, an introduction to SuDS, tools for the implementation of SuDS, and South African urban drainage legislation.

Chapter 3 describes the methods of investigation that were used in the compilation of the Century City case study. These include: the formulation of a bibliography, site selection and reconnaissance details, the presentation of a list for the procurement of SuDS information, the selection of Century City as a suitable case study, and supplementary research information such as desk studies, interdisciplinary feedback sessions, and national workshops and feedback processing.

Chapter 4 presents ‘part one’ of the Century City case study, which is an investigation of the development’s stormwater management system, entitled ‘Stormwater management investigation’. The following three developmental aspects of the system are discussed: (1) planning, (2) implementation and modelling, and (3) operation, monitoring and maintenance. A number of costs are also presented for the operation and maintenance of the development’s urban water system.

Chapter 5 presents ‘part two’ of the Century City case study. It comprises a brief assessment of ineffective design approaches to local control SuDS as well as an analysis of problematic management interventions in the development’s constructed wetland. The purpose of these assessments and analyses is to illustrate the differences in the management approaches to conventional and sustainable drainage infrastructure, and provide urban practitioners with an account of practical obstacles to the greater implementation of SuDS in South Africa.

Chapter 6 concludes the dissertation with ‘lessons learnt’ from the Century City case study. Key results and findings of the wider application and feasibility of SuDS in South Africa are also discussed.

Chapter 7 puts forth recommendations for further research into the development of SuDS options in South Africa. These recommendations should be of use to academics as well as urban design and management practitioners, particularly with regard to the development of prospective SuDS schemes.

Appendix 1 presents the ‘South African Draft Guidelines for Sustainable Drainage Systems (SuDS)’ as a supplementary component of the dissertation that is informed by the Century City case study. The SuDS Guidelines comprise a main text body and appendices A – C, which include general development frameworks, pollutant removal characteristics, and general designs for SuDS options. The guidelines’ appendices D – F have been omitted from the dissertation as they were compiled by Mr. Lloyd Fisher-Jeffes of the Urban Water Management Group at UCT. The guidelines are not prescriptive or regulatory and are intended for use by all urban design and management practitioners in South Africa.

Appendix 2 presents the SuDS Conceptual Design Poster. It is envisaged that the poster will be utilised by practitioners as a quick-referencing tool for the selection of appropriate SuDS options. The SuDS options included on the poster correspond to those presented in the South African Draft Guidelines for SuDS (Appendix 1).

2. Literature review

In order to present Century City as a case study for SuDS in South Africa, it is necessary to locate SuDS within a global and local literary space. The literature review is therefore a fundamental component of the dissertation and examines the main themes that are explored in subsequent chapters.

2.1 Introduction

The urban landscape is changing more rapidly in the 21st Century than it ever has. The concept of a 'city' is more complex, and more integral to humanity than ever before (Beall, 2010; Simone, 2010; Pieterse, 2008). Martine *et al.* (2008) suggests that the core argument among many scholars is that the world is experiencing the 'second wave of urbanisation', which has had significant effects on the shaping of cities in the global South and the present day environmental challenges they face. The 'second wave of urbanisation' is defined as the period of an unprecedented rate of urbanisation from 1950 until present, in contrast to the 'first wave of urbanisation' that took place in Europe and North America between 1750 and 1950 (Pieterse, 2008). Figure 2.1 graphically depicts the estimated rate of urban and rural population increase for the 'second wave of urbanisation', and illustrates that by the end of 2007 the total global urban population (developed and developing city urbanites) had surpassed the rural population for the first time in history. Pieterse (2010; 2008) and Revi *et al.* (2006) assert that the significance of the 'second wave of urbanisation' is that it presents a period where the transition to a low carbon, sustainability-oriented society must be effective in order to prolong human existence.

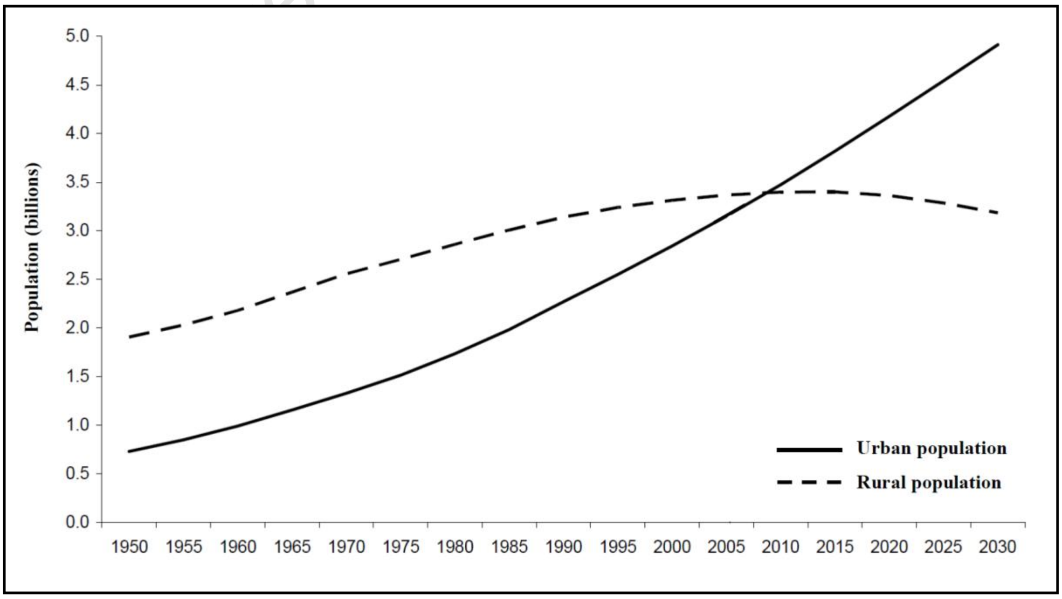

Figure 2.1: Second wave of urbanisation (After United Nations, 2005)

The urban population of South Africa has doubled since 1950 to constitute approximately 62% of the total population (United Nations, 2005). The sprawling of urban landscapes in South Africa has had a profound effect on stormwater drainage (Todes, 2009; Lems, 2008; Beall & Fox, 2009). Conventional drainage practices exacerbate the effects of stormwater on receiving watercourses and ecosystems by causing an increase in flow rates, volumes and flood peaks. In addition, conventional drainage practices prioritise stormwater quantity management with minor emphasis on the preservation of the environment (Parkinson *et al.*, 2007). On the other hand, SuDS has of late become increasingly recognised as an alternative approach to conventional drainage practices in South Africa. Globally, the philosophy of SuDS is not new; it has been widely used in Australia and the UK since its inception in the 1980's (Wilson *et al.*, 2004).

In light of the effects of rapid urbanisation on stormwater, and the prospect of the development of SuDS in South Africa, the following four themes are reviewed in this chapter:

i) Stormwater management history; this subsection provides a broad, historical overview of the technical advances and paradigm shifts in stormwater management infrastructure.

ii) Introduction to SuDS; the purpose of this subsection is to present an overview of the theory of SuDS options, which has been adopted in the South African Draft Guidelines for SuDS (Appendix 1).

iii) Tools to implement SuDS; this subsection details a number of modelling programmes and decision support systems that have been used internationally for the selection of appropriate SuDS options.

iv) Urban drainage legislation; in light of environmentally-oriented policies such as Brundtland (1987) and Agenda 21 (Sitarz, 1993; United Nations, 1992), this subsection details national acts, provincial ordinances, and local by-laws as well as policies and guidelines that pertain to the management of stormwater and the environment in South Africa.

The literature review is concluded with a synopsis that supports the investigation and analysis of Century City's stormwater management system.

2.2 Stormwater management history

Cities typically grow in areas that offer opportunities for transportation, housing, agriculture, and industry; therefore cities tend to be established along waterways. Over centuries waterways have almost always been viewed as a means of transportation, raw water supply, source of energy, and suitable location for organic and inorganic waste disposal. Growing cities have exploited rivers and other water bodies in every conceivable way, by using them as a means to an end, particularly in waste disposal (Brown, 2007). However, the physical connections, both natural and structural, between cities and their water resources have changed fundamentally throughout the centuries. Our conceptual models for these water related systems and our inherent understanding of their functionality and relationship with one another has also changed (Novotny & Brown, 2007). In terms of urban drainage, there have been several shifts in stormwater management paradigms that have led to the inception of SuDS in the South African urban environment. Debo & Reese (2003) describe stormwater management paradigms as follows:

> *"We each have a stormwater management paradigm. A paradigm is what we think is true and right about a certain subject. It is the grid through which we put all information and input into a subject. In fact, it is everything we think is true about something. Whether our paradigm is, in fact, true and effective, is not the point. We believe it is. And, we only reluctantly change our ways and agree to agree with someone else's paradigm. Knowing your own paradigm is the first step in understanding stormwater management. The second is seeing how far you have to go, and fearlessly setting out."*

Debo & Reese (2003) further assert that early stormwater paradigms were birthed out of evolving stormwater management practices that were influenced by social change and the effects of urbanisation. Scholars broadly suggest that nine stormwater management paradigms precede the inception of SuDS; described succinctly as follows:

i) Convey stormwater in ditches: At the outset of urbanisation in the 19th Century, rural practices were prevalent in urban areas, which led to the first stormwater paradigm – everything of liquid form and objects transported by liquids should run into ditches similar to those on a farm or small holding in a rural area (Debo & Reese, 2003). This presented a basic form of drainage, which was effective for a short period of time. However, problems soon arose as roads, other transport corridors and public open spaces became unusable due to the presence of contaminated mud (Novotny & Brown, 2007).

ii) Convey stormwater in piped infrastructure: Piped infrastructure was increasingly used after the 19th Century. Liquid waste from streets, flush toilets and kitchens was discharged into the nearest watercourse (Lems, 2008; Debo & Reese, 2003). This new system of piped infrastructure, still used by many countries in the 21st century, was termed the 'combined sewer' system. Combined sewers solved the initial problem of removing stormwater and wastewater out from under foot; however, Novotny & Brown (2007) suggest that it eventually overloaded receiving watercourses with raw sewage, creating health related problems downstream.

iii) Convey stormwater in stormwater pipes: This was the first of many 'urban' based stormwater design paradigms, which came into existence after the Second World War (Debo & Reese, 2003). At this time, the Rational Method became the design method of choice in South Africa, used concurrently with intensity-duration-frequency (IDF) curves (Thompson, 2007; Kuichling, 1889). Concurrently, impervious surfaces in cities were increasing, resulting in higher flows and volumes of stormwater runoff and more frequent flooding. The aim of these faster conveyance urban drainage systems was to remove larger volumes of polluted water as quickly as possible, with the intention of protecting public safety and property (Debo & Reese, 2003; CSIR, 2000b).

iv) Stormwater flow attenuation: The use of detention ponds became prevalent in the early 1970's to attenuate high flood peaks. According to Debo & Reese (2003) however, the effective construction of detention ponds requires the following considerations: availability of hydrological criteria, volume and peak flow calculations, geographic assessments downstream, realistic hydrograph routing, sufficient space, detailed plan reviews, health and safety certification, as-built certification, long-term maintenance agreements, and strict environmental enforcement. These are however, complex and time-consuming, and are rarely met (Novotny & Brown, 2007; Debo & Reese, 2003).

v) Stormwater master-planning: The first mainframe hydraulics and hydrology models were geared for use on computers in the late 1970's and became commonly available in the 1980's (Debo & Reese, 2003). This software became increasingly easy to use and was relatively effective for large scale stormwater quantity management, in the form of stormwater master-planning. Technically well-designed and managed stormwater master-plans solved most flooding problems in suburbs, but overlooked critical aspects such as the control of pollution (Water Research Commission, 1999a,b).

vi) Preventing pollution in stormwater runoff: Instituted in the 1980's, this was the first of the 'new breed' of stormwater management paradigms, which placed less emphasis on stormwater 'quantity' management and increasing emphasis on environmental vitality (Water Research Commission, 1999a,b). The growing complexities of stormwater management infrastructure in cities were however exacerbated with attempts to control pollution from diffuse, non-point sources – known as 'end-of-pipe control' (Debo & Reese, 2003). Many developed countries realised that regardless of the size of capital outlay for the reduction of regulated sources of pollution, the integrity of overused urban watercourses had already been severely impaired and would remain so if 'fast conveyance' infrastructure continued to be implemented (Novotny & Brown, 2007).

vii) Ecological focus: Ecologically-based methods of measuring river health and targeting programme efforts became popular in early 1990, known as biocriteria (Debo & Reese, 2003; Water Research Commission, 1999b). This technique utilised macroinvertebrates and fish as indicators of the quality of stormwater runoff from urban areas. Therefore, the stream restoration and conservation target became a measure of biological health, and stormwater programmes focussed on how to achieve and maintain this ‘health’. However, the concept of healthy waterways had not been universally defined, which created unrelenting issues (Water Research Commission, 1999b).

viii) Watershed management: Debo & Reese (2003) state that in the USA an organisational convergence began which saw whole federal agencies reorganised to be watershed focused institutions. Local governments began to operate in terms of holistic watershed planning. The US Environmental Protection Agency (EPA) organised many regulatory stormwater programmes using ‘watersheds’ as the focal point. A similar management approach was instituted in Europe in 2000, known as the ‘EU Water Framework Directive’. The directive instructs member states to present river basin management plans for all river basin districts in the EU (Chave, 2001). In the US, however, a critical setback of this paradigm was that it became too complex for citizens to understand and relate to. In addition, it did not address the problems at the planning and design stages where many originally occur (Debo & Reese, 2003).

ix) Green infrastructure: There has been growing interest in the promotion of sustainable development amongst governments and local municipalities throughout the world – and this includes the control of stormwater runoff (Ellis *et al.*, 2006). Novotny & Brown (2007) comment, *“A new paradigm is emerging from the successes and failures of efforts to control pollution that offers the promise of adequate amounts of clean water for all beneficial uses. Urban waterways are the historic core of our cities’ economies and have the potential to be rich sources of biological diversity, contributing to the quality, economy and health of urban life.”* Brown (2007) agrees, suggesting that urban elements such as the ‘environment’ and ‘energy’ are moving speedily ahead of elements such as ‘mobility’ and ‘economic growth’ with respect to their importance to the global public. Through a combination of structural, non-structural, and institutional practices, sustainable constructed environments can be created by, *inter alia*, mimicking natural and acceptable hydrology, enhancing biodiversity and natural aesthetics, balancing ecological conservation with economic development, and utilising stormwater as a valuable resource (Debo & Reese, 2003; Sitarz, 1993).

In South Africa, Sustainable Drainage Systems, abbreviated SuDS, has emerged as an urban drainage concept that considers the ideals of sustainable development holistically (Matthews, 2010). Globally, SuDS is synonymous with Sustainable Urban Drainage Systems (SUDS) and Best Management Practices (BMPs) in the UK, the stormwater component of Water Sensitive Urban Design (WSUD) in Australia, and similarly of Low-Impact Development (LID) in the USA (SEMCOG, 2008; Woods-Ballard *et al.*, 2007; MBWCP, 2006). In contrast to the preceding two paradigms that focused on large-scale stormwater management, this paradigm focuses on the management of stormwater runoff at ‘source’ (Furumai, 2009; Claytor & Flicker, 2005).

2.3 Overview and philosophy of SuDS

2.3.1 Introduction to SuDS

Sustainable Drainage Systems (SuDS) offer an alternative approach to conventional drainage practices. SuDS were developed to manage surface water drainage systems in line with the ideals of sustainable development (Woods-Ballard *et al.*, 2007; Wilson *et al.*, 2004). SuDS employ a sequence of options and/or technologies that manage urban stormwater runoff at its source to reduce the likelihood of flash flooding, improve water quality and enhance amenity and the environment. The primary objective of SuDS is to mimic the natural hydrological cycle within urban environments (Melbourne Water, 2005). This is can be achieved by implementing these options sequentially or in parallel, in a 'treatment train', to effectively manage stormwater runoff quantity and quality challenges, with the added benefit of boosting amenity, biomass and biodiversity (SEMCOG, 2008; Semple, 2004). The elementary focal points in the philosophy of SuDS are the management of stormwater runoff quantity, quality, and associated amenity and biodiversity. Figure 2.2 depicts the relationship between these focal points.

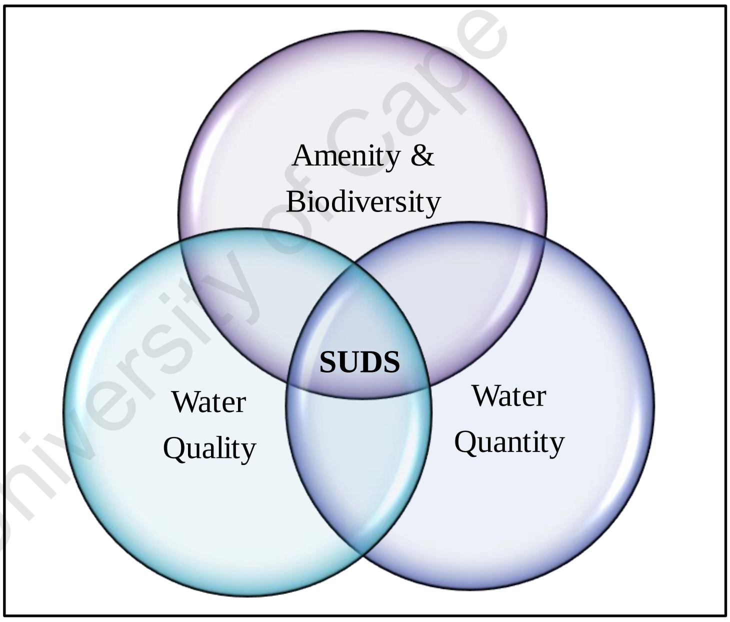

Figure 2.2: Relationship between elementary focal points of SuDS (After Wilson *et al.* 2004)

There has been growing interest within local municipalities to include the ideals of 'sustainable development' in urban engineering, particularly municipal services engineering (Matthews, 2010; Pieterse, 2008). Increasing pressure is being placed on urban design and management practitioners to achieve sustainable drainage solutions for the control of stormwater runoff (Brown, 2007; Ellis *et al.*, 2006). The correct planning, design and management of SuDS options and treatment trains has the potential to, *inter alia*, restore waterways, enhance water resources management, create thriving indigenous habitats, and improve livelihoods and the development thereof. There are however, core challenges that should be addressed by urban practitioners at the inception of prospective SuDS schemes, including:

- Varying hydrological cycles and associated systems;
- Varying geological formations and associated systems;
- Urban drainage dominant logic among practitioners (where 'dominant logic' refers to a belief system that individuals and/or institutions advocate);
- Greenfield, brownfield and retrofitting development options; and
- Settlement characterisation and inequality (MBWCP, 2006; Semple, 2004).

2.3.2 Impacts of urbanisation

> *"The water cycle is one of the most critical processes to supporting life on this planet, and fresh waters are central to all aspects of our lives. Historically, urbanisation has led to the loss and degradation of wetlands, rivers and groundwater resources through pollution, resource depletion and construction within natural flood plains" (Woods-Ballard, et al. 2007).*

Urban development typically reduces the natural permeability characteristics of land by replacing free draining surfaces with impermeable surfaces such as roofs, roads and paved areas that are typically drained by 'hard' infrastructure (i.e. pipes and lined channels) (ASLA, 2008; Armitage, 2009). Development also requires the removal of vegetation, often indigenous, which depresses stormwater buffering processes and prevents evaporation and transpiration processes, also referred to as evapotranspiration. Furthermore, subsoil stratums are normally compacted during development, altering the infiltration characteristics of the soil media onsite (Maine Department of Environmental Protection, 2006; Wilson *et al.*, 2004). Conventional drainage systems also neglect the design and management that is necessary for effective water quality management, catchment flood control, water resources management, and the vibrancy of biomass and biodiversity (Woods-Ballard *et al.*, 2007; CSIR, 2000a,b). The impact of urbanisation has arguably been the strongest driver for the implementation of sustainable development, including drainage interventions such as SuDS options (Pieterse, 2008; Reed *et al.*, 2001). Figure 2.3 depicts the pre- and post-development hydrological processes that are likely to exist in natural areas and as a result of the hardening of surfaces, respectively.

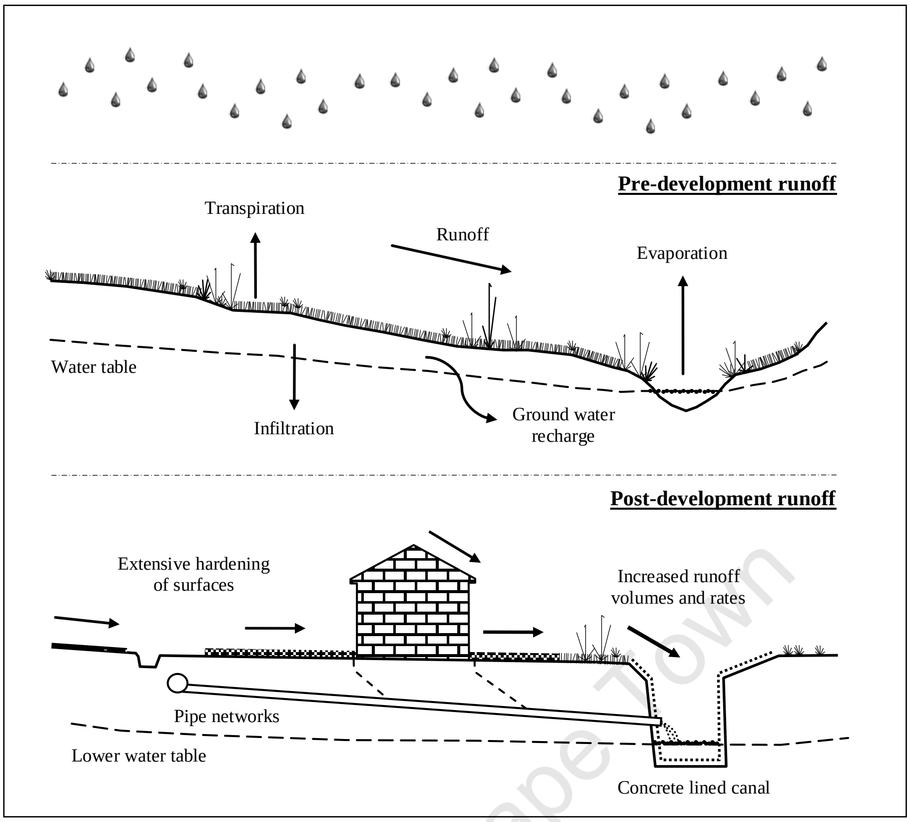

Figure 2.3: General pre- and post-development runoff characteristics
(Van Wieringen, 2010; Woods-Ballard *et al.*, 2007)

Under pre-development conditions, the dominant stormwater characteristics are transpiration, infiltration and ground water recharge. Under post-development conditions, however, the most dominant stormwater runoff characteristics are an increase in runoff volumes and rates as a result of hardened surfaces and fast conveyance infrastructure. This significantly increases the likelihood of flooding and channel erosion downstream. In addition, less stormwater infiltration into the soil stratum decreases baseflow discharges in receiving watercourses and reduces aquifer recharge (Field & Sullivan, 2004; Taylor, 2003; Minton, 2002). Table 2.1 displays the estimated stormwater runoff characteristics for three areas, for the purpose of exemplifying the effects of hardening surfaces.

These varying stormwater runoff characteristics are best represented in terms of their flow rates relative to time in a hydrograph. The relationship between the stormwater runoff flows and volumes that are generated from these pre- and post-development conditions is illustrated with two hydrographs in Figure 2.4.

Table 2.1: Estimated percentages of stormwater runoff characteristics
(After Atlantis, 2009; Wilson *et al.*, 2004)

Stormwater runoff characteristic	Natural areas	Built up areas (% imperviousness)	
		35% - 50%	75% - 100%
Evapotranspiration	40	35	30
Surface runoff	10	30	55
Shallow infiltration	25	20	10
Deep infiltration	25	15	5
Total	**100**	**100**	**100**

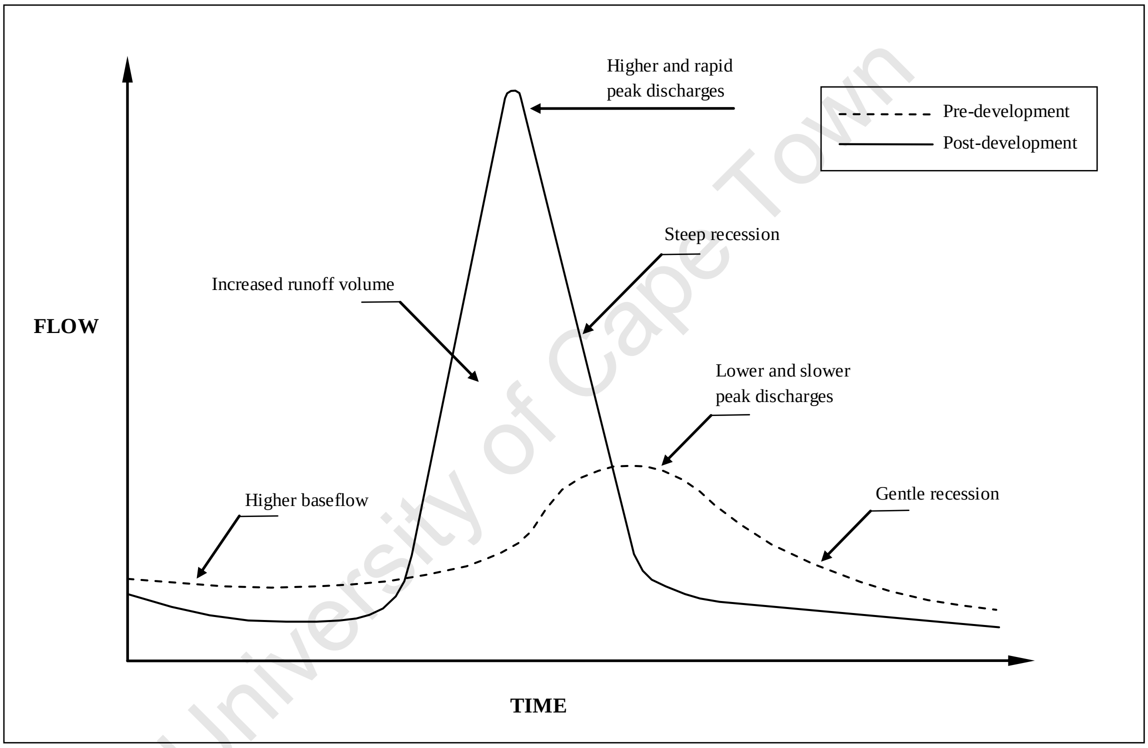

Figure 2.4: General pre- and post-development stormwater runoff hydrographs
(After Wilson *et al.*, 2004; Reed, 2000)

Another consequence of urbanisation is that it has the propensity to cause ‘heat island’ effects, particularly in dense urban areas such as central business districts (CBDs). This phenomenon creates micro-climates which result in more intense hydrological cycles over those immediate areas (Santamouris, 2001). With reference to Figure 2.4, this adds to the increase in runoff volumes and higher peak discharges, thereby exacerbating the problem of stormwater runoff associated with ‘hard’ conventional infrastructure development (Armitage *et al.*, 2009).

2.3.3 SuDS management processes

SuDS promotes the ‘dematerialisation’ of typical engineered stormwater infrastructure, and increases natural drainage processes through the development of several unit processes (Semple, 2004; Wilson *et al*. 2004). These unit processes relate to the three elementary focal points of SuDS, namely, water quantity, water quality, and amenity and biodiversity. Each of these unit processes is defined in the following subsections by SEMCOG (2008) and Woods-Ballard *et al.* (2007), and are expressed in matrix-form in Appendix 2.

2.3.3.1 Quantity processes of SuDS

The following represent the stormwater runoff ‘quantity’ management processes of SuDS:

- **Rainwater harvesting** – the direct capture of stormwater runoff, typically off rooftops, for supplementary water uses onsite;
- **Infiltration** – the soaking of stormwater runoff into the ground, physically reducing the volume of stormwater runoff over that surface;
- **Detention** – the slowing down of stormwater runoff before subsequent transfers downstream, using storage facilities and controlled outlets;
- **Conveyance** – the transfer of stormwater runoff from one location to another, using a range of controlled natural and built components;
- **Long-term storage** – the volumetric retention and control of stormwater runoff in a specified infiltrating area that will drain very slowly; and
- **Extended attenuation storage** – the retention of stormwater runoff to protect receiving watercourses in the event of flooding, if long-term storage and additional infiltration are not feasible onsite.

2.3.3.2 Quality processes of SuDS

The following represent the stormwater runoff ‘quality’ management processes of SuDS:

- **Sedimentation** – the removal of sediment particles attached to pollution in stormwater runoff, by reducing flow velocities to ensure sediment particles fall out of suspension;
- **Filtration and biofiltration** – the filtering of stormwater runoff pollutants that are conveyed with sediment by trapping these constituents on vegetative species or geotextiles within a structure;
- **Adsorption** – the complex process of stormwater runoff pollutants binding to the surface of aggregate particles in a control structure, in which there are associated, (1) Cation exchange, (2) Chemisorption, and (3) Absorption, processes.

- **Biodegradation** – the degradation of organic pollutants in stormwater runoff by microbial factions established within the control structure, using the oxygen nutrients supplied by stormwater runoff inflows;
- **Volatilisation** – the conversion of stormwater runoff compounds to gas or vapour typically as a result of heat, chemical reaction, a reduction of pressure or a combination of these;
- **Precipitation** – the removal of soluble metals in stormwater runoff through chemical reactions between pollutant constituents and aggregate in the control structure, to form a suspension of insoluble precipitates;
- **Plant-uptake** – the removal of stormwater runoff nutrients and metals through uptake by plants, generally in larger control structures;
- **Nitrification** – the oxidisation of ammonia and ammonium ions in stormwater runoff by microbial factions, to form nitrate that is readily used by most plant species; and
- **Photodegradation** – the breakdown and demise of organic pollutants in stormwater runoff through extended exposure to ultra-violet light.

2.3.3.3 Amenity and biodiversity processes of SuDS

The following represent several amenity and biodiversity considerations for SuDS:

- **Health and safety** – the planning and implementation of control measures to prevent the injury or death of people using components of SuDS schemes, including, *inter alia*, safe design practices, alert medical aid teams, and cooperative communities;
- **Ecological risk assessment and management** – the assessment and management of ecological subcomponents of SuDS schemes to ensure their longevity, including effective habitat creation;
- **Recreation and aesthetics** – the provision of interactive and attractive structural and non-structural components of SuDS by protecting, shaping and creating open spaces and enhancing the visual appearances of the specified systems; and
- **Education and awareness** – the creative dissemination of knowledge about specified SuDS schemes amongst interested and affected parties.

2.3.4 Selection basics for SuDS options

There are many different SuDS options and technologies that can be used to manage stormwater runoff on a specified site (Urban Water Technology Centre, 2009). The Idaho Department of Environmental Quality (2005) and Taylor (2003) suggest that the selection of these drainage components should be influenced by unique onsite characteristics. It is unlikely that all SuDS options and technologies are applicable and effective on any one site. Therefore, the advantages and limitations of each system should be identified during the planning and design phases (Donovan & Naji, 2003; Melbourne Water Corporation, 1999). With reference to Woods-Ballard *et al.* (2007) and Field & Sullivan (2003), the following five basic selection criteria should be considered:

i) Current and future land use characteristics;

ii) Site characteristics and utilisation requirements;

iii) Catchment characteristics;

iv) Stormwater runoff quantity and quality performance requirements; and

v) Amenity and biodiversity requirements.

For the effective management of stormwater runoff, a SuDS treatment train or 'management-train' should be used (Hobart City Council, 2006; Endicott & Walker, 2003). This incorporates a selection of SuDS options that are arranged in parallel or sequentially to improve the quantity and quality management of stormwater runoff. There is a hierarchy of management options and techniques that should be considered in developing SuDS treatment trains (Wilson *et al.*, 2004; Melbourne Water Corporation, 1999). Figure 2.5 depicts the SuDS management hierarchy.

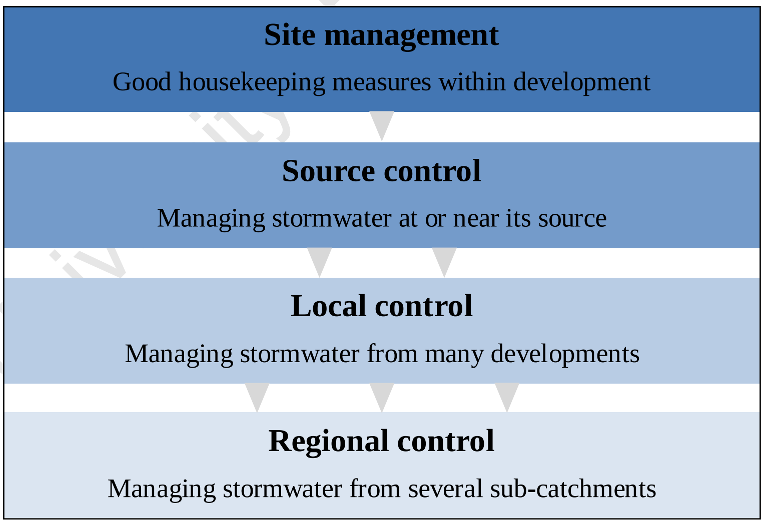

Figure 2.5: SuDS management hierarchy
(After Wilson *et al.*, 2004)

Descriptions for 'site management' and the three subsequent 'controls' for SuDS as well as descriptions of their associated options are briefly recorded as follows. Appendix 2 provides a conceptual design matrix for the selection of SuDS 'controls' according to this hierarchy.

2.3.4.1 Site management

Site management, also referred to as 'good housekeeping', is typically the preliminary focus and most preferred option of effective SuDS schemes (Melbourne Water Corporation, 1999). Site management is a set of 'preventative measures' that do not necessarily include natural drainage structures such as SuDS options and technologies. In the USA, significant emphasis is placed on good housekeeping procedures in order to minimise or prevent relatively large quantities of polluted runoff (Wilson *et al.*, 2004, Taylor, 2003). Site management tools or good housekeeping procedures include:

- High frequency sweeping of 'hard' surfaces;
- Environmentally friendly fertilisers, herbicides and fungicides;
- Management of construction sites to reduce sedimentation and soil erosion;
- Ensure adequate procedures for the removal of harmful spillages;
- Limit the contact of runoff and harmful pollutants; and
- Educating the public with respect to the use of weedkiller for lawns and detergents for washing cars (Wilson *et al.*, 2004).

2.3.4.2 Source controls

SuDS source controls are the most preferred structural options for the management of stormwater runoff (Figure 2.5). They are typically used to manage stormwater runoff as close to its source as possible. These SuDS options are generally applicable within household peripheries. A brief description of each source control option is provided as follows:

i) **Green roofs** – are vegetated covers that lie on the surface of roofs (Wanielista *et al.*, 2008; Stahre, 2006). *Sedum* is the most common plant species used for green roofs; however, other vegetation types can be used in a strategic manner to increase resilience during extreme climatic conditions. A continuous green roof survey conducted on the eThekwini Engineering Services building (Greenstone, 2010), as well as extensive international surveys, have indicated that green roofs are capable of absorbing light to moderate rainfall events – typically < 25 mm – with ease (Stovin, 2009; Dallmer Roach & Sargent, 2008). The most common types of green roofs include: extensive green roofs, intensive green roofs (Figure 2.6) and simple intensive green roofs. Green walls, and blue roofs (rainwater retained on rooftops) perform similar functions.

ii) **Sand filters** – also known as 'perimeter sand filters', are double chamber structures used to manage stormwater under the earth's surface. They are comprised of a sedimentation chamber and a filtration chamber that underlie a bed of sand or other filtration media through which stormwater runoff passes (Debo & Reese, 2003). Sand filters generally operate effectively when serving impervious areas less than 8 000 m^2, however, large sand filters have the capacity to manage stormwater runoff from areas as large as 100 000 m^2 (Endicott & Walker, 2003). Common technology derivatives of sand filters include: underground sand filters, surface sand filters, and filter drains.

iii) **Soakaways** – are excavated pits, normally square or circular in shape, and are packed with course aggregate and other porous media. Soakaways are commonly used for the temporary storage of stormwater runoff, and offer an effective alternative to channelling roof and surface runoff onto an open infiltration area. They generally store rapid runoff from a single property or development, which recharges the groundwater (Livingston & McCarron, 2008; Stahre, 2006). Soakaways are also particularly effective in removing particulate and suspended stormwater runoff pollutants (Melbourne Water, 2005). Common technology derivatives of soakaways include; oil and grit separators, and modular plastic geocellular structures.

iv) **Stormwater collection and reuse** – also known as ‘rainwater harvesting’ (Figure 2.7), is an essential element of Water Sensitive Urban Design (WSUD; McAlister, 2007), and includes the temporary storage and successive reuse of rooftop and/or surface runoff (Melbourne Water Corporation, 1999). The utilisation of stormwater for several household and industrial purposes, all with varying usage characteristics, optimises potable water savings and reduces stormwater discharges from roofs. Scholz (2006) and Parkinson & Mark (2005) suggest that it is during extreme rainfall events that rainwater harvesting systems are considered most useful, as they aid in reducing stormwater flood peaks and provide extended detention. According to Garcia Maldonado (2009) and Woods-Ballard *et al.* (2007), stormwater collection and reuse systems are configured as either: direct supply systems, gravity systems, or centralised supply systems.

Figure 2.6: Intensive green roof, City of Cape Town CBD

Figure 2.7: Rainwater harvesting tank, Selborne Estate, East London

2.3.4.3 Local controls

Local controls are used to manage stormwater runoff as a second ‘line of defence’ (Figure 2.5). These SuDS options are typically used in local or municipal areas such as roadway reserves and parks. A brief description of each local control option is provided as follows:

i) **Bio-retention areas** – also known as ‘rain gardens’ or ‘bio-retention filters’, are landscaped depressions used to manage stormwater runoff through several natural processes, such as filtration, adsorption, biological uptake and sedimentation (Debo & Reese, 2003). They typically reduce stormwater runoff quantities and rates, and improve the quality of stormwater discharging into downstream watercourses (Woods-Ballard *et al.*, 2007). Bio-retention areas normally incorporate a series of small stormwater management interventions such as grassed strips for infiltration, temporary ponding areas, sand beds, mulch layers and a wide variety of plant species (Figure 2.8; Endicott & Walker, 2003). The most common derivative of bio-retention areas is bio-retention ruts (Appendix 1; Section 4.1.6.1).

ii) **Filter strips** – are grassed areas of land that are used to manage shallow overland stormwater runoff through infiltration. These ‘grassed areas’ are densely vegetated and generally uniformly graded (Debo & Reese, 2003). Filter strips are most effective as pre-treatment options in treatment trains, especially to aid the stormwater management processes of bio-retention areas, infiltration trenches and swales (Melbourne Water Corporation, 1999). Filter strips can also be used to intercept and redirect stormwater runoff in order to spread it as sheet flow, thus attenuating flood peaks (Field & Sullivan, 2003; Melbourne Water, 2005). They are designed to use biofiltration as a primary means of stormwater runoff pollutant removal.

iii) **Infiltration trenches** – are excavated trenches which are backfilled with rock or other relatively large granular material, and wrapped in geotextile. They have a rectangular cross-section that lies flush with the ground (Figure 2.9; Hobart City Council, 2006). Infiltration trenches are typically designed to receive stormwater runoff from adjoining residential properties and transportation links such as asphalt roads and footpaths (Debo & Reese, 2003, Taylor, 2003). Field & Sullivan (2003) suggest that infiltration trenches remove as much as 90% of sediment, heavy-metals, coliform bacteria and organic matter for stormwater runoff. Hydraulically, they increase stormwater infiltration and groundwater recharge, which decreases the frequency of flooding (SEMCOG, 2008).

Figure 2.8: Bio-retention area underlying footbridge, Evergreen Retirement Village

Figure 2.9: Infiltration trench between residential properties

iv) **Permeable pavements** – are impervious surfacing products typically in the form of concrete block pavers (CBPs), which allow stormwater runoff to infiltrate through the development surface and into the sub-layers and/or underlying stratum (Figure 2.10; Taylor, 2003, Woods-Ballard, *et al.* 2007). This option typically includes a load-bearing, durable and pervious surface together with an underlying layered structure that temporarily stores stormwater runoff (Concrete Manufacturers Association, 2003). Stormwater runoff that is stored in the underlying layers can be collected, screened and reused for several non-potable, domestic purposes (Parkinson & Mark, 2005). Common technology derivatives of permeable pavements include: gravel pavement systems, porous asphalt and concrete systems, and modular pavements.

v) **Swales** – are shallow grass-lined channels with flat and sloped sides that typically remain dry between rainfall events (Mays, 2001; Parkinson & Mark, 2005). They are comprised of grass bases and sides but alternative materials can be used to suit the onsite drainage characteristics (Figure 2.11; Woods-Ballard *et al.*, 2007). They serve as an alternative drainage option to roadside kerbs and gutters in low and medium density residential areas, generally having larger stormwater infiltration and detention capacity (Jefferies, 2010; Field & Sullivan, 2003). Swales use partial infiltration and bio-infiltration to remove pollutants in stormwater runoff. The most common types of swales include: enhanced dry swales, wet swales, and vegetated buffers.

Figure 2.10: Concrete grass block permeable pavement, eThekwini

Figure 2.11: Enhanced dry swale, Cotswold Downs Golf Estate, eThekwini

2.3.4.4 Regional controls

Regional controls are typically used to manage stormwater runoff as a last 'line of defence' (Figure 2.5). These SuDS options receive stormwater runoff from source and local control options, which are typically smaller in size than regional control options. Regional controls are generally used in local, municipal or government precincts. A brief description of each regional control option is provided as follows:

i) **Constructed wetlands** – are man-made systems that attempt to mimic the characteristics of natural wetlands, and include marshy areas of open water and aquatic-resilient plants (NCDWQ, 2007; Woods-Ballard *et al.*, 2007). Wetlands are aesthetically pleasing and provide a vibrant habitat for fish, birds, rare and endangered species, and other wildlife (Figure 2.12). Constructed wetlands are effective ecosystem filters. They are most efficient in the removal of particulates and dissolved nutrients as well as noxious substances such as heavy metals (Debo & Reese, 2003). Meandering flows are ideal as they encourage extended detention times that typically increases the removal of pollutants (Melbourne Water Corporation, 1999). Common derivatives of constructed wetlands include: extended detention shallow wetlands, pocket wetlands, and submerged gravel wetlands.

ii) **Detention ponds** – also known as 'detention basins', are relatively large depressions below the natural ground level that store stormwater runoff for predetermined periods of time. They are typically unlined and vegetated, but lined ponds can be used if there are soil stability or land use issues (Jefferies, 2010; Melbourne Water Corporation, 1999). Stormwater runoff typically infiltrates into the underlying soil stratum or is drained out of the pond between rainfall events (Field & Sullivan, 2003). Detention ponds are also effective in regulating the volume and rate of stormwater flows discharging into downstream watercourses. This is particularly useful in preventing downstream scour and soil erosion (MBWCP, 2006; Semple, 2004). Common derivatives of detention ponds include: extended detention ponds and infiltration basins.

iii) **Retention ponds** – also known as 'retention basins', are formed by excavating below the natural ground water level and/or lining the base to retain stormwater runoff (Figure 2.13; Debo & Reese, 2003; Mays 2001). They are used extensively to manage relatively large quantity of stormwater runoff. The maximum storage capacity of retention ponds is typically greater than their permanent pond volume, in order to allow for the storage of inflow stormwater runoff in addition to controlling discharges (Field & Sullivan, 2003, NCDWQ, 2007). They are particularly effective in reducing stormwater flood peaks, and typically utilise a combination of sedimentation, filtration, infiltration and biological uptake processes to remove pollutants from stormwater runoff (Woods-Ballard *et al.*, 2007). Haskins (2010) and Van Duzer (2004) suggest that the stormwater pollutant removal capacities of retention ponds can be significantly improved with the installation of 'floating islands'.

Figure 2.12: Densely vegetated constructed wetland, eThekwini

Figure 2.13: Retention pond at foot of golf estate, eThekwini

2.3.5 SuDS treatment train theory

The effective harvesting, cleansing and routing of stormwater runoff are complex aspects of urban drainage design and management practice (Idaho Department of Environmental Quality, 2005; Endicott & Walker, 2003). The efficacy of these control and management processes is generally increased by utilising SuDS 'treatment trains', also known as 'management trains' (Wilson *et al.*, 2004; Minton, 2002). SuDS treatment trains should prioritise; (1) water quality treatment for low flows, and (2) attenuation and volume control for high flows. Furthermore, the number and size of SuDS treatment train components could depend on; (1) the sensitivity of receiving watercourses or other environments, (2) the size of contributing catchments upstream, and (3) the expected pollutant concentrations in stormwater runoff inflows (Woods-Ballard *et al.* 2007). It is not essential that each of the SuDS treatment train components is only used in accordance with the 'control categories' in which they are listed. Each SuDS option can be scaled to meet the drainage requirements of any specified site in a unique manner (Urban Water Technology Centre, 2009; Semple, 2004; Taylor, 2003). Figure 2.14 details the management of stormwater runoff according to three different control sizes, namely: source controls, local controls and regional controls (also textually illustrated in Appendix 2).

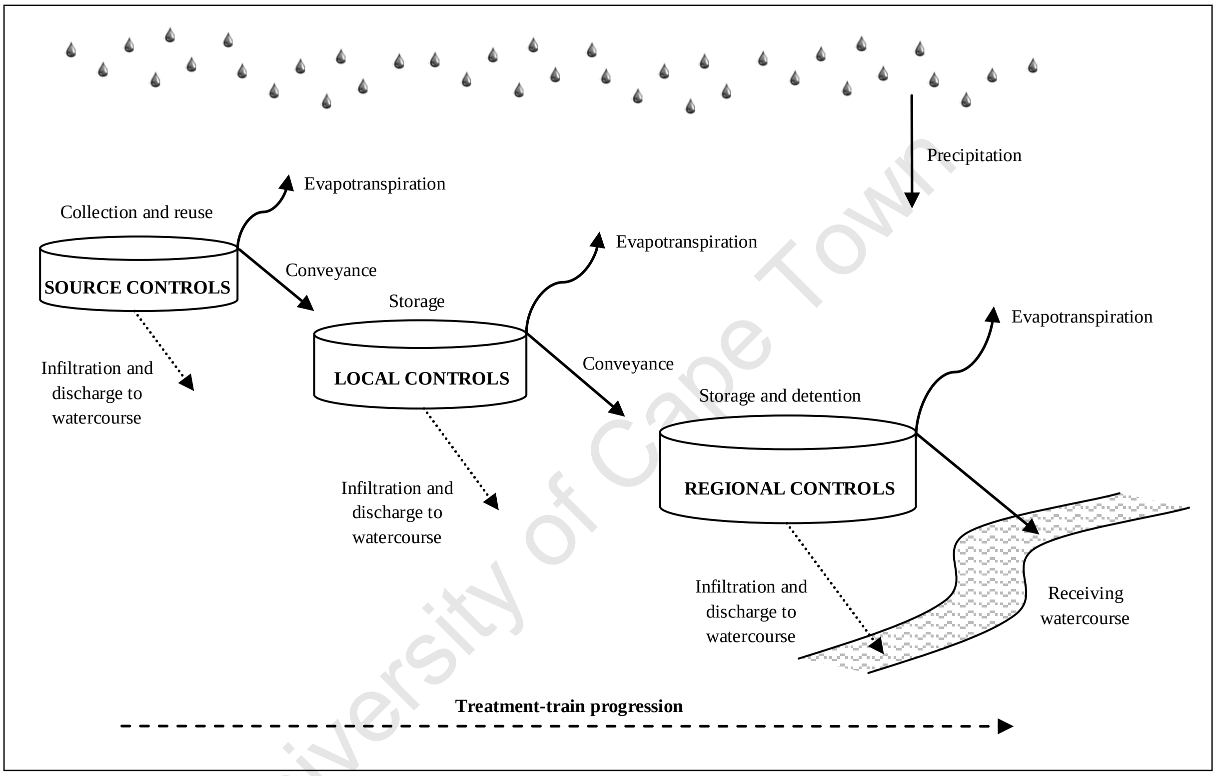

Figure 2.14: SuDS treatment-train progression (After Woods-Ballard *et al.*, 2007)

It is essential that wherever possible, stormwater runoff is controlled and managed in small and cost-effective landscaping features, which are located within sub-catchments. The management of stormwater runoff using source controls should be prioritised over controls further along the drainage system such as local and regional controls, as is also illustrated in Figure 2.5 (Woods-Ballard *et al.*, 2007; Field & Sullivan, 2003). The collection, storage and detention elements of several SuDS options are particularly useful in mimicking the natural drainage characteristics of a development. Where stormwater runoff is transported between SuDS options, natural conveyance systems such as filter strips and swales should be used (SEMCOG, 2008). Wilson *et al.* (2004) suggests that the performance of treatment trains is typically proportional to the number of SuDS options utilised. The greater the number of options used sequentially, the greater the performance of the specified treatment train is likely to be, and the smaller the risk of system failure (Taylor, 2003). Woods-Ballard *et al.* (2007) state that the following benefits are generally appropriated through the incorporation of a number of SuDS components:

- The treatment efficacy of a multi-component treatment train is maximised to remove a wide range of pollutants by utilising many treatment processes;
- Relatively high pollution loads are normally contained within pre-treatment options and upper SuDS components, which minimises the potential damage to the drainage system and ensures that relatively high concentrations of pollutants are not conveyed into the receiving watercourse;
- Water quality treatment is performed throughout many control processes, such as conveyance, infiltration and detention;
- Coarse sediments and other suspended solids are removed by SuDS options that provide reduced flow velocities and extended periods of detention; and
- Additional hydraulic and water quality protection is provided in the final stages of the treatment train, increasing the potential for amenity and biodiversity benefits.

Pre-treatment options and/or technologies for the removal of litter and sediment loads are pivotal elements in improving the longevity of treatment trains. Maintenance is also a critical aspect of the efficacy of treatment trains, and should be incorporated into a long-term management plan (Donovan & Naji, 2003; Melbourne Water Corporation, 1999). SuDS treatment trains are typically applicable in all developments; however, unique site constraints may limit the management potential of several SuDS options. The Hobart City Council (2006) and Woods-Ballard *et al.* (2007) suggest that as a rule of thumb, where the risks posed to the environment are relatively high, many SuDS options should be utilised in the specified treatment train. Conversely, fewer options are required when the risks are lower.

2.3.6 Best management practices

In many developed countries, 'best management practices', abbreviated 'BMPs', are used to denote interventions that increase the efficacy of urban design and management technologies (Endicott & Walker, 2003; Taylor, 2003). In terms of urban drainage, the term BMP is often used interchangeably with SuDS; alternatively it refers to distinctive 'structural' and 'non-structural' interventions that potentially enhance the performance of SuDS options, in order to cater for unique physical and environmental site characteristics and drainage requirements (SEMCOG, 2008; Semple, 2004; LASMD, 2000).

Structural BMPs typically include 'hard', conventionally engineered add-ons to SuDS options that enable, *inter alia*, a reduction in the potential of sedimentation and soil erosion

(Wilson *et al.*, 2004). These structures include, pipe networks, concrete energy dissipaters and gabions. Such devices are more readily used in dense urban areas such as in CBDs. It is likely that a combination of SuDS and conventional drainage infrastructure renders the most effective drainage system (Woods-Ballard *et al.*, 2007; Taylor, 2003; Minton, 2002). The following subsections present three simple examples of structural BMPs that increase the efficacy of SuDS options.

i) **Kerb inlet structures** – are commonly used to direct stormwater runoff from roadways, during relatively small rainfall events, into SuDS options such as swales or infiltration trenches (Figure 2.15). Stormwater runoff is channelled along the kerb edge and is led into the specified SuDS option via the kerb inlet (Wright Water Engineers, 2008). During larger rainfall events, stormwater runoff typically overtops the concrete kerb into the adjoining SuDS option (LASMD, 2000).

ii) **Gabion structures** – are used extensively as BMPs in SUDS schemes. They are particularly useful in preventing scour and sedimentation. Gabion structures are typically installed at the inlets and/or outlets of ‘regional’ controls such as detention ponds and retention ponds (SEMCOG, 2008; Wright Water Engineers, 2008). Their shape and form are generally tailored to maximise the efficacy of the SuDS scheme (LASMD, 2000). A use of these structures is depicted in Figure 2.16.

iii) **Energy dissipaters** – are commonly used as conventional drainage infrastructure to minimise or prevent damage to property (LASMD, 2000). They buffer high velocity flows before stormwater runoff is discharged onto or over a specified drainage area. They are typically used in conjunction with inlet structures, for SuDS options such as bio-retention areas and permeable pavements (Wight Water Engineers, 2008).

Figure 2.15: Kerb inlet structure directing stormwater runoff into vegetated swale, eThekwini

Figure 2.16: Gabion structure utilised as erosion protection inlet, eThekwini

Alternatively, non-structural BMPs include passive and/or intangible stormwater management interventions (Wright Water Engineers, 2008; LASMD, 2000). These BMPs do not typically have technical or engineered designs (NCDWQ, 2007; Regenold, 2005). Debo & Reese (2003) suggest that urban practitioners and municipal representatives should implement non-structural BMPs in SuDS schemes, including informative, regulatory and programmatic BMPs such as:

- Public education and participation;
- Household and garden material uses controls (less harmful alternative products);
- Solid waste dumping controls;
- Construction site stormwater runoff control;
- Discovery and reduction or elimination of illicit discharges;
- Intensive street maintenance and roadway cleaning; and
- Plant and other vegetation controls (NCDWQ, 2007; Debo & Reese, 2003).

Health and safety is another particularly important non-structural BMP that should be rigorously adopted in SuDS schemes (Woods-Ballard *et al.*, 2007; Wilson *et al.*, 2004). Post 2000 health and safety measures have been the most prominent non-structural BMPs as a result of the prevalence of biological unintended consequences in natural drainage systems (Debo & Reese, 2003). Debo & Reese (2003) list the following five steps to plan for or detect health and safety issues in SuDS schemes:

i) Identification of pollutant and/or vector of concern;

ii) Assessment of means by which pollutant and/or vector enters system;

iii) Selection of means by which pollutant- and/or vector-generating activity can be reduced or eliminated;

iv) Development of interception measures; and

v) Development of implementation requirements and funding.

It is important to utilise a combination of structural and non-structural BMPs in SuDS schemes for increased urban drainage efficacy (Regenold, 2005).

2.3.7 Ecosystem services

'Ecosystem services', also referred to as 'environmental goods and services' (EGS), are all possible goods and services that benefit human livelihoods, which are produced by ecosystem processes involving the interaction of living environmental elements (ASLA, 2008). In theory, the link between the philosophy of SuDS and the practical application thereof, is possible through the appropriation of 'ecosystem services'. These benefits are can also be monitored as performance criteria to indicate whether a SuDS treatment train is functioning sustainably. The objective of this approach should be to protect, restore and improve the immediate environment through efficient management (MBWCP, 2006). According to ASLA (2008) the following eight ecosystem services are likely to be appropriated with the correct design and management of SuDS options.

i) **Regulated climate** – maintaining an acceptable balance of atmospheric gases at historic levels and eliminating or minimising greenhouse gases, in order to regulate local temperatures, precipitation and humidity;

ii) **Water and air purification** – the removal and reduction of pollutants in water and in the air;

iii) **Regulated water supply** – the storing and provision of water within artificial storage facilities, watersheds and aquifers;

iv) **Erosion and sediment control** – Retaining soil within a specified environment, through the structural protection against damage from erosion and siltation processes;

v) **Hazard mitigation** – reducing the likelihood of, and vulnerability to, damage from extreme rainfall events and storm surges;

vi) **Habitat functions** – providing an ideal habitat for refuge and reproduction for vegetative species and wildlife, thereby contributing to nature conservation;

vii) **Waste treatment** – the decomposition of waste compounds and the recycling of associated nutrients; and

viii) **Human health, well-being and cultural benefits** – enhancing physical, mental and social well-being as well as improving cultural, educational, aesthetic and spiritual experiences, through interactions with nature (ASLA, 2008).

2.3.8 Integrating sustainability and SuDS

2.3.8.1 Sustainable development

'Sustainability' and 'sustainable development' have become recognised *buzzwords* in the 21st Century, especially in the urban infrastructure design and management sector. These are often misconceived as 'end states' and perceived as rigid project targets that are hoped to be achieved in an allotted time-frame (Hjorth & Bagheri, 2006). However, sustainable development should not be viewed as a project, which has an end state. It is neither the state of the system nor an attainable target, but rather an ideal to the system. It is an ongoing process which inter-relates aspects of economy, environment, society and other technicalities (Hjorth & Bagheri, 2006; Donovan & Naji, 2003). Hjorth & Bagheri (2006) state that *"sustainable development must,* *then, be seen as an unending process defined neither by fixed goals nor the specific means of achieving them, but by an approach to create change."*

O'Regan & Moles (1997) suggest that conventional drainage practices have, for one, failed to manage the complexities of environmental systems, which has resulted in a surplus of misguided paradigm shifts. Secondly, they suggest that common errors and undesirable side effects in urban management are often a result of the inability of decision-makers to understand the underlying structure of the system they are a part of. However, the notion of sustainability is rather an ideal and ongoing process that should always be considered by the designers and managers of SuDS schemes (Hobart City Council, 2006; MBWCP, 2006). The design and management of urban infrastructure in South Africa, and urban drainage practices more specifically, requires a shift from fragmented maintenance sciences to 'holism'. According to Hjorth & Bagheri (2006) and Senge *et al.* (2000), such a shift requires the yielding of linear and mechanistic thinking to non-linear, organic thinking – or 'systems thinking'. This places emphasis on management seeking to understand the relationships between the components of urban drainage systems, opposed to the sciences of the components themselves (Hjorth & Bagheri, 2006; Field & Sullivan, 2003).

2.3.8.2 Interdisciplinary partnerships

> *"Public sector municipal government and utility leaders responsible for providing reliable water, wastewater, and stormwater management are confronted by several important trends affecting the future of cities. These trends include the need to increase the social and economic benefits created by urban infrastructure, improving collaboration among overlapping agencies and jurisdictions, making the transition from "fast conveyance" to "closed-loop" systems, introducing public stakeholders into decision-making and program implementation, and preparing for extreme events" (Brown, 2007).*

Interdisciplinary partnerships are an essential element of the design and management of SuDS schemes. Scholars widely suggest that a successful design team incorporates a range of disciplines, of which civil engineers are simply one element (Woods-Ballard *et al.*, 2007; Ellis *et al.*, 2006). Armitage (2006) and Ellis *et al.* (2006) encourage urban practitioners to establish interdisciplinary partnerships within their means for added effectiveness at all stages of the implementation of urban development such as SuDS schemes. This strengthens the decision-making processes, which for the selection of these schemes involves a variety of stakeholders within public and private sectors, who contribute differing powers and opinions to different urban spheres (Ellis *et al.*, 2006). Table 2.2 lists professionals that are likely to provide fundamental input into SuDS schemes (listed alphabetically).

Table 2.2: Potential human capital for SuDS (After Armitage, 2006)

Professionals	Expertise and knowledge base	Elementary focal point(s) in SuDS
Architects	Infrastructure conceptualisation and structural aesthetics	Quantity / Amenity and Biodiversity
Botanists	Vegetation sciences and plant biology	Quality / Amenity and Biodiversity
Civil Engineers	Infrastructure design and management	Quantity / Quality
Clients	Conceptual specifications and appointments	–
Climatologists	Climatology issues and concerns, and ‘climate change’	Quantity / Amenity and Biodiversity
Economists	Funding, fiscal viability and investment opportunities	–
Engineering Geologist	Engineering geology and earthwork requirements	Quantity
Environmentalists	Environmental impacts and protection	Amenity and Biodiversity
Epidemiologists	Water-borne diseases, and related health provisos	Quality / Amenity and Biodiversity
Freshwater Ecologists	Urban rivers restoration, rehabilitation and remediation	Quality / Amenity and Biodiversity
Geohydrologists	Urban groundwater uses and requirements	Quantity / Quality
Geomaticians	Spatial data acquisition and spatial management systems	Quantity
Historians	Site heritage and historical significance	Amenity and Biodiversity
Landscape Architects	Urban vegetation and exterior landscape aesthetics	Quantity / Amenity and Biodiversity
Mechanical Engineers	Mechanical equipment operation and maintenance	–
Social Anthropologists	Local cultural studies and social impact assessments	Amenity and Biodiversity
Urban Planners	Urban layouts and land-use requirements	–
Zoologists	Wildlife biology and habitat requirements	Amenity and Biodiversity

2.4 Tools to implement SuDS

The purpose of this subsection is to present and discuss several models and decision support systems (DSSs) that urban practitioners can utilise as tools to select, design and manage SuDS options. Several SuDS modelling programmes are mentioned, followed by a brief review of two prominent DSSs that are used internationally for the selection of appropriate SuDS options, technologies and BMPs.

2.4.1 Modelling tools for SuDS

The final, detailed sizing of a SuDS scheme typically entails the use of modelling programmes to assess dimensioning and performance. All modelling procedures and outcomes should conform to the specified development proposal, and adhere to the consent requirements for adequate stormwater management (Woods-Ballard *et al.*, 2007). Modelling procedures in particular should conform to the treatment train ideals of SuDS (Wilson *et al.*, 2004). Valid data sources are a particularly important element of urban drainage software. Therefore, hydrological data to be inputted should be obtained from local authorities and/or authorised consultants. Alternatively, in South Africa, rainfall data and information, with accurate region specific data, can be extracted from the 'South Africa Rain Atlas' URL (last updated 2006; Zucchini & Nenadic, 2006; McNeill *et al.*, 1993). The South Africa Rainfall Atlas includes image and site specific databases in addition to a rainfall simulator. Daily, monthly and annual rainfall data and information can be extracted, as well as storm percentile data.

Table 2.3: SUDS component focus for selected design models (Elliot & Trowsdale, 2005)

	Imperviousness reduction	Ponds and wetlands	Soil protection	Reduction of contaminant generation	Infiltration Trenches/bores	On-site detention tanks	Swales	Run on	Rain tanks	Bio-retention, rain gardens Filtration devices	Permeable Paving	Green roofs
MOUSE												
MUSIC												
P8												
PURRS												
RUNQUAL												
WinSLAMM												
StormTac												
SWMM												
UVQ												
WinDes (Quantity only)												
WBM												

Table 2.3 displays eleven SuDS modelling programmes that are used internationally for the selection of appropriate SuDS options (key follows Table 2.4). Additionally, Table 2.4 displays the competencies of each of the eleven modelling programmes. Elliot & Trowsdale (2005) and the Melbourne Water Corporation (1999) assert that before utilising these or other software packages, users should be aware of the assumptions and limitations of each. The modelling of rainfall and stormwater runoff characteristics is essentially a guess at best. The greatest uncertainties experienced in predicting the performance of SuDS using modelling software are typically the complexities that are associated with biomass, biodiversity and human intervention (SEMCOG, 2008). According to Woods-Ballard *et al.* (2007), these uncertainties are not a function of a lack of modelling facility, but have been intentionally excluded to encourage practically derived approaches to SuDS schemes. Generally, the intention of modelling programmes is to fully utilise the intuition and experience of end-users in as many computations as is selected (Elliot & Trowsdale, 2005).

Table 2.4: Potential model uses for design computation (Elliot & Trowsdale, 2005)

	Public Education	Research	Developing Sizing rules for devices	Planning of land use in catchments/cities	Preliminary design of regional controls	Preliminary design of a subdivision or site	Detailed design of regional drainage system	Detailed design of subdivision or site	Site layout and materials selection
MOUSE		■	■	■	■	■	▒	▒	▒
MUSIC			■	■	■	■			
P8			■	■	■	▒			
PURRS		■	■			■			
RUNQUAL			■	■	■	▒			
WinSLAMM			■	■	■	▒			
StormTac				■	■				
SWMM		■	■	■	■	■	▒	▒	▒
PCSWMM		■	■	■	■	■	▒	▒	▒
UVQ		■	▒	▒	▒	■			
WinDes (Quantity Only)			▒		■	■	■	■	▒
WBM			■	■	■	■			

Tabular key: ■ Fully satisfied ▒ Partially satisfied □ N/A

2.4.2 Decision support systems for SuDS

Due to the extensive selection variety of SuDS options (38 SuDS options presented in the SuDS Guidelines in Appendix 1), a number of decision support systems (DSSs) have been developed to improve and support basic selection criteria and speed up decision making.

2.4.2.1 Overview of decision support systems

Holsapple (2008b) suggests that a DSS improves cognitive, temporal, spatial and/or economic limits of the decision maker. With additional support for decision makers, decisions should be expressed:

- More productively (faster, less expensively, and with less effort);
- With greater agility (alertness to the unexpected, and higher agility to respond);
- Innovatively (with greater insight, creatively, novelty, and surprise);
- Reputably (with higher accuracy, ethics, quality, and trust); and
- With greater satisfaction amongst stakeholders (participants, sponsors, consumers, and implementers) (Holsapple, 2008b).

These benefits are typically referred to as the PAIRS effect, where PAIRS abbreviates productivity, agility, innovation, reputation and satisfaction (Holsapple, 2008b). While the vast majority of decisions are predictions of future outcomes, as complexity builds upon complexity – typically in natural environments – decision-makers must increasingly rely on their intuition and judgment. Bennet & Bennet (2008) describe a complex situation as one that may be difficult to define, one that has the potential to significantly change in response to any particular solution, and one that may not have a single ‘correct’ answer. It is the condition of a system, situation or organisation that has a specific degree of order, but too many components and relationships to understand simply or logically. Therefore, to move from a complex state to a desired comprehendible state, requires a decision solution strategy that plans for a sequence of known actions (Bennet & Bennet, 2008; Liang *et al.*, 2008).

In light of the environmental complexities associated with SuDS schemes, Bennet & Bennet (2008) state the following five main considerations that are necessary in understanding complex decisions:

i) **Emergence** – a global property of a complex system that results from the interactions and relationships among its agents (people), and between the agents and their environment. Examples are culture, trust, attitudes, organisational identity, and team spirit.

ii) **Butterfly effect** – when a very small change in one part of a situation – which may initially go unrecognised in the environment – can, in certain circumstances, result in massive disruption, surprise, turbulence, or a change in the environment that is possible, or extremely difficult to predict.

iii) **Tipping point** – when a complex system changes slowly until all of a sudden it unpredictably hits a threshold which creates a large-scale change throughout the system. Examples of this include the stock market crashes of 1929, 1984 and 2008.

iv) **Feedback loops** – are excitements or energy surges due to a successful event, or perhaps a decrease in morale due to over-controlling management, which in turn leads to lower morale causing management to increase control, creating a reinforcing loop.

v) **Power laws** – are mathematical relationships that bring together two parameters (measures) within some complex system. For example, the number of earthquakes versus the magnitude of the earthquakes follows a simple power curve.

The applicability of DSSs in the selection of appropriate SuDS has become more prevalent in the 21st Century. Liang *et al.* (2008) and Ellis *et al.* (2006) affirm that relevant and robust DSS tools are extremely valuable in most project stages, particularly during preliminary negotiations as well as in the detailed selection and implementation of SuDS. They are also developed to investigate and examine the fundamental performances of SuDS options and treatment trains on specified sites (Jefferies *et al.*, 2008). Two international SuDS DSSs are briefly presented as follows.

2.4.2.2 Multi-criteria analysis DSS

A popular DSS structure for the selection of appropriate SuDS components is a multi-criteria analysis (MCA). The 'DayWater project' (www.daywater.org) is widely known for the development of a functional web-based multi-criteria analysis approach to stormwater management. According to Ellis, *et al.* (2006), a simplified and structured approach to a multi-criteria method for the assessment of water resources was proposed within the 1998 UNESCO International Hydrological Programme (UNESCO, 1998). The MCA designed in accordance with the 'DayWater decision support approach' seeks to provide a basis for the selection of BMPs for stormwater runoff management. It also accounts for a variety of stakeholders within public and private sectors holding differing powers and opinions regarding the significance they attribute to a range of technical, environmental, economic and social criteria (Ellis *et al.*, 2006).

A MCA approach to decision-making for SuDS schemes is particularly effective in enabling the handling of relatively large amounts of quantitative and qualitative developmental information in a consistent manner (Holsapple, 2008a,b). It also increases the transparency of the decision-making process and enables greater facilitation for stakeholder participation in this process. In addition, the decision-making process can be archived and fully audited at any point in time (Ellis, *et al.* 2006). The utilisation of the DayWater MCA requires the developer to refer to other hydraulic and water quality methods in order to correctly size BMP drainage technologies. In this instance, Ellis *et al.* (2006) suggests that the MCA is fundamentally a linear additive modelling approach that allows stakeholders to apply weights and scores to consider, assess and evaluate preferred BMP drainage options in a user-friendly methodological framework. The DayWater MCA approach recognises seven broad-topic criteria as principal areas of interest, listed as follows:

i) Site characteristics;

ii) Technical;

iii) Environmental;

iv) Economic;

v) Operation and maintenance;

vi) Social and urban community benefits; and

vii) Legal and urban planning (Ellis *et al.*, 2006).

The 'site characteristics' criterion is a pre-MCA check, which is primarily used to perform screening and any initial profiling that should clearly define 'exclusion criteria'. This process also facilitates the determination of acceptable and unacceptable BMP drainage alternatives. The other seven criteria are assessed according to their associated 'indicators', 'benchmarks' and 'units'. For example, the 'technical' criterion is assessed according to the indicators, benchmarks and units in Table 2.5.

Table 2.5: 'Units' for specified indicators and benchmarks (After Ellis *et al.*, 2006)

Criteria	Indicators	Benchmarks	Units
Technical	Storage and flood control	Overflow frequency	1...n
		Design storm return interval	RI yrs
		Extreme event control	H/M/L
	Pollution control	Dissolved pollutant capture	%; H/M/L
		Solid(s) pollutant capture	%; H/M/L
	System adaptability	Ease of retrofitting	H/M/L
		Design freeboard	%; Vol., m^3

The rational objective for grouping ‘benchmarks’, ‘indicators’, and their associated ‘units’ under broad-topic criteria was to prevent the discouragement of end-users with exhaustive detail weights distributed sparsely across many variables. A useful advantage of this particular MCA tool is that objective (quantifiable) and subjective (qualitative) information can be ‘mixed’ within the development of reasonable scaling (Ellis *et al.*, 2006). The MCA then plots ‘utility scores’ for each benchmark based on input data. The utility scores are finally translated into quantitative outcomes that reflect the best performing BMP according to five specified levels of protection (LOP) or levels of safety (LOS). A quantitative outcome illustrating the relative performances of BMPs in the removal of total settleable solids (TSS) is depicted in Figure 2.17.

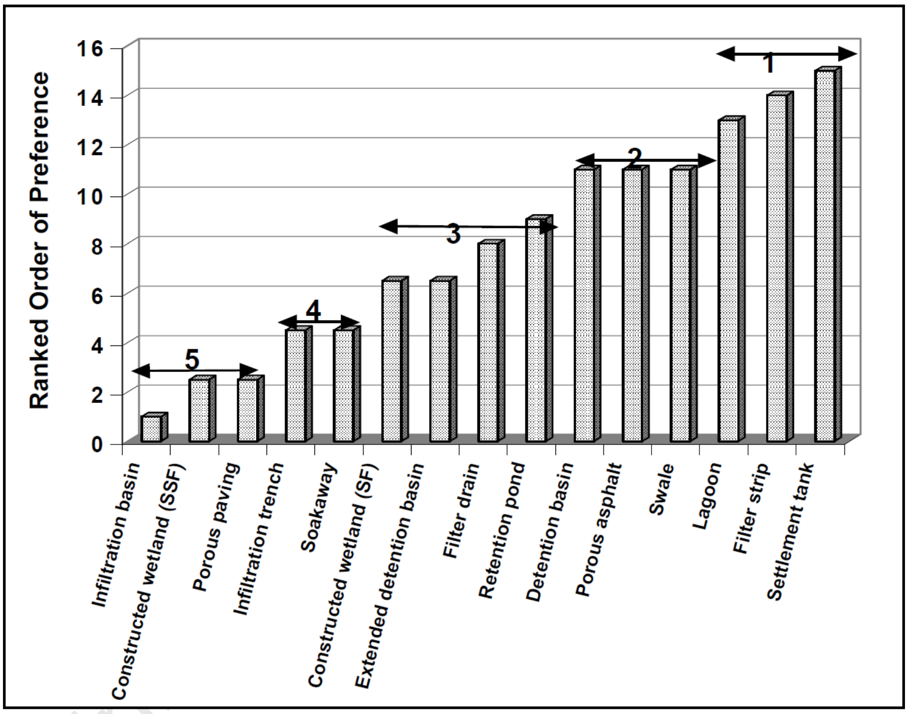

Figure 2.17: MCA scaling and scoring for BMPs in TSS removal (Ellis *et al.*, 2006)

Once the end-user has completed all the necessary inputs, the MCA performance matrix output becomes viewable on-line. End-users also have the liberty to apply different weightings to reflect varying significance placed on each of the criteria and their associated indicators, as specified by the stakeholders. Furthermore, the MCA can be repeatedly run using different weightings to reflect differing views, in the event that a consensus on weights cannot be reached. Moreover, sensitivity analyses can be performed by adjusting the values attributed to parameters with reference to their initial utility scores and weights (Ellis *et al.*, 2006).

2.4.2.3 SuDS treatment train assessment DSS

Although the aforementioned multi-criteria analysis DSS provides a comprehensive assessment of the performances of BMP drainage components with respect to a range of development conditions, the integration of these components into a 'treatment train' configuration is not discussed. This seems to be a particularly major shortfall of the DayWater project MCA, as the philosophy of SuDS is premised on the application and integration of more than one drainage control in series, so as to maximise stormwater quantity, quality, and amenity and biodiversity benefits. Conversely, Jefferies *et al.* (2008) place more emphasis on the formation of BMP drainage controls in a treatment train configuration, with the proposal of the SuDS Treatment Train Assessment Tool (STTAT).

STTAT is a proposed regulatory tool that provides guidance and regulatory consistency for developers concerning the requirements of the Scottish Environmental Protection Agency (SEPA). The tool is used to balance the risks of pollution entering receiving watercourses, taking into account the treatment that is provided by a selection of SuDS components in a treatment train. Importantly, the tool encourages developers to consider the requirements of SuDS schemes at the planning stage of a development, so as to avoid misunderstandings during development (Jefferies *et al.*, 2008; Woods-Ballard *et al.*, 2007). The tool proposes individual scores for single and multiple SuDS components within specified treatment trains. The assessment tool also reveals the robustness of some types of SuDS components in contrast to the vulnerability and inefficiency of others. STTAT is geared at meeting the pollution control requirements specified by the Water Framework Directive (WFD) and Controlled Activities Regulations (CAR) of Scotland. Through prudent adaption, however, these requirements can be adjusted to meet those specified in other countries such as South Africa. The tool also allows for the desired and acceptable level of transparency by the regulator and associated flexibility in choice of SuDS for the developers (Jefferies *et al.*, 2008). The scoring procedure adopted by Jefferies *et al.* (2008) utilises a simplified cost/benefit computation to determine the feasibility of selected SuDS treatment train options. Sufficient level(s) of treatment should be provided to satisfy the 'STTAT Equation' before development is permitted. The STTAT Equation is presented as follows:

$$\text{Treatment Train Scores} > \Sigma \text{ Risk Score}$$

The total 'Risk Score' is calculated by summing; (1) the 'Receiving Water Score', and (2) the 'Residential Catchment Score' or 'Non-Residential Catchment Score'. For example, the Receiving Water Scores and the Treatment Train Scores are displayed in Table 2.6 and Table 2.7, respectively.

Table 2.6: Receiving Water Score (After Jefferies *et al.*, 2008)

Receiving Water	**Score**
Sea water	0
Normal rivers	20
Significant existing / anticipated development / pollution pressures already on stream	30
Sensitive receiving environments e.g. SSSI; limited dilution watercourses; groundwater	30
Nutrient sensitive water bodies	50

Table 2.7: Treatment Train Scores (After Jefferies, *et al.*, 2008)

Description of Treatment Train combination	**Original Score**	**Revised Score (for use in practice)**
Permeable paving	25	40
Lateral inflow filter drain and infiltration trench	25	25
Swale with lateral inflow	25	40
Filter strip	25	40
Detention basin (no permanent water)	30	40
Detention Pond (with permanent pool of water with volume 1 x Vt)	45	50
Retention Pond (with permanent pool of water with volume 4 x Vt)	45	50
Permeable paving & underground storage	35	40
Infiltration trenches and basin	50	65
Filter strip or swale & detention basin	55	75
Permeable paving & detention basin	55	75
Permeable paving or swale & (1 x Vt) detention pond	70	90
Swales and (4 x Vt) retention pond	100	120
Filter strips or swales & detention basin & retention pond	120	140

In practice, Jefferies *et al.* (2008) suggest that the developer should provide non-controversial evidence of the type of land use for the development. Treatment train scores are comprised of several different aspects that influence the performance of SuDS. In most instances, scores allocated to individual components can be summed to disclose the total score. Jefferies *et al.* (2008) further asserts that the configuration of a SuDS treatment train should be a logical combination of various SuDS options. There are generally three key aspects of the assembly of SuDS options in the development of treatment trains; they should:

i) Be assembled in a logical order;

ii) Provide sequential treatment; and

iii) Provide acceptable backup in the event of failure of another drainage component (Jefferies *et al.*, 2008).

The sensitivity of the STTAT scoring mechanism was rigorously tested to determine whether the scores attributed to various risks within catchments were appropriate. The sensitivity testing and associated adjustments revealed that the specified scoring methods were robust in a variety of situations. Practical maintenance requirements and the resilience of SuDS options are also provided in STTAT (Jefferies *et al.*, 2008).

2.5 Legal context for stormwater management

A number of policies and guidelines bear influence on the management of stormwater and the environment in South Africa. In the engineering and built environment (EBE), these legal requirements and guidelines have shaped the 'dominant logic' of stormwater management (Buys & Aldous, 2009).

South Africa has three principal levels of government, listed according to the following hierarchy: national, provincial and local (Buys & Aldous, 2009). According to the Constitution of the Republic of South Africa (Act 108 of 1996), each level of government has the authority to pass laws, by-laws, policies, strategies and guidelines. National policies that relate directly to the management of stormwater do not currently exist. However, authoritative recognition has been given to watercourses and wetlands as being integral in urban environments (DWAF, 2006). There are several statutes and planning frameworks issued at the national, provincial and local government levels that influence the land use, development and economics of stormwater management in South African cities. In light of international obligations such as the WCED Brundtland Commission (Brundtland, 1987) and Agenda 21 (United Nations, 1992; Sitarz, 1993), an inventory of national legislation and guidelines that impacts the management of stormwater runoff (both quantity and quality) in South Africa is listed below. Provincial and local legislation and guidelines are described with reference to the Western Cape Province and the City of Cape Town Local Municipality, respectively, as these bear the greatest legislative context on Century City. Sections and clauses that are relevant in the investigation of Century City, if any, are briefly identified and discussed.

2.5.1 National legislation and guidelines

The following legislation and guidelines have been issued at a National government level.

2.5.1.1 National Water Act

The National Water Act (Act 36 of 1998; Government Gazette, 1998a; Government Gazette, 1999) places considerable responsibility on local authorities for the protection of water resource. Part 4, section 19(1), states that, *"An owner of land, a person in control of land or a person who occupies or uses the land on which – (a) any activity or process is or was performed or undertaken; or (b) any other situation exists; which causes, has caused or is likely to cause pollution of a water resource, must take all reasonable measures to prevent any such pollution from occurring, continuing or recurring."* This necessitates the need for stormwater 'quality' control on private and public land, which is the responsibility of the land owner. With respect to the management of water resource, nothing is stated regarding the 'sustainable' or 'integrated' management of water resources.

2.5.1.2 National Environmental Management Act

The National Environmental Management Act (Act 107 of 1998; Government Gazette, 1998b) largely acknowledges that many South African citizens reside in environments that are harmful to their health and wellbeing. In response to this challenge of widespread impoverished development, it is stated in the act that, *"everyone has the right to an environment that is not harmful to his or her health or well-being; sustainable development requires the integration of social, economic and environmental factors in the planning, implementation and evaluation of decisions to ensure that development serves present and future generations."* According to Buys and Aldous (2009) the act also places a responsibility on developers to prevent destructive practices that have deleterious effects on the environment.

The act also places significant emphasis on the importance of sustainable forms of development. Several principles for 'national environmental management' are listed, including an insert on sustainable development, which in section 2(3) and 2(4) states that, *"Development must be socially, environmentally and economically sustainable. (a) Sustainable development requires the consideration of all relevant factors including the following: (i) That the disturbance of ecosystems and loss of biological diversity are avoided, or, where they cannot be altogether avoided, are minimized and remedied; (ii) that pollution and degradation of the environment are avoided, or, where they cannot be altogether avoided, are minimised and remedied; (vii) that a risk-averse and cautious approach is applied, which takes into account the limits of current knowledge about the consequences of decisions and actions; and (viii) that negative impacts on the environment and on people's environmental rights be anticipated and prevented, and where they cannot be altogether prevented, are minimised and remedied."* These principles of sustainable development, as well as many others, largely underpin the fundamental philosophy of SuDS and environmental wellbeing.

2.5.1.3 National Health Act

The National Health Act (Act 61 of 2003; Government Gazette, 2004a) states that, *"every local authority is required to take all necessary, reasonable and practical measures to maintain a hygienic and clean district at all times and to prevent the occurrence of any nuisance or unhygienic condition."* Incidentally, this statement is becoming increasingly relevant in stormwater management, particularly recently with the inception of SuDS in many cities countrywide. Several SuDS options maintain open water bodies temporarily or permanently that could potentially attract nuisances such as mosquitoes and other vectors (Graham, 2003). It is likely that this responsibility will shift from municipalities to developers to ensure greater compliance. Local municipalities are likely to take the responsibility of compliance related investigations in order to maintain this health requirement (Barnes, 2010).

2.5.1.4 National Building Regulations and Building Standards Act

The National Building Regulations and Building Standards Act (Act 103 of 1977; Government Gazette, 1985; Government Gazette, 1985), issued by the Department of Trade and Industry in June 1977, provides support for local environmental policies. It states that local municipalities have the authority for approval of all types of developments. Section 4(1) states that, *"No person shall without the prior approval in writing of the local authority in question, erect any building in respect of which plans and specifications are to be drawn and submitted in terms of this Act."* This clause is supported by similar clauses in section 7, 8 and 9 of the act. As part of the definition of the 'erection of buildings' stated in the act, infrastructure for the management of stormwater runoff are included. Locally, this gives the City of Cape Town the authority to pass policies and compliance-related benchmarks for stormwater management.

2.5.1.5 SANS 10400-R: Stormwater Disposal

In April 2010, the South African National Standards (SANS) released a draft publication of national regulations that pertain to stormwater management, entitled, 'SANS 10400-R: The Application of the National Building Regulations – Part R: Stormwater Disposal' (SABS Construction Standards, 2010). At present the draft is being circulated for public comment. The document is heavily premised on 'hard', conventional urban drainage practices, and there is no consideration given to SuDS options that are effective in the disposal of stormwater runoff from properties. Section 4.2.1.1 states that, *"Stormwater emanating from the roof, paving area in the immediate vicinity of a building shall not cause damage to the building interior, structure, or structural elements, or accumulate in a manner that unduly inconveniences the occupant."* Little significance is placed on the utility of rainwater as a valuable resource, which can be used by land owners for many non-potable domestic requirements. Instead, emphasis is placed on the correct disposal of stormwater at 'source' in order to minimise or prevent damage to property. The onus is largely placed on land owners to ensure stormwater is efficiently disposed off their properties. In light of the fact that South Africa is one of the 30 driest countries in the world, this draft is environmentally short-sighted (Jacobs, 2010).

2.5.1.6 Human Settlement Planning and Design

The latest guidelines for Human Settlement Planning and Design (CSIR, 2000a,b) were compiled by the CSIR's Building and Construction Technology Sector in 2000, under the patronage of the National Department of Housing. The double volume guidelines are generally referred to as the 'Red Book' by civil engineers countrywide. Chapter 6 features 'Stormwater Management' guidelines. There are similarities between the guidelines and the SANS 10400-R: Stormwater Disposal regulations regarding the ideology of stormwater runoff. Both are fundamentally premised upon the notion of 'hard', conventional drainage practices. The guidelines follow 'three rules' of stormwater management which are stated as *"applicable throughout the world today as far as the drainage of surface runoff is concerned."* These rules are: (1) the 'common enemy' concept; (2) natural flows; and (3) reasonable use (CSIR, 2000b). It is stated in the guidelines that, *"stormwater runoff is considered a common enemy and each property owner may fight it off or control it by retention, diversion, repulsion or altered transmission. The focus of the common enemy rule has two focal points: (1) the need to make improvements to property, with the acknowledgement that some damage results from even minor improvements; and (2) the principle of granting each landowner as much freedom as possible to deal with his land essentially as he sees fit."*

Due to the spread of water crises countrywide over the past three decades, stormwater can no longer be understood as a 'common enemy'. It is a valuable resource that has a number of non-potable domestic uses (Jacobs, 2010). According to the 'common enemy' rule, land owners do however have the freedom to provide the necessary landscaping that will mimic natural, predevelopment hydrological conditions. In addition, the 'reasonable use' rule states that, *"each property owner is permitted to make reasonable use of his land, even though in doing so he may alter the flow of the surface waters and cause harm to others."* This also gives land owners freedom to manage their stormwater independently and potentially in a manner that treats discharges off their properties and boosts amenity and the associated biodiversity. It is likely that the guidelines will be updated to incorporate WSUD and SuDS principles in the near future.

2.5.1.7 Drainage Manual

The 5th edition of the Drainage Manual was published by the South African National Roads Agency Limited (SANRAL) in 2006, partly under the patronage of the national Roads and Stormwater Department (SANRAL, 2006). The manual was published as a guide to both students and practitioners to assist in meeting the challenges of stormwater drainage in urban environments. The manual is also premised on 'hard', conventional drainage practices, but provides useful equations and 'tools' that can be used to calculate drainage volume and flow characteristics for more sustainable forms of urban drainage. The manual focuses solely on the 'quantity' management of stormwater runoff with negligible reference to stormwater quality management or the amenity value therein. This is largely understandable as the purpose of its first publication in 1981 was to, *"combine useful information on road drainage in a usable format."* The focus of the manual's first edition was "road drainage" opposed to 'stormwater management' – a thread which is still evident in this 5th edition. This is most noticeable in the first chapter which states that, *"the Drainage Manual should be read in conjunction with the Code of Procedure for the Planning and Design of Highway and Road Structures in South Africa."* The strength of this approach has however been that it provides urban designers with comprehensive technical guidance for 'hard 'stormwater management infrastructure.

The SANS 10400-R: Stormwater Disposal regulations (SABS Construction Standards, 2010), Human Settlement Planning and Design guidelines (CSIR, 200a,b), and Drainage manual (SANRAL, 2006), have been instrumental in shaping the 'dominant logic' of stormwater management amongst urban practitioners, particularly civil engineers, for more than 30 years. This 'dominant logic' has typically been founded on 'hard', conventional drainage practices, which predominantly focus on the 'quantity' management of stormwater runoff – neglecting urban stormwater impacts externalised on immediate environments and downstream ecosystems (Matthews, 2010).

2.5.1.8 Supplementary national legislation and guidelines

The following acts have an indirect bearing on the management of stormwater in South Africa:

- National Water Services Act (Act 108 of 1997; Government Gazette, 1997)
- Municipal Systems Act (Act 32 of 2000; Government Gazette, 2000);
- Conservation of Agricultural Resources Act (Act 43 of 1983; Government Gazette, 1983);
- Disaster Management Act (Act 57 of 2002; Government Gazette, 2003);
- National Environmental Management: Biodiversity Act (Act 10 of 2004; Government Gazette, 2004b); and
- National Environmental Management: Protected Areas Act (Act 57 of 2004; Government Gazette, 2004c).

2.5.2 Provincial legislation and guidelines

There is limited provincial authority for stormwater management in the Western Cape. The following Act and Ordinance indirectly influence stormwater management in the Western Cape Province:

- Western Cape Planning and Development Act (Act 7 of 1999; Provincial Gazette, 1999); and
- Land Use Planning Ordinance (Ordinance 15 of 1985; Provincial Administration, 1999).

2.5.3 Local legislation and guidelines

The following legislation and guidelines have been issued at a Local Municipal level, and bear the most influence on the implementation of SuDS in Century City.

2.5.3.1 Stormwater Management By-Law

The City of Cape Town Stormwater Management By-Law (PG6300:2005; Provincial Gazette, 2005) was issued in September 2005 by the Province of Western Cape under the Provincial Gazette number 6300. The purpose of the by-law, as stated in the opening abstract of the by-law is to, *"provide for the regulation of stormwater management in the area of the City of Cape Town, and to regulate activities which may have a detrimental effect on the development, operation and maintenance of the stormwater system."* The by-law primarily focuses on the power and responsibility given to local authority in managing stormwater runoff. The following subjects are defined in terms of the local authority's power: prohibited discharges of stormwater, the protection of the stormwater system, the prevention of potential flooding, the management of stormwater systems on private land, and the provision of stormwater-related infrastructure. In addition, according to Section 10(1) Part (a), the Council has authority to, *"demolish or otherwise deal with any building, structure or other thing constructed, erected or laid in contravention of the provisions of this by-law."* According to section 10(1) Part (j), the Council also has the authority to, *"discharge stormwater into any watercourse, whether on private land or not."* The by-law also details the penalties for stormwater-related offences, stating that, *"any person who (a) contravenes any provision of this by-law; shall be guilty of an offence and be liable, on conviction, to the payment of a fine."*

2.5.3.2 Management of Urban Stormwater Impacts Policy

The City of Cape Town's Management of Urban Stormwater Impacts Policy (May 2009; Roads and Stormwater Department, 2009a) is the most advanced stormwater management policy in the country. It is the only accessible policy that fully supports principles of Water Sensitive

Urban Design (WSUD) and SuDS practices. It is the first policy to place value on stormwater in the context of the national water crisis and 'climate change'. The following is stated in the preamble; *"Well-managed urban water bodies are valuable resources providing environmental and recreational services which require protection and enhancement. This is particularly important in the context of changing weather patterns and the associated local, national and international strategies targeting sustainability, climate and energy issues."* The principal purpose of the policy is to minimise the undesirable effects of urban stormwater runoff on the environment, with the introduction of WSUD principles in urban planning and stormwater management in the Cape Metropolitan Area (Roads and Stormwater Department, 2009a).

The objectives of the policy correspond with the principles recorded in the City's Integrated Development Plan (IDP; Van Der Merwe, 2007) under the 'Roads and Stormwater' section. The objectives are listed as follow:

i) Reduce the impact of flooding on community livelihoods and regional economies;

ii) Safeguard human health, protect natural aquatic environments, and improve and maintain recreational water quality (Roads and Stormwater Department, 2009a).

The policy fundamentally targets the improvement of the 'quality' of stormwater that discharges from developments. Developers are required by the CSRM to reduce the amount of Settleable Solids (SS) and Total Phosphorus (TP) by 80% and 45%, respectively, or to predevelopment qualities as determined by the developers and approved by Council (Roads and Stormwater Department, 2009a). Natural stormwater management elements that treat polluted runoff are typically destroyed with the implementation of 'hard' or impervious development (Roads and Stormwater Department, 2009b). Therefore the policy attempts to maintain or mimic natural flow regimes and prevent the runoff of urban pollutants from entering receiving watercourses. SuDS is noted as the main criterion by which this can be achieved. The policy states that SuDS are grouped according to the following:

- ***"Structural Controls**, which are engineered devices that are implemented to manage runoff quality and quantity; examples may include litter traps, infiltration devices, bioretention cells or basins, detention ponds and constructed wetlands; and*
- ***"Non-structural Controls**, which are institutional and pollution prevention practices, designed to minimise pollutants from entering stormwater runoff and reduce the volume of stormwater requiring subsistent management; examples may include town planning incentives, stormwater master-plans, pollution prevention maintenance practices, and public education" (Roads and Stormwater Department, 2009a).*

A 'treatment train' approach is advised, which is incorporated into the planning and design of SuDS. This is because SuDS options in isolation are advocated by the policy as inadequate for the effective treatment of stormwater. 'Treatment trains' are commonly identified as combinations of different SUDS technologies that are implemented sequentially or concurrently, and vary from preventative measures at source, through development site controls to regional controls (Roads and Stormwater Department, 2009a).

For the purpose of the development of SuDS in private properties, the policy states that, *"council may require BMP measures to be constructed and remain located within the boundaries of a private development. This is particularly applicable to private single erf* (plot) *developments or private enclosed and/or gated office parks, industrial parks, blocks of flats, group housing estates, or similar developments where the infrastructure within the boundary of the development site remains in private ownership."* Regulations stated by the Council stipulate that where SuDS are located on such private land, the responsibility for the operation and maintenance, monitoring, and continued effective functioning of these measures, including meeting the costs thereof, will lie with the property owner or body corporate (Roads and Stormwater Department, 2009a). The implementation of SuDS in private developments, particularly through initiatives endorsed by private land owners, is largely encouraged in the policy. This is particularly important as the wider success of SuDS schemes is dependent on an increasing number of SuDS options implemented at 'source' (Matthews, 2010).

2.5.3.3 Floodplain and River Corridor Management Policy

In many ways, this policy is supplementary to the 'Management of Urban Stormwater Impacts Policy' (Roads and Stormwater Department, 2009b). The Floodplain and River Corridor Management Policy (May 2009) is not directly associated with stormwater management; however, it necessitates the importance of well managed and sustainable watercourses, and places significant value on the utility of stormwater runoff (Roads and Stormwater Department, 2009b). Part of the policy's preamble states that, *"a well managed watercourse/wetland is a valuable resource for improving the quality of life and aesthetic nature of an urban area and provides benefits for public health, recreation and economic growth."* In addition, the policy shares the same two principal objectives as those of the 'Management of Urban Stormwater Impacts Policy'; however, the Flood and River Corridor Management Policy places more emphasis on the latter objective – safeguarding human health, protecting natural aquatic environments, and improving and maintaining recreational water quality (Roads and Stormwater Department, 2009b). Furthermore, the socio-economic considerations associated with watercourses and wetlands are briefly discussed. In Section 9.5 the policy states that, *"Watercourses and wetlands are public resources which have the remarkable potential to stimulate local economies and to break down political, social and economic barriers if managed and used with this goal in mind."* In many instances, these same socio-economic benefits are achievable with the application of SuDS schemes.

2.5.3.4 Landscape and Indigenous Plant Species Guideline

This draft guideline was issued by the City of Cape Town's Catchment, Stormwater and River Management Branch in February 2011 (Roads and Stormwater Department, 2011), in response to the City's aforementioned 'Management of Stormwater Impacts Policy' (Roads and Stormwater Department, 2009a). This guideline is the first of its kind in South Africa, as it details the relationship between plant selection and SuDS. It focuses principally on the role of landscaping and plant selection for SuDS in the City of Cape Town and the greater Cape Town region. Section 4 states that, *"virtually all structural controls can be integrated into the landscape in an aesthetically pleasing manner, and many are compatible with multifunctional usage of public or private open spaces. Landscaping therefore plays a role in achieving this beneficial integration within the urban environment. The plants that are chosen for each SUDS type are also important since certain species and growth forms will enhance the functionality of the SUDS more than others."* The guideline briefly defines the climatic environments that are likely to be problematic in plant selection, and in so doing, alludes to the use of plant species that are indigenous to the Cape Town region. It also states, *"it is important to realize that the plants selected for SUDS controls must primarily perform a functional role i.e. aid stormwater infiltration, treatment and conveyance."*

The guideline supports the movement to more intensive maintenance procedures, stating that frequent and effective maintenance practices ensures the optimal functioning of vegetated SuDS schemes (Roads and Stormwater Department, 2011). A relatively extensive plant species list is provided to aid urban practitioners in the selection of appropriate plant species. According to Section 5, the list was developed with consultation obtained from ecologists, botanists, landscape architects and nurseries during and following a workshop held in the City of Cape Town in 2010, entitled, 'Planting to enhance Cape Town's stormwater management - Bringing new City policy, landscape architects, contractors and plant growers together to facilitate implementation of Sustainable Urban Drainage Systems in Cape Town'. Regarding the plant species list, Section 6 states, *"Indigenous species that are usually found growing in different zones of natural wetlands (pools, deep marsh, shallow marsh, wetland margins etc) were initially selected as primary candidates for use in SUDS controls. Other indigenous species that may not be typical "wetland" species but are capable of surviving different periods of inundation were also evaluated."* Reference to the guideline's plant list is now a requirement by the City of Cape Town's Catchment, Stormwater and River Management Branch when submitting engineering designs relating to SuDS.

2.5.3.5 Supplementary local legislation and guidelines

The following plans and strategies indirectly affect the management of stormwater in the City of Cape Town:

- Greening the City Open Space and Recreation Plan of Cape Town (Cape Town City Council, 1982);

- Biodiversity Strategy for the City of Cape Town (Environmental Planning, 2003a);
- Integrated Metropolitan Environmental Policy (Environmental Planning, 2003b);
- Coastal Zone Management Strategy (Environmental Planning, 2003c);
- Planning for Future Cape Town (Boshoff *et al.*, 2006);
- Integrated Development Plan 2007/8 – 2011/12 (Van Der Merwe, 2007); and
- City of Cape Town Environmental Agenda (Environmental Planning, 2009).

Most of the national, provincial and local legislation and guidelines presented herein have influenced either the planning, implementation or management of the Century City stormwater management system.

2.6 Synopsis

Globally, urbanisation has increased rapidly since 1950, and the number of urbanites is now greater than the rural population. South Africa's growing urban landscape, extensive hardening of surfaces, and the prolonged application of 'hard', conventional drainage practices, has resulted in an increase in stormwater runoff volumes and velocities in downstream environments. This approach to urban drainage has exacerbated adverse effects within water-related ecosystems. Brown (2007) comments that, *"development should continue however to be seen as an area to intervene in developing cities, in order to create sustainable constructed environments."* In light of these effects, SuDS has been introduced as an alternative approach to conventional drainage practices. In theory, SuDS manages surface water drainage in line with the ideals of 'sustainable development' by attempting to mimic the natural hydrological cycle within urban environments. Urban practitioners can employ a number of SuDS options in sequence to form a 'treatment train', in order to manage stormwater runoff quantity, quality, and amenity and biodiversity. According to the hierarchy of SuDS controls exhibited in Wilson *et al.* (2004), site management should initially be carried out as a preventative measure, followed by a number of SuDS options as 'source', 'local' and 'regional' controls. The efficacy and resilience of a treatment train is typically dependent on the number of SuDS options used throughout, and is likely to result in the appropriation of useful 'ecosystem services'.

There are a number of SuDS-related tools available internationally, typically in the form of modelling programmes and decision support systems, which aid urban practitioners in the selection of appropriate SuDS options. The national legislative context concerning urban drainage remains heavily weighted towards 'hard', conventional drainage practices. This concept is also extensively supported by building codes and guidelines. In 2009, however, the City of Cape Town issued policies in support of the notion of WSUD; recognising the potential of SuDS in the urban landscape. There is extensive experience in the implementation of SuDS options and the performance thereof in several developed countries; however, the development of SuDS schemes in South Africa has not been explored as inclusively. There is limited experience particularly in the planning, design and management of SuDS in South Africa. This is the end to which Century City is presented as an early endeavour to create a sustainable constructed environment using SuDS.

3. Method of investigation

This chapter details the development of research for the Century City case study. The methods used include, *inter alia*, the drafting of a bibliography, the site selection and reconnaissance for appropriate case studies, and the formulation of a 'key element list' for the review of case studies. The methods used in the investigation of Century City's stormwater management system aided in compiling the SuDS Guidelines; included in Appendix 1.

3.1 Bibliography

A bibliography was drafted over the period May to December 2010 (eight months), with the purpose of providing a reference index of significant literature for the development of SuDS in South Africa. Reference information was intuitively grouped into three categories, namely Category A, Category B and Category C. Category A references are the most relevant to the development of SuDS in South Africa. Category B references are topic specific publications for SuDS, whereas Category C references are less specific, supporting information. The bibliography has been omitted from this dissertation to limit document space, but key elements are included in Chapter 2. Reference information was arranged in the bibliography according to a hierarchy based on literary reliability. Preference was given to the following sources (in order):

i) Journal papers;

ii) Books and textbooks;

iii) Conference papers; and

iv) Web-based articles.

Once relevant information was sourced and the bibliography was drafted, the research was geared towards finding suitable case studies of the application of SuDS in South Africa.

3.2 Case studies for SuDS

Case study assessments were the main exploratory component in the formulation of the Century City case study and SuDS Guidelines. Case studies of preselected SuDS schemes were carried out over the period January to October 2009 (ten months). The following two subsections describe: the processes by which these studies were conducted, the compilation of the SuDS case studies report, and the selection of Century City as a suitable case study for more in-depth assessments and analyses. The investigation was limited by several constraints, the most critical of which were time, geographic distances and hydrology seasons. The compilation of the case studies report began in August 2009, which included two months allocated towards part-time data acquisitioning, and a further two months towards full-time data acquisitioning, site selection and reconnaissance and the associated assessments, write-up and editing. The case study report was subsequently completed in November 2009. The report was delivered to the WRC in 2009, entitled, *K5_1826_D4 – Report on Proposed Pilot Studies* (unpublished; Matthews, 2010). The report has been omitted from the dissertation's appendices to limit document space.

3.2.1 Site selection and reconnaissance

In January 2009, A/Prof. Neil Armitage carried out a number of field trips to assess what had been planned and implemented in South Africa regarding SuDS. These included visits to KwaZulu-Natal (January 2009), Gauteng (January 2009) and the City of Cape Town (between January and March 2009). During these field trips, a number of sites were identified as potential case studies. The research potential of each site was further evaluated and several were chosen to be reviewed in greater detail. In May 2009, the author was subsequently tasked with an assessment of each site in order to document SuDS case studies countrywide. The location of potential case studies was geographically limited to three provinces in South Africa, namely, the Western Cape, Gauteng and KwaZulu-Natal. Together these possess climatic conditions that are representative of most population centres throughout South Africa. SuDS options that had been implemented were assessed according to three groups, namely: source controls, local controls and regional controls, as described in Section 2.3.4. The following twelve SuDS options were assessed with reference to each of these control groups:

i) **Source controls**: green roofs; sand filters; soakaways; and stormwater collection and reuse systems;

ii) **Local controls**: bio-retention; filter strips; infiltration trenches; permeable pavements; and swales; and

iii) **Regional controls**: constructed wetlands; detention ponds; and retention ponds.

A total of nineteen sites were investigated and assessed, including Century City. The selected sites and their associated SuDS options are listed alphabetically as follows:

Gauteng Province

- *Menlyn Maine*: incorporation of WSUD principles and treatment trains (Janse van Vuuren, 2009);
- *Rainbow Junction*: incorporation of WSUD principles and treatment trains (Janse van Vuuren, 2009; Rude, 2006; Botha, 2005);

- *Topaz Industrial Park*: stormwater collection and reuse, and permeable pavements (Cement and Concrete Institute, 2009; Janse van Vuuren, 2009); and
- *University of Witwatersrand*: permeable pavements (Cement and Concrete Institute, 2009; Concor Technicrete, 2009; Voogt, 2009; Borgwardt, 2006; Knapton, 2006).

KwaZulu-Natal Province

- *Bishops Court*: permeable pavements (Tooley, 2009);
- *Clifton Hill Residential Estate*: swales, bio-retention areas, reed beds, permeable pavements and filter strips (Tooley, 2009);
- *Cotswold Downs Golf Estate*: incorporation of WSUD principles and treatment trains (Tooley, 2009; Torr, 2008; Torr, 2003a,b);
- *Diocese of Natal Anglican Church*: permeable pavements (Partners in Development, 2009; Still, 2009);
- *EThekwini City Initiatives*: detention ponds and filter strips (Tooley, 2009);
- *Hawaan Forest Estate*: incorporation of WSUD principles and treatment trains (Tooley, 2009; Knox, 2003); and
- *Heritage Market Shopping Centre*: constructed wetland and bio-retention areas (Tooley, 2009; Emery, 2006; Emery, 2004; LRI, 2004).

Western Cape Province

- *Capricorn Park*: retention pond (CSRM, 2002; CSRM 2008);
- *Century City*: constructed wetland, detention pond, infiltration trenches, detention pond, bio-retention areas, permeable pavements, reed beds and silt traps (CCPOA, 2009; Day, 2008a,b,c);
- *City of Cape Town Grand Parade*: permeable pavements and bio-retention ruts (British Board of Agreement, 2009a,b; Formpave, 2009; Knapton, 2006; Concrete Manufacturers Association, 2003);
- *Department of Environmental Affairs and Development Planning*: roof garden;
- *Evergreen Retirement Village*: bio-retention areas and small scaled treatment trains (CSRM, 2002; CSRM, 2008);
- *Fountain Centre Shopping Mall*: silt traps; and
- *Willow Bridge Shopping Centre*: detention pond.

Contact details of the developers were sourced for each of the potential case studies and a preliminary set of interviews were conducted with the specified clients, consultants and contractors who were personally involved in each. Important design and management documentation was subsequently sourced for each site according to a predetermined 'key element list' for the procurement of information (Table 3.1). Sites and their associated SuDS schemes were analysed and documented according to three aspects of their specified design lives, namely:

i) Planning phase;

ii) Implementation phase; and

iii) Operation and maintenance phase (Landcom, 2009a,b,c).

3.2.2 Key elements for case study reviews

The assessment of each site was conducted within a list of elements underpinned by principles of 'sustainability' and 'sustainable development'. The list was designed to record unique features of each stormwater management innovation with reference to six standard criteria. Several key components of the principles of sustainable development were reviewed in each pilot study. The basic investigation components and associated investigation items are displayed in Table 3.1.

Project costs that were made available were reviewed according to the notion of 'whole life-cycle costing'. Where possible, these costs included: (1) capital, (2) operating, (3) monitoring, (4) maintenance, (5) risk assessment, (6) environmental, (7) refurbishment, (8) replacement, and (9) disposal. Furthermore, each case study was concluded with a summary that highlighted the key issues of the investigated SuDS options and associated 'lessons learnt' which record the successes and failures of the stormwater management initiatives. These sections provide context to the site-specific challenges faced by the associated urban design and management practitioners, and describe unique remedial measures that were used in the event of structural or non-structural problems.

3.2.3 Selecting Century City as a case study

From the assessments of the nineteen aforementioned case studies performed in late 2009, several sites were briefly reassessed over the period February to June 2010. The purpose of the reassessment was to select sites that could be studied in greater detail to represent the early implementation of SuDS in South Africa. It was subsequently noted that the majority of sites had not progressed or advanced from what had been assessed in the initial case studies report. In addition, the development of SuDS options on particular sites had been radically slowed or temporarily halted due to economic constraints such as the global economic crisis which began in September 2008.

Table 3.1: Investigation components and associated items

Investigation component	Investigation item
Background information	Site location
	General site condition
	Basic purpose
	Noteworthy history
Technical information	Type of intervention
	Master plan
	Review of ground conditions
	Critical design elements
	Challenges faced and outcomes
	Programme summary (conceptualisation to completion)
	Operation and maintenance
	Photographs of main components
Environmental information	Criteria relating to flora
	Criteria relating to fauna
	Outcomes of environmental impact assessment
Economic information	Breakdown of major costs
	Units costs
	Analysis alternatives
Social, legal and institutional information	Engagement with interested and affected parties
	Social acceptability
	Significant legal issues
	Significant institutional issues
Discussions and conclusions	Relative success rating
	Significant challenges and outcomes
	Lessons learnt
	Recommendations

Century City, however, featured more prominently as an option for a more in-depth case study, as the development was well established and presented particularly interesting and controversial stormwater management approaches. Century City was one of the largest case study sites initially selected and the oldest documented SuDS scheme in the country – initiated in 1996. The SuDS options are also some of the most advanced in South Africa, and in many instances adhere to principles of WSUD (Section 2.2.9). Therefore a thorough investigation of

Century City's stormwater management system commenced in June 2010 and was carried out until April 2011 (eleven months). Key topics of the investigation were:

- Problematic design approaches to isolated SuDS options and treatment trains;
- The implemented drainage system that transitions between conventional and sustainable urban drainage practices;
- Problematic interventions for the management of the constructed wetland and adjoining canal network;
- Remedial interventions for the management of the constructed wetland and adjoining canal network;
- The utility and educational benefit of a sustainable 'eco-centre'; and
- The effects of biomass and biodiversity on natural stormwater management systems.

There are two parts to the Century City case study; the first focuses on an investigation of the development's stormwater management system (Chapter 4), and the second provides assessments and analyses of a number of design approaches and management interventions that were employed throughout the development's urban water system, with a particular focus on the constructed wetland (Chapter 5).

3.3 Supplementary research methods

The following methods provided supplementary context for the compilation of the Century City case study and SuDS Guidelines (Appendix 1).

3.3.1 Desk studies

A series of desk studies on the subject of SuDS was carried out over the period November 2008 to December 2010 (26 months) for the WRC project *K5/1826: Alternative technology for stormwater management*. A by-product of this was the formulation of a literature review that projected the global post-2000 progression of SuDS. This document was pivotal in the formulation of the literature review presented in this dissertation (Chapter 2), and provided context for the compilation of the Century City case study (Chapter 4; Chapter 5). The draft literature review was compiled over the period January to March 2009 (three months). The purpose of the draft literature review was to collect, filter and present pertinent information on preselected SuDS options. Thirteen SuDS options were selected and divided into two groups according to their geometry and sizing, namely: (1) private controls and (2) public controls. Fundamental information for each of these SuDS options was presented under the following subheadings: description, purpose, general design guidelines, advantages, limitations and maintenance requirements.

3.3.2 Interdisciplinary feedback

The integration of technical and non-technical knowledge bases provided insight into other elementary dimensions of 'sustainable development' that pertain to SuDS schemes. The following studies and/or activities aided in the compilation of the Century City case study:

i) Economic study – conducted by Mr. Lloyd Fisher-Jeffes of the Urban Water Management Group at UCT; the study is an investigation of the economic feasibility of the application of SuDS in South Africa using 'whole life-cycle costing' tools.

ii) Botanical/plant study – conducted by Mr. Stephan Milandri of the Urban Water Management Group at UCT; the study investigates the ability of selected vegetated filters to treat stormwater runoff in the City of Cape Town.

iii) Interdisciplinary feedback sessions – held fortnightly by the Urban Water Management Group at UCT. These meetings yielded constructive criticism for the compilation of the Century City case study, particularly with respect to investigative assessments and analyses. The group was comprised of landscape architects, social anthropologists, environmental scientists and civil engineers.

3.3.3 National workshops and feedback processing

Over the period March to May 2011, several SuDS workshops were hosted countrywide. The Century City case study was presented in conjunction with the SuDS Guidelines. The national workshops were held in the following cities:

i) City of Cape Town (10 March 2011);

ii) Johannesburg (23 March 2011);

iii) Tshwane (24 March 2011);

iv) George (16 May 2011); and

v) EThekwini (25 May 2011).

Verbal participation and feedback during and after the workshops was encouraged. Feedback from the presentation of the Century City case study was received and considered over the period March to June 2011.

4. Stormwater management investigation

The purpose of this chapter is to present an investigation of Century City's stormwater management system. Century City is located in the City of Cape Town, in the Western Cape of South Africa (Figure 4.1). Lessons learnt throughout this case study have been incorporated into the South African Draft Guidelines for Sustainable Drainage Systems (SuDS; Appendix 1).

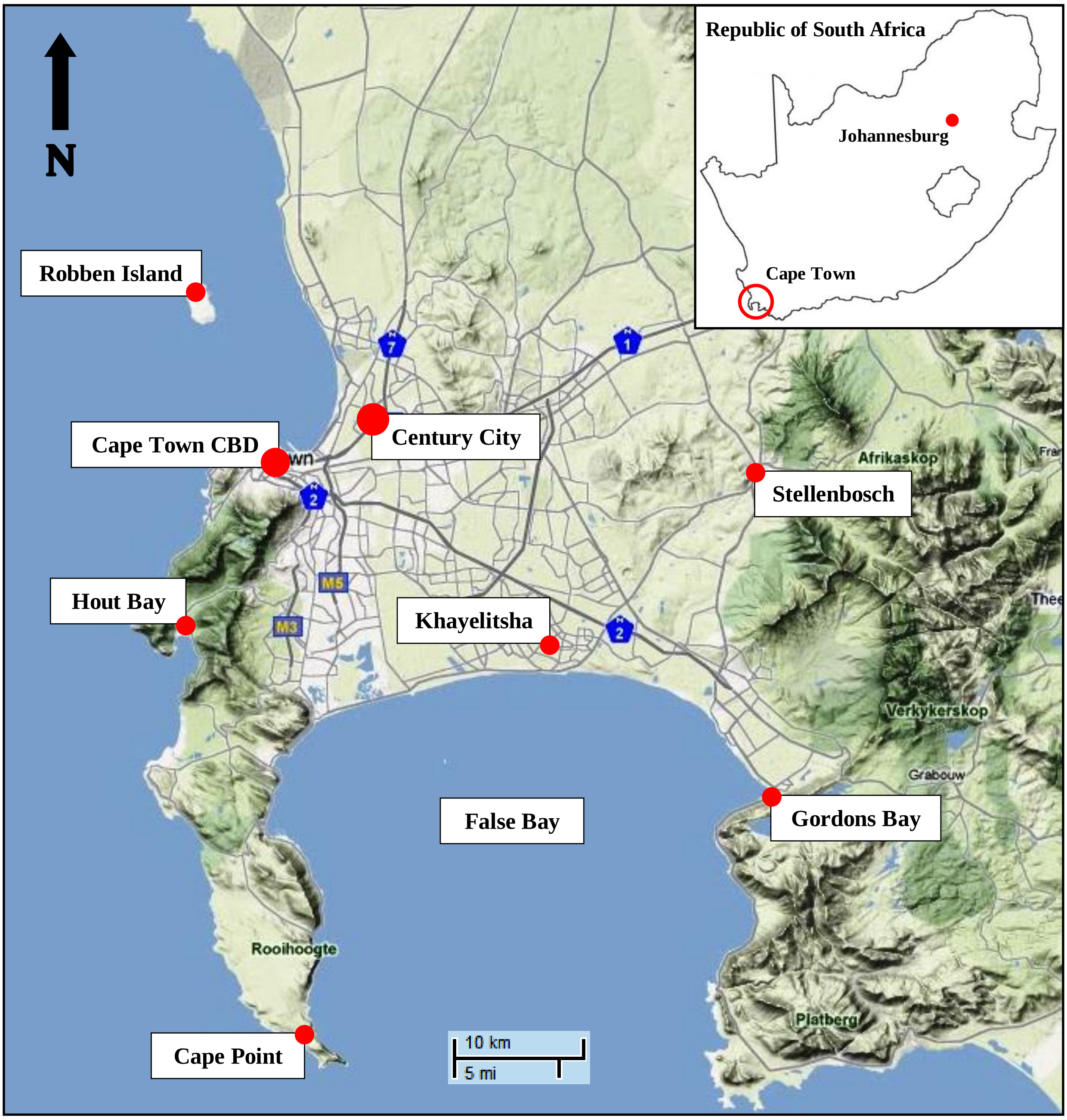

Figure 4.1: Century City locality plan (After Google Maps, 2011)

4.1 Introduction

The Century City development was originally conceived in 1995, and is now well established with multiple land uses in the suburb of Milnerton in the City of Cape Town. The development is approximately 250 ha in area and was initially covered largely by invasive alien vegetation and degraded wetlands and salt pans. The development maintains an 'upmarket' property classification with land-use zoning including: medium-high density residential, medium-high density commercial, public transport interchanges, educational facilities, internal private open spaces, as well as Africa's largest shopping mall, a theme park and a multi-purpose constructed wetland; totalling R16 billion in property investment (Century City Life, 2011). Figure 4.2 displays an aerial view of the Century City development (bounded in red).

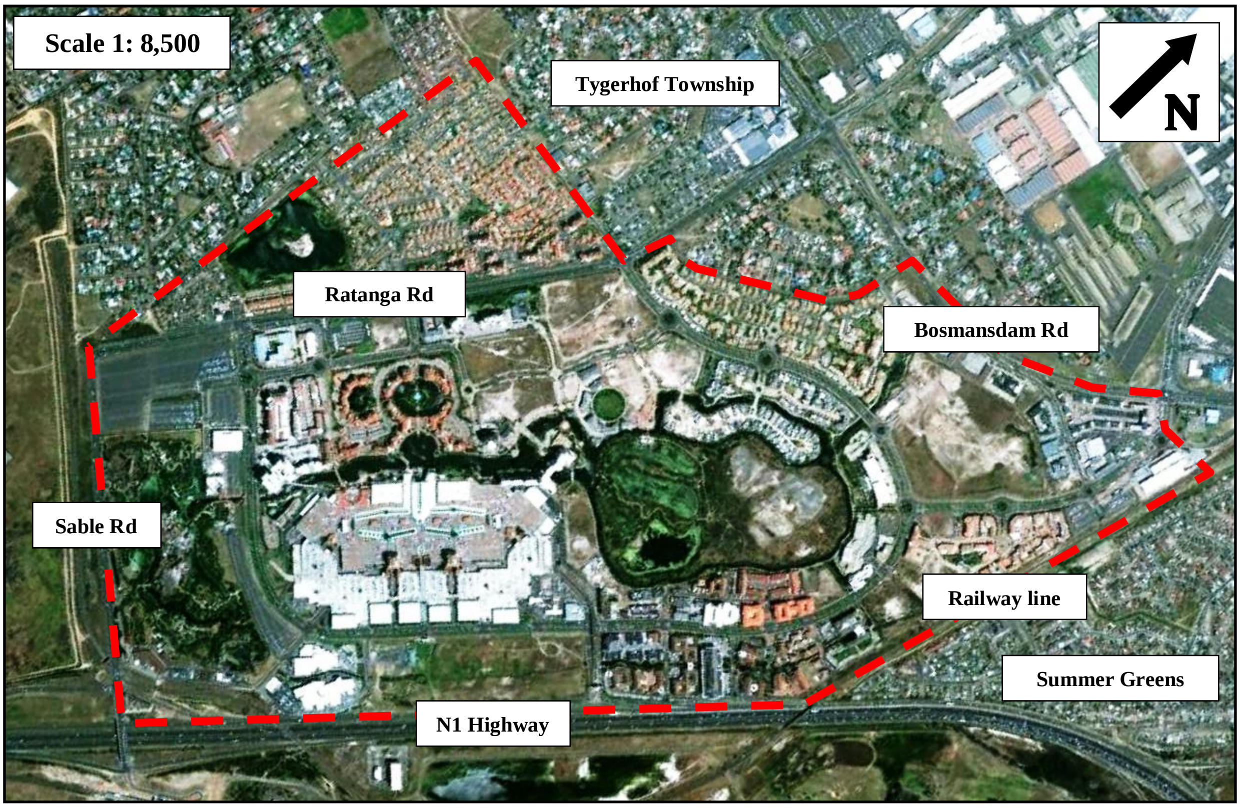

Figure 4.2: Aerial view of Century City development (After Google Earth, 2011)

To date, 69% of the developable land has been utilised with the remaining 31% (R11 billion) set to be developed by 2020 – most of which will be medium-high density commercial (CCPOA, 2011c; Century City Life, 2011). The slogan, *"Live, Work, Play"* coined by the Century City Property Owners' Association (CCPOA) markets Century City as a relatively 'self-sufficient' environment. Century City is situated on a natural low lying area of Cape Town known as the *Blouvlei*. The constructed wetland is situated in the heart of the Century

City development, and features as a "natural" locale. It has been built around 'Intaka Island', *intaka* meaning 'bird' in the isiXhosa language. The wetland is sixteen hectares in area, is home to 177 indigenous plant species and 120 bird species, has seven different natural habitats, and was awarded conservation status for its educational, self-guided nature trails for visitors in 2010. The multi-purpose constructed wetland aims to, *inter alia*, conserve a rare type of wetland and *Fynbos* habitat, preserve the breeding heronries of waterbirds, and naturally filter and purify water from the development's canals (CCPOA, 2011a,b,c; Liebenberg *et al.*, 2009).

Two aspects of management in Century City are prioritised higher than others, namely; (1) the safety and security of residents and daily users, and (2), and more pertinent for this study, the development's urban water system, referred to by the CCPOA as the "bloodline" of the development – after which the shopping centre is aptly named 'Canal Walk'. The system collects stormwater runoff within the Century City precinct as well as runoff from the neighbouring Summer Greens development, and channels it into the adjoining Tygerhof detention pond. The Wingfield outfall, located at the south-western end of Century City, is the stormwater outfall for the development (Liebenberg *et al.*, 2009). These stormwater management components are most effective in attenuating flood peaks. In addition, the constructed wetland is said to act as the "lung" of the urban water system by facilitating the polishing of stormwater runoff before it is detained and discharged into the Atlantic Ocean at Milnerton Beach. The treatment cells in the constructed wetland comprise of detention ponds, retention ponds, and seasonal salt pans. There are also a number of SuDS options utilised in the development that provide functional stormwater management and add an aesthetic quality that supports commercial property investments.

This stormwater management investigation focuses on three main aspects of the development of Century City in chronological order, namely:

i) Planning (between 1996 and 2005);

ii) Implementation and modelling (post-2006 applications); and

iii) Operation, monitoring and maintenance (post-2006).

These three aspects address the most important phases of the development of SuDS schemes in general (Landcom, 2009a,b,c). 'Planning' focuses primarily on the technical and environmental considerations that were documented at the onset of the development's construction between 1996 and 2005. 'Implementation and modelling' addresses the rationale, functionality and performance of the implemented system post-2006. Lastly, 'operation, monitoring and maintenance' identifies and assesses a number of management approaches used throughout the development's urban water system post-2006. Due to the large size of the development, there is considerable overlap between these three stormwater management development phases. The investigation is concluded with a brief costing appraisal for the year ending 2009.

4.2 Planning

Planning is an essential element of effective SuDS schemes (SEMCOG, 2008; Woods-Ballard *et al.*, 2007; Wilson *et al.*, 2004). During the planning phase, the developer endeavoured to create a sustainable constructed environment. The institution of an environmental management plan (EMP) that detailed regular operation and maintenance procedures proved to be key in ensuring the long-term functioning of isolated SuDS options and treatment trains. The first report on the proposed stormwater management system for Century City was issued by Monex Development Company (Pty) Ltd in April 1996 (Monex Development Company, 1996). The report outlines the stormwater management planning that was required for the development and highlights significant historical, geological and hydrological facts pertaining to Century City. The document formed the basis of the conceptual design for the proposed stormwater management system. A preliminary step was to consider the site and catchment history.

4.2.1 Site and catchment history

Century City is located on the Cape Flats of the City of Cape Town in the natural low lying *Blouvlei*. Cape Town is subject to a Mediterranean climate, which typically includes hot, dry summers and mild, wet winters. The development is bounded by the N1 highway to the south, Sable Road to the west, Ratanga Road to the north, and Bosmansdam Road and a Railway line to the east (Figure 4.2). The stormwater catchment area includes most of the Century City precinct (196 ha) and a significant portion of the neighbouring Summer Greens development (63 ha). This 'greenfield' site required draining before construction could commence. Stormwater investigations had been carried out as early as the 1960s to assess the viability of residential developments in the area (Monex Development Company, 1996). Initially, it had been established that potential flooding of the development could only be mitigated by providing an outfall to the Milnerton Lagoon or directly to the ocean. In addition, an extended detention facility for balancing inflows and outflows would be required to adequately manage the 1 in 100 year rainfall event (explained in section 4.3.4). Subsequent studies concluded that the construction of a stormwater outfall and major detention facility would also be sufficient to improve stormwater runoff quality. These interventions would most likely supplement the existing natural forms of surface drainage, namely, minor infiltration and evaporation.

The soil characteristics onsite are consistent over the development area, primarily comprising decalcified Aeolian sands (Van Wieringen, 2010). The Monex Development Company (1996) states however, that there was variance in soil permeability which affected infiltration capacities in specific areas. In areas of fine silty sand, a high water table in the form of a perched aquifer was prevalent, minimising infiltration capacities during winter months. Terminal infiltration rates vary between 40.0 mm/hr – 52.5 mm/hr throughout the development. According to the plans drafted by the Monex Development Company (1996) the development is situated in a region 10 m – 20 m above mean sea level (MSL), and is susceptible to flooding.

Major bulk earthworks were carried out between 1995 and 1997, in which loose sand was used to fill low lying areas and depressions. The purpose of this was to increase stormwater infiltration rates in specific areas in order to balance the infiltration capacities over the site as uniformly as possible. This inadvertently favoured the implementation of several infiltration-type SuDS options.

According to the Weather Bureau (Publication WB40), the mean annual precipitation (MAP) for Milnerton is 530 mm. The MAP for the Cape Town International Airport (CTIA), which was the next closest rain gauge, is 555 mm, using approximately 30 years of data. However, Century City is significantly closer to the Milnerton rain gauge, therefore, a MAP of 530mm was selected by the developers (Monex Development Company, 1996). The consultants, KFD Wilkinson and Partners agreed that due to the relatively low intensities and long durations of Western Cape rainfall events, the most critical technical requirement would be the sizing of the detention and extended detention facilities. The Rational Method was used to determine a flood analysis of a 1 in 100 year rainfall event for the sizing of the detention facility. The purpose of designing the facility for a 1 in 100 year rainfall event was to minimise damage to property and prevent fatalities, as stipulated in local regulations.

4.2.2 Adherence to local regulations

The stormwater planning report compiled by Monex Development Company (1996) features environmental, technical and legal requirements for stormwater management in Century City. In addition, rezoning regulations for the City of Cape Town in the 1990s were jointly presented, and in response to these, the following three aspects were considered regarding Century City's stormwater management:

i) The necessity of an external stormwater outfall from the site for the primary purpose of conveying stormwater from the development, and discharging it into a larger watercourse that will transport it into the ocean;

ii) Whether extended detention capacity would be required to attenuate flood peaks before the external stormwater outfall is utilised; and

iii) Concerns related to the management of stormwater runoff quality, to protect natural environments downstream (Monex Development Company, 1996).

These objectives clearly highlight the challenges that were faced during the planning phase. A conventional drainage design was issued to the City comprising of a network of catchpits, pipe networks, adjoining manholes, and concrete lined channels, which would discharge untreated stormwater runoff into a detention facility and outfall (Monex Development Company, 1996). The design of this system adequately catered for runoff quantity, but it failed to consider the effects of poor quality stormwater runoff on downstream environments. The design included a constructed wetland and detention pond which may be classified as regional control SuDS (Section 2.3.4.4). These SuDS options are however, not able to treat stormwater runoff at source, which is the preferred area of treatment according to the philosophy of SuDS. The design also did not investigate more vegetated systems that could have been incorporated as 'source' or 'local' control SuDS. At the time the planning report had been completed, there were no local or national stormwater quality regulations that pertained to developments such as Century City, and little was known about the technical application of SuDS in South Africa. This created an all-round lack of endorsement for the development of SuDS in Century City. As a result, the stormwater infrastructure that was initially planned was of conventional form.

4.2.3 Planned stormwater infrastructure

The earliest stormwater infrastructure plan for Century City was designed by KFD Wilkinson and Partners in 1996. Waterways and canal networks were designed to meander through and run adjacent to office parks, retail centres and residential complexes. The stormwater management plan specified that the urban water system in the development, including the waterways, canal network, and constructed wetland, would occupy 30 ha – approximately 15% of the proposed precinct. Conventional drainage infrastructure such as pipes, catchpits, culverts, manholes and headwalls were planned to complete the drainage system (Monex Development Company, 1996).

The existing Sable Road stormwater outfall was originally identified as a possible 'tertiary' component to drain the Century City and Tygerhof developments. However, the additional construction to accommodate the expected stormwater runoff volumes would have required a significantly increased bulk infrastructure budget. An investigation was therefore conducted by Mr. Alan Walker of the Cape Town City Council to identify the potential of the Wingfield culvert (at the Western edge of the development) to provide additional capacity for stormwater. This particular stormwater outfall serviced the adjacent Wingfield Military base, and less than 50% of its capacity was being utilised. KFD Wilkinson and Partners Consulting Engineers were subsequently appointed to investigate the Wingfield outfall as a regional stormwater outfall. A proposal was made for a combined stormwater outfall of 1,350 mm in diameter to serve both Century City and Tygerhof, which would run between both developments and into the existing Wingfield culvert. This scheme required extended detention in the form of a stormwater detention pond in Tygerhof at the northern head of the outfall (Monex Development Company, 1996). Runoff from the Century City development would be discharged into this detention pond for volume and flow balancing purposes, before being discharged into the Wingfield stormwater outfall. The detention storage requirements were subsequently specified.

4.2.4 Detention storage requirements

It was determined that the accepted rate of stormwater discharge from Century City into the Wingfield stormwater outfall would be approximately 0.85 m^3/s. The planned location of the outfall is displayed in Figure 4.3. It was then calculated that the stormwater runoff from a relatively minor storm would exceed this accepted discharge rate. Therefore, the Monex Development Company (1996) decided that additional storage should be provided within Century City. During rainfall events, runoff volumes would be detained and discharged into the outfall. The maximum storage volume was designed to accommodate a 1 in 100 year rainfall event.

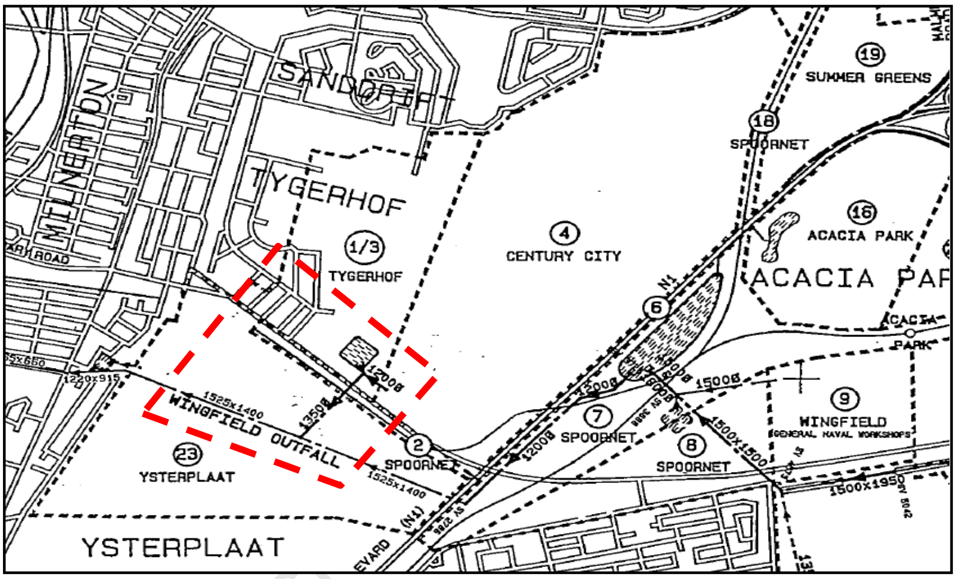

Figure 4.3: A plan view of the Wingfield stormwater outfall
(After Monex Development Company, 1996)

The storage volume required for a 1 in 100 year rainfall event was determined as approximately 185,000 m^3. In addition, the minimum storage requirement for a 1 in 50 year rainfall event was approximately 125,000 m^3. This storage capacity was planned to have the same elevation as the other urban water bodies in the development, to provide additional storage capacity when water levels rise higher than the average annual water level. The proposed location of the stormwater detention pond, as of April 1996, is depicted in Figure 4.4. To achieve the required detention volumes, additional storage areas adjoin the main water bodies in the form of landscaping, roadways, parking-lots and recreational areas.

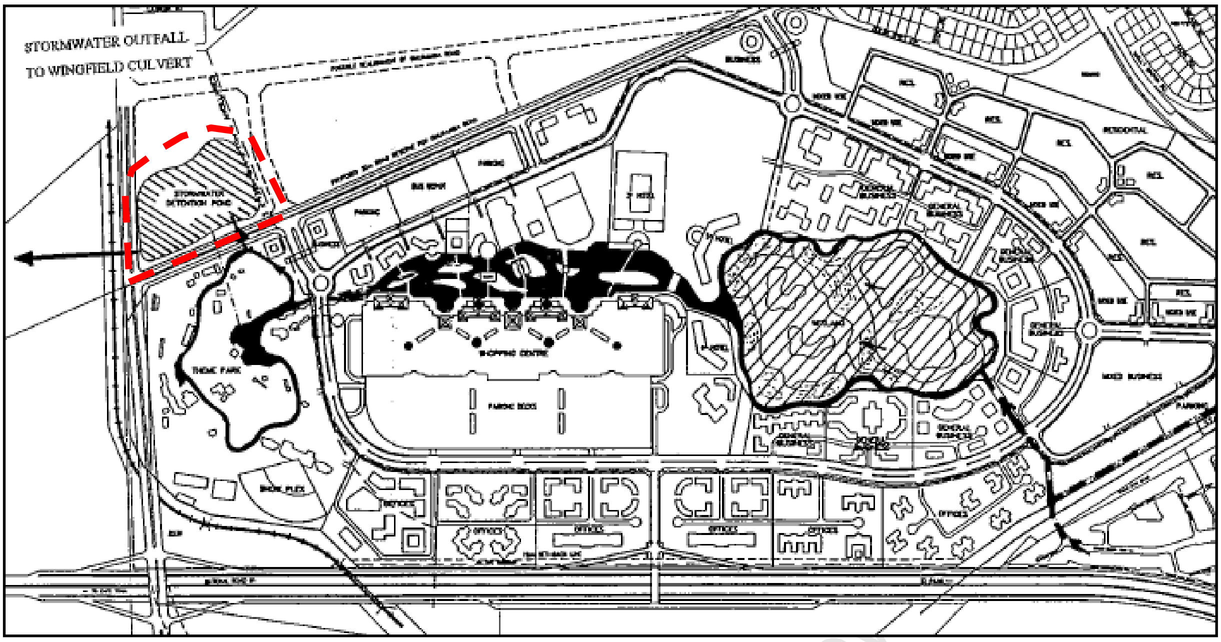

Figure 4.4: Proposed location for the stormwater detention pond
(After Monex Development Company, 1996)

According to the planned major and minor stormwater infrastructure, the following land use, volume and storage depth criteria were systematically determined by the Monex Development Company (1996), presented in Table 4.1, Table 4.2 and Table 4.3, respectively:

Table 4.1: Land use areas and associated runoff coefficients
(After Monex Development Company, 1996)

Land-use type	Area (ha)	Coefficient
Residential	85	0.4
Office/mixed use	83	0.65
Shopping centre/hotels/roads	45	0.95
Theme park	17	0.4
Water areas	30	1
Weighted average	260 (total area)	0.65

Table 4.2: Detention volume required for specified rainfall events
(After Monex Development Company, 1996)

Rainfall event	Storm duration (hours)	Intensity (mm/h)	Required storage (m^3)
1 in 50 year	6	13.8	121356
	24	4.9	124440
	48	2.8	78528
1 in 100 year	6	14	123384
	24	6.4	185280
	48	3.5	135312

Table 4.3: Depth of varying detention areas for required storage volume
(After Monex Development Company, 1996)

Detention area (ha)	50 Year storm (125,000 m^3) (m)	100 Years storm (185,000 m^3) (m)
20	0.62	0.93
30	0.42	0.62
35	0.36	0.53

4.2.5 Environmental considerations

In order to sustain the indigenous biomass and biodiversity in the Century City precinct it was important to ensure that there were environmental controls thoughout the development. Apart from the quantitative management of stormwater runoff, the qualitative management of runoff has a significant effect on the immediate environment. The developers had an assessment made of the Blouvlei ecology and introduced, *inter alia*, the following environmental controls to ensure better stormwater quality throughout and exiting the development:

- A set of technical and environmental guidelines to be issued to body corporates and managers within individual complexes in order to determine the specifications and detailing of internal stormwater systems, and control the entry point of stormwater into the main urban water system and minimise harmful stormwater quantities and qualities.

- A supplementary set of environmental guidelines and considerations to be issued in residential complexes in order to reduce the potential of wasteful housekeeping and neutralise pollution at source (this includes wastewater and solid waste removals, and street/paving/terrain cleaning).
- The proposed detention pond for Tygerhof Township to be positioned immediately upstream of the discharge pipeline to the Wingfield culvert. Mechanical and vegetated screening devices and artificial wetlands throughout the pond to improve the quality of stormwater runoff before discharging into the Wingfield outfall.
- Stormwater runoff from larger rainstorms that is managed within the development to be screened and sediment removed before entering the constructed wetland. This was a preventative measure, because wetlands typically have the ability to absorb potential pollution ‘shock loads’.
- Polluted stormwater runoff during the summer season to bypass the Tygerhof storage facility where possible for additional treatment by means of sedimentation, biofiltration and plant-uptake, before being discharged into the stormwater outfall. Stormwater generated in pre-seasonal rainfall events during the drier summer season is typically more contaminated than surface runoff in other seasons, and required treatment in order to minimise harmful environmental effects (Monex Development Company, 1996).

It was decided by the developers that stormwater management in Century City would form an essential part of the prospective environmental management plan (EMP). This placed significant emphasis on the maintenance of SuDS over their life cycle. According to Donovan & Naji (2003), stormwater systems are only effective if they are prioritised in a long-term management plan during the planning phase.

4.3 Implementation and modelling

The implemented stormwater management system in Century City is different to the system as originally conceived. There are a number of reasons for this, most of which are economic and relate to changes in stakeholders between 1996 and 2006. The implemented stormwater management system has a complex configuration, characterised by three principal drainage components, namely:

i) Conventional drainage practices;

ii) Individual SuDS options; and

iii) SuDS options in treatment train configuration.

Liebenberg *et al.* (2009) suggests that the system can be considered a “transitional” drainage system, as the infrastructural requirements and management approaches shift between conventional and sustainable drainage practices; often to the detriment of the SuDS options, particularly in the case of operation and maintenance requirements. The localised catchment collects stormwater runoff from the Century City precinct and neighbouring Summer Greens development, and channels it into the Tygerhof detention pond and adjoining stormwater outfall (both located at the western edge of the development). The detention pond and outfall form the ‘bulk’ stormwater management components and are typically effective in attenuating major flood peaks. The detention pond is designed to facilitate ‘tertiary’ treatment of stormwater runoff before it is detained and discharged into the stormwater outfall, and ultimately the Atlantic Ocean (HHO Africa, 2006).

In 2006 a stormwater management report was issued by HHO Africa (2006) which detailed the bulk infrastructure for the removal of stormwater from Century City. The report evaluates the performance of the stormwater management systems that were implemented in Century City. SuDS have been used in and around the development, among smaller sections of less attractive conventional drainage infrastructure, to manage stormwater runoff for Century City, Summer Greens as well as a portion of the Tygerhof Township. Each of the contributing catchment areas are defined as follows:

- **Century City** – The total catchment area of 212 ha is subdivided into smaller components largely corresponding to a number of isolated complexes and precincts. This catchment also includes seasonal salt pans.
- **Summer Greens** – This development is bounded by the N1 and N7 highway reserves, the South African Rail Commuter Corporation (SARCC) goods line embankment, and the Bosmansdam roadway reserve totalling an area of 65 ha that contributes wholly to the Century City drainage system.
- **Tygerhof Development Triangle** – This comprises an area of 40 ha, but has no direct impact on the Century City urban water system. Stormwater does however accumulate in the Tygerhof detention pond with stormwater runoff from Century City and Summer Greens (HHO Africa, 2006).

Figure 4.5 is a pictorial representation of the three main areas that contribute stormwater runoff to the Century City urban water system and Tygerhof detention pond.

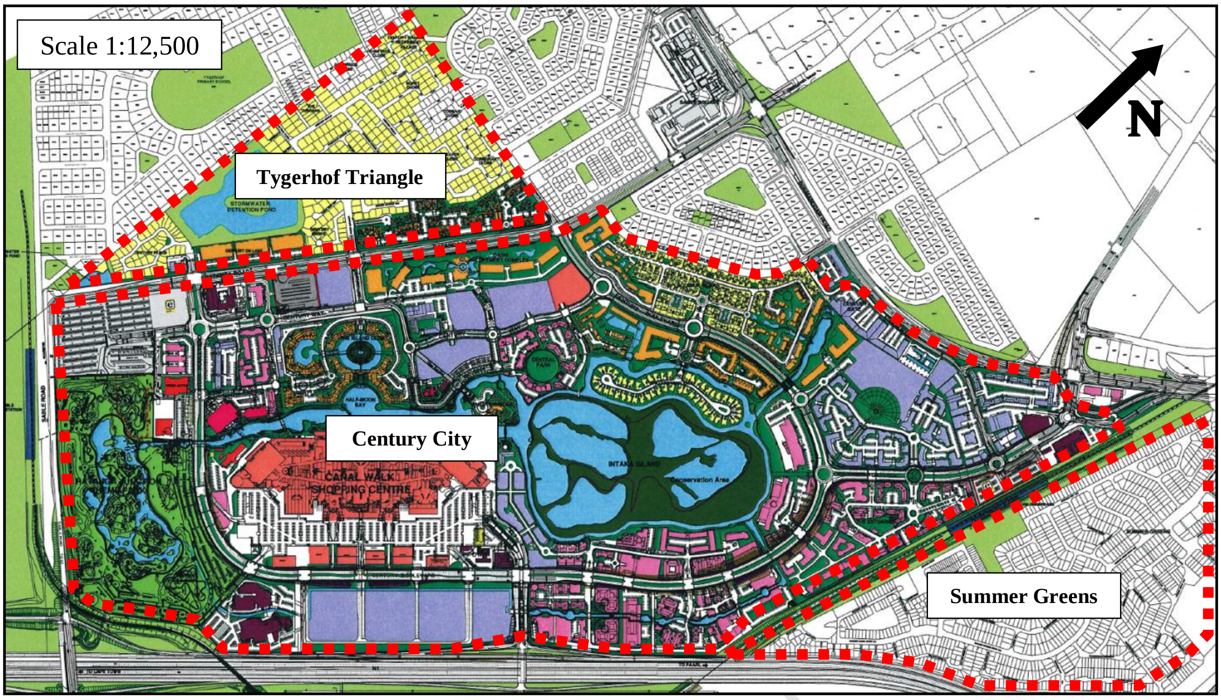

Figure 4.5: Contributing catchments to detention pond and stormwater outfall
(After CCPOA, 2009)

Figure 4.6 displays the major and/or 'regional' stormwater management infrastructure for the three developmental areas that are depicted in Figure 4.5.

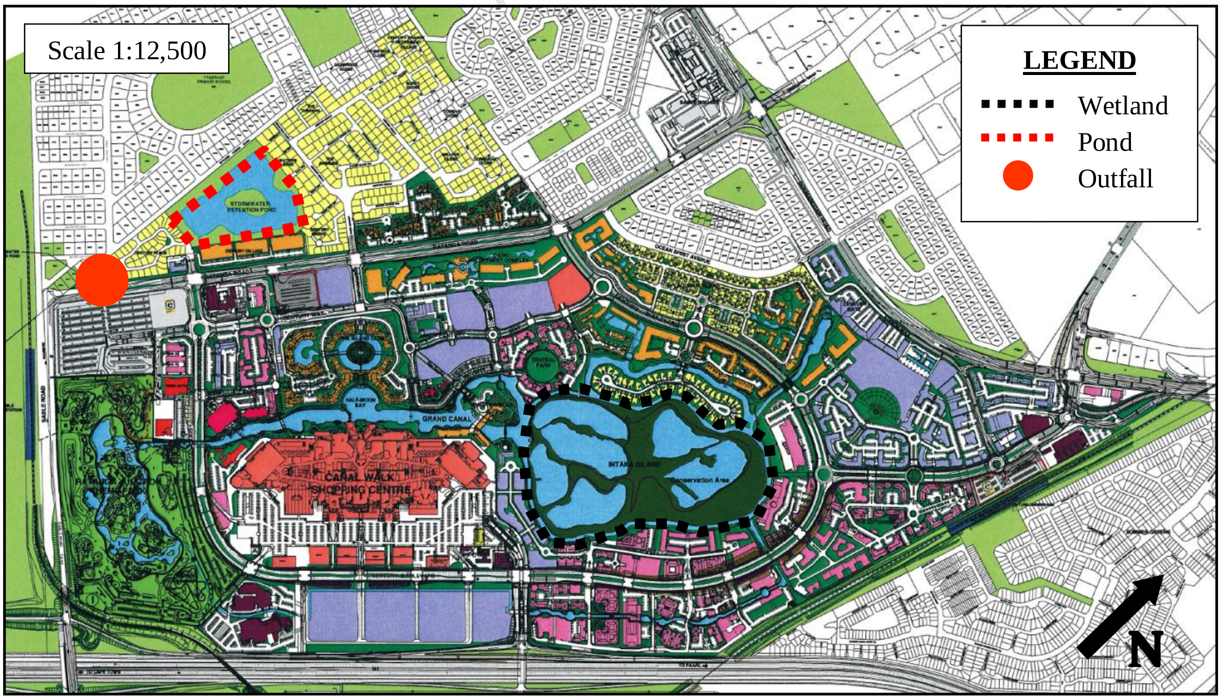

Figure 4.6: Major stormwater infrastructure for neighbouring developments
(After CCPOA, 2009)

The stormwater infrastructure implemented throughout Century City is grouped according to three management components. They include a single minor system component and two major system components, listed as follows (After HHO Africa, 2006):

i) Low flow system;
ii) Waterways and constructed wetland; and
iii) Tygerhof detention pond and stormwater outfall.

Each of these management components is detailed and described in the subsections that follow. A number of SuDS source and local controls are described as part of the ‘low flow system’ section, and briefly assessed in Chapter 5. Likewise, SuDS regional controls are described as part of the ‘waterways and constructed wetland’ and ‘Tygerhof detention pond and stormwater outfall’ sections.

4.3.1 Low flow system

It is common for small, intense rainfall events to produce relatively high concentrations of pollutants in stormwater runoff, known as the ‘first flush’ phenomenon. For this reason, runoff in Century City from relatively small rainfall events (< 15 mm/h) is prevented from entering the urban water system directly. The purpose of this is to minimise or prevent the long-term demise of structural and vegetated stormwater controls within the development. Stormwater runoff from Summer Greens is conveyed through an underground stormwater main that bypasses the Century City urban water system and discharges directly into the Tygerhof detention pond. Pollution from medium to high rainfall events (15 mm/h – 50 mm/h) is likely to enter the development’s waterways, but is expected to be diluted by greater runoff volumes. An increase in stormwater volumes also allows pollutants to be flushed through the urban water system more efficiently, and largely prevents stagnant pools of polluted stormwater.

A number of SuDS source and local controls have been implemented throughout Century City, typically in residential complexes and medium-high commercial areas. The most prominent source controls are pocket wetlands, which are scattered throughout all the residential complexes (Figure 4.7), and rainwater harvesting devices (Figure 4.8). Other typical source controls such as green roofs and sand filters are not as prevalent; however, according to Liebenberg *et al.* (2009) there is increasing potential for the application of green roofs on medium-high density commercial buildings, particularly extensive green roofs which incorporate low growing and low maintenance plant species. In addition, the non-conventional approach to stormwater management in the development has resulted in the implementation of many grass-lined and vegetated public open spaces which typically increase the residence time of stormwater runoff.

Figure 4.7: Pocket wetland at the low point of a residential complex

Figure 4.8: Solar powered stormwater collection and reuse system

The most prominent local controls are bio-retention areas (Figure 4.9), filter strips, swales, infiltration basins (Figure 4.10) and permeable pavements. Bio-retention areas are used extensively throughout the development, and provide an increase in amenity benefits, and supplementary habitats for indigenous biomass and biodiversity. Other local controls such as infiltration trenches are not as prevalent. SuDS local controls are more prominent in Century City than smaller source controls. Liebenberg *et al*. (2009) suggests that this is largely a result of the relatively maintenance-intensive requirements of SuDS.

Figure 4.9: Bio-retention corridor at the foot of an infiltration basin

Figure 4.10: Infiltration basin draining a commercial car parking-lot

Most of the later SuDS source and local controls (post-2000) were implemented by Rabie Property Group in accordance with SuDS literature and WSUD principles (Liebenberg *et al.*, 2009). In many instances, however, there is a disparity between the theory of SuDS and the practical application thereof. A number of these disparities are exemplified in Chapter 5.

4.3.2 Waterways and constructed wetland

4.3.2.1 Waterways and canal network

There are approximately 7 km of waterways in Century City (Century City Life, 2011). These are used as transportation corridors to link small residential water features to major water bodies, and double up as conduits for the conveyance of stormwater runoff. The canal network has been designed to provide extended detention and temporary storage during high rainfall events (50 mm/h), primarily due to the limited discharge capacity at the Wingfield stormwater outfall. The seasonal salt pans or *ephemeral* wetlands are an exception to this principle. The environmental management plan (EMP) prohibited any developmental interference in this area in order to ensure natural salinity levels were kept constant in the development throughout construction phases. They are flooded naturally in winter and dry out over summer periods (HHO Africa, 2006). These naturally occurring systems are protected against ‘temporary storage’ water levels because the water levels of the constructed wetland and adjoining canals were designed 0.4 m – 1.1 m lower. Under intense rainfall conditions, any rainfall in the *ephemeral* wetlands overflows into the adjacent canal network. The canals have a total storage area of approximately 25 ha, a maximum depth of storage of 0.7 m and a maximum storage volume of 83,000 m^3 (HHO Africa, 2006). The canal network meanders through residential and medium-high commercial developments, as well as alongside the main shopping centre and within the Ratanga Junction Theme Park (Figure 4.11). The canals also provide amenity in the form of water sports such as canoeing, canoe polo and dragon boat racing (Figure 4.12).

Figure 4.11: Canal ‘meandering’ through eastern office park complex

Figure 4.12: Canoeists take to the canal on a weekly basis

Stormwater runoff from the development’s roadways is discharged via sand traps into the canal network and circulates into the constructed wetland where it is ‘polished’. The sand traps were implemented as ‘best management practices’ (BMPs) and discharge stormwater into the canal network at a lower level than the standard water elevation in the development. Any excess flow that cannot be accommodated in the subsurface storage discharges directly into the canal network via base flows. Conventional pipe networks (Figure 4.13) and deep grassed 'wet' swales (Figure 4.14) complete the conveyance system.

Figure 4.13: Adjoining pipe network

Figure 4.14: Deep grassed 'wet' swale

4.3.2.2 Constructed wetland

The Century City constructed wetland is located in Intaka Island, which also includes a bird sanctuary and seasonal salt pans. Intaka Island is 16 ha in area and is considered the main feature of the development's natural assets. This multi-purpose constructed wetland aims to: conserve a rare type of wetland and *Fynbos* habitat, preserve the breeding heronries of waterbirds, and naturally filter and purify water from the development's canals (CCPOA, 2011c; Liebenberg *et al.*, 2009). The CCPOA (2011c) suggest that this is a good example of the interaction between engineering and natural processes, and how these are integrated to enhance stormwater management. The wetland is comprised of four main treatment cells (TC), two large seasonal salt pans (SP), and an adjoining canal network – all depicted in Figure 4.15.

During the wetter and milder half of the year – typically April to September – rainwater and resultant baseflows supplement the wetland through the canal network and underlying aquifer. Over the drier and hotter half of the year – typically October to March – treated sewage effluent from the nearby Potsdam wastewater treatment works (WWTW) was used to maintain the water levels in the wetland. The treated effluent was implemented with effect from December 2008, but needed to be halted in 2009 due to a rapid increase in phosphorous levels throughout the wetland (Day & Ross-Gillespie, 2008). Instead, water from the canal is now pumped into the wetland in the summer season. Figure 4.16 illustrates the direction of the flow within the wetland.

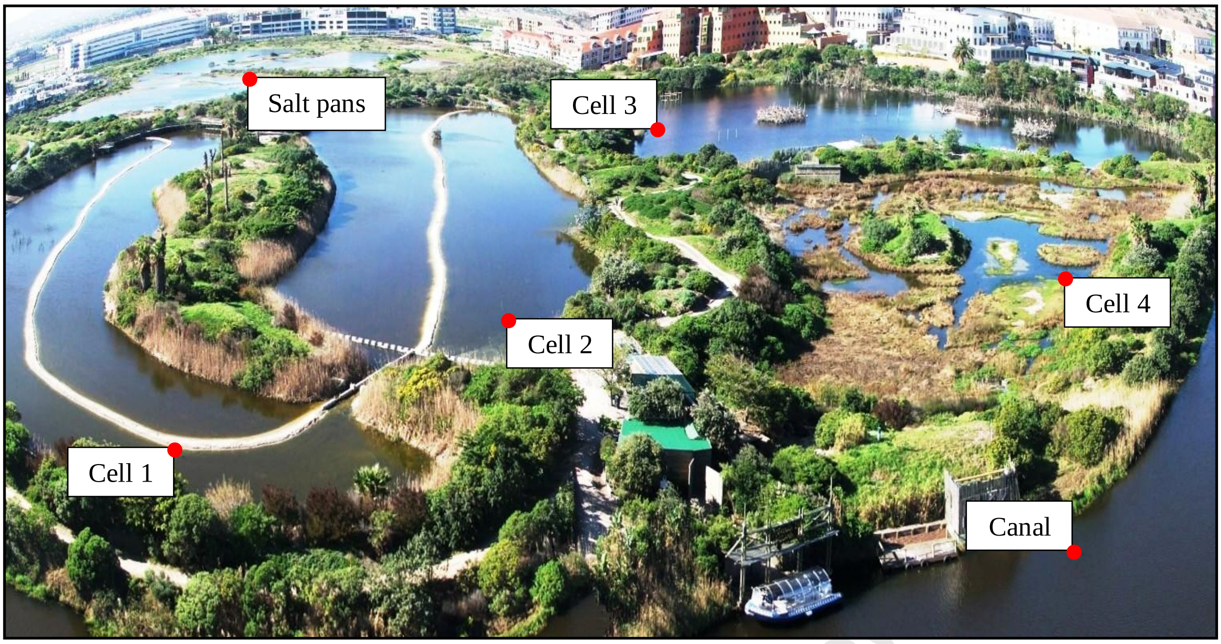

Figure 4.15: Panoramic view of the Century City constructed wetland

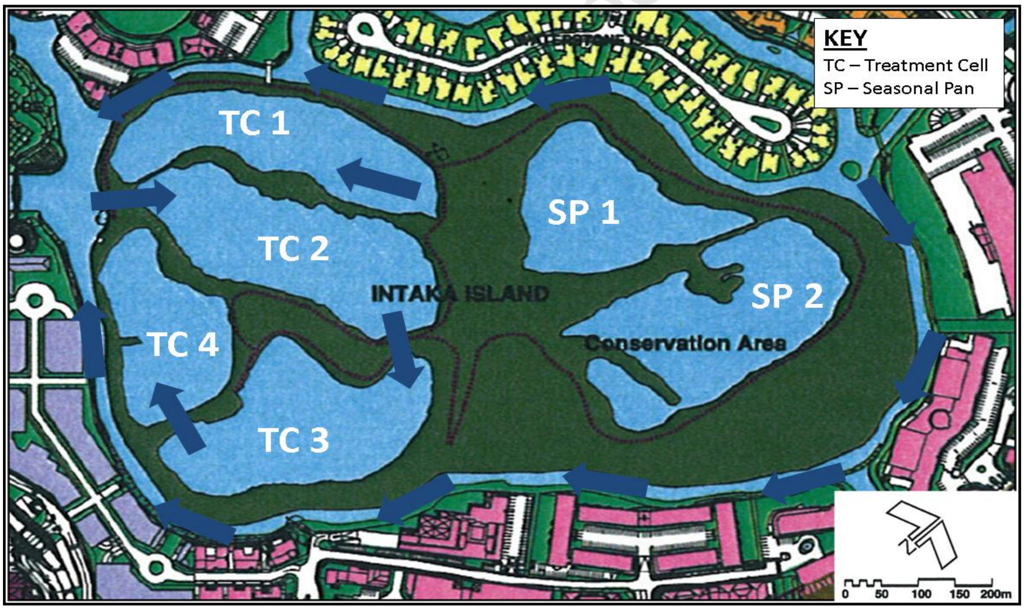

Figure 4.16: A plan view schematic of the constructed wetland's treatment cells (TC) and seasonal salt pans (SP) (After CCPOA, 2009)

The stormwater runoff entering the wetland is designed to pass through all four treatment cells every 72 days on average. Water from the canal is pumped into Cell 1 (TC1; Figure 4.17) via a mechanical spreader. It is then gravity fed through to the other three cells and polished through nine main mechanical and biological treatment processes, namely: sedimentation, filtration and biofiltration, adsorption, biodegradation, volatilisation, precipitation, plant-uptake, nitrification, and photodegradation. The cleansed stormwater is subsequently discharged back into the canal where it can be used by residents and visitors for recreational purposes. The processes within each of the constructed wetland's treatment cells are described as follows:

i) **Cells 1 and 2** – The first two treatment cells are partly covered with *P. australis* reedbeds and *Typha capensis* (*T. capensis*) bulrushes. These vegetation types grow relatively fast and are capable of absorbing significant quantities of phosphate, which is an essential nutrient for plant growth. They are, however, subject to endogenous respiration and die off rapidly (Ekama *et al.*, 2007), which adds to the nutrient load in these cells. The clearing of dead biomass is therefore a critical maintenance procedure in these cells. As a result, stormwater that is discharged from Cells 1 and 2 should have significantly lower phosphorous counts. Cells 1 and 2 are displayed in Figure 4.17 and Figure 4.18, respectively.

Figure 4.17: Cell 1 after routine dredging

Figure 4.18: Cell 2 during the wetland's construction phase

i) **Cell 3** – This cell has the characteristics of a retention pond, and is larger and deeper than the other treatment cells. Its relatively large surface area allows important aeration processes over the surface of the retained stormwater (Figure 4.19). In the aerobic zone, bacteria that breaks down nitrogenous compounds generally flourishes in this environment, thus eradicating most nitrogenous compounds that enter this cell from Cell's 1 and 2.

ii) **Cell 4** – The fourth and final cell is shallower than the other cells and is the most densely vegetated. Lower water levels in the cell ensure that stormwater is adequately aerated to encourage aerobic treatment processes. The vegetation provides the last remaining biological treatment that targets residual phosphates and nitrates that escaped the previous three treatment cells. According to Day (2009a,b), stormwater discharging from this final cell into the canal network between October 2008 and February 2009 had fluctuating *E. Coli* counts of 800/100ml – 1750/100ml. These counts are safe for recreational uses such as canoeing and punting, but not safe enough for swimming or potable purposes. Cell 4 is depicted in Figure 4.20.

Figure 4.19: Overlooking Cell 3, Canal Walk shopping centre and Table Mountain

Figure 4.20: Overlooking Cell 4 and the Knightsbridge residential quarters

iv) **Seasonal Salt Pans:** The two seasonal pans are situated to the north-east of the four retention ponds and fall within Intaka Island (Figure 4.21 and Figure 4.22). They are natural systems that were originally a part of the pre-development low-lying *Blouvlei* area. These natural systems are sensitive to the relatively extreme climatic changes that are typical of the prevailing climate conditions. A mandate was therefore drafted by the CCPOA as part of the development's EMP to protect and preserve the seasonal salt pans as it is in their vested interest (CCPOA, 2011a,b). The pans dry out completely during the dry summer season, and fill with water to no more than a 0.5 m during the wetter winter season. In the event of long rainfall durations and increased stormwater runoff volumes, excess stormwater is discharged into the canal network adjacent to both seasonal pans. The seasonal pans do not contribute substantially to the treatment of stormwater runoff, but control the salinity of underground aquifers, and benefit the development's amenity and biodiversity – also key elements of effective SuDS schemes.

The constructed wetland is linked to the detention pond and stormwater outfall via the canal network that bypasses the northern periphery of Canal Walk shopping centre, to form the bulk stormwater management components in the development.

Figure 4.21: Eastern seasonal salt pan, August 2009

Figure 4.22: Western seasonal salt pan, August 2009

4.3.3 Detention facility and stormwater outfall

The City appointed a steering committee in the suburb of Milnerton to oversee the design of the proposed stormwater outfall described in Section's 4.2.3, 4.2.4 and 4.2.5. Late in 1996 the steering committee accepted KFD Wilkinson and Partners' outfall design proposal, which was subsequently implemented. The Wingfield outfall now drains the combined stormwater runoff from Century City, Summer Greens and the Tygerhof Township. The Wingfield outfall and associated infrastructure is depicted in Figure 4.23 and Figure 4.24.

Figure 4.23: Wingfield outfall depression covered by reeds (*Phragmites australis*)

Figure 4.24: Wingfield outfall pump station and hydraulic testing pit

To provide sufficient storage for the lack of capacity previously established at the old outfall, a detention facility was implemented in the Tygerhof Triangle. The Tygerhof detention pond limits the discharge from a 1 in 100 year rainfall event to a maximum of 1.1 m^3/s. The detention pond is depicted in Figure 4.25 and Figure 4.26.

Figure 4.25: Northern view of Tygerhof detention pond

Figure 4.26: Eastern view of Tygerhof detention pond

Although HHO Africa (2006) describes the Tygerhof pond as a ‘detention pond’, which should typically detain water and dry out between rainfall events, it has the fundamental characteristics of a ‘retention pond’ (as described in Section 2.3.4.4). Firstly, the pond retains water, even in summer seasons, and secondly, it provides primary storage by way of extended detention in the pond’s freeboard. The Tygerhof detention pond has a surface area of approximately 5.4 ha, a maximum depth storage of 3.8 m, and a maximum volume of 190,000 m^3. The detention pond receives stormwater runoff from Tygerhof and the Century City low flow system. During high rainfall events, stormwater overflows from the development’s canal network and discharges directly into the pond. From here, stormwater is discharged via a 900 mm diameter pipe into the Wingfield outfall. Figure 4.27 presents a long-section of the bulk components of stormwater management and illustrates the hydraulic relationships between the seasonal pans, canal network, detention pond, and outfall. HHO Africa (2006) modelled each of these bulk stormwater management components to validate their design.

4.3.4 Model outputs analysis

The modelling was conducted to assess the hydraulic performances of each stormwater component under preselected rainfall events and flow conditions. HHO Africa (2006) assume that under low flow conditions, stormwater runoff is treated by ‘source’ and ‘local’ control SuDS and discharges directly into the Tygerhof detention pond via the Century City outfall. During higher rainfall events (> 25 mm/h), however, there is an overflow into the canal network (HHO Africa, 2006). Stormwater from the canal network typically discharges into the Tygerhof pond via an 8.0 m wide sharp crested weir and two box culverts (1.5 m x 1.2 m). The resultant flow into the detention pond was calculated by assuming free-flowing conditions. This calculation was then used to evaluate the relationship between the storage and discharge parameters of the key stormwater management components, particularly the detention pond.

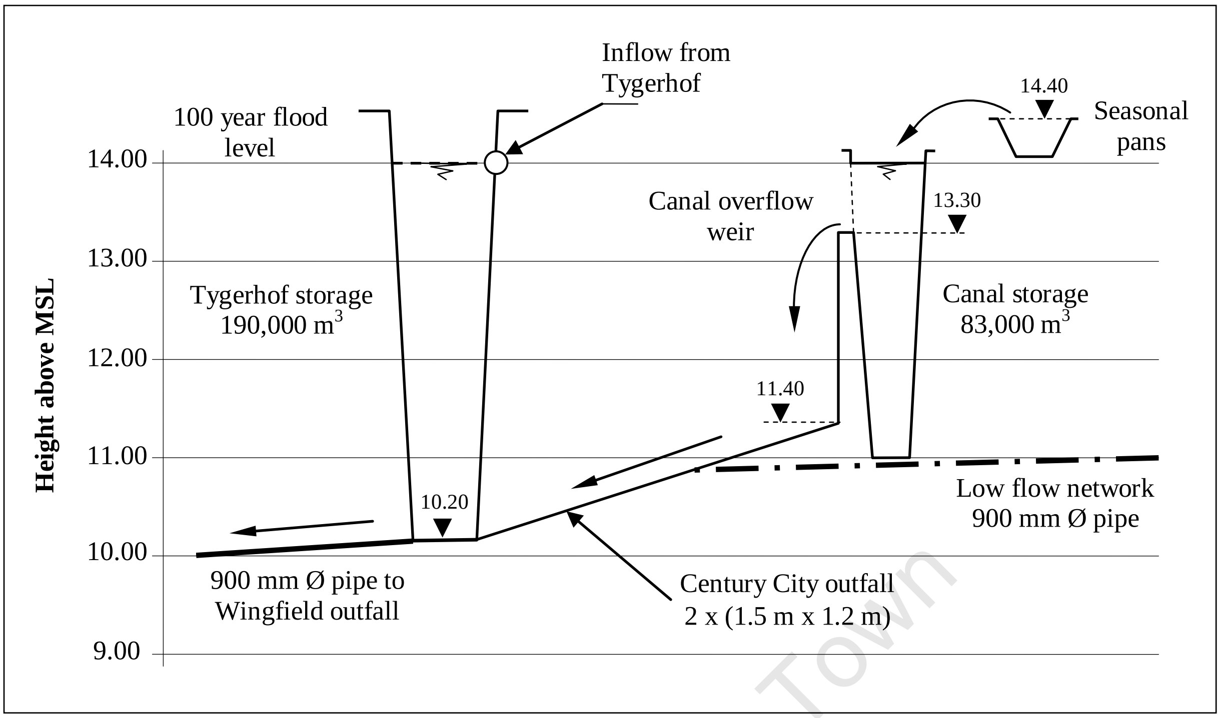

Figure 4.27: Cross section of bulk stormwater components (After HHO Africa, 2006)

According to HHO Africa (2006) however, since the box culverts discharge stormwater at the invert level of the detention pond, the flow in the culverts is limited by the depth of the pond. This limitation becomes particularly problematic in the event of long storm durations such as 24 hours – 72 hours. In addition, longer storm durations result in an increase in the saturation state of underlying soil stratum. This, in turn, limits the detention, extended attenuation storage and infiltration capacity of many SuDS options. Relatively long storm durations (24 hrs – 72 hrs) limit the quality control processes of most SuDS options; sedimentation, filtration and biofiltration, plant-uptake, and nitrification capacities are all significantly limited as the ability of stormwater to infiltrate into the ground decreases with increasing storm durations (AAS, 2004).

Another complication in the system is that the parking-lots for Ratanga Junction, Virgin Active and Transport Interchange, as well as the Tygerhof Development Triangle, discharge stormwater runoff directly into the detention pond with varying flood peaks. As a result, this limited the modelling of the relationship between the detention pond storage and the canal storage. The ILLUDAS (Illinois Urban Drainage Area Simulation) ‘stormwater suite’ was used to determine the sizing of ‘required’ storage volumes throughout the development which approximated the key parameters of the stormwater management system (HHO Africa, 2006). The following five simplifications and assumptions were made to the model:

i) All stormwater discharged from the development’s low flow system was routed via a weir at the Wingfield outfall. The discharge equation for the weir was calculated using half the permissible depth of the canal (13.7 m above MSL) after which flow typically reduces linearly to zero at the maximum storage level (14.0 m above MSL). This model simplification also considers the effect of the filling of the detention pond from the Century City culvert.

ii) It was assumed that the canal network had 100% storage capacity available at the beginning of each rainfall event.

iii) It was assumed that the Tygerhof detention pond had 100% storage capacity at the beginning of each rainfall event.

iv) Flows entering the canal network from the seasonal salt pans were taken as negligible.

v) A runoff coefficient of 0.8 was assumed over the catchment area in question (i.e. 80% runoff from the development) (HHO Africa, 2006).

Perhaps these assumptions, particularly assumptions (i), (ii), (iii) and (iv), were too idealistic to render conservative model outputs. The storm frequency that was used to determine the storage requirements was the 1 in 100 year rainfall event, with a triangular storm distribution being assumed, and 13 storm duration increments tested between 1.5 hrs – 84 hrs. Rainfall data was obtained from the City of Cape Town Intensity-Duration-Frequency (IDF) curves, using the Athlone gauging station for storm durations from 1.5 hrs – 24 hrs (HHO Africa, 2006). Storm durations greater than 24 hours were extrapolated from the data. The purpose of running the model was to determine peak values for the volumetric storage requirements in the key stormwater components. The results of the model are displayed in Table 4.4, and are graphically depicted in Figure 4.28 which displays the canal, detention pond and total storage volumes on the left vertical axis, and the flow rate to the Wingfield outfall on the right vertical axis. The results illustrate that the storage requirement in the canal peaks at 50,140 m^3 (after approx. 6 hrs) for the 1 in 100 year storm. The peak storage requirement for the Tygerhof detention pond occurred significantly later at 60 hours and more than four times larger at 218,136 m^3. Both the table and graph illustrate that the total storage requirement peaks at 254,591 m^3 after 60 hours, which is influenced significantly by the peak storage requirement of the detention pond.

Previously in Section 4.3.3 it was stated that the flow entering the Wingfield outfall was limited to approximately 1.1 m^3/s. The ‘flow to outfall’ illustrated in relation to the secondary vertical axis on the graph shows that this limitation was exceeded at approximately 33 hours (interpolated from Figure 4.28). In addition, once the storm durations exceed 24 hours the volumetric requirements become unrealistic, because according to HHO Africa (2006), as the detention pond begins to fill, the weir becomes subject to increased ‘backwater’ effects which redistribute storage between the two storage components.

Table 4.4: Storage results for 1 in 100 year rainfall events (HHO Africa, 2006)

Storm duration (hours)	Total precipitation (mm)	Volume required (m^3)			Peak discharge (m^3/s)	
		Canal	Tygerhof pond	Total storage	Century City outfall	Flow to Wingfield outfall
1.5	40.4	40135	65446	105581	3.10	0.45
2.0	43.9	42090	69900	111990	3.30	0.50
4.0	56	48615	86961	135606	3.75	0.57
6.0	63.0	50140	98950	149090	3.75	0.66
8.0	68	49335	108665	158000	3.70	0.68
10.0	70	44965	111888	156853	3.70	0.71
12.0	72	42320	114731	157051	3.30	0.72
24.0	93.6	38640	148425	187065	2.90	0.95
36.0	118.8	38180	181504	219684	2.85	1.13
48.0	144.0	37950	207568	245518	2.75	1.30
60.0	162.0	36455	218136	254591	2.75	1.38
72.0	172.8	34155	217331	251486	2.40	1.38
84.0	176.4	31165	207995	239160	2.10	1.31
Available Capacity		**83000**	**190000**	**273000**	**N/A**	**1.10**

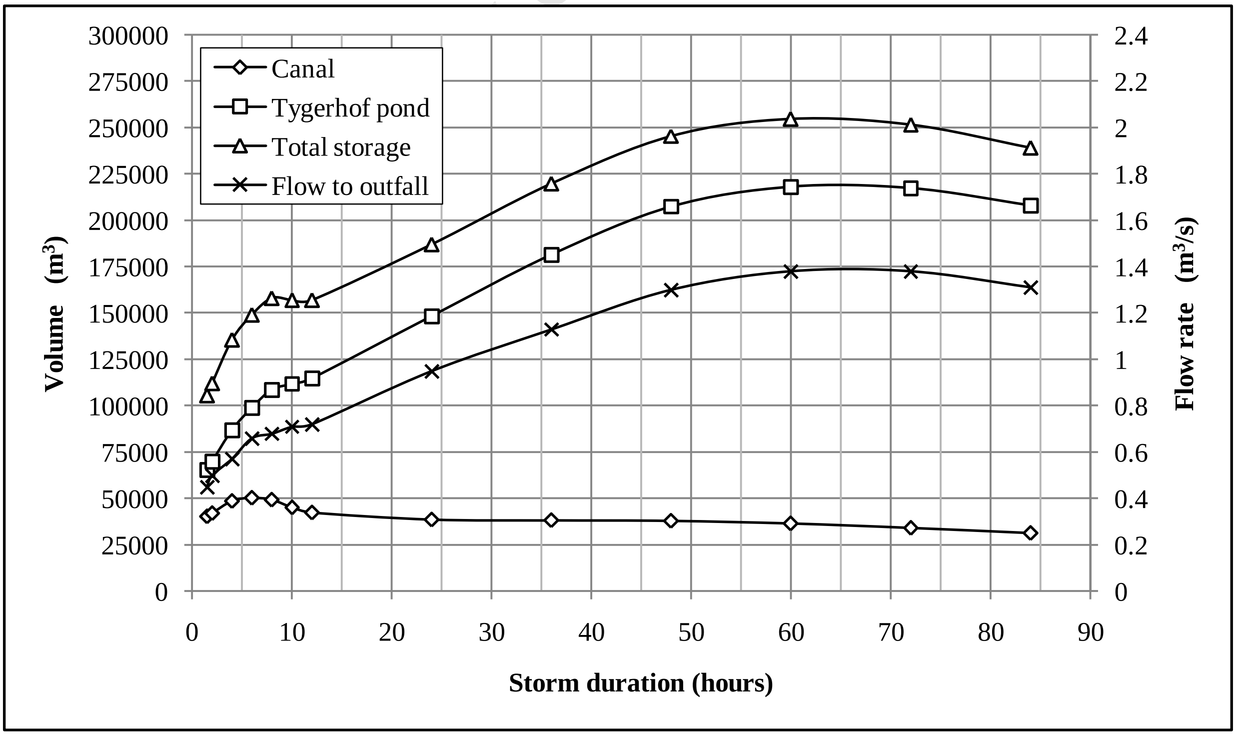

Figure 4.28: Graph of 1 in 100 year event volumetric storage requirements

The model outputs were validated using a 'simple global check', which was undertaken for the same storm durations. The total stormwater runoff was determined (i.e. 80% of total precipitation over development) and then used to calculate the required storage volume (HHO Africa, 2006), as follows:

(Required storage volume) = (Total rainfall volume) – (Total discharge through outlet pipe)

The results of this simple global check computation are tabulated in Table 4.5, and graphically depicted in Figure 4.29 as follows.

Table 4.5: Simple global check for storage volume requirements (HHO Africa, 2006)

Storm duration (hours)	Total storm volume (m^3)	Total discharge to Wingfield outfall (m^3)	Total storage volume required (m^3)		% Variance
			Global check	Table 4.4	
1.5	102870	1215	101655	105581	3.7
2.0	112268	1800	110468	111990	1.4
4.0	142240	4104	138136	135606	-1.9
6.0	160020	7128	152892	149090	-2.6
8.0	174752	9792	164960	158000	-4.4
10.0	177800	12780	165020	156853	-5.2
12.0	192024	15552	176472	157051	-12.4
24.0	237744	41040	196704	187065	-5.2
36.0	301752	71280	230472	219684	-4.9
48.0	365760	95040	270720	245518	-10.3
60.0	411480	118800	292680	254591	-15.0
72.0	438912	142560	296352	251486	-17.8
84.0	448056	166320	281736	239160	-17.8

This table and corresponding graph show that there is reasonable agreement across the range of storm durations for the storage requirements of the development's water bodies. This is noted from the variance between the two storage estimations (on the right hand vertical axis), which illustrates a maximum variance of 12.4 % at the 12 hour storm duration. The majority of the variances for the 24 hour storm duration are below 5 %. Therefore, the available storage in the form of detention and extended detention was taken as sufficient for the 24 hour, 1 in 100 year rainfall event.

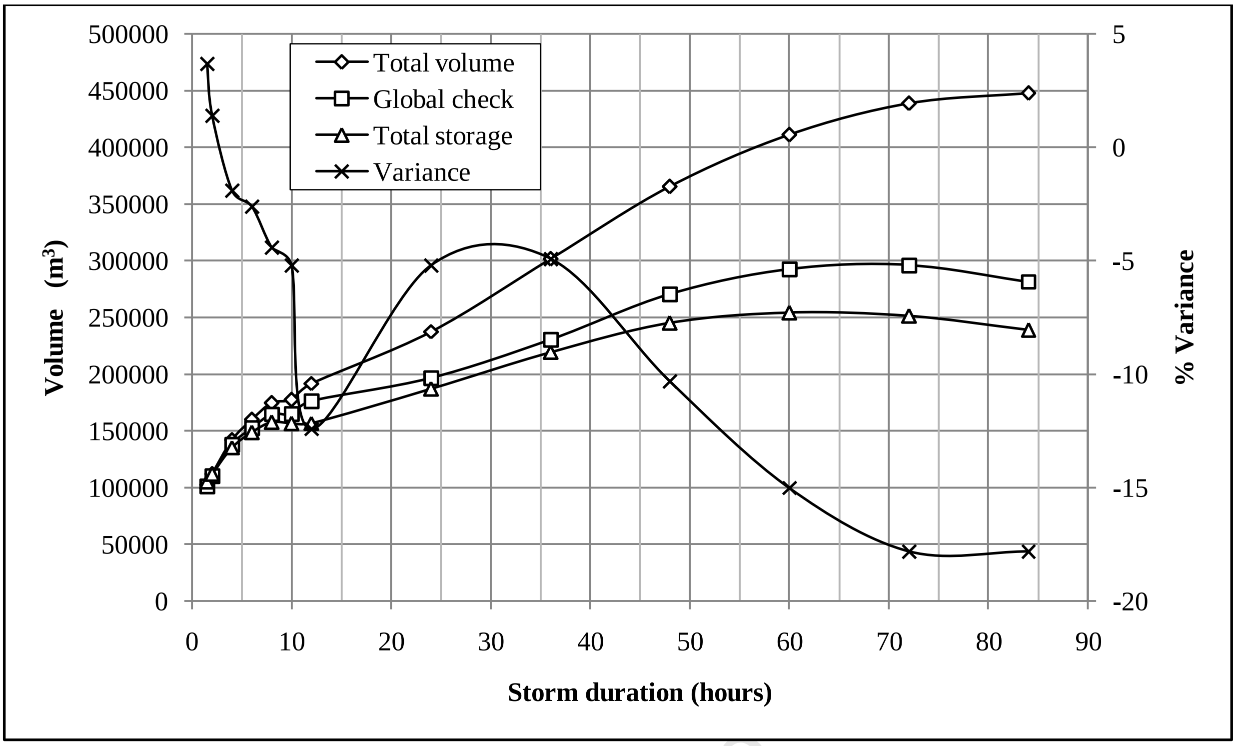

Figure 4.31: Graph for global check of 1 in 100 year rainfall storage requirements

There is a significant factor of safety (FOS) for these storage requirements in the event of a 100 year return period storm. The probability of this event occurring is one percent. Table 4.6 illustrates the FOS for the storage volumes in two of the bulk stormwater components.

Table 4.6: Factors of safety for storage volumes of key stormwater components

Stormwater component	Storage volume required (m^3)	Maximum storage capacity (m^3)	FOS (1:X)
Canal network	38640	83000	2.1
Tygerhof detention pond	148425	190000	1.3
Total storage	187065	273000	1.5

The model outputs illustrate the efficacy of detention ponds as ‘regional control’ SuDS in managing relatively large quantities of stormwater runoff. The extended detention that the canal network provides proved to be of hydraulic value by adding approximately 83,000 m^3 to the total storage capacity. The model is however relatively conservative as it fails to consider the long-term storage capacity in the constructed wetland. Constructed wetlands are typically more effective in managing small rainfall events (< 15 mm/h) and ‘first flush’ volumes;

however, as much as 12,500 m^3 can be stored as 'extended attenuation storage' in the wetland's pond-like treatment cells.

4.3.5 Planting to enhance SuDS

Plant selection and landscaping are critical elements of SuDS schemes. According to Roads and Stormwater Department (2011) and Century City's environmental and 'eco-centre' manager, Mr. Jarrod Lyons, plant selection should typically favour indigenous species for increased resilience in testing climatic conditions. The selection of resilient plants provides SuDS with the ability to treat stormwater all-year-round, and provides the added benefit of amenity and the potential for vibrant biomass and biodiversity. There are two terrestrial vegetative types used throughout Century City, namely, Sand Plain Fynbos and Strandveld. These vegetation types are indigenous to the Cape Flats area of Cape Town. The Cape Flats area is a particularly challenging environment for vegetation because the deep and sandy soils have relatively low nutrient levels, and are rapidly infiltrated by rainfall. This is further exacerbated by particularly strong winds and hot and dry summer periods in the Cape, forcing vegetation to cope with relatively high water stress.

Three groups of plants are used throughout the development that have adapted to cope with the relatively tough growing conditions in the Cape Flats, namely: (1) Perennials (water finders), (2) Annuals (drought evaders), and (3) Geophytes (water storers) (CCPOA, 2011b; Lyons, 2011). An example of a 'Perennial' is the Sour Fig, *Carpobrotus edulis* (Figure 4.30). These plants store water in thick fleshy leaves by means of a mucous-like substance. Perennials prevent water loss by utilising leaf structures with minimum surface areas, and improve water access by growing deep roots. Annuals, however, evade the dry and hot summer period and germinate from seed when the growing conditions are more suitable in the wetter winter period. They grow rapidly during the rainy season, flower typically in spring, and produce seed before dying out at the outset of the dry summer season. The third group, the water storing Geophytes, is made up of modified stem structures and leaves in the form of bulbs, corms or tubers, which store water and nutrients. Geophyte means 'earth plant', because the most critical part of the plants body typically resides beneath the ground's surface (CCPOA, 2011a,b). These plant groups enhance the 'source' and 'local' control SuDS as well as the constructed wetland and Tygerhof detention pond by providing stormwater runoff treatment all-year-round, especially during the wetter winter season. Stormwater is typically cleansed by vegetation through processes of plant-uptake, evapotranspiration, biofiltration, and volatilisation.

The four plant biomes in the greater Cape Town region offer many possibilities for indigenous plant selection to control stormwater runoff. In addition to the plant species already mentioned, the following indigenous plant species have also been effective in managing stormwater runoff in Century City, and resilient during prolonged climatic extremes (Lyons, 2011):

- Blue Water Lily (*Nymphaea nouchali*) – a floating herb that typically grows and flowers in summer months;
- Saw Grass (*Cladium mariscus*) – a tufted Graminoid residing in sand that typically requires low-nutrient conditions to grow;
- Reed (*Restio tetragonus*) – a tufted Restio residing in sand that typically requires low-nutrient conditions (Figure 4.31);
- Vleibiesie (*Scirpodies nodosus*) – a tufted Graminoid residing in sand or clay that is fast growing and resilient, can be relocated and manages year-round inundation or drought;
- Oorttjies (*Falkia repens*) – a mat-forming Forb residing in sand that is typically prevalent in coastal marshes and seeps with moderate growth;
- Keurboom (*Virgilia orobiodes*) – a tree that grows 5.0 m tall in sand, but is relatively short lived (typically 8 to 15 years); and
- Sedge (*Ficinia nigrescens*) – a tufted Graminoid that resides in very dry climates and grows in coastal alkaline sands (Roads and Stormwater Department, 2011).

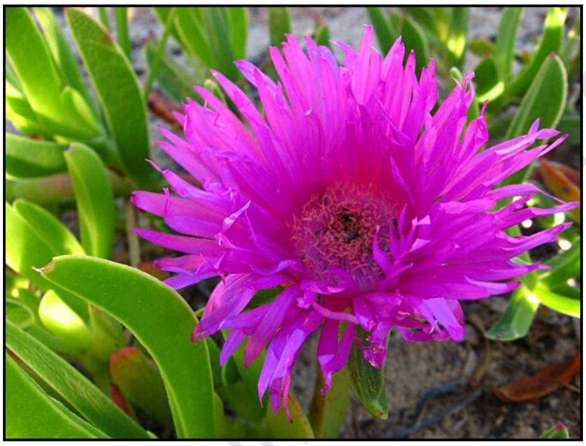

Figure 4.30: Sour Fig, *Carpobrotus edulis*, flowering (New Plant Nursery, 2011)

Figure 4.31: Reeds, *Restio quadratus* and *Restio tetragonus*, Century City

4.3.6 Public education and water saving initiatives

In April 2010 the CCPOA commissioned the erection of an 'eco-centre' at the entrance to the constructed wetland. The Intaka Island Environmental Education Centre or 'Eco-Centre' was subsequently established and opened in October 2010 (Figure 4.32). The primary concern over the construction of the eco-centre was the isolation of stormwater flows as well as biomass and biodiversity in the northern part of Cell 1 (CCPOA, 2011c; Lyons, 2011). Isolating the first cell would prevent stormwater flows from circulating through to the other treatment cells and prevent the expected stormwater cleansing processes. The purpose of the eco-centre is to provide high-quality educational facilities for visiting schools and institutions (Figure 4.33). To date (June 2011), classes from eighteen schools have regularly attended talks and presentations in the eco-centre. Most of the talks and presentations are conducted by members of the CCPOA and focus on aspects of the immediate environment, particularly the ecology, biomass and biodiversity in the constructed wetland. The most prominent educational aspect at the eco-centre is the relationship between the wetland's biodiversity and biomass, and how these contribute to the polishing of stormwater. Scholars are also taught geography, mathematics and natural sciences, most of which relate to the natural surroundings of the wetland.

Figure 4.32: Intaka Island Environmental Education Centre or 'Eco-Centre'

Figure 4.33: Education facility suspended over Cell 1

Educational talks are also given on the conservation and sustainable use of water. Water reuse is an important educational point at the eco-centre (Chanan *et al.*, 2009). All greywater at the eco-centre is reused to flush toilets, and for a variety of irrigation purposes (Figure 4.34). All sewage generated from the building is treated onsite and used to irrigate non-edible vegetation. The toilets and urinals are also flushed using rainwater that is collected as roof runoff (Lyons, 2011). The eco-centre has also commissioned a major recycling initiative that is set to cover the Century City precinct and spread into other parts of Milnerton. The recycling initiative promotes the separation of organic and inorganic waste, efficient litter collection services, and an increase in recycling bins per person (Figure 4.35; Lyons, 2011). A benefit of these interventions is that they provide effective 'catchment litter management', which minimises the quantity of litter that enters stormwater systems before being discharged into the nearest water related environment. This illustrates effective 'site management' (Section 2.3.4.1).

The eco-centre has also been pivotal in facilitating management forums for the operation and maintenance of the development's urban water system.

Figure 4.34: Greywater digesters used daily at eco-centre

Figure 4.35: Recycling bins for solid waste separation education at eco-centre

4.4 Operation, monitoring and maintenance

4.4.1 Operational requirements

Sections of the urban water system in Century City have been operating for fifteen years. The CCPOA coordinate a number of operation, monitoring and maintenance activities that are required to ensure the effective functioning of the urban water system, especially the vegetated systems such as the SuDS options. These typically include three main components, namely: (1) routine operation and maintenance procedures, (2) a response-oriented task force to remedy irregular situations, and (3) *ad hoc* management interventions. Furthermore, there are four key management objectives stated in the development's EMP. These suggest that the urban water system should be managed in order to, *inter alia*:

- Provide a habitat for birds, particularly breeding water birds;
- Provide an aesthetically pleasing constructed wetland that symbolises a "green lung";
- Cleanse stormwater in the constructed wetland, which can then be used throughout the canal network and for numerous irrigation requirements; and
- Provide the public with high quality recreational facilities and educational amenity (Blouvlei Environmental Committee, 2003).

In order to satisfy the aforementioned environmental requirements, the CCPOA have over the past four years employed ecological specialists, Freshwater Consulting Group (FCG). The FCG presented findings regarding the quality of the input water source into the wetland. The constructed wetland and adjoining water bodies are monitored and reviewed on a monthly basis, with focus predominantly given to the quality of water in the development, sediment data acquisitioning, and remedial measures linked to organism growth. The FCG have over the past three years provided detailed monitoring reports of ecological activity in and adjoining the wetland system, which is useful literature for future development planning. Each report focuses on the basic amenity and system dynamics of biomass and biodiversity in the constructed wetland and canal network. To date (June 2011), the FCG have drafted nine reports that specify a number of environmental issues in the development and have resulted in major technical interventions since 2008 (recorded in Chapter 5).

4.4.2 Water quality monitoring

Due to the hydrological and geographical nature of the Century City development area, the constructed wetland and associated urban water bodies are subject to an erratic stormwater quality. In response to this continual problem, the CCPOA have employed a monitoring programme that highlights degradation and potential degradation in water quality in the constructed wetland and canal network (Liebenberg *et al.*, 2009). Water quality monitoring is critical as reduced functioning in the wetland is likely to decrease the aesthetic appeal of water features in the development and destroy ecological treatment processes; the effects of which are likely to increase the potential for a major loss in property investment and degraded downstream environments. Water quality data is collected on a monthly basis with additional *ad hoc* collections on a weekly basis if a particular aspect of water quality has been 'red-flagged' and requires more intensive monitoring (Liebenberg, 2001). The following key water quality criteria and general criteria are monitored monthly:

- Dissolved and total phosphorous concentrations;
- Chlorophyll-*a*;
- Turbidity (measured as Nephelometric Turbidity Units or NTUs, but also represented by Secchi depth and total suspended sediment values);
- Oxygen concentration;
- Ammonia concentrations;
- The presence of disease-causing bacteria (key indicator organisms are *Escherichia coli* and faecal coliform data);
- Phaeophytin analysis;
- Taxonomic identification and enumeration of phytoplankton;
- Rate of recovery of aquatic macroinvertebrate communities after Rotenone (remedial agent) application; and
- Measurement of sediment quality and depth in the treatment wetland cells prior to and after draining of the cells (CCPOA, 2011c).

4.4.3 Maintenance interventions

Monthly water quality results yielded from the monitoring programme aid the CCPOA's maintenance task team in performing routine and remedial procedures as often as is necessary. In addition, due to the environmental complexities associated with the development's urban water system, there are many irregular maintenance requirements each year. For example, human intervention led to the introduction of alien vegetation and fish species that required innovative removal measures to prevent widespread ecological destruction. One of the challenging aspects of this type of maintenance is that the associated financial implications are generally unknown. The following interventions represent six more 'regular' maintenance procedures that are required in the wetland's treatment cells and adjoining canal network:

i) Annual draining and dredging of wetland cells 1, 2 and 3, followed by periodic re-design (minor and irregular) to allow improved flow distribution between cells;

ii) Annual removal of fish, typically Carp (*Cyprinus carpio*) as well as large numbers of Tilapia species and indigenous Cape Kurper (*Sandelia capensis*) from the artificial canals and treatment wetland system, using the pesticide 'Rotenone';

iii) Monthly addition of barley straw bales to selected areas of the urban water system to minimise the potential for algal blooms and to prevent sedimentation (Figure 4.36);

iv) Biweekly removal of invasive aquatic weeds and alga from water bodies, including: *Azolla filiculoides*, *Lemma gibba*, and *Cladophora sp*.;

v) Weekly cutting and removal of *Potamogeton pectinatus* from the beds and surface of the canal network; and

vi) Bimonthly pumping and removal of bird faeces (high in Ortho-phosphate and Total phosphate) from sludge sumps installed beneath the heronries (Figure 4.37; CCPOA, 2011c, Day, 2009a,b).

Figure 4.36: Barley straw bales at canal network inlet

Figure 4.37: High phosphate producing heronries in constructed wetland

4.5 Costing appraisal

Due to the confidentiality and exclusivity of costing data held by the CCPOA and Rabie Property Group, only limited costing data was made available. Rabie Property Group is the principal developer of Century City, and bears the capital costs of all bulk stormwater infrastructure in the development. Once construction and installation is completed, the CCPOA are liable for the operation and maintenance costs as well as residual costs that typically exist in developments of this scale. Perhaps the stormwater management processes initiated by the developers would not be viable in most developments due to the urban water system's high annual operation and maintenance costs (Liebenberg *et al.*, 2009). These are, however, sustained each year by large monthly rates and levies, and increasing investment in Century City. An example of these operation and maintenance costs are displayed in Table 4.7, which tabulates the water quality budget for the 2009 year end. The costs represent only those for the constructed wetland and canal system; they are not inclusive of those relating to the Tygerhof detention pond, or 'source' and 'local' control SuDS throughout the development.

Table 4.7: Stormwater operation and maintenance costs 2009

Income	Amount (R)	Expenses	Amount (R)
Canal water testing	121,473	Canal maintenance	8,760
		Chemicals	68,200
		Chemistry	144,600
		Contingency	6,000
		Consultant	75,000
		Motor vehicles fuel & oil	12,000
		Licensing	450
		Motor vehicles repairs	8,700
		Printing & stationery	600
		Protective clothing	8,250
		Staff training	2,720
		Staff welfare	3,750
		Telephone	5,400
		Wages	248,600
Subtotal	**121,473**	**Subtotal**	**593,030**

These annual costs are often accompanied by large residual costs, ranging from additional construction costs to costs that are necessary for the optimal operation of several SuDS options

(Liebenberg *et al.*, 2009). For the 2009 financial year, *ad hoc* costs for two capital expenditure items were incurred by CCPOA; tabulated in the Table 4.8.

Table 4.8: Residual stormwater expenditure 2009

Expenditure item	Amount
Aquatic weed harvester	1,200,000
Canal dredging	350,000
Subtotal	**1,550,000**

Table 4.7 and Table 4.8 illustrate the need for abundant and accessible financial capacity. The two expenditure classes total over two million rand for the 2009 year end; this is excluding capital costs and salaries, which are likely to be considerably higher as the CCPOA have six full-time, highly qualified staff managing the development's urban water system (Lyons, 2011). Most of these costs would be externalised on the environment as part of conventional drainage systems; however, they have become the responsibility of the managers – the CCPOA (Liebenberg *et al.*, 2009; Taylor, 2003). Most prospective SuDS schemes in South Africa are likely to be smaller in scale than Century City, but will require prudent economic planning and/or restructuring to ensure the system has the financial capacity and human capital to function effectively in the long-term.

5. System analysis and discussion

The inception of SuDS in South Africa, illustrated in the Century City stormwater management investigation (Chapter 4), presents a likely shift in the stormwater management paradigm. In anticipation of this shift, this chapter briefly analyses critical aspects of the design and management of SuDS in Century City in an attempt to highlight some practical obstacles to their greater implementation in South Africa. Ineffective design approaches to three local control SuDS are briefly assessed, and an analysis of problematic management approaches to the Century City constructed wetland is presented using Systems Thinking (ST) theory.

5.1 Ineffective design approaches to SuDS

There are a number of SuDS options in Century City that are unable to operate optimally as a result of problematic design. For example, Figure 5.1 depicts a roadside rocky swale ending in a *Phragmites australis* (*P. australis*) reedbed. The swale is positioned at a high point relative to its immediate surroundings, thereby cutting it off from stormwater and the stormwater quantity and quality processes that it would typically provide. Figure 5.2 illustrates how a roadside curb and catchpit reduces the stormwater management potential of the rocky swale. During low flow conditions (< 15 mm/h) stormwater runoff is likely to run along the kerb and enter the stormwater pipe network via the cast iron catchpit, opposed to being conveyed to the reedbed or infiltrating into the ground via the swale. As a result, the *P. australis* that caps the rocky swale dries out and dies frequently (approx. every three months). Furthermore, Figure 5.3 (partly extracted from Appendix C of Appendix 1: Figure 4.5) illustrates that the swale requires a permanent micropool of water to function most efficiently due to the underlying perched aquifer in the area. The swale is 'starved' of this water as a result of its placement, which has significantly decreased the efficacy of the rocky swale. The swale is likely to, however, provide extended detention storage during high rainfall events (50 mm/h).

Figure 5.1: Rocky swale capped by a reed bed of *P. australis*

Figure 5.2: Roadside kerb and cast iron catchpit superseding swale

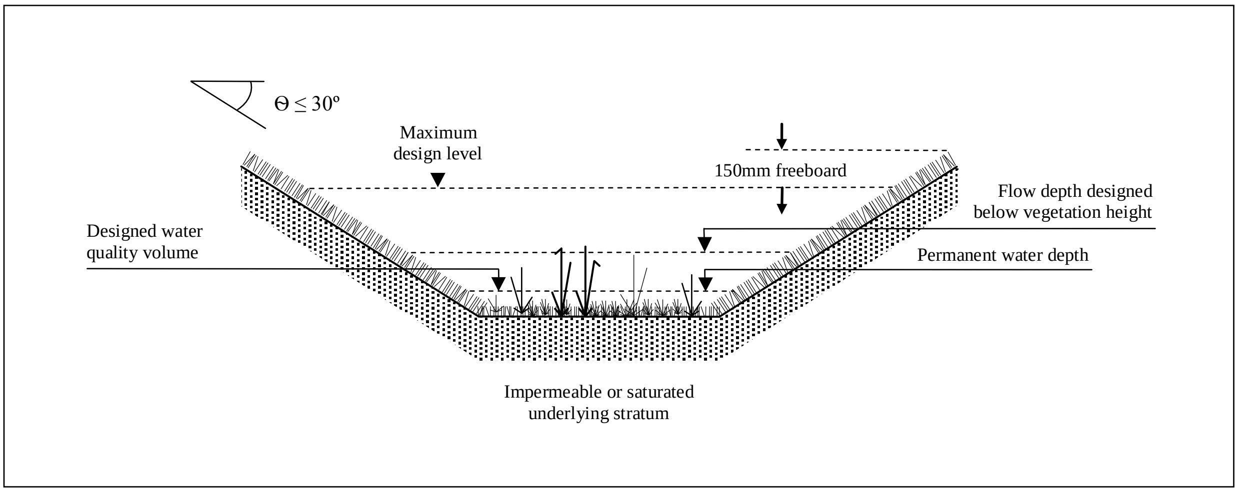

Figure 5.3: General design schematic for ‘wet’ swales (After Woods-Ballard *et al.*, 2007)

This problematic design example is not uncommon in the development; it does, however, expose a design flaw common to many SuDS options throughout Century City, namely, the ineffective ‘hydraulic routing’ of stormwater runoff. ‘Hydraulic routing’ is defined by the American Meteorological Society (2011) as, *“methods of flood routing that are based on the equation of continuity and various forms (extent of approximation) of the momentum equation of the flow.”* Rehman *et al.* (2003) suggest that hydraulic routing can also be understood as the routing of stormwater runoff to a preselected catchment outlet – with emphasis on the ‘routing’ or flow path of stormwater runoff opposed to the ‘catchment outlet’ structure. This common design flaw is further illustrated in the following two SuDS local control options. The first local control is a bio-retention area depicted in Figure 5.4. Its primary purpose is for traffic directing and/or calming as a traffic circle, but has also been designed to manage stormwater runoff by means of bio-retention (Liebenberg, 2011).

Figure 5.4: Bio-retention area featuring as a traffic circle

Figure 5.5: Topsoil, vegetation and wood mulch used in bio-retention area

It comprises topsoil, indigenous plant species such as Perennial and Geophyte groups, and wood mulch, which typically supplements the quantity and quality management of stormwater runoff (Figure 5.5). The bio-retention area in question is 29.0 m in diameter with a surface area of approximately 660 m^2. There are six bioretention areas with the same dimensions and vegetation characteristics in the development and five bioretention areas that are smaller, with approximately half this diameter and less than a third of the specified surface area. According to Figure 5.6 (partly extracted from Appendix C in Appendix 1: Figure 4.1), this particular bio-retention area has the potential to detain a maximum of 99 m^3 of stormwater runoff, with an additional capacity exceeding 100 m^3 in the subsoil stratum. However, due to the ineffective hydraulic routing of stormwater through the bio-retention area, this detention capacity is not accessible; therefore rendering this local control ineffective. The bio-retention area has a converse design to that of the general design schematic in Figure 5.6. Its 'convex' long-section prevents stormwater infiltration into the substratum and increases the likelihood of overland flow onto the adjoining pavement surface. In addition, with reference to the estimated pollutant removal table in Appendix B of Appendix 1: Table 2.6, the bio-retention area's capacity to remove 50-90% of heavy metals from the adjoining pavement surface will be underutilised due to its convex long-section that demotes typical infiltration and detention processes. The economic implications of this design include an increase in maintenance for vegetation upkeep, and an additional cost to remove sediment from the pavement surface after relatively high rainfall events (> 25 mm/h).

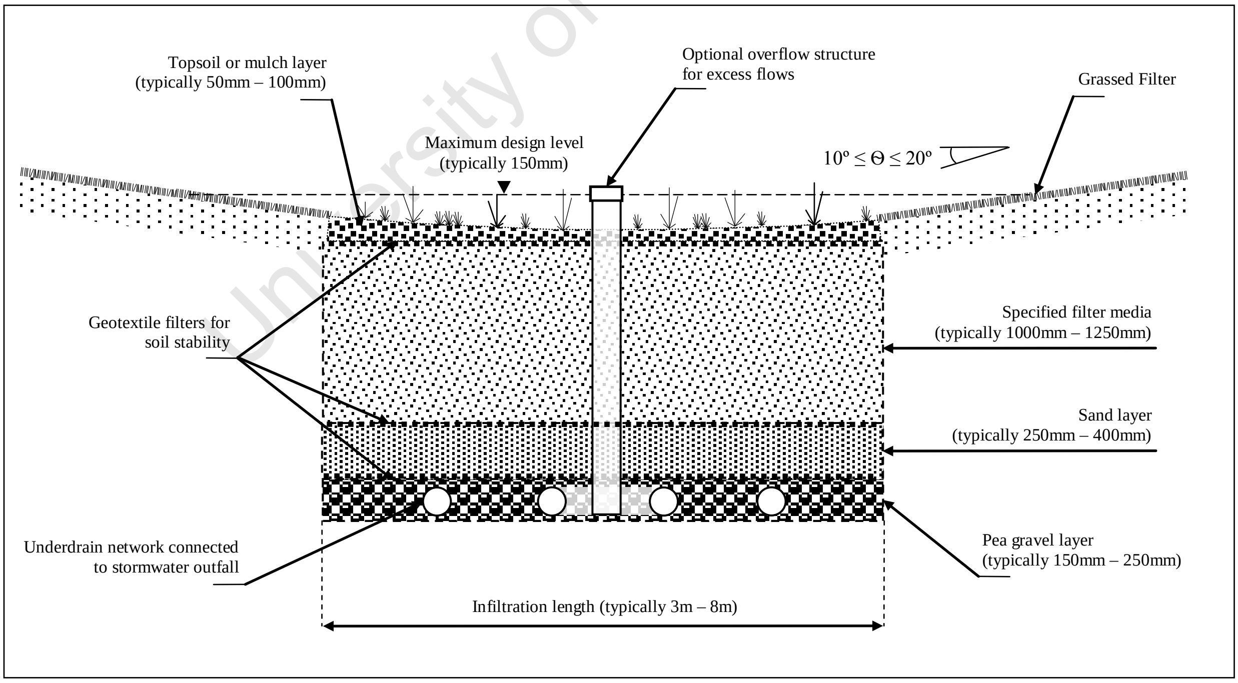

Figure 5.6: General design schematic for bioretention areas and underdrain network
(After Woods-Ballard *et al.*, 2007)

The final 'local control' example used to illustrate this flaw in design is a filter strip separating a dual carriageway in the northern section of Century City; depicted in Figure 5.7. The filter strip in question is 201.5 m in length, 5.1 m in width, and has a surface area of approximately 1030 m^2. According to Liebenberg *et al.* (2009), this particular filter strip has the potential to detain a stormwater runoff depth of approximately 20 mm over its surface area, which amounts to a detention capacity of approximately 20.6 m^3. There are 21 filter strips separating dual carriageways in Century City with similar average widths and varying lengths. In terms of stormwater runoff quality treatment, filter strips are typically used for the removal of TSS and hydrocarbons through primary processes of stormwater runoff interception and secondary processes of infiltration (Donovan & Naji, 2003). There is a sufficient grade on the roadway to support sheet flow across the pavement surface; however, the convex cross-section of the filter strip prevents these stormwater quantity and quality control processes. This design inefficiency is similar to that of the rocky swale depicted in Figure 5.1 and Figure 5.2. Stormwater runoff is obscured from running over the filter strip by a concrete lined kerb, and is channelled into a series of cast iron catchpits that line the pavement surface (Figure 5.8). Stormwater runoff from low to medium rainfall events (< 25 mm/h) enters the minor stormwater pipe network without any screening or treatment, and is directly discharged from the development into downstream environments.

Figure 5.7: Filter strip separating dual carriageway

Figure 5.8: Conventional cast iron catchpit situated at foot of filter strip

Hydraulic routing is a critical element of the design of SuDS options. Stormwater runoff correctly routed through source and local control SuDS can significantly reduce stormwater quantity and pollution loads on regional control SuDS and downstream environments. Although these particular SuDS local control options have been significantly ineffective relative to their typical stormwater management capabilities, they remain less harmful to the immediate environment than 'hard', conventional systems and provide increased amenity.

5.2 Problematic management approaches to SuDS

The following subsection analyses a number of problematic management approaches to the Century City constructed wetland using Systems Thinking (ST) theory. Hjorth & Bagheri (2006) propose that 'sustainability' and 'sustainable development' have been misunderstood by practitioners as 'project goals' that have 'end-states', which are likely to be achieved in fixed periods of time. It is this linear thinking – typically employed in the design of conventional drainage practices – that fails to adequately take into account the complex structures of environmental systems. The reoccurring errors and undesirable side effects that are frequently evident in the management of urban development generally reflect the inability of decision-makers to understand the underlying structure of the system in a holistic manner (O'Regan and Moles, 1997). Perhaps managers should consider enabling the principles of sustainable development using 'Systems Thinking', defined by Hjorth & Bagheri (2006) as, *"the art and science of linking structure to performance – often for purposes of changing structure (relationships) so as to improve performance."* This demonstrates a means of gaining a deeper understanding of the relationships between the parts of each system, as opposed to analyses of the properties of the parts in isolation. ST merges the economic, environmental, social, technical, political and institutional dimensions that govern or influence a system to provide a more universal basis for understanding and managing future change (Hjorth & Bagheri, 2006; Meadows, 1999). The management of the Century City constructed wetland can be usefully assessed using ST.

5.2.1 Effects of supplementary water supply

The supplementation of the treated sewage effluent in the constructed wetland began in December 2008. Figure 5.9 and Figure 5.10 display the piped infrastructure used to discharge the treated effluent into the wetland.

Figure 5.9: Treated effluent discharges beneath Cell 1 walkway

Figure 5.10: Treated effluent inlet into Cell 1

To date, this initiative has had a pronounced effect on the concentrations of phosphorous in the wetland's treatment cells. Recorded effluent data from the Potsdam WWTW for the period December 2008 to mid-January 2009 indicates that poor quality effluent was entering the wetland with particularly high phosphorous levels. Figure 5.11 displays a relative increase in Total Phosphorous (TP) and Ortho-Phosphorous (Ortho-P) in effluent from the Potsdam WWTW over this period.

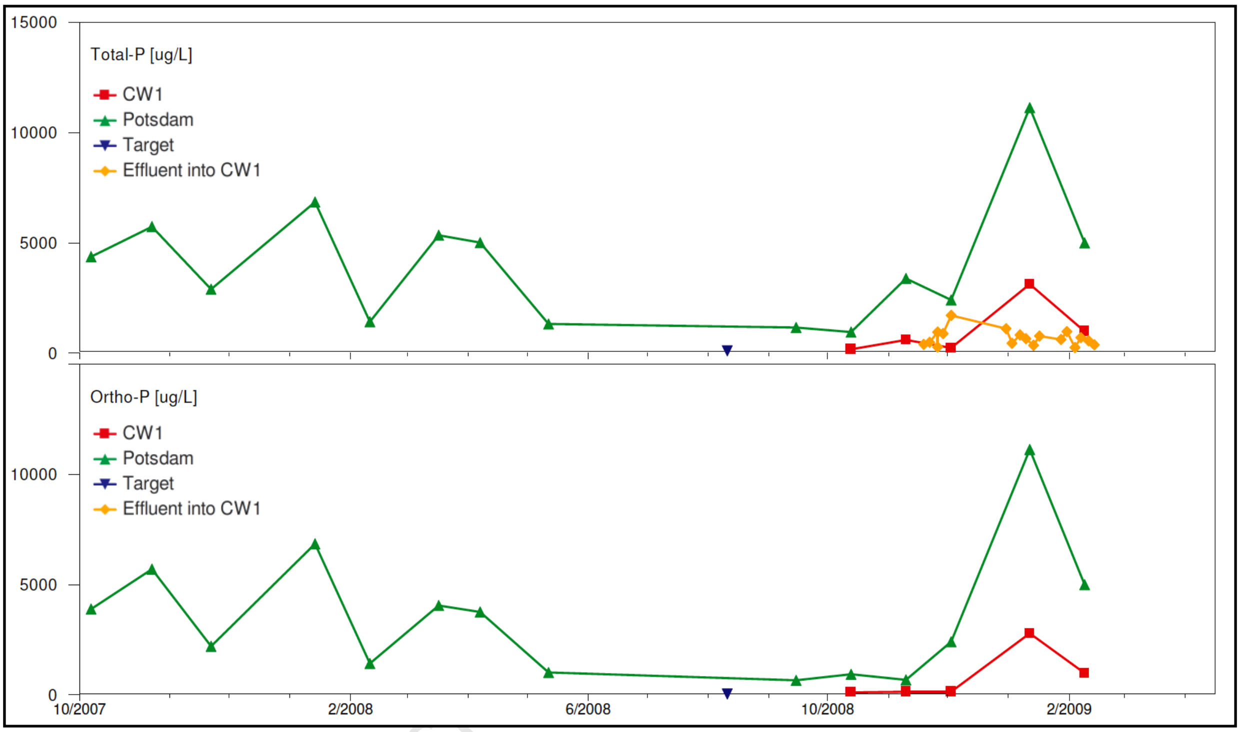

Figure 5.11: Total phosphorous and ortho-phosphate levels in effluent from Potsdam WTWW, and in the constructed wetland's (CW) treatment cells: CW 1 (Day, 2009b)

In 'Cell 1' the TP levels increased from approximately 300 – 3,100 µg/ℓ (1,033%), and orthophosphate (Ortho-P) levels increased from approximately 200 – 2,800 µg/ ℓ (1,400%). TP and Ortho-P levels in the wetland's other three treatment cells also increased rapidly over this period – as much as 500% in some instances (Day, 2009b). These significant increases in TP and Ortho-P are depicted graphically in Figure 5.12.

During the course of this same period a floating aquatic fern, namely *Azolla filiculoides* (*A. filiculoides*) multiplied and established itself in all four of the wetlands treatment cells, covering extensive areas of these water bodies (Figure 5.13 and Figure 5.14). The vegetative species is indigenous to South America and is listed as a 'Category 1' invader in South Africa in terms of the Conservation of Agricultural Resources Act, 1983 (Act 43 of 1983, amended 2001; Government Gazette, 1983).

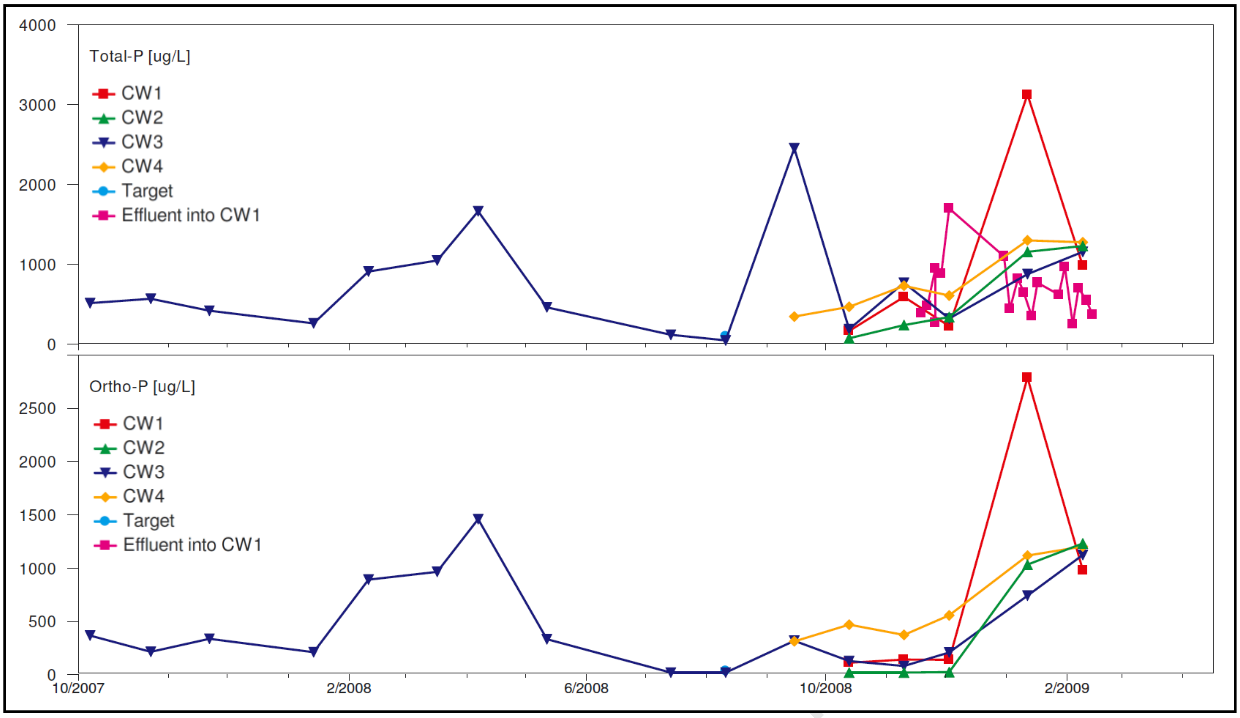

Figure 5.12: Total phosphorous and ortho-phosphate levels in the constructed wetland's (CW) four treatment cells: CW 1,2,3 and 4 (Day, 2009b)

This particular vegetative species thrives in warm, still and phosphorous-enriched water, and spreads rapidly over the surface of a water body by means of spores. It prevents the aerobic treatment of stormwater runoff as it smothers the surface of water bodies, significantly lowering local dissolved oxygen concentrations. Water quality data for the period mid-January to mid-February 2009 indicates that the quantity of dissolved oxygen (DO) in 'Cell 1' decreased from approximately 6.0 mg/ℓ to 2.5 mg/ℓ (58%). A rapid decrease in DO in the other three treatment cells was also observed in the months that followed. This species has a symbiotic relationship with blue-green algae, namely *Anabaena azollae* (*A. azollae*), frequently present in the upper part of each leaf (Day, 2009b).

The application of a bio-control agent such as the frond-feeding weevil *Stenopelmus rufinasus* (*S. rufinasus*) was considered the most effective intervention to remedy the spread of *A. filiculoides*. Application of the weevil in the Century City constructed wetland in the last quarter of 2008 eradicated the *A. filiculoides* from the affected water bodies within a month of its appearance, through cycles within *S. rufinasus* of rapid consumption and reproduction. During the course of the elimination of the aquatic fern however, there were concerns of organic enrichment that was likely to occur throughout the wetland's treatment cells and adjoining canal bed due to the decay of biomass (Day, 2009b).

Figure 5.13: ***A. filiculoides*** **covering wetland treatment Cell 1**

Figure 5.14: ***A. filiculoides*** **spreading rapidly over wetland treatment Cell 3**

Hjorth & Bagheri (2006) and Lems (2008) assert that with the joining together of the three dimensions of environment, economy and society, sustainable development presents the basis upon which natural resources can be saved from ruin, and environmental services can assist in the improvement of livelihoods and income. The wetland has been partly effective in appropriating these benefits. There have, however, been a number of problematic management approaches that have prohibited the delivery of environmental goods and services. In August 2009, Day (2009a) concluded that a number of these issues stemmed from the mismanagement of environmental complexities associated with the constructed wetland. Technically; there were hydraulic irregularities with water level fluctuations in the wetland that threatened to disrupt the hydraulic routing processes and cause undesirable ecological and environmental impacts in other parts of the development's urban water system. Environmentally; the variable quality of treated stormwater that discharges from the wetland, controls the impact on amenity and biodiversity value in the precinct and neighbouring developments. Poorly treated stormwater over an extended period of time has deleterious effects on environmental goods and services. Ecologically; the sewage effluent which supported the hydraulic requirements during the drier half of the year proved to be a major 'role player' in the slowing and prevention of cleansing processes within the wetland's treatment cells. High nutrient treated effluent has the potential to cause eutrophication in these water bodies, leading to ecological degradation throughout the adjoining urban water system.

5.2.2 'Systems Thinking' analysis

To reiterate, Systems Thinking (ST) may be used to gain a deeper understanding of complex system dynamics. In this example, ST tools are used to identify and assess problematic management approaches to the Century City constructed wetland over the period 2008/9. A principal 'system archetype' may therefore been constructed for the wetland, as depicted in Figure 5.15. It was developed to offer a baseline understanding of the links and interactions of each of these management interventions, and reveals the potential of unintended consequences that are likely to affect the system. An assessment of these interventions using ST tools illustrates the causal relationship between system management and the effects on the constructed wetland.

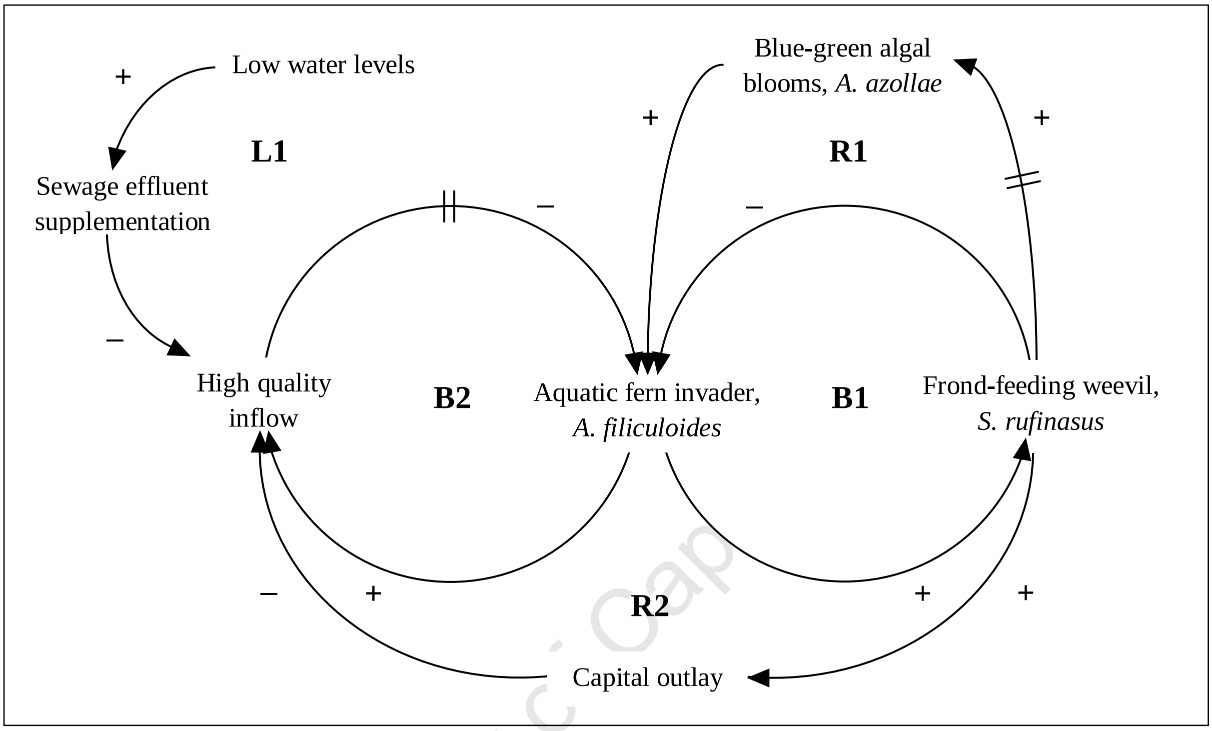

Figure 5.15: Primary archetype of management interventions carried out in the Century City constructed wetland over the period 2008/9.

'System archetypes' are typically behavioural patterns of a system, expressed as circles that represent the relationship between 'causes' and 'effects'. The identification of system archetypes in a system and the influence they attribute to the system, enable the possibility of change within the specified system. The principal system archetype in Figure 5.15 displays both diagnostic and prospective uses of system archetype theory in relation to management interventions in the constructed wetland. Diagnostically, it may be used to provide greater insight into the structure that already exists in the wetland system, to assess the likely performance of specific management interventions. Prospectively, it may be used to anticipate potential problems and/or problem symptoms that are likely to occur as a result of specific management interventions (Braun, 2002). The archetype presented in Figure 5.15 was constructed with the amalgamation of three fundamental system sub-archetype structures. The main sub-archetype is the 'Shifting the Burden' sub-archetype, characterised by 'Balancing Loop' 1 (B1), 'Balancing Loop' 2 (B2) and 'Reinforcing Loop' 2 (R2) (O'Regan and Moles, 2006). Braun (2002) describes the 'Shifting the Burden' sub-archetype as; *"...a problem* *symptom can be resolved either by using a symptomatic solution or applying a fundamental solution. It hypothesizes that once a symptomatic solution is used, it alleviates the problem symptom and reduces pressure to implement a fundamental solution, a side effect that undermines fundamental solutions."*

In light of this dynamic theory, management interventions and approaches to the Century City constructed wetland can otherwise be conceived as: **Balancing Loop 1**; the rapid spread and establishment of *A. filiculoides* (aquatic fern invader) increases the need for immediate maintenance interventions (+). *A. filiculoides* is virtually and/or temporarily eliminated from the wetland surface within a period of approximately four weeks (–), with the application of *S. rufinasus* (frond-feeding weevil) and infrequent maintenance practices (such as surface screening). **Balancing Loop 2**; once *A. filiculoides* is well established on the specified water bodies it, in turn, requires the input of high quality water (rich in dissolved oxygen) (+) to maintain its relatively high rates of respiration. The input of high quality water over a delayed period of time (||) however, acts as a fundamental preventative measure against the reproduction and/or regeneration of *A. filiculoides* (–) if the aquatic invasive has not established itself over the wetland's water bodies. **Reinforcing Loop 2**; the maintenance interventions and practices temporarily initiated to eliminate *A. filiculoides* increase the requirement for 'capital outlay' as well as increased vested interest (+). The accessibility of continued and seemingly inexhaustible financial support may result in a gradual and invariable deficiency in the implementation of more fundamental solutions (–), as opposed to more direct and attractive symptomatic solutions. Perhaps in this instance, a fundamental management solution would be to reduce the poor quality water discharging into the constructed wetland's treatment cells using additional onsite treatment processes.

The principal archetype displayed in Figure 5.15 also illustrates an interrelationship between the primary 'Shifting the Burden' sub-archetype and a partial 'Limits to Growth' sub-archetype. The 'Limits to Growth' sub-archetype characterised by 'Limiting Arm' 1 (L1), poses a partial limiting action on the primary archetype structure. Braun (2002) describes the 'Limits to Growth' sub-archetype as; *"...a reinforcing process of accelerating growth (or expansion) will encounter a balancing process as the limit of that system is approached. It hypothesizes that continuing efforts will produce diminishing returns as one approaches the limits."* There is always an element of a limited system that 'pushes back' and prevents unrestricted positive reinforcing behaviour. The partial 'Limits to Growth' sub-archetype may be conceived as: **Limiting Arm 1**; low water levels in the constructed wetland's treatment cells during the drier half of each year is provisionally alleviated with the supplementation of sewage effluent (+). This also aids in the balancing of predetermined water levels and improves the hydraulic control of stormwater entering the wetland. This however, results in a lack of high quality flow into and throughout the wetland's treatment cells (–), due to poor effluent qualities discharged from the Potsdam WWTW.

The final sub-archetype structure that contributes to the principal archetype structure (Figure 5.15) is the 'Fixes that Fail' sub-archetype. It is characterised by 'Balancing Loop' 1

(B1) and 'Reinforcing Loop' 1 (R1). Braun (2002) describes the 'Fixes that Fail' sub-archetype as; *"…a quick fix solution can have unintended consequences that exacerbate the problem. It hypothersizes that the problem symptom will diminish for a short while and then return to its previous level, or become even worse over time."* Accordingly, the 'Fixes that Fail' sub-archetype may be conceived as: **Balancing Loop 1**; the rapid spread and establishment of *A. filiculoides* (aquatic fern invader) increases the need for immediate maintenance interventions (+). *A. filiculoides* is virtually and/or temporarily eliminated from the wetland surface within a period of approximately four weeks (–), with the application of *S. rufinasus* (frond-feeding weevil) and infrequent maintenance practices (such as surface screening). **Reinforcing Loop 1**; an increase in the application of immediate, symptomatic solutions (+), and a lack of more fundamental solutions over an extended period of time (||), may result in a 'system-wide collapse' in the form of 'blue-green algal blooms' (*A. azollae*). The unintended consequences of symptomatically motivated maintenance further characterises mismanagement of the constructed wetland. In addition, this greatly increases the nutrient supply in the wetland's treatment cells, increasing the likelihood of *A. filiculoides* growth (+).

Balancing mechanisms that control the destructive potential of undesirable positive reinforcing loops should be maintained to ensure the sustainable operation of the constructed wetland (Parkinson *et al.*, 2007; Meadows, 1999). It is evident that the institution of symptomatic maintenance practices to address stormwater treatment issues in the Century City constructed wetland was comparatively short-sighted, by failing to consider the complexities embedded in environmental systems. Perhaps, the dynamic tension between the symptomatic and fundamental solutions, both of which present potential remedies to problems in this constructed environment, should be considered by management. Fundamental solutions, such as a reliable and high-quality input water source, are likely to benefit the constructed wetland in the long-term – over its design life.

5.3 Remedial interventions

There have been two major remedial measures carried out in the wetland over the past two years (2010/11). In order to remedy the increase in phosphorous throughout the treatment cells of the constructed wetland the treated effluent inflow from the Potsdam WWTW was discontinued in early 2009 (Century City Life, 2011). The decision to stop the inflow was informed by the results of annual maintenance procedures that were carried out at the constructed wetland's pump station. At such time, a detailed study was performed on the depth of the water table beneath Century City. The treated effluent input was supplementing the constructed wetland with approximately 100 mm – 150 mm of additional water depth. This input was essential during the dry summer seasons. The water table study (Day, 2011) revealed that by ceasing the input of treated effluent there would be no drastic effects on water level fluctuations in the wetland and the adjoining urban water system. The accuracy of this decision has been reviewed over the past two summer seasons, but it is inconclusive whether this intervention has been successful due to two major leakages in the system that supplemented the water table throughout the development. The leakages were identified by Dr. Liz Day from the FCG and have since been repaired. Having remedied these problems, the first test for the fluctuation in the water level in the wetland will come in the summer season of 2011/12. Treated effluent from Potsdam is still pumped to a regional reservoir in Century City twice a week (typically every Wednesday and Saturday), and is used for irrigation purposes throughout the development, particularly in the residential areas for lawns and flowerbeds (Liebenberg, 2011). According to Day (2011), the ceasing of the input of treated effluent in the constructed wetland has rapidly reduced the phosphorous levels in the wetland. This supports the 'Shifting the Burdens' sub-archetype depicted in Figure 5.15, which endorses the input of 'high-quality inflow' as a fundamental means of preventing floating aquatic invasives such as *A. filiculoides*.

The second major remedial measure was the targeting of bird faeces in Cell 3. There have been no studies performed on the exact increase of phosphorous in the water bodies as a result of the bird faeces, but there is sound international evidence to suggest that bird faeces cause undesirably high levels of phosphorous in water (Day, 2011; Day, 2010a,b). This problem has been addressed by decreasing the number of heronries from five to three through technical restructuring measures, and by constructing each of the newly formed heronries on sludge collection sumps. Two heronries sit on 20,000 ℓ uPVC tanks that are submerged in the water, and the third heronry rests on a square reinforced concrete wall that is also submerged. According to the Senior Environmental Manager of the wetland, Mr. Alan Liebenberg, this specific measure neutralised the increase in phosphorous throughout the wetland by hydraulically isolating bird faeces in the third treatment cell. The sludge that forms in the bottom of the sumps is subsequently pumped out of the sumps every three months. Water quality measurements and visual evidence suggests that the wetland is functioning far better in 2011 than it had been in 2008 (Century City Life, 2011). Figure 5.16 and Figure 5.17 illustrate the extent to which the *A. filiculoides* spread across the constructed wetland's treatment cells in 2008, and the efficacy of fundamentally-oriented management interventions, respectively.

Figure 5.16: The prevalence of *A. filiculoides* in the constructed wetland, 2008

Figure 5.17: The efficacy of fundamental management interventions, 2009

5.4 Shifting stormwater management paradigms

The analysis of the Century City constructed wetland demonstrates that the mindset and approach underpinning the development of SuDS is immeasurably different to that which underpins the development of conventional drainage practices. Where conventional drainage systems focus on linear and/or mechanistic management interventions, SuDS require holistic management approaches that typically include processes of evaluation and change as illustrated in the ST analysis of the development's constructed wetland. The analysis shows that the efficiency of environmentally-oriented systems typically requires more frequent and intensive monitoring than 'hard', conventional drainage infrastructure such as catchpits, pipes and culverts. Furthermore, the analysis illustrates that the efficacy of even simple management interventions should be regularly monitored in order to curb undesirable consequences. Once the FCG had garnered a better understanding of the functioning of the constructed wetland, the CCPOA were able to make changes to their management approaches to increase the stormwater cleansing benefits of the wetland. In order to enable the ideals of sustainable development in the upkeep of the constructed wetland, the managers needed to focus on fundamentally-oriented management interventions. Perhaps the greatest element of the shift to a sustainable drainage paradigm in South Africa will be the management of environmental complexity.

Another likely pitfall in the development of SuDS in South Africa is the isolation of SuDS options from conventional drainage infrastructure. Neither urban drainage approach can be seen as a completely separate entity. The investigation of Century City's stormwater management system (Chapter 4) illustrated that there are many components of conventional drainage infrastructure that should be amalgamated with natural systems to enhance the stormwater management potential of SuDS. Examples of these components include:

- Pipes used to control flow between source, local and regional controls such as those typically used between bio-retention areas, swales and detention ponds;
- Cast iron grids and catchpits constructed as simplified flow spreaders to restrict channel erosion and siltation in the canal network;
- Trash racks to prevent litter from entering the urban water bodies in Century City; and
- Concrete kerbs used to channel stormwater runoff into pocket wetlands, bio-retention areas and infiltration basins.

Therefore the institution of SuDS should not simply be the implementation of completely nature-mimicking systems and the subsequent abolishment of conventional infrastructure, but should be the creation of a sustainable constructed environment – equally beneficial to humans and the surrounding environment.

6. Conclusion

The stormwater management system at Century City is among the most advanced SuDS schemes in the country that has been researched as part of the WRC project *K5/1826: Alternative technology for stormwater management*. It is advanced particularly in terms of its age and management approaches, yielding a number of important lessons for the prospective development of SuDS in South Africa.

Planning is a critical element of effective SuDS schemes. In the planning phase of Century City's stormwater management, the institution of the Blouvlei Environmental Management Plan (EMP) promoted efficient and well structured management approaches to support the health and vibrancy of the development's urban water system, biomass and biodiversity, and adjoining natural water ecosystems. In addition, a key aspect of the original planning phase was the integration of society with the development's waterways to create a sustainable constructed environment. This part-urban, part-natural setting was utilised to, *inter alia*, provide economic investment opportunities, support socio-economic development, cultivate resilient natural habitats, and facilitate primary and tertiary education and research. The planned SuDS options for the development adhered to these objectives by supplying functional environmental goods and services.

An assessment of the implementation and modelling phase revealed the shortfalls of an inconsistent developmental approach to stormwater management infrastructure. The successive implementation of conventional drainage infrastructure, SuDS options in isolation, and SuDS treatment trains – over a period of fifteen years – proved to be problematic. This 'transitional drainage system' posed particularly complex environmental and technical challenges, such as the provision of additional storage capacity and extended detention in the existing urban water bodies in the event of flooding. The 'low flow' system comprising 'source' and 'local' control SuDS is particularly effective in managing 'first flush' flows and volumes. However, many SuDS options had been incorrectly implemented and functioned ineffectively as a result. This was illustrated by a number of infiltration-oriented SuDS options implemented in areas that cannot receive runoff from the adjoining impervious surfaces. To some extent, this testifies to the disparity between the theory of SuDS and its practical application. The implemented system also pioneered the planting of suitable vegetation species for the operation of SuDS and treatment of stormwater runoff. Indigenous plant species were favoured throughout Century City due to their resilience in prolonged periods of climatic extremes, which proved to be an effective initiative (Liebenberg, 2011; Lyons, 2011).

The operation, monitoring and maintenance phase illustrated a number of useful as well as restrictive management interventions employed by managers in Century City. The environmental systems in Century City, such as selected SuDS options, required frequent monitoring to assess water quality as well as the vibrancy of biomass and biodiversity. This was a stringent specification of the development's EMP. It is clear from the investigation that the management requirements of conventional drainage infrastructure are less demanding than those of SuDS – as they are typically vegetated systems which require frequent attention in order to function optimally. If the maintenance of SuDS options is neglected, even temporarily, they are likely to fail and spur failure elsewhere in the associated system. Hence, the intensive management requirements of SuDS options are likely to be the greatest contention in the shift of the stormwater management paradigm in South Africa.

Flaws in management were present throughout the development's urban water system, represented in the 'Systems Thinking' (ST) analysis of management interventions in the constructed wetland. The ST example details a new approach to analysing the complexities associated with environmental systems such as SuDS. The development of a simplified three-part system archetype exhibited the 'diagnostic' and 'prospective effects' of management interventions in the wetland, and illustrated the benefits of a shift from fragmented maintenance sciences to 'holism'. Enabling principles of 'sustainable development' in the design and management of SuDS options, particularly constructed wetlands, should not be viewed as attainable targets, but as holistic processes of adaption and change (Hjorth & Bagheri, 2006). The remedial interventions demonstrated that the yielding of linear and mechanistic thinking, and the endorsing of non-linear and organic thinking, brought about a more desirable water quality state in the constructed wetland. The assessment also emphasised the benefits in understanding the relationships between the environmental components, as opposed to analyses of the components in isolation. The dynamic tension between symptomatic and fundamental solutions should readily be considered by management; symptomatically-oriented solutions are likely to be destructive, whereas fundamentally-oriented solutions are likely to enhance the performance of SuDS.

Brown (2007) suggests that globally, the post-2000 challenge of 'sustainability' is to create greater economic and social returns from infrastructure projects which are designed to protect and improve the environment and public health. With reference to the nineteen SuDS case studies performed in 2009 and the successes exemplified in the Century City case study, it is evident that a number of developers have embraced the socio-economic and environmental benefits of SuDS. Perhaps, however, a greater catalyst is required to introduce and establish SuDS practices in the South African urban environment on a much larger scale. This is likely to be achieved with the institution of WSUD principles and SuDS practices in local policy documents, national guidelines, and compliance-related benchmarks. Shifting paradigms from conventional towards sustainable systems in South Africa will require the restructuring of economic, technical, social, environmental, political and institutional dimensions of urban drainage, to meet the ideals of sustainable development. In affirmation, Jefferies *et al.* (2008) comments that the procedures that should be followed to satisfy regulatory requirements as to the instilling of SuDS practices, will undoubtedly become more relevant as national, provincial and local legislation is geared towards principles of 'sustainable development'. Hence, an objective of the South African Guidelines for SuDS (Appendix 1) and the SuDS Conceptual Design Poster (Appendix 2) is to advocate these principles in the government sector.

7. Recommendations for further research

The purpose of this chapter is to offer recommendations for prospective research into the development of SuDS in South Africa. Due to the destruction of natural ecosystems as a result of mismanaged urban stormwater, there is likely to be a rapid increase in research that explores the applicability of SuDS countrywide. In light of this, and with reference to the Century City case study and proposed SuDS Guidelines, there is potential for the following research according to the fundamental elements of sustainable development stipulated by Pieterse (2010):

i) Economic

According to ASLA (2008) there are eight principal environmental goods and services (EGSs) which can be appropriated through the implementation of SuDS. These include, *inter alia*; regulated climate, water and air purification, erosion and sediment control, hazard mitigation, and habitat functions. However, the economic benefits and/or potential for increased revenue with the appropriation of these EGSs are less known. There is room to assess and define the economic and fiscal relationship between EGSs and specific SuDS options.

ii) Environmental

SuDS promotes a paradigm shift in stormwater management from 'fast-conveyance' systems to more holistic, self-sufficient systems (Brown, 2007). However, the environmental dynamics of SuDS poses many complex management challenges. Several environmental complexities were highlighted for the Century City constructed wetland. There is potential to identify and analyse the underlying environmental complexities associated with other source, local and regional control SuDS.

iii) Social

Brown (2007) and Mays (2001) suggest that, to effectively transition from 'hard' engineering solutions for urban drainage towards those that restore and mimic the natural predevelopment state, practitioners should increasingly rely on the most dynamic force in the urban landscape – its human inhabitants. There is potential for researchers to analyse the effectiveness of verbal and visual communication tools used to increase public stakeholder participation and education regarding the development and management SuDS options. Another undefined social research area is the assessment of the interaction, organisation and communication of human capital to increase the efficacy of interdisciplinary partnerships in SuDS schemes.

iv) Technical

In transitioning towards SuDS, the technical tools of conventional drainage practices, such as hydrological equations and graphs, should not be discarded altogether. These are particularly useful in the quantification of SuDS treatment train configurations, and should be partly integrated to increase drainage performance. Technical decision support systems (DSSs) such as the DayWater DSS or STTAT are effective in combining conventional drainage knowledge and principles of environmental preservation to render the most effective SuDS treatment train configurations. A significant contribution to technical SuDS literature would therefore be the development of similar technical DSSs to assist urban practitioners and other decision-makers in the implementation of SuDS options and treatment trains in South Africa.

v) Political and institutional

The political and institutional dimension of sustainable development refers to the importance of governance systems in guiding the relationship between different stakeholders for the appropriation of the other four dimensions (Pieterse, 2010). Meadows (1999) affirms that governance is one of the most effective "places to intervene" in a system. This presents a research opportunity to review procedures to institute WSUD principles and SuDS practices in local policy documents, national guidelines, and compliance-related benchmarks. In relation to these regulations and guidelines, the potential for a stormwater 'utility bill' could be assessed. Theoretically, a public 'utility bill' for stormwater management should provide the monetary capacity to endorse SuDS schemes countrywide.

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Appendix 1

South African Draft Guidelines for SuDS

Note to reader:

The author compiled the following guidelines for the planning, design and management of SuDS in South Africa. The guidelines are a deliverable of the WRC project K5/1826: Alternative technology for stormwater management. The guidelines were published as a draft copy in March 2011 and disseminated throughout South Africa between March and May 2011 in the form of a SuDS Resources DVD (version 10). Urban practitioners attending SuDS workshops in Cape Town, Johannesburg, Tshwane, George, and eThekwini, received the DVD and were encouraged to provide feedback for the contents therein. Appendices D, E and F of the guidelines were compiled by Mr. Lloyd Fisher-Jeffes and have therefore been omitted from this dissertation.

The South African Draft Guidelines for Sustainable Urban Drainage Systems (SUDS)

Disclaimer:

These draft guidelines are being developed as part of the requirements of the Water Research Commission of South Africa (WRC) project K5/1826: Alternative technology for Stormwater Management. Any use that might be made of the information contained herein is at the risk of the user. Neither the WRC nor the authors take any responsibility for any loss of life or damage of property that might result from the use of these draft guidelines.

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Glossary of Terms

Abstraction is the portion of rainfall that does not contribute to runoff typically including, interception, infiltration and storage in local depressions.

Absorption refers to the taking up of one substance into the body of another. i.e. stormwater runoff taken up into a plant.

Aerobic is the state requiring or allowing the presence of free essential oxygen.

Anaerobic is the absence of free elemental oxygen, or a state not requiring or damaged by the absence of free elemental oxygen.

Annual exceedance frequency refers to the frequency that a particular flood level may be expected to occur once per year.

Annual probability of exceedance is the statistical probability of a hydrological rainfall event of a given magnitude being equalled or exceeded in any given year.

Aquifer is a porous, water-logged subsurface geological formation generally restricted to mediums capable of yielding a substantial supply of water.

Attenuation means the reduction of peak stormwater flow.

Berm is a raised horizontal mound or shelf constructed an embankment to intercept the continuity of a long slope, for the reduction of erosion or the increase in the embankment size.

Biodegradation is the degradation of organic pollutants in stormwater runoff by microbes.

Bioretention area is a depressed landscaping area that collects stormwater runoff so that it infiltrates into the soil below the area, thus prompting pollutant removal.

Block paver is a precast concrete or clay brick sized flexible modular unit.

Brown-field means a site or land that is or was occupied by a permanent structure, which may have become vacant, under-used or derelict and has the potential for redevelopment.

Buffer strip is a vegetated area of gently sloping ground designed to drain water evenly off impermeable areas and filter out insoluble pollutants. It is also known as a filter strip.

Catchment means the area from which any rainfall will drain into a watercourse or wetland, through surface flow to a common point or common points.

Channel is a natural or artificial watercourse through which a body of water flows periodically or continuously or forms connecting links between other bodies of water.

Check dam is a low and fixed weir or dam that lies across a drainage channel to retard or reroute flow from a channel, ditch or canal, for the purpose of erosion or scour reduction.

Climate change is a continuous phenomenon and refers to the change in global climatic conditions, e.g. as a result of temperature increases due to anthropogenic emissions.

Confined aquifer is an aquifer which is enclosed by formations that are less permeable or impermeable media.

Contamination refers to the introduction of microorganisms, factory produced chemicals, or wastewater in concentrations that deem water unsuitable for most human uses.

Conveyance is the transfer of stormwater runoff from one location to another.

Critical duration is the length of rainfall event that typically results in the greatest rate of flow, flood volume or flood zone level at a specified location.

Degradation refers to the general and progressive lessening of stream or channel profiles, or earth's surface, due to long-term periods of water induced erosion and/or scour.

Depression storage refers to precipitation stored in surface depressions.

Design probability of exceedance is the selected probability of exceedance of a particular event being equalled or exceeded for a drainage system or a component thereof.

Design period is usually the length of time a structure or asset will be expected to have a useful life, or the amortisation period if loans have been procured to finance the construction of the structure or asset.

Design storm encompasses the properties of a selected storm, which include the depth, spread and duration of the rainfall as well as variations in rainfall intensity in space and time over the catchment area during the storm.

Detention pond is a depression that is normally dry except following larger storm events when it stores stormwater on a temporary basis to attenuate flows. It may allow infiltration of stormwater into the ground.

Development means any man-made change to property including, but not limited to, the construction or upgrading of buildings or other structures, paving, municipal services, etc.

Drainage is commonly referred to as one of the following: (1) the removal of excess groundwater or surface waters by gravity or pumping; (2) the behaviour in which waters are removed from an area; (3) the area from which water bodies are removed; or (4) the general flow of all liquids under the force of gravity.

Drainage area is that part of a catchment above a specified point that contributes to the runoff at that point.

Drainage corridor is an area usually extending on either side of the centreline of a watercourse along its longitudinal length, including; vleis, wetlands, dams or lakes, that can be linked to the conveyance of runoff.

Drainage system refers to the network comprising drains, hydraulic control structures, levees, and pumping mechanisms that drain land or protect it from potential flooding.

Drawdown is the lowering of the surface level of a water body as a result of the withdrawal of water, typically in the case of groundwater tables, ponds or wells.

Dry pond is a detention pond that remains dry during dry weather flow conditions.

Dry weather flow means flow occurring in a water course not attributable to a storm rainfall event. Dry weather flows do not fluctuate rapidly.

Effluent is generally wastewater that flows from a process or confined space that has been partially or completely treated.

Evapotranspiration means the evaporation from all water, soil, snow, ice, vegetation and other surfaces plus transpiration of moisture from the surface membranes of leaves and other plant surfaces.

Event probability is the probability of a particular threshold being equalled or exceeded by the associated rainfall event.

Extended attenuation storage is the retention of stormwater runoff to protect receiving watercourses in the event of flooding, if long-term storage and additional infiltration are not feasible onsite.

Filtration, also referred to as biofiltration, means the filtering of stormwater runoff pollutants that are conveyed with sediment by trapping these constituents on vegetative species, in the soil matrix or on geotextiles.

Flood means a temporary rise in water level, including ground water or overflow of water onto land not normally covered by water.

Floodplain means the area susceptible to inundation by larger rainfall events.

Floodplain fringe is that area in a river defined as being below the level reached by the regional maximum flood and above the level reached by normal flow.

Flood zone or floodway means the area inundated by the regional maximum flood (RMF).

Freeboard means the vertical distance from the water surface to the top of a confining structure, usually a wall and/or gate.

Gabion is a rectangular shaped steel wire basket that is generally filled with rock for embankment protection and flood control.

Geotextile is a textile or plastic fabric designed to separate different fill materials, which is normally relatively permeable.

Green-field means a site or land such as parkland, open space and agricultural land which has previously been undeveloped.

Green roof is roof on which plants and vegetation can grow. The vegetated surface provides a degree of retention, attenuation, temperature insulation and treatment of rainwater.

Gross pollutants are waste items generally larger than 10 mm in diameter, which typically include; plastics, cardboard packaging, metals, plastic and glass bottles, paper products, and organic material.

Hydrograph is a plot of discharge or runoff relative to time.

Hydrology refers to the physical, chemical and physiological sciences of the water bodies of the earth and the interaction to the life thereon, which includes: occurrence, distribution, circulation, precipitation, surface runoff, stream-flow, infiltration, storage and evaporation.

Hyetograph is a plot of rainfall relative to time.

Hydraulic roughness is a composite of the physical characteristics that influence the flow of water across the ground, whether natural or channelized.

Impervious surface is land where water cannot infiltrate into the subsurface but is conducted by gravity on the surface as overland flow. Roads, parking lots, sidewalks and rooftops are typical examples of impervious surfaces in urban areas.

Infiltration is the process of runoff penetration into the Earth's surface and flow through the upper soil surface.

Infiltration device is a SUDS element designed to aid infiltration of surface water into the ground.

Infiltration trench is a trench that is usually filled with granular material designed to promote infiltration of surface water to the ground.

Interception refers to precipitation stored on vegetation as opposed to rain stored in surface depressions (termed depression storage).

Lag time is defined as the time from the centroid of the excess rainfall to the peak of the runoff hydrograph.

Long-term storage is the volumetric control of stormwater runoff in a specified infiltrating area that will drain very slowly.

Major drainage system is a stormwater drainage system which caters for severe, infrequent storm events, to prevent fatalities and minimise damage to property.

Minor drainage system is a stormwater drainage system which caters for frequent storms of a minor nature, to minimise inconveniences.

Nitrification is the oxidisation of ammonia and ammonium ions in stormwater runoff by microbial factions to form nitrite and nitrate.

Non-structural measures are planning, institutional and pollution prevention practices designed to prevent or minimise pollutants from entering stormwater runoff and/or reduce the volume of stormwater requiring management.

Overland flood escape route is an area over which stormwater in excess of the capacity of a stormwater system will flow to safeguard property from flooding.

Perennial stream is a watercourse that flows continuously for all or most periods of the year.

Permeability refers to the ability of a material to allow water to flow through when fully saturated and subjected to an unbalanced pressure.

Peak discharge (also known as 'peak flow') is the maximum rate of flow of water passing a given point during or after a rainfall event.

Photosynthesis means the breakdown of organic pollutants in stormwater runoff through extended exposure to ultra-violet light.

Plant-uptake is the removal of stormwater runoff nutrients and metals through uptake by plants.

Polish means to provide additional treatment.

Porous asphalt is an asphalt surface that is pervious, with open voids to allow water to pass through.

Precipitation is the water received from atmospheric moisture as rainfall, hail, snow or sleet, normally measured in millimetres according to depth.

Rainfall excess is the additional water that produces runoff after interception, depression storage, and infiltration have been satisfied.

Rainwater harvesting is the direct capture of stormwater runoff, typically off rooftops, for supplementary water uses onsite.

Receiving waters are natural or man-made aquatic systems which receive stormwater runoff e.g. watercourses, wetlands, canals, estuaries, groundwater and coastal areas.

Recurrence interval or return period is the average interval between events exceeding a stated benchmark. The recurrence interval is usually expressed in years and is the reciprocal of the annual probability. That is, the event having an annual probability of occurrence of 2% (0.02) has a recurrence interval of 50 years. This does not imply that such an event will occur after every 50 years, or even that there will necessarily be one such event in every 50 years, but rather that over a much longer period (like a 1,000 year period) there will be approximately 20 events of equal or greater magnitude (1000/20 = 50 years).

Retention pond is a pond-like structure where runoff is detained for a sufficient time to allow settlement and possibly biological treatment of some pollutants.

Retrofitting means the process of modification or installation of additional or alternative stormwater management devices or approaches in an existing developed area in order to achieve better management of stormwater.

Return period is the average time interval of hydrological event occurences of a given or greater magnitude. The interval is normally expressed in years.

Riparian refers to anything that is situated next to or adjoining the embankment of a watercourse or other water bodies.

Riprap refers to stone or blocks, which are intentionally placed along the embankment of watercourses to minimise the potential for erosion.

Runoff generally refers to the excess water that flows after precipitation.

Scour refers to the movement of solid material due to the forces of flowing water.

Sedimentation is the deposition of soil particles that have been carried by flowing waters, typically during flood peaks, as a consequence of a decrease in the velocity of flow below the minimum transportation velocity.

Sheet flow is runoff over a relatively flat or flattend surface.

Soakaway is a subsurface structure that is designed to promote infiltration into the ground.

Source controls are non-structural or structural best management practices to minimise the generation of excessive strormwater runoff and/or pollution of stormwater at or near the source.

Spillway is a waterway adjoining ponding areas or other hydraulic structures, used for the routing of excess water.

Stormwater is water resulting from natural precipitation and/or accumulation and includes rainwater, groundwater and spring water.

Stormwater attenuation pond is a facility which temporarily stores excess stormwater runoff with the intention of reducing the flood peak.

Stormwater outfall is the point at which runoff discharges from a conduit.

Stormwater runoff refers to the portion of rainfall which flows to the surface drainage system.

Stormwater system is constituted by both the constructed and natural facilities including: stormwater pipes, canals, culverts, overland escape routes, ‘vleis’, wetlands, dams, lakes, and other watercourses, whether over or under public or privately owned land, used or required for the management, collection, conveyance, temporary storage, control, monitoring, treatment, use and disposal of stormwater.

Structural measures/controls are permanent, engineered devices implemented to control, treat or prevent stormwater pollution and/or reduce the volume of stormwater that requires management.

Subdrain is generally a drain-type structure that is implemented beneath lined conduits such as sewers, stormwater networks, canals, or roadways, to manage groundwater flows in order to mitigate potential damage to property.

Subsurface runoff is the flow derived from water infiltrating the soil and flowing laterally in the upper soil strata. It usually reaches the receiving streams or bodies of water fairly soon after a rainfall event without joining the main body of groundwater (referred to as 'interflow').

SUDS is the abbreviation for sustainable drainage systems or sustainable (urban) drainage systems, which are a sequence of management practices and/or control structures or technologies designed to drain surface water in a more sustainable manner than conventional techniques.

Surface runoff is that part of the runoff that travels over the ground surface and in channels to reach the receiving streams or bodies of water.

Sustainable development means development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

Swale is a shallow vegetated channel designed to conduct and retain water, but may also permit infiltration. The vegetation assists in filtering particulate matter.

Time of concentration is the time required for water to flow from the most hydraulically remote point of the basin to the point/location of analysis.

Treatment train is a combination of different methods implemented in sequence or concurrently to achieve best management of stormwater. These methods include source control, non-structural and structural measures.

Volatilisation is the conversion of stormwater runoff compounds to gas or vapour typically as a result of heat, chemical reaction, a reduction of pressure or a combination of these.

Watercourse means a river, stream, channel, canal or other visible topographic feature, whether natural or constructed, in which water flows regularly or intermittently including any associated storage and/or stormwater attenuation dams, natural vleis or wetland areas.

Watercourse edge means the top edge of a discernable bank or canal in the case of natural and constructed watercourses respectively. Where an edge is not readily discernable, the extremity of the area susceptible to inundation by the 1:2 year storm is often deemed the watercourse edge.

Watershed is the upper boundary of a specified catchment area for rainfall that contributes to a given drainage area.

Water pollution incident means an occurrence that has the potential of prejudicing the quality of water in the stormwater management system or threatening public health or safety.

Water quality volume is the volume of runoff which requires water quality treatment in order to reduce/remove a specified percentage of pollutants.

Water table is the upper most level of the zone of saturation below the Earth's surface, except where this surface is formed by an impermeable body.

Weir is a relatively small dam-type structure across a waterway used to divert flow, reduce erosion and/or measure flow volumes.

Wetland means land translational between terrestrial and aquatic systems where the water table is usually at or near the surface, or is periodically covered with shallow water, and which land in normal circumstances supports or would support vegetation typically adapted to life in saturated soil. This includes water bodies such as lakes, salt marshes, coastal lakes, estuaries, marshes, swamps, 'vleis', pools, ponds, pans and artificial impoundments.

Whole Life Cost means to estimate the present day value of total costs of a structure throughout its likely operating life.

1. Introduction to SUDS

There has been growing interest in the promotion of sustainable development amongst governments and local municipalities throughout the world – and this includes the control of stormwater runoff (Ellis, *et al.* 2006). Sustainable Urban Drainage Systems (SUDS) offer an alternative approach to conventional drainage practices by attempting to manage surface water drainage systems holistically in line with the ideals of sustainable development. They achieve this by mimicking the natural hydrological cycle, often through a number of sequential interventions in the form of a 'treatment train' (Figure 1.4). The key objectives of the SUDS approach are the effective management of stormwater runoff quantity, quality and the associated amenity and biodiversity of the urban drainage system. The relationship between each of these elements is represented in Figure 1.1.

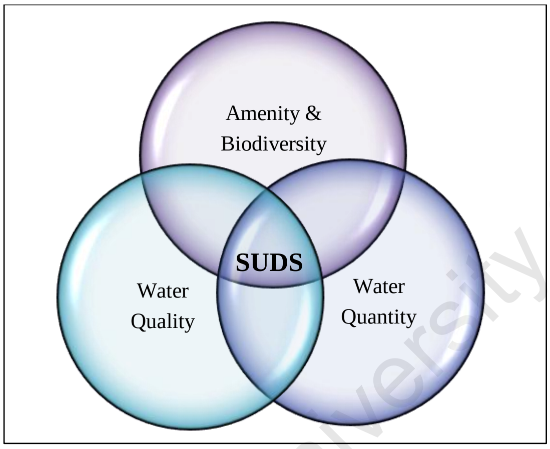

Figure 1.1: Relationship between the different SUDS elements

Prior to the design of any stormwater system there are a number of important considerations including:

- Variations in the hydrological cycle and associated systems;
- Varying geological formations and associated systems;
- Differences in the rational approach to urban drainage within professional teams;
- The different challenges of development on green-field versus brown-field / retro-fitted sites;
- The impact of different types of settlement and social inequality in particular; and
- The influence of any existing laws, ordinances or bylaws.

Whilst each of these will be mentioned in these guidelines they are largely outside the scope of the document which is focused more on the available technology options. Section 1 introduces the notion of sustainable drainage and describes important design and management concepts associated with SUDS. Section 2 describes the basic design approach. Sections 3, 4 and 5 present twelve general SUDS options and technologies in the categories of 'Source Controls', 'Local Controls', and 'Regional Controls' respectively. Appendix A presents a simplified SUDS conceptual design framework. Appendix B presents the expected pollutant removal for various SUDS options. Appendix C presents typical design details for various SUDS options. Appendix D is intended to give a brief introduction to life cycle costing for stormwater management. Appendix E describes a costing model that is available as part of the guidelines. Appendix F provides supplementary data for the aforementioned model. These SUDS Guidelines are intended for use by all practitioners working in the field of stormwater management and promotes the notion of interdisciplinary partnerships at all levels and phases of development.

1.1 The impacts of urbanisation

"The water cycle is one of the most critical processes to supporting life on this planet, and fresh waters are central to all aspects of our lives. Historically, urbanisation has led to the loss and degradation of wetlands, rivers and groundwater resources through pollution, resource depletion and construction within natural flood plains" (Woods-Ballard, *et al.* 2007)

Development normally reduces the natural permeability characteristics of land by replacing free draining surfaces with impermeable surfaces such as roofs, roads and paved areas that are typically drained by 'hard' infrastructure (i.e. pipes and lined channels).

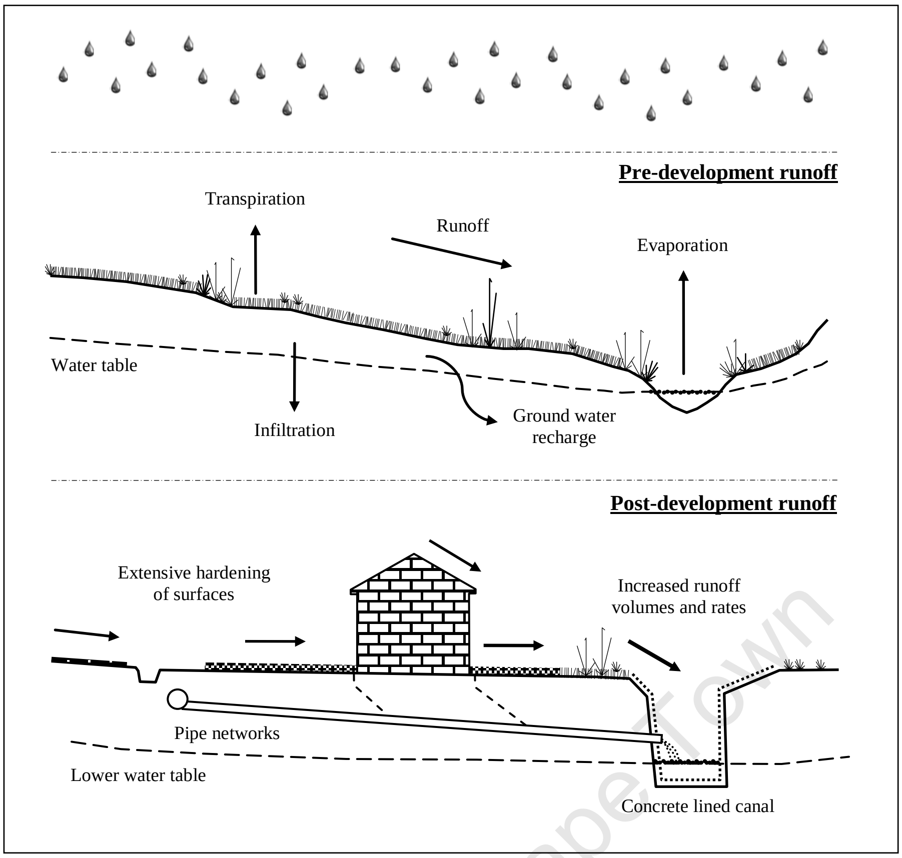

Figure 1.2: Typical pre- and post-development runoff scenarios with the conventional approach (After Haskins, 2010, Wilson, *et al.*, 2004)

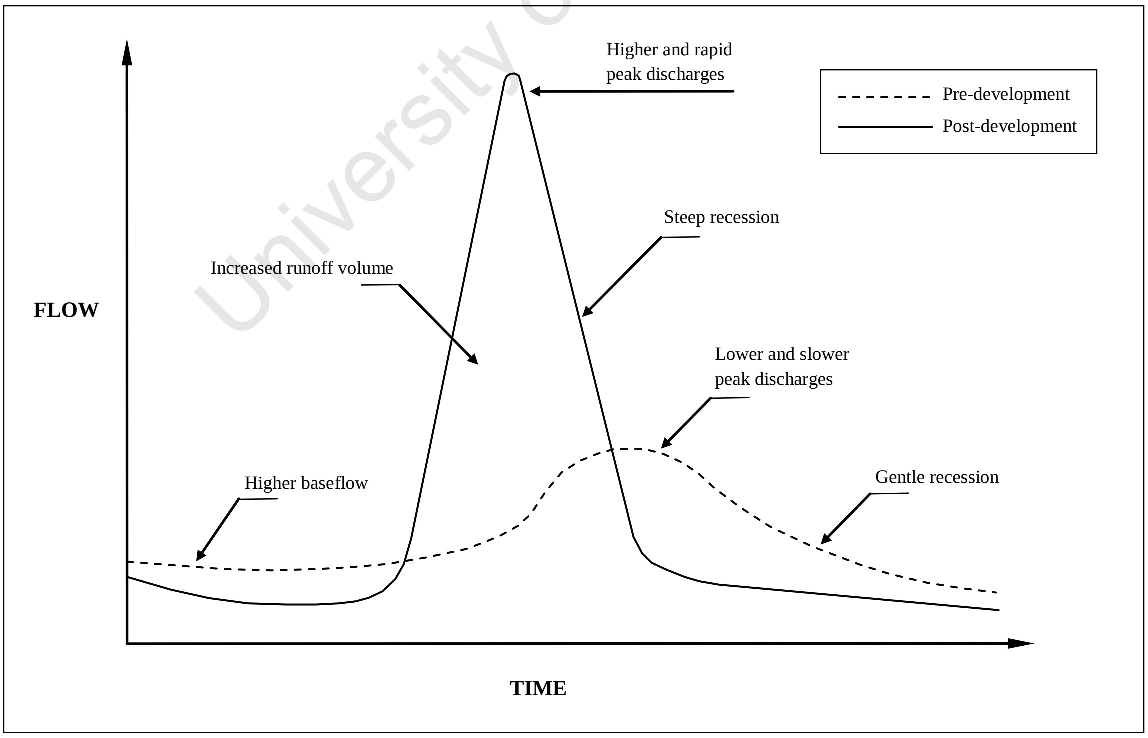

Figure 1.3: Typical hydrographs associated with pre- and post-development employing the conventional approach to stormwater management (After Wilson, *et al.*, 2004, Woods-Ballard, *et al.*, 2007)

Development also leads to a general loss of vegetation, often indigenous, which reduces stormwater buffering through interception storage, ponding as well evapotranspiration. Subsoil strata are often compacted during development thereby reducing their infiltration capacity.

Conventional drainage systems are generally focused on eliminating local flood nuisances and largely ignore the need to preserve or improve water quality and the associated aspects of amenity and biodiversity. They frequently have an adverse impact on flooding within the wider catchment and ignore the potential for the use of stormwater as a water resource. Figure 1.2 is a simplified schematic that illustrates typical pre- and post-development scenarios with the conventional approach to stormwater management. The associated hydrographs are illustrated in Figure 1.3.

Under post-development conditions the likelihood of extreme flooding and channel erosion downstream of developments is significantly increased. Less stormwater infiltration into the soil strata decreases the recharge of the underlying aquifers and hence baseflow discharge into receiving watercourses. Overland discharge is generally considerably more polluted than baseflow discharge. The overall outcome is damage to the receiving waters and loss of biodiversity. The situation may be exacerbated by the heat-island effect associated with most central business districts (CBDs) which may result in more intense stormwater runoff over those areas.

1.2 SUDS processes

SUDS promote more natural drainage through the use of a number of key unit processes. These unit processes are linked to the three elementary focal points of the binding philosophy of SUDS, namely:

i) Quantity;

ii) Quality; and

iii) Amenity and biodiversity.

Each of these unit processes is briefly described in the following sections (After Wilson, *et al.* 2004 and Woods-Ballard, *et al.* 2007):

1.2.1 Stormwater quantity management

- **Rainwater harvesting** – the direct capture of stormwater runoff, typically off rooftops, for supplementary water uses onsite;
- **Infiltration** – the soaking of stormwater runoff into the ground thereby physically reducing the volume of stormwater runoff on the surface;
- **Detention** – the slowing down of stormwater runoff before subsequent transfer downstream;
- **Conveyance** – the transfer of stormwater runoff from one location to another;
- **Long-term storage** – the volumetric control of stormwater runoff in a specified infiltrating area that will drain very slowly; and
- **Extended attenuation storage** – the retention of stormwater runoff to protect receiving watercourses in the event of flooding, if long-term storage and additional infiltration are not feasible onsite.

1.2.2 Stormwater quality management

- **Sedimentation** – the removal of sediment particles attached to pollution in stormwater runoff by reducing flow velocities to ensure sediment particles fall out of suspension;
- **Filtration and biofiltration** – the filtering of stormwater runoff pollutants that are conveyed with sediment by trapping these constituents on vegetative species, in the soil matrix or on geotextiles;
- **Adsorption** – the process whereby stormwater runoff pollutants bind to the surface of aggregate particles. Types of adsorption include cation exchange, chemisorption and absorption;
- **Biodegradation** – the degradation of organic pollutants in stormwater runoff by microbes;
- **Volatilisation** – the conversion of stormwater runoff compounds to gas or vapour typically as a result of heat, chemical

reaction, a reduction of pressure or a combination of these;

- **Precipitation** – the removal of soluble metals in stormwater runoff through chemical reactions between pollutant constituents and aggregate in the control structure to form a suspension of insoluble precipitates;
- **Plant-uptake** – the removal of stormwater runoff nutrients and metals through uptake by plants;
- **Nitrification** – the oxidisation of ammonia and ammonium ions in stormwater runoff by microbial factions to form nitrite and; and
- **Photosynthesis** – the breakdown of organic pollutants in stormwater runoff through extended exposure to ultra-violet light.

1.2.3 Amenity & biodiversity management

- **Health and safety** – the planning and implementation of control measures to prevent the injury or death of people including, *inter alia*, safe design practices, alert medical aid teams, and cooperative communities;
- **Environmental risk assessment and management** – the assessment and management of the various environmental subcomponents to ensure their longevity;
- **Recreation and aesthetics** – the provision of interactive and attractive structural and non-structural components by protecting, shaping and creating open spaces and enhancing the visual appearances of the specified systems; and
- **Education and awareness** – the dissemination of knowledge about stormwater management amongst interested and affected parties, through proactive campaigns, field trips and interactive stakeholder agreements.

1.3 SUDS selection

1.3.1 Selection basics

It is important to understand that SUDS generally embrace a number of options that are arranged in a treatment train. In other words, stormwater is managed through a series of unit processes (Section 1.2) in much the same way as, for example, wastewater is treated in a wastewater treatment works through a number of unit processes. To complicate matters slightly, the unit processes – which are described in the previous section – are generally to be found incorporated in a number of SUDS options. Twelve general SUDS options – together with a number of derivatives – are presented here. Treatment trains are the subject of Section 2.4. The selection of any particular option is determined by the unique characteristics of the site. It is unlikely that all options will be applicable or effective on any one site. It is thus important that the advantages and limitations of each option should be identified during the planning and design phases. According to Wilson, *et al.* (2004) and Woods-Ballard, *et al.* (2007), there are five basic selection criteria:

i) Current and future land use characteristics;

ii) Site characteristics and utilisation requirements;

iii) Catchment characteristics;

iv) Stormwater runoff quantity and quality performance requirements; and

v) Amenity and biodiversity requirements.

As previously mentioned, SUDS should be arranged in a treatment train for the effective management of stormwater runoff. There are three key intervention points in the treatment train, each having slightly different combinations of SUDS options to control the stormwater:

i) **Source Controls** manage stormwater runoff as close to its source as possible, typically on site. Typical SUDS options include: green roofs, rainwater harvesting, sand filters and soakaways.

ii) **Local Controls** manage stormwater runoff in the local area, typically within the road reserves. Typical SUDS options include:

bio-retention areas, filter strips, infiltration trenches, permeable pavements and swales.

iii) **Regional Controls** manage the combined stormwater runoff from several developments. Typical SUDS options include: constructed wetlands, detention ponds and retention ponds.

Figure 1.4 depicts a simplified SUDS treatment train schematic, illustrating the relationship between the three SUDS control types. SUDS treatment trains should prioritise: (1) water quality treatment for low flows; and (2) attenuation and volume control for high flows. Furthermore, the number and size of the SUDS treatment train components depends on: (1) the sensitivity of receiving watercourses or other environments; (2) the size of contributing catchments upstream; and (3) the expected pollutant concentrations in stormwater runoff inflows (Woods-Ballard, *et al.* 2007). Whilst the different SUDS options tend to be associated with a particular point in the treatment train, it is often possible to utilise them elsewhere depending on the site. For example, constructed wetlands are generally regarded as a regional control but they may also be used as an effective source control, for example in the form of a pocket wetland in a residential complex. A more comprehensive review of the theory of SUDS treatment trains and their application is included in Section 2.4.

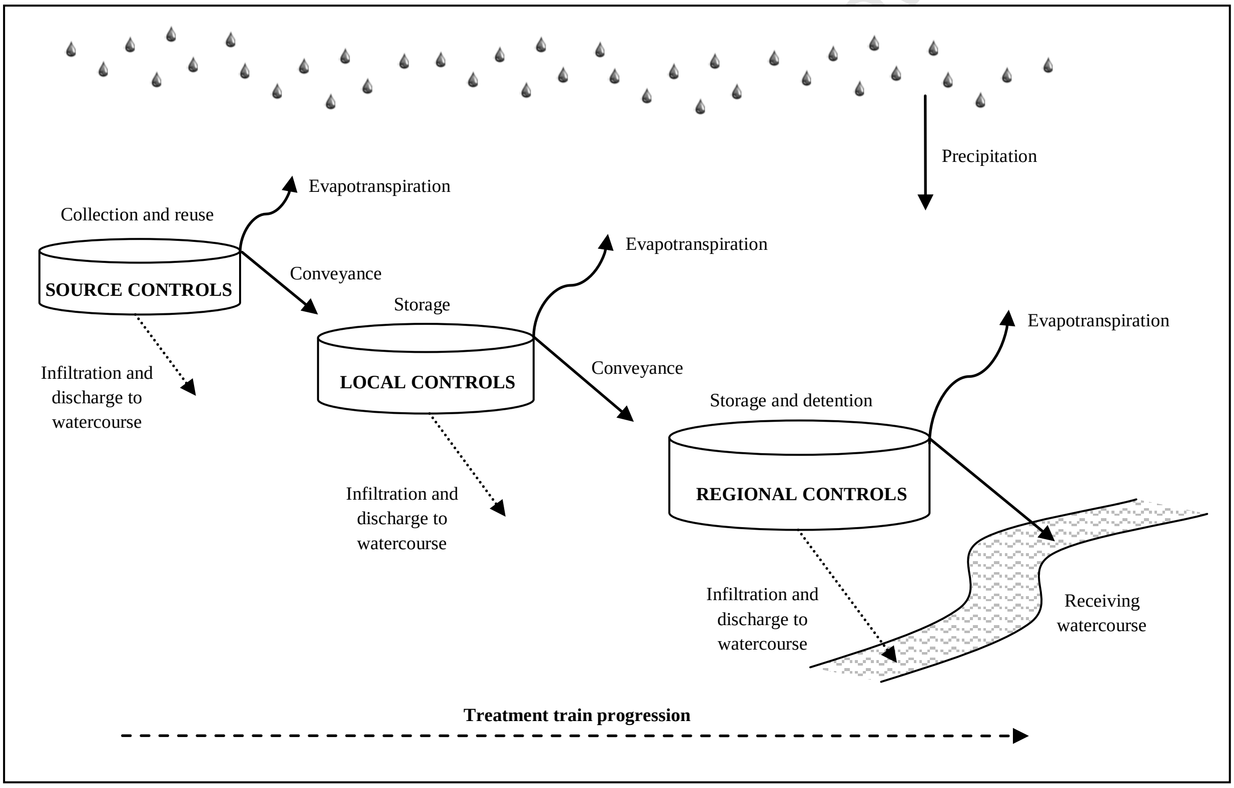

Figure 1.4: SUDS Treatment train schematic (After Woods-Ballard, et al., 2007)

1.3.2 Ecosystem services

According to the American Society of Landscape Architects (2008), 'ecosystem services' are defined as '*all possible goods and services that benefit human livelihoods, which are produced by ecosystem processes involving the interaction of living environmental elements*'. Hypothetically, the link between the philosophy of the SUDS approach and its practical application is related to the promotion of ecosystem services. These services can be monitored as performance criteria to indicate whether a SUDS treatment train is functioning in a sustainable manner. The objective should be to protect, restore and improve pertinent ecosystem services on site. The following eight ecosystem services are the ones most likely to be promoted through the use of SUDS (After American Society of Landscape Architects, 2008):

i) **Regulated climate** – maintaining an acceptable balance of atmospheric gases at historic levels and eliminating or minimising greenhouse gases in order to regulate local temperatures, precipitation and humidity;

ii) **Water and air purification** – the removal and reduction of pollutants in water and in the air;

iii) **Regulated water supply** – the storing and provision of water within artificial storage facilities, watersheds and aquifers;

iv) **Erosion and sediment control** – Retaining soil within a specified environment, through the structural protection against damage from erosion and siltation processes;

v) **Hazard mitigation** – reducing the likelihood of and vulnerability to damage from extreme rainfall events, flash floods and storm surges;

vi) **Habitat functions** – providing an ideal habitat for refuge and reproduction for vegetative species and wildlife, thereby contributing to nature conservation;

vii) **Waste treatment** – the decomposition of waste compounds and the recycling of associated nutrients; and

viii) **Human health, well-being and cultural benefits** – enhancing physical, mental and social well-being as well as improving cultural, educational, aesthetic and spiritual experiences, through interactions with nature.

1.4 Interdisciplinary partnerships

"*Public sector municipal government and utility leaders responsible for providing reliable water, wastewater, and stormwater management are confronted by several important trends affecting the future of cities. These trends include the need to increase the social and economic benefits created by urban infrastructure, improving collaboration among overlapping agencies and jurisdictions, making the transition from "fast conveyance" to "closed-loop" systems, introducing public stakeholders into decision-making and program implementation, and preparing for extreme events*" (Brown, 2007).

1.4.1 'Sustainable Development' and SUDS

'Sustainability' and 'Sustainable Development' have become buzzwords in the 21st Century, especially in the urban infrastructure design and management sector. Brundtland, *et al.* (1987) define sustainable development as, "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*". According to Hjorth & Bagheri (2006), it is often misconceived as an 'end state' and perceived as a rigid project target to be achieved in an allotted time-frame. Sustainable development, however, should not be viewed as a project that has an end state. It is neither the state of the system nor an attainable target, rather an ideal. It is an ongoing process which inter-relates aspects of economy, environment, society and other technicalities. O'Regan & Moles (1997) suggest that conventional practices in environmental management, for one, fail to manage the complexities of environmental systems which has resulted in a surplus of misguided paradigm shifts. They suggest that common errors and undesirable side effects in urban management are often a result of the inability of decision-makers to understand the underlying structure of the system of which they are a part.

Sustainability is both an ideal and an ongoing process that should be considered by managers in all decision-making processes. The design and management of urban infrastructure in South Africa, and urban drainage practices in particular, requires a shift from fragmented 'service provision' to 'holism'. According to Hjorth & Bagheri (2006) and Senge, *et al.* (2000), such a shift requires the yielding of linear and mechanistic thinking to non-linear and organic thinking – or 'systems thinking'. This places emphasis on management seeking to understand the relationships between the various components of the urban drainage system.

1.4.2 Role players in SUDS

The ideals of sustainability dictate that a successful design team should incorporate many disciplines, of which stormwater design and management engineers are simply one element. Therefore, urban practitioners are encouraged to establish interdisciplinary partnerships for increased efficacy at all stages of the implementation of SUDS schemes. The decision-making process for the selection of these schemes involves a variety of stakeholders within public and private sectors, who also add value to various aspects of urban design and management (Ellis, *et al.* 2006). Cognisant of the complexities embedded in the planning, design, construction, operation and maintenance phases of SUDS schemes, an interdisciplinary partnership could be comprised of any or all of the urban design and management professionals listed in Table 1.1 (listed alphabetically).

Table 1.1: Potential human capital for SUDS interdisciplinary partnerships

Professionals	Expertise and knowledge base	Elementary focal point(s) in SUDS
Architects	Infrastructure conceptualisation and structural aesthetics	Quantity / Amenity and Biodiversity
Botanists	Vegetation sciences and plant biology	Quality / Amenity and Biodiversity
Civil Engineers	Infrastructure design and management	Quantity / Quality
Clients	Conceptual specifications and appointments	–
Climatologists	Climatology issues and concerns, and 'climate change'	Quantity / Amenity and Biodiversity
Economists	Funding, fiscal viability and investment opportunities	–
Engineering Geologists	Engineering geology and earthwork requirements	Quantity
Environmentalists	Environmental impacts and protection	Amenity and Biodiversity
Epidemiologists	Water-borne diseases, and related health provisos	Quality / Amenity and Biodiversity
Freshwater Ecologists	Urban rivers restoration, rehabilitation and remediation	Quality / Amenity and Biodiversity
Geohydrologists	Urban groundwater uses and requirements	Quantity / Quality
Geomaticians	Spatial data acquisitioning and spatial data management systems	Quantity
Historians	Site heritage and historical significance	Amenity and Biodiversity
Landscape Architects	Urban vegetation and exterior landscape aesthetics	Quantity / Amenity and Biodiversity
Mechanical Engineers	Mechanical equipment operation and maintenance	–
Social Anthropologists	Local cultural studies and social impact assessments	Amenity and Biodiversity
Urban Planners	Urban layouts and land-use requirements	–
Zoologists	Wildlife biology and habitat requirements	Amenity and Biodiversity

2. Design criteria and methods

This section introduces a design and management framework for effective drainage design. It is largely a summary of Woods-Ballard, *et al*. (2007). In it, the hydraulic, water quality, and amenity and biodiversity requirements for effective SUDS are linked to design criteria in an attempt to:

i) Prioritise public livelihoods and the safeguarding of property when storing and/or conveying stormwater;

ii) Ensure that the risk of flooding is no greater than that prior to development – and preferably less;

iii) Remove pollutants from the stormwater before it is discharged from the site;

iv) Prevent excessive downstream channel and bank erosion; and

v) Promote amenity and biodiversity.

The management of stormwater is a complex task and practitioners need to carefully consider all the associated risks in the light of:

- The specified level of service (LOS);
- Acceptable costs; and
- The sustainability of the proposed drainage solution.

Subsequent sections will look at the various SUDS options and give guidance as to their likely performance against these three criteria. A SUDS Conceptual Design Framework (Appendix B; Figure 2.1) is included as an addendum to help guide the design process.

2.1 Hydraulic design

2.1.1 Flood protection for developments

It goes without saying that an important objective of stormwater management is the protection of people and property from flooding. According to Clause 144 of the South African National Water Act (No. 36 of 1998), "*no person may establish a township unless the layout plan shows, in a form acceptable to the local authority concerned, lines indicating the maximum level likely to be reached by floodwaters on average once in every 100 years*." Development should be discouraged within the 1 in 100 year flood-lines – particularly on functional floodplains. Developments should also not raise the risk of flooding in neighbouring areas.

As with conventional design, SUDS should cater for the more common storms without causing major inconvenience (the minor system). Typical design flood frequencies for different types of development are reproduced from "*The Red Book*" (CSIR, 2000) in Table 2.1.

Table 2.1: Design flood frequencies for minor systems (CSIR, 2000)

Land use	Design flood RI
Residential	1 – 5 years
Institutional (e.g. school)	2 – 5 years
General commercial and industrial	5 years
High value central business districts	5 – 10 years

The impact of more severe storms needs to be assessed to ensure that they do not pose a serious risk to life and property (the major system). Some form of storage may be prescribed to reduce this risk. It is assumed that the majority – if not all – flow will be overland flow as there is always a danger that any underground stormwater infrastructure will be overwhelmed and/or the inlets potentially blocked under such circumstances. If necessary, flow paths must be established to direct the surplus water safely away from any development to the nearest receiving water. The following additional issues should also be considered for severe storms:

- Potential blockages in the system need to be identified and removed or significantly reduced.
- The intensified flooding impacts of potential blockages, interferences or system failures need to be assessed and catered for;
- The impact of the structural failure of any relatively large storage facility in the system needs to be considered;
- Potentially unstable or vulnerable structures and properties need to be positioned away from overland flood routes;

- Basements and other low-lying human settlement structures should be assessed for flood risk and appropriate action taken; and
- Unhindered access to key municipal and government buildings should be ensured.

Minimum floor levels should ideally be above the maximum anticipated flood level anticipated – with allowance for freeboard and the potential impacts of climate change. All calculations should be inspected and verified by the appropriate local catchment management authority prior to development approval.

According to Woods-Ballard, *et al*. (2007), the consequences in the event of exceedance are normally significantly less with SUDS than conventional drainage systems.

2.1.2 Flood protection for receiving watercourses

The protection of the receiving watercourse is a critical aspect in the design of SUDS. According to Woods-Ballard, *et al.* (2007), there are two general principles with respect to the protection of receiving watercourses from the threat of increased flood risk:

i) To ensure, wherever possible, that the frequency of discharge **rates** from the new or proposed development are similar to that of the equivalent green-field conditions; and

ii) To ensure, wherever possible, the frequency of **volumes** of runoff from the new development are similar to that of the equivalent green-field conditions.

Each of these is briefly discussed to illustrate the necessity of these drainage characteristics in the proposed SUDS design.

2.1.2.1 Assessment of runoff rates

According to the SANRAL '*Road Drainage Manual*' (2006), urbanisation typically increases the runoff rate by 20-50% compared with natural conditions. In the extreme, the peak flow can be as much as 6.8 times that pertaining before development. This typically causes flash floods in streams and rivers, and an increased number of 'bankfull' flows. Excessive scour and erosion that could negatively affect the ecology of these watercourses is likely to follow. This is mitigated by ensuring that the post-development runoff rates are limited to the green-field runoff rate through local storage and/or infiltration. It is not essential that the post-development runoff rates from individual storms should be identical to the green-field runoff rate, only the frequency of these rates should be matched as closely as possible.

2.1.2.2 Assessment of runoff volume

The frequency of runoff volumes from a new or proposed development should also be designed to be similar to those of the equivalent green-field conditions. Particular consideration should be given to the following (after Woods-Ballard, *et al.* 2007):

- Increased runoff volumes from developed areas associated with the reduction in pervious area usually results in less groundwater recharge and thus reduced base-flow in the receiving watercourses;
- The relatively smaller, more frequent rainfall events from developed areas contribute the largest total pollutant load to the receiving watercourse. In most green-field situations, small rainfall events do not generate runoff. Runoff volumes from these events should thus be minimised which will in turn significantly reduce the pollutant loads; and

For small events, infiltration devices and interception storage are easily capable of trapping the first 5-10 mm of rainfall. Much larger storage capacity will be required for the more extreme rainfall events which can, in the extreme, cause total runoff volumes from developed areas to be up to 10 times the runoff volume from the equivalent green-field conditions.

2.1.3 Hydraulic design

Stormwater flows are impossible to model accurately. To begin with, rainfall characteristics are highly variable and may be affected by climate change. Secondly, the physical layout of the catchment is both complex and is being continuously altered. Attempts have been made to model flow using a wide variety of empirical, deterministic and stochastic models – with many commercial software packages available. None of them are particularly accurate. All rely – to at least some extent – on the experience of the modeller.

Whatever approach is taken, it is imperative that the designers agree on the basic approach with the local authorities responsible for overseeing any development as early as possible. A conceptual drainage solution then needs to be developed. The 'simplified site development process' in Appendix A; Figure 2.1, and the 'SUDS conceptual design framework' in Appendix A; Figure 2.2, can be used to assist practitioners in the development process and conceptual process, respectively. In addition, it is essential that an environmental regulator is assigned to monitor the conceptual design interventions that will be used on the specified site.

In the interests of simplicity, some simple models are introduced below. This does not preclude the use of more sophisticated – and potentially more accurate – methods.

2.1.3.1 Green-field runoff rates and volumes

The green-field runoff rates and volumes should be estimated to determine the acceptable maximum discharge from the designated site. These values should be primarily regarded as indicative.

The green-field runoff rate for a specified catchment may be estimated in a number of ways, including the use of historical records. A number of simple methods are offered in the *Drainage Manual* (SANRAL, 2006). A quick assessment of the expected runoff rates from small catchments – typically less than 1.5 km^2 – may be obtained with the aid of the Rational Method:

$$Q = \frac{C\,i\,A}{3.6}$$

Where:

Q = design peak runoff rate (m^3/s)
C = runoff coefficient (0 – 1)
i = rainfall intensity (mm/hr)
A = catchment area (km^2)

The biggest challenge is the determination of the runoff coefficient *C*. Guidance in the use of the Rational Method in South Africa is given in Section 3.1 of the *Drainage Manual* (SANRAL, 2006).

The runoff volume may be estimated from (Woods-Ballard, *et al*, 2007):

$$RV = PR \times A \times d$$

Where:

RV = runoff volume (m^3)
PR = percentage runoff (0 – 1)
A = catchment area (km^2)
d = rainfall depth (mm)

In this equation, the biggest challenge is the estimation of an appropriate percentage runoff. Section 4.2.2 of Woods-Ballard, *et al*. (2007) makes some recommendations for the UK in this respect, but these may not be applicable to South Africa.

2.1.3.2 Development runoff rates and volumes

Relative to green-field sites, runoff from many developments is almost instantaneous. Normally, the runoff is modelled using one of the many commercial software packages available. Alternatively the two formulae presented in previous section for green-field calculations could be used. It may be necessary for the conceptual drainage design to be tested for a range of storm durations from less than half-an-hour to more than 48-hours.

2.1.3.3 Simplified conveyance design

Although SUDS are conceived as an alternative to conventional stormwater management, this does not preclude the use of pipes and channels. The flow through such components is readily described by the Manning equation:

$$Q = \frac{A^{5/3} \times S^{1/2}}{n \times P^{2/3}}$$

Where:

Q = design peak flow rate (m^3/s)
A = cross-sectional area of flow (m^2)
S = slope of water surface (m/m)
n = Manning roughness coefficient

2.1.3.4 Storage design

The storage of stormwater runoff from a development is an important unit process in SUDS. There are two primary objectives:

- Adequate water quality treatment by the provision of extended residence (treatment storage); and
- Flood protection downstream of the site by attenuation of the peak flows (attenuation storage).

The water storage capacity of a structure is readily estimated as follows:

$$V = \sum_{i=0}^{n} \frac{(A_i + A_{i+1})}{2} \times d_i$$

Where:

V = storage volume (m^3)
A_i = surface area at elevation i (m^2)
A_{i+1} = surface area at elevation i+1 (m^2)
d_i = vertical height difference (m)

According to Debo & Reese (2003), storage facilities designed for water quality treatment are generally sized according to a specified 'Water Quality Volume' (WQV) computed as follows:

$$WQV = \frac{P\, R_V\, A}{1000}$$

Where:

WQV = Water Quality Volume (m^3)
P = total rainfall depth to be included (mm)
R_V = volumetric runoff coefficient (0.05 – 0.95)
A = total drainage area (m^2)

$$R_V = 0.05 + 0.009 \times I$$

And:

I = percentage of impermeable cover (%)

There are three alternative methods that could be used to determine the total rainfall depth, *P*, for the determination of the WQV:

i) A predetermined rainfall depth, typically in the region of 10 mm – 25 mm. Wilson, *et al.* (2004) suggest that rainfall depths of 10, 15 and 20 mm are adequate to wash off: fine dust or soluble pollutants; oils and greases; and pollutants on pervious surfaces, respectively.

ii) *P* can be determined with the aid of a rainfall event analysis over the specific area in question. According to Wilson, *et al.* (2004) and Debo & Reese (2003), the 90^{th} percentile of the daily rainfall can be used determined by plotting a 24-hour-rainfall exceedance curve. The percentage of days where a specific rainfall depth was exceeded should be plotted against the total number of rainfall days.

iii) Alternatively the rainfall depth generated by the half-year 24-hour rainfall event could be used.

Whatever method is chosen, the rainfall depth should not be less than 10 mm.

Debo & Reese (2003) also recommend a water balance calculation. This assists designers in determining whether the specified stormwater drainage area is large enough and has the necessary characteristics to support a permanent pool of water during more extreme conditions. This calculation is particularly useful in the design of constructed wetlands and retention ponds (Section 5). A water balance calculation accounts for the change in volume of permanent pools of water resulting from the difference between the inflows and outflows:

$$\Delta V = P + Ro + Bf - I - E - Et - Of$$

Where:

ΔV = change in permanent pool volume (m^3)
P = precipitation on surface of pool (m^3)
Ro = runoff volume (m^3)
Bf = baseflow volume (m^3)
I = infiltration component (m^3)
E = evaporation component (m^3)
Et = evapotranspiration component (m^3)
Of = overflow volume (m^3)

2.1.3.5 Infiltration design

Infiltration is a critical design characteristic in most SUDS. It serves two primary objectives:

- Reducing the attenuation storage volume requirements; and
- Replenishing the groundwater.

Infiltration is an acceptable and feasible means of stormwater disposal in most locations although the structural stability of adjoining soils, structures, services and slopes should be rigorously assessed and suitable remedial action taken if infiltration systems are to be implemented. Care must also be taken to ensure that natural water resources, especially groundwater resources, are protected against contamination by polluted stormwater runoff. This might require the pre-treatment of the stormwater prior to infiltration.

The suitability of a site for infiltration is dependent on a number of variables, particularly the permeability and saturation-state of the surface and sub-surface soil media. These soil properties usually dictate the performance of infiltration systems. In the first instance, a soil's capacity to infiltrate water is limited by the coefficient of permeability. Table 2.2 lists typical permeability coefficients categorised in terms of their general suitability for infiltration. The soil texture may be determined from the sand, silt and clay percentages using the United States Department of Agriculture (USDA, 1938) Soil Texture Triangle (Figure 2.3).

The coefficient of permeability is one of the greatest uncertainties in the design of infiltration-type SUDS, the efficiency of which also are likely to reduce over time due to clogging and compaction. If necessary, a geotechnical investigation should be performed prior to the design to ensure that infiltration-type SUDS are capable of performing the task that they have been assigned.

Since infiltration-type SUDS are prone to significant changes in infiltration performance due to the changes in the state of infiltration media over their specified design lives, a factor of safety (FOS) should be used in their design. Table 2.3 lists typical FOS.

Table 2.2: Typical soil texture permeability coefficients (After Jefferies, 2010)

Soil texture	Permeability coefficients (mm/h)	Adequacy
Gravel	10000 – 1000000	Yes
Sand	100 – 100000	
Loamy sand	10 – 1000	
Sandy loam	50 – 500	
Loam	1 – 100	
Silt loam	0.5 – 50	
Sandy clay loam	1 – 100	
Silty clay loam	0.05 – 5	No
Clay	< 0.1	
Unstratified soil	0.01 – 10	
Rock	0.01 – 100	

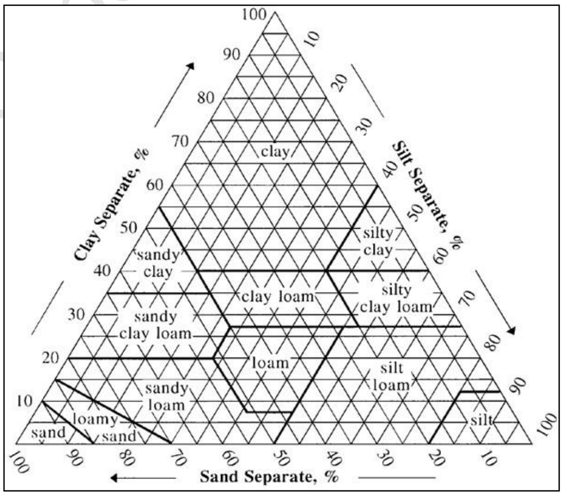

Figure 2.3: Soil Texture Triangle (USDA, 1938)

Table 2.3: Factors of safety for infiltration-type SUDS (After Jefferies, 2010)

Drainage area	Low risk	Moderate risk	Major risk
< 100 m^2	1.5	2	10
100 m^2 – 1000 m^2	1.5	3	10
> 1000 m^2	1.5	5	10

2.1.3.6 SUDS sizing and modelling

Various modelling tools are available to assist with SUDS design. Some of these are profiled in Tables 2.4 and 2.4. A key input is rainfall data. This is often available from the local authority; alternatively, rainfall data and information for South Africa with region specific data and information may be extracted from the *South Africa* (2006). The *South Africa Rainfall Atlas* includes image and site specific databases in addition to a rainfall simulator. Daily, monthly and annual rainfall data and information can be extracted from these online databases, as well as storm percentage and percentile data and information.

Before utilising any form of modelling, users should be aware of the model assumptions and limitations. The greatest uncertainties in the prediction of the performance of SUDS are as a result of the complexities associated with the vegetated and amenity components (Woods-Ballard, *et al.*, 2007).

2.2 Water quality design

The main principle in water quality design is the effective implementation of a SUDS treatment train to prevent and alleviate the risk of pollution associated with the site in question.

The amount of pollution discharging from any site during a specific rainfall event is dependent on the following three main factors:

i) The duration and intensity of the rainfall event;

ii) The land use characteristics of the site, with light and heavy industrial areas normally yielding more polluted discharges; and

iii) The time between rainfall events, with longer periods normally resulting in higher levels of pollution (Wilson, *et al.*, 2004, Woods-Ballard, *et al.*, 2007).

The use of a treatment train enhances the pollutant removal capabilities of each of the various SUDS over the course of the drainage system. The estimated pollutant removal capabilities of a number of SUDS options and/or technologies are listed in Appendix B; Table 2.6. The pollutant removal capabilities are dependent on a number of variables, such as: rainfall event characteristics, soil characteristics – and their associated infiltration capacities, vegetation type and the geological lie of the land.

Currently there are no national or provincial standards for pollutant removal from stormwater – although this will surely come within the next few years. The City of Cape Town has, however, released interim criteria that specify required performance standards for SUDS schemes (CCT, 2009). These may be utilised as acceptable pollutant removal standards until such time as more appropriate performance standards are published.

2.1.1 First flush phenomenon

Pollution concentrations during rainfall events are neither constant nor proportional relative to the rainfall duration and intensity. Instead, they are relatively higher during the early stages of a rainfall event. This phenomenon is known as the first flush and is normally attributed to the following rainfall induced characteristics:

- The build up of sediment and other pollutants on surfaces between rainfall events;
- Relatively higher erosion potential after an extended dry period; and
- Relatively higher rainfall intensities towards the beginning of many rainfall events.

It is particularly important that the capture and treatment of the first flush is prioritised in the design process to ensure that the initial stormwater runoff that is discharged into the receiving watercourse is of an improved quality (Jefferies, 2010, Woods-Ballard, *et al.* 2007). Interception storage is a particularly useful way of dealing with this phenomenon as it provides considerable water quality benefits.

Table 2.4: Potential model uses for design criteria computation (After Elliot & Trowsdale, 2005)

	Public Education	Research	Developing Sizing rules for devices	Planning of land use in catchments/cities	Preliminary design of regional controls	Preliminary design of a subdivision or site	Detailed design of regional drainage system	Detailed design of subdivision or site	Site Layout and materials selection
MOUSE		■	■	■	■	■	▒	▒	▒
MUSIC			■	■	■	■			
P8			■	■	■	▒			
PURRS		■	■			■			
RUNQUAL			■	■	■	▒			
SLAMM			■	■	■	▒			
StormTac				■	■				
SWMM		■	■	■	■	■	▒	▒	▒
PCSWMM		■	■	■	■	■	▒	▒	▒
UVQ		■	▒	▒	▒	■			
WinDes (Quant. only)			▒		■	■	■	■	▒
WBM			■	■	■	■			

Table 2.5: SUDS component focus for selected design models (After Elliot & Trowsdale, 2005)

	Imperviousness reduction	Ponds and wetlands	Soil protection	Reduction of contaminant generation	Infiltration trenches/bores	On-site detention tanks	Swales	Run on	Rain tanks	Bioretention, rain gardens Filtration devices	Permeable Paving	Green roofs
MOUSE	■	■	▒	▒	▒	■	■		▒	▒	▒	
MUSIC	■	■	▒	▒	■	■	■	▒	■	■	▒	▒
P8	■	■	▒	▒	■	■	■		▒			
PURRS	■	▒	▒		■	■		■	■			
RUNQUAL	■	■	▒	▒	■							
WinSLAMM	■	■	▒	▒	■		■			■		
StormTac	■	■	▒	▒			■					
SWMM	■	■	▒	▒	▒	■	■	■	▒	▒	▒	▒
UVQ	■	■	▒	▒	■	▒		■	■	▒		
WinDes (Quant. only)	■	▒			▒	▒	▒		▒	▒	▒	▒
WBM	■	■	■		■	▒	■	■		■	▒	■

2.3 Amenity and biodiversity

The Collins English Dictionary (2004) defines amenity as, "*a useful or pleasant facility; or the fact or condition of being agreeable*." The New Penguin English dictionary (2000) defines biodiversity as, "*the number and diversity of distinct living species within the world or a particular environment*." Unlike with conventional urban drainage practices, the adequate provision of amenity and protection of biodiversity is a primary objective of SUDS. The three key principles for the effective provision of amenity and biodiversity benefits in SUDS schemes are discussed as follows.

2.3.1 Health and safety

There are a number of circumstances where some SUDS options are unsafe; for example where there is a serious risk of drowning in the case of ponds and wetlands, or of damage to motor vehicles in ditches. These risks should be taken into consideration in the design and, if necessary, precautions taken. Areas of particular concern include:

- Transportation nodes and links;
- Pre-primary and primary schools; and
- Informal dwelling areas.

Examples of precautions that could be taken include: the provision of gentler side slopes (e.g. less than 1 in 3), shallower depths around the edges of ponds, or the strategic placement of vegetation around them to act as a barrier to unsupervised children from entering the water body areas.

Another significant health and safety concern relates to breeding of mosquitoes and other vectors and the associated risk of transmission of various diseases. In these circumstances, ponds could be designed to drain within, say, three days of the specified rainfall event to prevent the stagnation of water. Other natural controls could be introduced in the case of permanent bodies of water. The expertise of an appropriately qualified biologist will be useful in these circumstances.

Education and awareness campaigns are often an effective means of reducing the perceived risks associated with various SUDS. According to Wilson, *et al.*, (2004) and Woods-Ballard, *et al.* (2007), the following four risk management questions should be asked:

i) What are the possible hazards?

ii) Who is at risk?

iii) How can these possible hazards be avoided or mitigated?

iv) What is the associated residual risk?

2.3.2 Aesthetic impact and amenity benefit

Many SUDS have a visual impact therefore the issue of public acceptability needs to be addressed. Some possibilities (Woods-Ballard, *et al.* 2007):

- The dissemination of information on the proposed SUDS and its role in supporting and/or enhancing the environment;
- Landscaping the area to maximise the aesthetic appeal of the specified system;
- Ensuring that an appropriate maintenance plan is developed and adhered to so as to ensure that the SUDS have a positive visual impact all year round; and
- Adjoin open water areas to recreation sites where the health and safety risks can be well managed.

Landscaping and planting procedures may require the expertise of a Landscape Architect and Botanist, respectively.

2.3.3 Ecological services

According to the American Society of Landscape Architects (2008) and Woods-Ballard, *et al.* (2007), the maximization of the ecological services of SUDS is important for two main reasons:

i) To provide the necessary amenity and biodiversity enhancements at the specified development site; and

ii) To adequately facilitate the natural movement of wildlife species through the 'green' corridors within the development precinct.

Ecological diversity can be maximised, *inter alia*, in the following manner:

- The planting of indigenous vegetation;
- Pre-treatment before polluted water is discharged into open water bodies;
- Retaining, protecting and enhancing existing natural drainage systems;
- Creating a range of diverse habitat types; and
- Including a relatively shallow aquatic bench zone in wetland and pond design.

2.4 Treatment train design

SUDS drainage system design includes all the various aspects that link together to control and manage stormwater with the greatest efficiency and efficacy. The purpose of this section is to briefly describe how a SUDS treatment train is developed for any particular situation.

In Section 1.3 it was mentioned that the management of stormwater cannot be done in one operation, it requires a treatment train – also called a 'management' train – as it is highly unlikely that all the stormwater can be managed in one facility. This 'train' can have any number of 'coaches', but it is convenient to conceive of three main groups called in this Guideline: Source Controls (Section 3), Local Controls (Section 4) and Regional Controls (Section 5). These are schematically illustrated in Figure 1.4.

As with the pre-development conditions, stormwater runoff should be controlled and treated as close to its source as possible. The collection, storage, re-use, infiltration and evapotranspiration processes inherent in many local SUDS controls (Section 3) are particularly useful in mimicking the natural drainage characteristics. Where stormwater is to be conveyed from one place to another, more 'natural' channels such as filter strips swales are preferred to pipes and concrete-lined canals which speed up the flow and provide no water quality benefit. If the stormwater cannot be handled on site, the next best option are local SUDS controls (Section 4) which attempt to manage all the stormwater generated in a local area. Only then is the stormwater passed to regional SUDS controls (Section 5) which represents the last 'line of defence' for the management of the stormwater before it is passed to the appropriate receiving waters. The basic design process may be summarised as follows:

i) Carry out a preliminary analysis of the amount (volume and flow) and the quality of stormwater to be treated.

ii) Map out the preferred flow path/s – with preference being given to overland routes. This may differ between the minor system and the major system (Section 2.1.1).

iii) Determine the number, type and location of the various SUDS options in a treatment train. Generally, the performance of the treatment train is related to the number of SUDS options that the stormwater passes through. Multi-component treatment trains can be more readily designed to remove a wide range of pollutants by utilising a variety of treatment processes. Furthermore, the greater the number of SUDS interventions, the smaller the risk of an entire system failure.

iv) Determine the performance of each of the different SUDS options in the treatment train for each of a variety of design storms ranging from frequent storms through the design storm for the minor system, the design storm for the major system – and perhaps even the probable maximum storm. The SUDS treatment train would be expected to treat the entire pollution load from the frequent storms, handle the design storm for the minor system and survive the design storm for the major system without significant damage.

v) Aggregate the contributions from each of the elements in the SUDS treatment train and compare with the stormwater management objectives – which should ideally be the pre-development conditions, but which may have been relaxed by an agreed performance standard set, perhaps, by the local authority. If the design meets the objectives and is agreed to by all parties, detailed design follows, otherwise the designer needs to return to step ii) and try out other treatment train options

vi) Once a number of potential treatment train solutions have been found, they must be costed to determine the most cost-effective solution (Appendix D); and

vii) The team needs to make a decision!

For the purpose of detailed technical design guidelines for SUDS options and the establishment of treatment trains, the following four international design manuals can be used. These provide a range of comprehensive SUDS designs that are relevant to the South African urban drainage context (listed alphabetically):

i) Hobart City Council, 2006, *Water Sensitive Urban Design Site Development Guidelines and Practice Notes*, Hobart City Council, Tasmania, Australia

ii) Moreton Bay Waterways and Catchments Partnership, 2006, *Water Sensitive Urban Design – Technical Design Guidelines for South East Queensland*, Brisbane City Council and Moreton Bay Waterways and Catchments Partnership, South East Queensland, Australia

iii) North Carolina Division of Water Quality, 2007, *Stormwater Best Management Practices Manual*, NCDWQ, North Carolina, United States of America

iv) Southeast Michigan Council of Governments, 2008, *Low Impact Development Manual for Michigan: A Design Guide for Implementers and Reviewers*, SEMCOG, Michigan, United States of America

The following three major sections – Section 3, Section 4 and Section 5 – describe several SUDS options that can be used independently or in a treatment train, to potentially provide sustainable drainage on-site or in a larger catchment.

3. Source controls

3.1 Green roofs

3.1.1 General description

A roof that is deliberately covered in vegetation may be described as a 'green roof' (Semple, *et al.* 2004; Stahre, 2006; Figures 3.1 & 3.3). *Sedum* is the most common vegetation type used for green roofs, however, many other vegetation types can be used depending on the conditions. Generally, green roofs that contain moss-*sedum* mixtures are able to endure longer periods of drought (Stahre, 2006). Flat roofs often incorporate a thicker layer of vegetation or roof gardens that promote general rooftop accessibility and other forms of outdoor recreation. The use of vegetative roof covers and roof gardens is an important source control for stormwater runoff. They provide great benefits in densely urbanised areas where there is less space for other SUDS options (NCDWQ, 2007, Semple, *et al.* 2004).

Figure 3.1: Ethekwini Green Roof Pilot Project, Durban CBD

A study on the efficacy of a green roof constructed in the Durban CBD by eThekwini Municipality (Greenstone, 2010; Figure 3.1), as well as many international studies, indicate that green roofs are capable of completely absorbing light to moderate rainfalls (<10 mm). They also provide some minor stormwater detention which increases the 'time of concentration', significantly delaying runoff peaks and decreasing runoff volumes. Vegetative roof covers and roof gardens are usually at their most efficient in the summer and spring growing seasons, with reduced efficiencies in autumn and winter seasons. According to Stovin (2009), structural appraisal of a variety of flat roof types suggests that retrofitting green roofs is a feasible option in many instances, particularly for concrete roof slabs. Pollution control characteristics for green roofs are included in Appendix B; Table 2.6.

3.1.2 General design guidelines

Post 2000 advances in synthetic drainage materials now allow green roofs to be built on flat and gently sloped roofs, typically between 0° and 20°. On roof slopes greater than 20°, support systems such as horizontal strapping should be used to prevent slipping or slumping of the growing vegetation. The vegetative layer is typically 30 – 40 mm thick and sits upon a drainage layer approximately half this thickness. The drainage layer in turn lies on a waterproof membrane to prevent leakage into the specified building (Figure 3.2). Green roofs constructed using these dimensional characteristics generally have specific weights of 40 – 60 kg/m^2 (Stahre, 2006, Wanielista, *et al.* 2008). The structural design of the roof needs to account for the additional weight of the green roof component materials and expected water detention volumes – including any possible snow accumulation (NCDWQ, 2007).

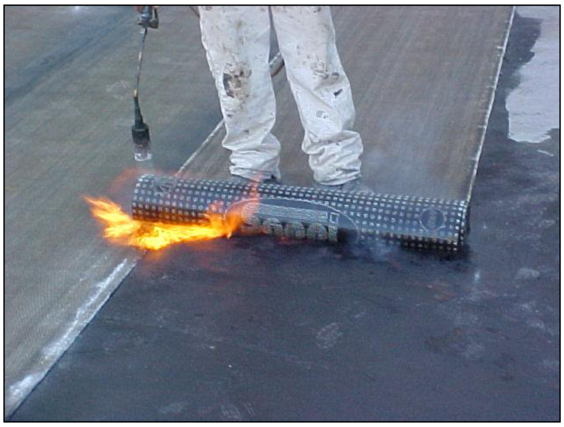

Figure 3.2: Waterproofing a roof in preparation for the construction of a green roof

The detention volume available in a green roof is a function of the depth and porosity of the vegetation bedding that is added to the new or existing roof structure (Semple, *et al.* 2004). It is recommended that a pollution control layer be fitted beneath the vegetation for additional stormwater runoff pollution alleviation. Green roofs are especially effective when implemented over roofs with large surface areas, particularly industrial and commercial buildings, and blocks of flats. If a green roof is retrofitted on an existing rooftop particular care should be taken to ensure that the stormwater can freely flow into the various components of the roof drainage system (NCDWQ, 2007). Drip irrigation for green roof water reticulation provides greater water use efficiency and fewer maintenance requirements. The general design for green roofs and the adjoining inspection compartment is given in Appendix C; Figure 3.1.

3.1.3 Advantages

i) Green roofs may be established on both existing and new buildings;

ii) The insulation characteristics of green roofs help to regulate building temperatures with consequent savings of energy (Greenstone, 2010);

iii) The biophysical nature of the vegetation used in green roofs may improve air quality;

iv) Green roofs can be designed to closely mimic the pre-development state of the buildings (Greenstone, 2010, Woods-Ballard, *et al.* 2007); and

v) Green roofs can significantly improve amenity and biodiversity where they are implemented.

3.1.4 Limitations

i) The implementation phase for green roofs requires experienced professionals that are competent in waterproofing and plant requirements;

ii) Green roofs are generally more costly than conventional roof-runoff practices due to their added structural, vegetative and professional requirements;

iii) The detention of water within the green roofs storage layers could result in the failure of waterproofing membranes which in turn could increase the threat of the roof collapsing (Stahre, 2006);

iv) Green roofs may only be used on steep roofs (>20°) if additional support systems such as horizontal strapping are provided; and

v) Plant varieties for green roofs may be quite limited; indigenous vegetation is generally best (Wilson, *et al.*, 2007).

3.1.5 Operation and maintenance

Maintenance cycles should generally include three to four inspections per year to search for vegetation related problems such as weeds and bare patches, and any stress related damages to the roof and building structure (Hobart City Council, 2006). General plant maintenance is also required. It may also be deemed necessary to irrigate during the establishment of the vegetation. The application of fertilizers can be performed periodically; however, it is preferable that fertilizers are not used as this will impact the quality of the stormwater runoff (NCDWQ, 2007).

3.1.6 Technology derivative(s)

There are three main types of green roofs, namely: extensive green roofs (Figure 3.1), intensive green roofs (Figure 3.3), and simple intensive green roofs (Woods-Ballard, *et al.* 2007). Two other derivatives are also applicable for urban drainage, namely; green walls and blue roofs. Each of these is briefly described as follows.

3.1.6.1 Extensive green roofs

Extensive green roofs incorporate low growing and low maintenance vegetation that cover the entire roof surface. They are typically accessed for maintenance purposes only, and can be implemented on both flat and sloped surfaces. Extensive green roofs usually comprise a growing vegetation medium 25 – 125 mm in thickness, covered with hardy and drought tolerant flora. Indigenous mosses, herbs and grasses are commonly used – which are intended to be reasonably self-sustaining.

3.1.6.2 Intensive green roofs

Intensive green roofs incorporate planters and trees that have a high level of accessibility (Figure 3.3).

It is recommended that rainwater harvesting is used as the primary irrigation source for intensive green roof flora. This system generally places higher dead and live loads on the roof and building structures, and will undoubtedly require more intensive ongoing maintenance.

3.1.6.3 Simple intensive green roofs

Simple intensive green roofs have elements in common with both extensive and intensive green roofs; having both larger plants as well as low growing and/or ground covering plants such as lawns. They often require a lot of maintenance, such as cutting, fertilizing and watering, as well as increased accessibility. There are fewer demands on the strength of the roof structure than intensive green roofs, which may lower roof system costs.

Figure 3.3: Intensive green roof, Department of Environmental Affairs and Development Planning, Cape Town

3.1.6.4 Green walls

Green walls are vegetated walls that may be implemented as elements of a building or as free-standing partitions. They significantly attenuate first-flush flows from buildings by detaining rainwater on the surfaces of leaves and other parts of the vegetation. The vegetation is usually grown in an inorganic stratum. Green walls require high frequency maintenance especially if they are located in dense urban areas such as central business districts (CBDs). The construction of green walls is quite complex and should be carried out by experts.

3.1.6.5 Blue roofs

Blue roofs are typically flat roofs with kerbed peripheries that serve to store and/or detain rainwater. The roof structure must be waterproofed and able to carry the additional load. Blue roofs require regular maintenance checks to ensure that there is no build up of debris and sediment. An annual structural maintenance check should be carried out by certified professionals.

3.1.7 Case studies

Greenstone, C, 2009, *Rooftop Gardens and the Greening of Cities – A case Study of University of KwaZulu-Natal*, University of KwaZulu-Natal, eThekwini: A case study of the feasibility and performance of a variety of green roof vegetation to treat and control stormwater and provide internal temperature control in KwaZulu-Natal.

Rickards, B, 2006, *Low Impact Development Case Study: City Hall Green Roof*, Coastal Smart Growth Program, City of Boston: A concise case study of the project scope, timeline and budget as well as design and implementation phases of the Boston City Hall green roof.

USEPA, 2007, 'Reducing Stormwater Costs through Low Impact Development (LID) Strategies and Practices', *Toronto Green Roofs, Toronto, Ontario (A Modelling Study)*, Washington: A brief case study that evaluates the benefits of greatly expanded green roofs in Toronto using a geographic information system (GIS).

3.1.8 Further reading

Feller, M, Traver, R, Wadzuk, B, 2010, *Estimation of Green Roof Evaptranspiration: Experimental Results*, ASCE Low Impact Development 2010: Redefining Water in the City, Los Angeles

Hopkins, G, 2009, Green Infrastructure: *Re-interpreting natural systems (WSUD) from ground to green walls and roofs within the urban form*, The 6th International Water Sensitive Urban Design Conference and Hydropolis #3, Perth

Jianlong, W, Wu, C, Guoqing, P, Junqi, L, 2009, *Innovative Design of Low Impact Development* *to Harvest Rainwater, Reduce Runoff and Pollutant Loads*, 8th Urban Drainage Modelling and 2nd Rainwater Harvesting Conference, Tokyo

Kasmin, H, Stovin, VR, Hathway, EA, 2009, *Towards a generic rainfall-runoff model for green roofs*, 8th Urban Drainage Modelling and 2nd Rainwater Harvesting Conference, Tokyo

3.2 Sand filters

3.2.1 General description

Sand filters come in many forms. The type most often to be found used as a source control are also known as 'perimeter sand filters'. They normally comprise of a sedimentation chamber and an underground filtration chamber comprising sand or other filtration media through which stormwater runoff passes (Debo & Reese, 2003). The sedimentation chamber facilitates the removal of suspended particulates and heavy metals, whilst the filtration chamber removes smaller particulate pollutants that pass through the sedimentation chamber. The removal mechanism is partly through filtration by the sand bed and partly through microbial action within the media. (Melbourne Water, 2005, MBWCP, 2006). Once the treatment process is completed, stormwater either percolates into the surrounding stratum or is returned to the conveyance system (Woods-Ballard, *et al.* 2007). According to Field & Sullivan (2003), sand filters have been used in France since the 1820's, however they have only recently become popular for the treatment of stormwater runoff elsewhere. They are usually installed in conjunction with land uses having relatively large percentages of impervious surfaces.

Sand filters are generally used for impervious areas less than 8,000 m^2, however, sand filters may be designed to manage stormwater runoff from areas as large as 100,000 m^2 (Endicott & Walker, 2003). The operation of sand filters is similar to that of bio-retention areas (Section 4.1) and other bio-retention systems with the exception that stormwater runoff passes through a linear filter medium without vegetation (MBWCP, 2006). The primary control component of stormwater management for sand filters is water quality improvement. They are particularly effective in the removal of hydrocarbons (Debo & Reese, 2003). They are also used extensively to remove sediment and other particulate pollutants from the first flush (Section 2.2.1) off adjoining impervious areas (Semple, *et al.* 2004). Pre-treatment is required for the removal of coarse sand and gravel from stormwater (Field & Sullivan, 2003, Environment Protection Authority – Melbourne Water Corporation, 1999). Pollution control characteristics for Sand Filters are included in Appendix B; Table 2.6.

3.2.2 General design guidelines

Sand filters may be used in a variety of situations and can function for an indefinite period if designed and maintained correctly (Field & Sullivan, 2003, Woods-Ballard, *et al.* 2007). According to Field & Sullivan (2003), sand filters are most commonly used:

- In areas of fine soils and relatively low associated infiltration rates;
- In arid regions with high evaporation rates, where limited rainfall and high evaporation rates preclude the utilisation of retention ponds or wetlands for stormwater management (Sections 5.1 and 5.3);
- In areas where there is limited open ground, sand filter systems can be implemented beneath impervious surfaces; and
- When there is a significant requirement to protect groundwater resources.

Sand filters are prone to clogging, especially from sediment-carrying runoff from construction sites and areas with open soil patches. In light of this, it is often useful to pre-screen out litter, coarse sediment and the larger debris (MBWCP, 2006).

The most common filter media used in sand filters is sand – often in layers. Other filter media include peat, limestone and topsoil (Environment Protection Authority – Melbourne Water Corporation, 1999, Woods-Ballard, *et al.* 2007). For optimal efficiency, they generally require a hydraulic head of 1 – 1.5 m. Ideally, they are designed to cater for 85% of the annual stormwater runoff (Taylor, 2003). Filtered effluent from sand filters is typically used for:

i) Recharging the groundwater resources;

ii) Adding polished runoff into treatment train waterway; and

iii) Non-potable domestic water uses.

If the sand filter effluent is to be used for domestic water uses, periodic water quality checks should be carried out to mitigate possible health risks. A typical sand filter design is given in Appendix C; Figure 3.2.

3.2.3 Advantages

i) Sand filters are particularly effective in removing settleable solids (TSS);

ii) Sand filters are efficient stormwater management technologies in areas with limited space, as they can be implemented beneath impervious surfaces;

iii) They manage stormwater runoff effectively on relatively flat terrains with high ground water tables, where bioretention systems are inappropriate (NCDWQ, 2007);

iv) The filtered effluent can be reused for most non-potable domestic water uses including: toilet flushing, dish washing and garden watering; and

v) Sand filters may be retrofitted with relative ease into existing impervious developments, constrained urban locations or in series with conventional stormwater management systems (Melbourne Water, 2005).

3.2.4 Limitations

i) 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;

ii) Large sand filters are not generally attractive, especially if they are not covered with grass or other vegetation;

iii) Sand filters are generally ineffective in controlling stormwater peak discharges (NCDWQ, 2007);

iv) Sand filters are expensive to implement and maintain relative to most other SUDS options and/or technologies (NCDWQ, 2007, Taylor, 2003); and

v) Some sand filters, especially if designed and/or implemented incorrectly, may fail resulting in standing pools of water which have the potential to attract nuisances such as mosquitoes and midges.

3.2.5 Operation and maintenance

To ensure their longevity, sand filters require a higher frequency of maintenance than most other SUDS options (Field & Sullivan, 2003, McAlister, 2007). Regular maintenance should be a top priority in the management plans of sand filters at the design stage of their application. The surface material should be periodically screened to minimise larger quantities of litter and debris, especially in dense urban areas. Designers should take care in the selection and implementation of the filtration media. The utilisation of silty or clayey filtration media tend to increase the probability of clogging (Debo & Reese, 2003, MBWCP, 2006, Taylor, 2003).

The frequency of cleaning required for sand filters can be determined by performing weekly filter inspections, especially during the dominant wet season (Melbourne Water, 2005, Taylor, 2003). Furthermore, sand filters should be inspected at least once after a relatively large rainfall event to clear sediment, litter and debris, and to ensure all stormwater has been drained within 72 hours of the specified rainfall event. According to Taylor (2003), 50 – 100 mm of filtration media should be removed from the filtration surface and be replaced with fresh filter media if stormwater is taking longer than 72 hrs to drain. Sand filters which are not properly maintained, typically over a period of six months or longer, tend to form a crust-like layer of finer material on the filtration surface. This generally decreases the performance of these specified sand filters (Debo & Reese, 2003, MBWCP, 2006, Taylor, 2003).

3.2.6 Technology derivatives

Wilson, *et al.* (2004) and Woods-Ballard, *et al.* (2007) make particular reference to three sand filter derivatives, namely; underground sand filters, surface sand filters, and filter drains. Each of these is briefly described as follows.

3.2.6.1 Underground sand filters

Underground sand filters are very similar in design, performance, operation and maintenance to perimeter sand filters. They may receive stormwater runoff from single or multiple pipe inlets. They are particularly effective in areas with extremely limited space. Unfortunately, limited space usually means limited accessibility which can make maintenance difficult (Woods-Ballard, *et al.* 2007).

3.2.6.2 Surface sand filters

A surface sand filter is a type of filtration basin (Section 5.2.6). It generally consists of a forebay for the removal of sediment followed by the infiltration basin. It often receives stormwater runoff from other SUDS options in a treatment train. (Woods-Ballard, *et al.* 2007).

3.2.6.3 Filter drains

A filter drain, also referred to as a 'French drain', is a type of infiltration trench (Section 4.3). The trench is filled with permeable media, often stone. Filter drains typically receive stormwater runoff in the form of sheet flow from impervious surfaces. The water may be stored for later non-potable use, passed on down the treatment train, or infiltrated into the ground. Perforated pipes may be installed at the base of the trench to improve the drainage characteristics. The stormwater runoff residence time is generally lower in filter drains than in sand filters due to the relatively high permeability of the gravel backfill material (Wilson, *et al.* 2004).

3.1.7 Case studies

Angelis, G, Shaw, M, 2004, *Barnwell Golf Course Stormwater Treatment and Reuse*, Sustainable Water Challenge Project, Canada Bay: <u>A case study of the treatment and reuse of stormwater pollution entering Canada Bay using, *inter alia*, a sand filters and gross pollutant trap for treatment and collection purposes.</u>

Chanan, A, 2003, *Low Flow Filtration & Reuse Project*, Kogarah Municipal Council, Kogarah: <u>A case study of the designs, construction, installation and costs of a low flow sand filtration and reuse system for treating and reusing stormwater from a roadway arterial.</u>

Jones, C, 2005, *Hindmarsh Park Sand filter*, A Sustainable Water Challenge 2005 Project, Kiama: <u>A comprehensive case study of a stormwater treatment train comprising of gully pits, litter traps and a 'state of the art' sand filter that incorporate *HydroCon* permeable concrete pipes.</u>

3.1.8 Further reading

Howard, DJ, Roberts, AG, Symes, P, Somes, N, 2009, *Royal Botanic Gardens Melbourne: Lessons Learnt in Transforming an Existing Garden Bed Feature into a Functioning Rain Garden*, The 6th International Water Sensitive Urban Design Conference and Hydropolis #3, Perth

Mladenovski, I, Dalton, S, Jayasuriya, N, 2009, *The effectiveness of University Hill constructed wetland in treating stormwater*, The 6th International Water Sensitive Urban Design Conference and Hydropolis #3, Perth

Sansalone, J, Pathapati, S, Becciu, G, 2008, *Simulation of Particulate Matter Fate and Head Loss in a Passive Urban Drainage Radial Filter*, 11th International Conference on Urban Drainage, Endinburgh

3.3 Soakaways

3.3.1 General description

Soakaways are excavated pits, normally square or circular in shape, packed with course aggregate or other porous media. They are similar to infiltration trenches in operation, but usually have a smaller plan area (MBWCP, 2006). Soakaways are most commonly used for the temporary storage of stormwater runoff which is then infiltrated into the ground. They are often used to handle roof runoff from a single building (Figure 3.4).

Figure 3.4: Groundwater recharge of runoff from a single residential dwelling, Cotswold Downs Estate, Hillcrest

Soakaways can be arranged in series and/or linked to drain larger areas including parking lots and motor highways. In such instances, modular geocellular structures can be used as a more suitable 'backfill material'. The cross-section of the soakaway and the type of material utilised determines the infiltration characteristics of the device. Modular geocellular structures provide relatively high stormwater treatment and rates of groundwater recharge. On the negative side, the rapid movement of water through soakaways leads to an increased risk of groundwater contamination. It is thus important to ensure that adequate stormwater pre-treatment is implemented upstream of the soakaway if necessary. The pollutant removal processes associated with soakaways include: volatilisation, sedimentation, bio-degradation and filtration (Wilson, *et al.* 2004, Woods-Ballard, *et al.* 2007). Pollution control characteristics for soakaways are included in Appendix B; Table 2.6.

3.3.2 General design guidelines

The soakaway size is dependent on the voids ratio of the course aggregate or geocellular material that is used to fill the excavated pit. They are emptied either by the percolation of the stormwater directly into the underlying soil or via perforated drainage sub-drains installed near the base of the structure. They should be installed above the groundwater table. Measures should be taken to prevent fine grained material from entering the backfill portion of the structure, especially during the construction and maintenance phases. Soakaways that are situated in fine grained soils should be lined with a geo-textile to prevent the migration of fines into the coarser porous media (Stahre, 2006). A custom designed oil and sediment collection compartment may also be implemented as a simple and effective pre-treatment device if required (Woods-Ballard, *et al.* 2007).

Soakaways are usually designed to store the entire volume from the design storm and be able to infiltrate at least half of this within 24 hrs to create additional capacity for the runoff from subsequent rainfall events. They normally serve areas less than 1000 m^2, but groups of soakaways can serve areas as large as 100,000 m^2 (MBWCP, 2006). They are usually 1 – 4 m deep although soakaways serving single residences are seldom more than 1.5 m in depth. They are often constructed using preformed polyethylene or precast concrete rings, 1 – 2.5 m in diameter. The lined excavation can be kept hollow, but a high voids fill material reduces the turbulence associated with high flow rates into the structure (Woods-Ballard, *et al.* 2007). To prevent groundwater contamination, soakaways should be constructed at least 1.5 m above the groundwater table to allow for additional filtration (Livingston & McCarron, 2008). The general design for soakaways with the adjoining oil and sediment collection compartment is given in Appendix C; Figure 3.3.

3.3.3 Advantages

i) Soakaways can handle relatively high volumes of groundwater recharge;

ii) Soakaways that are operated and maintained regularly normally have design lives of up to 20 years, after which the fill should be replaced (Stahre, 2006);

iii) Soakaways can be used in most climatic regions;

iv) Soakaways significantly decrease both the runoff volume and rate; and

v) Soakaways are particularly effective in removing particulate and suspended stormwater runoff pollutants.

3.3.4 Limitations

i) Soakaways are not suitable in areas where infiltrating water would negatively impose on adjacent structural foundations or adversely affect existing drainage characteristics;

ii) Soakaways are normally limited to relatively small connected areas (Woods-Ballard, et al. 2007);

iii) Soakaways do not function well when constructed on steep slopes and in loose or unstable areas;

iv) Sub-drain piping systems must be utilised when soakaways are implemented in very fine silt and clay stratum because of the low infiltration rates; and

v) Sedimentation intrusion will cause a gradual reduction in the storage capacity (Stahre, 2006).

3.3.5 Operation and maintenance

As with most SUDS options and technologies, the design life of soakaways is directly related to the frequency and quality of inspection and maintenance cycles. Soakaways situated in fine soils, such as silts and clays, require a more detailed inspection and maintenance routine than those in more porous stratum (Melbourne Water, 2005). An inspection opening makes routine inspections easier and allows greater accessibility to the backfill material. The entrance into the soakaway should be visible through the inspection opening. Such accessibility also makes it easier to manually clear out debris and sediment build-up. Adjoining stormwater runoff contributing areas, such as parking lots and roadways should be regularly swept to prevent the intrusion of silt into the soakaway. Clogged soakaways may attract mosquitoes and other associated vectors as well as foul odours as a result of standing water (Taylor, 2003). In this instance, the replacement of the 'backfill material' will most likely be necessary (Woods-Ballard, *et al.* 2007).

3.3.6 Technology derivatives

Soakaways are similar to infiltration trenches (Section 4.3) and infiltration basins (Section 5.2.6). Pre-treatment can be effected through the use of oil and grit separators. Modular plastic geocellular structures can be used to improve their performance. Each is briefly described as follows.

3.3.6.1 Oil and grit separators

Oil and grit separators are often included in SUDS treatment trains to provide the pre-treatment of stormwater runoff where necessary. They are most applicable in areas where stormwater runoff from commercial or industrial areas may be polluted with high levels of hydrocarbons, heavy metals and/or TSS (Wilson, *et al.* 2004). They require frequent maintenance to prevent the build-up of fine grained and oil-based pollutants. One advantage is that they do not require much space as they are typically implemented underground.

3.3.6.2 Modular plastic geocellular structures

Modular plastic geocellular structures are geometric structures with high void ratios that are used to increase storage capacity without significant loss of structural strength. Due to the modular nature of these geocellular structures, they can be made to suit the specific requirements of a wide variety of sites (Woods-Ballard, *et al.* 2007). They normally have a high load capacity relative to their light weight, which allows for their use beneath heavily trafficked areas such as parking bays. They are also commonly used in retrofitted systems. According to Woods-Ballard, *et al.* (2007), modular plastic geocellular structures generally have long-term physical and chemical stability when utilised beneath the earth's surface.

3.3.7 Case studies

Atlantis, 2010, *Case studies: Infiltration/Soakaway systems*, Atlantis Water Management, New South Wales: Eight concise case studies of large infiltration devices and soakaways implemented in Australia, the USA, the UAE, Malaysia and Chile.

Environment Agency, 1999, *Case Study: Soakaways help reduce run-off*, The environmental issues: Managing surface water, Ipswich: A concise case study that highlights

several benefits of the uses of soakaways to manage stormwater runoff.

Owen, R, Butler, P, Cullan, P, Herd, D, Happold, B, Fisher, N, 2008, *Wessex Water Operations Centre, Claverton Down*, Wessex Water Operations Centre, Bath: A brief case study of use of permeable paving, soakaways, swales and rainwater harvesting to mange stormwater runoff from residential developments.

3.3.8 Further reading

Bergman, M, Binning, P, Kuczera, G, Mikkelsen, PS, Mark, O, 2009, *Integrating soakaway infiltration devices in distributed urban drainage models – from allotment to neighbourhood scale*, 8th Urban Drainage Modelling and 2nd Rainwater Harvesting Conference, Tokyo

Endo, J, Fujiwara, H, Tamoto, N, Sakakibara, T, 2009, Deterioration of rainwater infiltration facilities with time, 8th Urban Drainage Modelling and 2nd Rainwater Harvesting Conference, Tokyo

Hewa, GA, Argue, JR, Pezzaniti, D, 2009, *Setting Criteria for Channel-Forming, Environmental and Flood Flows for Waterways in Urbanising Catchments*, The 6th International Water Sensitive Urban Design Conference and Hydropolis #3, Perth

Hossain, MA, Furumai, H, Nakajima, F, Kasuga, I, 2008, *Accumulated sediments within soakaways in an old infiltration facility: source or sink for heavy metals?*, 11th International Conference on Urban Drainage, Endinburgh

3.4 Stormwater collection and reuse

3.4.1 General description

"Water resources sustainability is the ability to use water in sufficient quantities and quality from the local to the global scale to meet the needs of humans and ecosystems for the present and the future to sustain life, and to protect humans from the damages brought about by natural and human-cause disasters" (Mays, 2007).

Stormwater collection and reuse, also referred to as 'rainwater harvesting', is an essential element of effective Water Sensitive Urban Design (WSUD) as stormwater is utilised as a water resource. Conventional stormwater infrastructure results in the pollution and loss of millions of cubic metres of water into watercourses and oceans each year. With minimal treatment this water could be used to supplement the potable water supply for secondary water uses such as toilet flushing, garden irrigation and laundry – which typically comprise 85% of the total potable water consumption in a normal household (Donovan & Naji, 2003). Storage of runoff from roofs and other elevated impervious surfaces is provided by rainwater tanks, barrels and other storage structures until the water is required (Figure 3.5) (Hobart City Council, 2006, Stahre, 2006). It is very common in developing countries where it is often the primary water supply.

The utilisation of stormwater as a water source not only saves potable water, it also reduces stormwater discharge from roofs. Stormwater storage facilities may also be connected to other SUDS options such as infiltration trenches or soakaways, which can manage the overflow and recharge the groundwater. Parkinson & Mark (2005) and Scholz (2006) suggest that rainwater harvesting systems are particularly useful during extreme rainfall events as they help protect receiving watercourses by reducing the initial runoff volumes and the associated pollutants (McAlister, 2007). Pollution control characteristics for stormwater collection and reuse are included in Appendix B; Table 2.6.

Figure 3.5: Roof runoff storage tanks for household purposes

3.4.2 General design guidelines

Many different stormwater collection and reuse systems are commercially available. According to Donovan & Naji (2003), the principal element requirements for an effective stormwater collection and reuse system are:

- Strategic placement of the roof gutters;
- A first-flush trap and/or filter sock to catch leaves and other debris;
- A rainwater storage facility (tank, barrel or sump);
- Leaf and organic debris diverters;
- A means of getting the water to its point of use; preferably by gravity or otherwise a pump and pipeline;
- An inline filter and/or UV disinfection device if there is any risk of human contact; and
- An overflow system – preferably linked to another option in a SUDS treatment train.

Taylor (2003) and Stahre (2006) suggest that a minimum of two rainwater storage facilities with a storage capacity of 1,000 litres should be implemented for single residential households. There is no upper limit; 25,000 litre rainwater tanks and 40,000 litre underground sumps have been installed on single-unit properties. There are five main considerations when selecting a storage facility (Hobart City Council, 2006):

i) Budgetary constraints;

ii) Local rainfall characteristics;

iii) On-site and off-site space availability;

iv) Impervious catchment areas (including, but not limited to roof areas); and

v) Future rainwater uses.

The network of gutters should preferably be partially covered in a low permeability filter screen to reduce the debris, animal contaminants and other likely pollutants from entering the collected stormwater runoff system – whilst ensuring adequate capacity. Furthermore, a small pollutant trap or bypass filter should be installed to prevent debris and/or contaminants from entering the collected stormwater system. Storage facilities that are childproof as well as insect and vector proof should be given preference in the selection process. Excess stormwater runoff should be channelled toward adjoining SUDS options (Taylor, 2003). In the event of extreme rainfall, stormwater runoff volumes that cannot be contained in the available rainwater storage facilities should be removed using diversion structures. This prevents or minimises damage to property and potential fatalities. 'Stormwater' signs should be placed above the outlet of the specified rainwater storage facility in an effort to prevent people, especially children, from drinking the water or utilising it for other potable demands (Hobart City Council, 2006). Designers may use the following simple water balance equation to calculate the volume of usable rainfall, also referred to as the annual collectable rainfall (ACR) (After Wilson, *et al.*, 2004, Woods-Ballard, et al., 2007):

$$V = R \times A \times C \times FE$$

Where:

V = Volume of usable rainwater (ℓ)
R = Average rainfall over period (mm)
A = Area contributing to runoff (m^2)
C = Run-off coefficient (0 – 1)
FE = Filter Efficiency (0 – 1)

The runoff coefficient is the realistic proportion of rainfall runoff that enters the specified storage facility. Table 3.1 indicates commonly used runoff coefficients.

Table 3.1: Typical runoff coefficients for rainwater harvesting off roofs

Roof classification	Runoff coefficient C
Pitched roof, tiled	0.85
Flat roof, tiled	0.6
Flat roof, gravel	0.4
Extensive green roof	0.3
Intensive green roof	0.2

The filter efficiency refers to the proportion of water post filtration available for use. Generally manufacturers recommend a conservative 0.9. The rainfall period selected for the calculation depends on the climate but monthly values are generally the most appropriate. Although average values will generally be used in the determination of the cost-effectiveness of the rainwater harvesting system, designs should be tested out against both high and low values to determine overflow and shortfalls respectively.

3.4.3 Advantages

i) The optimal utilisation of stormwater collection and reuse systems in residential, commercial and industrial units can significantly reduce potable water consumption;

ii) The collection of stormwater runoff reduces the pollutant loads that enter nearby watercourses;

iii) The collection and reuse of stormwater runoff attenuates flood peaks; and

iv) There is a wide variety of rainwater storage facilities commercially available in South Africa which are simple and quick to install.

3.4.4 Limitations

i) Roof collection systems tend to be ineffective in areas that have hot and dry climatic conditions for a significant part of the year;

ii) There is no real assurance that stormwater collection and reuse systems will consistently provide dirt-free water, hence their limited non-potable supplementary uses;

iii) Rainwater storage facilities that are implemented above the ground level are generally not aesthetically pleasing; and

iv) Currently, rainwater reuse on a domestic scale is a relatively expensive means to obtain potable quality water over a short to medium term, with rainwater tanks constituting the most significant cost of the system.

3.4.5 Operation and maintenance

Households that utilise harvested rainwater for potable purposes should be aware of the potential health risks and take the necessary operation and maintenance precautions. Harvested rainwater should be filtered as well as boiled or chlorinated if it is to be used for potable purposes (Hobart City Council, 2006, Parkinson & Mark, 2005).

3.4.6 Technology derivatives

There are three types of stormwater collection and reuse systems that are generally applicable to residential, commercial and industrial uses, namely: direct supply systems, gravity supply systems and centralised supply systems. Each approach has a different performance with respect to their water supply efficiency, electrical consumption, noise pollution, maintenance intensity, operation requirements, and space requirements (Woods-Ballard, *et al.* 2007). The main elements of each approach are briefly described below.

3.4.6.1 Direct supply systems

Stormwater runoff from impervious surfaces (typically rooftops) passes through a coarse filter and is collected in a storage facility (rainwater barrel, tank or sump). Water is then pumped by a booster pump directly into the specified application points in and around the connected building. Once the specified storage facility runs dry, allowance should be made for water from the main reticulation to be fed into the system. If this is done manually, it will require regular checks on the water level in the storage facility (Woods-Ballard, *et al.* 2007).

3.4.6.2 Gravity supply systems

Stormwater runoff from impervious surfaces (typically rooftops) passes through a coarse filter and is collected in a storage facility (rainwater barrel, tank or sump). Water is then pumped by a booster pump into a raised reservoir termed a ‘header tank’. This water is then gravity fed into the specified application points in and around the connected building. Once the specified storage facility runs dry, there should be a water main back up supply as with direct supply systems (Wilson, *et al.*, 2004, Woods-Ballard, *et al.* 2007). Unlike direct supply systems, gravity supply systems do not require electrical energy which saves on costs and means that supply can be maintained during power outages.

3.4.6.3 Centralised supply systems

Stormwater runoff from impervious surfaces (typically rooftops) passes through a coarse filter and is collected in a large storage facility. Booster pumps are housed in each of the buildings linked to the system. When required, water is pumped out of storage and into the reticulation of the building concerned. A connection to the normal external water distribution system provides back-up when the water in storage runs out.

3.4.7 Case studies

Angelis, G, Shaw, M, 2004, *Barnwell Golf Course Stormwater Treatment and Reuse*, Sustainable Water Challenge Project, Canada Bay: A case study of the treatment and reuse of stormwater pollution entering Canada Bay using, *inter alia*, a sand filters and gross pollutant trap for treatment and collection purposes.

Butterworth, J, 2006, *Showcasing Sustainability North Sydney Community Centre*, NSW Sustainable Water Challenge Awards 2006, New South Wales: A case study discussing the water sensitive urban design principles used in the design and construction of a community centre, including an innovative rainwater harvesting system.

Chanan, A, 2003, *Low Flow Filtration & Reuse Project*, Kogarah Municipal Council, Kogarah: A case study of the designs, construction, installation and costs of a low flow sand filtration and reuse system for treating and reusing stormwater from a roadway arterial.

Owen, R, Butler, P, Cullan, P, Herd, D, Happold, B, Fisher, N, 2008, *Wessex Water Operations Centre, Claverton Down*, Wessex Water Operations Centre, Bath: A brief case study of use of permeable paving, soakaways, swales and rainwater harvesting to mange stormwater runoff from residential developments.

3.4.8 Further reading

Gold, A, Goo, R, Hair, L, Arazan, N, 2010, *Rainwater Harvesting: Policies, Programs, and Practices for Water Supply Sustainability*, ASCE Low Impact Development 2010: Redefining Water in the City, Los Angeles

Jianlong, W, Wu, C, Guoqing, P, Junqi, L, 2009, *Innovative Design of Low Impact Development to Harvest Rainwater, Reduce Runoff and Pollutant Loads*, 8th Urban Drainage Modelling and 2nd Rainwater Harvesting Conference, Tokyo

Lesjean, B, Schmidt, M, Schroeder, K, Huau, MC, 2009, *International Review of Rainwater Harvesting Management: Practices, Market and Current Developments*, 8th Urban Drainage Modelling and 2nd Rainwater Harvesting Conference, Tokyo

Rodrigo, S, Sinclair, M, Leder, K, 2009, *Urban Tanks – Are they properly maintained?*, 8th Urban Drainage Modelling and 2nd Rainwater Harvesting Conference, Tokyo

4. Local controls

4.1 Bio-retention areas

4.1.1 General description

Bio-retention areas, also referred to as 'rain gardens' or 'bio-retention filters', are landscaped depressions used to manage the quality of stormwater runoff through several natural processes (Figure 4.1). These include, *inter alia*, filtration, adsorption, biological uptake and sedimentation (Debo & Reese, 2003). Bio-retention areas normally incorporate a series of small stormwater management interventions such as grassed strips for infiltration, temporary ponding areas, sand beds, mulch layers and a wide variety of plant species (Endicott & Walker, 2003). They are particularly effective in managing stormwater runoff from minor and more frequent rainfall events. Excess stormwater runoff generated during major rainfall events is routed to other structural stormwater controls. Bio-retention areas are applicable for managing stormwater runoff on many sites, such as: between residential plots, parking lots, adjoining roadways, and within large landscaped impervious areas. Furthermore, the concept of 'bio-retention' can be incorporated into most other SUDS options and/or technologies, such as swales and detention ponds (Sections 4.5 and 5.2), to improve pollutant removal potential and enhance the amenity and biodiversity of the immediate environment (Woods-Ballard, *et al.* 2007).

Figure 4.1: Bio-retention area situated between housing units, Evergreen Retirement Village, Cape Town

Bio-retention areas maximise the management potential of engineered soil media and the associated vegetation to capture and treat the specified water quality volume (WQV) of stormwater runoff. A portion of the stormwater runoff volume is generally removed through infiltration and evapotranspiration within the ponded area. The outflow, at least partially cleaned through the various processes in operation in the bio-retention area, is directed to the next link in the SUDS treatment train (Debo & Reese, 2003). In this manner, bio-retention areas are able to reduce stormwater runoff quantities and rates, and improve the quality of stormwater entering watercourses further downstream (Woods-Ballard, *et al.* 2007). They are particularly effective in removing particulates from stormwater runoff. The particulates that are normally removed include nutrients, heavy metals, pathogens and various suspended solids (Endicott & Walker, 2003, NCDWQ, 2007). Pollution control characteristics for bio-retention areas are included in Appendix B; Table 2.6.

4.1.2 General design guidelines

The use of bio-retention areas is appropriate in relatively small catchments, typically in the region of 1,000 – 4,000 m^2. Several smaller bio-retention areas can be linked together for larger catchments (Endicott & Walker, 2003, Woods-Ballard, *et al.* 2007). The base and sides of the infiltration pit may require lining in areas where infiltration is deemed unsuitable due to groundwater contamination. Bio-retention areas may also need to be lined in areas where slope stability is of concern or where the infiltration of stormwater runoff may result in foundation or other structural issues. In these instances, an under-drain network should be designed to minimise the risk of failure. In addition, suitable flow routes should be identified to convey any excess stormwater runoff towards more appropriate receiving structural stormwater controls (Woods-Ballard, *et al.* 2007). Small energy dissipating structures can be used to prevent high flows from adversely affecting the management capacity of the specified bio-retention area. These can be designed to spread piped-flow over the infiltration areas. Flow dissipaters and spreaders typically include shallow weirs, check dams, perforated pipes, rip-rap mattresses and stilling basins (Environment Protection Authority – Melbourne Water Corporation, 1999).

Bio-retention areas are generally designed to ensure that the acceptable water quality volume depth does not exceed 150 mm. This enables enhanced evaporation and transpiration processes and should limit the ponding time on the surface. Ideally they should empty over a period of about 48 hours after a storm event – up to a maximum of 72 hours. It is a trade-off between allowing sufficient contact time between stormwater runoff and the specified vegetation for effective pollutant removal whilst ensuring that the system is able to receive subsequent rainfall events (Endicott & Walker, 2003, Woods-Ballard, *et al.* 2007). Plants that are selected for bioretention areas should be hardy in order to not only withstand the quantity and quality of stormwater runoff that is expected on specified sites, but also potentially long, hot and dry periods in between rain events. They should preferably be indigenous vegetation species because these should not only be adapted to the local climate, but will assist in preserving the amenity and natural biodiversity of the immediate environment. The selection of a diverse range of trees and shrubs is advised to provide adequate protection against insects and/or disease. An herbaceous surface should be grown to protect the topsoil or upper mulch layers from erosion (NCDWQ, 2007). According to Woods-Ballard, *et al.* (2007) trees and large shrubs are often included for the following reasons:

- Interception of precipitation and the improvement of evaporation processes;
- Dissipation of runoff forces from rainfall events;
- Facilitation of surface water infiltration and the associated groundwater recharge processes; and
- Boosting of the amenity and biodiversity through, *inter alia*, the provision of shade and the reduction of potential runoff temperatures.

The general design for bio-retention areas is displayed in Appendix C; Figure 4.1.

4.1.3 Advantages

i) Bio-retention areas are more effective at the removal of most stormwater runoff pollutants compared with most other SUDS options;

ii) Due to their flexible application characteristics, bio-retention areas are easily incorporated into a wide variety of landscapes;

iii) Stormwater runoff rates, volumes and flood peaks are effectively attenuated with the correct use of bio-retention areas;

iv) Bioretention areas are generally satisfactory as a retrofit options; and

v) Bioretention areas are typically more aesthetically pleasing than most other SUDS options and/or technologies.

4.1.4 Limitations

i) Bioretention areas are normally impractical in areas with steep or insistently undulating slopes;

ii) Bioretention areas are not suited to areas where the water tables are shallower than 1.8 m (Endicott & Walker, 2007);

iii) Bio-retention areas require frequent landscaping and maintenance in order to function successfully over their design life;

iv) If the areas adjacent to bio-retention areas, either permeable and impervious, are poorly maintained, then they become increasingly susceptible to clogging; and

v) The construction costs incurred for bio-retention areas are generally higher than most other SUDS options (Wilson, *et al.* 2004).

4.1.5 Operation and maintenance

To ensure that bio-retention areas function effectively, routine inspection and maintenance needs to be performed on a roughly monthly and annual basis. As with most other SUDS options, the design life of bio-retention areas is related to the frequency and quality of the maintenance. If bio-retention areas are correctly designed and maintained, they have the potential to manage stormwater indefinitely. The most important maintenance procedures include: monthly debris and litter removal, annual weeding, annual replacement of the topsoil or upper mulch layers, annual replacement of damaged vegetation, regular pruning and treatment of diseased trees and plants, and sediment removal whenever there is considerable build-up (Endicott & Walker, 2003, Woods-Ballard, *et al.* 2007). According to Woods-Ballard, *et al.* (2007), there should be no need to use fertilisers as the nutrients remaining in the bioretention areas are normally elevated, especially with the use of an upper mulch layer. The inappropriate application of fertilisers has the potential to increase the stormwater runoff pollutant content downstream of the bio-retention area.

4.1.6 Technology derivative

Bio-retention ruts are often an effective type of bio-retention area.

4.1.6.1 Bioretention ruts

Bio-retention ruts, also referred to as 'bio-retention allotments' or 'bio-retention gullies', are small dugout trenches filled with vegetation. They are commonly established in the centre of local depressions over the surface of impervious areas such as parking lots or open public spaces (Figure 4.2). They can be any shape in plan, and are typically 1 – 10 m^2 in area. Normally they are filled with sand or coarse aggregate over selected soil media in which a selection of vegetation is planted. Stormwater runoff that passes through these layers should be removed through infiltration into the underlying stratum, or if the infiltration rates are inadequate, a subsurface pipe drainage network should be provided. They assist in decreasing stormwater runoff rates and volumes as well as pollution in the same manner as the larger scale bio-retention areas but, naturally, in proportion to their relative areas.

Figure 4.2: Bio-retention rut filled with a coarse aggregate and planted with a tree, Grand Parade, Cape Town

4.1.7 Case studies

Alderete, D, Scharff, M, 2005, *Case Study: The Design of a Bioretention Area to Treat Highway Runoff and Control Sediment*, International Erosion Control Association (IECA) Conference, Dallas: <u>A case study that describes the design, construction and investigation of a bioretention area, and assesses the water quality performance thereof.</u>

City Projects, 2006, *Barcom Avenue Park Upgrade – Water transfer & Bioretention*, 2006 Sustainable Water Challenge Project, Sydney: <u>A case study of a bioretention retrofit to improve the stormwater quality in a catchment by limiting the quantity of pollution and reducing the peak flow running into stormwater drains.</u>

Melbourne Water, 2004, *Stawell Street Reconstruction*, Melbourne Water, City of Kingston: <u>A case study of the aims, maintenance requirements and costs of bioretention basins that collect stormwater runoff from roads and properties before it is discharged into the conventional drainage system.</u>

4.1.8 Further reading

Howard, DJ, Roberts, AG, Symes, P, Somes, N, 2009, *Royal Botanic Gardens Melbourne: Lessons Learnt in Transforming an Existing Garden Bed Feature into a Functioning Rain Garden*, The 6th International Water Sensitive Urban Design Conference and Hydropolis #3, Perth

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LeFevre, GH, Novak, PJ, Hozalski, R, 2010, *Quantification of Petroleum Hydrocarbon Residual and Biodegradation Functional Genes in Rain Garden Field Sites*, ASCE Low Impact Development 2010: Redefining Water in the City, Los Angeles

O'Neill, SW, Davis, AP, 2010, *Analysis of Bioretention Media Specifications and Relationships to Overall Performance*, ASCE Low Impact Development 2010: Redefining Water in the City, Los Angeles

4.2 Filter strips

4.2.1 General description

Filter strips are grassed areas of land that are used to manage shallow overland stormwater runoff through several filtration processes in a similar manner to vegetated buffers (Section 4.5.6). They can be as simple as uniformly graded strips of lawn alongside a drain (Field & Sullivan, 2003, Melbourne Water 2005). They are most effective as pre-treatment options in treatment trains, especially to aid the stormwater management processes of bio-retention areas, infiltration trenches and swales (Section 4.1, 4.3 and 4.5). They are also particularly effective as stormwater runoff mitigation options in low-density developments (Debo & Reese, 2003, Environment Protection Authority – Melbourne Water Corporation, 1999). They intercept and spread out stormwater runoff thus helping to attenuate flood peaks. Filter strips are commonly used along stream banks as vegetated buffer systems (Figure 4.3), but are also used downstream from agricultural land to intercept and infiltrate stormwater runoff. They are particularly useful for providing a first line of defence against sheet flows from large paved areas such as parking lots and arterial roadways (Debo & Reese, 2003).

Figure 4.3: Vegetated filter strips adjoining a meandering stream

Filter strips use vegetative filtering as a primary means of stormwater runoff pollutant removal. Properly designed filter strips remove most sediment and other settleable solids such as hydrocarbons; however, soluble nutrients and heavy metals are often not adequately removed. Soluble pollutants generally pass through filter strips although some infiltrate into the underlying soil. There, additional removal is effected when pollutants are bound to organic matter and removed through biological processes (Debo & Reese, 2003, Field & Sullivan, 2003, Melbourne Water, 2005). With the use of appropriate indigenous vegetation, filter strips have the potential to provide a habitat corridor for wildlife (Environment Protection Authority – Melbourne Water Corporation, 1999). Pollution control characteristics for filter strips are included in Appendix B; Table 2.6.

4.2.2 General design guidelines

Filter strips are generally sized against the 6-month, 24-hour recurrence interval storm. As with other bio-retention and infiltration options, the pollutant removal characteristics of filter strips is determined by the relationship between their length, width, slope and soil permeability compared to the stormwater runoff rate and its associate velocity (Field & Sullivan, 2003). Typically, filter strips are at least 5 m long and 7 m wide to provide sufficient contact time for the adequate functioning of the water quality treatment processes. They normally serve areas smaller than 20,000 m^2 with slopes between 2% and 6% (Debo & Reese, 2003). As a rule of thumb, the initial sizing of the specified filter strip should allow for an infiltration area approximately twice that the contributing impervious stormwater runoff surface, or at least be as long and wide (Field & Sullivan, 2003, Woods-Ballard, *et al.* 2007). Excess water running off the infiltration area should be carefully managed to ensure that it does not run onto adjoining developments or create stagnant pools of water in local surface depressions, which could potentially attract mosquito breeding and other nuisances (Stahre, 2006).

The primary treatment process of filter trips is filtration – with limited pollutant uptake. The main design and management objective should therefore be to develop a dense and sustainable vegetation growth in order to maximise the filtration processes and reduce to potential for erosion (Environment Protection Authority – Melbourne Water Corporation, 1999). To promote the settling of pollutants, stormwater runoff velocities should not exceed 0.3 m/s (Woods-Ballard, *et al* 2007). The provision of dense vegetation, preferably indigenous, potentially improves the runoff attenuation in addition to boosting amenity and biodiversity in the immediate vicinity (NCDWQ, 2007). Vegetation selection is linked to the soil and climatic conditions for the specified site, however the height of the chosen vegetation should exceed the expected depth of the overland flow to ensure that the entire flow volume is filtered. Small flow distribution structures can be used to spread the flow more uniformly over the filter area if necessary. Some examples include shallow weirs, check dams, perforated pipes, rip-rap mattresses and stilling basins. As a further rule of thumb, filter strips should not receive any overland flow until the specified vegetation media has been established (Environment Protection Authority – Melbourne Water Corporation, 1999). The general design for filter strips is presented in Appendix C; Figure 4.2.

4.2.3 Advantages

i) The installation and maintenance costs for filter strips are relatively low;

ii) The layout of filter strips is quite flexible;

iii) Infiltration of the stormwater runoff helps to attenuate flood peaks;

iv) Filter strips generally trap the pollutants close to source; and

v) Filter strips normally integrate well within the natural landscape to provide open spaces for uses such as recreation.

4.2.4 Limitations

i) The primary limitation of filter strips is clogging of the subsurface drainage media, which is generally a result of poor solid waste management and irregular maintenance practices;

ii) There is relatively limited potential for filter strip to remove fine sediments and dissolved pollutants;

iii) The stormwater runoff needs to be spread out in order for filter strips to operate optimally;

iv) Filter strips have minimal stormwater runoff storage capacity and are not very good at treating high velocity flows;

v) Because filter strips are not able to manage high velocity stormwater runoff flows, they are not effective on steeply sloping landscapes.

4.2.5 Operation and maintenance

Filter strips are relatively low maintenance stormwater management options. Maintenance largely comprises regular inspection and cutting. In addition, they need to be periodically checked for signs of erosion and cleared of litter. From time to time, sediment may have to be removed which might require re-levelling and the planting of new vegetation (Woods-Ballard, *et al.* 2007). They should also be occasionally inspected during rainfall events to ensure that the flow distribution is relatively uniform over the infiltration area. According to Debo & Reese (2003), clogging of the underlying soil media accounts for the failure of as many as 30% of all infiltration-type SUDS. Vegetation should be kept in a healthy condition, especially in areas of abnormally high or low rainfall. In order to achieve this, weeding and fertilizing in addition to routine watering should be carried out on a regular basis. Vegetation replacement will be necessary in areas that have died-off or have been subject to excess sediment build-up (Field & Sullivan, 2003, Debo & Reese, 2003).

4.2.6 Technology derivative

Vegetated buffers (Section 4.5.6) work in a similar manner to filter strips.

4.2.7 Case studies

Belan, G, Otto, B, 2004, *Catching the Rain: A Great Lakes Resource Guide for Natural Stormwater Management*, American Rivers, Washington D.C., pp. 40: A brief cases study of a vegetated filter strip used to protect a stream from the stormwater runoff from an adjoining building.

Stabenfeldt, L, 1996, *Forest & Riparian Buffer Conservation,* Forestry Workgroup of the Nutrient Subcommittee, Washington: Several case studies on the implementation and conservation of vegetated filter strips and riparian buffers, used for primarily for sustainable stormwater management.

4.2.8 Further reading

Endo, J, Fujiwara, H, Tamoto, N, Sakakibara, T, 2009, *Deterioration of rainwater infiltration facilities with time*, 8th Urban Drainage Modelling and 2nd Rainwater Harvesting Conference, Tokyo

Hathaway, JM, Hunt, WF, 2008, *Field Evaluation of Level Spreaders in the Piedmont of North Carolina, USA*, 11th International Conference on Urban Drainage, Endinburgh

Schooler, PLS, 2010, *An alternate approach to size vegetative filter strips as elements of a highway LID stormwater management strategy*, ASCE Low Impact Development 2010: Redefining Water in the City, Los Angeles

Winston, RJ, Hunt, WF, 2010, *Low Impact Development Benefits of Level Spreader – Vegetative Filter Strip Systems*, ASCE Low Impact Development 2010: Redefining Water in the City, Los Angeles

4.3 Infiltration trenches

4.3.1 General description

Infiltration trenches are excavated trenches that are backfilled with rock or other relatively large granular material (Figure 4.4). A geotextile is used to provide separation between the trench media and the surrounding soil. They normally have a rectangular vertical cross-section. They are usually designed to receive stormwater runoff from adjacent properties and transportation links such as asphalt roads and footpaths (Debo & Reese, 2003, Melbourne Water, 2005, Taylor, 2003). Stormwater permeates through the voids in the trench and is temporarily stored. Over a period of time, this water infiltrates into the underlying soil and replenishes the groundwater (Hobart City Council, 2006). Stormwater volume reductions are significantly higher during small to moderate rainfall events (say <10 mm) than higher rainfall events (say >10 mm) (SEMCOG, 2008). Unlike soakaways (Section 4.3.3), infiltration trenches are usually designed without piped outlets (Endicott & Walker, 2003). However, the installation of perforated pipes in the trenches provides for the outflow of surplus stormwater when infiltration into the surrounding soil is inadequate (Field & Sullivan, 2003, Mays 2001).

Figure 4.4: Infiltration trench system adjacent to a highway

Pollution control characteristics for infiltration trenches are presented in Appendix B; Table 2.6.

Studies have shown that as much as 90% of sediment, metals, coliform bacteria and organic matter are removed from stormwater by infiltration trench systems (Taylor, 2003, Field & Sullivan, 2003). Infiltration trenches are most effective in pollutant removal when provided with an appropriately designed pre-treatment system (Morton Bay Waterways and Catchments Partnership, 2006, Woods-Ballard, *et al*. 2007).

4.3.2 General design guidelines

Appendix C; Figure 4.3 shows typical trench dimensions. The inner perimeter of the trench, which is usually rectangular in cross section, is normally lined with a geotextile fabric to prevent soil and other fine materials from migrating into the rock and/or aggregate fill. The top of the coarse fill material may be capped with the geotextile and covered with a layer of top soil or other growth medium (Melbourne Water, 2005). The aggregate material used to fill the infiltration trench is typically 6 – 40 mm in diameter (Taylor, 2003). When operating optimally, the stormwater infiltrates into the underlying soil or is discharged from the trench within 24 hours after a moderate rainfall event (say 10mm) (Hobart City Council, 2006). Berms may be constructed down-slope of infiltration trenches to encourage further groundwater recharge (Endicott & Walker, 2003, Field & Sullivan, 2003). According to Field & Sullivan (2003), there are four aspects to consider in the design:

i) Infiltration rates in the surrounding soil stratum;

ii) The required stormwater treatment flow rates;

iii) The type of porous media to be used for backfilling the trench; and

iv) The clogging potential of trench.

Infiltration trenches are most effective when implemented adjacent to impervious areas such as roads, footpaths, parking lots and other hardened areas (Mays, 2001, Woods-Ballard, *et al.* 2007). They are most commonly implemented in residential areas; however, if properly designed, infiltration trenches have been used in industrial areas as well (NCDWQ, 2007). It is important that attention is given to the control of sediment as this can lead to premature clogging (Environment Protection Authority – Melbourne Water Corporation, 1999). As a consequence, consideration should be given to the addition of vegetated swales and buffers and/or small detention ponds to reduce the quantity of sediment reaching the trench. The pollutant removal ability of infiltration trenches can also be enhanced by utilising washed aggregate and layering the subsoil with organic matter and top soil (Taylor, 2003).

4.3.3 Advantages

i) Infiltration trenches increase stormwater infiltration and corresponding groundwater recharge;

ii) Infiltration trenches decrease the frequency and extent of flooding;

iii) Infiltration trenches are particularly effective in removing suspended particulates from stormwater;

iv) Infiltration trenches are efficient in most climatic regions with minor design modifications required for particular cold or dry climates;

v) Due to their relatively narrow cross section, infiltration trenches can be utilised in most urban areas, including brown-field or retrofit sites; and

vi) Infiltration trenches can be designed to have minimal visual impact as they are normally implemented and function below ground.

4.3.4 Limitations

i) Infiltration trenches are not appropriate on unstable or uneven land, or on steep slopes;

ii) If infiltration trenches are situated in coarse soil strata, groundwater contamination is a possibility;

iii) Infiltration trenches are prone to failure if sediment, debris and/or other pollutants are able to clog the gravel surface and/or backfilled aggregate material (Taylor, 2003); and

iv) They are generally restricted to areas with permeable soils.

4.3.5 Operation and maintenance

Infiltration trenches require regular maintenance, particularly to avoid clogging in the aggregate infiltration media (Woods-Ballard, *et al.* 2007). For the first year after the trench has been constructed, it should be inspected after every large rainfall (>10 mm) for sediment and debris build up, and the quality and quantity of stormwater. It can be checked quarterly thereafter. The construction costs of infiltration trenches are relatively low compared with other infiltration based SUDS options, however, the cost of maintaining infiltration trenches is relatively higher, especially if they are implemented in areas with fine-grained soils (Taylor, 2003). The top layers of the trench should be periodically cleaned to prevent undesirable sediment build up (Debo & Reese, 2003, Melbourne Water, 2005). If the infiltration trench is clogged by sediment and/or debris, there is also a greater likelihood that mosquito and other vector breeding will occur. If it takes longer than 72 hours for the trench to drain, then the backfilled aggregate infiltration media should be removed and all dimensions of the trench should be increased to improve infiltration into the underlying soil (Taylor, 2003).

4.3.6 Technology derivative(s)

Soakaways (Section 3.3) and infiltration basins (Section 5.2.6) are both similar to infiltration trenches.

4.3.7 Case studies

Carpenter, V, Littleboy, R, Hoyland, J, 2001, *Bognor Regis Sports Centre*, West Sussex County Council, West Sussex: <u>A concise case study on the implementation of an infiltration trench which receives excess stormwater runoff from a porous parking lot and sports pitch.</u>

Melbourne Water, 2003, *Riviera Street Reconstruction*, Melbourne Water, City of Kingston: <u>A case study discussing the alleviation of the problem of stormwater runoff from roads in a suburban neighbourhood, by incorporating vegetated inlet zones and infiltration trenches.</u>

USEPA, 2008, *Case Studies for Stormwater Management on Compacted, Contaminated Soils in Dense Urban Areas*, USEPA: <u>A case study briefly describing the use of infiltration trenches as part of a larger stormwater management system.</u>

4.3.8 Further reading

Browne, D, Deletic, A, Mudd, GM, Fletcher, TD, 2009, *A 2D Stormwater Infiltration Trench Model*, The 6th International Water Sensitive Urban Design Conference and Hydropolis #3, Perth

Endo, J, Fujiwara, H, Tamoto, N, Sakakibara, T, 2009, *Deterioration of rainwater infiltration facilities with time*, 8th Urban Drainage Modelling and 2nd Rainwater Harvesting Conference, Tokyo

Watanabe, A, Ishikawa, Y, Yoshida, K, 2008, *Reduction of non-point source pollutants using infiltration facilities and model analysis of the reduction effects*, 11th International Conference on Urban Drainage, Endinburgh

4.4 Permeable pavements

4.4.1 General description

Permeable pavements refer to pavements that are constructed in such a manner that they promote the infiltration of stormwater runoff through the surface into the sub-layers and/or underlying strata (Figures 4.5 and 4.6). There are many alternatives for the load-bearing surface material including: specially designed concrete block pavers (CBP), brick pavers, stone chip, gravel, porous concrete and porous asphalt. The latter two are also referred to as porous pavements. In places with suitable climates and low traffic loading, even grass can be used with or without reinforcement as the situation demands. Patented open celled concrete grass pavers or cellular plastic grids are often used for the reinforcement of the grass surface layer. The permeable paving surface is suitable for pedestrian and vehicular use, and can be modified to carry heavier loadings (Taylor, 2003, Woods-Ballard, *et al.* 2007). Design software is widely available.

Figure 4.5: Permeable concrete block pavers with open joints and slotted ends filled with pea-sized gravel

Permeable paving is generally constructed on a coarse gravel sub-base which creates temporary storage facilities and allows stormwater runoff to infiltrate into the underlying stratum, promoting the recharge of the groundwater table (Semple, *et al.* 2004, Stahre, 2006). Stormwater that is stored can be collected and reused for several domestic purposes (Section 3.4), typically gardens and lawns (Hobart City Council, 2006). Sub-drains can be utilised for this purpose. Stahre (2006) suggests that evaporation can account for as much as 30% of stormwater stored in permeable paving structures. Permeable pavements generally do not remove litter and other debris from stormwater runoff as this is left on the surface and usually transported elsewhere. Furthermore, soluble pollutants tend to pass through the permeable pavement structures owing to the lack of extended detention. Pollution control characteristics for permeable pavements are listed in Appendix B; Table 2.6.

4.4.2 General design guidelines

It is critical to account for two fundamental negative characteristics of permeable pavements at the planning and design phases; by:

i) Capturing the estimated water quality volume (WQV) and discharging it to the specified drainage system or outfall in a controlled manner; and

ii) Providing adequate structural support to withstand the expected loadings from pedestrian, vehicles, plant or other machinery (Woods-Ballard, *et al.*, 2007).

Permeable pavement technologies are best suited for residential driveways and other light-commercial uses; however some systems can be designed to suit most loading specifications. Typical installations include (Debo & Reese, 2003):

- On-street parking bays in residential areas;
- Parking bays at recreational facilities;
- Private roads, public service roads and fire-engine lanes;
- Industrial storage and loading areas; and
- Bike pathways, walkways, terraces and around swimming pools.

Heavily polluted stormwater containing large quantities of sediment should not be discharged onto permeable paving as it inevitably results in clogging throughout the system (Stahre, 2006). Permeable pavements are prone to clogging and structural failure in high traffic volume areas (Debo & Reese, 2003 and Minton, 2002). Furthermore, the use of permeable pavements should be restricted to slopes less than 5% – ideally flat – as the high velocity stormwater from steep slopes is not readily able to penetrate the pavement surface (Stahre, 2006 and Debo & Reese, 2003). Particular care should be taken to protect the pavements from sediment deposition during construction (Hobart City Council, 2006). The base layers are typically constructed of compacted stone that is able to support the required vehicle loadings (Figure 4.6). These layers must be designed for immersion in water for extended periods of time (Taylor, 2003).

Permeable concrete block pavers (PCBPs) are commonly used for more heavily trafficked areas. They are normally placed on a layer of nominal 5 mm clean stone that sits on a geotextile membrane. The membrane is laid on a 200 mm deep layer of stone aggregate which may in turn be placed on other base layers with or without geomembranes separating the layers (Figure 4.6). Note that there is some controversy concerning the use of geotextiles to separate the layers with some researchers claiming that they are subject to blockage over time from fine material as well as the potential build-up of impermeable organic films. If the permeable pavements can be designed to obviate the need for geotextiles with the aid of a graded filter, this would be preferable. The operation of permeable pavements is highly dependent on the workmanship of the pavement configuration (Woods-Ballard, *et al.* 2007). PCBPs should be laid correctly with even spaces between each paver, and reconfigured as such where necessary.

If there is any concern about the ability of the in-situ material being able to absorb the stormwater trapped in the base-layers of the permeable pavement after rainfall, then perforated drainage pipes should be provided. These pipes typically lie along the first layer of geofabric and span the length of the permeable pavement system.

Figure 4.6: Section through the base layers that will support permeable concrete block pavers

According to the British Board of Agreement (2009), the mean compressive strength of PCBPs is approximately 30 – 40 N/mm^2, with an absolute minimum strength of 30 N/mm^2. PCBPs are generally designed with impact resistance sufficient to prevent the cracking of pavers during the handling and laying implementation phases. Furthermore, they are usually manufactured from C40 concrete which is able to resist the corrosive effects of chemicals, oils and flammable fuels that could potentially spill onto these pavers over their specified design life. PCBPs are normally placed by hand; however, there are several placement devices that can be used to speed up the laying process over larger areas. The general design for permeable pavements is given in Appendix C; Figure 4.4.

4.4.3 Advantages

i) Permeable pavements reduce stormwater discharges rates and volumes from impervious areas;

ii) Permeable pavements increase the 'usable' area on specified developments by utilising, *inter alia*, roadways, driveways and parking lots as stormwater drainage areas;

iii) Stormwater runoff stored in permeable pavements can be used to recharge the groundwater table and for several domestic purposes;

iv) Lined permeable pavement systems can be utilised where foundation or soil conditions limit infiltration processes; and

v) If correctly designed, constructed and maintained, permeable pavements eliminate surface ponding and freeze-thawing in cold regions (Woods-Ballard, *et al.* 2007).

4.4.4 Limitations

i) The implementation of permeable pavements is generally limited to sites with slopes less than 5% (Melbourne Water, 2005);

ii) Permeable pavements should not be constructed over fill materials, as these soils could fail when saturated;

iii) Permeable pavements are normally not suitable for high traffic volumes and speeds greater than about 50 km/hr, or for the usage of heavy vehicles and/or point loads (Woods-Ballard, *et al.* 2007);

iv) If managed incorrectly, there is a great potential for clogging by fine sediment, which significantly reduces the effectiveness of the specified system; and

v) The pollutant removal ability of permeable pavements is significantly lower than most other SUDS options.

4.4.5 Operation and maintenance

The maintenance requirements should be clearly specified and reviewed during the planning and design phases (Taylor, 2003). Regular inspection and maintenance are recommended for ensuring the long-term effectiveness of permeable pavements. The fine stone aggregate in the joints and slots of PCBPs should be replaced from time to time to prevent blockage. Research has shown that these areas are the most prone to blockage; they also tend to trap the most pollutants – including particulate heavy metals which adhere to the fine-grained soil. A typical maintenance procedure includes vacuum-sweeping and/or high pressure jet-washing of the surface every three months or four times per year (Donovan & Naji, 2003, Field & Sullivan, 2003, Melbourne Water, 2005). In the event of failure throughout the specified permeable pavement system, Woods-Ballard, *et al.* (2007) suggest that the following five procedures should be followed for reconstruction:

i) Remove the surface layering and laying course;

ii) Remove the geotextile filtering layers;

iii) Inspect, remove, wash and replace sub-base if required;

iv) Renew or replace the geotextile layering; and

v) Renew the laying course and/or PCBPs.

Having said all of the above, there are many examples around the world of permeable pavement systems that are still operating successfully after many years with minimal maintenance. In many cases, the enormous infiltration capacity of the permeable pavement system – they are frequently designed for an infiltration capacity some ten times greater than theoretically required for the design storm – means that considerable clogging can be tolerated before the system fails.

4.4.6 Technology derivatives

According to Wilson, *et al.* (2004) and Woods-Ballard, *et al.* (2007), permeable pavements are one sub-type of pervious pavements; the other being porous pavements. There are numerous permutations of the basic systems, some of which are described below.

4.4.6.1 Gravel pavement systems

Gravel pavement systems are generally comprised of single-sized aggregate without the addition of a binding product (Figure 4.7). These systems are the simplest and least expensive permeable pavement available. Gravel pavement systems may require daily maintenance procedures, including the raking, sorting and re-levelling of their specified aggregate surfaces. They are most effectively used for parking lots and driveways, where traffic volumes and speeds are relatively low. Geosynthetic materials and plastic grid structures can be utilised beneath the gravel surfacing to provide structural reinforcement. Local crushed aggregate should be used for the surface to avoid excessive transportation costs.

Figure 4.7: Gravel pavement system, Bishops Court Office Park, Hillcrest

4.4.6.2 Porous asphalt and concrete systems

Porous asphalt and concrete systems are generally made from a specially formulated mixture of asphalt or Portland cement and a uniformly graded coarse stone and water. The end result is a material that has a very high permeability, usually several times more permeable than the underlying soil layer. They are then placed on a suitable base course. Porous paving should be avoided in areas where large quantities of sediment, windblown sand and debris may block the porous paving surface. Care must also be taken near shallow aquifers as the system has poor pollution removal characteristics and hence the aquifers could easily be contaminated unless the some barrier is put in place (Debo & Reese, 2003, Hobart City Council, 2006). Under these circumstances, water percolating through the porous paving should be trapped and safely removed from the underlying layers. Porous paving does have the aesthetic advantage that they can be designed to 'blend' into the surrounding urban landscape. They are particularly effective in the removal of suspended solids and sediment from stormwater runoff. On the other hand, they require regular maintenance to ensure their ongoing efficiency (Wilson, *et al.* 2004). Cleaning is generally carried out with the aid of specially designed vacuum cleaners.

4.4.6.3 Modular pavements

Modular pavements typically comprise of modular paving blocks (MPBs) with large openings filled with pervious materials such as stone, sand and grass (Figure 4.8). These blocks interlink to form a pavement surface that is able to support relatively heavy loads. A gravel base course provides storage space for the stormwater runoff that infiltrates through the modular block surface (Stahre, 2006).

Figure 4.8: Modular pavement system planted with grass, Clifton Hill Estate, Hillcrest

There are many modular paving materials commercially available including: flexible plastic cellular confinement systems, moulded plastic materials, interlocking concrete blocks and cast-in-place concrete blocks (Debo & Reese, 2003; Hobart City Council, 2006). Modular block paving is only suited to areas that have low traffic volumes (Debo & Reese, 2003; Minton, 2002).

4.4.7 Case studies

Dourehi, A, Moore, J, 2006, *Raleigh Street stormwater capture and re-use, Cammeray*, 2006 Sustainable Water Challenge, Sydney: <u>A case study on the installation of a permeable paving system that receives stormwater runoff from a shopping centre complex, laden with litter and oil.</u>

Owen, R, Butler, P, Cullan, P, Herd, D, Happold, B, Fisher, N, 2008, *Wessex Water Operations Centre, Claverton Down*, Wessex Water Operations Centre, Bath: <u>A brief case study of use of permeable paving, soakaways, swales and rainwater harvesting to mange stormwater runoff from residential developments.</u>

Still, D, 2009, *Diocese of Natal: Upgrade of Cathedral Centre parking Area*, Partners in Development, Pietermaritzburg: <u>A brief pictorial case study on the upgrade of aging asphalt parking area surfacing with permeable concrete block pavers (PCBP).</u>

4.4.8 Further reading

Kevern, J, 2010, *Maintenance and Repair Options for Pervious Concrete*, ASCE Low Impact Development 2010: Redefining Water in the City, Los Angeles

Myers, B, van Leeuwen, J, Beecham, SC, 2009, *An Experimental Study on the Long-Term Water Quality Impacts of Gravel Media in Storage Underlying Permeable Pavements*, The 6th International Water Sensitive Urban Design Conference and Hydropolis #3, Perth

Smith, DR, Hunt, WF, 2010, *Structural/Hydrologic Design and Maintenance of Permeable Interlocking Concrete Pavement*, ASCE Low Impact Development 2010: Redefining Water in the City, Los Angeles

Young Lee, J, Yang, JS, Park, YT, Choi, J, Han, MY, 2009, *A Pilot-scale study of permeable pavements for surface runoff control at source*, 8th Urban Drainage Modelling and 2nd Rainwater Harvesting Conference, Tokyo

4.5 Swales

4.5.1 General description

Swales are shallow grass-lined channels with flat and sloped sides (Mays, 2001, Parkinson & Mark, 2005). Although they are normally lined with grass (Figure 4.9), alternative linings can be used to suit the characteristics of the specified site (Section 4.5.6) (Field & Sullivan, 2003). They serve as an alternative option to roadside kerbs and gutters in low density residential areas but because they generally have a larger stormwater storage capacity, they help to reduce runoff volumes and peak stormwater flows. They are normally avoided in areas with a high population density as they require relatively large surface areas to function effectively.

Figure 4.9: Roadside swale, Cotswold Downs Golf Estate, Hillcrest

For increased sustainable stormwater management efficacy, swales are commonly combined with buffer and bio-retention systems in a treatment train (Figure 4.10). Swales are usually dry between rainfall events (Stahre, 2006, Endicott & Walker, 2003, Environment Protection Authority – Melbourne Water Corporation, 1999). Swales use a combination of infiltration and bio-infiltration to remove dissolved pollutants in stormwater runoff. The larger particles are filtered by the vegetation (Debo & Reese, 2003; Field & Sullivan, 2003; McAlister, 2007).

Figure 4.10: Swale combined with Bioretention areas, Hawaan Estate, Umhlanga

Apart from serving as open drainage systems for stormwater runoff and providing some minor infiltration area, swales also serve as stormwater pre-treatment facilities for larger SUDS options in the treatment train (Hobart City Council, 2006, Melbourne Water, 2005). A well-designed swale system should provide (Debo & Reese, 2003):

i) Reduction of impervious cover;

ii) Pronouncement of the surrounding natural landscape; and

iii) Multiple aesthetic enhancements.

In natural areas with poor soil stability, paved swales can be used to reduce soil erosion and downstream sedimentation. Paving the swales, however, inhibits their ability to reduce stormwater rates and volumes, possibly adding to the strain on stormwater systems further downstream (Stahre, 2006). The pollution removal characteristics for swales are listed in Appendix B; Table 2.6.

4.5.2 General Design Guidelines

Swales are generally suitable for road medians and verges, car parking runoff areas, parks and recreation areas (Environment Protection Authority – Melbourne Water Corporation, 1999). They should be designed to meet two chief stormwater management processes, namely, (1) flow conveyance requirements, and (2) effective stormwater pre-treatment (Debo & Reese, 2003). According to the MBWCP (2006), the following five steps are typically required for design:

i) Determine the likely treatment performance of the conceptual design, and specify associated plant species and planting densities;

ii) Determine the design flows and resultant dimensions of the swale(s), cognisant of site constraints;

iii) Estimate and optimise the design inflow of the system, verifying the design with scour velocity and treatment performance checks;

iv) Size the overflow area(s) and/or pit(s), making allowance for traffic; and

v) Draft a maintenance plan.

Swales generally form part of the minor flood design and should be sized accordingly (Section 2.1.1.3). Design recurrence intervals vary from two to ten years. Care must be taken to ensure that the flow velocities are not too high and that there is sufficient freeboard level to prevent flooding (Section 2.1.3). Grassed swales are gently sloped in the flow direction, whilst the side slopes are kept gentle enough – typically less than 30° – for the grass to be easily cut using mechanical grass-cutters (Stahre, 2006). In flatter areas, swales may be designed to act as small detention basins with very small flow velocities. If the in-situ soil has a low permeability the base of the swale can be underlain with a granular stone material drained with the aid of perforated pipes. If standing water is a problem, the longitudinal slope of swales should exceed 2.5% (Hobart City Council, 2006, Taylor, 2003). Swales that are long and wide with gentle longitudinal slopes (< 5%) typically perform better than short and narrow configurations (Field & Sullivan, 2003, Debo & Reese, 2003, Melbourne Water, 2005).

The grass covering on and around swales should be kept healthy to assist in the removal of pollutants. Grassed swales remove pollutants by binding them to soil particles and other organic matter. The extent to which soluble pollutants are removed depends on the density of the grass and the exposure of the soil to the stormwater. If the grass is too dense, very little soil will be in contact with the stormwater and the soil may not be very effective in removing contaminants (Minton, 2002; Hobart City Council, 2006; Parkinson & Mark, 2005). Studies have shown swales to be very effective in the removal of heavy metals and suspended solids but not so effective in the long-term removal of nutrients (Debo & Reese, 2003). The MBWCP (2006) list the following four vegetation types for use in and around swales to enhance pollutant removal:

i) Groundcovers for sedimentation removal and erosion protection;

ii) Shrubs for screening, glare reduction and aesthetic value;

iii) Trees for shading and character; and

iv) Indigenous and existing vegetation for ecological stability.

The general design for swales is depicted in Appendix C; Figure 4.5.

4.5.3 Advantages

i) Vegetated swales are normally less expensive and more aesthetically pleasing then kerbs and their associated concrete- and stone- lined channels;

ii) The ponding that results from the runoff from adjacent impermeable areas is often completely infiltrated *in-situ* using swales;

iii) Swales retain particulate pollutants as close to the source as possible; and

iv) Swales generally reduce stormwater runoff volumes and delay runoff peak flows.

4.5.4 Limitations

i) Swales normally require a larger land area than conventional kerb and channel drainage systems;

ii) Swales have very limited removal capabilities for soluble pollutants and fine sediment;

iii) Swales are impractical on properties that have a relatively steep topography;

iv) Standing water in swales have the potential to result in the breeding of mosquitoes and the generation of foul odours; and

v) If they are not properly maintained, failure is likely to occur more quickly with swales than with most other SUDS options.

4.5.5 Operation and maintenance

The effective design life of swales is directly related to the standard of maintenance. Swales have the potential to manage stormwater indefinitely if properly maintained. Maintenance activities generally include, *inter alia*; the regular mowing of grassed surface, weed control, watering during extended dry periods, re-seeding of uncovered areas, and the frequent clearing of litter, debris and visible blockages (Melbourne Water, 2005). The most important maintenance period is the first two years during the 'plant establishment period' when frequent weed control and replanting may be required. The flow inlet and outlet areas require particular attention at the establishment of the specified swale as they may be subject to erosion (MBWCP, 2006). Accumulated sediment should be removed once it typically exceeds approximately 100 mm in depth or starts to overwhelm the vegetation cover (Endicott & Walker, 2003, Field & Sullivan, 2003). The swale should be inspected at least twice year, generally at the beginning and end of the wet season, to check for areas of erosion and channelization (Taylor, 2003).

4.5.6 Technology derivatives

There are several variations which can be considered for stormwater management. Two are described below.

4.5.6.1 Enhanced dry swales

Dry swales are vegetated conveyance systems that include a bed of prepared soil to enhance the filtration of the stormwater runoff volume that passes through it (Figure 4.10). The filter soil overlies an under-drain system. They are designed to treat the entire volume of water that passes through. Dry swales are the preferred option in private properties as they dry out between rainfall events (Debo & Reese, 2003).

Figure 4.10: Gabion-lined dry swale, Hawaan Estate, Umhlanga

4.5.6.2 Wet swales

Wet swales are vegetated conveyance systems designed to retain stormwater and to create marshy conditions that are ideal for wetlands. They require a high water table and/or poorly drained soils if they are to remain wet. Wet swales are generally not used in residential areas as the presence of standing and stagnant water can create foul odours and increase the likelihood of mosquito breeding (Debo & Reese, 2003, NCDWQ, 2007).

4.5.7 Case studies

Chanan, A, Woods, P, Ghetti, I, Singh, G, Spyrakis, 2006, *Connells Point Drainage Project*, NSW Sustainable Water Challenge Awards 2006, Kogarah: A case study on the diversion of stormwater runoff flows through a grassed swale that offered adequate flood protection and environmental benefits.

Melbourne Water, 2005, *Altona Green Park*, Melbourne Water, Hobsons Bay: A case study on the provision of a safe and active recreational area for public use through the implementation of a swale and stormwater collection and reuse system.

Owen, R, Butler, P, Cullan, P, Herd, D, Happold, B, Fisher, N, 2008, *Wessex Water Operations Centre, Claverton Down*, Wessex Water Operations Centre, Bath: A brief case study of use of permeable paving, soakaways, swales and rainwater harvesting to mange stormwater runoff from residential developments.

4.5.8 Further reading

Backstrom, M, 2001, *Particle trapping in grassed swales*, NOVATECH 2001, Lyon-Villeurbanne

Brown, T, Berg, J, Underwood, K, 2010, *Replacing Incised Headwater Channels and Failing Stormwater Infrastructure with Regenerative Stormwater Conveyance*, ASCE Low Impact Development 2010: Redefining Water in the City, Los Angeles

Robert Bray Associates, 2007, *A Sustainable Drainage Design Strategy For Urban Development: Creating A Suds Landscape To Replace The Storm Sewer*, SUDSnet National Conference, Coventry University

5. Regional Controls

5.1 Constructed wetlands

5.1.1 General description

Wetlands are organically shaped, natural systems that are generally comprised of marshy areas of open water and aquatic-resilient plants (Figure 5.1). They may be categorised into: natural, modified natural or constructed. They provide a vibrant habitat for fish, birds and other wildlife – including rare and endangered species. Their aesthetic appeal encourages use for recreation as well for research and education (Debo & Reese, 2003). Constructed wetlands are man-made systems designed to mimic the natural wetlands that would be expected in the area under consideration (Scholz, 2006, Stahre, 2006). They are most often to be found serving catchments larger than 10 hectares, and are particularly useful in attenuating stormwater flood peaks and 'polishing' the runoff from residential areas (Endicott & Walker, 2003). The most common stormwater runoff pollutant treatment processes that occur in constructed wetlands are: sedimentation, fine particle filtration and biological nutrient and pathogen removal (Field & Sullivan, 2003, Parkinson & Mark, 2005).

Figure 5.1: Constructed Wetland, Century City, Cape Town

Constructed wetlands are generally considered to be effective ecosystem filters as they can be very efficient in the removal of particulates and dissolved nutrients as well as noxious substances such as heavy metals (Debo & Reese, 2003, Parkinson & Mark, 2005). Constructed wetlands typically include four zones:

i) The **inlet zone**, which includes a sediment forebay for the removal of coarse sediments;

ii) The **macrophyte zone** (Figure 5.2), which is a shallow and heavily vegetated area that facilitates the removal of fine particles and the uptake of soluble nutrients;

iii) The **macrophyte outlet zone**, which channels cleaner stormwater runoff into adjoining structures downstream; and

iv) The **high flow bypass channel**, which protects the inlet, outlet and macrophyte zones from vegetation damage and structural scour during periods of abnormally high flow (MBWCP, 2006).

Figure 5.2: The macrophyte zone in a constructed wetland, Century City, Cape Town

Constructed wetlands may require a supplementary water supply to support the relatively dense aquatic vegetation with their micro-organisms (Woods-Ballard, *et al.* 2007). Pollution control characteristics for constructed wetlands are included in Appendix B; Table 2.6.

5.1.2 General design guidelines

Constructed wetland processes involve the interaction between stormwater runoff and the vegetation. Their successful implementation requires their effective incorporation into the landscape design and management (MBWCP, 2006). Local conditions should be taken into account in their design. Public access should also be prioritised at the planning and design phases, and the involvement of local interest groups such as wildlife associations and nurseries should be encouraged (Stahre, 2006). The provision of public benches should be considered.

It is critical that a suitable sediment forebay should be provided in the inlet zone to prevent litter, debris, coarse sediment and other gross pollutants from entering the macrophyte zone. The design should also facilitate the easy removal of the accumulated material (Field & Sullivan, 2003). The water level in the wetland needs to be carefully regulated; this is usually carried out with the aid of a suitable level control structure. Consideration should be given to the installation of trash racks on the outlet structure to prevent floating litter or debris from being carried downstream (Debo & Reese, 2003, Stahre, 2006).

The establishment of even flow distribution throughout the constructed wetland system is important to avoid the 'short-circuiting' of flow and stagnation in areas. Meandering flows are ideal as they encourage extended detention times and hence increase the removal of pollutants. In general, pollution removal is related to the time spent in the macrophyte zone. The use of appropriate indigenous vegetation also aids in maintaining biodiversity (Environment Protection Authority – Melbourne Water Corporation, 1999, Field & Sullivan, 2003, Woods-Ballard, *et al.* 2007). Vegetation promotes the settlement of suspended matter and facilitates nutrient uptake processes. Bacteria associated with wetland vegetation assist in the reduction of nitrogen. According to Scholz (2006), the following aspects should be considered in the selection of appropriate vegetation:

i) Rapid establishment and growth;

ii) Minimum disease or weed risk;

iii) Suitable for the local climate;

iv) Tolerant of hypertrophic water-logged conditions; and

v) Having a relatively high stormwater runoff pollutant removal capacity.

Care must be taken to ensure that the wetland vegetation does not act as a source of pollution itself (Minton, 2002). For example, birds roost in certain types of vegetation which can lead to high nutrient loads from their droppings. This should be taken into account in the design of the macrophyte zone(s). The general design for constructed wetlands is given in Appendix C; Figure 5.1.

5.1.3 Advantages

i) Constructed wetlands perform significantly better in the removal of pollutants from stormwater runoff than other regional controls of equal volume;

ii) Constructed wetlands that are effectively incorporated into the urban landscape of neighbouring residences have the potential to add great aesthetic value to those properties provided there is adequate maintenance;

iii) Constructed wetlands are considered the most effective SUDS option for the removal of TSS from stormwater runoff (Debo & Reese, 2003, NCDWQ, 2007);

iv) Small aquaculture wetlands have the ability to produce various kinds of food (Hobart City Council, 2006); and

v) Constructed wetlands can be retrofitted into existing 'flood retarding basins' (Environment Protection Authority – Melbourne Water Corporation, 1999).

5.1.4 Limitations

i) Constructed wetlands could potentially attract mosquitoes and other nuisances, which is of particular concern in areas associated with mosquito related diseases;

ii) Constructed wetlands are limited to application on relatively flat land, as they become costly to incorporate on steep and potentially unstable slopes;

iii) Constructed wetlands may require supplementary water during long dry periods;

iv) Wind action can cause the re-suspension of organic solids where the water is shallows potentially resulting in adverse changes in the soil chemistry; and

v) The vegetation used in constructed wetlands has to adapt to a wide range of stormwater runoff flows and their associated pollutants (Debo & Reese, 2003, Environment

Protection Authority – Melbourne Water Corporation, 1999).

5.1.5 Operation and maintenance

Relative to their size, constructed wetlands generally require less maintenance than most other SUDS options. Nevertheless, they do require relatively frequent and detailed inspections. The maintenance frequency can be reduced through effective pre-treatment. A typical inspection would check for the accumulation of sediment, organic debris, litter, oils, weed growth, nuisances, algal blooms and scour (Environment Protection Authority – Melbourne Water Corporation, 1999). Maintaining healthy vegetation and adequate flow conditions is essential to the functioning of a constructed wetland (Taylor, 2003). From time to time the vegetation will need to be pruned and harvested. Harvested organic matter can often be composted and re-used (Endicott & Walker, 2003, Parkinson & Mark, 2005). Weeds tend to spread rapidly after periods of heavy rainfall and should be removed as soon as practicable. During some seasons, for example in winter, plants naturally 'die-off'. The resultant dense litter layer can enhance stormwater runoff pollutant removal (NCDWQ, 2007).

The breeding of mosquitoes and other disease vectors is a common problem in constructed wetlands. There are several natural methods for controlling this including: the introduction of predators such fish, and deliberately varying the water levels through the breeding season to disturb breeding cycles (MBWCP, 2006). Poorly maintained wetlands are vulnerable to invasive plant species that threaten indigenous wetland vegetation. The removal of invasive plant species is a critical to the sustainability of constructed wetlands (NCDWQ, 2007, Woods-Ballard, *et al.* 2007).

5.1.6 Technology derivatives

Wetlands are complex entities which should be planned and designed for incorporation into natural surroundings. Wilson, *et al.* (2004) and Woods-Ballard, *et al.* (2007) give reference to three constructed wetland derivatives, namely: extended detention shallow wetlands, pocket wetlands and submerged gravel wetlands. Each is briefly described as follows.

5.1.6.1 Extended detention shallow wetlands

Extended detention shallow wetlands store most of the stormwater runoff 'water quality volume' (WQV) in relatively shallow marshy depths within the macrophyte zone(s). Part of the WQV is provided temporarily as extended detention above the marshy surface, and is gradually released for increased stormwater runoff control. This enhanced design allows for the management of a greater volume of stormwater runoff than in a simple shallow wetland. The selection of plants that can tolerate irregular wet and dry periods is essential at the planning and design phases (Woods-Ballard, *et al.* 2007).

5.1.6.2 Pocket Wetlands

Pocket wetlands are typically less than 400 m^2, and serve developments no greater than 40,000 m^2. The water depth in pocket wetlands should not exceed 1.5 m. They generally require excavation down to the water table or a consistent baseflow to support the immediate ecosystem (Woods-Ballard, *et al.* 2007). The outlets often comprise a broad-crested weir which may be equipped with a trash rack and/or drain pipe and valve which can be used to empty the pond for maintenance purposes. Owing to their small size and generally limited stormwater retention period they are not as effective as the larger constructed wetlands. Despite this, they can be an attractive SUDS option for smaller developments (Debo & Reese, 2003).

5.1.6.3 Submerged gravel wetlands

Submerged gravel wetlands are designed with one or more treatment cells backfilled with rock or coarse gravel. The outlet is designed in such a way that the surface of the water remains below the top of the rock/gravel layer during small to medium rainfall events (<10 mm). Algae and microbes thrive on the surface area of the backfill material and the anaerobic conditions near the base of the backfill material promote the removal of nitrogen. This is a technique that is used extensively for the treatment of municipal wastewater; however, it is a relatively new practice in the management of stormwater runoff (Woods-Ballard, *et al.* 2007). For increased pollutant removal efficiency, suitable vegetation may be established elsewhere in the wetland.

5.1.7 Case studies

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5.2 Detention ponds

5.2.1 General description

Detention ponds or detention basins are temporary storage facilities that are ordinarily dry but are designed in such a manner that they are able to store stormwater runoff for relatively short periods of time (Figure 5.3). The captured stormwater runoff either infiltrates into the underlying soil stratum or, more usually, is drained into the downstream watercourse at a predetermined rate. This means that detention ponds are particularly effective at regulating the flow in the downstream watercourses and/or supplementary treatment systems. They are usually unlined and vegetated, but lined ponds can be used if there are soil stability or land use issues (Environment Protection Authority – Melbourne Water Corporation, 1999, Field & Sullivan, 2003, Parkinson & Mark, 2005). The use of detention ponds depends on the availability of adequate space.

Figure 5.3: Large roadside detention pond, Hillcrest

Insoluble pollutants from stormwater runoff are typically removed through sedimentation processes. In this regard, the detention time and volume of stormwater runoff govern the pollutant removal efficacy of the system. Hence, the larger detention ponds with greater surface areas and volumes tend to have better pollutant removal capabilities than smaller ponds. Detention ponds are most effective with small magnitude, high frequency storms (Debo & Reese, 2003, Environment Protection Authority – Melbourne Water Corporation, 1999, Field & Sullivan, 2003). Typical pollution control characteristics for detention ponds are listed in Appendix B; Table 2.6.

5.2.2 General design guidelines

In general, detention ponds are designed to temporarily store as much water as possible whilst aiming to provide a safe and secure public environment (Field & Sullivan, 2003). According to the Environment Protection Authority – Melbourne Water Corporation (1999) and Woods-Ballard, *et al.* (2007), the following four factors should be considered at the planning and design phase:

i) The local catchment hydraulics and hydrology;

ii) The implementation of appropriate safety structures including pest and vector controls;

iii) The ground slopes around the pond perimeter; and

iv) Upstream treatment systems and outlet structures.

Detention ponds generally include 'hard' engineered outlet structures that regulate the discharge of stormwater (Debo & Reese, 2003, Endicott & Walker, 2003). An emergency spillway should also be provided if there is a risk of damage from an overflowing point (Figure 5.4). Detention ponds are vulnerable to erosion from high speed flows so particular care must be taken to ensure that this does not happen. This can be accomplished in a number of ways from the construction of entrance structure that spreads the inflow to the planting of hardy vegetation in and around the entrance. In arid regions, any vegetation should be drought tolerant (Debo & Reese, 2003, NCDWQ, 2007).

Figure 5.4: Detention pond emergency overflow structure, New Heritage Market, Hillcrest

The pollutant removal performance of detention ponds can be improved through the construction of upstream pre-treatment SUDS options and/or the construction of a sediment trap at the entrance. The addition of a sediment trap at the inlet to the pond potentially reduces the long-term operation and maintenance requirements. For best performance in pollution removal, detention ponds typically require a surface area of at least 2% of the total tributary development area (Field & Sullivan, 2003, MBWCP, 2006). In industrial areas, they should be designed to trap common and hazardous pollutants and other probable contaminated particulates. For safety purposes, detention ponds should be fenced. It should also be possible to rapidly drain them if urgently required (Stahre, 2006). Typical design details for detention ponds are given in Appendix C; Figure 5.2.

5.2.3 Advantages

i) They are able to temporarily store large volumes of stormwater thus attenuating downstream flood peaks;

ii) Owing to the simplicity of their design, detention ponds are relatively inexpensive to construct and easy to maintain;

iii) They provide an alternative to wetlands in areas which are not appropriate for the latter;

iv) Detention ponds may serve multiple purposes during drier seasons, particularly recreational purposes such as sports fields, play parks or commons; and

v) If managed regularly, detention ponds 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.

5.2.4 Limitations

i) Detention ponds are not very good at removing dissolved pollutants and fine material;

ii) They are most effective at or near their design flow; their efficacy drops off quite rapidly with very low or high flows;

iii) Siltation can be a problem;

iv) If they are not properly designed and maintained there is a possibility that previously deposited sediment and debris will be re-suspended and transported downstream;

v) The floors of detention ponds can become swampy for some time after major rainfall;

vi) For best results, detention ponds have a large plan area. This takes valuable land; and

vii) Detention ponds are 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 (Hobart City Council, 2006, Taylor, 2003).

5.2.5 Operation and maintenance

The hydraulic and pollution removal performance of detention ponds depend on good maintenance. Regular inspections should be carried out to check whether the clearing of accumulated sediment is necessary. This is particularly important if the pond serves a dual purpose such as a sports field, play area or commons (NCDWQ, 2007). The management of vegetation (e.g. mowing the grass) should also be carried out when appropriate (Woods-Ballard, *et al.* 2007). Inspections should be carried out after larger rainfall events (>10mm) to ensure that the pond is performing as designed and that the inlet and outlet structures are free of debris and litter (Environment Protection Authority – Melbourne Water Corporation, 1999). Detention ponds may require desilting from time to time (typically every 5 years).

5.2.6 Technology derivatives

SEMCOG (2008), Wilson, *et al.* (2004) and Woods-Ballard, *et al.* (2007) describe two detention pond derivatives: extended detention ponds and infiltration basins. Each is briefly described as follows.

5.2.6.1 Extended detention ponds

Extended detention ponds function in a similar manner to constructed wetlands except that they are allowed to dry out. Stormwater is treated by passing it through vegetation and infiltrating it into the soil. Particular care should be taken to prevent the compaction of the underlying soils to maintain infiltration rates and encourage seedling and plant growth. Ideally, indigenous plants are utilized to maintain natural landscapes and biodiversity (Figure 5.5).

Figure 5.5: Extended detention pond, Century City, Cape Town

5.2.6.2 Infiltration basins

Infiltration basins are very similar to detention ponds in design, construction and maintenance except that they do not ordinarily discharge into a downstream watercourse. Instead, stormwater runoff is infiltrated into the ground where it recharges the underlying aquifers. The quality of the water is improved through filtration through the sand medium. This can be enhanced through the use of vegetation in the same manner as a bio-retention device (Figure 5.6). They are usually designed to handle small rainfall events from catchment areas of less than 4 ha.

Figure 5.6: Infiltration basin, Century City, Cape Town

5.2.7 Case studies

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5.3 Retention ponds

5.3.1 General description

Retention ponds, also referred to as 'retention basins', may be constructed by excavating to below the water table. They thus have a permanent pool of water in them (Debo & Reese, 2003, Mays 2001). Alternatively, they are formed through the construction of a dam wall (or walls) which is usually equipped with a weir outlet structure (Figure 5.6). The maximum storage capacity of retention ponds is larger than their permanent pond volume. Stormwater coming into the pond is mixed with the permanent pond water prior to release over the weir (Field & Sullivan, 2003, NCDWQ, 2007). Retention ponds are usually capable of handling relatively large quantities of stormwater runoff, releasing it in a controlled manner so as to reduce the downstream flood peak (Woods-Ballard, *et al.* 2007). In addition, the permanent pond volume can be utilised as a source of water for various non-potable purposes (Section 3.4).

Retention ponds generally provide a medium to high pollutant removal capacity (Woods-Ballard, *et al.* 2007). They normally utilize a combination of sedimentation, filtration, infiltration and biological uptake processes to remove pollutants from stormwater runoff. Retention ponds strategically placed adjacent to commercial and industrial sites may be used as separators for oil-based products and heavy metals that flow from impervious surfaces (Stahre, 2006). As a consequence, there is a greater likelihood of the removal of dissolved pollutants in retention ponds than in detention ponds (Endicott & Walker, 2003, Minton, 2002). Generally, retention ponds are less problematic to maintain than detention ponds (Field & Sullivan, 2003), although care must be taken to ensure that they are not a drowning hazard. Pollution control characteristics for retention ponds are listed in Appendix B; Table 2.6.

Figure 5.6: Large retention pond, Cotswold Downs Golf Estate, Hillcrest

5.3.2 General design guidelines

Retention ponds can be used for a wide variety of land uses – provided that sufficient space is available. They are also effective as a retrofit option (NCDWQ, 2007, Woods-Ballard, *et al.* 2007). Water loss through the floor and sides of the ponds can be reduced by installing clay or plastic liners below the permanent water level (Debo & Reese, 2003). At the design stage, it is important to address various concerns associated with the open water characteristics of retention ponds. These typically include: the mitigation of health and safety risks, aesthetic appeal, and the eradication of potential mosquito breeding and other nuisances (Field & Sullivan, 2003, Endicott & Walker, 2003). Safety can be improved by designing the pond with moderate side slopes and relatively shallow depths, as well as providing a barrier – which could be vegetation – around its perimeter (Stahre, 2006).

The performance of retention ponds is significantly improved with the construction of a sediment forebay at the inlet. The outlet structure should typically enable the temporary storage of the runoff from the design storm; releasing the volume over a 24-hour period. It should also be able to allow for the complete drainage of the pond for maintenance purposes (Endicott & Walker, 2003, Woods-Ballard, *et al.* 2007). Effective pollutant removal is enabled by increasing the time the stormwater resides in the pond (Debo & Reese, 2003, Field & Sullivan, 2003).

Flood control is provided with the addition of extended detention storage volume above the permanent water line. This area typically comprises a minimum 3 m wide vegetated littoral zone surrounding the pond. The addition of a shallow 'bench' along the perimeter can provide an aquatic habitat that has the potential to enhance biological pollutant removal for the influent stormwater runoff, and reduce the likelihood of algal mat formation (Field & Sullivan, 2003). Vegetation can also be used to stabilise adjoining side slopes and prevent soil erosion (NCDWQ, 2007, Woods-Ballard, *et al.* 2007). The use of appropriate indigenous vegetation is recommended in order to maintain local biodiversity and to ensure that the vegetation grows with ease and can tolerate the conditions in the pond (Debo & Reese, 2003). The general design for retention ponds is to be found in Appendix C; Figure 5.3.

5.3.3 Advantages

i) The incorporation of retention ponds into the natural landscape provides amenity and biodiversity benefits and can also be used for recreational purposes where adequate supervision is available;

ii) Retention ponds generally have the capacity to remove a wide range of common stormwater runoff pollutants;

iii) Retention ponds have superior cost, performance and maintenance criteria relative to most other SUDS options;

iv) Retention ponds have high community acceptability (Endicott & Walker, 2003, Woods-Ballard, *et al.*, 2007); and

v) Stormwater runoff that is captured in retention ponds can be reused for secondary domestic purposes and for various irrigation requirements.

5.3.4 Limitations

i) The permanent open pool of water creates health and safety concerns and therefore requires social impact considerations at the design stage;

ii) The permanent open pool of water could display floating debris and scum, in addition to the attraction of nuisances such as foul odours and mosquito breeding if maintained infrequently or irregularly;

iii) Retention ponds are normally restricted to sites with shallow slopes;

iv) Retention ponds require a baseflow or the addition of supplementary water to maintain a specified permanent water line.

v) Retention ponds normally require relatively large footprints and are thus impractical in dense urban areas;

5.3.5 Operation and maintenance

Retention ponds and detention ponds share similar operation and maintenance requirements, the most important being sediment and litter removal cycles, especially if the specified pond is situated in an area of high visibility – for aesthetic reasons (Parkinson & Mark, 2005). Other requirements typically include the mitigation and eradication of nuisances such as foul odours and mosquito breeding, and the stringent implementation of weed control (Field & Sullivan, 2003). The outlet structure must be designed in such a way that it can be opened and the pond drained so that it can be cleaned in the event of excessive pest populations or rapid algae growth. Taylor (2003) suggests that appropriately chosen fish could be introduced into retention ponds to improve natural mosquito and midge control. Inlet and outlet structures are prone to clogging from accumulating floating debris and litter, and should thus be inspected and cleared frequently, especially after large rainfall events (Endicott & Walker, 2003, Woods-Ballard, *et al.* 2007). Any damaged structural components that are identified should be repaired as quickly as possible to prevent major structural collapse (Hobart City Council, 2006).

5.3.6 Technology derivatives

Reference is commonly given to several augmentations that can be used to improve the performance of retention ponds in managing stormwater runoff. According to Van Duzer (2004) and Haskins (2010), the stormwater runoff pollutant removal capabilities of retention ponds can be significantly improved with the addition of floating islands. This retention pond derivative is briefly described as follows.

5.3.6.1 Floating islands

Floating islands, also referred to as 'managed aquatic plant systems' (MAPS) or 'floating treatment wetlands' (FTW), are floating material structures packed with aquatic plants and other aquatic vegetation types, which are released to meander on the surface of retention ponds or other open water sources. The specially selected aquatic plants and vegetation are supported on floating material and rooted in matrix-like soil media. They are particularly useful in the uptake of dissolved nutrients suspended in the water column. The root structures are able to hang freely in the water and are naturally covered with biofilm that supports nutrient uptake (Haskins, 2010). To ensure this intervention remains a permanent means of stormwater runoff pollutant removal, the aquatic plants and vegetation should be frequently harvested and replaced when necessary.

5.3.7 Case studies

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Appendix A

SUDS design framework

Adapted from: Debo & Reese (2003)

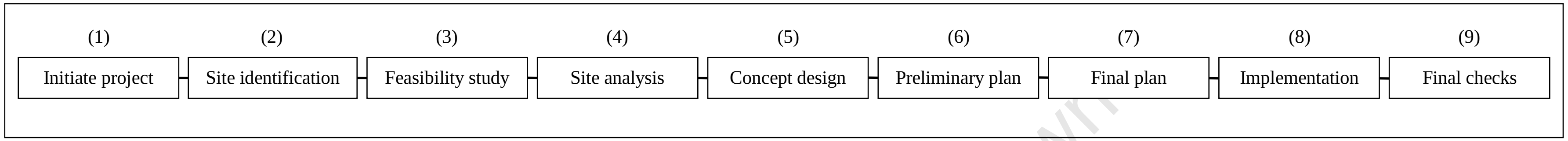


Figure 2.1: Nine step Simplified Site Development Process (SSDP)

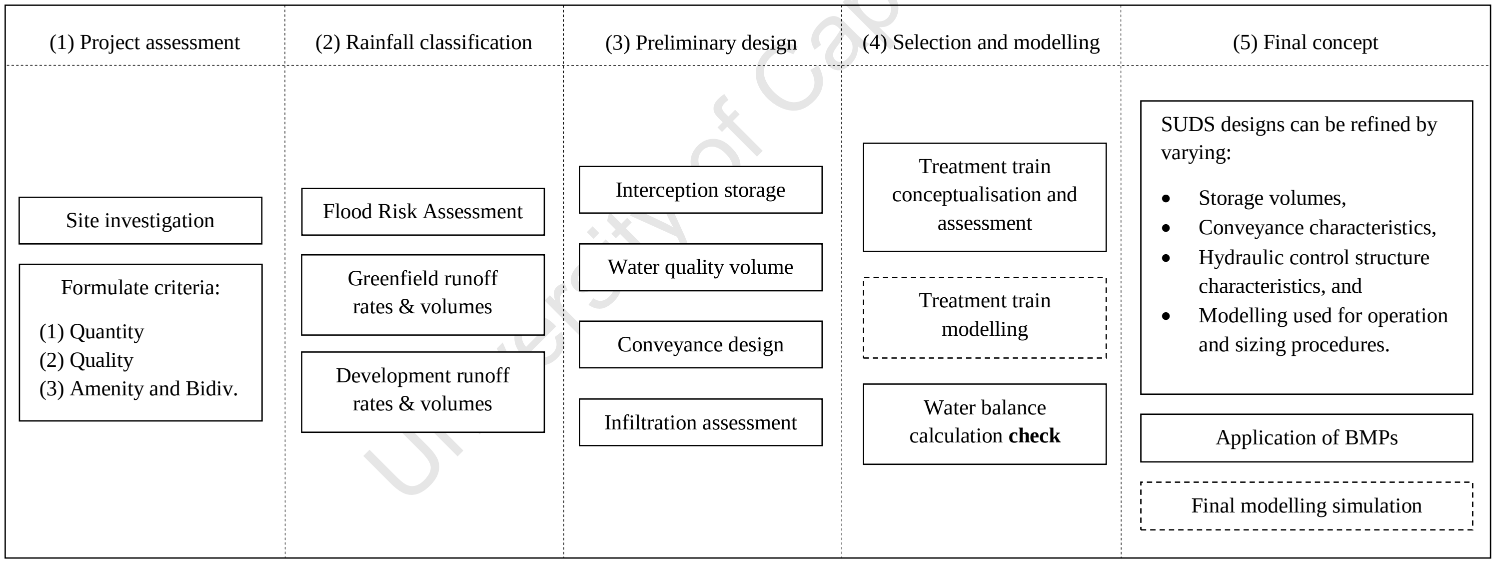


Figure 2.2: SUDS Conceptual Design Framework (CDF)

Appendix B

Pollutant removal capacities

Table 2.6: Estimated pollutant removal capacities of selected SUDS options and technologies
(After Debo & Reese, 2003, Minton, 2002, NCDWQ, 2007, Wilson, et al.2004, Woods-Ballard, et al.2007)

Option and/or Technology	Pollutant Removal Capabilities (%)					
	TSS	Hydro-carbons	TP	TN	Faecal Coli Forms	Heavy Metals
Source controls						
Green roofs	60-95	-	-	-	-	60-90
Extensive green roofs	-	-	-	-	-	-
Intensive green roofs	-	-	-	-	-	-
Simple intensive green roofs	-	-	-	-	-	-
Green walls	-	-	-	-	-	-
Blue roofs	-	-	-	-	-	-
Sand filters	80-90	50-80	50-80	25-40	40-50	50-80
Underground sand filters	75-90	-	30-60	30-50	40-70	40-80
Surface sand filters	-	-	-	-	-	-
Filter drains	50-85	30-70	-	-	-	50-80
Soakaways	70-80	-	60-80	25-60	60-90	60-90
Oil and grit separators	0-40	40-90	0-5	0-5	-	-
Modular geocellular structures	PS	PS	PS	PS	PS	PS
Stormwater collection and reuse	PS	PS	PS	PS	PS	PS
Direct supply system	PS	PS	PS	PS	PS	PS
Gravity supply system	PS	PS	PS	PS	PS	PS
Centralised supply system	PS	PS	PS	PS	PS	PS
Local controls						
Bioretention areas	50-80	50-80	50-60	40-50	-	50-90
Bioretention ruts	-	-	-	-	-	-
Filter strips	50-85	70-90	10-20	10-20	-	25-40
Infiltration trenches	70-80	-	60-80	25-60	60-90	60-90
Permeable pavements	60-95	70-90	50-80	65-80	-	60-95
Gravel pavement systems	-	-	-	-	-	-
Porous asphalt and concrete systems	PS	PS	PS	PS	PS	PS
Modular pavements	PS	PS	PS	PS	PS	PS
Swales	60-90	70-90	25-80	30-90	-	40-90
Enhanced dry swales	70-90	70-90	30-80	50-90	-	80-90
Wet swales	60-80	70-90	25-35	30-40	-	40-70
Vegetated buffers *****	50-85	70-90	10-20	10-20	-	25-40
Regional controls						
Constructed wetlands	80-90	50-80	30-40	30-60	50-70	50-60
Extended detention shallow wetland	-	-	-	-	-	-
Pocket wetland *****	80-90	50-80	30-40	30-60	50-70	50-60
Submerged gravel wetland	-	-	-	-	-	-
Detention ponds *	45-90	30-60	20-70	20-60	50-70	40-90
Extended detention ponds	65-90	30-60	20-50	20-30	50-70	40-90
Infiltration basins	45-75	-	60-70	55-60	-	85-90
Retention ponds	75-90	30-60	30-50	30-50	50-70	50-80
Floating islands	-	-	-	-	-	-

PS - Product Specific; TSS - Total Settleable Solids; TP - Total Phosphorous; TN - Total Nitrogen
* Estimated values based on similar SUDS options

Disclaimer:
The values quoted in this table may be used to assess the general relative performance of selected SUDS options and technologies so as to minimise the risk of stormwater runoff pollutants entering receiving watercourses. The values should ***not*** *be considered or used as absolute values as the performance of SUDS and SUDS Treatment trains is subject to many complex variables that are site specific. These values should be used to support judgement when assessing the risk of system failure and to compare the relative performance between combinations of different SUDS Treatment trains.*

Appendix C

General designs for SUDS options

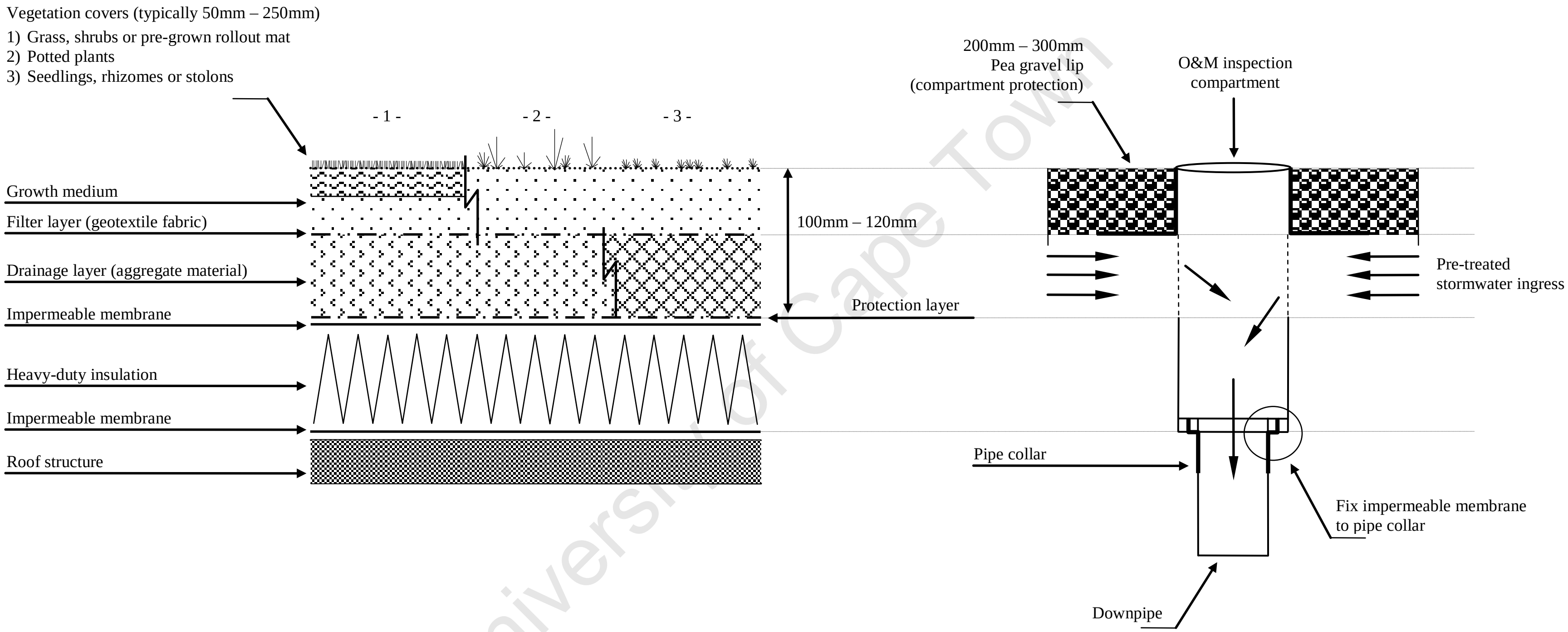


Figure 3.1: General design for green roofs and adjoining inspection compartment

[After Wilson, *et al.*, (2004) and Woods-Ballard, *et al.*, (2007)]

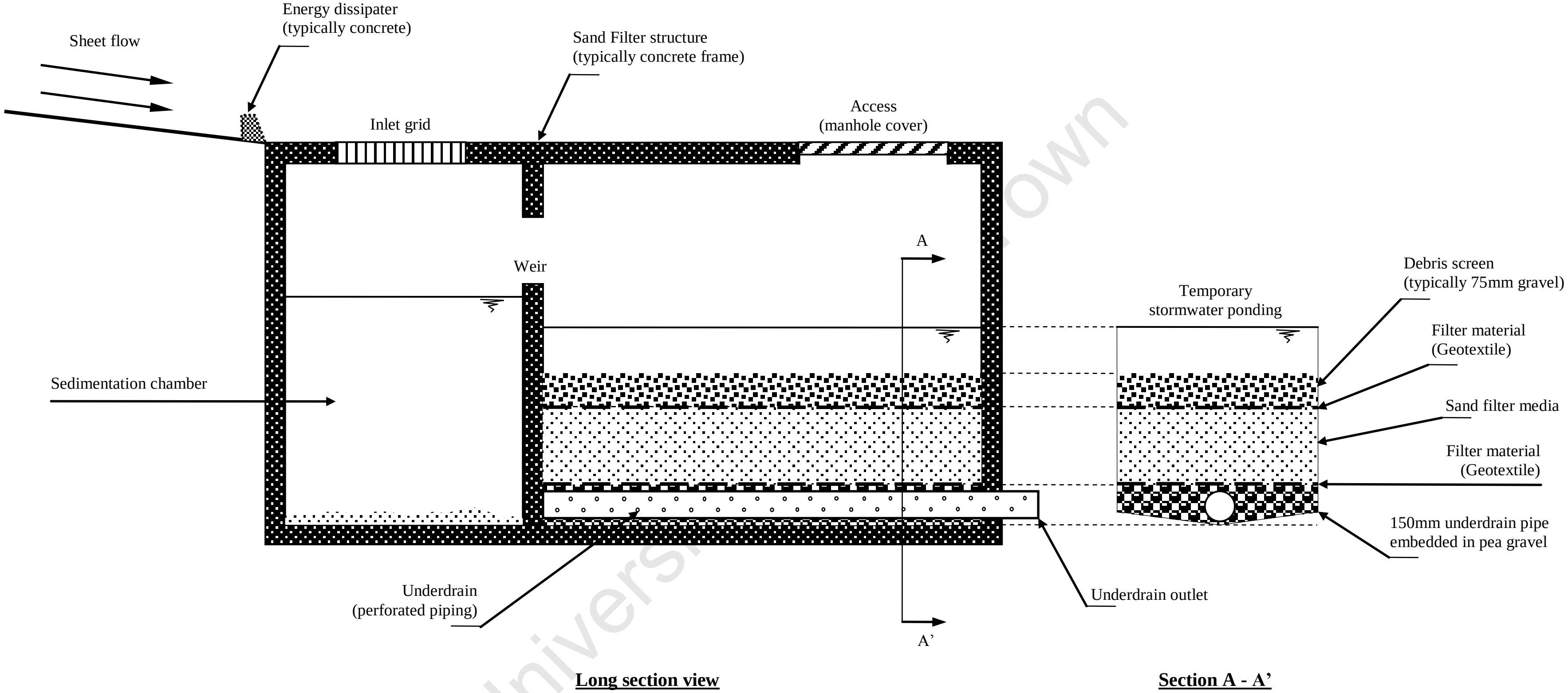


Figure 3.2: General design for sand filters with pre-treatment chamber
[After Wilson, et al. (2004) and Woods-Ballard, et al. (2007)]

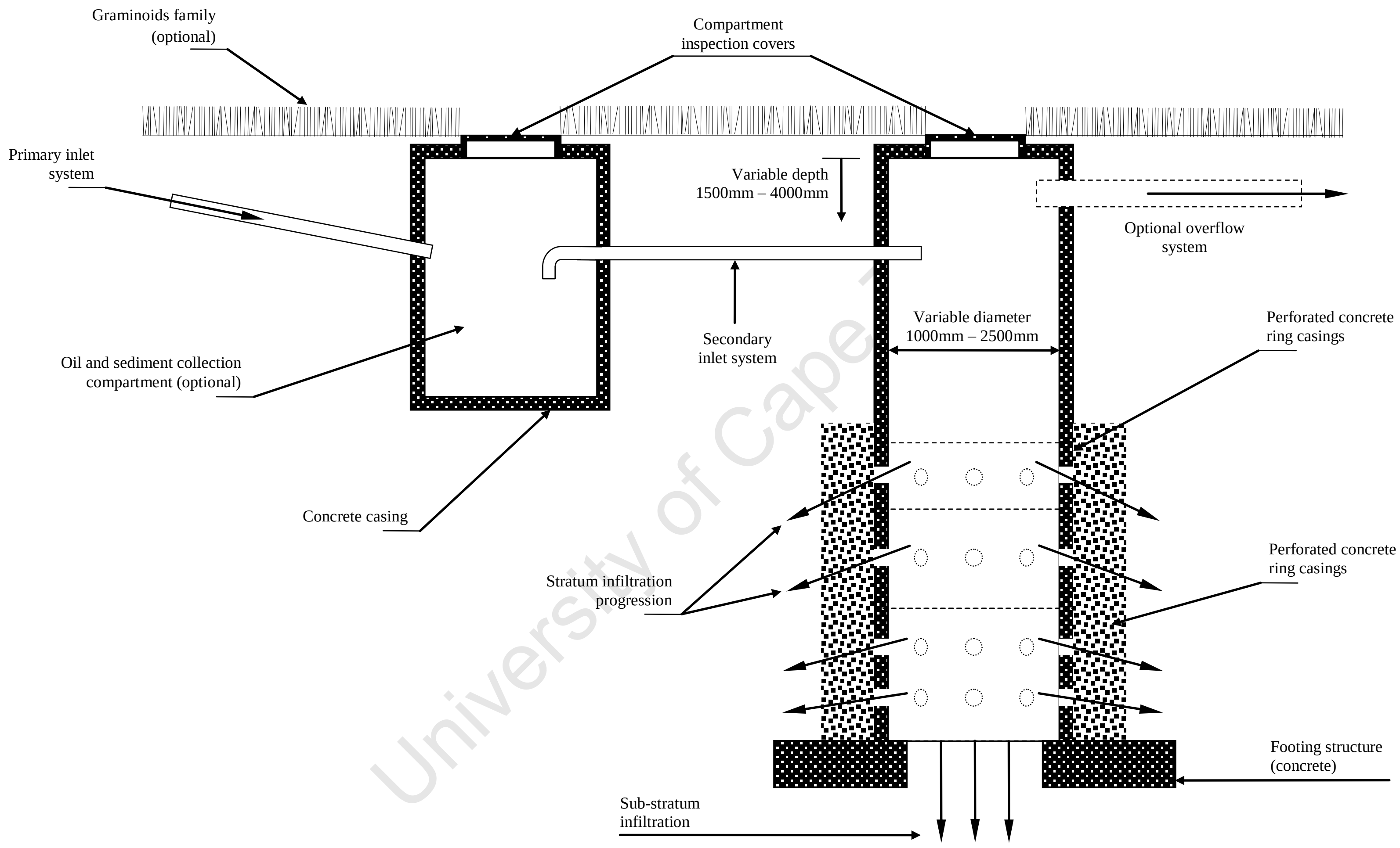


Figure 3.3: General design for soakaways with pre-treatment compartment
[After Woods-Ballard, et al. (2007)]

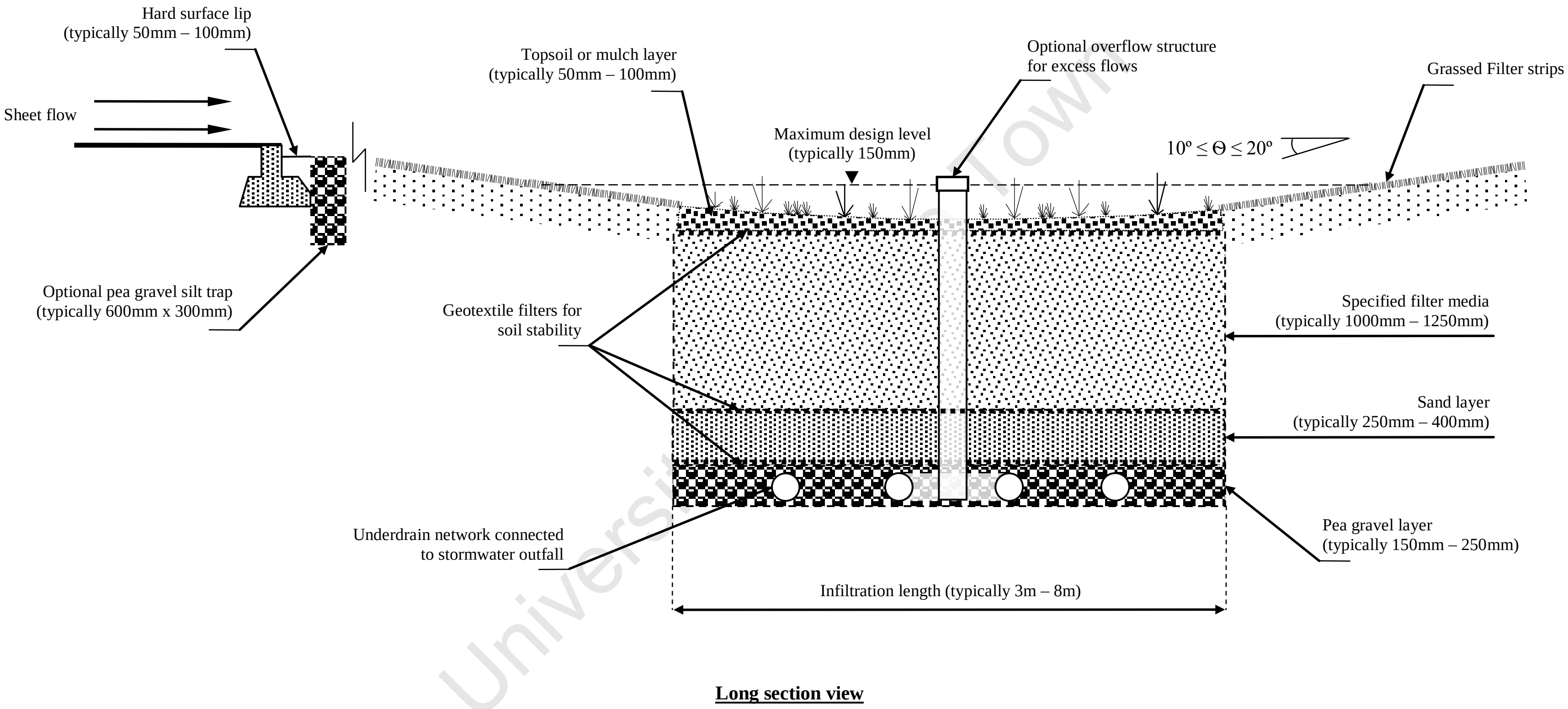


Figure 4.1: General design for bio-retention areas
[After Wilson, et al. (2004) and Woods-Ballard, et al. (2007)]

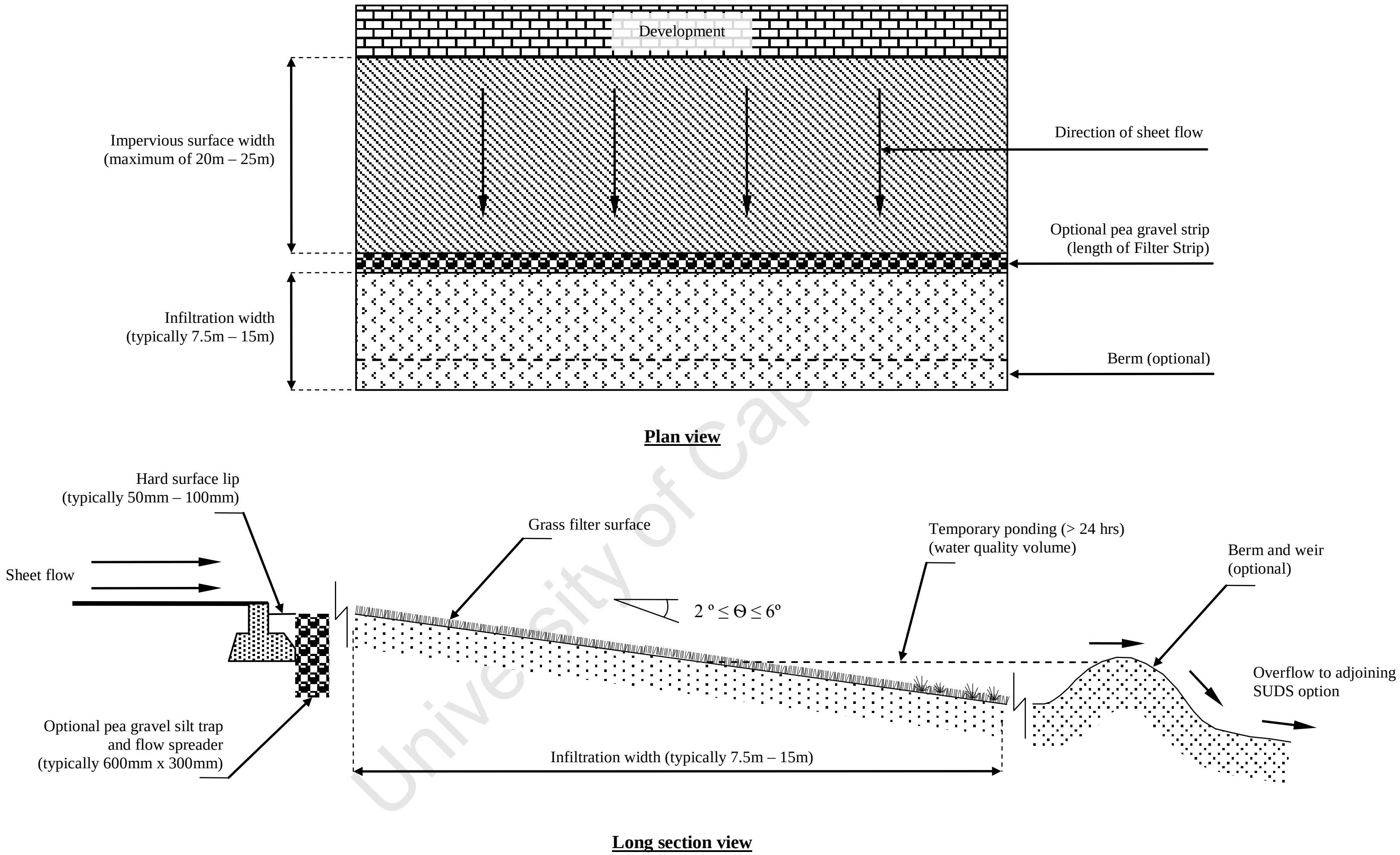


Figure 4.2: General design for filter strips and adjoining silt trap and berm
[After Wilson, et al. (2004) and Woods-Ballard, et al. (2007)]

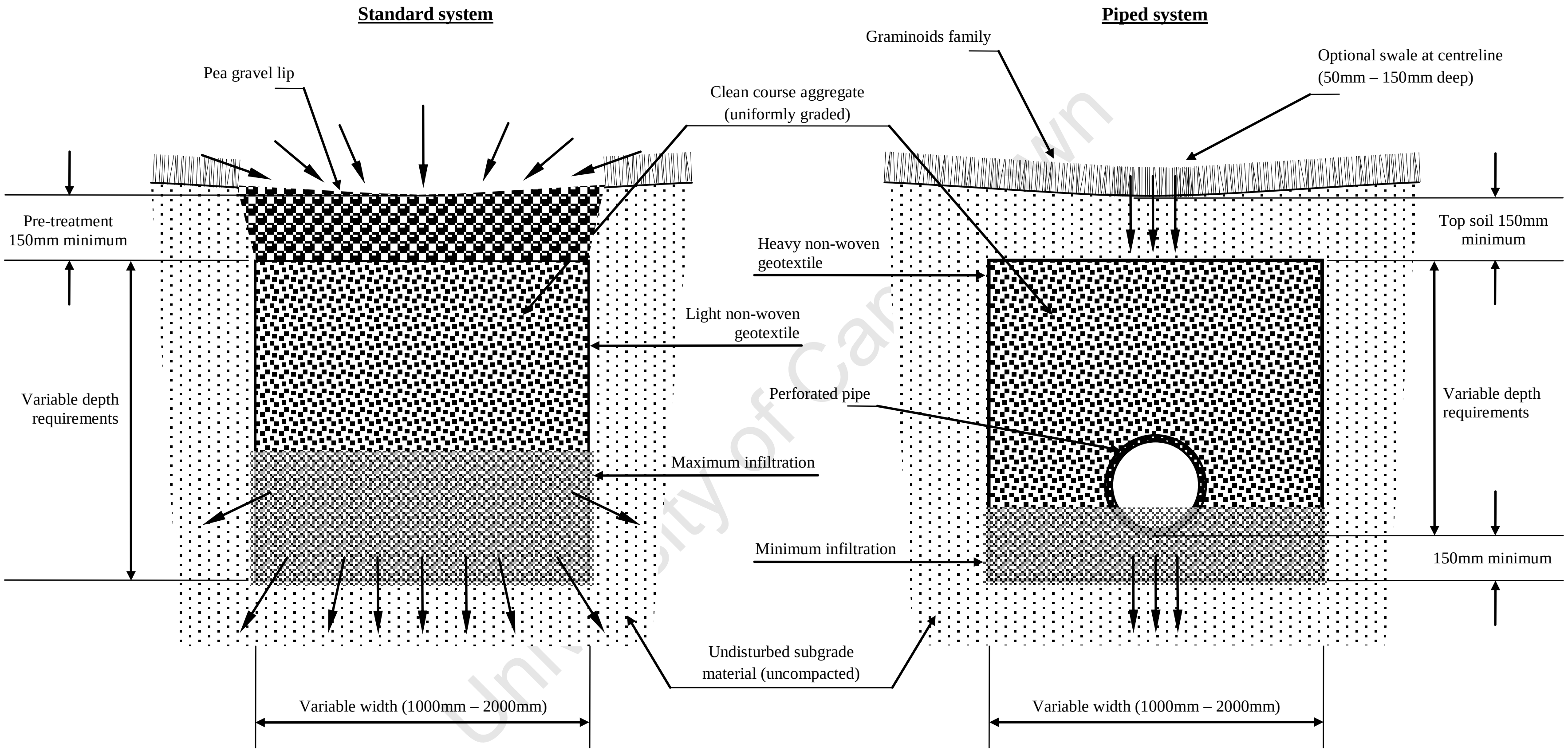


Figure 4.3: General design for dual system infiltration trenches
[After SEMCOG (2008)]

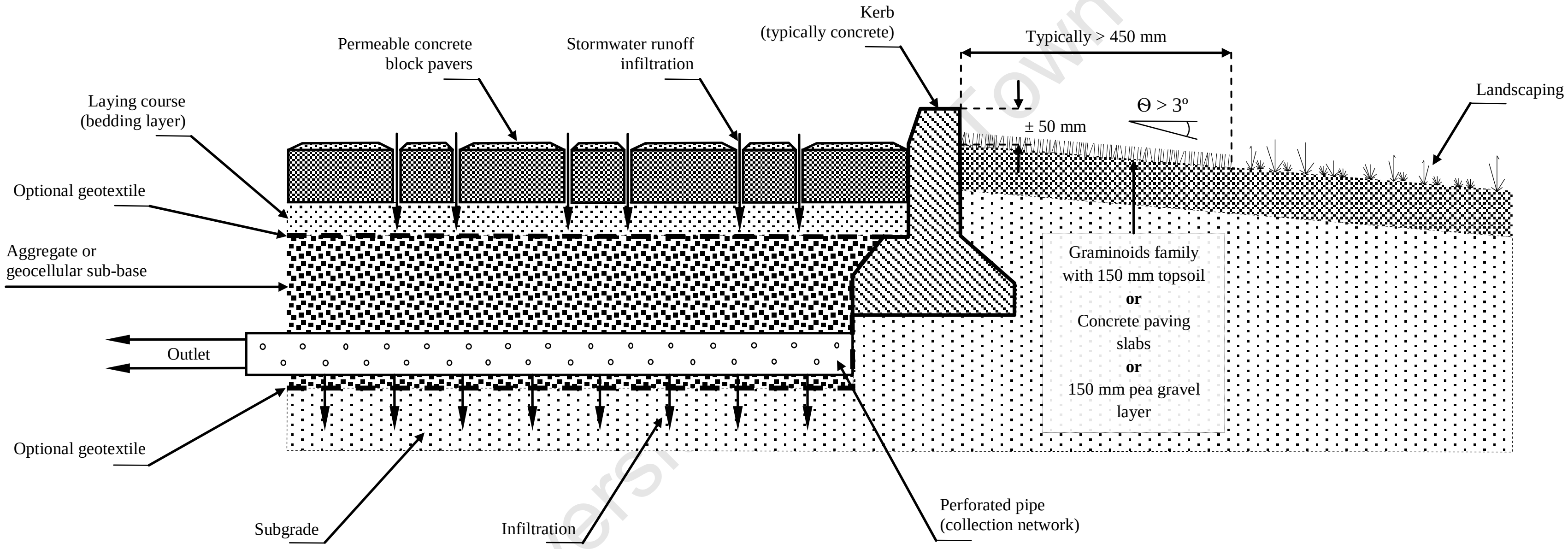


Figure 4.4: General design for permeable pavements and adjoining landscaped areas
[After Wilson, et al. (2004) and Woods-Ballard, et al. (2007)]

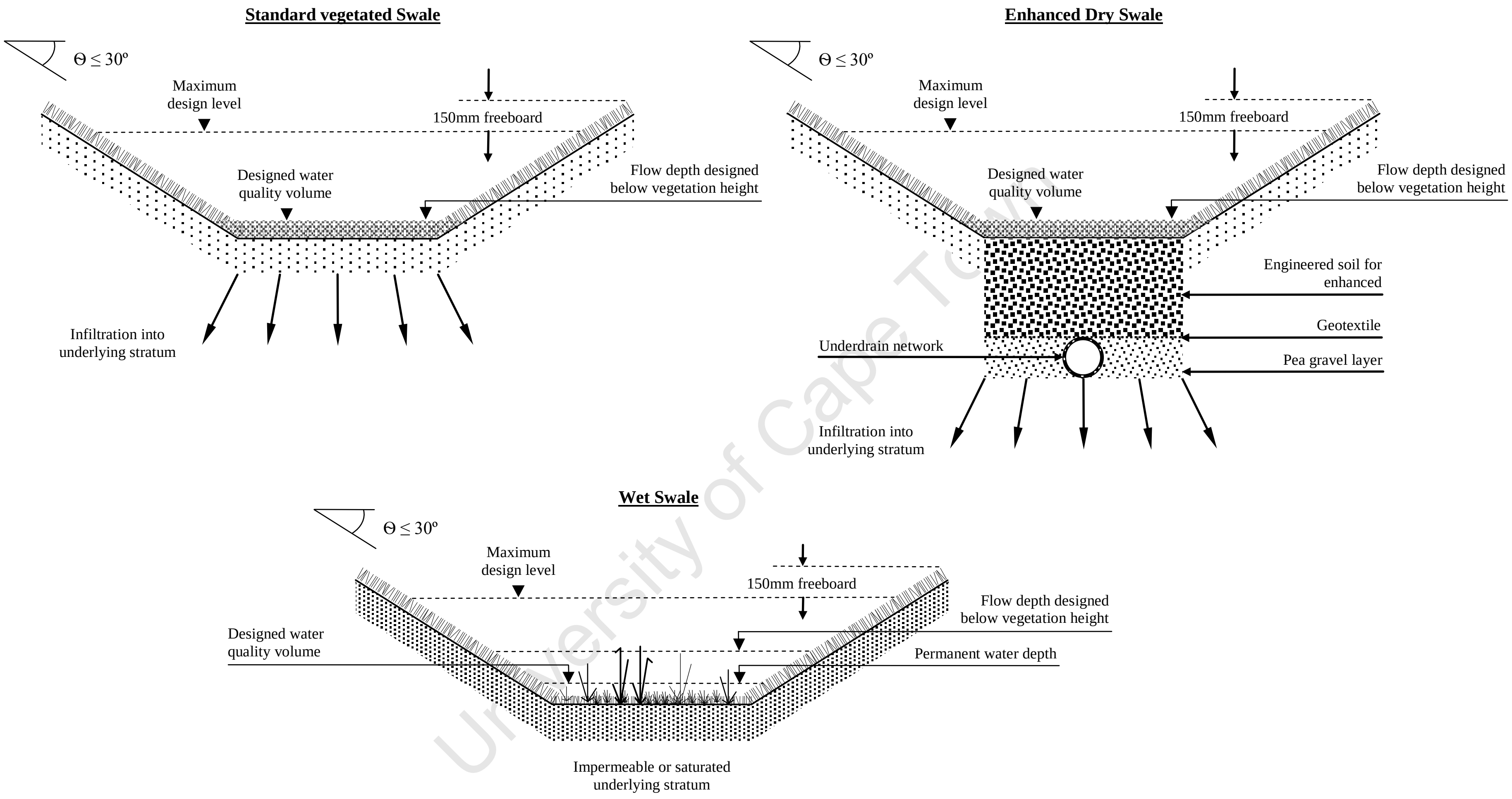


Figure 4.5: General design for swales

[After Wilson, et al. (2004) and Woods-Ballard, et al. (2007)]

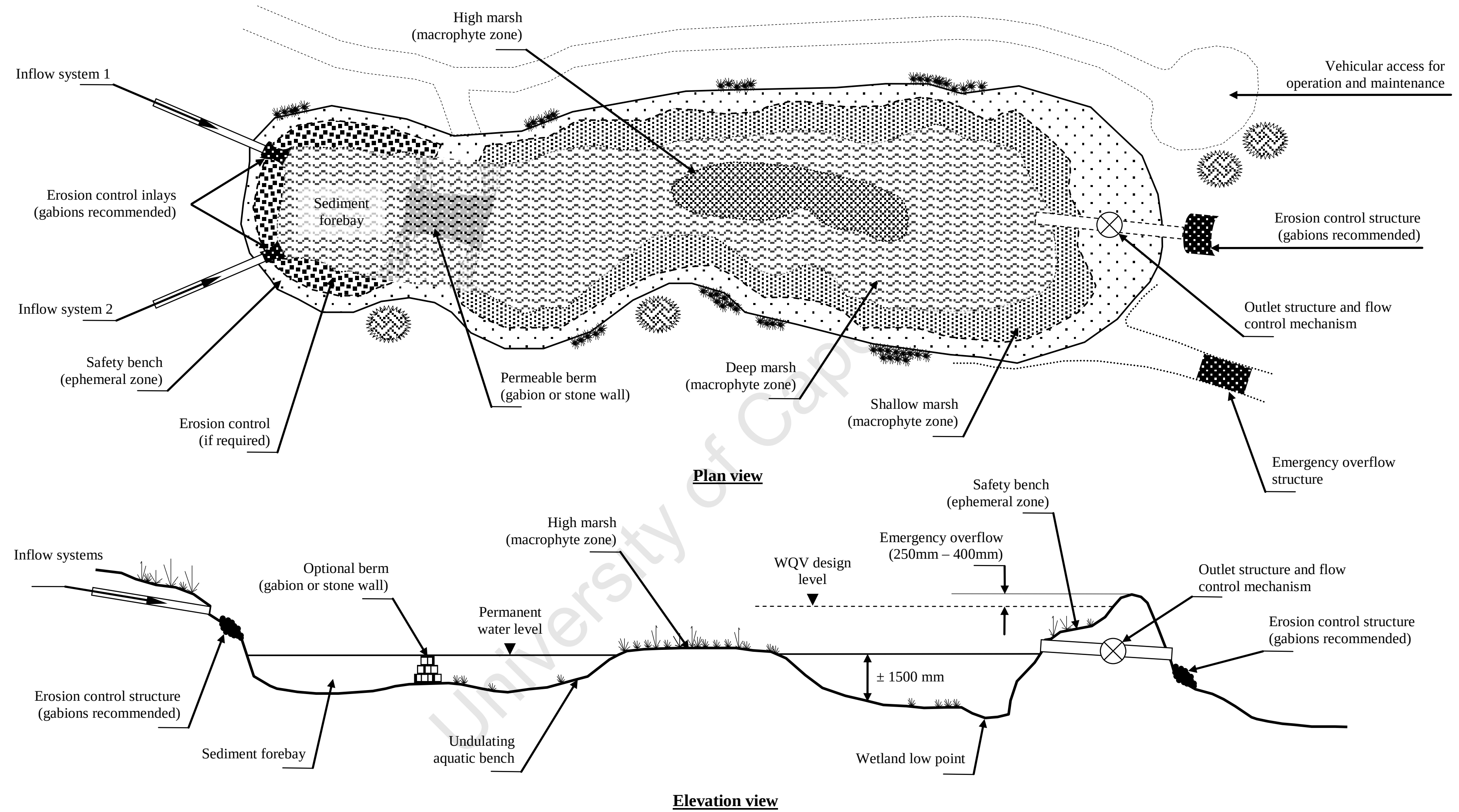


Figure 5.1: General design for constructed wetlands

[After Wilson, et al. (2004) and Woods-Ballard, et al. (2007)]

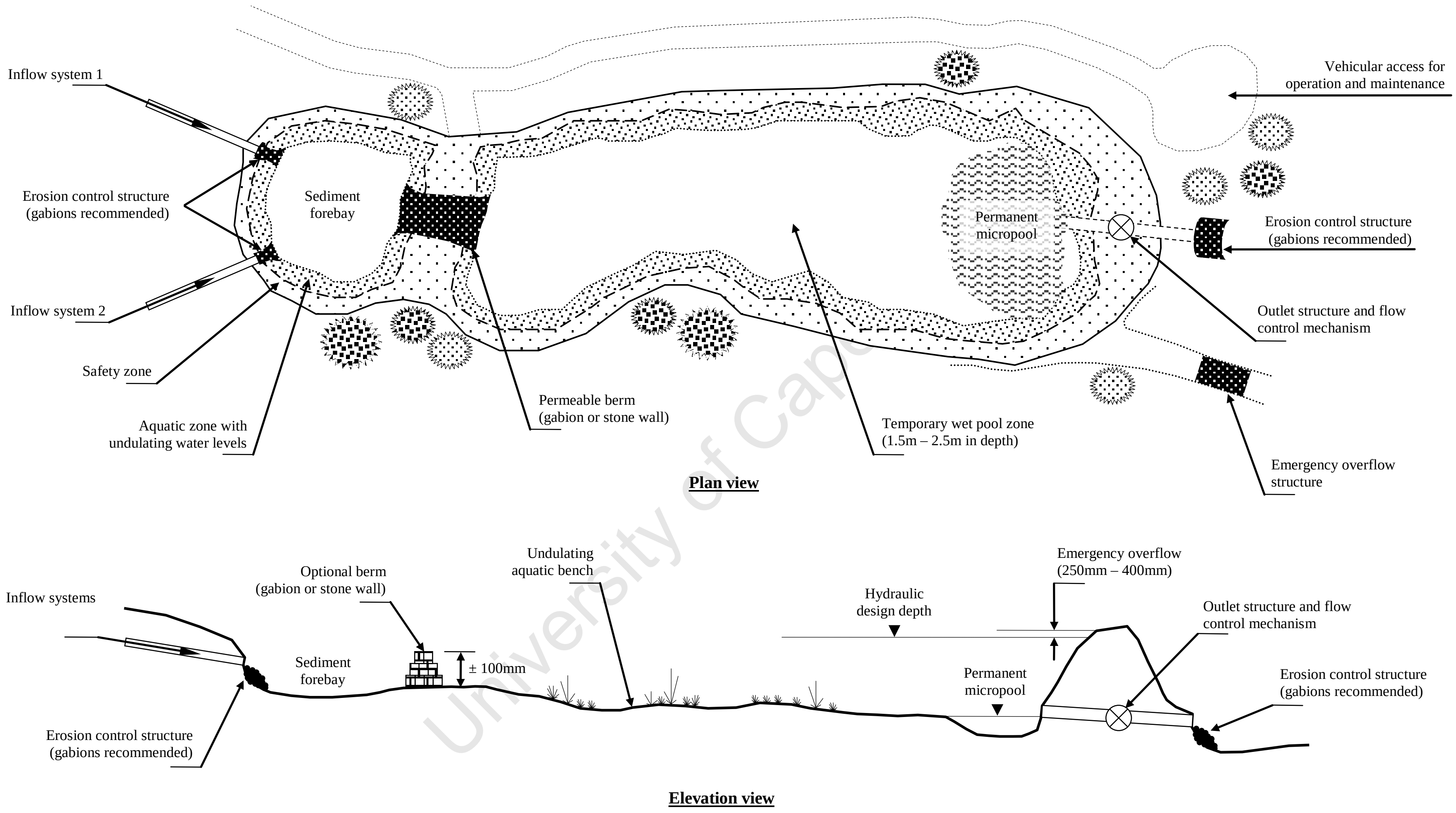


Figure 5.2: General design for detention ponds

[After Wilson, et al. (2004) and Woods-Ballard, et al. (2007)]

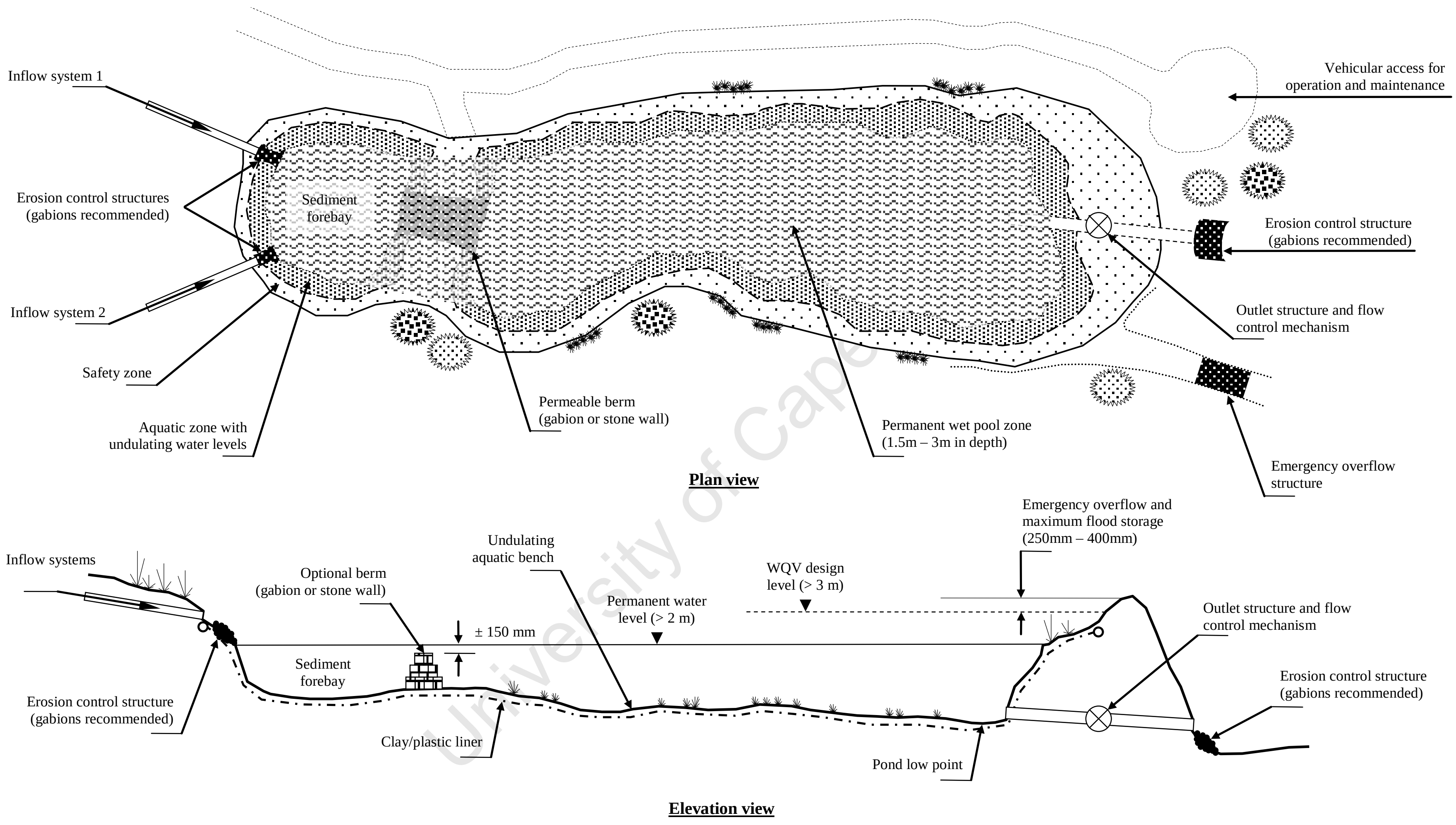


Figure 5.3: General design for retention ponds
[After Wilson, et al. (2004) and Woods-Ballard, et al. (2007)]

Appendix 2

SuDS Conceptual Design Poster

Note to reader:

The author compiled the following SuDS Conceptual Design Poster as a 'quick-referencing tool' to accompany the South African Draft Guidelines for SuDS (Appendix 1). The poster is a deliverable for the WRC project K5/1826: Alternative technology for stormwater management. It can be utilised by designers and managers for the conceptual selection and design of SuDS options. The poster is presented in this dissertation in A3 size (297 mm x *420 mm), but is typically published in A1 size (594 mm* x *841 mm). Urban practitioners attending SuDS workshops in Cape Town, Johannesburg, Tshwane, George, and eThekwini, were presented with the poster and were encouraged to provide feedback for the contents thereon.*

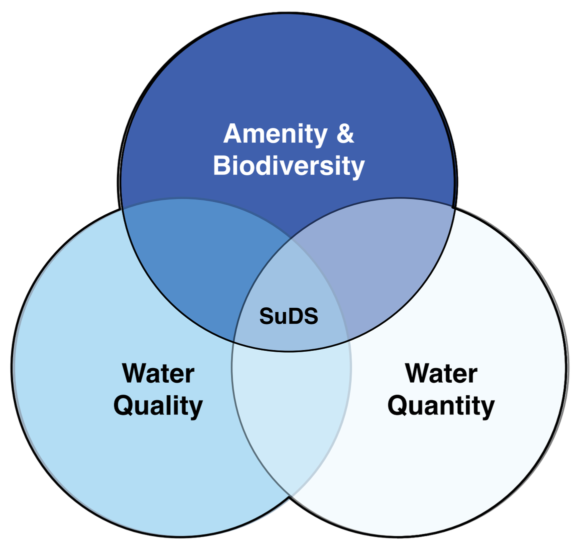
Sustainable Drainage Systems (SuDS) Conceptual Design

Site Design Process

Nine step Simplified Site Development Process (SSDP)

1. Initial project
2. Site investigation
3. Feasability study
4. Site analysis
5. **Concept design**
6. Preliminary plan
7. Final plan
8. Implementation
9. Final checks

Sustainable Drainage Systems (SuDS) Conceptual Design Matrix



		Quantity						Quality						Amenity and Biodiversity						Site Suitability						Costing		
		Rainwater harvesting	Infiltration	Detention	Conveyance	Long-term storage	Exten. attenuation storage	Sedimentation	Filtration and bio-filtration	Adsorption	Biodegradation	Plant-uptake	Nitrification	Health and safety	Environ. risk assessment	Environ. risk management	Recreational benefits	Aesthetic enhancement	Education and awareness	Rooftops	Parks and landscaped areas	Courtyards and walkways	Major roads and parking	Overflow parking	Natural areas	Land take	Capital	Operation and maintenance
Source	Green roofs	×	∽	✓	×	×	∽	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	✓	✓	×	×	×	×	×	×	L/M	M
	Sand filters	×	∽	✓	×	×	×	×	✓	✓	✓	×	×	×	×	×	×	×	×	×	×	✓	∽	∽	×	L	L/M	M
	Soakaways	×	✓	∽	×	∽	×	×	✓	✓	✓	×	∽	×	×	×	×	×	×	×	✓	✓	∽	∽	×	×	L	L
	Stormwater collec. and reuse	✓	×	∽	×	✓	×	×	∽	×	×	×	×	✓	✓	✓	×	✓	✓	✓	✓	∽	∽	∽	×	×	L/M	L/M
Local	Bio-retention areas	×	✓	✓	×	×	∽	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	∽	✓	✓	H	L	M
	Filter strips	×	✓	∽	∽	×	×	✓	✓	✓	✓	∽	∽	×	×	×	✓	✓	×	×	✓	✓	✓	✓	×	H	L	L
	Infiltration trenches	×	✓	✓	∽	×	×	×	✓	✓	✓	×	∽	×	×	×	×	×	×	×	✓	✓	∽	∽	×	L	L/M	M
	Permeable pavements	∽	✓	✓	∽	∽	∽	✓	✓	✓	✓	×	×	×	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	×	L	L/M	L
	Swales	×	∽	✓	✓	×	×	✓	✓	✓	✓	∽	∽	✓	×	×	×	✓	×	×	✓	✓	✓	✓	×	H	L	M
Regional	Constructed wetlands	∽	∽	✓	∽	✓	∽	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	×	×	×	✓	H	H	L/M
	Detention ponds	×	∽	✓	×	∽	✓	✓	∽	∽	✓	×	∽	✓	✓	✓	✓	✓	✓	×	✓	×	✓	✓	✓	M	L	L
	Retention ponds	✓	∽	✓	∽	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	×	×	×	✓	H	M	M

Primary process (✓) Secondary process (∽) | Consider (✓) | Suitable (✓) Pretreatment required (∽) | High (H) Medium (M) Low (L)

Treatment Trains

Treatment trains are critical in designing an effective SuDS scheme.

The following treatment train hierachy of SuDS options is listed in order of preference.

Good Housekeeping

- Good site design and efficient housekeeping measures.
- eg. sweeping, litter removal, sewage disposal, water reuse and landscaping.

Source controls

- Stormwater runoff quanitity and quality control at or near its source.
- Green roofs, sand filters, soakaways, stormwater collection and reuse.

Local Controls

- Management of stormwater runoff from many source control catchments.
- Bio-retention areas, filter strips, infiltration trenches, permeable pavements, swales.

Regional Controls

- Management of stormwater runoff from local catchments.
- Constructed wetlands, detention ponds, retention ponds.

Source controls, local controls and regional controls should be used sequentially to successfully reduce stormwater run-off:

1. Pollution 2. Flow rates 3. Volumes

Stormwater collection and reuse

Annual Collectable Rainfall (ACR) = AAR x A x C x FE

Where: **ACR** is Annual Collectable Rainfall
AAR is Average Annual Rainfall (mm/year)
- Review local meteorological data
- Visit *South Africa Rain Atlas*

< http://134.76.173.220/rainfall/index.html >

A is runoff contributing catchment area (m^2)

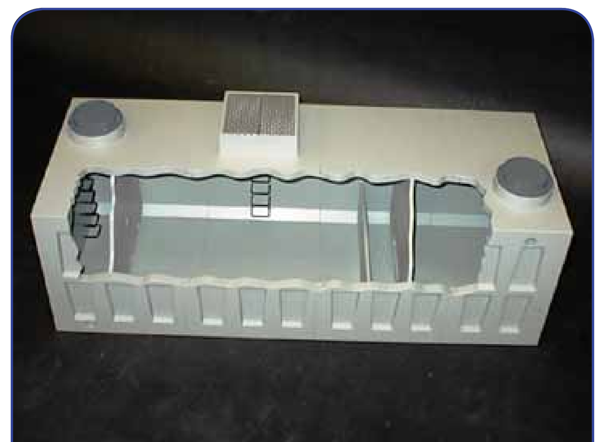
C is runoff coefficient (0 - 1)
This is the realistic proportion of rainfall runoff that enters the specified storage facility

The following coefficients are comonly used:

Roof Classification	Runoff Coefficient
Pitched roof tiled	0.85
Flat roof tiled	0.6
Flat roof gravel	0.4
Extensive Green Roof	0.3
Intensive Green Roof	0.2

FE is Filter Effeciency (0 - 1)
- Post-filtering proportion of collected water for use
- Manufacturers recommend a conservative 0.9

1. Green roof



2. Sand filter

3. Soakaway

4. Stormwater collection and reuse

5. Bio-retention area

6. Filter strip

7. Infiltration trench

8. Permeable pavement

9. Swale

10. Constructed wetland

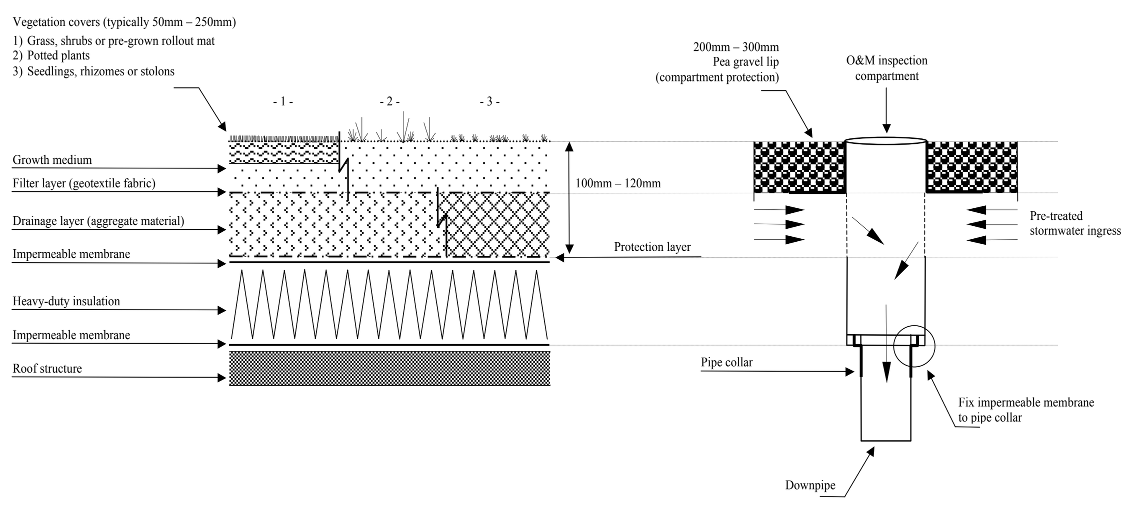
11. Detention pond

12. Retention pond

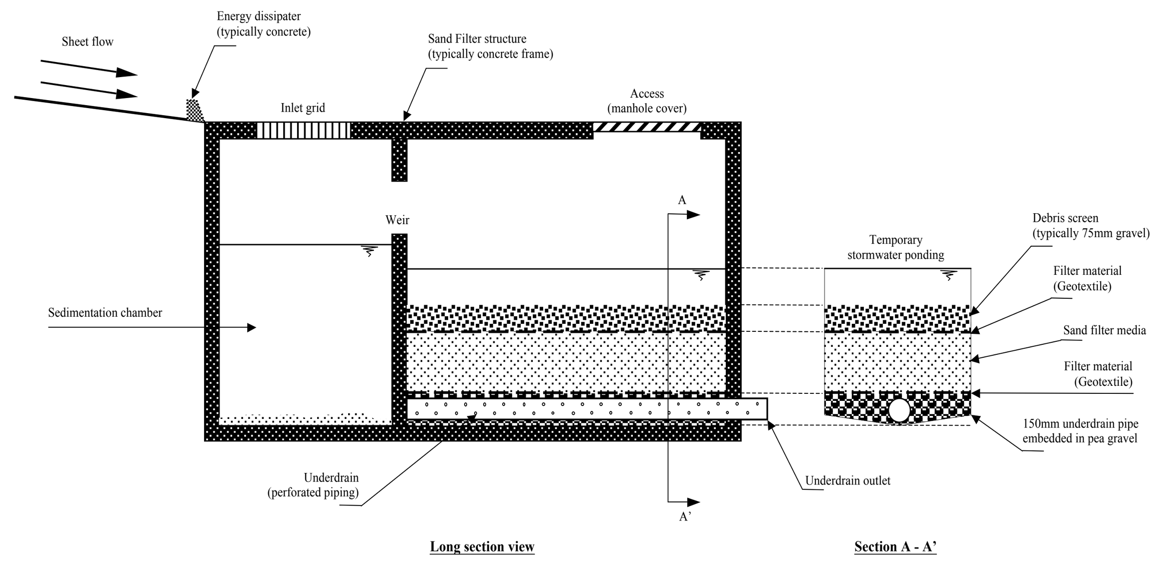
poster: www.imago-visual.com

General designs for SuDS options

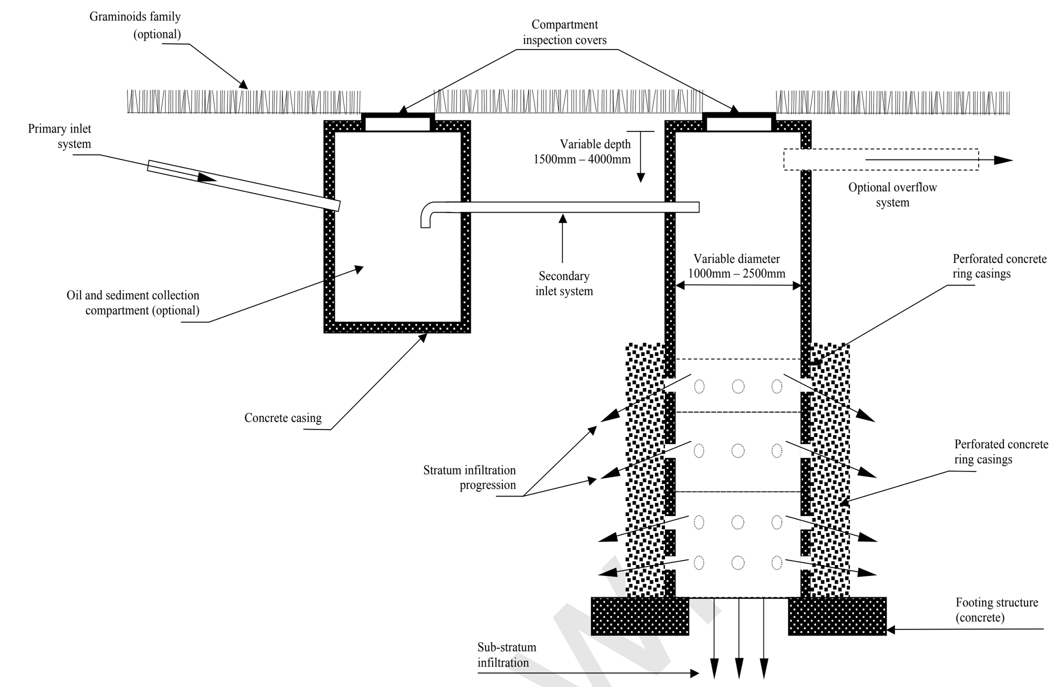
1. Green roof and adjoining inspection compartment



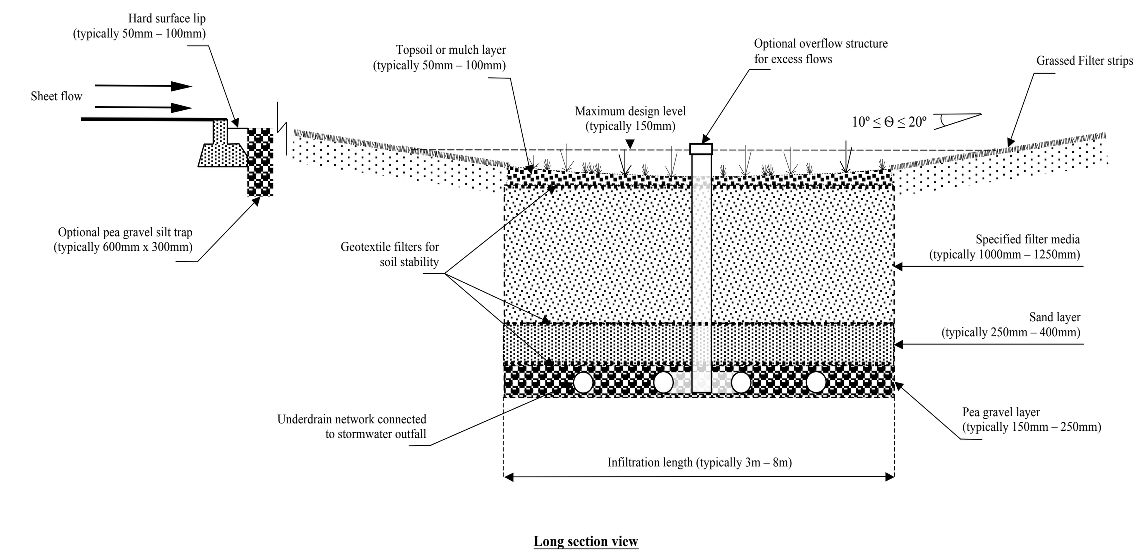
2. Sand filter with pre-treatment chamber



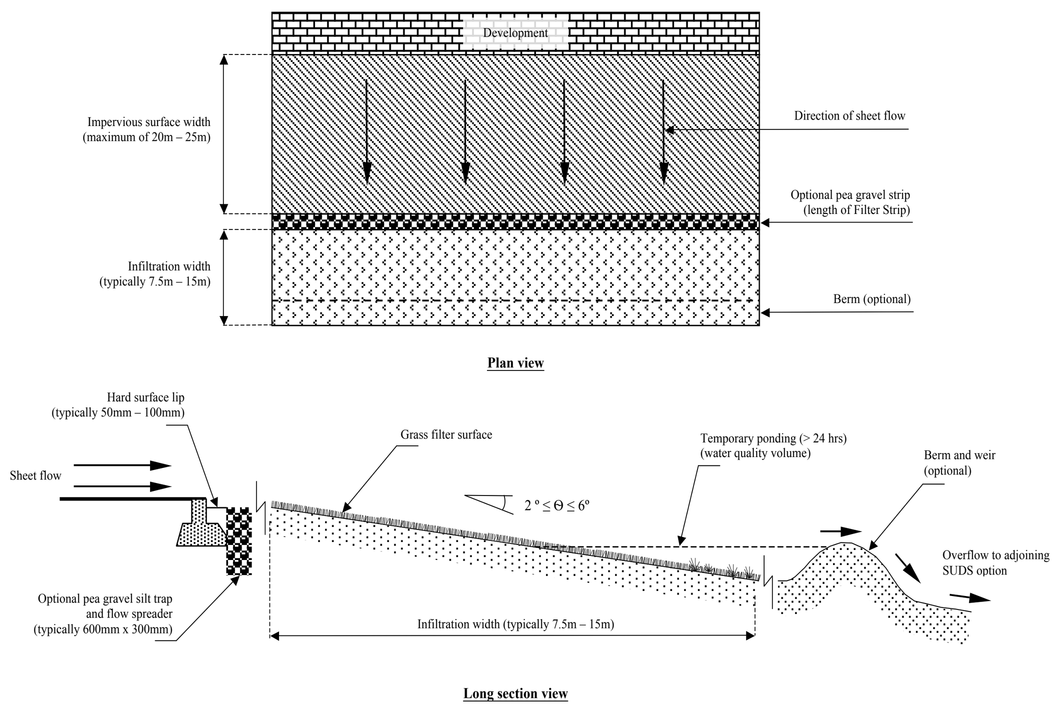
3. Soakaways with pre-treatment compartment



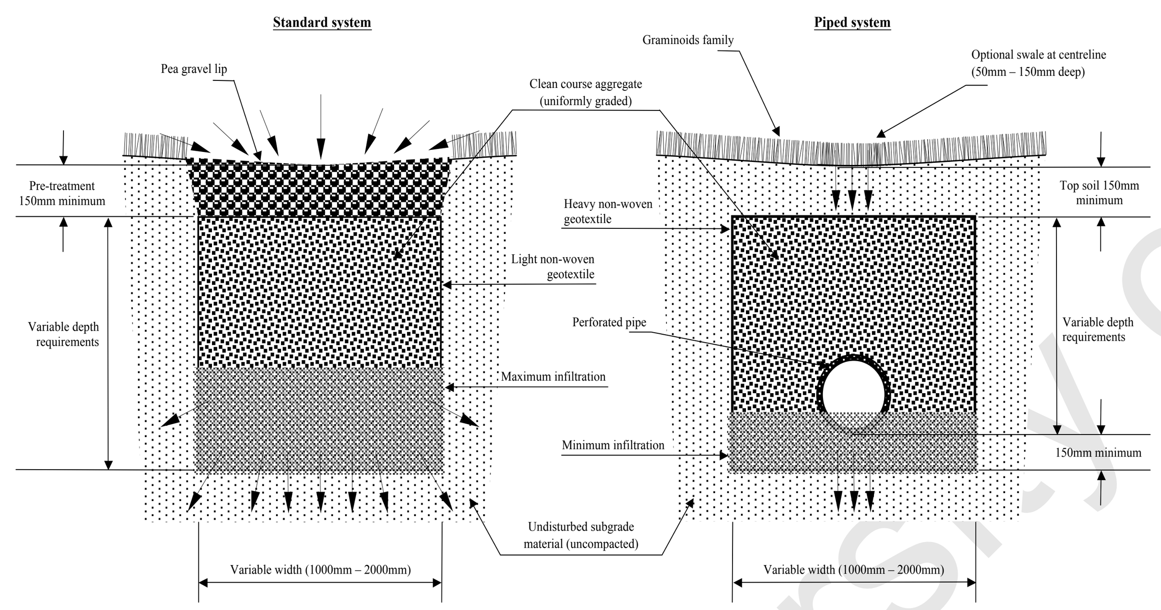
5. Bio-retention area



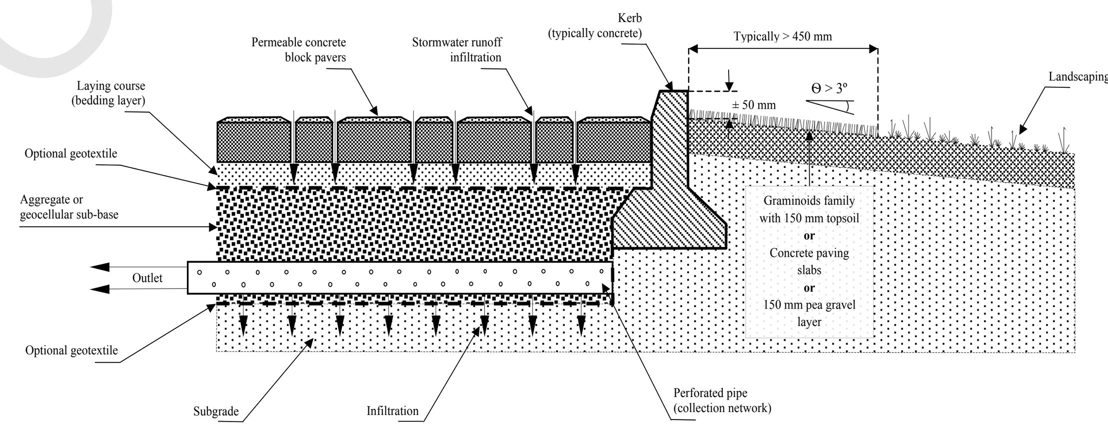
6. Filter strip and adjoining silt trap and berm



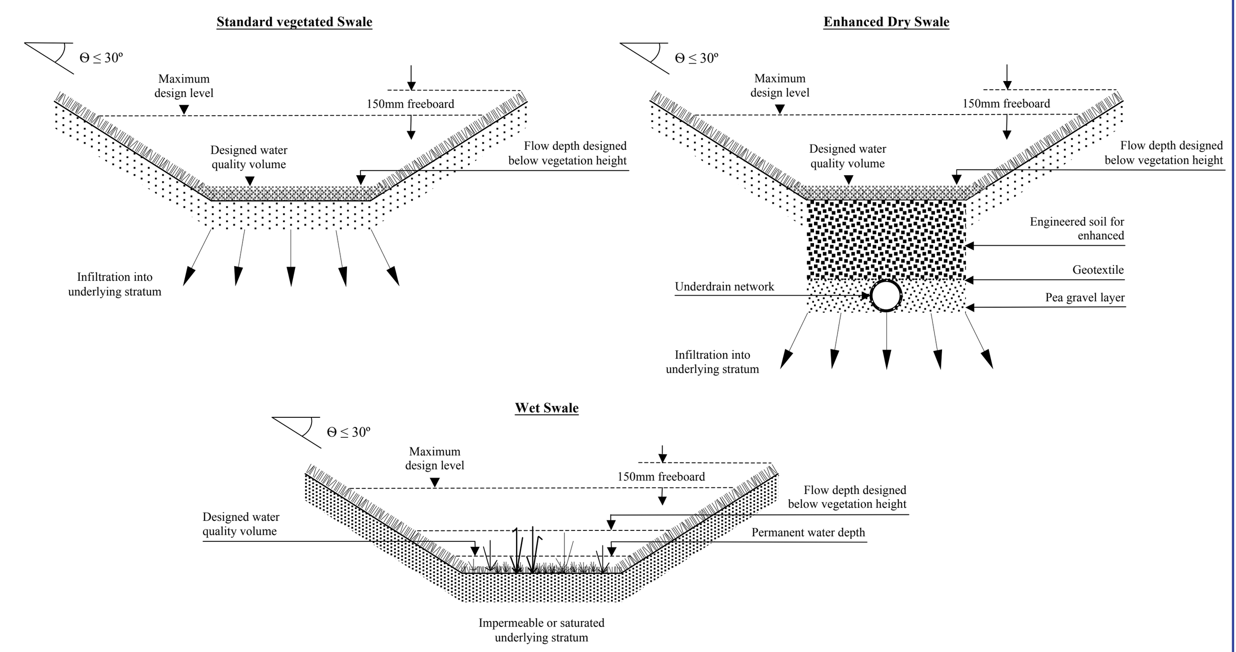
7. Dual system infiltration trench



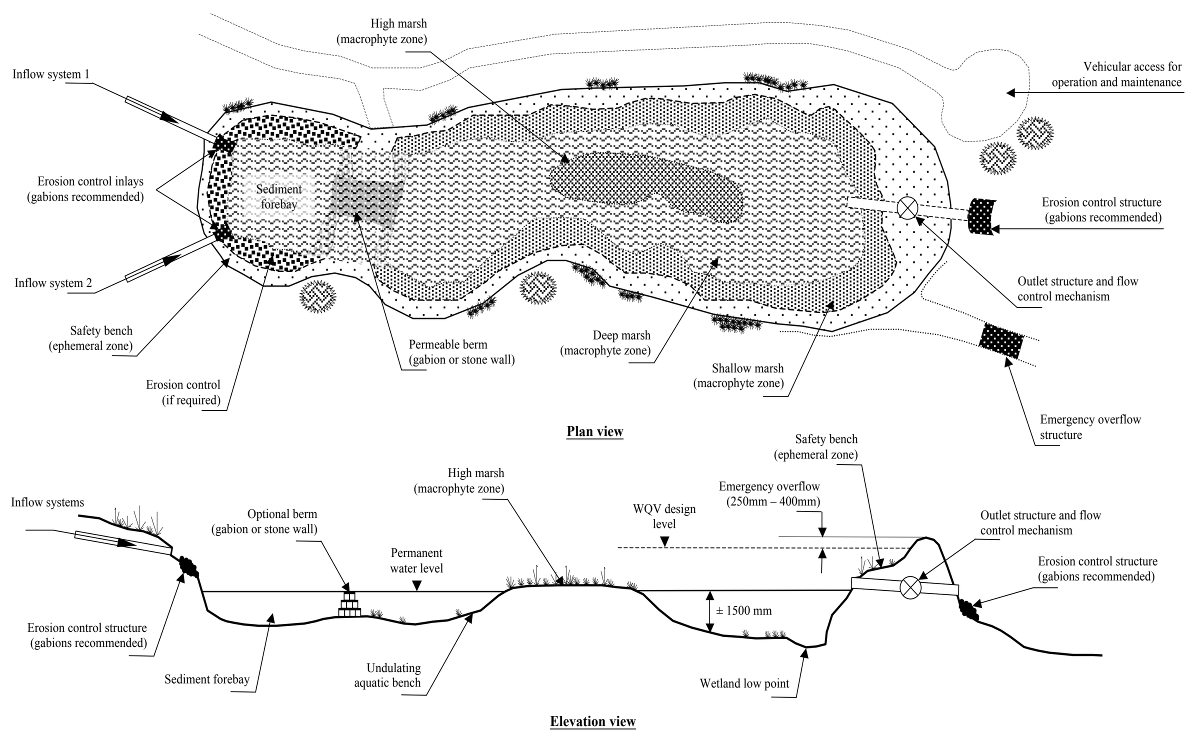
8. Permeable pavement and adjoining landscaped area



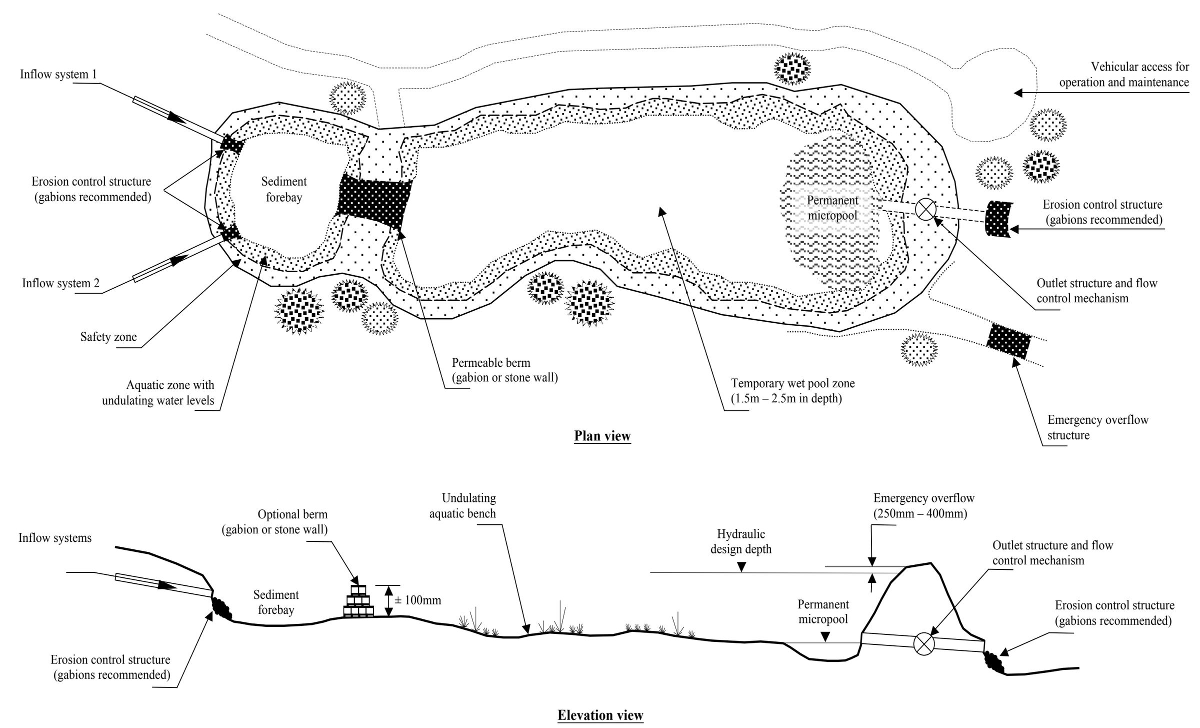
9. Swale



10. Constructed wetland



11. Detention pond



12. Retention pond