Section L
Stormwater

The Neighbourhood Planning and Design Guide

Part II

Planning and design guidelines

Symbols at text boxes

More detailed information is provided about the issue under discussion

Important considerations to be aware of are highlighted

Relevant content from a complementing resource is presented

Developed by

Department of Human Settlements

Published by the South African Government

ISBN: 978-0-6399283-2-6

© 2019

Version 1. Printed January 2019

human settlements

Department:

Human Settlements

REPUBLIC OF SOUTH AFRICA

Section L
Stormwater

The Neighbourhood Planning and Design Guide

Table of contents

L.1 Outline of this section

L.1.1 Purpose

Settlements (and neighbourhoods as the 'building blocks' of settlements) are integrated systems, in which various components are interconnected, and this section highlights the role of stormwater and stormwater management in this system.

Stormwater is rainwater or melted snow that runs off streets, lawns and other sites. In natural systems, the bulk (typically 85% to 90%) of rainfall is returned to the atmosphere through evapotranspiration and the remainder is filtered and ultimately replenishes aquifers (about 4% or 5%) or flows into streams and rivers either as surface runoff or shallow groundwater flow (8% to 10%). Stormwater should be regarded as a resource and it should be integrated into the settlement water cycle.

The aspects addressed in this section play an essential role in achieving the vision for human settlements outlined in **Section B** and relate in particular to the sections dealing with water supply (**Section J**), sanitation (**Section K**), and transportation and road pavements (**Section I**).

L.1.2 Content and structure

This section (Section L) is structured to support effective decision-making related to the provision of stormwater management. The decision-making framework is outlined in Figure L.1, and the structure of this section is briefly described below.

Universal considerations

General aspects that should be taken into consideration when making higher level decisions regarding the provision of stormwater infrastructure are highlighted, including the following:

- The regulatory environment, including key legislation, policies, frameworks and strategies
- The key objectives that should be achieved as a result of the application of the guidelines provided
- Local or international approaches, mechanisms, concepts and current trends that could possibly be utilised to achieve the key objectives
- Contextual factors specific to the development project to be implemented such as the development type and setting

Planning considerations

Factors to consider when making more detailed decisions regarding the provision of stormwater infrastructure are outlined, including the following:

- The characteristics of the development, including the nature of the proposed neighbourhood, the anticipated number of residents and specific features that would have to be incorporated or requirements that would have to be met
- The existing features of the site and immediate surroundings (built and natural environment) as determined by the physical location of the proposed development

- Options related to the provision of stormwater management systems that are available for consideration

Design considerations

Guidelines to assist with the design of stormwater management systems and infrastructure.

Glossary, acronyms, abbreviations and endnotes

A glossary, a list of acronyms and abbreviations, and endnotes (containing sources of information, explanatory comments, etc.) are provided at the end of Section L.

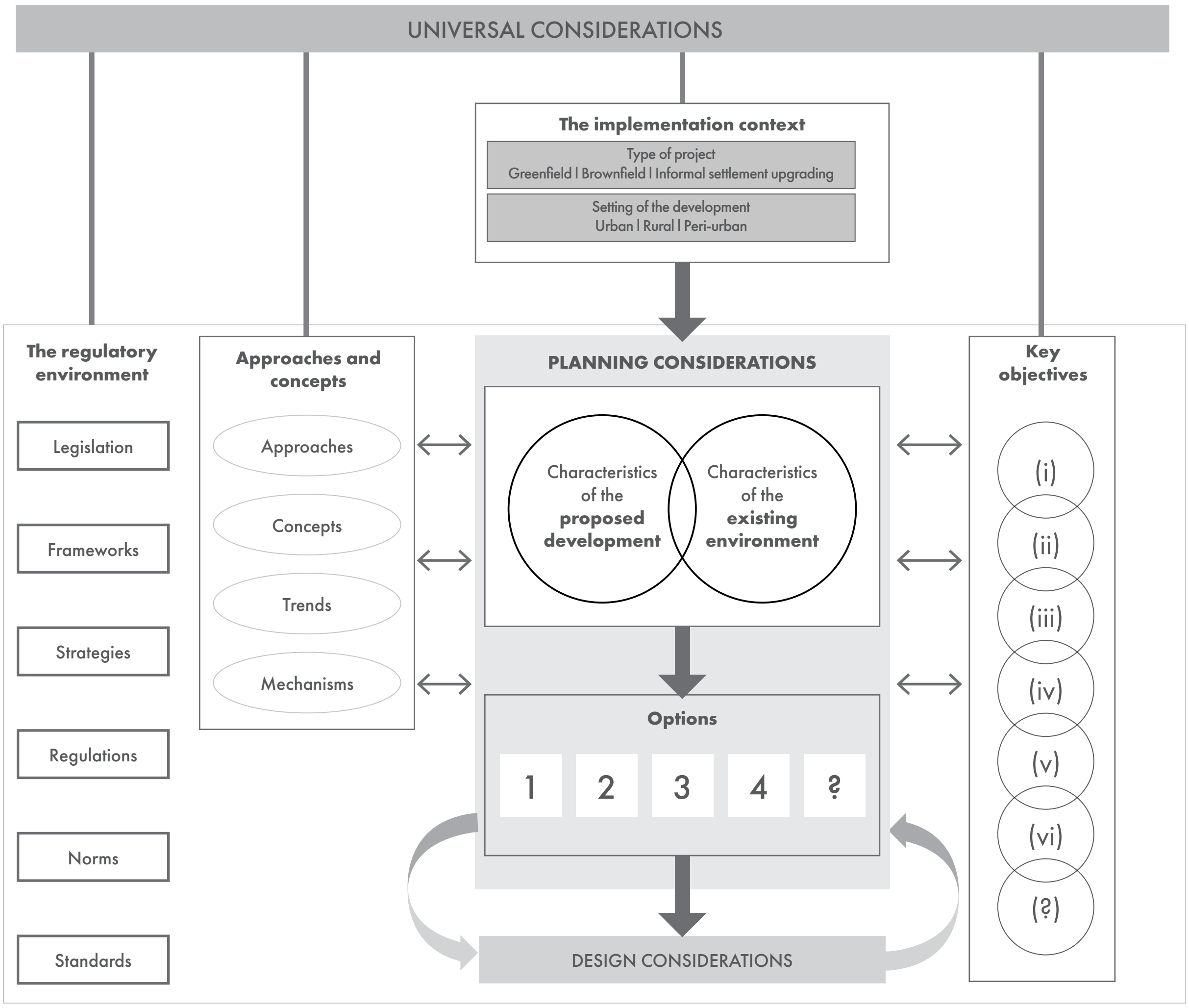


Figure L.1: A framework to assist with planning and design decisions

L.2 Universal considerations

L.2.1 The regulatory environment

A range of legislation, policies and strategies guide the management of stormwater in South African settlements. Some of these are listed below. Since they are not discussed in detail, it is vital to consult the relevant documents before commencing with any development. (Also see **Section D.1**.)

All building and construction work in South Africa is governed by the National Building Regulations and Building Standards Act, 1977. Always refer to *SANS 10400 – The application of the National Building Regulations available from the South African Bureau of Standards (SABS).*[1] Municipalities may have additional guidelines, regulations and by-laws that may be applicable.

The Department of Water and Sanitation (DWS) is the custodian of the country's water resources. Its legislative mandate seeks to ensure that the country's water resources are protected, managed, used, developed, conserved and controlled through regulating and supporting the delivery of effective water supply and the management of stormwater. Below is a summary of the main acts and policies pertaining to stormwater management.

- **The National Water Services Act and the National Water Act**

The National Water Services Act (NWSA), 1997 and the National Water Act (NWA), 1998 refer specifically to the legal responsibility to insert the 100-year flood line on township plans to protect sewage treatment works, cemeteries and solid waste sites from flooding.

- **The National Environmental Management Act**

The National Environmental Management Act (NEMA), 1998 requires that all relevant factors be considered in stormwater management, including (among others) that pollution and degradation of the environment be avoided. In cases where this is not possible, the consequences must be minimised and remedied; and environmental justice must be pursued.

- **The National Framework for Sustainable Development**

The principles of the National Framework for Sustainable Development (NFSD), overseen by the Department of Environmental Affairs, emphasise a cyclical and systems approach to achieving sustainable development through the efficient and sustainable use of natural resources; socio-economic systems embedded within, and dependent upon, ecosystems; and meeting basic human needs to ensure that resources necessary for long-term survival are not destroyed for short-term gain.

- **The Conservation of Agricultural Resources Act**

The Conservation of Agricultural Resources Act, 1983 controls the use of natural agricultural resources to promote the conservation of the soil, water resources and vegetation, and the combatting of weeds and invader plants.

- **The National Roads Act**

The National Roads Act, 1971 regulates the construction and control of national roads, including the disposal of stormwater on a national road.

- **The Minerals Act**

The Minerals Act, 1991 and its Regulations focus on specific issues relating to the Environmental Management Programme (EMP) and implement the prescriptions of the DWS with regard to the disposal of waste and wastewater.

- **The Health Act**

The Health Act, 1977) focuses on the promotion and protection of public health in the managing of stormwater.

- **The Atmospheric Pollution Prevention Act**

The Atmospheric Pollution Prevention Act, 1965 requires the prevention of pollution of the atmosphere through specific measures aimed at the purification of effluent and the prevention (or reduction to a minimum) of any noxious or offensive constituents from such effluents getting into drains and drainage canals.

- **The Environment Conservation Act**

The Environment Conservation Act, 1989 provides for the effective protection and controlled utilisation of the environment.

- **The Second National Water Resource Strategy**

The Second National Water Resource Strategy (NWRS2) of 2013 provides a framework for the protection, use, development, conservation, management and control of water resources in South Africa and emphasises the need to protect fresh water ecosystems that are under threat because of pollution occurring during rain events and influx of polluted stormwater into the watercourses.

L.2.2 Key objectives

In developed areas, impervious surfaces such as pavement and roofs prevent precipitation from soaking naturally into the ground. These surfaces also reduce the opportunities for evapotranspiration, as water runs rapidly into storm drains, sewer systems and drainage ditches. This can cause downstream flooding; stream bank erosion; increased turbidity (muddiness created by stirred-up sediment) from erosion; habitat destruction; sewer overflows; infrastructure damage; and contaminated streams, rivers and coastal waters. The following objectives should guide decisions regarding the planning and design of stormwater management systems:

- Minimise the threat of flooding to the area
- Protect the receiving water bodies in the area
- Preserve biodiversity in the area
- Promote the multi-functional use of stormwater management systems (provide amenity to communities)
- Promote the use of the stormwater itself as a water resource
- Develop sustainable stormwater systems

Effective stormwater management limits negative impacts on the environment and enhances the positive impacts. It also caters for the hydraulic needs of a development while minimising the associated negative environmental impacts. The design of a sustainable stormwater management system considers all the factors that will affect the future operation and maintenance of the system. Stormwater systems should ideally be planned and designed to require minimum maintenance.

L.2.3 Approaches and concepts

This section briefly summarises possible approaches, strategies and mechanisms, as well as local or international concepts, ideas and trends that could be considered to achieve the objectives discussed in Section L.2.2.

L.2.3.1 Water Sensitive Urban Design / Water Sensitive Design

Water Sensitive Urban Design (WSUD), an approach to urban water management that originated in Australia, is an approach aimed at managing the urban water cycle in a more sustainable manner so as to improve water security.[2] Within the South African context, WSUD is also referred to as Water Sensitive Design (WSD) to acknowledge the fact that the approach could be applied to settlements in general, not only to those in an urban setting.[3] The basic premise of WSUD/WSD is that water is a scarce and valuable resource, and therefore it needs to be managed wisely and with due care (sensitively). This approach encompasses all aspects of the water cycle and integrates urban design with the provision of infrastructure for water supply, sanitation, wastewater, stormwater and groundwater.

The purpose of WSUD/WSD is to reduce the negative impact of urban development on the environment and to enhance the sustainability of water. The intention is to, as far as possible, mimic the natural process of maintaining the water balance when planning and designing a neighbourhood or settlement (see Figure L.2).

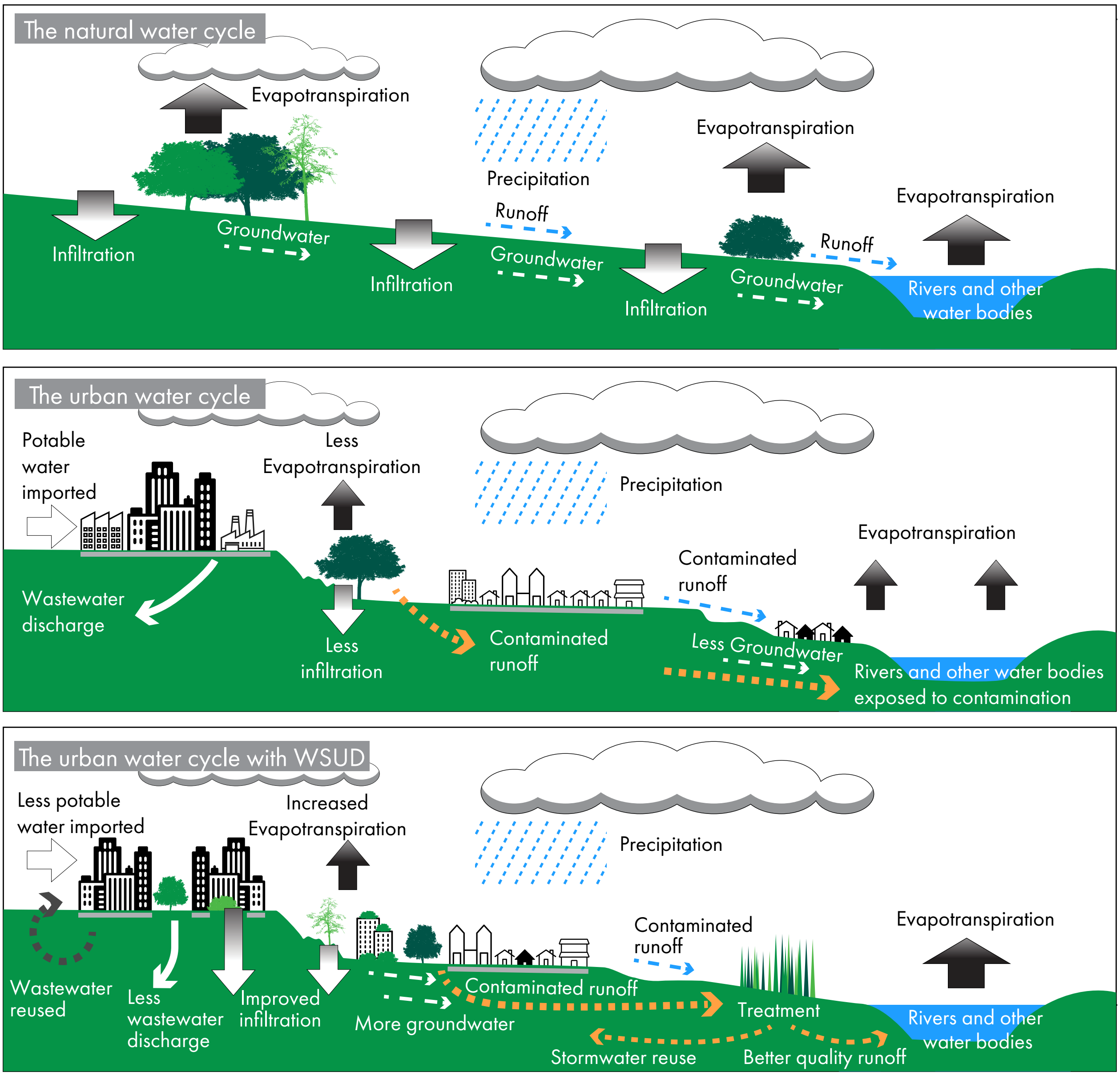


Figure L.2: The water cycle under different conditions

The natural process (water cycle) involves, among others, precipitation, evapotranspiration, runoff and infiltration. However, in a built-up area other components are added to the process. In addition to precipitation, potable water is imported into the area, wastewater is generated that needs to be discharged somewhere, and evapotranspiration is inhibited. Furthermore, because a substantial part of the area is covered with hard surfaces (buildings, streets, paving etc.), infiltration of water into the earth is reduced while the volume of (poor quality) runoff increases. WSUD/WSD aims to reduce the adverse effects of the built environment on the water sources and to create settlements that preserve the natural water cycle. Strategies or interventions that could be implemented include the following:[4]

- **Sustainable Drainage Systems (SuDS)**. See Section L.2.3.2 for a description.
- **Appropriate sanitation and wastewater systems**. Technologies that reduce water use, allow for the use of treated wastewater or recycled water, and minimise wastewater could contribute significantly to the effective and efficient utilisation of water resources in a settlement.

- **Groundwater management.** Groundwater should be regarded as a resource, and therefore aquifers should be conserved and protected from contamination and artificial recharge options should be considered where appropriate.
- **Sustainable water supply.** Various aspects should be considered to improve efficient water use and reduce the demand for potable water, including water conservation, water demand management, addressing water losses, and developing alternative water sources (e.g. rainwater, stormwater, wastewater and groundwater).

WSUD/WSD requires a multi-disciplined, holistic approach to neighbourhood and settlement planning and design. Various sections of this guide relate directly to this approach, in particular **Section F** (Neighbourhood layout and structure), **Section G** (Public open space), **Section I** (Transportation and road pavements), **Section J** (Water supply) and **Section K** (Sanitation).

L.2.3.2 Sustainable Drainage Systems

Sustainable Drainage Systems (SuDS) constitute an approach towards managing stormwater runoff that aims to reduce downstream flooding, allow infiltration into the ground, minimise pollution, improve the quality of stormwater, reduce pollution in water bodies, and enhance biodiversity. Rather than merely collecting and discarding stormwater through a system of pipes and culverts, this approach recognises that stormwater could be a resource. SuDS involve a network of techniques aimed at controlling velocity and removing pollutants as runoff flows through the system. This involves mechanisms and methods such as rainwater harvesting, green roofs, permeable pavements, soakaways, swales, infiltration trenches, bio-retention areas, detention ponds, retention ponds and wetlands. These interventions can form a natural part of open spaces in a settlement and contribute to the quality of the environment and the character of a neighbourhood.[5]

L.2.3.3 Integrated Water Resources Management

Integrated Water Resources Management (IWRM) is a cross-sectoral policy approach, designed to replace the traditional, fragmented sectoral approach to water resources and management. IWRM is based on the understanding that water resources are an integral component of the ecosystem, a natural resource, and a social and economic good. According to the Global Water Partnership, IWRM "promotes the coordinated development and management of water, land and related resources, in order to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems".[6]

L.2.3.4 Water quality

It is essential that water, which is a scarce resource, be utilised judiciously and sensibly for the benefit of all users. Certain standards of water quality (water that is 'fit for use') are required for all users – from primary domestic use to water for irrigation, stock watering, recreation, and maintaining aquatic habitats.[7] Efficiently managing the quality of stormwater would aid in utilising the resource in a sustainable manner. Harvested stormwater could be used as a water resource as long as the water quality is of an adequate standard. See **Section L.4.1.4** for water quality checks regarding the use of stormwater for sanitation, recreation or irrigation.

L.2.3.5 The dual drainage system

Traditionally, runoff from frequent (minor) storms has been carried in the urban formal drainage systems. Typically this was achieved by draining runoff from properties into the streets and then via conduits to the natural watercourses. The system was intended to accommodate frequent storms and associated runoff. Today, the value of property is of such significance that engineers need to consider not only frequent storms but the more severe storms, which can cause major damage with sometimes catastrophic consequences. The dual system incorporates a minor system for the frequent storm events and a major system for the less frequent but severe storm events. The major system may include conduits and natural or artificial channels, but would commonly also make use of the road system to convey runoff overland to suitable points of discharge. This is not very different from what has happened de facto except that formal cognisance is now given to the routing of runoff from all storms via the secondary use of roads and other facilities in the urban environment. Despite imposing inconvenience to users, the use of the road system and open spaces (such as parks and sports fields) as drainage components of the major system is considered acceptable during these severe storm events.

L.2.3.6 Stormwater harvesting and use

Stormwater harvesting is the collection, treatment, storage and use of stormwater runoff in settlements. Harvested stormwater can be used as an alternative or additional water resource for municipal water supply, e.g. sanitation system flush water, irrigation, etc. Stormwater that has been harvested is either stored on a permanent basis in a retention pond or it could be stored in detention ponds, where water is stored temporarily following a large storm. Detention ponds reduce downstream flooding.[8] Any harvested stormwater to be used as potable water needs to go through a treatment process.

L.2.3.7 Infrastructure asset management

Asset management is a collection of management practices using assets as the starting point for making operation and strategic decisions. Life cycle asset management includes the management of assets, their associated performance, risks and expenditures over their life cycles to extract an optimum functional life from these assets. The infrastructure life cycle comprises three distinct phases, namely the planning of the full asset life cycle, the establishment of the infrastructure (design, procure and construct) and the operation and maintenance of the infrastructure. Well-planned, resourced and implemented asset management reduces costs by postponing expensive replacement and avoiding breakdowns. In the water sector, assets are the physical components of water systems, e.g. water sources, treatment works, pipes, pumps, meters, storage tanks and valves.[9]

All projects need to be planned for the full life cycle, i.e. every infrastructure project plan must include a life cycle cost analysis that provides for all resources required to ensure the municipality has the finances, materials, equipment, artisans and labour to manage the assets and implement effective operation and maintenance for the whole design life of the infrastructure element. Refer to the *Asset Management Guideline*[10] available from the DWS for more information.

Energy and stormwater management

Energy is needed in the operation of water infrastructure systems through processes related to the treatment, transfer, and discharge of stormwater. Any infrastructure for the management of stormwater that requires an external energy source should consider renewable energy as a viable power source for such infrastructure during its design life. Stormwater can also be used in the generation of electrical energy. Refer to **Section N** for guidance on the planning for electrical energy provision in neighbourhoods.

L.2.4 The implementation context

This section highlights the contextual factors – specifically related to the type of project and the setting of the development – that should be considered when making decisions for planning and designing for stormwater management. Also refer to **Section D.2.1** (Type of development) and **Section D.2.2** (The setting of the planned development). The interdependencies between stormwater management and the various other water-related services, such as water supply (see **Section J**) and sanitation (see **Section K**) should be considered in the planning and design of stormwater management systems.

L.2.4.1 The type of development

(i) Greenfield development

When planning and designing the stormwater management of a neighbourhood as part of a greenfield development project, the following has to be considered:

- Undisturbed portions of the natural environment are often found on greenfield sites. When planning and designing stormwater management, the preservation or improvement of natural freshwater ecosystems, and the creation of additional freshwater habitats that can contribute to the availability of appropriate, high-quality river and wetland habitat (which mimics the natural condition of open space, trees and on-site natural features) should be considered.
- Greenfield sites often do not have adequate access to municipal services, such as water supply, sanitation, stormwater management systems, electricity supply, and solid waste removal. These service connections may be a substantial distance away, especially if the site is in a rural area. The capacity of the existing services may also not be sufficient for the proposed development and may require an upgrade to service the proposed development adequately.

(ii) Brownfield development

When planning and designing the stormwater system for a brownfield development project, the following has to be considered:

- Brownfield sites are potentially contaminated by previous industrial uses or by leftover building materials and might need environmental rehabilitation. If rehabilitation is not possible or appropriate, the contaminated land might affect the management and quality of stormwater.
- Sites for redevelopment often have built structures that may have heritage value. Identify heritage elements that need to be protected when constructing the stormwater infrastructure.
- The layout and structure of the brownfield development project should link up with existing movement patterns, as well as surrounding streets and stormwater systems.

(iii) Informal settlement upgrading

Informal settlement upgrading often involves in-situ development. This usually implies that existing houses are left in place, while the neighbourhood is upgraded – streets are aligned and widened, drainage is improved and homes are connected to the water and sanitation grids. When planning and designing a stormwater system as part of an informal settlement upgrading project, the following needs to be considered:

- Informal settlements are often isolated from the street grid. Linking up with existing stormwater networks may have a major impact on the existing system (which needs to be mitigated).
- Informal settlements grow organically and there may be layouts that seem unconventional. The stormwater system of an upgraded informal settlement must accommodate these anomalies.
- The increasing number of dwellings that are erected below the flood line in informal settlements is of concern. Appropriate interventions are required when planning and designing for stormwater management to ensure that people and dwellings are not exposed to flood hazard.

L.2.4.2 The setting of the development

(i) Rural

The rural areas of South Africa comprise a variety of settlement types, including rural villages and towns, dense rural settlements and dispersed settlements. The stormwater management systems appropriate to the setting will therefore also vary and will be dictated by a range of factors.

- Most traditional villages are located on farm portions or in some instances on land that has not been surveyed. The land is communally owned and is usually managed by a hierarchy of traditional leaders. Stormwater management planning and design are guided by these decision makers rather than by the local municipality's planning and development policies.
- Often, rural settlements can only be accessed by dirt roads or even footpaths.[11] These roads are particularly vulnerable to degradation during rains. The organic nature of the internal street layout of rural settlements also makes it difficult to achieve optimum efficiencies.
- Due to lower population densities, the provision of stormwater management infrastructure in rural areas may sometimes require an approach that differs from that taken in cities or towns. The use of pipe or box culverts are typically minimised, and the minimum diameters are larger than for urban areas, due to higher sediment loads. Surface drainage is often more appropriate.

(ii) Peri-urban

The development setting of peri-urban areas is diverse and includes a mix of settlement patterns, socio-economic statuses and access to services. Settlement on the periphery of metropolitan areas and towns may include informal settlements, low-income housing and high-income low-density developments. When planning and designing stormwater infrastructure for a development in the urban fringe area, the following should be considered:

- Peri-urban areas are under pressure, as most new urban-based developments and changes are concentrated in these zones of rural-urban transition.[12] The often high rate of urbanisation should be considered when planning and designing the stormwater infrastructure of new developments as these peri-urban areas are likely to accommodate even more people and higher densities in future.
- The costs of providing conventional urban infrastructure in peri-urban areas are often prohibitive. In many cases, alternative ways of service provision need to be considered. For instance, several SuDS measures can generally be provided at reasonable cost.

(iii) Urban

Urban settings can take on different forms, and therefore developments will vary in nature. Urban areas include central business districts (CBDs), residential suburbs, informal settlements, and so-called townships, and this will influence the type of stormwater management system to be provided.

L.3 Planning considerations

This section deals with the planning of stormwater management infrastructure. In this context, the term 'planning' means making informed decisions regarding the type or level of service to be provided, and then choosing the most appropriate stormwater management option(s) based on a thorough understanding of the context within which the planned development will be implemented.

This section outlines a range of questions that should be asked and factors that have to be considered to inform decisions regarding stormwater infrastructure and services to be provided as part of a development project.

Decisions regarding stormwater management should be informed by a clear understanding of the features and requirements of the proposed project. This would require an assessment of the characteristics of the proposed development. Furthermore, the characteristics of the environment in which the new development will be located, need to be examined and possible services and infrastructure that could be utilised must be identified.

L.3.1 Characteristics of the proposed development

Decisions regarding stormwater management need to be guided by an assessment of the characteristics of the proposed development and an understanding of the requirements or needs that will have to be met. Aspects that should be considered are discussed below.

L.3.1.1 The nature of the proposed development

Various factors relating to the nature of a development could influence decisions regarding stormwater management. For instance, mixed-use, mixed-income projects and projects that are primarily residential in nature would need different approaches to stormwater management. Similarly, inner city infill projects would be different from (for instance) an informal settlement upgrading project. The nature of a project therefore needs to be understood to make informed decisions regarding appropriate stormwater management options. The following questions can be asked to gain clarity:

- What is the dominant land use of the proposed development? Reliable information will ensure an accurate estimate of stormwater flow, which in turn forms the basis of designing stormwater infrastructure of adequate capacity. Outfall locations, and receiving systems should be identified.
- What is the average plot size per land use category? Information on parking areas, open spaces and streets and sidewalks is critical in the planning for stormwater management. If available, the coverage of buildings is also used in calculating flow rates.
- If a mixed development is proposed, what type of mix is proposed, e.g. a variety of housing types, sizes, densities and/or tenures? (see Section F.4.5)
- What is the possible drainage densification in the catchment (this refers to an increase in the ratio of conduit length : land area)? Conduit length refers to the length of the pipe or swale. This ratio is used as a measure of the reduction in effective overland flow length.
- What is the perviousness (the ability to allow water to percolate through) of the surfaces planned for the proposed development? What are the likely or planned future vegetation of the development? Pervious surfaces

and certain types of vegetation will allow stormwater to soak into the ground, while impervious surfaces and other types of vegetation (or no vegetation at all) will result in more runoff.

- What is the planned application of Water Sensitive Design measures (refer to **Section L.2.3.1**) in the proposed development? The successful implementation of these measures will have an impact on the volume of runoff in the proposed development.

> One of the most unstable periods in any development occurs during the construction phase. Stormwater runoff from sites should be collected in temporary check dams to prevent erosion. Straw bales can be positioned at kerb inlets to prevent silt entering the underground drainage systems while construction is taking place.

L.3.1.2 The residents of the area to be developed

Decisions relating to the stormwater management system to be provided in a development should be guided by information about the potential residents and users of the planned facilities. It may be possible to make assumptions regarding the nature of the future residents by assessing the surrounding neighbourhoods or similar developments in comparable locations or contexts. It is important to establish the total number of people (and households) to be accommodated. Actual numbers may be higher than anticipated because the provision of services may attract more people than originally planned for.

L.3.2 Characteristics of the existing environment

The selection of any option for stormwater management is determined by the unique characteristics of the particular site. Not all options or models will be applicable or effective for all sites. The advantages and limitations of each option should be identified during the planning and design phases, taking into consideration the site-specific characteristics and the context within which the development will be located. Issues that should be considered are discussed below.

L.3.2.1 The physical location of the proposed development

Constraints and opportunities posed by the site could influence the stormwater management infrastructure to be provided.

(i) Topography

Stormwater management systems have to reduce and/or eliminate the energy generated by flowing water. The water must not be allowed to develop sufficient volume or velocity to cause harm. The topography of the project site as well as surrounding sites is therefore a key factor when making decisions regarding the provision of stormwater management infrastructure. Important issues to consider include the following:

- What are the details of the upstream catchment? Catchment characteristics (e.g. size and elevation) will inform modelling discretisation.

- What does the existing natural drainage system comprise? Stormwater systems should result in the minimum disturbance of the natural drainage pattern. Obtain updated contours and cadastral information to identify sub-catchments.
- What is the slope shape, slope gradient and slope length? Runoff volume generally increases with steepness of slope. Slope shape determines whether water is dispersed or concentrated. Slope gradients are important when planning a stormwater management system because erosion and scour as a result of stormwater should be minimised by ensuring the flow velocities are maintained below critical values.
- What are the details and sensitivity of the receiving system? Stormwater management systems that convey stormwater to bodies of water that are classified as environmentally sensitive, for recreational use, or in public spaces, should specifically be planned to minimise or eliminate pollution.

(ii) Climate

The micro- and macro-climates of the site will have an impact on the stormwater management system. It is critical to obtain relevant rainfall data to inform the modelling of the expected runoff quantity. It is also important to determine whether there is a risk of seasonal flooding, earthquakes, veld fires, tremors and landslides. For assistance with the development of actions to adapt settlements to the impacts of climate change, consult the *Green Book: Adapting South African settlements to climate change*[13].

Information on seasonal flooding is especially important when planning for a stormwater management system. The information is used to determine the flood Recurrence Interval (RI), or return period, referring to the average interval between flood events exceeding a stated benchmark. The RI is usually expressed in years and is the reciprocal of the annual probability – i.e. the flood event with an annual probability of occurrence of 2% (0.02) has an RI of 50 years. This does not imply that a flood event will necessarily occur every 50 years, but rather that over a very long period (e.g. 1 000 years) – assuming there is no climate change – there will be approximately 20 flood events of greater magnitude (1 000/20 = 50 years).

(iii) Geotechnical characteristics

Runoff varies with soil characteristics. The following information should be considered when planning a stormwater management system:

- What types of soil are present on the site? What are the permeability and infiltration capacity of these soils? Any condition that adversely affects the infiltration characteristics of the soil will increase the amount of runoff.
- Is the soil prone to erosion? Examples of highly erodible soils in South Africa include the granitic soils found in Mpumalanga and the Highveld (Kyalami system). Although erosion is a natural phenomenon, human interference with the natural environment can rapidly increase erosion. Methods for constructing safe and economic stormwater structures in dispersive clays should be carefully considered. Dispersive clays can be highly erosive and subject to damage or failure, and they can occur in any soil with high exchangeable sodium percentage (ESP) values. The testing procedures for the identification of dispersive clays are available from the South African Institute for Civil Engineers (SAICE).[14] Design guidance on erosion prevention is provided in Section L.4.2.4.
- Are there any aggressive chemicals or minerals present? Site-specific conditions will severely affect stormwater quality. For example, stormwater conveyed to public parks should not contain chemicals or contaminants that are outside of the regulated parameters for human contact or recreational use.

- Is the site part of or close to a dolomitic area? (see the text box for a discussion on development on dolomitic sites)
- Is there groundwater present? What is the height of the water table?

Development on dolomites

Development on dolomitic land is generally governed by the Dolomite Area Designation assigned to a specific portion of the land, i.e. designation D1, D2, D3 and D4 in terms of Table 1 of *Development of Dolomite Land Part 1: General principles and requirements* (SANS 1936-1):[15]

D1	Requires no precautionary measures
D2	Requires general precautionary measures, in accordance with the requirements of SANS 1936-3[16], that are intended to prevent the concentration of water into the ground
D3	Requires precautionary measures in addition to those pertaining to the prevention of concentrated ingress of water into the ground, in accordance with the relevant requirements of SANS 1936-3
D4	Requires additional site-specific precautions

Any kind of development, including stormwater management, should be conducted in terms of the SANS 1936[17] requirements. If residential, the development should be enrolled with the National Home Builders Registration Council (NHBRC) and it should be designed and constructed in accordance with the requirements for residential buildings on dolomite as prescribed in the NHBRC *Home Building Manual.*[18] The following precautionary measures regarding the installation and maintenance of wet services on dolomite are important:

- The Responsible person(s) should compile and use a site-specific Dolomite Risk Management Plan for the site. The owner/responsible persons should be made aware of the risks involved in building on dolomite, and be informed about how to be vigilant and act pro-actively by applying sound water management principles.
- The precautionary measures as set out in *SANS 1936-3 Development of Dolomite Land – Part 3: Design and construction of buildings, structures, and infrastructure*[19] should be studied and implemented for D2 and D3 sites.
- The professional team involved should carefully consider the appropriate site-specific water precautionary measures and then ensure and finally certify that these have been implemented.
- Wet services should be laid exactly where indicated on the drawings presented to the relevant local authority and these may not be laid below structures. The contractor, or his appointed professional team, should certify that the services have been placed as indicated.

An appropriate site-specific Dolomite Stability Investigation (DSI) in terms of Section 4.1 of *SANS 1936-2 Development of Dolomite Land – Part 2: Geotechnical investigations and determinations*[20] should be conducted prior to any development on dolomitic land. This should include a thorough assessment in terms of the site-inherent hazard. Adequate data should be collected to confidently compile a zonation map for the area of interest.

(iv) Landscape and ecology

The physical features of the landscape are important when designing a stormwater management system. Gain an understanding of how the landscape is continuously evolving and changing, either through natural or human-induced processes, to assist in developing the site in the most ecologically sensitive manner. Gather information about the following:

- The type and extent of existing vegetation on the site and surrounding areas. Vegetation can affect the volume and velocity of stormwater runoff through interception (vegetation capture precipitation, resulting in evaporation rather than water falling on the ground and contributing to runoff), transpiration (vegetation draws water from the soil and releases it as water vapour) and infiltration (roots increase the infiltration of water in the ground). Vegetation is regarded as a critical element in Sustainable Drainage Systems (SuDS) (see Section L.3.3.1 for a discussion on SuDS as an option for stormwater management).
- The type of agricultural activities in the surrounding area. One of the major reasons for soil erosion that occur in many rural areas is the over-stocking of animals. Planning for stormwater management needs to take this into account.
- Wetlands, surface water bodies, or other ecologically sensitive areas on or near the site. Information on Critical Biodiversity Areas (CBAs) or Ecological Support Areas (ESAs) is available on the website of the South African National Biodiversity Institute (SANBI)[21].
- Endangered or protected animal and plant species on or near the site.
- Natural features that may have cultural significance.
- The prevalence of veld fires in the area.

(v) Adjacent land uses and edge conditions

Existing and likely future land use on the site and in the surrounding areas will have an impact on the planning of a stormwater management system. The impact will be related to stormwater runoff quantity (peak flow and flood volume) and stormwater runoff quality and the following should be considered:

- Peak flows and flood volumes are influenced by the surfaces of adjacent properties. It is important to obtain information on parking areas, open spaces, streets and sidewalks in the vicinity of the project site. If available, the coverage of buildings is also used in calculating flow rates.
- Where are solid waste management sites (specifically landfill sites) positioned? The location is important, as stormwater flows through these sites and may have a significant environmental impact on the ground and on adjacent or nearby surface water bodies. Such site positioning is regulated by the DWS, from whom the minimum requirements to be adhered to are available in *Minimum Requirements for Waste Disposal by Landfill*[22], *Minimum Requirements for the Handling and Disposal of Hazardous Waste*[23] and *Minimum Requirements for Monitoring at Waste Management Facilities*[24].
- Are there any cemeteries in the surrounding area? Cemeteries pose a pollution threat in that they can contaminate water resources. Microbiological and chemical pollutants (including bacteria, viruses and parasites) can travel considerable distances and remain active within the water table for long periods[25,26,27]. The potential pollution of groundwater and surface water by cemeteries requires a thorough technical evaluation. See Section G.3 for a discussion on the provision of cemeteries.

Stormwater management systems that convey stormwater to bodies of water that are classified as environmentally sensitive, for recreational use, or in public spaces, should specifically be planned to minimise or eliminate pollution.

The best way of dealing with pollution is to try and prevent the pollution at the source. Information on potential sources of pollution that may be associated with certain land uses is presented below:

Air pollution

- Sources of air pollution should be identified, as air pollution can cause acidic deposition by rain (acid rain), which may be transported through stormwater management systems and may result in acidification of freshwater ecosystems, denudation of forested and agricultural areas, corrosion of metal surfaces, and destruction of masonry structures.

Point sources of water pollution

- **Industrial pollution:** Many industrial processes use water and produce effluent that could become part of the water released into the stormwater management systems. Abattoirs, breweries, pharmaceutical companies, as well as the fishing, tanning, and fruit and vegetable industries are relevant examples.
- **Mining:** Many pollutants emanate from mining operations. The main concern for the design of stormwater systems is acid mine drainage and its associated dissolved heavy metals. Mines are required to implement the DWS standards for the separation of clean and polluted water. For guidance, refer to *Stormwater Water Management Best Practice Guidelines for Water Resources in the South African Mining Industry*[28] and *A Manual on Mine Water Treatment and Management Practices in South Africa*[29].

Non-point sources of water pollution

Non-point sources of water pollution are difficult to locate. Technologies such as infra-red aerial photography[30] can prove helpful in identifying non-point source pollution problems, for example runoff from city streets, farms, forests, mines, construction sites, and atmospheric deposition.

- **Agricultural pollution:** Poor farming practices often have a negative impact on water in the environment. Some of the observed consequences are decreasing biodiversity; overgrazing through overstocking; pollution by fertilisers, pesticides, herbicides and fungicides; soil crusting; irrigation with polluted water; excessive sediment wash-off; and dust pollution. Guidelines in terms of the sodium adsorption ratio[31] and the adjusted sodium adsorption ratio should be consulted to ensure that the water quality does not limit productivity, and that users downstream are not disadvantaged by poor agricultural land use.
- **Urban pollution:** Polluted stormwater runoff from urban catchments has a major impact on the water-receiving bodies. Sources of pollution include road wash-off, leaky and overflowing sewers, deliberate discharge of sewage into the stormwater drainage system, and illegal dumping into stormwater systems.

L.3.2.2 Available engineering infrastructure

The provision of stormwater management infrastructure may mean the extension of existing systems. The following questions should be asked:

- What existing stormwater management infrastructure is available close to the proposed development? Does the existing stormwater management infrastructure have enough capacity to handle additional runoff? Is the existing stormwater management system in working order? Are any 'as-built' records available for stormwater management systems near the proposed development?

- What are the long-term stormwater management requirements of the neighbourhood and the settlement? Is there an existing drainage master plan available?

Master planning

Master planning is predominantly concerned with the major system. The minor system is considered a supporting system for the major system. Master planning typically involves the following:

- Allocation of space for stormwater management and drainage. Runoff will make its way downhill whether a safe drainage path has been provided or not, and management interventions cannot be implemented unless there is space to do so.
- Determination of an appropriate recurrence interval of the major flood event. This is typically 1:100 years; however, consideration should be given to using the Probable Maximum Flood (PMF) or Regional Maximum Flood (RMF). Remember that flood lines may change with development – as well as with climate change.
- Determination of an appropriate recurrence interval for the minor flood events.
- Provision of overall guidelines for runoff detention requirements, pollution abatement strategies, and the powers and responsibilities of developers and authorities within the catchment area.
- Consideration of land use on flood plains and multi-use of stormwater facilities.
- Guidelines on safety and maintenance.
- Guidelines on environmental conservation.

- What are the sizes of existing pipes in the stormwater management system? The dissipation of energy of water in canals, or of water discharging from pipes or culverts must be considered when downstream erosion and scouring are possible. The size and type of an energy dissipation system will depend on the scale. The energy of water discharging from small- to medium-sized pipes can effectively be dissipated in preformed scour holes or riprap aprons. Large pipes and culverts will require more elaborate and robust energy dissipation structures. See Section L.4.2.4 for design guidance for energy dissipation.
- Where are the water supply points on the site and in the neighbourhood? The drainage of excess water from water supply points should be given serious consideration in developing communities and rural settlements. Erosion can occur when water flows over unprotected areas. Puddles may also be formed where disease-carrying vectors (mosquitoes) can breed.
- What are the water supply sources currently available to the site? Stormwater can be considered a water source to augment the water mix. However, the harvested stormwater needs to be treated to fit the purpose of the use. Refer to Section J.4.2 for a discussion on different water sources available for neighbourhood water supply.

Figure L.3: Excess water at a communal standpipe redirected for garden use (L) and excess water causing erosion (R)

L.3.3 Stormwater management options

To meet the key objectives of stormwater management (see **Section L.2.2**), the system that is selected should minimise the change in stormwater runoff from pre-development to post-development conditions for all storm durations and recurrence intervals. This section starts with a discussion of Sustainable Drainage Systems (SuDS) as an option for neighbourhood stormwater management. Options related to different elements of the stormwater system are then discussed. The issues relevant to minor and major stormwater systems (refer to **Section L.2.3.5** for an explanation of the dual drainage system) conclude the section.

L.3.3.1 Sustainable Drainage Systems

Neighbourhood development projects typically replace (permeable) natural drainage surfaces with roofs, roads and paved areas, resulting not only in an increase in stormwater runoff quantity (peak flow and flood volume), but quite often also affecting stormwater runoff quality. These man-made surfaces are typically drained by conventional infrastructure (including pipes and lined channels), which is focused on minimising and eliminating local flood nuisances. SuDS promote more natural drainage, aiming to reduce downstream flooding, allow infiltration into the ground, minimise pollution, improve the quality of stormwater, reduce pollution in water bodies, and enhance biodiversity. Stormwater is not merely collected and discarded through a system of pipes and culverts, but is recognised as a valuable resource.

SuDS encourage more natural drainage through the use of a number of key processes. These processes are linked to four elementary focal points of SuDS, namely: quantity (flow and volume); quality; amenity; and biodiversity. Refer to *The South African Guidelines for Sustainable Drainage Systems*[32] for detailed descriptions of the different processes that SuDS use to promote more natural drainage.

This section starts with a discussion on the issues that have to be considered when selecting SuDS options. Then, as per *The South African Guidelines for Sustainable Drainage Systems*[33], the various SuDS options are grouped and discussed as 'source controls', 'local controls' and 'regional controls'. The SuDS options are listed in Table L.1.

Table L.1: SuDS options

Group	SuDS intervention
Source controls: Stormwater runoff is managed as close to its source as possible, usually on site	• Green roofs • Rainwater harvesting • Soakaways • Permeable pavements
Local controls: Stormwater runoff is managed in the local area, typically within the road reserve	• Filter strips • Swales • Infiltration trenches • Bioretention areas • Sand filters
Regional controls: The combined stormwater from several developments is managed	• Detention ponds • Retention ponds • Constructed wetlands

(i) SuDS selection

Stormwater is managed by selecting an appropriate combination of SuDS options based on the unique characteristics of the site as well as the management objectives of the local municipality. The matrix presented in Table L.2 can assist in choosing between different SuDS options and selecting an optimal combination of interventions. Information is provided on each of the controls (source, local and regional) relating to their possible impact on stormwater quantity and quality issues. An indication is given whether the selected intervention will contribute to improved amenity and biodiversity in the area. The last three columns provide an indication whether costs (in terms of land take; capital; and operation and maintenance) related to the intervention are likely to be high, medium or low.

Table L.2: SuDS conceptual design matrix

		Quantity					Quality						Amenity		Biodiversity	Costing		
		Rainwater harvesting	Infiltration	Detention	Conveyance	Long-term storage	Sedimentation	Filtration	Adsorption	Biodegradation	Plant-uptake	Nitrification	Recreational benefits	Aesthetic enhancement	Habitat provision	Land take	Capital	Operation and maintenance
Source controls	Green roofs	S	×	P	×	×	P	P	P	P	P	P	Y	Y	Y	×	L/M	M
	Rainwater Harvesting	P	×	S	×	P	PR	×	×	×	×	×	×	×	N	L	M/H	M
	Soakaways	S	P	S	×	×	PR	P	P	P	×	×	×	×	N	×	M	L
	Permeable pavements	S	P/S	P/S	S	×	×	P	P	S	×	×	Y	Y	N	×	L/M	L
Local controls	Filter strips	×	S	S	P	×	P	P	P	P	S	S	Y	Y	Y	H	L	L
	Swales	×	S	S	P	×	S	P	P	S	S	S	×	Y	Y	M	L	M
	Infiltration trenches	S	P	S	×	×	PR	P	P	S	×	S	×	×	N	L	L/M	M
	Bio-retention areas	S	P	P/S	×	×	P	P	P	P	P	P	×	Y	Y	M	M	M
	Sand filters	S	S	P	×	×	S	P	P	S	×	×	×	×	N	L	L/M	M
Regional controls	Detention ponds	×	S	P	×	×	P	×	×	×	×	×	Y	Y	Y	H	L	L
	Retention ponds	P	S	P	×	P	S	S	S	P	P	P	Y	Y	Y	H	M	M
	Constructed wetlands	S	S	P	×	P	S	S	P	P	P	P	Y	Y	Y	H	H	L/M
		Primary process (P) Secondary process (S) Pre-treatment Required (PR) Not applicable (×)											Provides amenity/habitat (Y) Does not provide amenity/habitat (N)			High (H) Medium (M) Low (L)		

Acknowledgement: Armitage et al.[34]

Each of the control measures utilises slightly different SuDS processes, which are grouped in Figure L.4 as minimised release of pollutants (good housekeeping); source controls; local controls; and regional controls. A combination of these interventions results in a treatment train (a combination of different methods implemented in sequence or concurrently, and illustrated in Figure L.4) that should achieve the desired level of treatment. A consistent and regular maintenance plan is required for the effective operation of each stormwater control measure and they should also be inspected and maintained after large storm events.

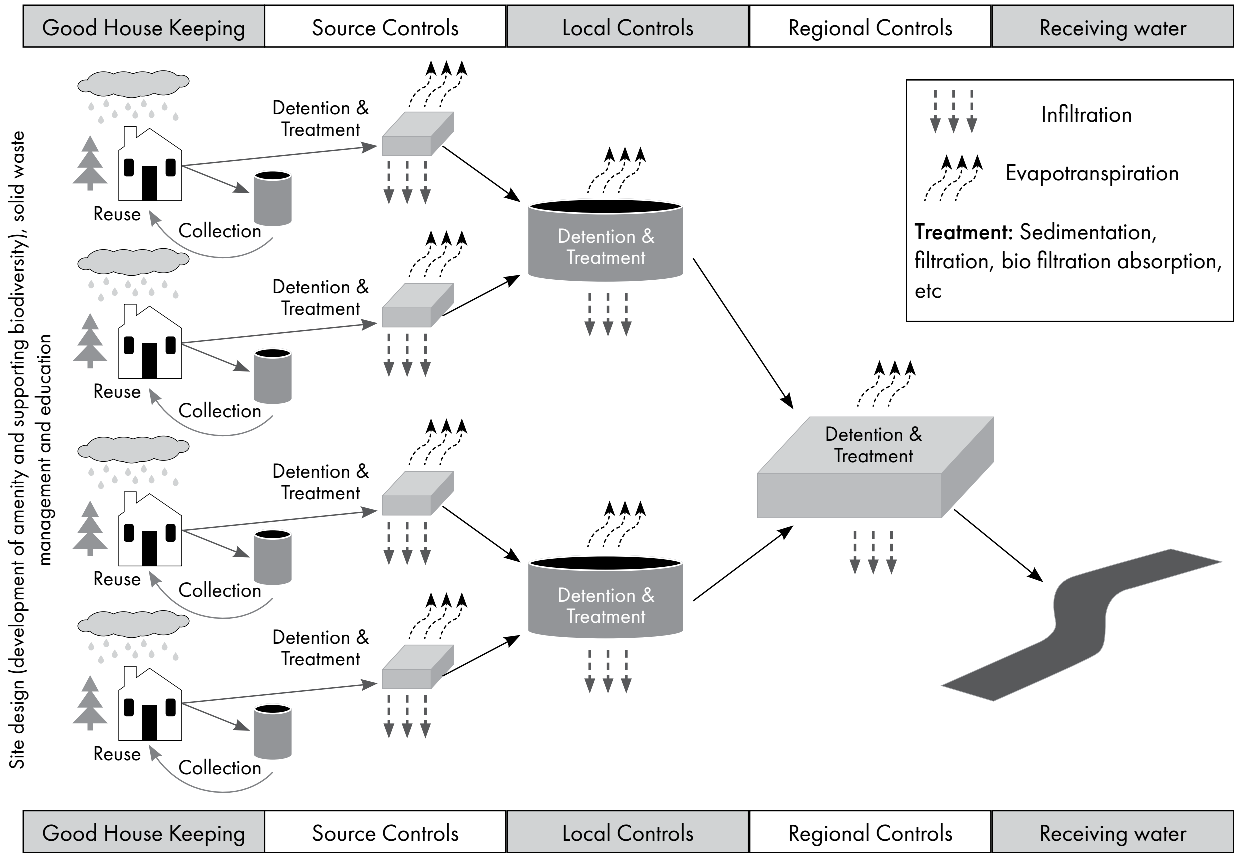


Figure L.4: SuDS treatment train schematic

Acknowledgement: *Armitage et al.*[35]

The increased complexity introduced by a SuDS approach to stormwater management has required the following terms to be defined:

WQV (m^3) The Water Quality Volume is the volume of water from small storm events where the focus is on treating for water quality. The storm events typically have an RI of less than one year; they are less than the 90th percentile storm, or have less than a set depth of precipitation, e.g. 25 mm in the drier areas of the country and 30 mm in the wetter areas.

ReV (m^3) Recharge Volume is the proportion of the WQV that should be infiltrated on site to make up for the reduction of natural infiltration.

CPV (m^3) The Channel Protection Volume refers to the volume and rate of flow required for management to reduce the potential for degradation in natural channels. It is usually achieved through the detention of runoff on site. The critical storm event typically has an RI of around two years.

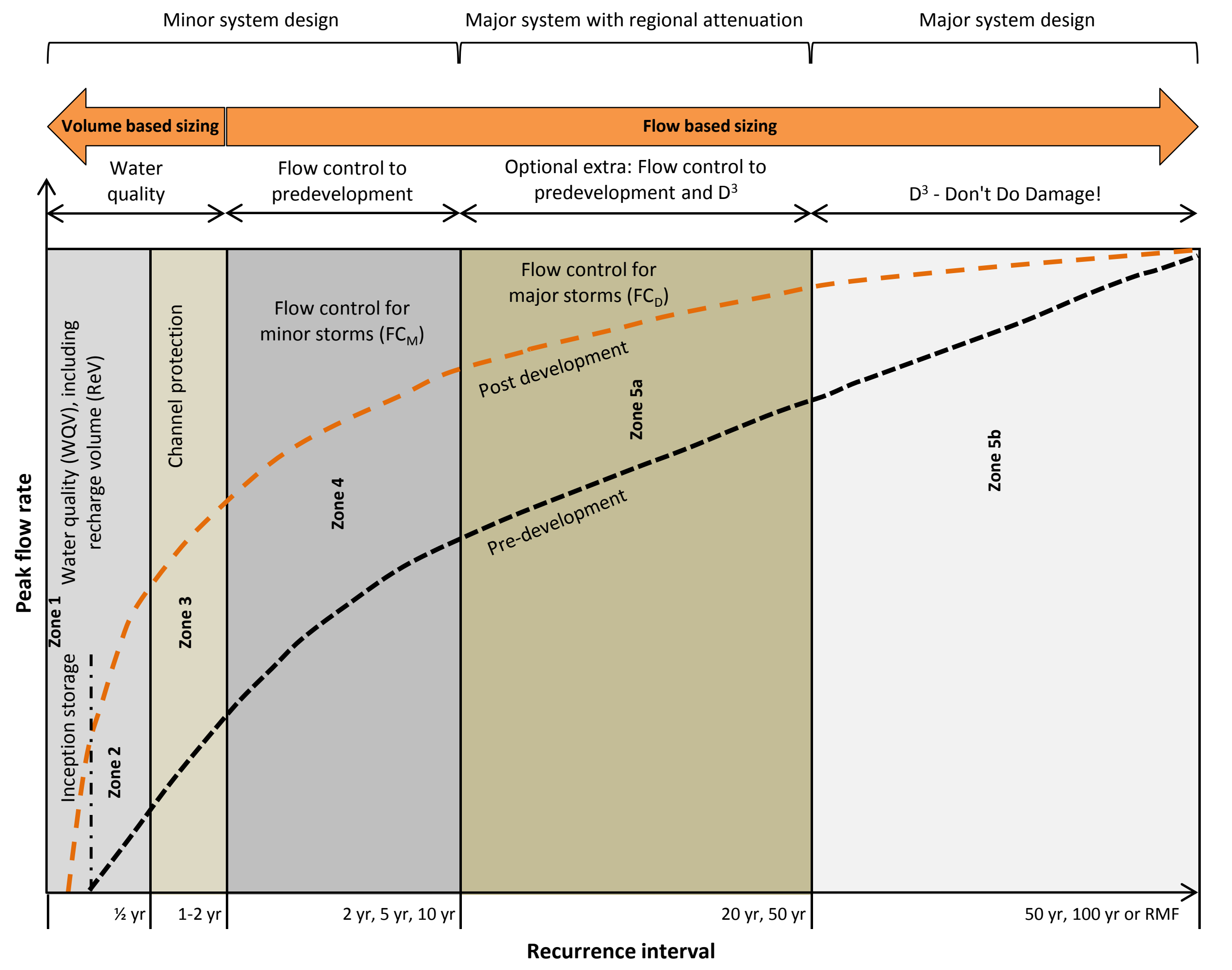
FCM (m^3/s) Flow Control (minor storms) refers to the reduction of peak flow to the pre-development scenario typically for storm events with an RI of between two and ten years, depending on the type of development.

FCD(m^3/s) Flow Control (major storms) is also required for maintaining pre-development flows and preventing damage to property and risks to life for storm events with an RI of greater than, say, ten years.

D^3 Don't Do Damage refers to the importance of ensuring that extreme storm events do not cause significant damage to property and pose significant risks to life.

Using these terms, SuDS design event criteria have been developed. The proposed design RIs are listed in Table L.3, and the range of applicability is illustrated in Figure L.5.

Table L.3: Proposed design Recurrence Intervals[36]		
RI (years)	Objective/Component	Treatment
0.25 to 0.5	Interception storage; Water Quality Volume (WQV) including Recharge Volume (ReV)	None or good housekeeping or source or local controls or combinations
0.5 to 2	Channel Protection Volume (CPV)	Source and local controls
2 to 10	Flow Control for minor storms (FC_M)	Local and regional controls
10 to 20	Flow Control for major storms (FC_D)	Roadway and regional attenuation
>20	Don't Do Damage (D^3)	Major design interventions



Acknowledgement: Adapted from Armitage et al.[37]

Figure L.5: Conceptual stormwater design framework

Figure L.5 indicates the following five distinct design 'zones' that need to be considered for SuDS design:[38]

- All precipitation is absorbed through interception storage and infiltration in Zone 1.
- As the storm intensity increases, the focus (in Zone 2) moves to the management of runoff quality and quantity.
- It is often very difficult to handle water quality issues for all but small storms; past a certain threshold the emphasis starts to move to one of channel bed protection (Zone 3).

- There is still a need to minimise inconvenience, so SuDS must give the equivalent peak overland flow protection offered by conventional systems beyond that achieved in Zones 1-3. This is covered in Zone 4.
- SuDS need to be designed for major events just like conventional systems. Zone 5 may thus be divided into two: Zone 5a where peak flows may be reduced to pre-development, and Zone 5b where the emphasis moves to minimising damage to property and potential loss of life (D3 = Don't Do Damage).

(ii) SuDS source controls

Source controls are used to manage stormwater runoff as close to its source as possible – generally within the boundaries of the property – and include green roofs and buildings; rainwater harvesting; infiltration and evapotranspiration; soakaways and permeable paving. Design guidance for these source control measures is provided in Section 4.2.1(i).

Green roofs and buildings

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

Rainwater harvesting

Rainwater harvesting is the direct capture of stormwater runoff, typically from roads, pavements, large buildings, rooftops, etc., for supplementary water, which can be used on site. See Section J.4.2 for a discussion on rainwater harvesting as augmentation to the water resource mix.

Infiltration and evapotranspiration

The most frequently used methods of controlling runoff frequency and volume are systems that promote infiltration and evapotranspiration. These can range in complexity from informal to semi-formal rain gardens that promote infiltration and evapotranspiration. This may incorporate a filtration medium, or structural soakaways that promote infiltration only. Bioswales promote both infiltration and evapotranspiration and provide an environment for biological processes that improve water quality, often by incorporating filtration, storage media and an underdrain system. Where possible, rain gardens or bioswales are favoured over soakaways because they can provide visual interest and habitat diversity in the landscape. These devices are scalable in that they can be used for small- to medium-sized catchments, but are most effective for controlling the runoff from more frequent events.

Soakaways

The purpose of a soakaway or French drain, is to provide temporary storage and facilitate the infiltration of stormwater into the groundwater. Storage is provided in a tank or in an excavation filled with a stone medium of high porosity.

Photo credit: Achim Hering -Wikimedia Commons (R)[39]

Figure L.6: A rainwater harvesting system (L) and permeable pavement (R)

Permeable pavements

Permeable pavements are a stormwater control measure that replaces traditional impervious paving with a permeable surface that allows stormwater to drain through into an underlying storage and drainage layer. Water is lost from the storage layer either by infiltration into the subgrade, or via a subsurface drainage system. The water may be harvested for landscape irrigation.

(iii) SuDS local controls

SuDS local controls are used to manage stormwater runoff as a second 'line of defence', typically in public areas such as road reserves and parks. SuDS local controls include detention basins; filter strips; swales; infiltration trenches; bioretention areas; and sand filters. Design guidance for these local control measures is provided in Section 4.2.1(ii).

Detention basins

Detention basins are temporary storage facilities that are ordinarily dry but store stormwater runoff for short periods of time during periods of high flow. The size will depend on the extent of the developed area. The detention basins have limited treatment capacity other than that achieved through the deposition of silt and solid waste.

Filter strips

Filter strips are maintained grassed areas of land that are used to manage shallow overland stormwater runoff through several filtration processes.

Swales

A swale is a shallow vegetated channel designed to convey stormwater, but it may also permit infiltration. The vegetation assists in filtering particulate matter and capturing nutrients.

Infiltration trenches

Infiltration trenches are excavated trenches that are filled with broken rock, coarse gravel, or commercial void-forming products (like soakaways described above).

Bioretention areas

Bioretention areas (rain gardens, bioretention cells, bioswales) are landscaped depressions typically employed to manage the runoff from the first 25 mm or so of rainfall by passing the runoff through several natural processes (filtration, adsorption, biological uptake, sedimentation, infiltration and detention). Different bioretention areas include:

- **Rain gardens:** A rain garden is a planted depression that receives stormwater runoff from impervious areas and less pervious vegetated areas such as compacted lawns, giving this water an opportunity to soak into the ground. It can be as simple as a small depression in the natural soil, or a more elaborate system containing an engineered growing medium and a gravel storage layer. Rain gardens are the simplest of all SuDS interventions and, because of their simplicity and scalability, can be among the most effective.
- **Bioretention cells:** A bioretention cell is a planted depression that receives stormwater runoff from impervious areas and less pervious vegetated areas such as compacted lawns. It drains this water away by slow surface and subsurface flow, while giving it an opportunity to soak into the ground. It is a more elaborate system than a rain garden, containing an engineered growing medium, a gravel storage layer, and a gravel drainage layer with or without an agricultural drain.
- **Bioswales:** A bioswale differs from a rain garden or a bioretention cell in that it has a linear drainage component. It differs from a conventional cell because it is constructed with selected filtration media and underdrains to improve water quality. Bioswales can serve additional purposes, for example eliminating the need to irrigate street trees.

Figure L.7: Examples of a rain garden (L) and a bioswale (R)

Photo credit: Wikimedia Commons - Rogersoh (L)[40], Chris Hamby (R)[41]

Sand filters

Sand filters normally consist of a sedimentation chamber linked to an underground filtration chamber that comprises sand or other filtration media through which stormwater runoff passes.

(iv) SuDS regional controls

SuDS regional controls are used to manage stormwater runoff as a last 'line of defence', and typically constitute large-scale intervention on municipal land. All regional facilities should be accessible by the local authority for inspection and maintenance purposes. The key management tool is water storage, which may be incorporated into the stormwater system in many ways to regulate the rate of discharge from the system, improve water quality and reduce peak flow rates. The controls may also have recreational or biodiversity functions and include detention ponds; retention ponds; and constructed wetlands. Design guidance for these regional control measures is provided in **Section 4.2.1 (iii)**.

Detention ponds

Detention ponds or detention basins are temporary storage facilities that are ordinarily dry, but they store stormwater runoff for short periods of time during periods of high flow. These facilities can be designed to be multi-purpose, e.g. they can serve as parks or sports fields when not required for flood management. The captured stormwater runoff either infiltrates into the underlying soil layers or, more usually, is drained into the downstream watercourse at a predetermined rate.

Retention ponds

Retention ponds store water permanently. They are generally formed through the construction of a dam wall equipped with a weir outlet structure. The maximum storage capacity of retention ponds should be larger than their permanent pond volume. Stormwater flowing into the pond is mixed with the permanent pond water and released over the weir at a reduced rate. Retention ponds are frequently combined with stormwater detention facilities to provide blue/green storage systems.

Constructed wetlands

Wetlands are marshy areas of shallow water partially or completely covered in aquatic vegetation, or "water-dominated areas with impeded drainage where soils are saturated with water and there is a characteristic fauna and flora"[42]. Other water bodies, such as vleis, water sponges, marshes, bogs, swamps, pans, river meadows, and riverine areas, are often called wetlands. Their ecological importance has been emphasised by the RAMSAR Convention in 1971, and many municipalities and industries are using artificial wetlands to treat wastewater.[43]

For the purposes of stormwater management, wetlands may be categorised into natural, modified natural, or constructed wetlands. The most common stormwater runoff pollutant treatment processes that occur in constructed wetlands are sedimentation, fine particle filtration, and biological nutrient and pathogen removal.

The effective functioning of a wetland is dependent on the presence of environmental conditions conducive to the required processes and the rate of hydraulic and nutrient loading. A major advantage is that wetlands are not dependent on external energy or chemical inputs and generally require little maintenance. Constructed or created wetlands simulate processes occurring in the natural wetland system. These may include:

- flood attenuation; and
- water quality improvement through the removal of substances such as suspended solids, nitrogen, trace metals, bacteria and sulphates.

In addition to their water purification functions, wetlands provide habitats and life-support systems for a wide range of flora and fauna, particularly birds, plants, reptiles and invertebrates. Wetlands can be aesthetically pleasing and offer an opportunity for recreation and education.

L.3.3.2 Elements of stormwater management systems

(i) Drainage of stormwater

Local topography and rainfall can lead to the formation of pans, dams and lakes, which form part of the conveyance route of stormwater until it finally infiltrates, evaporates, or reaches the sea. To protect the built environment, various man-made stormwater conveyance strategies and structures have been developed. Conventional drainage systems typically incorporate hard engineered structures such as pipes or culverts. The SuDS approach is to avoid hard structures where possible and provide for conveyance in swales or overland vegetation-lined drainage ways. The need to treat (alter and manage) the stormwater runoff of areas is primarily because of increased peak flows (normally due to development upstream), or to convey stormwater through and out of new developments. Erosion, flood, environment and health protection requirements should always be considered as part of conveyance. Design guidance for different drainage elements (infrastructure that conveys stormwater) is provided in Section L.4.2.2.

Channels

The main purpose of channels is to convey flows up to a certain RI within their cross-section. Channels should be designed to be 'fail-safe' so that the water level rises gradually if their design discharge is exceeded. Channels should also be designed to meet safety, maintenance and aesthetic requirements. Decisions about channel design should involve considering the following: conduit route; slope; cross-section shape; lining material (if materials other than concrete are chosen, careful attention must be given to durability and structural stability); flow regime (subcritical or supercritical flow conditions – the latter should be avoided wherever possible).

Land use, as well as environmental, economic and topographic considerations govern the route of a channel. The best channel route should follow the existing natural drainage lines. The slope of a channel tends to be the same as the natural ground slope; however, it could be made steeper (straightening of a winding natural channel), or flatter (incorporating drop structures or an aqueduct).

The selection of the channel cross-section and lining is governed by the site conditions, as well as by the character of the subgrade. For example, if space is limited and the subgrade is highly erodible, a concrete-lined channel with a rectangular or trapezoidal cross-section should be considered.

Photo credit: Wikimedia Commons - Nick D (L)[44], Nankai (R)[45]

Figure L.8: Examples of a stormwater channel (L) and a grass-lined swale (R)

- **Grass-lined channels (swales):** Often referred to as 'swales', grass-lined channels may have advantages over hard-lined channels in terms of aesthetic and recreational planning concerns, although they normally require higher maintenance. The presence of vegetative cover protects the soil from the erosive power of wind and water, reduces the runoff volume through infiltration, decreases flow velocities through retardation, improves water quality through filtration and various other biological processes, and can be aesthetically more pleasing if properly maintained.

- **Conduits:** The main purpose of conduits is to convey flows of a certain RI within its cross-section where an open channel is not suitable or desirable. Conduits should be able to convey flows greater than the design flood in a controlled manner and meet safety requirements and needs for maintenance. Decisions about conduit design involve a selection of the following: conduit route; slope; cross-section shape; material lining; and flow regime (subcritical or supercritical flow conditions).

  Land use, as well as environmental, economic and topographic considerations govern the route of a conduit. The best conduit route should generally follow the existing natural drainage lines. The slope of a conduit tends to be the same as the natural ground slope; however, it could be made steeper (straightening of a winding natural channel) or flatter (by decreasing the cover or using drop structures).

  The selection of the conduit cross-section, material type and joint type is governed by site-specific conditions and by overall planning concerns. For example, if the area is underlain with dolomite, a sealed joint should be considered.

- Transitions

  - **Kerb inlet transitions:** Kerb inlets (lateral stormwater inlets) are widely used with kerbs and surfaced roads. On moderate to steep road gradients, the capacity of kerb inlet transitions could be substantially improved by incorporating an extended length of depressed gutter upstream of the inlet. The effect of clogging should be minimised. More information is available in international literature.[46]

- **Kerb inlets:** The purpose of kerb inlets is to guide surface flow, e.g. from roads or parking areas, into the underground drainage system. The standards used by municipalities vary considerably. Generally, cognisance should be taken of the following: hydraulic performance; accessibility for cleaning purposes; ability of the top section of the culvert to bear heavy traffic; safety for all road users; and cost. Additional kerb inlet capacity of about 20% should be allowed to prevent blockages. More information is available from SAICE[47].

- **Culvert transitions:** Culvert transitions are structures that attempt to converge wide, shallow flow to pass through a narrow throat.

• **Road drainage:** The main function of urban roads is the carrying of vehicular, cycle, and pedestrian traffic. But they also have a stormwater management function. During minor storm events, these two functions should not be in conflict. During major storm events, however, the flood control function becomes more important as the roads 'double up' as channels and the traffic function is at least partially interrupted. It is thus essential that the road design and the stormwater design be done simultaneously. Coordinated planning between the road and drainage engineers is crucial at the pre-feasibility stage to ensure that the objectives of each service are met as comprehensively as possible.

It may be possible to design an integrated road and stormwater system that obviates the need for underground stormwater conduits altogether. This could for example be done by lowering the median between dual carriageways and draining the road pavements into them, instead of raising the medians as a physical barrier between the carriageways. This approach can lead to considerable savings and it allows the median to be designed as a swale with the attendant advantages of retention and water quality improvement. The pipes draining a median swale can often be considerably smaller than those required for draining the roads along the outside road shoulders. There may be a consequent space saving along the shoulders. Vegetated medians may not require irrigation as this will occur automatically through the drainage of the carriageways. Roundabouts at road intersections often provide an opportunity for the inclusion of bioretention areas with similar benefits to median swales. Road drainage issues related to unsurfaced roads; open channels; and the traffic-carrying capacity of roads are discussed below.

- **Unsurfaced roads:** The integration between the road and the stormwater drainage system becomes even more critical with unsurfaced roads. The drainage function of unsurfaced roads is dependent – and has a significant impact – on the planning of the road and access layout. If the roadway is to be used to channel and drain stormwater runoff, the velocity of this runoff should be such that minimal erosion potential exists (which implies flat longitudinal gradients). Roads with steep gradients should, as far as possible, not be used as drainage ways, nor should any adjacent side drains be used without proper protection against erosion. This protection can include drop structures, lined channels at critical sections, or regular drainage from the roadway into intersecting roads or drainage ways.

  Runoff from earth or gravel roads will contain grit and its conveyance in pipes can eventually block or damage the pipe network. Such blockages are difficult to clear. If maintenance is not done regularly, it will render the network ineffective. Use of pipelines in environments of high erosion potential is not recommended because of the high expense of maintenance and the high risk of failure or non-performance. Suitable protection against erosion of the canal invert, including drop structures and silt traps, is also important.

Photo credit: Wikimedia Commons - SuSanA Secretariat (R)[48]

Figure L.9: An example of erosion on an unsurfaced road (L) and lack of maintenance of an open channel (R)

- **Open channels:** Open channels – including swales (grassed open channels) – are an alternative to a network of pipes on the roadsides for conveying minor storm runoff. These may also convey dry weather flow in areas where the water tables are high or perched, and where the potential greywater/sullage from low-income households or from communal (shared) water points exist. The positioning of communal water points should be carefully considered and the appropriate drainage from these points should be included in their design.

  The use of open roadside channels may necessitate wider road reserves than those required to accommodate subsurface drains. This is particularly pertinent where open channels intersect with roadways or property access ways. The width of an open channel may increase progressively as the drain accepts more runoff. The road reserve may have to be widened or the channel deepened. Open drains, like all systems, will require maintenance; however, one advantage of an open channel system is that problems are not 'out of sight, out of mind'. Siltation and other problems will immediately become apparent.

  The crossfall of the road should generally be against the natural ground slope so that the whole road width can act as a drainage way in the major system. Protection against erosion on the downstream road edge may be required. Ideally, township layouts should be planned in such a way that the greatest length of road closely follows the ground contour (see Section F.4.3). Roadside channels are accessible, therefore safety considerations, especially relating to flow velocity or specific energy, are important.

- **Traffic-carrying capacity:** Stormwater runoff may affect the road's traffic-carrying capacity in the following manner:
  Sheet flow across the road surface – Sheet flow generated on a road surface is usually the least at the road crown, and increases towards the road edge. This can lead to hydroplaning, in other words when a vehicle travelling at speed has its tyres separated from the road surface by a thin film of water. Sheet flow can also interfere with traffic when splashing impairs the vision of drivers. Roads must be designed to avoid sheet flow crossing the traffic lanes, and attention must be paid to transition geometry.

Figure L.10: Examples of a river that has been restored

Channel flow along the road – Channel flow is generated from sheet flow and from overland flow from adjacent areas. As the flow proceeds, it increases in volume, encroaching on the road surface until it reaches a kerb inlet or drain inlet. The result is reduced effective road width. Splashing produced by car tyres can lead to dangerous driving conditions. It is important that emergency vehicles should still be able to use the road during major storms.
Ponding of runoff on road surfaces – Ponding on roads may occur at low points, at changes in gradient, at sump inlets, and at road intersections. This can have a serious effect on traffic flow, particularly as it may reach depths greater than the kerb height or remain on the roadway for long periods. A hazard of ponding is that it is localised; traffic may enter a pond at high speed, resulting in accidents.
Flow across traffic lanes – Flow across traffic lanes may occur at intersections when the capacity of the minor system is exceeded. As with ponding, localised cross-flows can create traffic hazards. Care should be taken to mitigate dangerous situations.

- **River restoration or renaturalisation:** Rivers and natural channels should ideally not be disturbed by construction activities. Should this be unavoidable, they should, under the guidance of appropriately qualified experts, be restored to such an extent that the channel would continue to behave in a hydraulic and ecological manner similar to that of the undisturbed natural stream. Failure to meet this requirement may lead to ecological collapse, erosion, and possible failure of drainage infrastructures. Newly constructed open channels must be properly integrated into the surrounding ecological, physical, visual, and social environments.

The morphology of urban streams is driven largely by hydrological changes in the catchment. Increased volumes of runoff and increased peak discharges will cause the stream to widen and deepen its channel. Along with increased frequency of runoff, these may destabilise the riparian vegetation that creates habitat diversity and helps protect the channel bed and banks against erosion. A stream rehabilitation plan should address the following:

- Returning the stream to a functional ecological condition, including establishment of habitat diversity
- Returning the stream to a functional morphological condition with a mix of features, such as meanders, pools, riffles, rapids, falls, bars, and bed and bank materials appropriate to the topography

- Re-establishing a flood regime of low flows, bank full flow, and overbank flow
- Restoring the riparian corridor, including replacement of alien invasive vegetation with suitable locally indigenous species to provide cover, resting, feeding, and breeding opportunities for animals and birds using the corridor
- Creating a socially and aesthetically attractive environment
- Ensuring sustainability of the recreated environment

The construction of rectangular channels with near vertical or stepped sides and level beds, using gabions or similar systems may be necessary under certain circumstances, but this cannot be defined as restoration or rehabilitation. Several publications give comprehensive guidance in the process of restoring urban streams.[49]

Relevant authorities should be consulted in the rehabilitation process as they may have special requirements for existing channels relating to riparian improvement programmes; soil conservation programmes; stream rehabilitation plans; natural channel design programmes; and ecological sustainability programmes.

(ii) Control structures

Weirs and orifices are structures widely used in hydraulic engineering to control or measure flow. Many of these structures are complex to analyse and difficult to build. Complex structures should only be considered in exceptional circumstances or where they are to be incorporated into the aesthetics of the structure as objects of urban sculpture. Design guidance is provided in Section L.4.2.3.

(iii) Detaining and retaining stormwater

Runoff can be stored in constructed basins. Such basins usually require large areas to be effective. Successful detention/retention of runoff may have to rely on several technologies, including detention ponds (detention facilities); rooftop detention; retention ponds; and/or wetlands. More information on SuDS regional controls to detain and retain stormwater is provided in Section L.3.3.1 (iv). The feasibility should be investigated of harvesting rainwater either directly from roofs and impervious surfaces (as rainwater harvesting), or from the stormwater drainage system (as stormwater harvesting).

(iv) Stormwater outfall

The discharge from a proposed development, including the provision for the potential flow from the outside drainage area, should be either into a natural watercourse, or to a point of acceptance agreed upon by the landowner downstream and approved by the authority concerned. Stormwater system outlets should discharge stormwater of roughly equal quantity and quality than those of the pre-development conditions into receiving drainage ways at points that are least likely to erode. Discharge of stormwater should occur in a way similar to water that naturally entered the receiving system, for example if a wetland naturally received distributed surface and subsurface inflow, the stormwater outlet should mimic this regime. Design guidance for outfall management is provided in Section L.4.2.4.

The discharge of stormwater from a planned development should not be concentrated on a downstream property where it was not concentrated before, unless a servitude for conveyance of the stormwater is acquired to cross that property and any other low-lying properties until it reaches a specific point of discharge. The post-development peak flow rate may not exceed that of the pre-development peak rate of flow (see Section L.4.1.1 for guidance on the modelling of peak flow rates). If the rate of runoff is increased, or may aggravate an existing problem post-development, stormwater management satisfactory to the controlling authority system should be provided to preclude any adverse impacts related to the higher or concentrated flow rate. Every outfall structure is a potential source of water that could, through innovative planning, be used as a valuable resource.

L.3.3.3 The dual drainage system

The dual system incorporates a 'minor system' for the frequent storm events and a 'major system' for the less frequent but severe storm events (see **Section L.2.3.5**). The main functions of minor systems are to ensure convenience to the public and compliance with regulatory targets, while the major system operates during overflow from or failure of the minor system, generally during major or infrequent storm events. It includes natural watercourses, large conduits, roads, stormwater attenuation facilities (ponds), drainage servitudes, wetlands and flood plains. Public open spaces, sports fields and parking areas can also be utilised to form part of the major system.

(i) Minor systems

Minor systems are usually managed by setting targets to best control the following measurable parameters of stormwater runoff: peak discharge rate; total volume of runoff; frequency of surface runoff; and water quality. The minor system supports the major system by mitigating the risks that might result from more frequent storms. The main functions of minor systems are to ensure convenience to the public and compliance with regulatory targets.

The minor stormwater system minimises the nuisance value of storms with relatively frequent recurrence intervals (typically from 2 to 10 years, depending on the development). Ideally, at least the first 25-30 mm of rainfall (typically 1:3 months to 1:6 months RI) – which is the most polluted – is managed via SuDS source controls (green roofs, rain harvesting, permeable pavements, etc.) or SuDS local controls (infiltration trenches, bio-retention areas, etc.). Surplus water may be conveyed via swales, catchpits, road-edge channels, pipes, etc. to SuDS regional controls (ponds, wetlands, etc.). There it is temporarily stored and treated (sometimes harvested) before being released into the natural drainage system in a controlled manner that emulates the natural runoff process. Direct conveyance of stormwater from source to receiving water from an urban area without some form of treatment is strongly discouraged, as it frequently results in heavy downstream environmental costs. Table L.4 shows the minimum flood frequencies to be used for initial planning of minor systems per land use type.

Table L.4: Flood frequencies for minor system planning

Land use	Design flood recurrence interval
Residential	1 - 5 years or more in informal areas to ensure sufficient space to convey runoff
Institutional (e.g. schools)	2 - 5 years
General commercial and industrial	5 years
High-value central business district	5 - 10 years

The indications in Table L.4 and Table L.5 are guidelines, and the onus is on the drainage engineer to determine the risk associated with a certain recurrence interval. For areas where the risk to life, or the risk of monetary loss, loss of revenue, or loss of utilities is unacceptably high, a more stringent (or higher) recurrence interval and a higher level of service may need to be considered. For large structures such as bridges and major culverts, consult the Department of Transport's *Guidelines for the hydraulic design and maintenance of river crossings*[50].

(ii) Major systems

Major systems usually comprise roads, public open space and servitudes that will generally be free of major obstacles to overland flow. Although it is common for designers to assume that the minor system (see previous section) is available to assist with major floods, this is often not the case, as inlets and channels are easily blocked by debris. It is safer to assume no assistance from the minor system.

Natural streams, even where highly affected and degraded, form part of the major system and should receive special attention to ensure minimal damage in the event of a major flood. During a major flood, temporary disruption of many normal activities within the catchment will occur; the loss of convenience is tolerable if no inundation of private property occurs up to the design recurrence interval and the disruption is restricted to residential and lower-order roads, recreational areas and public open space, and parking areas.

The major system can be supported by the minor system, and can accommodate the unusually high runoff from infrequent hydrologic events. Its main function is to ensure public safety and protection of the built and natural environment during such events. A 100-year RI flood line is required on residential development plans in terms of the National Water Act. The minimum flood frequency to be used for initial planning of major systems, irrespective of land use, is an RI of 100 years. A more conservative approach (up to PMF/RMF) should be considered for vulnerable communities or where high hazard activities (sanitary land fill, cemeteries, fuel storage, etc.) are envisaged. Essential community facilities, especially those that are likely to play an important role in the event of significant flooding, also require a more conservative approach. The likely impact of climate change should be considered. Minimum design RIs applied in Australia are given in Table L.5 and could be used for South African situations.

Table L.5: Design Recurrence Intervals of essential community infrastructure

Type of essential community infrastructure	Design Flood Recurrence Interval
Emergency services (fire station)	500 years
Emergency services (emergency shelter)	200 years
Emergency services (police station)	200 years
Hospital and health care services	500 years
Community facility (storage of valuable records or items of historic or cultural significance, e.g. galleries and libraries)	200 years
Power station or renewable energy facility	500 years
Major electricity infrastructure (major switch yard)	500 years
Substations	200 years
Utility installation (water treatment plant)	200 years

It is important to note that the lifetime risk is much greater than the annual risk. The default value may therefore not be appropriate and planning should be considered for a much longer recurrence interval, the RMF or PMF. The concepts of best management practices (BMPs)[51], good practice, or best available technology not entailing excessive cost (BATNEEC) may require that more stringent recurrence intervals be considered. Municipalities may also stipulate more stringent flood lines, depending on the development type and location.

L.4 Design considerations

Once the elements of an appropriate stormwater management system have been identified, the infrastructure can be designed. This section first provides guidance on the modelling criteria for the design of stormwater systems and then guidance on the various elements of minor and major systems. The section concludes with highlighting important operation and maintenance considerations.

L.4.1 Modelling criteria for the design of stormwater systems

The runoff rates and volumes of storm events, determined by hydrological simulation, define the required capacity of the interventions and conveyance options for the specified design event. The facility dimensions necessary to achieve the required capacity are determined by hydraulic calculation.

L.4.1.1 Design peak flow rate

The design peak flow rate should ideally be determined by computer modelling by using one of the many commercially available software packages. A combination of other statistical methods (based on measured runoff data), empirical relationships, or deterministic methods (Rational, Unit Hydrograph, Standard Design Flood (SDF) and Soil Conservation Services (SCS-SA)) may also be used – either alone or in conjunction with computer modelling.

(i) Statistical methods

Statistical methods involve the use of historical data to determine the design flood for a given period. The use is limited to catchments with suitable long flow records. Statistical methods are recommended when suitable data is available. Any extrapolation of such data records should be handled with caution, as statistical methods assume a stationary data set – trends that are due to climate change or changing land use in the catchment are not reflected.

(ii) Empirical methods

Empirical methods, for example the Regional Maximum Flood (RMF)[52] and the Probable Maximum Flood (PMF)[53,54] are important tools for determining the peak discharges of rare flood events for risk analysis. Refer to the *SANRAL Drainage Manual*[55] for guidelines on these methods.

(iii) Deterministic methods

The Rational Method

The Rational Method – the conservation of mass adjusted by the runoff factor – is recommended for small catchments (15 km^2 maximum) only. Uniform temporal and spatial distributions of rainfall and a constant runoff factor are assumed, but these are only accurate for small impervious catchments. A first estimate of the peak flow in a drainage system can be obtained by using the Rational Method.

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

Where:
Q = design peak runoff rate (m^3/s)
C = runoff coefficient (0 – 1 where 0 indicates no runoff and 1 indicates complete runoff)
i = rainfall intensity (mm/hr)
A = catchment area (km^2)

A first estimate of the runoff volume may be determined as follows:

$$RV = C \times A \times d$$

Where:
RV = runoff volume (m^3)
C = runoff coefficient
A = catchment area (km^2)
d = rainfall depth from the Rational Method Depth Duration Frequency (DDF) curve (mm)

The Unit Hydrograph Method

The Unit Hydrograph Method is based mainly on the regional analyses of historical data and is independent of personal judgement. The results are reasonably reliable for medium-sized rural catchments (15 to 5 000 km^2). The typical minimum time step in the S-curve method of hydrograph derivation is one hour, which is regarded as too long for most stormwater management calculations.

The Standard Design Flood method

The Standard Design Flood (SDF) method[56] provides a uniform approach to flood calculations. The SDF method is based on calibrated discharge coefficients for recurrence periods of 2 and 100 years. These calibrated discharge parameters are based on historical data for 29 homogeneous basins in South Africa. The method is applicable to catchments between 10 km^2 and 40 000 km^2 in area. It should be used with caution because of its assumption that the local catchment conditions are the same as the regional basin characteristics that were used to derive the parameters, which are unlikely in the case of an urban catchment.

The Soil Conservation Services method

The Soil Conservation Services (SCS-SA) method[57] is suitable for calculating catchment runoff volumes for catchments smaller than 30 km^2. The method considers factors that affect runoff such as soil moisture, soil type and rainfall.

(iv) Computer models

Computer models are models where the catchment is represented by smaller sub-catchments of consistent characteristics (topographical slope, imperviousness ratio, soil characteristics, etc.) and the drainage system by a linked network of conduits representing the drainage pattern of the catchment. Runoff from sub-catchments is computed as a function of rainfall that may be a measured continuous time series, or a design storm derived from the local Intensity Duration Frequency (IDF) curves.

Flow in the conduits is computed by aggregating the runoff hydrographs from the sub-catchments and routing resulting hydrographs down the drainage network. Computer models can be extended to include groundwater and water quality parameters.

L.4.1.2 Storage capacity

In the initial stages of the design of storage ponds, it should always be considered what the consequences would be when the design storm is exceeded and whether an emergency overflow has been provided for to ensure the pond is not breached in an uncontrolled manner.

The storage capacity of a basin is determined as follows:

$$V = \sum_{i=0}^{n} \frac{A(i) + A(i+1)}{2} \times di$$

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)
di	= vertical height difference (m)
n	= number of horizontal sections
i	= integer variable

The required storage for Water Quality Volume (WQV) can be computed as follows:

$$WQV = P \times C \times A \times 10$$

Where:

WQV	= Water Quality Volume (m^3)
P	= total rainfall depth to be included (mm) (typically 25 mm or use the Rational Method depth for specific RI)
C	= runoff coefficient (0.05 – 0.95)[58]
A	= total drainage area (ha)

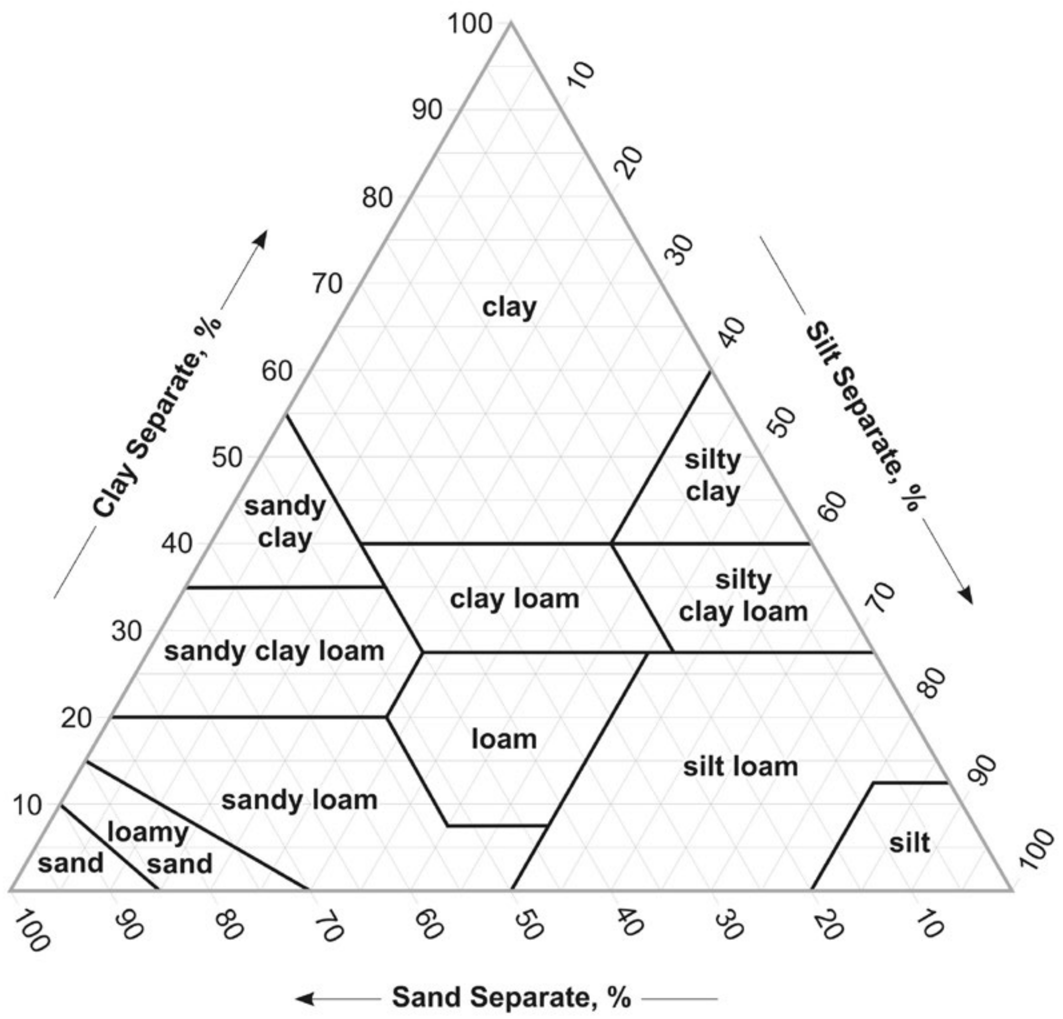
L.4.1.3 Infiltration

A geotechnical investigation should be performed prior to the design to ensure that infiltration-type SuDS can perform effectively. It is important to check the structural stability of adjoining soils, structures and services as well as the presence of groundwater pollution before designing infiltration systems. In the case of groundwater pollution, pre-treatment may be necessary.

The coefficient of permeability depends on many factors and is likely to change over time, but Table L.6 and Figure L.11 can be used as a first estimate, based on the grading analysis of the soil. A notable exception is the Halfway House Granites where there is little downward flow. Most transverse flows occur in well-defined strata within the soil column.

More information and guidance on the calculation of the hydraulic characteristics of soils can be found in Saxton *et al*[59].

Table L.6: Typical Soil Texture Permeability Coefficients[60]		
Soil texture	**Permeability coefficients (mm/h)**	**Adequacy**
Gravel	10 000 - 1 000 000	Generally inadequate treatment
Sand	100 - 100 000	
Loamy sand	10 - 1 000	Yes
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	



Acknowledgement: United States Department of Agriculture[61]

Figure L.11: Soil texture triangle

L.4.1.4 Water quality

Runoff from urban environments can be highly polluted. Efforts to reduce this pollution should be coordinated between those responsible for refuse removal, sanitation, and industrial effluent.

There is no single treatment process for treating stormwater economically for all pollutants. A combination of treatment processes could be used to improve the water quality and/or reduce erosion. The actual combination and treatment processes that are selected depend on the nature of the pollutant load and the desired water quality standard.

Three common constituents are normally tested for: E.coli, blue green algae, and algal pigments. To adequately cover the site-specific needs of the project, testing should not be limited to these three constituents, but should be informed by the site-specific conditions and guided by the water quality standards set by the DWS. Pollution abatement measures in applying SuDS are presented in Table L.7.

Table L.7: SuDS Water Quality[62]

SuDS OBJECTIVES	Greenfield developments and Brownfield and existing development sites located in catchments of sensitive receiving water systems	Brownfield and existing development sites >50 000 m^2	Brownfield and existing development sites 4 000 m^2 – 50 000 m^2 and Total impervious area (existing and new) >15% of site	Brownfield and existing development sites <4 000 m^2 and Total impervious area (existing and new) > 600m^2
	Design storm event for water quality treatment: ½-year RI, 24 h storm			
IMPROVE QUALITY OF RUNOFF Remove pollutants through combination of reducing and/or disconnecting impervious areas and the use of best management practices to infiltrate or capture and treat stormwater runoff	Pollutant removal target: Reduction of post-development annual stormwater pollutant load discharged from development site: SS and TP – reduce to undeveloped catchment levels or SS – 80% reduction TP – 45 % reduction *Whichever requires higher level of treatment*	Pollutant removal target: On-site reduction of post-development annual stormwater pollutant load discharged from development site: SS – 80% reduction TP – 45 % reduction	Pollutant removal target: Combination of on-site and regional off-site measures to achieve target reductions: SS – 80% reduction TP – 45 % reduction	On-site stormwater treatment not required but encouraged where practicable. Regional off-site treatment measures to achieve target reductions: SS – 80% reduction TP – 45 % reduction
	All development are required to trap litter, oil, grease at source			

Note: SS = Suspended Solids; TP = Total Phosphorus

L.4.2 The design of a minor system

L.4.2.1 SuDS interventions

This section provides design guidance on SuDS source controls, local controls and regional controls (see Section L.3.3.1).

The conceptual design process to assist in both the development process and the conceptual design of a minor system includes the following:[63]

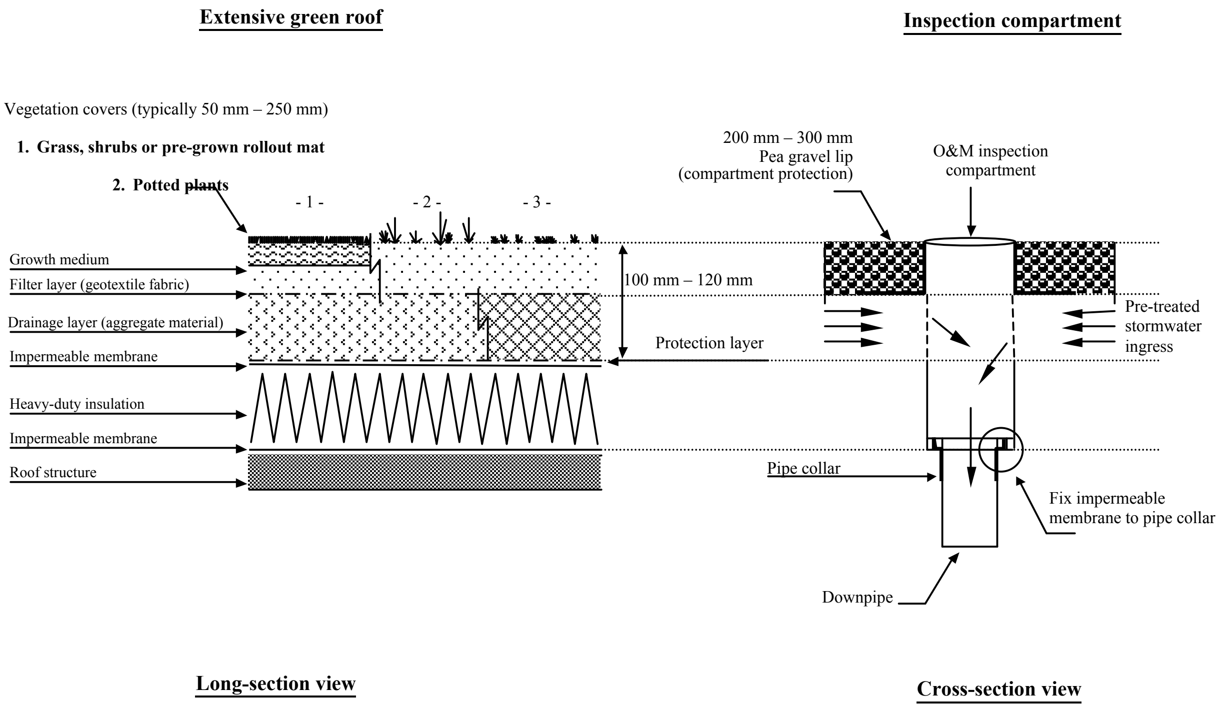
- **Project summary**
  - Site investigation
  - Formulate criteria (quantity; quality; amenity; biodiversity)
- **Hydraulic assessment**
  - Flood risk assessment
  - Greenfield runoff rates and volume assessment
  - Development runoff rates and volume
  - Interception storage
  - Water Quality Volume (WQV)
  - Infiltration assessment
- **Preliminary design**
  - Treatment train conceptualisation and assessment
  - Conveyance system layout
- **Modelling**
  - Treatment train modelling
  - Water balance calculation
- **Final concept**
  - SuDS design refinement by varying storage volumes; treatment train design; conveyance design
- **Implementation**

(i) SuDS source controls

SuDS source controls (introduced in Section L.3.3.1) that can be used as part of minor stormwater systems include green roofs, stormwater harvesting, soakaways and permeable pavements.

Green roofs

Flat or gently sloping roofs (0 to 20 degrees) can be vegetated according to the typical cross-section showed in Figure L.12, on condition that the structural capacity is adequate, water proofing is done well, and suitable indigenous vegetation is used (to be specified by a landscape architect). The section applies only to extensive (shallow) green roofs. Other options, such as intensive green roofs, blue roofs, green walls, etc., require specialist input.



Acknowledgement: Armitage et al. [64]

Figure L.12: General design for green roofs and adjoining inspection compartment

Stormwater harvesting

The quality of harvested stormwater is dependent on the quality of the rain itself and possible contamination of the catchment. Rainwater is naturally slightly acidic, but can be made very acidic by industrial pollution.[65,66] Careful choice of fabrication materials is important to avoid dezincification of brass, or rapid corrosion of galvanised sheeting. The following should be considered when designing a stormwater harvesting facility:

- The strategic placement of catchment structures
- A first-flush trap and/or filter sock to catch leaves and other debris
- A water 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
- An in-line filter and/or UV disinfection device if there is any risk of human contact
- An overflow system – preferably linked to an option in a SuDS treatment train

The volume of usable rainfall can be estimated as follows (see **Section J.4.2.3** for design guidance on rainwater harvesting from roofs):

$$V = R \times A \times C \times FE$$

Where:
V = Volume of usable rainwater (L)
R = Average rainfall over period – usually monthly (mm)
A = Area contributing to runoff (m^2)
C = Runoff coefficient (0-1)
FE = Filter Efficiency (0-1) – if applicable – usually 0.9

Runoff coefficients are variable and dependent on the antecedent moisture conditions and the depth of rainfall. The coefficient for a particular storm rainfall depth can be estimated as follows:

$$C = (1 - \frac{Ia}{\mathrm{p}})$$

Where:
Ia = Initial abstraction (mm)
P = Precipitation depth of event (mm)

Typical runoff coefficients for different surfaces are presented in Table L.8.

Table L.8: Runoff coefficient for different surfaces[67]

Surface of catchment	Coefficient
Tiles	0.8 – 0.9
Concrete and asphalt	0.9
Metal (corrugated iron, flat iron sheet, IBR profile)	0.95
Tar and gravel	0.8 – 0.85
Thatch	Not suitable for rainwater harvesting

The actual yield of a stormwater harvesting system is a function of the variability of the rainfall, the runoff efficiency of the catchment, the volume of storage provided, and the rate of abstraction. A properly designed system will balance the components to optimise yield and cost. Storage requirements can be estimated using a Rippl diagram[68] or by modelling based on daily rainfall and expected demands. Harvested rainwater can be used directly for site irrigation or non-potable domestic purposes or, with suitable treatment, as potable water.

Soakaways

The following should be considered when designing a soakaway:

- The permeability of the soil at different depths should be determined (digging a deep soakaway pit when the bulk of the outflow is horizontal or downslope via the leached upper horizons of the soil profile will be pointless). These values can be measured by specialist hydro-pedological testing or measured by conducting infiltration tests at different depths in the soil.
- Fine-grained material should be prevented from washing into the soakaway (either allow the influent water to flow over a grassed verge or provide a sediment trap). Consider a geotextile for fine-grained material, but be careful of the chemistry of some groundwater that may precipitate insoluble salts, which will rapidly block the pores of the geofabric.

- The soakaway should be able to drain 50% of design storm in 24 hours.
- Soakaways should mostly be used for areas smaller than 1 000 m^2.
- To prevent groundwater contamination, soakaways should be constructed at least 1.5 m above the groundwater table to allow for additional filtration[69].

The effective storage volume of a stone fill soakaway is calculated as follows:

$$V_{eff} = V_{tot} \times Porosity\ (n)$$

Where:
V_{tot} = total volume occupied by the stone fill

Note that porosity should not be confused with voids ratio:

Porosity: $n = \frac{V_v}{V_t}$

Voids ratio: $e = \frac{V_v}{V_s}$

Where:
V_v = Volume of voids containing either air or water
V_s = Volume of solids
V_t = Total volume

The values for n and e can be calculated from each other as:

$$n = \frac{e}{(1 + e)} \qquad \text{or} \qquad e = \frac{n}{(1 - n)}$$

Estimating the infiltration rate

A method for estimating the infiltration rate involves the following: Dig a hole 1 m x 1 m to the desired depth and in the bottom of this, dig a smaller hole 0.3 m x 0.3 m x 0.3 m deep. Fill the smaller hole with water and record how long it takes for the water level to drop by an accurately measurable depth, refill the hole and again record the time it takes for the water level to drop a measured depth. Repeat this procedure 5 or 6 times at intervals until the rate of drop is approximately constant. For each refilling, calculate the rate of drop in mm/h. Then plot the rate of drop against the elapsed time. The resulting curve should show an infiltration rate that decays exponentially with time to some equilibrium value, which can be used to estimate the rate at which water will soak out of the soakaway.

A number of documents give guidelines for the design of soakaways[70,71,72]. Typical soakaway arrangements are shown in Figure L.13, but remember that the sides do not need to be vertical; it is easier and safer to dig a hole with sloping sides.

Acknowledgement: Armitage et al.[73]

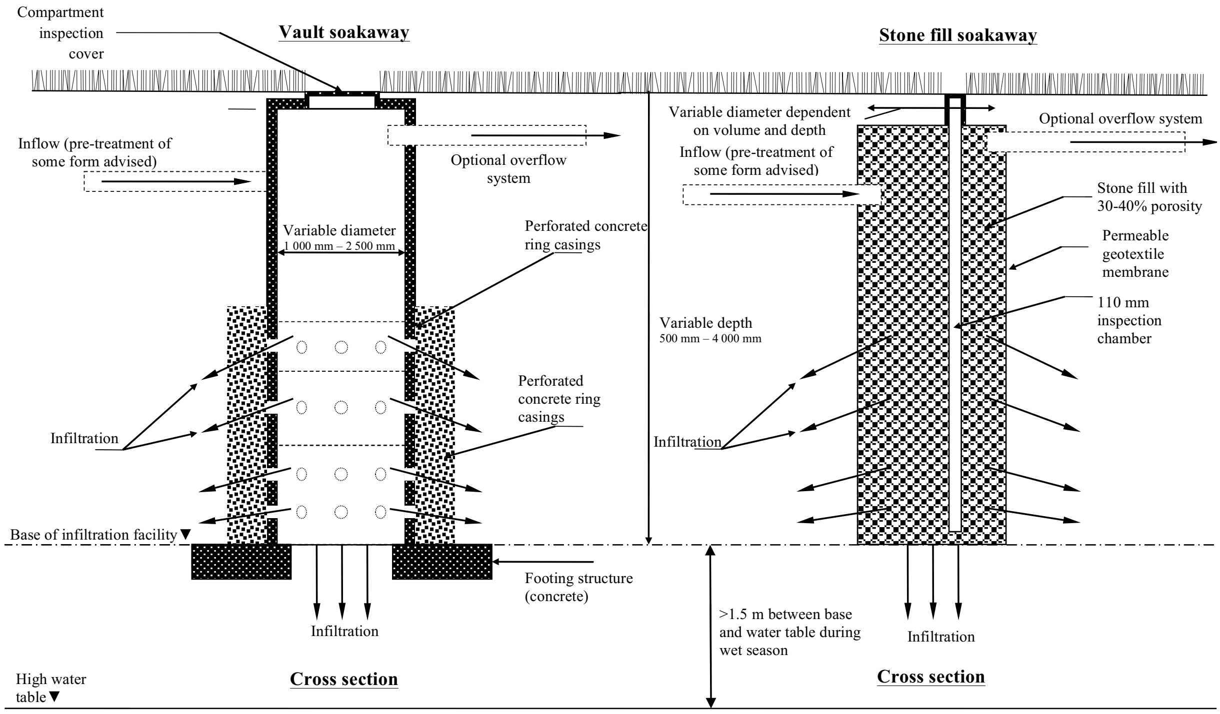


Figure L.13: General designs for soakaways

Permeable pavements

Runoff rates and volumes should be modelled for the design of permeable pavements. Many commercial software packages are available, but a first estimate can be obtained by using the Rational Method discussed in Section L.4.1.1. Typical porosity of the reservoir medium is about 0.3, excluding run-on. The depth of the reservoir layer should be about three times the design rainfall depth. A reservoir layer 0.35 m thick would therefore store about the 20-year RI 1-day rainfall depth in Johannesburg. The following should be considered when designing permeable pavements:

- Meticulous attention should be paid to detail during design and construction, as permanently saturated pavement layers result in significantly reduced shear strength.
- Any materials used – particularly stone – should be properly cleaned prior to installation or they will introduce pollutants into the outflow. In the case of stone, this should be washed until there is no more visible sediment coming off the material. Beware of soil from tree-pits or surrounding embankments that could wash over the pavers rendering them impermeable.
- Permeable pavements should preferably be used in lightly trafficked applications such as residential driveways, parking areas, private roads, cycle pathways, walkways and terraces.
- The entire volume from the design storm over the paved area should be captured and the excess flows should be treated. Fine-grained material should be prevented from washing onto the surface of the paving.

- A suitable geotextile should be laid for fine-grained soils or in places where the flow between the permeable pavement and the underlying soil is of concern.
- Polymer-based geofabrics placed between the bedding layer and the reservoir layer can help trap and degrade hydrocarbons, but they can also lead to premature blocking. Therefore the outlet where the permeable pavement is constructed should be raised with an underdrain – creating a semi-permanent 'reservoir' in the base of the pavement layers.
- Since the transverse conductivity of the reservoir layer is high, the initial design should assume that the water surface in the reservoir layer is horizontal. Permeable pavements are only suitable for use on very flat slopes.
- Permeable pavements should be maintained by periodical cleaning using specially designed vacuum trucks equipped with rotating brooms, or by hand. It is usual to design the surface infiltration rates with a safety factor of 10, i.e. theoretically 90% of the surface can be blocked before remedial action is required – which could include reconstruction of the pavement. Keeping the local environment relatively clear of dust can significantly extend the time between maintenance activities.

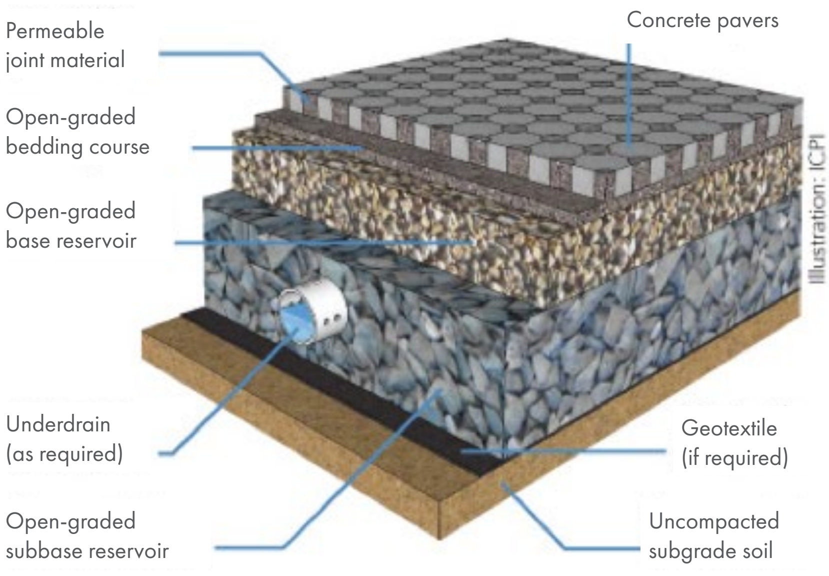


Figure L.14: Typical arrangement of a permeable pavement system

Acknowledgement: Interlocking Concrete Pavement Institute (ICPI)[74]

(ii) SuDS local controls

This section provides design guidance for SuDS local controls (introduced in **Section L.3.3.1**) that can be used as part of minor stormwater systems. These SuDS local controls include filter strips; swales; infiltration trenches; bioretention areas; rain gardens and bioretention cells; bioswales; and sand filters.

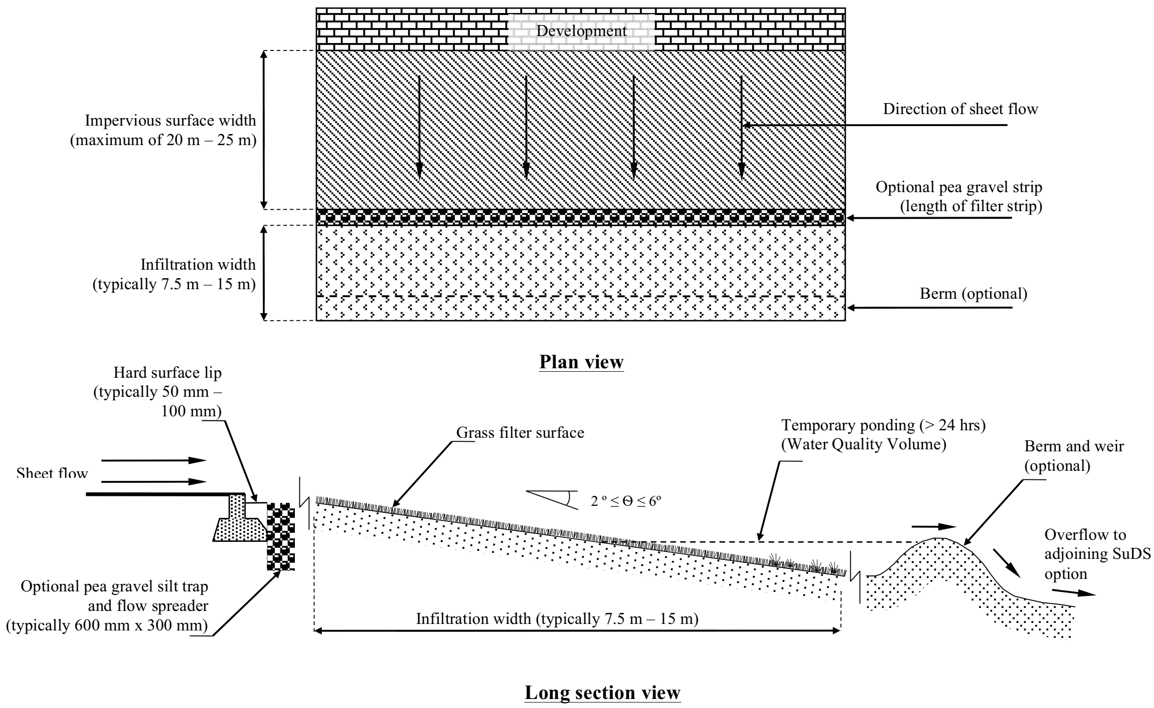
Filter strips

The following should be considered when designing filter strips:

- Filter strips rely on even distribution of flow, thus channelling or rilling must be avoided
- Filter strips are used to manage shallow overland stormwater from low-density developments

- Filter strips are commonly used along stream banks as vegetated buffer or to intercept sheet flow from large parking areas and arterial roadways
- A 24-hour rainfall of 0.5 year to 1 year recurrence interval should be designed for
- Filter strips are normally used to serve areas smaller than 20 000 m^2 with slopes between 2% and 6%
- Maximum flow velocity for filter strips is 0.3 m/s
- Consider clogging of subsurface material

Typical filter strip arrangements are shown in Figure L.15.



Acknowledgement: Armitage et al.[75]

Figure L.15: Design for filter strips and adjoining silt trap and berm

Swales

The following should be considered when designing swales:

- Shallow grass-lined channels with flat side slopes serve as alternative to kerbs and gutters for low-density residential developments
- Side slopes should be flatter than 1:3 V:H (18 degrees) for stability and maintenance
- Swales are often used with bioretention facilities in a treatment train
- Swales are suitable for road medians and verges, parking runoff areas, parks and recreation areas
- Design RI should be used for the minor system

- Site constraints should be taken into account when designing the design flows and resultant dimensions (usually parabolic or trapezoidal)
- Maximum permissible velocity depends on the characteristics of the subgrade soil and the type of grass and grass length
- Standing water should be prevented by ensuring a consistent gradient
- The likely treatment performance should be determined and plant species and planting density should be specified
- Design inflow should be optimised and verified with scour velocity and treatment performance checks
- Overflow areas should be sized
- A maintenance plan should be drafted

Typical swale arrangements are shown in Figure L.16.

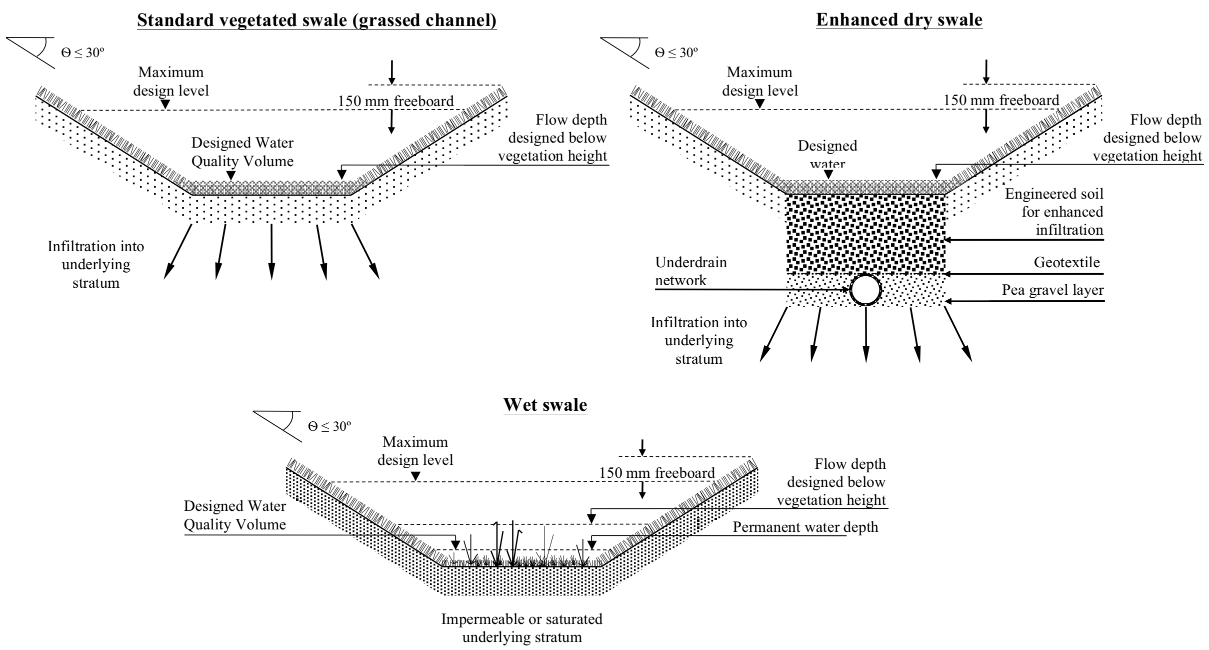


Figure L.16: Design for swales

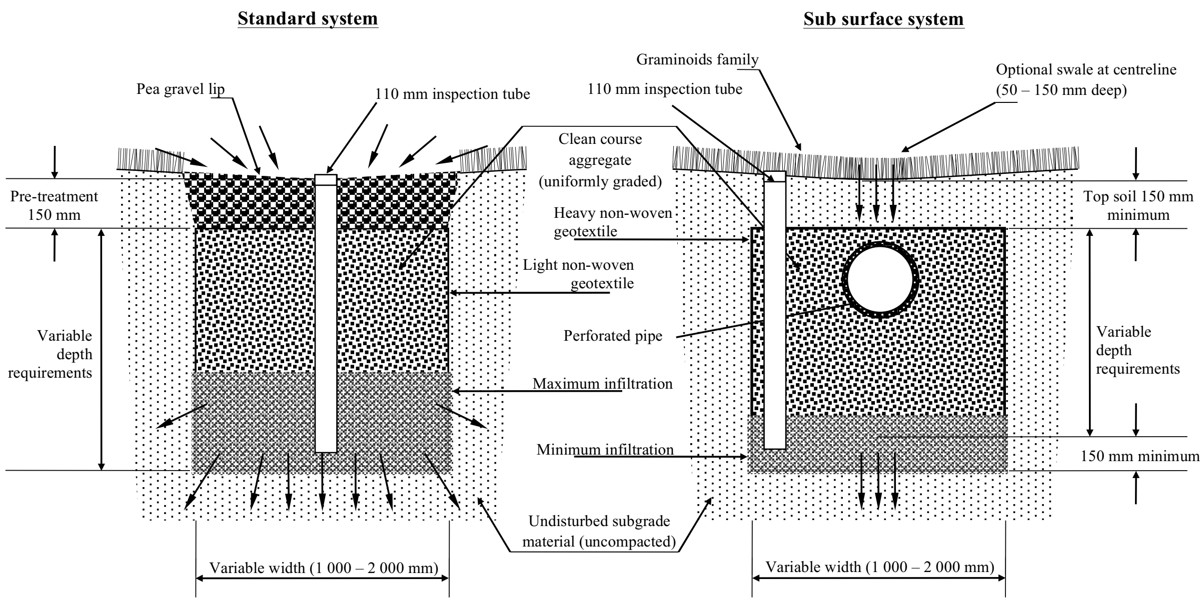
Acknowledgement: Armitage et al. [76]

Infiltration trenches

The following should be considered when designing infiltration trenches:

- The infiltration rates in the surrounding soil stratum
- The required stormwater treatment flow rates
- The type of porous media to be used for backfilling the trench
- The geology of the area (this will affect the potential flow path of the infiltrated water, e.g. the Halfway House Granites in Gauteng could result in saturation of downstream foundations where the bed rock is shallow)
- The clogging potential of the trench

Typical infiltration trench arrangements are shown in Figure L.17.

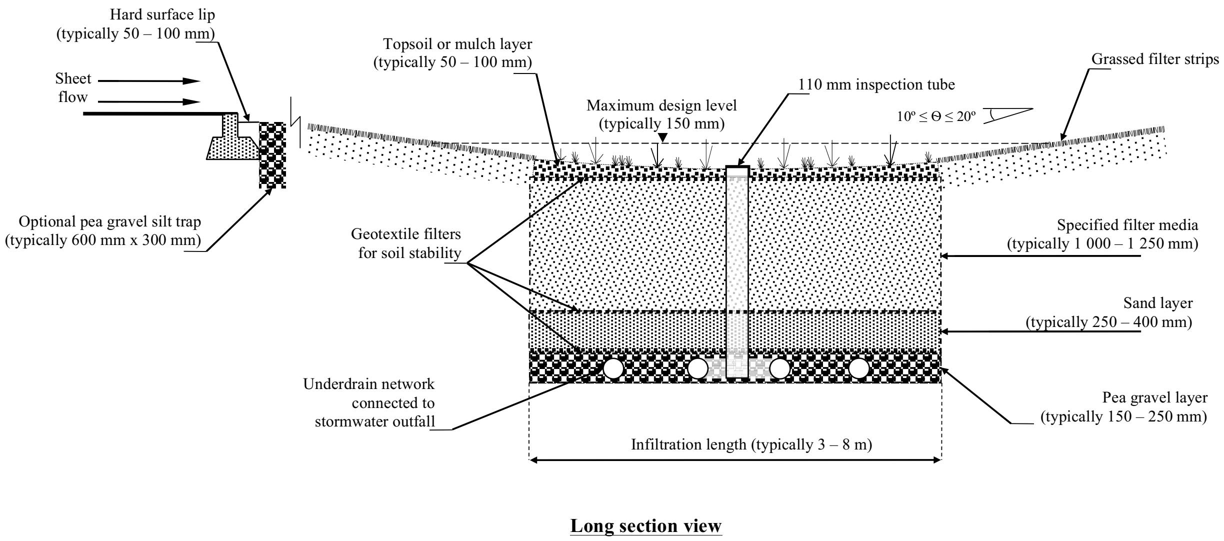


Acknowledgement: Armitage et al.[77]

Figure L.17: General design for dual infiltration trenches

Bioretention areas

Typical bioretention area arrangements are shown in Figure L.18.



Acknowledgement: Armitage et al.[78]

Figure L.18: Design for bioretention

Rain gardens and bioretention cells

A rain garden differs from a bioswale in that it has no linear drainage component, water is lost by spill, infiltration, and evapotranspiration. Water quality is improved by sediment trapping and by the biological and chemical processes that take place in the root zone. Runoff is reduced by infiltration and evapotranspiration, and it is attenuated by the storage in the surface pond and in the porous growing medium, as well as by the gravel drainage medium. Rain gardens and bioretention cells comprise some or all of the following (rain gardens are bioretention cells without the gravel storage medium):

- A surface open water pond that will usually be temporary
- A mulch layer at least 50 mm thick
- A growing medium that should be a special mix of reworked natural soils (this is likely to compact and lose permeability over time)
- A gravel storage medium
- The subgrade

It may be necessary to provide a separation layer between the gravel storage medium and the subgrade below and the growing medium above. Chemical precipitates or biological slime layers can rapidly block geofabrics, therefore the use of graded filter layers is preferred.

The planting medium in the rain garden should be sufficiently permeable to ensure infiltration of the surface water. Depending on the infiltration capacity of the subgrade, the water in the growing medium will gradually drain away until the field capacity of the soil is reached after two or three days, and continue to be lost by evapotranspiration until the wilting point is reached.

Water quality in biocells is improved by sediment trapping, by the biological and chemical processes that take place in the root zone, and by filtration as the water percolates through the growing medium. Organic contaminants, such as polycyclic aromatic hydrocarbons (PAHs), can be trapped in the soil and oxidise chemically or by biological action over time. Pathogens can be deprived of nutrients or predated by heterotrophic soil organisms. Nutrients are typically taken up by plant growth. Phosphorous is a persistent nutrient that will have to be removed by harvesting plant growth. Heavy metals can concentrate in the growing medium and gradually poison the soil.

The planting medium in the biocells should be sufficiently permeable to ensure infiltration of the surface water, but not so permeable that the water runs straight through. Water should be retained long enough for the bioremediation processes to be effective. The growing medium is underlain by a drainage medium similar to that of a golf course green. When there is no hydraulic gradient through the growing medium, the water is affected by capillary action because it cannot easily flow across the interface between the finer growing medium and the coarser drainage material. The water will gradually drain away until the capacity of the soil is reached after two or three days.

The planting medium should also have sufficient organic content for good plant growth and to help retain water. A typical mix would be 70% washed river sand, 20% topsoil from the site if it is not too clayey, and 10% sifted compost. At least 50 mm of mulch should be placed on the surface immediately after planting and replaced or topped up annually.

Plant selection can be difficult, especially in the case of no irrigation. In the dry season the temperatures are high enough for significant evaporation to take place (in Gauteng potential evaporation is about 120 mm/month even in July), and in the wet season there may be quite long periods between rainfall events. The wilting point of the soil can be reached quite often during either season. Conditions in the rain gardens may be quite extreme, from inundation to wilting point, several times per year.

Bioswales

A bioswale comprises some, or all, of the following:

- A surface flow channel with intermittent flow. Densely planted or covered with gravel or cobbles to prevent erosion. Side slopes flatter than 1:5 (V:H) and a longitudinal slope less than 1:200. Small steps may be required at intervals to reduce the slope.
- A mulch layer at least 50 mm thick if the channel is planted.
- A growing medium that may be a special mix, or simply reworked natural soil if it has suitable characteristics.
- A gravel storage and drainage medium.
- An agricultural drain embedded in the gravel drainage medium.
- The subgrade.

If the relative gradings of the subgrade and the component soils of the bioswales allow it, geofabrics should be avoided if the chemistry of the groundwater indicates that blockage by metal precipitates is possible.

Sand filters

Sand filters are generally used for impervious areas of less than 8 000 m^2. Sand filters can be difficult and costly to maintain, especially because the 'out-of-sight – out-of-mind' principle will often apply. Careful consideration should be given to the use of alternative interventions. 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; in areas where there is limited open ground and where sand filter systems can be implemented beneath impervious surfaces; and when there is a significant requirement to protect groundwater resources.

(iii) SuDS regional controls

This section provides design guidance for the SuDS regional controls (introduced in **Section L.3.3.1**) that can be used as part of minor stormwater systems. These SuDS regional controls include detention ponds; retention ponds; outlet structures; and constructed wetlands.

Detention ponds

The following should be considered when designing stormwater detention ponds:

- The local catchment hydraulics and hydrology (the sizing and positioning should form part of the master drainage plan)
- Guidelines for RI and total volume requirements
- The implementation of appropriate safety structures, including disease vector controls
- The prevention of dangerously steep ground slopes around the pond perimeter
- Safe and obvious escape routes
- Design outlets for people or animals to not be trapped by water pressure
- The prevention of erosion at the inlet
- Upstream treatment systems and outlet structures

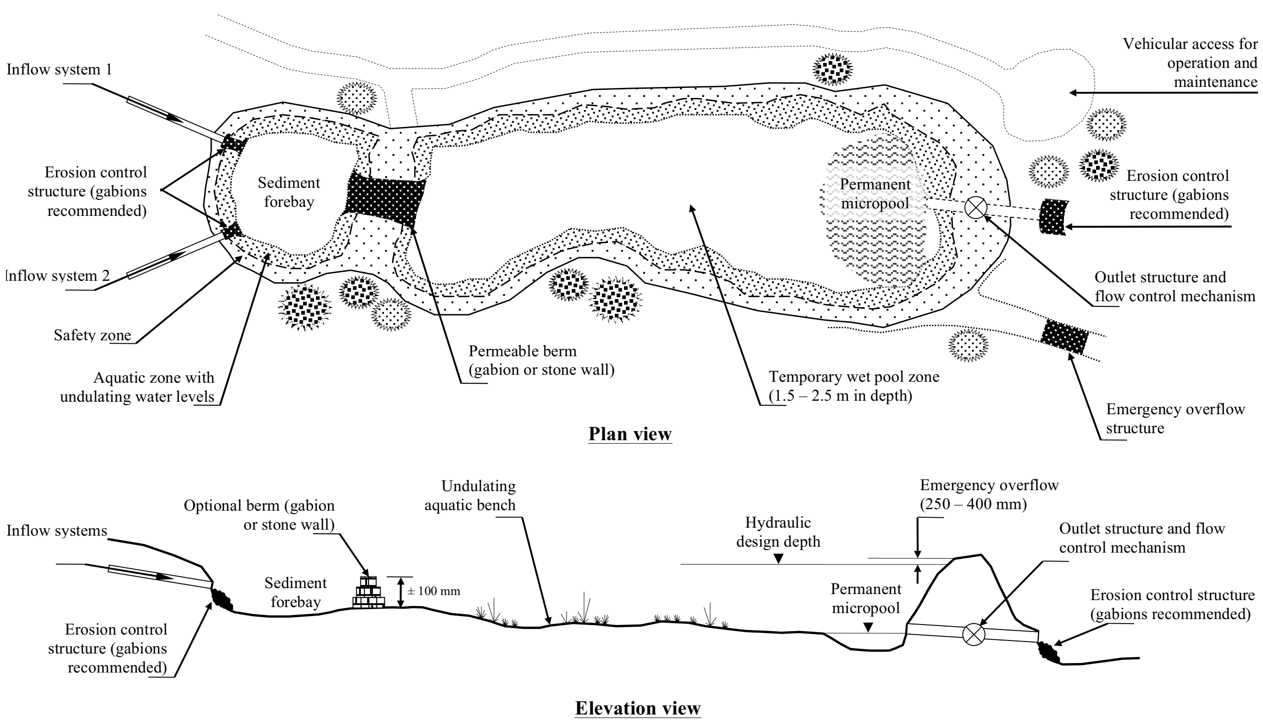
To ensure that all events – from the smallest to the largest – are managed, a 300 mm thick gravel layer should be constructed at the bottom of a dry pond. This will provide storage while the shallow water infiltrates into the subgrade, without exposing the water surface. If the subgrade is impermeable, a very low capacity subsurface drain should be provided.

Inflow hydrographs can be obtained from catchment modelling. Care should be taken when using the Rational Method to estimate the volume (with the duration of the runoff equal to three times the time of concentration), as this gives excessive values for small, relatively impervious catchments (i.e. with a high runoff coefficient). The method only works for larger catchments with lower runoff coefficients. A duration of runoff equal to twice the time of concentration should rather be used, as this does not violate the law of conservation of mass.

Outflow hydrographs are calculated by reservoir (level pool) routing, dependent on the stage/storage and stage/discharge characteristics of the pond. Detention ponds therefore require specially designed outlets to control the discharge and frequently emergency spillways are required to accommodate overtopping.

Other facilities, such as parking areas, sports fields, and areas upstream of road embankments can be designed to provide stormwater detention in an emergency.

Typical detention pond design arrangements are shown in Figure L.19.



Acknowledgement: Armitage et al.[79]

Figure L.19: Typical design for stormwater detention ponds

Retention ponds

Retention systems can be combined with stormwater detention systems by providing for storage above the full supply level (FSL) of the retention pond. The following should be considered when designing retention ponds:

- The local catchment hydraulics and hydrology
- The possible use of floating islands
- The implementation of appropriate safety structures, including disease vector controls
- The prevention of dangerously steep ground slopes around the pond perimeter
- The prevention of erosion at the inlet

To effectively determine the parameters of such a facility, the design inflow hydrographs should be routed through the storage in the basin and outlet system to determine the outflow hydrographs. In this way, downstream effects can be evaluated. Typical design data will include the following:

- The relevant hydrographs for each of a range of design flood recurrence intervals or frequencies, taking cognisance of the ultimate possible post-development characteristics of the catchment (the event that yields the highest outflow peak will have a storm duration longer than that which yields the highest inflow peak)
- Details of the storage and stage characteristics of the detention basin
- Details of the outlet structures with reference to the discharges from the structures at the various stages
- Structural and geotechnical details of the dam wall (type of wall, materials, filters, founding details, spillway structure, protection against erosion and freeboard)
- Safety precautions related to floods and other hazards

- Possible recreational use of the facility
- Maintenance, including sedimentation and maintenance of vegetation

Typical retention pond arrangements are shown in Figure L.20.

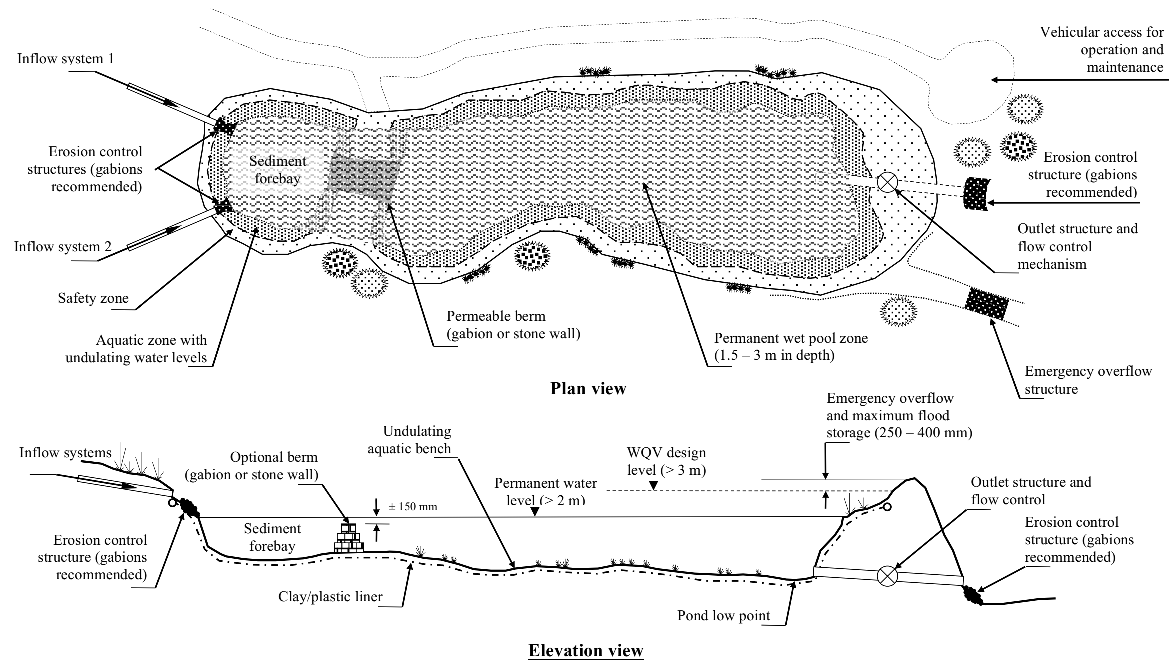


Figure L.20: Typical design for retention ponds

Acknowledgement: Armitage et al. [80]

The dam may need to be registered, classified and evaluated as a 'dam with a safety risk' if it has a wall height greater than 5 m and a capacity exceeding 50 000 m^3. Retention ponds usually have wall heights between 2 and 3 m, which generally do not constitute a safety risk. However, it is imperative that the safety risk of any dam is evaluated. The evaluation process should involve an Approved Professional Person (refer to section 117(a) of the NWA) if the lives of people could be threatened.

Well-designed retention ponds can make provision for stormwater harvesting. Stormwater harvesting yields can be substantially improved through Real-Time Control (RTC). In its simplest form, RTC opens and closes outlet valves in response to water levels in the retention pond – and perhaps others downstream. More sophisticated RTC uses rainfall predictions to regulate the storage in the retention ponds and ensures that the ponds generally remain as full as possible whilst simultaneously containing flood flows through pre-emptive emptying.

Several documents and guidelines[81,82,83,84,85] can be consulted for more information. Software programs are available to design/calculate the flood routing of an inflow hydrograph through a stormwater detention facility to produce the downstream outflow hydrograph.[86,87] Many of these use the storage indication Working Curve Method or Modified Puls Method[88], which is discussed in more detail in Annexure A to this section.

Aquatic weed growth can be reduced in wet (retention) ponds by designing the ponds to have a minimum depth of water of 1 m (after allowing for sedimentation). Aeration of the water may also be necessary to maintain the required quality. The proper design of grids over outlets (limiting the opening to about 300 mm^2) assists in reducing outlet blockages. Reliable emergency spillways that cannot block should be provided. The pollution of ponds can be reduced to some extent by installing grease and sediment traps upstream of the pond inlet. However, reduction or elimination of the pollutants at their source is generally the preferred option.

A common failure of pond embankments is due to piping, either because of poor soils (e.g. dispersive soils), inadequate filter designs, animals that burrow into the embankment, or tree root systems. Legumes should not be used as plant cover for earth embankments as this result in a concentration of nitrogen in the roots, which attracts rodents.

When sports fields are used as stormwater detention facilities, playing surfaces are generally raised slightly above the surrounding area to facilitate drainage and clearing of general debris and siltation. The cysts of pathogenic organisms such as Giardia and Cryptosporidium are common in faecal polluted water and persistent in the environment. The first flush of potentially contaminated water should not be allowed onto fields used for active recreation.

Outlet structures

Various structures can be used to control the outflow from a basin – each with its own advantages and disadvantages. The stage/discharge characteristics of the control, its constructability, ease of maintenance and the possibility of blockage need to be considered in the design. In some instances, aesthetics may be significant, for example the basin and its outlet could be regarded as an urban sculpture.

Where water is discharged to a natural stream, effective energy dissipation is required to prevent erosion of the channel by the jet of water exiting the discharge structure or pipe outlet.

Where water is discharged to a wetland, the outlet structure should be designed to distribute the flow laterally and vertically in the soil profile to emulate the natural pattern of water entering the wetland. One way of doing this would be to construct a French drain at the pipe outlet. The excavation of long 'daylighting' trenches into the wetland is not acceptable.

Constructed wetlands

The following should be considered when designing constructed wetlands:

- Local interest groups, such as nurseries, wildlife and birding associations, should be involved.
- The forebay must protect the macrophyte zone from litter, debris, coarse sediment, and other gross pollutants. Easy access of the forebay should be ensured for maintenance purposes.
- Meandering flow should be created and 'short circuiting' prevented.

The following aspects should be considered in the selection of appropriate vegetation:

- Rapid establishment and growth
- Minimum disease or weed risk
- Suitability for the local climate

- Tolerance of hypertrophic water-logged conditions
- Capacity to remove stormwater runoff pollutants
- Species diversity to provide habitat diversity as well as resilience against disease, and to multiply bioremediation processes

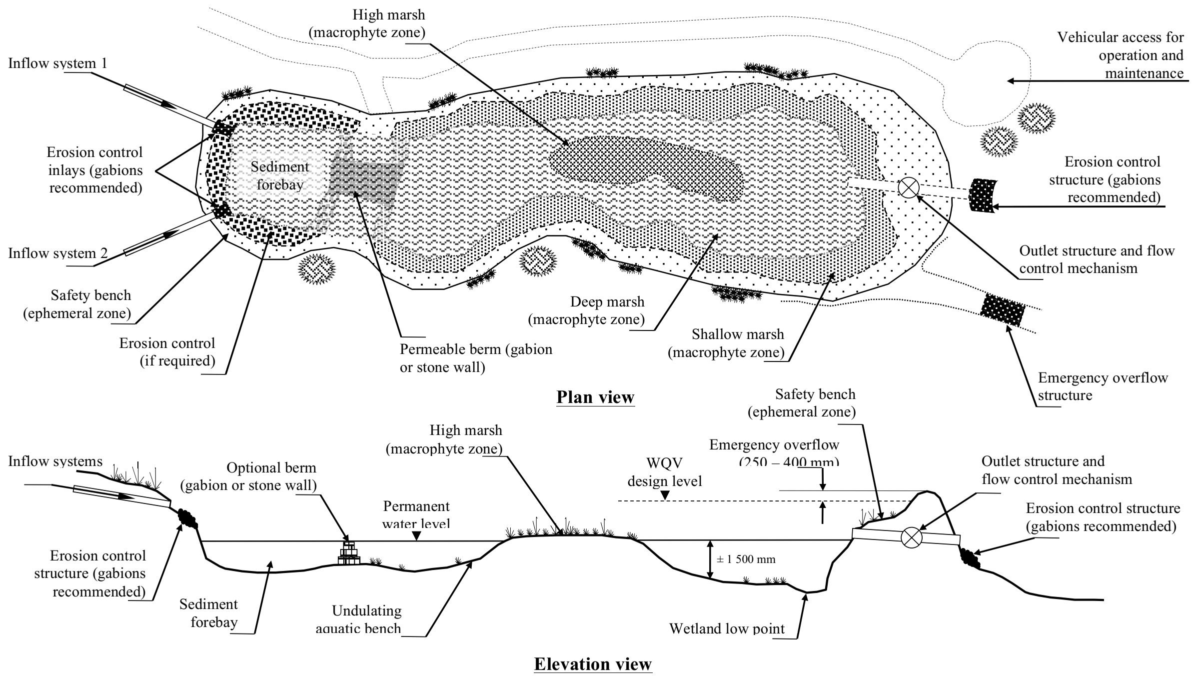
Constructed wetlands typically include the following four zones:

- The inlet zone, which includes a sediment forebay for the removal of coarse sediments
- The macrophyte zone, which is a shallow and heavily vegetated area that facilitates the removal of fine particles and the uptake of soluble nutrients
- The macrophyte outlet zone, which channels cleaner stormwater runoff into adjoining structures downstream
- 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[89]

The principal function of the vegetation in wetlands is to create additional environments for microbial populations. The stems and leaves in the water obstruct flow, facilitate sedimentation, and increase the surface area for the attachment of microbes that constitute thin films of reactive surfaces. Wetland plants also increase the amount of aerobic microbial environment in the substrate. Unlike their terrestrial relatives, wetland plants have specialised structures that enable them to conduct atmospheric gases (including oxygen) down into the roots in waterlogged conditions. This oxygen leaks out of the root hairs, forming an aerobic rhizosphere around every root hair, while the remainder of the subsurface water volume remains anaerobic. This juxtaposition of aerobic/anaerobic environments is crucial to the treatment of nitrogenous compounds and other substances.

- **Microbial organisms:** Microbes (bacteria, fungi, algae, and protozoa) alter contaminant substances to obtain nutrients or energy to complete their life cycles. The effectiveness of wetlands in water purification is dependent on developing and maintaining optimal environmental conditions for the desirable microbial populations. Most of the desirable microbes are ubiquitous and likely to be found in most wastewaters that contain nutrients and energy; hence inoculation of specific strains is generally not necessary.
- **Substrate:** The primary role of the substrate – whether soil, gravel, or sand – is to provide a support for the plants and a surface for attachment by microbial populations. The substrate can also be selected for its chemical characteristics, where pollutant removal is achieved through complexing (a chemical and physical process allowing more complex substances to be formed, which then remain in the substrate zone).[90]
- **Plant selection:** The diversity and complexity of natural wetland vegetation is principally the result of interactions between hydrology, substrate, and climate. If the intention is to mimic a 'natural' wetland, thorough knowledge of local wetland vegetation is a distinct advantage. If, however, the intention is to use the wetland for water purification, several universal species can be used. By far the most commonly used genera are *Phragmites* (the common reed), and *Typha* (referred to locally as the bulrush). Other genera that have been used successfully are various *Scirpus* and *Cyperus* species.

Typical wetland arrangements are shown in Figure L.21.



Acknowledgement: Armitage et al. [91]

Figure L.21: Typical design for constructed wetlands

L.4.2.2 Drainage elements

This section provides design guidance for the drainage elements of the stormwater management system (introduced in Section L.3.3.2).

(i) Simplified Conveyance Design

Channel design

A number of documents that cover channel hydraulic principles[92,93,94,95,96] can be consulted for more information. As a first approximation, steady flows and normal depth conditions are often assumed to determine the channel cross-section that would convey the design flow. Suitable equations for velocity calculation (see Section K.4.3.2) include:

- Manning's formula
- Chezy's equation
- Colebrook-White's equation (substitute 4·R (hydraulic radius) for the diameter D)

Normal flow depth conditions seldom occur in practice, since channel sections are too short or irregular for normal flow depths to be established – thus, gradually varied flow is the norm. Subcritical flow conditions, characterised by large flow depths and low velocities, generally occur upstream of a hydraulic control, whilst supercritical flow conditions, with shallow flow depths and high velocities, occur downstream of a control. Designers must identify the flow conditions and allow for sufficient channel depth to accommodate depths greater than normal flow depth, with allowance for freeboard. Backwater curve calculations can be carried out to determine the variations of water level in gradually varied flow. Backwater curves can be determined by hand (Direct and Standard Step methods) or with computer simulation programs, such as HEC-RAS and DHI Software.

Assuming that normal depth does occur, a first estimate of the depth of flow or the capacity of conduits can be estimated using the Manning equation below.

$$Q = \frac{A^{\frac{5}{3}} \times \sqrt{S_0}}{n \ x \ P^{\frac{2}{3}}}$$

Where:

Q = design peak flow rate (m^3/s)
A = cross-sectional area of flow (m^2)
S_0 = slope of water surface (m/m)
P = wetted perimeter (m)n = Manning roughness coefficient ($s/m^{1/3}$)

Portal and pipe culverts

Culvert design techniques are well established and a number of documents give information on selection and hydraulic design of culverts.[97,98,99] Nomographs could be used with circumspection as they relate to specific design conditions, using basic hydraulic principles.[100] Some municipalities and provincial governments have their own design guidelines regarding flow through culverts.

- **Types and velocities:** Flow types through culverts are categorised according to inlet control, barrel control, or outlet control. The greatest calculated damming height at the culvert inlet is accepted as representing the controlling flow level for the specific flow rate.

  Flow velocities through a culvert should be above 1 m/s to prevent siltation. The potential for scouring at the culvert exit should be examined. If necessary, the flow velocity should be reduced by means of energy dissipaters.

- **Debris and boulders:** Debris and/or boulders can significantly reduce the flow capacity of a culvert, or they may cause forces that threaten the integrity of the structure. Either the culvert should be large enough to allow the flow to pass undisturbed, or debris grids should be provided upstream of the culvert.

- **Culvert transitions:** Culvert transitions are structures that attempt to converge wide, shallow subcritical flows into high-velocity critical flows that can be passed through deep, narrow throats that are more cheaply constructed as culverts or bridges. Sometimes termed minimum energy or maximum discharge designs, this concept allows large flows to be routed through smaller, more efficient and economical culverts or bridges without the usual backwater or headwater required to provide the energy necessary to pass the flow through a typical opening.[101] Consideration must be given to the immediate downstream effects and energy dissipation.

  Modification of the headwall and culvert opening details to conventional culverts and bridges can also reduce the energy loss at the entrance. This lends itself to a more efficient hydraulic design.[102] However, a more efficient hydraulic design through the culvert structure generally leads to higher-energy waters at the outlet. Energy dissipaters may have to be incorporated into the design. Careful design of these structures is required to ensure that they function efficiently through the entire range of expected discharges.

- **Barriers to fish movement:** Culverts with homogeneous high-velocity flow conditions (e.g. greater than or equal to 3 m/s) during flood or spate flow conditions are significant barriers to the upstream migration of fish. Suitable refuges should be constructed at intervals of 3 m to 5 m in the culverts closest to the stream banks. These refuges should provide quiescent flow conditions where fish can rest before setting off upstream with the next burst of high speed swimming. The dimensions and spacing of these refuges will depend on the fish species in the area. Expert advice should be sought in the design of all culverts on watercourses where fish may exist.

Grass-lined channels

The vegetative cover type determines the level of protection against erosion. The grass selected should be easy to establish, drought tolerant, have a low nutrient requirement, a low long-term growth rate and inhibit weed invasion, as well as be capable of withstanding periods of inundation. The basin/channel should drain within 72 hours of a storm event to prevent the breeding of mosquitoes.

The effectiveness of the grass cover also depends on the type of soil, the quality of the cover and the duration of the flow.[103] The permissible flow velocity for soil with a grass cover must be limited to a maximum of 1.3 times the allowable velocity for unprotected soil. The design flow velocity of the grass-lined channel is decided upon by comparing the permissible maximum flow velocity for the specific grass cover and the permissible flow velocity for soil with grass cover.

The side slopes of grass-lined channels should not be steeper than 1:4 (V:H) for maintenance purposes, and they should never be steeper than 1:3, so that persons do not plunge suddenly into deep water. Plastic or fibre netting could be used to reinforce the grass side slopes. 3D plastic meshes are, however, death traps for small reptiles and should be avoided.

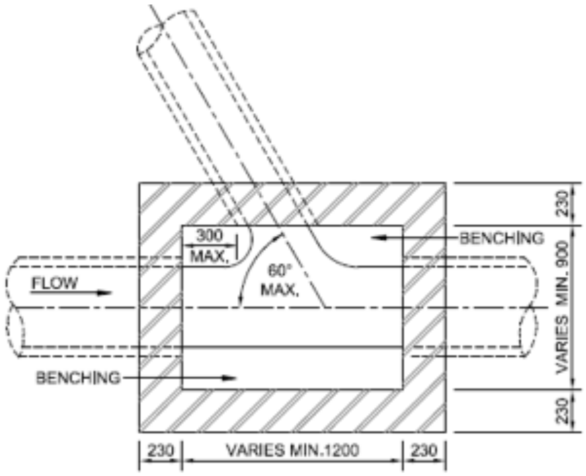
Where flow conditions make grass lining ineffective, loose rock riprap with soil-filled voids is an environmentally acceptable alternative lining. Loose rock riprap is preferred to grouted riprap because it retains the connection between the groundwater and the surface water in the channel and can support vegetation growth. The grading of the riprap will be determined by the bed shear applied by the flowing water, and by uncertainties such as turbulence caused by changes in direction of flow. Design guidance can be found in HEC-11.[104]

Kerb inlets and junction boxes

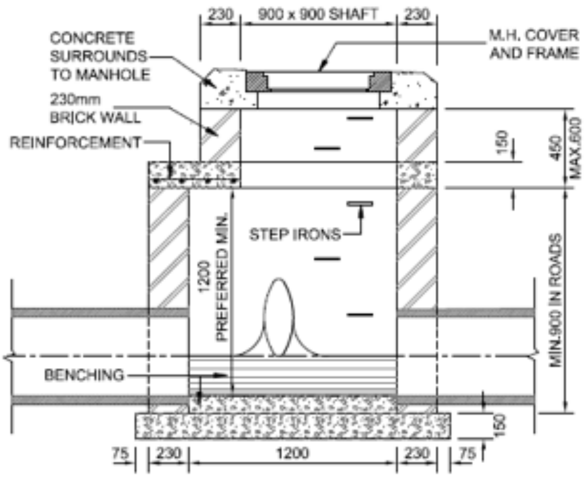
The standards used by municipalities for kerb inlets vary considerably. Generally, the following should be considered:

- Hydraulic performance
- Accessibility for cleaning purposes
- Ability of the cover slabs to bear heavy traffic loads
- Safety for all road users
- Cost

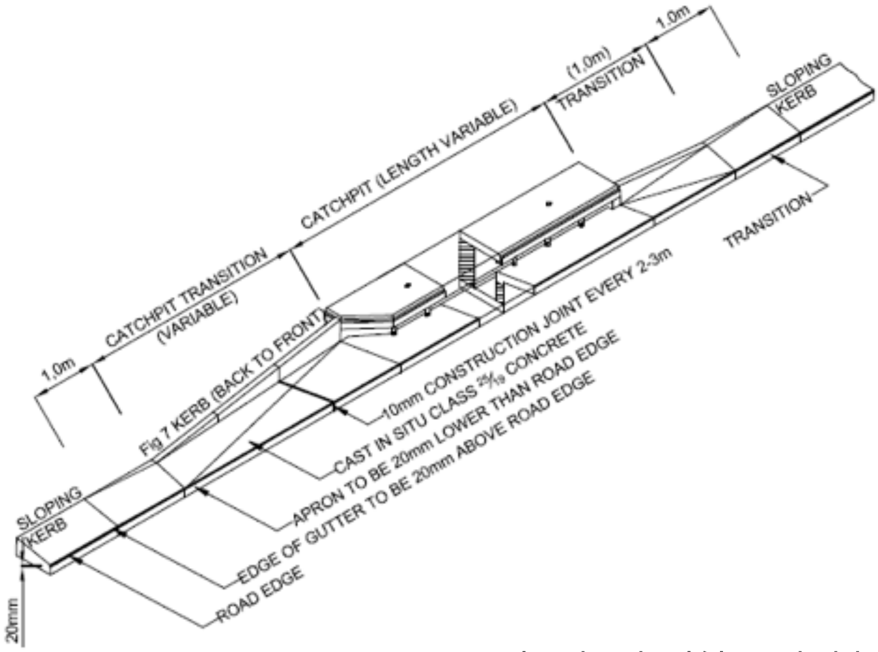
Refer to the literature for guidance in the design of inlets with depressed gutters[105] and in the design of kerb inlets with transitions[106], including the Pretoria-type outlet, which has been widely used. About 20% allowance in capacity must be made for potential blockage.



Typical plan section through junction box



Section through shallow manhole with shaft



Typical catchpit detail (sloping kerb both sides)

Figure L.22: Typical detail of kerb inlets and junction boxes

Acknowledgement: SANRAL Drainage Manual[107]

Road drainage

- **Channel flow:** Manning's formula is the most common method used to determine kerb and channel capacity. Different forms of Manning's equation, modified for specific channel shapes[108], are presented in the literature, but it is recommended here that the basic form of the equation be used and that the variables 'area' (*A*) and 'wetted perimeter' (*P*) be calculated from the conduit geometry.
- **Flow in traffic lanes:** Table L.9 presents the suggested maximum encroachment of runoff on roads during minor storms.

Table L.9: Suggested maximum encroachment of runoff on roads during minor storms	
Road classification	**Maximum encroachment**
Residential and lower-order roads	No kerb overtopping * Flow may spread to crown of road
Residential access collector	No kerb overtopping * Flow spread must leave at least one traffic lane free of water
Local distributor	No kerb overtopping * Flow spread must leave at least one lane free in each direction
Higher-order roads	No encroachment is allowed on any traffic lane

* Where no kerb exists, encroachment should not extend over property boundaries.

- **Encroachment on roads by runoff**
  - **Major storm events**: The encroachment by runoff from a major storm event onto primary roads should not exceed a depth of 150 mm at the crown of the road. This will allow access by emergency vehicles.
  - **Minor storm events:** The suggested maximum encroachment on roads by runoff from minor storms is given in Table L.9.
- **Road gradients**
  - **Maximum road gradients:** The maximum road gradient should be such that the velocity of runoff flowing in the road edge channels does not result in a specific energy of flow of Es> 0.6 m. Where the velocity of flow exceeds this value, design measures should be incorporated to dissipate the energy.
  - **Minimum road gradients:** The minimum gradient for road edge channels should be not less than 0,4% (to reduce deposition of sediment).
  - **Maximum road crown slope:** The maximum slope from the crown of the road to the road edge channel is not governed by stormwater requirements.
  - **Minimum road crown slope:** The minimum slope from the road crown to the channel should be not less than 2% for a plain surface or an average of 2% where the surface has a variable cross slope.
  - **Maximum flow depth:** The depth of flow during a 1:5-year storm should not exceed 6 mm at the crown of the roadway in order to minimise the potential risk of hydroplaning.

Minimum pipe diameters

To ensure pipes are unlikely to block with debris, the minimum pipe diameters for conventional systems should be as follows:

- 600 mm in a servitude
- 450 mm in a road reserve

Minimum velocities and gradients in pipes

The average velocity needs to be above a certain threshold for at least 0.5 hour twice a year to ensure scouring of deposited material. The critical bed shear model indicates that the shear stress of the water on a boundary is related to the velocity gradient at the boundary of the pipe, which means that the deeper the water, the higher the required velocity to reach the required shear force for scouring. As a rule of thumb, the capacity should be designed with a minimum velocity in the range of 0.9 – 1.5 m/s at 100% full uniform design flow for storms of relatively frequent recurrence intervals (two years), but this should be tested against the criterion above. Lower velocities during low flow will not prevent siltation; therefore, maintenance of pipe networks needs to be considered at the design stage.

Table L.10: Suggested minimum grades for pipes[109]

Pipe diameter (mm)	Desirable minimum gradient (1 in ...)	Absolute minimum gradient (1 in...)
300	80	230
375	110	300
450	140	400
525	170	500
600	200	600
675	240	700
750	280	800
825	320	900
900	350	1 000
1 050	440	1 250
1 200	520	1 500

Anchor blocks

Concrete anchor blocks (20 MPa concrete strength) should be provided to eliminate any chance of joint movement on steep gradients, as shown in Table L.11.

Table L.11: Suggested spacing of anchor blocks[110]

Gradient (1 in...)	Spacing for 2.44 m pipe lengths
2 (50%)	Every joint
2 – 3.33 (50% - 30%)	Alternate joints
5 (20%)	Every 4th joint
10 (10%)	Every 8th joint

NOTE: Steep pipes with gradients exceeding a slope of 1:5 are not recommended, due to the very high flow velocities that will result. Drop structures should be considered to reduce slopes.

L.4.2.3 Control structures

This section provides design guidance for control structures that form part of stormwater management systems (see Section L.3.3.2).

(i) Orifices

An orifice outlet where $Q \alpha H^{0.5}$ makes the most efficient use of available storage. Orifices may be any shape, but circular or rectangular openings are easiest to construct. When unsubmerged, i.e. when H/D < 1.2 to 1.5, an orifice will act as a weir.

$$Q = C_d \times A \times \sqrt{2g \times (H - C_h \times D)}$$

Where:
Q = discharge rate (m^3/s)
C_d = discharge coefficient in the range 0.6 to 0.9 depending on the shape of the orifice
A = cross-sectional area of the opening (m^2)
H = depth of water measured from the bottom of the opening (m)
C_h = contraction coefficient[111, 112]
D = opening height (m)

(ii) Weirs

Weirs are divided into two broad categories: transverse weirs where the crest is aligned perpendicular to the direction of approach flow, and longitudinal weirs where the crest is aligned parallel to the direction of approach flow. Typical transverse weirs include the following:

- Unsubmerged orifices
- Broad-crested weirs
  - Rectangular
  - Triangular
- Sharp-crested weirs
  - Rectangular
  - V-Notch
  - Cipoletti weir
  - Proportional or Sutro weir
- Parshall flume
- Spillway crests
- Multi-stage outlet structures

The discharge equation of a weir is:

Q = Coefficient x breadth x head ^ exponent

The shape of the crest and its end conditions determine the coefficient of the discharge equation and the relationship between width, while the head determines the value of the exponent. The discharge characteristics of weirs are well covered in the available literature.[113] All weirs with a level crest of constant breadth will have the same exponent and their discharge equation will have the form:

$$Q = C \times L \times H^{\frac{3}{2}}$$

Where:
Q = Discharge [m^3/s]
C = Discharge coefficient, typically in the range 1.5 to 1.8
C = $C_d \times \frac{2}{3} \times \sqrt{2g}$
C_d = Contraction coefficient, depending on the shape of the weir crest and the ratio of the depth of approach flow to the height of water above the weir crest (a typical value of C_d is about 0.61, but see **Annexure B** for more information)

L = Length of the weir crest transverse to the direction of flow
H = Energy head above the level of the weir crest (for reservoirs or ponds, the energy head is equal to the depth of water)

Weirs can have many different crest shapes. The shape of the crest in the direction of flow affects the discharge coefficient (C_d), whereas the shape of the crest transverse to the direction of flow affects the exponent. A number of documents give information on the selection and hydraulic design of weirs[114, 115, 115, 117, 118]. See **Annexure B** for more information on different weir crest shapes.

The crest of a side weir is parallel to the direction of flow, such as a kerb inlet diverting gutter flow from a road into the underground drainage system. In stormwater management, the principal use of a side weir is to bypass flow up to some value, after which increasing amounts are diverted. An example of this is where a dry, offline basin is used to 'clip' the top off a flood hydrograph. The discharge characteristics can be complex as the magnitude, and hence the depth, of the approach flow varies along the length of the weir. More information is available internationally.[119]

L.4.2.4 Outfall management

Outfall management (see **Section L.3.3.2**) is largely a function of the receiving system, which could range from minimal to no intervention required (outfall to a concrete-lined channel), moderate intervention required (outfall to a river) and complex integrated measures required (outfall into a wetland).

The governing authority's standard should be adhered to as a minimum, but the flow from the outfall should never damage the receiving system. A rule of thumb is to limit the velocity of discharge from an outlet structure to less than 1 m/s and the depth to 100 mm. If the design indicates that this condition will be exceeded, additional energy dissipation measures may be required. The discharge should mimic the characteristics of the natural system, for example, if a wetland naturally receives distributed surface and subsurface flow, then the stormwater management design should ensure that the inflow has similar characteristics.

(i) Protection against erosion

Swales

Swales are generally a cost-effective way to convey stormwater. The use of indigenous plants for stabilisation is recommended. Velocity of water flowing in the waterway should be limited in relation to the erodibility and slope of the waterway. Planting used for protection against erosion should meet the following requirements:

- Cover the ground surface as densely as possible – lawn-forming grasses can be combined with forbs or tussock-forming grasses to achieve this
- Be sufficiently robust and dense to provide the hydraulic resistance required
- Be sufficiently deep rooted to resist the hydraulic forces imposed on them
- Be hardy and able to thrive in the harsh environmental conditions that are likely to occur (locally indigenous plants are preferred)
- Protect the ground surface from the impact of raindrops
- Be visually attractive and diverse
- Be ecologically and structurally diverse to enhance habitat diversity

Fencing

Fencing off the waterway in an environment where rural or urban agriculture can be expected is usually an effective way of controlling livestock until the grass cover has been established. Once a grass cover has been established, livestock can be introduced onto the grassed waterway in a controlled manner.

African ecosystems have evolved to tolerate and rely on trampling by herd animals. Access by livestock should be managed to mimic this condition if locally indigenous vegetation is used to protect the swale.

(ii) Energy dissipaters

The purpose of energy dissipaters is to reduce the energy in the flow discharging from the outfall to a level that will not damage the receiving system. Most energy dissipaters work by forcing a sudden expansion in the flow, either by creating a hydraulic jump or by discharging the flow into a plunge pool.

The size and type of an energy dissipation system will depend on the scale. The energy of water discharging from small- to medium-sized pipes can effectively be dissipated in preformed scour holes or riprap aprons. Large pipes and culverts will require more elaborate and robust energy dissipation structures. The following should be considered when designing energy dissipaters:

- Widen the drainage way and decrease the depth of flow. This will have the effect of reducing the velocity of flow. Overland flow is a typical example. Supercritical flow does not expand easily, so careful design will be required to force the streamlines to diverge.
- Increase the roughness of the canal or drainage way. Although this will increase the total cross-sectional area of flow, it will decrease the velocity. Roughness elements must be designed to resist the shear and drag forces imposed on them.

Structures for energy dissipation include the following:

- Roughness elements
- USBR type II basin
- USBR type III basin
- USBR type IV basin
- SAF stilling basin
- Contra Costa energy dissipater
- Hook-type energy dissipater
- Trapezoidal stilling basin
- Impact-type energy dissipater
- USFS metal impact energy dissipater
- Drop structures
- Corps of Engineers stilling well
- Riprap basins

A number of documents[120, 121, 122] provide information on the selection and hydraulic design of energy dissipation structures.

(iii) Structural elements

The *SANRAL Drainage Manual*[123] gives design guidelines on various protective linings.

The structural elements that are typically used include the following:

- Geocells
- Geotextiles
- Geomembranes
- Riprap
- Gabions (refer to *SABS 1200 Standardised Specification for Civil Engineering construction*[124])
- Reno mattresses (refer to *SABS 1200*[125])
- Linings
- Stone pitching (refer to *SABS 1200*[126])
- Concrete
- Grass linings

The stability of lining materials can be determined by comparing the shear stress applied by the flowing water to the stream bed with the critical shear required to move the particles of the bed material. The critical shear is a function of particle size and specific gravity, while the bed shear is a function of the energy slope and depth of the flowing water.

The shape of some proprietary products also induces uplift, which should be included in the stability analysis.

Wiring may not enhance the local stability of concrete block products. It should be determined how much the block must move before stabilising forces applied by the wires become effective.

In a lined channel, the flow between the lining and the subgrade will have the same energy gradient as the flow in the channel. This flowing water can cause the migration of fine material from underneath the lining material. Care should be taken to ensure that the protective layers are not undermined by providing filter material. Geofabric filters are often ineffective because it is not possible to eliminate all voids between the fabric and the subgrade, and these voids can provide preferential flow paths that result in erosion of the subgrade. Graded filters comprising successive layers of adequate thickness and appropriate material size are preferred. Refer to the *SANRAL Drainage Manual*[127] for design guidelines for granular filter materials.

The effective roughness of grassed linings varies with the velocity of the flowing water, and the resistance of the lining to erosion is a function of the velocity and duration of flow. A number of documents give information on the selection of the effective roughness of grass linings[128, 129].

What is riprap?

Riprap is a heavy stone facing on a shore bank or stream bed used to protect it and the adjacent upland against wave scour and erosion by flowing water. Riprap depends on the soil beneath it for support and should be built only on stable shores and bank slopes. The grading and thickness of the riprap are dependent on the forces that will be imposed on it. A number of documents give information on the selection and hydraulic design of riprap.[130]

(iv) Environmental health and safety

All designs for stormwater should incorporate elements to achieve the relevant authority's minimum environmental, health and safety standards where relevant, e.g. dam safety, flood-warning systems, and suitable recreational facilities. Technologies available for the design include the following:

Silt fencing and straw bale barriers

Silt fences and hay/straw bale barriers are two types of filter barriers. They are temporary structures that are installed across, or at the toe, of a slope. They are used to control sheet flow and are not effective in areas of concentrated flow, such as ditches or waterways.

Temporary check dams

Small temporary check dams constructed across a ditch or small channel reduce the velocity of concentrated stormwater flows. They also trap small amounts of sediment. Temporary check dams are useful on construction sites, or for temporary stabilisation of erosion areas where protection is required for the establishment of vegetation. Careful design and sizing is required, since overtopping of a check dam can result in erosion of the wall and excessive volumes of sediment being washed downstream.

Other technologies

Geofabrics, matting, netting, mulching and brush layering are other technologies that attempt to protect the soil from rain impact and impede the flow of stormwater runoff. The alternative biological approach is often integrated with the structural technologies. Many of the indigenous flora can be effectively used to form vegetation buffer strips and other natural barriers, sponges and stable riverine corridors.[131]

Street cleaning

Street cleaning, which can be an effective method of removing litter and sand-sized particles, needs to be designed for (refer to **Section M.4.1**). Overall pollutant removal by street sweeping is not, however, very efficient, with a typical removal of 10% to 30%.[132] Organics and nutrients are not effectively controlled, but regular – daily or twice daily – street cleaning can remove up to 50% of the total solids and heavy metal yields in urban stormwater.[133] It can also be a very effective method of removing litter.

L.4.3 The design of a major system

L.4.3.1 Flood protection

The stormwater management system for all new neighbourhoods (or settlements) should be designed to safely contain floods up to the 1:20-year flood without the flooding of properties, i.e. within the road reserve boundaries. Conditions should also be checked for the 1:100-year event to assess the risk of dwellings' floor levels being inundated. Floor levels should be 300 mm (minimum) above the 1:100 flood levels. For safety of road users, the specific energy ($Es = h + v^2/2g$) of water flowing in public roadways should not exceed 0.6 m.

The underground pipes of the minor system are sometimes assumed to be flowing full during a major storm event. However, inlets of the minor system are easily blocked by the debris associated with major floods and it is usually assumed that the minor system makes no contribution to the flow. Modern design software allows minor and major drainage systems to be modelled concurrently in the case of floods.

L.4.3.2 Flood lines

The determination of flood lines is usually based on the routing of stormwater through the watercourse (drainage way). The capacity of a channel, whether natural or constructed, is affected by the interaction of local features and the varying flow profile. The routing in a channel has been addressed in different documents and guidelines[134, 135, 136, 137].

Numerous computer programs (such as the HEC-RAS and subsequent updates) are available to aid in the determination of water surface profiles to show flood lines. The HEC-RAS is used most often and is capable of computing one-dimensional steady flow to determine the sub-critical and super-critical water surface profiles by energy balance. It then combines these by using momentum to determine a mixed profile, for example to estimate the positions of hydraulic jumps.

The HEC-RAS has the capability to analyse unsteady flow, such as may arise from a dam failure. The numerical routines used by HEC-RAS have, however, proven to be unstable in some tests, and variations of SWMM may be easier to work with.

In many instances, for example in flooding of urban areas, flow paths are divided and flow changes direction rapidly, thus violating the assumption of one-dimensional flow. Software to model two-dimensional flow for better analysis of these conditions includes inter alia, HEC-RAS 2D, HydroSWMM, PCSWMM 2D, TUFLOW, Mike 21, and Infoworks. Software should be selected based on the physical processes[138] included in the model equations, rather than on the numerical methods used to solve them. Some models can combine 1D and 2D processes, which can simplify model construction and reduce computational overheads.

L.4.3.3 Flood routing and bridge backwaters

Flood routing is based on the continuity equation:

$$Q_{out} = Q_{in} - \frac{dS}{dT}$$

Where:

Q_{out} = outflow discharge (rate of flow)
Q_{in} = inflow discharge (rate of flow)
dS/dT = the rate of change of storage within the system

See Annexure A for a more detailed description of the flood-routing equation.

While backwater curves at bridges can be calculated by hand, computer software programs such as HEC-RAS and DHI Software can also be used. Consider the detail on the design of bridge waterways[139, 140, 141]. Consideration should be given to the additional backwater effects at bridges near the ocean, due to tidal effects and high sea levels that may be caused by storm surges.

L.4.4 Operation and maintenance considerations

It is of prime importance that the stormwater management system be maintained and operated in accordance with the objectives of the design. Obtaining the cooperation of the public and (in particular) local residents will help ensure the success and optimal use of the system. Education programmes, projects in association with groups such as schools (e.g. 'adopt-a-wetland') and 'Friends' groups should be encouraged. Effective monitoring based on the requirements of an Operation Management Plan is stressed[142]. Maintenance programmes should be initiated and led by national or local authorities (government-led) or by local communities (community-led).

Appropriate operational and maintenance considerations made during the design stage will ease operations and minimise maintenance, which will also promote and enhance water quality in the system. Some maintenance guidance for different stormwater system elements is provided in this section.

(i) Rain gardens

Maintenance of rain gardens should include replanting or pruning, topping up of the mulch layer, and possibly skimming accumulated fine sediment from the surface to restore permeability of the soil.

(ii) Bioswales

To ensure that bioswales function effectively, routine inspection and maintenance should be performed. Maintenance of bioswales should include the repair of any surface erosion, replanting or pruning, topping up of the mulch layer and possibly skimming accumulated fine sediment from the surface to restore permeability of the soil. If the swales receive runoff from roads or other areas that may be sources of heavy metals, the growing medium should be tested from time to time and be removed and replaced if found to be contaminated. Soil contaminated by heavy metals should be disposed of at a properly licenced facility. Compost made from hyper-accumulator plants may be contaminated with metals and should not be returned to the environment, but appropriately disposed of.

(iii) Pond facilities

The nature of a stormwater pond facility depends on its type, function, location, and general environment. Many problems can be avoided by proper design and construction procedures. The control of weed growth and invader plants, and the mowing of lawns are necessary for aesthetic and health (mosquito control) reasons. Table L.12 lists some of the problems commonly experienced with stormwater detention facilities.

Problem	Comments
Weed growth	Easy access to the site will enable the maintenance department to combat weed growth. Designers should establish acceptable pioneer grasses in consultation with a landscape architect.
Maintaining grass	Bank slopes should be gentle enough to allow access by maintenance equipment where banks are grassed.
Sedimentation and urban litter	Site-specific measures are required with the aim of providing a sediment trap upstream of the facility. Urban litter is difficult to remove.[145]
Mosquito control	Regular mowing is required – keeping the grass short facilitates evaporation and provides access for predators of mosquito larvae. Different mosquito species have different breeding strategies. Take specialist advice on the likely species in the project area. Avoid the use of insecticides and oil films.
Outlet blockages	Regular inspection and cleaning are required. Incorporate straw bale filters and trash racks. Control litter. Maintain vegetation.
Soggy surfaces	A gravel layer should be used in the bottom of the basin and a low-capacity subsurface drain be installed if soil infiltration capacity is low.
Inflow water pollution	Regular maintenance of detention facilities during wet season is required. Consider wetland filters at inlets.
Algal growth	Attempts should be made to create a balanced ecology.
Fence maintenance	Fences should be avoided. It is better to design ponds, including wet ponds that are reasonably safe for the public e.g. no vertical walls for kids to fall down.
Unsatisfactory emergency spillway design	Dam design requirements need to be adhered to.
Dam failures and leaks	Dam design requirements (e.g. dispersive soils) need to be adhered to.
Public safety during storm events	Flood-warning systems should be considered where hazard is high.

Table L.12: Problems commonly experienced with detention facilities[143, 144]

(iv) Recreational use of watercourses

Watercourses should be managed and maintained in urban environments. The commitment to maintain these natural corridors should be communicated to all involved and not be the burden of the authorities only. Many campaigns exist to encourage public participation in maintaining natural areas.

(v) River restoration or renaturalisation

Note that stream rehabilitation or renaturalisation is not synonymous with channel lining to stabilise banks or reduce bed erosion. Renaturalisation objectives should be defined and recorded before design geometry and materials are considered. Some rehabilitation measures that could be implemented include the following:

- Protect the channel directly (covering the channel with a lining that is less erodible than the in-situ material) or indirectly (providing obstructions that cause damming to reduce flow velocity, i.e. drop structures) against erosion (see Section L.4.2.4).
- Establish vegetative cover to protect the soil from the erosive power of wind and stormwater runoff (see Section L.4.2.2).
- Clear the area of debris and solid waste.
- Implement runoff water quality treatment measures (see Section L.4.1.4).

Annexure A

Storage indication Working Curve Method or Modified Puls Method

The flood standard routing equation is

$$\left(\frac{I_1 + I_2}{2}\right) \Delta T - \left(\frac{Q_1 + Q_2}{2}\right) \Delta T = S_2 - S_1 = \Delta S$$

This can be transposed to

$$\left(\frac{I_1}{2}\right) + \left(\frac{I_2}{2}\right) + \left(\frac{S_1}{\Delta T}\right) + \left(\frac{Q_1}{2}\right) - Q_1 = \left(\frac{S_2}{\Delta T}\right) + \left(\frac{Q_2}{2}\right)$$

Where:
I_1 and I_2 are the inflow rates at times T_1 and T_2 respectively
Q_1 and Q_2 are the outflow rates at times T_1 and T_2 respectively
S_1 and S_2 are the storage rates at times T_1 and T_2 respectively
ΔT is the time increment between time T_2 and T_1

The Modified Puls Method is performed as follows:

- Use hydrological calculations to obtain an inflow hydrograph for the catchment through which water needs to be routed, using the appropriate outlet structure (e.g. weir or orifice).
- Determine the storage volume (S) for different water levels.
- Determine the head/discharge relationship for the outlet structure (outflow Q).
- Draw a graph showing the relationship between the outflow Q and $(\frac{S}{\Delta T}) + (\frac{Q}{2})$ for a selected timestep ΔT.
- By developing the relationship between Q and $(\frac{S}{\Delta T}) + Q$, Q_2 can be interpolated from the value of $(\frac{S_2}{\Delta T}) + (\frac{Q_2}{2})$ and S_2 can be interpolated from the relationship between Q and S.
- In the next time step the terms Q_2 and $(\frac{S_2}{\Delta T}) + (\frac{Q_2}{2})$ become $Q1$ and $(\frac{S_1}{\Delta T}) + (\frac{Q_1}{2})$ respectively, so that the third storage value and discharge can be deduced, and so on.

Refer to the *SANRAL Drainage Manual*[146] for more information on flood routing.

Annexure B

Weirs

Weirs may have many different crest shapes. The shape of the crest in the direction of flow affects the discharge coefficient (C_d). The shape of the crest transverse to the direction of flow affects the exponent. Transverse rectangular sharp-crested and broad broad-crested weirs are used most commonly.

Sharp-crested weirs

The discharge equation for a sharp-crested weir is:

$$Q = C \times L \times H^{\frac{3}{2}}$$

Where:
Q = Discharge [m^3/s]
C = Discharge coefficient, typically in the range 1.5 to 1.8
C = $C_d \times \frac{2}{3} \times \sqrt{2g}$
C_d = Contraction coefficient, depending on the shape of the weir crest and the ratio of the depth of approach flow to the height of water above the weir crest
L = Length of the weir crest transverse to the direction of flow
H = $h + h_v$ = Energy head above the level of the weir crest (for reservoirs or ponds $V_0 = 0$, so the energy head is equal to the depth of water)

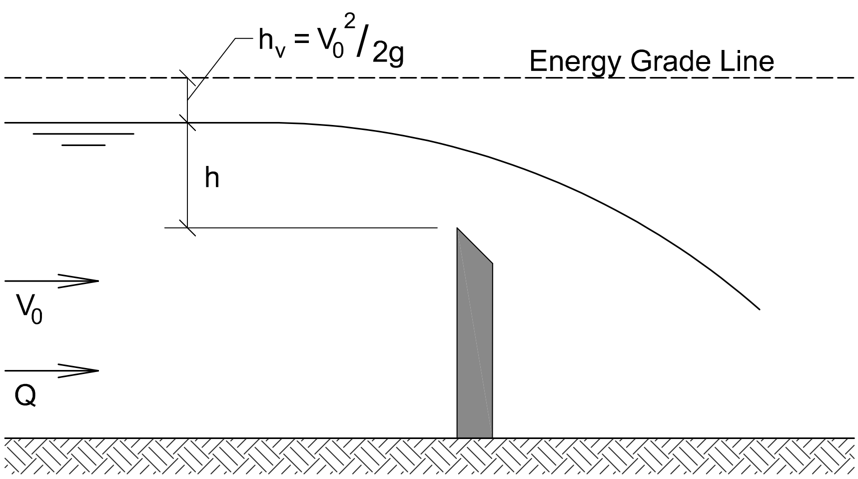


Figure L.B.1: Sharp-crested weir

Broad-crested weirs

A broad-crested weir is where flow becomes critical and stream lines are parallel over the width of the crest. The standard formula for calculating flow over a broad-crested weir is:

$$Q = C \times L \times H^{\frac{3}{2}}$$

Where:
Q = Discharge [m³/s]
C = Discharge coefficient, typically 1.7
H = $h + h_v$ = Energy head above the level of the weir crest (for reservoirs or ponds $V_0 = 0$, so the energy head is equal to the depth of water above the weir crest)
L = Length of the weir crest

In Figure L.B.2, dc is the critical depth and w the width of the weir.

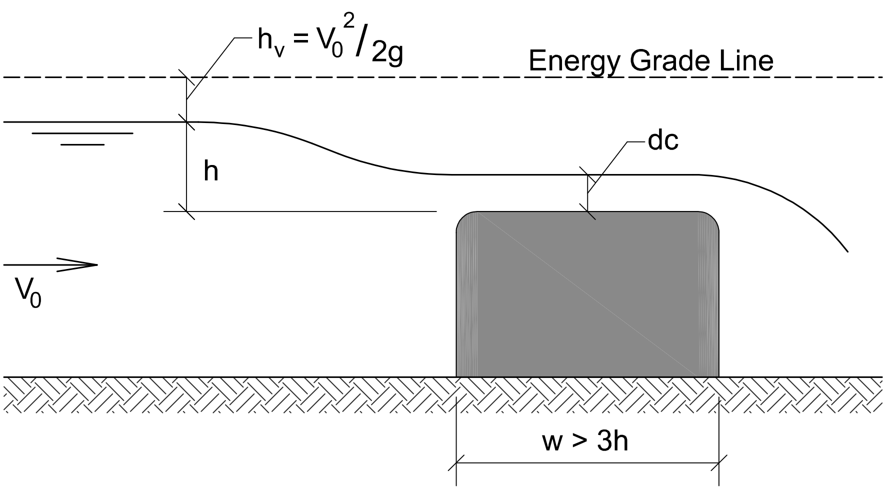


Figure L.B.2: Broad-crested weir

Spillway-crested weirs

Overflow spillway crests are widely used as outlets from stormwater detention facilities. Guidelines are available for the design[147].

Trapezoidal weirs

The stage/discharge equation of trapezoidal weirs with a level crest and sloping ends has a compound form with the exponent of the level part equal to 3/2 and the exponent of the sloping part equal to 5/2. A special form of the trapezoidal weir is the Cipoletti Weir, where the ends slope at 1:4 (H:V) and the coefficient of the equation is corrected to account for the increasing width – in other words the exponent remains constant at 3/2.

Proportional weirs

The proportional weir has a linear head-discharge relationship, i.e. the value of the exponent in the discharge equation is unity. Two forms of the proportional weir are summarised below, i.e. the improved inverted V-notch weir with straight sides and the Sutro weir with curved sides.

- **The Sutro weir**

The relationships for a Sutro weir are as follows:

$$Q = C_D \times \sqrt{2ga} \times b \times (h - \tfrac{a}{3})$$

and

$$\tfrac{x}{b} = 1 - \tfrac{2}{\pi} \times \tan^{-1} \left(\sqrt{\tfrac{y}{a}}\right)$$

Where:
Q = the flow in m^3/s
C_D = the discharge coefficient, assumed to be approximately 0.62
a, b, h, x and y are given in metres

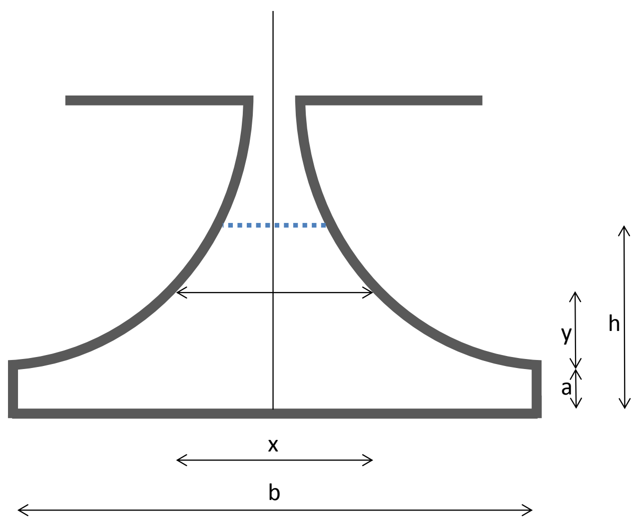


Figure L.B.3: Sutro weir

- **The Improved inverted V-notch or chimney weir**

For flows through this weir over a depth of 0.22d but less than 0.94d (where d is the V-sloped section height) – discharges are proportional to the depth of flow[148]. See Figure L.B.4.

$$q = \frac{2}{3} \times C_D \times \sqrt{2g} \times 2 \times W \times h^{\frac{3}{2}} - \frac{8}{15} \times C_D \times \sqrt{2g} \times tan\ \theta \times h^{\frac{5}{2}}$$

for $O < h < d$

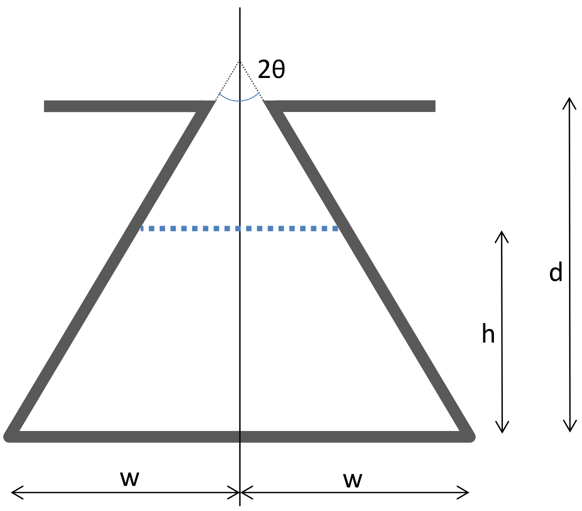


Figure L.B.4: Inverted V-notch or chimney weir

Side weirs

Side weirs are structures often used for irrigation, sewer networks and flood protection, for example a kerb inlet.[149, 150] Side weirs can be used to divert peak discharges from a channel into a management pond, while allowing base flow or spate flow to bypass the diversion. Hydraulic design of side weirs can be complex if the channel water surface profile changes significantly along the length of the weir[151].

Glossary, acronyms, abbreviations

Glossary

Bioretention area
A depressed landscaped area that collects stormwater runoff and infiltrates it into the soil below through the root zone, thus prompting pollutant removal.

Bioswale
A planted depression that receives stormwater runoff from impervious areas and from less pervious vegetated areas such as compacted lawns. It drains this water away by slow surface and subsurface flow, while giving the water an opportunity to soak into the ground.

Catchment
The area contributing runoff to any specific point on a watercourse or wetland.

Channel
Any natural or artificial watercourse.

Conveyance
The transfer of stormwater runoff from one location to another.

Channel protection volume
The volume and rate of flow required for management to reduce the potential for degradation in natural channels. It is usually achieved through the detention of runoff on site. The critical storm event typically has a recurrence interval of around two years.

Culvert
A structure made from reinforced concrete or other material, which is used for stormwater conveyance.

Detention pond
A pond that is normally dry except following large storm events when it temporarily stores stormwater to attenuate flows. It may also allow infiltration of stormwater into the ground.

Don't Do Damage
The importance of ensuring that extreme storm events do not cause significant damage to property or pose significant risks to life.

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

FC_d – Flow control (major storms)
The reduction of peak storm flow rate (m^3/s) to the equivalent of the pre-development scenario (or accepted alternative), while simultaneously ensuring that risks to property and human life are mitigated. This is typically used for storm events with a recurrence interval greater than 10 years.

FC_m – Flow control (minor storms)
The reduction of peak storm flow rate (m3/s) to the equivalent of the pre-development scenario. This is typically used for storm events with a recurrence interval of between 2 and 10 years.

Filter strip
Maintained grassed areas of land that are used to manage shallow overland stormwater runoff through several filtration processes.

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

Flood
A temporary rise in water level, including groundwater or overflow of water, onto land not normally covered by water.

Flood plain
The area susceptible to inundation by floodwater escaping from a natural or constructed waterway.

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

Geotextile
A textile or plastic fabric designed to separate different fill materials. It is normally permeable.

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

Hydrology and hydraulics
The design of drainage structures is based on the sciences of hydrology and hydraulics. The former deals with the occurrence and form of water in the natural environment (precipitation, streamflow, soil moisture, etc.), while the latter deals with the engineering properties of fluids in motion.

Infiltration
The process of penetration of rainwater into the ground.

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

Local control
Interventions to manage stormwater runoff typically in public areas such as road reserves or parks.

Major system
A stormwater drainage system that caters for severe, infrequent storm events. Design criteria are primarily based on safety. The major system is supported by the minor drainage system.

Minor system
A stormwater drainage system that caters for frequent storms of a minor nature. Design criteria are primarily based on convenience.

Nomograph
A chart or graph from which, given a set of parameters, other dependent parameters can be ascertained.

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

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

Rain garden
A planted depression that receives stormwater runoff from impervious areas and less pervious vegetated areas such as compacted lawns, giving this water an opportunity to soak into the ground.

Rainwater harvesting
The direct capture of stormwater runoff, typically from rooftops, for supplementary water uses on site.

Recharge volume
Recharge volume (ReV) is the proportion of the Water Quality Volume (WQV) that needs to be infiltrated on site to make up for the reduction of natural infiltration.

Recurrence interval
The Recurrence Interval (RI) is the average interval between events exceeding a stated benchmark (also known as return period). The recurrence interval is usually expressed in years and is the reciprocal of the annual exceedance probability (AEP) – for example, 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 very long period (e.g. 1000 years), assuming no climate change, there will be approximately 20 events of greater magnitude (1000/20 = 50 years).

Regional Maximum Flood
An empirically established upper limit of flood peaks that can be reasonably expected at a given site.

Regional control
A large-scale intervention used to manage stormwater runoff on municipal land.

Reno mattress
A rectangular-shaped steel wire basket that is generally filled with rock for embankment protection and flood control.

Retention pond
A basin where runoff is retained for a sufficient time to allow settlement of solids and possibly biological treatment of some pollutants.

Runoff

The water that constitutes streamflow may reach the stream channel by any of several paths from the point where it first reaches the earth as precipitation. Water that flows over the soil surface is described as surface runoff and reaches the stream soon after its generation as rainfall. Other water infiltrates through the soil surface and flows beneath the surface to the stream.

Sand filter

Normally comprises a sedimentation chamber linked to an underground filtration chamber containing sand or other filter media through which stormwater flows.

Sheet flow

Runoff over a relatively flat or flattened surface. It has no defined channel.

Soakaway

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

Source control

Non-structural or structural management practice to minimise the generation of excessive stormwater runoff and/or pollution of stormwater at or near the source.

Spillway

A waterway adjoining ponding areas or other hydraulic structures used for the routing of excess water.

Swale

A shallow vegetated channel designed to convey stormwater, but may also permit infiltration. The vegetation assists in filtering particulate matter.

Weir

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

Wetland

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

Water Quality Volume

The design volume of runoff that requires water quality treatment to reduce/remove a specified percentage of pollutants.

Acronyms and abbreviations

CPV	Channel protection volume
D3	Don't Do Damage
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
IWRM	Integrated Water Resource Management
NHBRC	National Home Builders Registration Council
NWA	National Water Act
PMF	Probable Maximum Flood
ReV	Recharge Volume
RI	Recurrence Interval
RMF	Regional Maximum Flood
RTC	Real-time Control
SABS	South African Bureau of Standards
SANRAL	South African National Roads Agency Limited
SANS	South African National Standards
SCS	Soil Conservation Services
SDF	Standard Design Flood
SS	Suspended Solids
SuDS	Sustainable Drainage System
TP	Total Phosphorus
WQV	Water Quality Volume
WRC	Water Research Commission
WSD	Water Sensitive Design
WSUD	Water Sensitive Urban Design

Endnotes

1 *SANS 10400 - The application of the National Building Regulations (NBR)* is available for purchase from the South African Bureau of Standards (SABS) at https://www.sabs.co.za/

2 Wong, T.H.F. 2006. Water sensitive urban design - the journey thus far. *Australasian Journal of Water Resources.* 10(3), 213–222. DOI: 10.1080/13241583.2006.11465296.

3 University of Cape Town. 2018. *UCT Urban Water Management: Water Sensitive Design.* http://www.uwm.uct.ac.za/

4 Armitage, N., Fisher-Jeffes, L., Carden, K., Winter, K., Naidoo, V., Spiegel, A., Mauck, B., Coulson, D. 2014. *Water Sensitive Urban Design (WSUD) for South Africa: Framework and Guidelines.* Report No. TT 588/14. Water Research Commission, Pretoria.

5 Armitage, N., Vice, M., Fisher-Jeffes, L., Winter, K., Spiegel, A., Dunstan, J. 2013. *The South African guidelines for sustainable drainage systems.* Report No. TT558/13. Water Research Commission, Pretoria.

6 Global Water Partnership. 2017. *The Need for an Integrated Approach.* https://www.gwp.org/en/About/why/the-need-for-an-integrated-approach/

7 Department of Water Affairs and Forestry (DWAF). 1996. *South African Water Quality Guidelines.* Second edition. Volumes 1 to 6. Department of Water Affairs and Forestry, Pretoria.

8 Carden, K., Fisher-Jeffes, L. 2017. Stormwater harvesting could help South Africa manage its water shortages. *Water Wheel.* June 2017. Water Research Commission, Pretoria.

9 Boulenouar, J., Gibson, J. 2015. *Asset management in rural South Africa. A case study of Amatole and Chris Hani district municipalities.* IRC, The Hague.

10 Van Zyl, F., Manus, A., Pensulo, E. 2008. *Water Services Infrastructure Asset Management for Municipal Managers.* Department of Water Affairs and Forestry, Pretoria.

11 Department of Rural Development and Land Reform (DRDLR). 2013. *Climate Change Adaptation Sector Strategy for Rural Human Settlements.* Department of Rural Development and Land Reform, Pretoria.

12 Adam, A.G. 2016. Urbanization and the Struggle for Land in the Peri-Urban Areas of Ethiopia. *Proceedings of the Annual Bank Conference on Africa.* The World Bank Group, Oxford.

13 CSIR. 2019. *Green Book: Adapting South African settlements to climate change.* https://greenbook.co.za

14 Elges, H.F.W.K. 1985. Dispersive soils. *Civil Engineer in South Africa,* 27(7): 347-353. South African Institute for Civil Engineering, Pretoria.

15 *SANS 1936-1 Development of Dolomite Land – Part 1: General principles and requirements* is available for purchase from the South African Bureau of Standards (SABS) at https://www.sabs.co.za/

16 *SANS 1936-3 Development of Dolomite Land – Part 3: Design and construction of buildings, structures and infrastructure* is available for purchase from the South African Bureau of Standards (SABS) at https://www.sabs.co.za/

17 *SANS 1936 Development of Dolomite Land – Part 1, 2, 3 and 4* is available for purchase from the South African Bureau of Standards (SABS) at https://www.sabs.co.za/

18 National Home Builders' Registration Council (NHBRC). 2016. *Home Building Manual.* National Home Builders' Registration Council, Pretoria.

19 *SANS 1936-3 Development of Dolomite Land – Part 3: Design and construction of buildings, structures and infrastructure* is available for purchase from the South African Bureau of Standards (SABS) at https://www.sabs.co.za/

20 *SANS 1936-2 Development of Dolomite Land – Part 2: Geotechnical investigations and determinations* is available for purchase from the South African Bureau of Standards (SABS) at https://www.sabs.co.za/

21 South African National Biodiversity Institute. https://www.sanbi.org

[22] Department of Water Affairs and Forestry. 1994. *Minimum Requirements for Waste Disposal by Landfill*. Waste Management Series. CTP Book Printers, Cape Town.

[23] Department of Water Affairs and Forestry. 1994. *Minimum Requirements for the Handling and Disposal of Hazardous Waste*. Waste Management Series. CTP Book Printers, Cape Town.

[24] Department of Water Affairs and Forestry. 1994. *Minimum Requirements for Monitoring at Waste Management Facilities*. Waste Management Series. CTP Book Printers, Cape Town.

[25] Zychowski, J., Bryndal, T. 2015. Impact of cemeteries on groundwater contamination by bacteria and viruses – a review. *Journal of Water Health*, 13(2): 285.

[26] Engelbrecht, J.F.P. 1993. *An Assessment of Health Aspects on the Impact of Domestic and Industrial Waste Disposal Activities on Groundwater Resources: a literature review*. Water Research Commission, Pretoria.

[27] Engelbrecht, J.F.P. 1998. *Groundwater Pollution from Cemeteries*. Water Institute of South Africa.

[28] Department of Water Affairs and Forestry (DWAF). 2006. *Stormwater Water Management Best Practice Guidelines for Water Resources in the South African Mining Industry*. Department of Water Affairs and Forestry, Pretoria.

[29] Pulles, W., Howie, D., Otto, D., Easton, J. 1996. *A Manual on Mine Water Treatment and Management Practices in South Africa*. Report No. TT80/96. Water Research Commission, Pretoria.

[30] Perchalski, F.R., Higgins, J.M. 1988. Pinpointing nonpoint pollution. *Civil Engineering - ASCE*, 58(2): 62-64. American Society of Civil Engineers.

[31] Ayers, R.S. 1977. Quality of water for irrigation. *Journal of the Irrigation and Drainage Division*, 103(2): 135-154. American Society of Civil Engineers.

[32] Armitage et al. 2013.

[33] Armitage et al. 2013.

[34] Armitage et al. 2013.

[35] Armitage et al. 2013.

[36] Armitage et al. 2013.

[37] Armitage et al. 2013.

[38] Armitage et al. 2013.

[39] Achim Hering [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC BY 3.0 (https://creativecommons.org/licenses/by/3.0)], from Wikimedia Commons.

[40] Rogersoh [CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0) or GFDL (http://www.gnu.org/copyleft/fdl.html)], from Wikimedia Commons.

[41] ChrisHamby [CC BY-SA 4.0 (https://creativecommons.org/licenses/by-sa/4.0)], from Wikimedia Commons.

[42] Walmsley, D. 1987. *A Description of the Wetland Research Programme*. CSIR, Pretoria.

[43] Gillette, B. 1993. Everything's ducky. *American City and County*, 108(2): 36-44. Penton Media, Atlanta.

[44] Nick-D [CC BY-SA 4.0 (https://creativecommons.org/licenses/by-sa/4.0)], from Wikimedia Commons.

[45] Nankai [CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0)], from Wikimedia Commons.

[46] Guo, J., MacKenzie, K. 2012. *Hydraulic Efficiency of Grate and Curb-Opening Inlets Under Clogging Effect*. Colorado Department of Transportation, Colorado.

[47] Forbes, H.J.C. 1976. Capacity of lateral stormwater inlets. *The Civil Engineer in South Africa*, 18(9). South African Institute for Civil Engineers, Johannesburg.

[48] SuSanA Secretariat [CC BY 2.0 (https://creativecommons.org/licenses/by/2.0)], via Wikimedia Commons.

[49] Riley, A.L. 1998. *Restoring Streams in Cities*. Island Press, Washington DC.

[50] Committee of State Road Authorities. 1994. *Guidelines for the hydraulic design and maintenance of river crossings*. The Department of Transport, Pretoria.

[51] Roesner, L., Matthews, R. 1990. Stormwater management for the 1990s. *American City and County*. Penton Media, Atlanta.

[52] Kovacs, Z. 1988. *Regional Maximum Flood Peaks in Southern Africa.* Report TR 137. Department of Water Affairs, Pretoria.

[53] Midgley, D.C. 1972. *Design Flood Determination in South Africa.* University of Witwatersrand Hydrological Research Unit Report 1/72. University of the Witwatersrand, Johannesburg.

[54] World Meteorological Organisation. 2009. *Manual on Estimation of Probable Maximum Precipitation.* Report WMO-No. 1045. World Meteorological Organisation, Geneva.

[55] SANRAL. 2015. *Drainage Manual.* The South African National Roads Agency SOC Ltd, Pretoria.

[56] Alexander W.J.R. 2002. The Standard Design Flood. *Journal of South African Institution of Civil Engineering,* 44(1): 35.

[57] Schmidt, E., Schulze, R.E. 1987. *Flood volume and peak discharge from small catchments in Southern Africa based on SCS technique.* Report TT 31/87. Water Research Commission, Pretoria.

[58] SANRAL. 2015.

[59] Saxton, K.E., Rawis, W.J., Romberger, J.S., Papendick, R.I. 1986. Estimating Generalized Soil-Water Characteristics from Texture. *Soil Science Society of America Journal,* 50 (4): 1031-1036. http://dx.doi.org/10.2136/sssaj1986.03615995005000040039x

[60] Jefferies, C. 2010. In Armitage et al. 2013.

[61] United States Department of Agriculture (USDA). 1938. *Soil Texture Triangle.* United States Department of Agriculture, Washington DC.

[62] City of Cape Town Roads & Stormwater Department. 2009. *Management of Urban Stormwater Impact Policy.* City of Cape Town, Cape Town.

[63] Armitage et al. 2013.

[64] Armitage et al. 2013.

[65] Mpheya, J.N., Pienaar, J.J., Galey-Lacaux, Held, G., Turner, C.R. 2004. Precipitation Chemistry in Semi-Arid Areas of Southern Africa: A Case Study of a Rural and an Industrial Site. *Journal of Atmospheric Chemistry,* 47(1): 1-24.

[66] Mpheya, J.N., Pienaar, J.J., Galey-Lacaux, Held, G., Turner, C.R. 2006. Precipitation Chemistry and Wet Deposition in Kruger National Park, South Africa. *Journal of Atmospheric Chemistry,* 53(2): 169-183.

[67] Farreny, R., Morales-Pinzon, T., Guisasola, A., Taya, C., Rieradevall, J., Gabarrell, X. 2011. Roof selection for rainwater harvesting: Quantity and quality assessments in Spain. *Water Research,* 45(10): 3245-3254.

[68] Abdel-Magid, I.M., Mohammed, A.H., Donald, R. 1996. *Modeling Methods for Environmental Engineers.* CRC Press, Florida.

[69] Livingston, E., McCarron, E. 1990. *Stormwater Management – A guide for Floridians.* Florida Department of Environmental Regulation, Florida.

[70] Armitage et al. 2013.

[71] Transport Infrastructure Ireland. 2015. Design of Soakaways. National Roads Authority, Dublin.

[72] Watkins, D.C. 1991. The Hydraulic Design and Performance of Soakaways. HR Wallingford, Oxfordshire.

[73] Armitage et al, 2013.

[74] Interlocking Concrete Pavement Institute (ICPI). N.d. https://www.icpi.org/

[75] Armitage et al. 2013.

[76] Armitage et al. 2013.

[77] Armitage et al. 2013.

[78] Armitage et al. 2013.

[79] Armitage et al. 2013.

[80] Armitage et al. 2013.

[81] Brink, A.B.A. 1979. *Engineering Geology of Southern Africa.* Volumes 1, 2, 3, 4. Building Publications, Pretoria.

[82] Gerber, F.A., Harmse, H.J. 1980. *'n Identifikasiemetode vir die identifisering van dispersiewe grond.* Technical Report TR 104. Department of Water Affairs, Forestry and Environmental Affairs, South Africa.

[83] Jennings, J.E., Brink, A.B.A. 1978. Application of geotechnics to the solution of engineering problems – essential preliminary steps to relate the structure to the soil which provides its support. *Proceedings of the Institution of Civil Engineers*, Part 1, 64: 571-589.
[84] Knight, K. Everitt, P.R., Sugden, M.B. 1977. Stability of shale slopes in the Natal Coastal Belt. *Proceedings of the Fifth Southeast Asian Conference on Soil Engineering*, Bangkok. pp. 201-212.
[85] South African Institution of Civil Engineering (SAICE). 1985. Problem soils in South Africa – state of the art symposium. *The Civil Engineer in South Africa*, 27(7): 341-406.
[86] Bentley Systems. 2009. *Detention Pond Design and Urban Hydrology Modeling*. Bentley Systems, Exton, Pennsylvania.
[87] Brown, S.A. 1989. *HEC-11 Design of Riprap Revetment*. US Department of Transportation, Georgetown.
[88] Golding, B.L. 1981. Flood routing program. *Civil Engineering, 51(6): 74-75*.
[89] Moreton Bay Waterways and Catchment Partnership (MBWCP). 2006. *WSUD Technical Design Guidelines for South East Queensland*. Moreton Bay Waterways and Catchment Partnership, Queensland.
[90] Batchelor, A. 1993. Division of Water, Environment and Forest Technology, CSIR. *Personal Communication*.
[91] Armitage et al. 2013.
[92] SANRAL. 2015.
[93] Chadwick, A., Morfett, J., Borthwick, M. 2004. *Hydraulics in civil and environmental engineering*. Spon Press, New York.
[94] Chow, V.T. 1959. *Open-channel hydraulics*. McGraw-Hill Book Company, New York.
[95] Henderson, F.M. 1966. *Open channel flow*. Macmillan, New York.
[96] Munson, B.R., Okiishi, T.H., Huebsch, W.W., Rothmayer, A.P. 2009. *Fundamentals of Fluid Mechanics*. John Wiley & Sons.
[97] SANRAL. 2015.
[98] Chow. 1959.
[99] French, R.H. 1994. *Open-channel hydraulics*. McGraw-Hill, New York.
[100] Henderson, F.M. 1966. *Open Channel Flow*. Macmillan, New York.
[101] Cottman, N.H., McKay, G.R. 1990. Bridges and culverts reduced in size and cost by use of critical flow transitions. *Proceedings of the Institution of Civil Engineering*, 88(3): 421-437.
[102] United States Department of Transportation Federal Highway Administration. 2012. *Hydraulic Design of Highway Culverts*. Third edition. Report No. FHWA-HIF-12-026 HDS 5. US Department of Transportation, Georgetown.
[103] Hewlett, H.W.M., Boorman, L.A., Bramley, M.E. 1987. *CIRIA Report 116 Design of Steep Grassed Waterways*. Construction Industry Research and Information Association (CIRIA), London.
[104] Brown. 1989.
[105] Forbes, H.J.C. 1976. Capacity of lateral stormwater inlets. *Civil Engineering*, 18(9): 195-205.
[106] SANRAL. 2015.
[107] SANRAL. 2015.
[108] SANRAL. 2015.
[109] City of Durban. 1984. *Guidelines for the Design of Stormwater Drainage Systems*. Drainage and Coastal Engineering Department, Durban.
[110] City of Durban. 1984.
[111] Henderson. 1966.
[112] Stephenson, D. 1981. *Stormwater Hydrology and Drainage*. Elsevier, Amsterdam.
[113] Reese, A.J., Maynord, S.T. 1987. Design of spillway crests. *Journal of Hydraulic Engineering*, 113(4): 476.
[114] Chadwick et al. 2004.
[115] Chow. 1959.
[116] French. 1994.
[117] Francis, J.R.D. 1969. *A Textbook of Fluid Mechanics*. Hodder & Stoughton Educational, London.

118 Keller, R.J. 1989. Sloping crest crump weir. *Journal of Irrigation and Drainage Engineering*, 115(2): 231-238.
119 Stephenson. 1981.
120 SANRAL. 2015.
121 United States Department of the Interior Bureau of Reclamation. 1978. *Hydraulic Design of Stilling Basin for Pipe or Channel Outlets*. A Water Resources Technical Publication, Report No. 24. US Bureau of Reclamation, Denver.
122 United States Department of the Interior Bureau of Reclamation. 1984. *Hydraulic Design of Stilling Basins and Energy Dissipators*. A Water Resources Technical Publication, Engineering Monograph No. 25. US Bureau of Reclamation, Denver.
123 SANRAL. 2015.
124 *SANS 1200 - Standardised Specification for Civil Engineering construction* is available for purchase from the South African Bureau of Standards (SABS) at https://www.sabs.co.za/
125 *SANS 1200 - Standardised Specification for Civil Engineering construction* is available for purchase from the South African Bureau of Standards (SABS) at https://www.sabs.co.za/
126 *SANS 1200 - Standardised Specification for Civil Engineering construction* is available for purchase from the South African Bureau of Standards (SABS) at https://www.sabs.co.za/
127 SANRAL. 2015.
128 Henderson. 1966.
129 Hewlett et al. 1987.
130 Brown. 1989.
131 Oberholzer, L. 1985. River bank stabilisation - an alternative biological method. *Veld and Flora*, 71(2): 39.
132 Sartor, J.D., Gaboury, D.R. 1984. Street sweeping as a water pollution control measure: Lessons learned over the past ten years. *Science of the Total Environment*, 33: 171-183.
133 Field, R. 1985. Urban Runoff: Pollution sources, control and treatment. *Journal of the American Water Resources Association*, 21(2): 197-206.
134 Chow. 1959.
135 Henderson. 1966.
136 French. 1994.
137 Bakhmeteff, B.A. 1932. *Hydraulics for Open Channels*. McGraw-Hill Book Company, New York.
138 Néelz, S., Pender, G. 2009. *Desktop Review of 2D Hydraulic Modelling Packages*. Science Report-SC080035. Environment Agency, Bristol.
139 SANRAL. 2015.
140 Committee of State Road Authorities. 1994.
141 United States Department of Transportation, Federal Highway Administration. 1978. *Hydraulics of bridge waterways*. Hydraulic Design Series No 1. US Department of Transportation, Washington DC.
142 City of Cape Town. 2002. *Environmental Management Programme (Version 5) for Civil Engineering Construction Activities*. Cape Town.
143 American Public Works Association (APWA). 1981. *Urban stormwater management*. APWA Special Report No. 49. American Public Works Association, Missouri.
144 DeGroot, W. 1982. Stormwater Detention Facilities: Planning, design, operation and maintenance. *Proceedings of the Conference on Stormwater Detention Facilities*. Henniker, New Hampshire.
145 Armitage, N., Rooseboom A. 2000. *The Removal of Urban Litter from Stormwater Conduits and Streams*. Water Research Commission, Pretoria.
146 SANRAL. 2015.
147 Reese & Maynord. 1987.
148 Murthy, K., Giridhar, D.P. 1990. Improved Inverted V-Notch or Chimney Weir. Journal of *Irrigation and Drainage Engineering*, 116(3): 374.
149 Hager, W.H. 1987. Lateral flow over side weirs. *Journal of Hydraulic Engineering*, 113(4): 491.

[150] Burchard, W.V., Hromadka, T.V. 1986. A simple weir structure floodflow bypass analysis program. *Microsoftware for Engineers*, 2(4): 215-218.

[151] May, R.W.P., Bromwich, B.C., Gasowski, Y., Rickard, C.E. 2003. *Hydraulic design of side weirs.* ICE Publishing. London.

human settlements

Department:
Human Settlements
REPUBLIC OF SOUTH AFRICA