DECLARATION

I declare that this thesis is my own, unaided work. It is being submitted for the Degree of Doctor of Philosophy in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

(Signature of candidate)

------------------- day of --------------------------------- 2008

ABSTRACT

Managing the quality of stormwater and greywater in informal settlements are essential to their growth. In this thesis, methodologies are developed for the assessment and management of stormwater and greywater quality based on the analysis of both non-structural and structural control interventions.

The objectives of the research were as follows:

- Review stormwater runoff quality and treatment practices and the extent of runoff and greywater management in rural and peri-urban areas of South Africa. The review was to also determine the extent of quality control awareness and experience among stormwater management professionals and collate information upon which present and future needs can be assessed and addressed.
- To develop a methodology to identify factors causing water quality management issues in low-cost, high-density settlements.
- To develop a methodology to characterize storm and grey water quality as well as setting ambient water quality and management objectives.
- To develop a methodology to identify and select potential non-structural and structural control interventions to manage storm and grey water quality.
- Based on the above, to develop a decision support system for evaluation of potential interventions for storm and grey water management at planning level.

The methodologies used to achieve the above objectives consisted of: literature review; consultations with stakeholders; data analysis and computations; model development; and model application.

The current status of managing water quality pollution in urban areas is outlined and the related problems, specifically those applicable to developing areas are discussed. Management interventions employed to date in the management of water quality effects are set out and the applicability of such interventions to developing areas is identified. The potential of expert systems is evaluated and the application of this system to stormwater quality management models is assessed. A decision support system (DSS) was developed for rapid assessment of various water quality management interventions. The model is primarily targeted at those who are involved or are likely to be involved in stormwater quality management including catchment managers, local governments or municipalities, catchment management agencies, private consultants and researchers.

The DSS and the related methodologies have been shown through Alexandra Township (north of Johannesburg) case study, to be useful and to satisfy all the objectives set out for the research. The results of the research are summarised and the merits and limitations of the decision support systems are discussed. Recommendations for the direction of future research and the development of the existing model are detailed. Specifically, it is recommended that:

- Extensive monitoring be undertaken in order to improve the defaults in the model
- A research be undertaken into the extent to which GIS can be integrated to the DSS to select appropriate management interventions and their sites
- A research be undertaken into privatization and partnership in the ownership and operation of stormwater management systems.
- Selection of least cost strategy with the DSS is presently achieved by trial and error process. The selection process can be improved if the DSS can be linked to an optimizer.

DEDICATION

To the many informal communities awaiting control of stormwater and greywater quality to improve lives.

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LIST OF PUBLICATIONS

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Owusu-Asante, Y., and Ndiritu, J. 2008. Comparison of a simple and a complex urban stormwater model. Under preparation.

Owusu-Asante, Y., and Stephenson, D. 2006. Estimation of storm runoff loads based on rainfall-related variables and power law models – case study in Alexandra. Water SA, 32(2), 137-143.

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LIST OF SYMBOLS

A_{com}	=	Commercial land use area
A_{res}	=	Residential land use area
A_{redev}	=	Area of land to be redeveloped for impervious cover reduction program
A_r	=	Typical retrofit drainage area
A_{res}	=	Residential area
A_{si}	=	Area surveyed or inventoried for retrofitting
$\sum A_{lu}$	=	Sum of all land use areas
A_{stm}	=	Area captured by structural treatment measure
A_c	=	Total area of catchment
A_{ac}	=	Area of construction site
A_L	=	Lawn area
A_S	=	Area of Hydrologic Soil Groups A, B, C, and D
A^{st}	=	Total street area swept
BMP	=	Best Management Practice
B_{rp}	=	Riparian buffer width
B_u	=	number of businesses
B_w	=	fraction business connections that are wash water only
C_{fs}	=	effluent concentration of failing septics
C_r	=	Runoff coefficient for cleared land
C_{ss}	=	Concentration of suspended solids
C_t	=	combined wash water and wastewater pollutant concentration from business illicit connection
C_w	=	wash water pollutant concentration from business illicit connection
C_{ws}	=	effluent concentration of working septics
C_{ww}	=	wastewater concentration
C_{daw}	=	Concentration of a pollutant in domestic animal waste
D_{da}	=	Fraction of households with domestic animal
D_f	=	Fraction of dwelling unit with septic system
D_{icd}	=	Total number of homes disconnected

D_r = delivery ratio

D_u = Number of dwelling units

$E_{n/p}$ = Enrichment factor of nitrogen or phosphorus

E_{rb} = Removal efficiency of riparian buffer

E^s = Efficiency of sweeping

F_{com} = Fraction of commercial imperviousness as rooftop

F_{bus} = Fraction of businesses disconnected

F_{pw} = Fraction of pollutant delivered to water course

F_f = fraction of complete failures of septic systems

F_I = Fraction of infiltrated rainfall into Hydrologic Soil Groups A, B, C, and D

F_t = total flow per business illicit connection

F_{st} = Fraction of surveyed area that is treatable

F_w = wash water flow from business illicit connection

F_r = Fraction of retrofits

F_s = Fraction of area underlain by each soil group

$F_{n/p}$ = Fraction of nitrogen or phosphorus lost as surface runoff for a particular soil group

F_{implem} = Implementation factor

H_p = Planning horizon

I_b = fraction of businesses with illicit connections

I_r = fraction of dwelling/households illicitly connected

I_{redev} = Fraction impervious cover reduced

I_c = Fraction of total impervious cover in the catchment

I = Fraction of impervious cover

I_{res} = Fraction of impervious cover in residential land use

I_{com} = Fraction of impervious cover in commercial land use

K_c = Factor to account for compaction of urban soils

K_{app} = Typical Fertilizer application rates

K_r = Fertilizer reduction

K_l = Fraction of fertilizer lost to the environment

l = Length of sanitary sewer

L_{rp} = Riparian buffer length

L_{escs} = Sediment annual pollutant load reduction from ACESC program

L_{escn} = Nutrient annual pollutant load reduction from ACESC program

L_{exs} = Annual pollutant load from exfiltration system program

L_{acss} = Annual load of sediment from active construction site

L_{acn} = Annual load of nutrients from active construction site

L_{ill} = Annual pollutant load from Illicit connections

L_{lawn} = Annual pollutant load from lawn or subsurface flow

L_{sso} = Annual pollutant load from sanitary sewer overflows

L_{ssor} = Annual pollutant load reduction from sanitary sewer overflow repair program

L_{ssr} = Annual pollutant load from septic system inspection/repair program

L_{sep} = Annual pollutant load from septic systems

L_{stm} = structural treatment control measure annual pollutant load reduction

L_{dawe} = total annual pollutant load reduction from domestic animal waste education program

L_{ss} = total annual pollutant load reduction from street sweeping program

L_{icd} = total annual pollutant load reduction from impervious cover disconnection program

L_{rt} = total annual pollutant load reduction from rainwater tank use program

L_{cesc} = Total annual pollutant load reduction from catchment surface erosion and sediment control program

L_{fue} = total annual pollutant load reduction from fertilizer use education program

L^{ps} = Total pollutant annual storm load from primary sources

L_{sse} = Annual pollutant load reduction from septic system education program

L^{icd}_{r} = Annual pollutant load reduction from impervious cover disconnection in residential area

L^{icd}_{c} = Annual pollutant load reduction from impervious cover disconnection in commercial areas

L_{icr} = Annual pollutant load reduction from impervious cover reduction program

L^{ps}_{ir} = Total primary source pollutant annual storm load from impervious residential land use

L^{ps}_{ic} = Total primary source pollutant annual load from impervious commercial land use

$L_{catchescs}$ = Sediment annual pollutant load reduction from CacthESC program

$L_{catchescn}$ = Nutrient annual pollutant load reduction from CatchESC program

L_{rb} = Annual pollutant load reduction from riparian buffers program

$L^{ps+secs}$ = Total pollutant annual storm load from primary sources non-storm load from secondary sources

L_{ficr} = Annual pollutant load reduction from future Illicit connection removal program.

L_{rt} = Annual pollutant load reduction from rainwater tank program

L_{rac} = Annual pollutant load reduction from river assimilative capacity

L_{secs} = Total pollutant annual non-storm load from secondary sources

N_i = number of dwelling/households with illicit connection

N_o = Number of annual overflows per kilometers

N_r = Number of retrofits built per year

P = Mean Annual Precipitation

P_{eff} = Erosion and sediment control program efficiency at construction site

P_u = Persons per dwelling units

R_f = Fraction of annual rainfall that produces runoff

R_{pt} = Typical roof footprint area

S_f = Fraction of septic systems failing

$S_{n/p}$ = Soil content of nitrogen or phosphorus (% by weight)

T_{eff} = pollutant reduction efficiency of treatment control measures

U_t = Total disconnected impervious cover area

V = Volume per overflow

W_u = Water use or per capita wastewater generation

W_{pro} = Domestic animal waste production

η_a = *Treatable risk factor,* defined as a fraction of catchment area that can be treated by an intervention

η_b = *Capture risk factor,* defined as a fraction of annual rainfall that can be captured by control intervention

η_c = *Design risk factor*, a factor to reflect design adequacy of an intervention

η_d = *Maintenance risk factor,* a factor to reflect maintenance level of an intervention

η_e = *Awareness risk factor,* defined as a fraction of population that can be reached with education programs

η_f = *Participation risk factor,* defined as a fraction of population that will change behaviour or participate in the program or comply with standard

ξ = *Measure of assuredness* defined as the proportion of pollutant loads that can '*reliably*' be reduced by an intervention under the prevailing conditions

ω = Implementation factor, defined as the magnitude (%) of management intervention implemented

Ω = Cost of an intervention

ϵ = Cost of a strategy (consisting of different interventions)

NOMENCLATURE

Term	Description/definition
Best Management Practice (BMP)	A structural control intervention employed in stormwater management for stormwater quantity and/or quality control.
DSS	Decision support system
Greywater (also grey water)	Return flows from the laundry, bathroom and kitchen or combinations of these.
Management strategy	Combination of various mixes and magnitudes of non-structural and structural control interventions
Non-Point Source Pollution	Non-point source is a diffuse pollution source without a single point of origin or specific discharge point.
Non-structural interventions	Stormwater management intervention which use natural measures to reduce pollution levels, do not require extensive construction efforts and/or promote pollutant reduction by eliminating the pollutant source.
Retrofits	Structural interventions implemented in existing developments (or after developments have occurred).
Retrofitting	The renovation of an existing structure or facility to meet changed conditions or to improve performance.
Stormwater (also storm water)	The water running off urban surfaces, as a consequence of rainfall over urban catchments.
Stormwater management	A process employing various non-structural and structural interventions to control stormwater runoff with respect to its quantity and quality.
Stormwater quality	A term used to describe the physical, chemical and biological characteristics of stormwater.
Stormwater quantity	A term used to describe the volume characteristics of stormwater
Structural interventions	Devices which are constructed to provide temporary storage and treatment of stormwater runoff and greywater.

1 INTRODUCTION

1.1 Background

Inadequate sanitation and drainage is one of the major environmental and health problems facing high-density low-income settlements in developing countries today. The unprecedented population growths in these settlements have severely strained the ability of municipalities to meet the need for drainage and treatment. As local governments have tried to cope with insufficient services, priority has been given generally to high-income areas where full or partial cost recovery is considered feasible. Low-income areas are often left unserved or served by woefully inadequate facilities. The principal reason for this situation is the high cost of conventional drainage and treatment practices.

The rapid population growth, little or non-existent solid waste removal or sanitation services in these settlements (especially in South Africa) have resulted in the rapid build-up of pollutants on catchment surfaces which when washed off by stormwater has a great impact on the receiving waters (Campbell, et al., 2001). Increased concerns about such impacts led to the introduction of stormwater quality management, which represents a system of control and treatment strategies designed to mitigate such impacts either fully or partially.

Current norm is that water pollution controls be approached on a catchment basis. A catchment approach allows tradeoffs between pollution sources, point source treatment and pollution prevention, and optimal balances between these. It requires community-level involvement and often includes the use of both structural and non-structural stormwater control interventions to protect or restore catchments from chemical, physical, or biological stressors. The catchment approach allows simultaneous pollution, flood, and erosion-sedimentation control by properly instituting non-structural control interventions and siting structural control interventions within the catchment to maximize pollutant removals and reduce stormwater-associated stressors.

Historically, structural control interventions were employed to capture peak flows, assist in local drainage, and manage the quantity of runoff produced during wet-weather flow, i.e. flood control. While these objectives will probably remain a goal of catchment management planners, structural control interventions are now also considered for pollutant removal, stream restoration, and groundwater recharge infiltration. Source control and pollution prevention are considered “good housekeeping” practices i.e., practices that keep pollutants out of runoff such as street cleaning, improved maintenance levels, education, capacity building, and controlled application of pesticides/herbicides. Runoff source controls are used to reduce runoff generated at the source of specific activities. End-of-pipe or treatment controls are used to remove pollutants from contaminated runoff. The key stressors or pollutants of concern are nutrients, litter, suspended solids, pathogens, flow, and toxic substances. These stressors have worldwide significance and their impacts are detailed in Metcalf & Eddy, 1991.

Development of tools for selection of appropriate stormwater runoff management and treatment systems is invariably determined by such factors like; hydrological, land-use and development types, socio-economic status (including housing type, income, levels of service provision and maintenance), population density and demographic characteristics, biophysical catchment characteristics (soil, relief, climate, hydrology), types of runoff problems (i.e. pollutants, the sources of these pollutants, concentrations and loading rates of these pollutants), and cultural practices (Schoeman et al., 2001).

1.2 Statement of the problem

High-density low-income settlements in developing countries have backlog in sanitation and drainage. This includes sewage, greywater and severely contaminated stormwater runoff. In low-income areas the paths are often merged; sewage, greywater, solid waste and contaminated runoff enter surface drains, which eventually discharges into streams, rivers and impoundments that are used for drinking water supply and recreation. These cause water quality problems, pose potentially serious human and environmental health risks through contact recreation and through the use of untreated water, result in high drinking water purification costs and cause a loss of amenity value and diminished recreation potential (Ashton and Bhagwan, 2001).

Development of comprehensive tools for selection and design of drainage management interventions even at planning levels is still at its early stage in South Africa. Hence planners and engineers are not equipped with the necessary knowledge and tools to deal with stormwater and greywater quality problems in informal settlements. It suffices therefore to state that the needs of stormwater and greywater management planning in South Africa (national, provincial and municipal levels) have not received adequate attention in terms of quality control. Whether we can take it to the next step of appropriate treatment and/or management needs a research like this study.

1.3 Hypotheses and research questions

The Oxford Advanced Learners Dictionary defines hypothesis as: *suggestion that is based on known facts and is used as a basis for reasoning or further investigation*. The suggestions which provided the basis or the need for this research have been highlighted in sections 1.1 and 1.2 and is summarised below.

Discharges from informal settlements cause numerous adverse water quality impacts on urban areas and on receiving waters including erosion, sedimentation, dissolved oxygen depletion, nutrient enrichment and eutrophication, toxicity, reduced biodiversity, high drinking water purification costs, and the associated impacts on beneficial water uses. These problems reflect local conditions with respect to the climate, economic development, the level of environmental protection practice (including the associated infrastructures), institutional arrangements and public awareness. Given these adverse effects on receiving waters, the selection of stormwater quality management interventions must be efficient and effective. Efficient and effective selection requires that various alternative interventions be identified and evaluated at planning stage based on the principles of sustainability, hierarchical management approach, public consultation, and adaptive management.

Based on the above hypotheses the research questions were conceived as follows:

- Which area or land use within an urban catchment has the greatest potential or need for stormwater quality improvement?
- How critical are pollutants from secondary sources such as sanitary sewer overflows, illicit connections, and active construction in an urban catchment, which are often overlooked in simple or complex models?
- How to meet specified target load reduction as required?
- What interventions should be considered to treat/manage current and future contaminant sources to a receiving river body?
- Which combination of interventions (or strategies) would produce a minimum cost in meeting a community's stormwater quality management objectives?
- What pollutant reduction has been achieved by current or existing programs?
- What level of assuredness/risk does the estimated load reduced by an intervention represent?
- How effective are investments in educational and other non-structural control programs to manage stormwater quality?

1.4 Aims and Objectives of the study

The primary aim of this study is to develop a general guideline for effective management of stormwater and greywater quality in South Africa with particular reference to low-income, high-density urban developments. To achieve this, the following specific objectives were set:

- Review stormwater runoff quality and treatment practices and the extent of runoff and greywater management in rural and peri-urban areas of South Africa. The review was to also determine the extent of quality control awareness and experience among stormwater management professionals and collate information upon which present and future needs can be assessed and addressed.
- To develop a methodology to identify factors causing water quality management problems in low-cost, high-density settlements.

- To develop a methodology to characterize storm and grey water quality as well as setting ambient water quality and management objectives.
- To develop a methodology to identify and select potential non-structural and structural control interventions to manage storm and grey water quality.
- Based on the above, to develop a decision support system for evaluation of potential interventions for storm and grey water management at planning level.

1.5 Justifications and specifications

Water quality management is a critical component of overall integrated water resources management. Most users of water depend on adequate levels of water quality. When these levels are not met, these water users must either pay an additional cost for water treatment or incur at least increased risks of damage or loss. As populations and economies grow, more pollutants are generated. Many of these are waterborne, and hence can end up in surface and groundwater bodies. Increasingly, the major efforts and costs involved in water management are devoted to water quality protection and management. Conflicts among various users of water are increasingly over issues involving water quality as well as water quantity.

The problem statement identified in this research is supported by stormwater quality management issues identified worldwide. Ahmed and James (1995) conducted a survey among stormwater management professionals worldwide. Water quality was rated an important issue in stormwater control by 81% of the respondents. 77% believed that a need exists for more applied research, mathematical modelling or active participation. Comments also included: (1) shortage of information/data regarding alternative stormwater management interventions (2) the low number of stormwater management intervention applications reflect the need for decision-making tools.

In this study, 'structural control interventions' are used interchangeably with 'treatment control interventions' and 'Best management practices (BMPs)'. The terms 'interventions, practice, and measure' are used interchangeably. Non-structural control interventions are also used interchangeably with the term 'stormwater management programs' or simply 'management programs'. Both non-structural and structural control interventions are together referred to in this thesis as 'stormwater management interventions'. Primary sources of pollution produces storm loads (e.g. loads in runoff from catchment surfaces) and are generally from wet weather flows. Secondary sources (e.g. from illicit connections to storm drains) produces non-storm loads and are generally from dry weather flows.

1.6 Framework for this study

The guideline emanating from this study has been prepared to comply with the requirements and principles as detailed below:

National Water Policy(1997) and Act (1998) – The White Paper "A National Water Policy for South Africa" (DWAF, 1997), and the National Water Act (Act 36, 1998) places particular emphasis on protection of the water environment from pollution, and makes provision for both resource- and source-directed measures.

The resource-directed measures is based on identifying an appropriate level of protection for different water resources by setting the "Resource Quality Objectives" (RQOs), based on a Water Resources Classification System. Source-directed measures is based on setting of standards (or management practices) that are appropriate to manage different pollution sources (including requirements or incentives for achieving end-of-pipe effluent discharge standards, implementing on-site management practices to control diffuse impacts, and performing in-stream mitigation and rehabilitation). These standards aim to minimize the impact on the water resource and are implemented using precautionary approach.

The National Water Act (Act 36 of 1998 1xv) defines pollution as:
Alteration of the physical, chemical or biological properties of a water resource so as to make it:-

(a) Less fit for any beneficial purpose for which it may reasonably be expected to be used; or

(b) *Harmful or potentially harmful: (i) to the welfare, health or safety of human beings; (ii) to the any aquatic or non-aquatic organism; (iii) to the resource quality; or (iv) to property.*

By this definition, greywater and urban runoff with characteristics that cause such alteration to receiving water is a source of pollution and needs to be managed.

National Environmental Management Act (1998) – Section 2 of the National Environmental Management Act (1998) sets the following as part its principles of which this study adheres to:

- **Ecologically sustainable development (ESD)** which requires the effective integration of economic, social and environmental considerations in decision-making processes when planning, constructing and operating infrastructure. ESD can be achieved through the implementation of the following principles and programs:
    - The precautionary principle – namely, that if there are threats of serious or irreversible environmental damage, lack of full scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation.
    - Inter-generational equity – namely, that the present generation should ensure that the health, diversity and productivity of the environment is maintained or enhanced for the benefit of future generations.
    - Conservation of biological diversity and ecological integrity.
    - Improved valuation and pricing of environmental resources.
- **Hierarchical Pollution/Waste Management Approach** which requires pollution or waste management to be carried out in the order of: prevention, reduction, reuse, recycle, and treatment. This hierarchy can also be translated as managing pollution firstly at source, and thereafter proceeding down to the end-of-pipe;
- **Public Consultation** which assumes that all affected stakeholders are consulted and given the opportunity to provide input to decisions. Community wellbeing and empowerment must also be promoted through environmental education, the raising of environmental awareness, the sharing of knowledge and experience.

- **Selection of the best practicable (environmental management) option** which recognizes we are dealing with very complex natural and man-made systems whose responses is not fully predictable with the currently available science-based tools. Best practice therefore requires selecting management options (and designing) on the basis of best available data, ongoing monitoring and data collection, and revisiting decisions to produce improved management (and designs).
- **Polluter pays** which requires that the costs of remedying pollution, environmental degradation and consequent adverse health effects and of preventing, controlling or minimizing further pollution, environmental damage or adverse health effects must be paid for by those responsible for harming the environment.

The National Strategy to Manage Water Quality Effects of Settlements (1999) **–**

The National Water Act makes provision for the development of a National Water Resource Strategy, which is given effect at a regional level by Catchment Management Strategies. As a first step in this process, Department of Water Affairs and Forestry (DWAF) has divided the country into 18 Water Management Areas. Water Resources Management Strategies will be developed for each of these areas. This is supported by a number of cross cutting strategies addressing different aspects of water resources management such as the National Strategy to Manage Water Quality Effects of Settlements (1999) (or simply the National Strategy), which focuses on addressing pollution from densely populated settlements. Thus the National Strategy forms one of the building blocks of Water Resources Management Strategies (DWAF, 1999). The following principles underlie the National Strategy:

- *Implementation of the Strategy should include negotiation with other government bodies, at all three spheres of government, and with the affected communities.*
- *Recommendation for any settlements must be compatible with, and should complement national policies that address poverty, service delivery, and environmental protection both within the Department of Water Affairs and Forestry, and other Departments.*

- *Implementation of the strategy should not slow or prevent service delivery under other national, provincial or local government programs.*
- *DWAF should participate in education campaigns that raise community awareness of the dangers of poor water quality and pollution.*
- *Water quality management in this sector should take cognizance of, and in some cases explicitly address, the inequalities of the past.*
- *Recommendation should address all components that contribute to the water quality problem, be these social-economic, physical or behavioural.*
- *Water quality management actions should not only aim to provide engineering and other services, but should include capacity building and education with respect to the services provided,*

1.7 Methodology of the study

The methodology used in this study comprised the following:

1.7.1 Literature Review

Extensive literature review was conducted on the subject in both local and international conditions focusing principally on informal settlements, while at the same time reviewing studies in formal or urban areas in a view of drawing some techniques and experiences that can be applied in informal settlements as well. The review revealed the extent, achievements, gaps, issues and current norms of stormwater management and treatment practices upon which present and future needs were assessed and addressed. The information collated from the literature enabled the formulation of guidelines which are developed as methods to: (a) characterize storm and grey water quality as well as setting water quality and management objectives; (b) identify potential stormwater quality issues and their causes; (c) identify and select potential non-structural control interventions to manage storm and grey water quality; (d) identify and select potential structural control interventions to treat runoff and grey water. Based on the above, a decision support tool was developed for evaluation of management interventions at planning level.

1.7.2 Consultations with stakeholders

A steering committee was formed by Water Research Commission to guide this study. The committee consisted of representatives from Water Research Commission, Department of Water Affairs and Forestry, interested parties from private engineering consultancies and educational institutions. Representatives from Alexandra and Kliptown township development committees were also consulted during the study. Alexandra and Kliptown townships are located at north and south of Johannesburg respectively. The objectives of the study were developed as part of a consultative process among the steering committee members during the early stages of the study. The outcome of each phase of the study was presented in steering committee meetings which were held biannually. At each meeting, progress and deliverables of each phase of the study were assessed against the set objectives and a way forward was outlined.

1.7.3 Analysis of information

Collateral evaluation of information gathered from the literature review was carried out as a basis for meeting the set objectives.

1.7.4 Model development

A model for future runoff and greywater management and treatment at planning level was developed. Engineers and planners look for solutions, which can achieve pollutant load reduction requirements cost-effectively. Modelling is a financially attractive and time saving approach that can be used to assess (predict) future water quality situations resulting from different management strategies. Many professionals feel somewhat handicapped by the present shortage of data and tools for assessing the need to treat stormwater pollution. One of the tools that are useful to professionals who are active in stormwater management is a computer based decision-support tool for stormwater quality planning. The tool developed under this study features: (a) knowledge of various interventions that can be included in a quality control plan; (c) a framework for formulating and evaluating alternative strategies to meet management objectives.

1.7.5 Model application

The decision-support tool developed was applied using Alexandra as case study. Stakeholders need to accept the model developed for use in any informal settlement (or urban) water quality management study. Given the increasing role of stakeholders in water management decision processes, they need to understand and accept the models, at least to the extent they wish to do so, and this can only be accomplished if the model is tested in local conditions and proven to be reliable.

1.8 Layout of the thesis

Chapter 1 presents the background of water quality management in informal settlements. It defines the problem statement, aims and objectives of the study, framework of the study, and the methodology used to achieve the objectives. Chapter 2 presents a review of previous work done locally and internationally. Chapter 3 presents the structure of the decision models. Chapter 4 presents how the model was developed and it describes: methods to identify factors causing water quality management issues; methods to develop ambient water quality objectives and management objectives; methods to select management interventions; methods to formulate alternative management strategies; and methods to evaluate interventions and strategies. Chapter 5 is an extension of Chapter 4 and it describes the various computations in the model development. Chapter 6 and 7 are devoted to model implementation and case study application respectively. Finally, the conclusions and recommendations resulting from this study are presented in chapter 8.

2 REVIEW OF STUDIES ON URBAN WATER QUALITY MANAGEMENT

2.1 South African case studies

Several monitoring studies related to urban runoff water quality have been conducted in South Africa over last decade in areas such as Gauteng Province (Stephenson and Green, 1998; Silberbaurer and Moolman, 1991; Wimberley, 1992; Van Veelen and DWAF, 1994 a, b; Coleman 1992; Campbell, 2001; Armitage et. al., 1998), Kwa Zulu Natal (Simpson, 1986; Kelbe et. al., 1991; Umgeni Water, 1991; Archibald, 1994 a-c; Simpson and Coleman, 1992; Kelbe et. al., 1992; Pillay and Buckley, 2001), Western Cape Province (Kloppers, 1989; Wright, 1991; Wright et. al., 1992; Armitage et. al., 1998; Grobicki, 2001), Eastern Cape Province (Mackey, 1993, 1994 a, b; Van Ginkel et. al., 1993, 1996), Free State Province (Grobler et. al., 1987), Olifants river catchment (Quibell et. al., 2003), Vaal river catchment (Herold and Roux, 2004), South Africa in general (Pegram and Gorgens, 2001; Pegram et. al., 1998; Wood et. al., 2001).

These studies span over a wide range of conditions, with variations in local climate, relief, soils, dominant hydrological processes, land use, development type and density, level of service as well as different demographic aspects and environmental concerns. Most of these studies follow a similar approach in that a catchment is chosen and monitoring points selected. Samplings for water quality analysis are taken at specific intervals within the monitoring period. In few of the studies, flow is also measured concurrently in order to determine the loading of the pollutants. In most of these studies also the monitoring points were located at the point of discharge to the watercourse and as a result, site-specific causes of contamination of runoff were often overlooked.

Review of all the studies conducted in South Africa indicates that, very few of them provides meaningful data with regards to water quality and flow monitoring to allow derivation of even semi-quantitative relationships. For an assessment of this kind, at least the minimum, maximum and median values for flow and concentrations, loads and export coefficient of water constituents are required for low flow and storm flow. However, for most studies, only mean values were reported, and flow was very seldom measured concurrently with water quality sampling. Detailed physical, geographical and demographic information was often not recorded (Schoeman and MacKay, 1995).

Ashton and Bhagwan (2001) have compiled an excellent review of the studies prior to 1995. Ashton and Bhagwan (2001) summarized issues or factors related to urban runoff contamination, identified some management options namely; pond systems, filtration systems, vegetated infiltrations systems, chemical treatment systems, wetlands systems and some policy tools and regulatory instruments.

The literature review of South African case studies also revealed that, contaminations of urban runoff water quality are related principally to:

- Predominant type of land use activity (residential, industrial, commercial and agricultural)
- Development type (formal versus informal)
- Development density (expressed as number of people or dwelling units per unit area)
- Standard or cost of development (low-cost high-density versus high-cost low-density)
- Level of services provided and degree of service maintenance.

Table 2-1 presents a summary of studies undertaken in South Africa up to date in relation to the above factors, as well as other socio-economic factors, biophysical catchment characteristics and pollution problems, where data is available. An examination of the management strategies that have been used on existing stormwater systems in South Africa revealed the following problem areas (Ashton and Bhagwan, 2001):

- *Prior to 1994, planning and development strategies did not include long-term measures for dealing with urban runoff problems or options for coping with increased runoff due to rapid increases in settlement areas and rising population densities.*
- *In general, insufficient (if any) consideration was given to reserving sufficient space or facilities for future stormwater management or treatment facilities.*

- *Despite the fact that the encroachment of shacks and buildings onto river banks (flood plains) poses a serious danger to lives during floods and exacerbates the seriousness of water quality problems, very little attention was given to providing alternative options to the residents concerned.*
- *All previous attempts to implement remedial actions without the full and active participation of the affected residents have failed.*

Key management issues that require attention in catchment stormwater management as revealed in the literature include the following (Ashton and Bhagwan, 2001):

- *Concentrations of feacal bacteria should meet given water quality standards for recreational use of receiving water bodies at all times*
- *Unsightly litter in and along drains and natural water courses should be kept to a minimum*
- *Dissolved oxygen concentrations should not be depleted to below 60% of saturation in the initial mixing zones of coastal stormwater outfalls and, ideally, should not fall below 80% of saturation in any part of a freshwater body that receives urban runoff*
- *Urban runoff should not contain high loads of suspended sediment so as to ensure that water clarity is not adversely affected in the long-term*
- *The nutrient balances in rivers, estuaries and lagoons receiving urban runoff should not be changed significantly (<15%) from their present status*
- *No toxic chemical should be discharged into receiving waters (this includes pesticides and heavy metals)*
- *Salt marshes, fringing wetlands, mud flats and lagoons should not be disturbed by urban runoff to the point that their structure or functions become adversely affected (MacKay, 1994a)*
- *Management actions aimed at reducing diffuse source pollution from urban runoff and informal settlements must form part of an integrated catchment management plan so that all management actions can be properly integrated (Wright et. al., 1992).*

Table 2-1: Summary of urban water quality management studies undertaken in South Africa

Table to be printed on A3 sheet and inserted on this page

Synthesis of studies undertaken in South Africa provide estimates of the range of concentrations likely to be observed, for a given development type and density, and is provided in Table 2-2 (Coleman, 2001). The shortcoming of the information in Table 2-2 is that none of the monitoring/sampling studies used to derive the predicted concentrations was optimally planned. Most (if not all) of the studies were based on grab sampling, and the length and frequency of sampling were not given due consideration to yield statistically significant data worthy of producing a forecast as shown in Table 2-2, hence, Table 2-2 may taken as indicative only.

Table 2-2: Expected pollutant concentration ranges for categories of residential catchments (Coleman, 2001).

Develop-ment type	Develo-pment density	Devel-opment costs	Pollution potential	NH_4 (mg/l as N)	TKN (mg/l as N)	EC (mS/m)	SS (mg/l)	PO_4 (mg/l as P)	COD (mg/l)	DO (mg/l)	Feacal Coliform (/100 ml)
Formal	High Density	High Cost	High	3-7	4-14	13-100	20-1000	0.2-6.0	60-500	3-6	10^4-10^5
			Low	1-3	2-8	12-50	40-150	0.2-3.0	40-300	3-6	10^3-10^4
		Low Cost	High	1-30	10-40	70-2500	40-1850	0.4-14.0	150-400	1-6	10^4-10^6
			Low	1-5	2-8	15-200	21-400	0.2-3.0	15-70	3-6	10^4-10^6
	High Density	High Cost	High	1-21	1-16	30-200	1-2500	0.1-6.0	5-800	3-6	10^3-10^4
			Low	0-3	1-5	10-50	21-350	0.0-3.0	20-80	1-6	0-10^3
		Low Cost	High	-	-	-	-	-	-	-	-
			Low	-	-	-	-	-	-	-	-
Informal	High Density	Low Cost	High	5-24	7-103	25-700	800-8000	1.0-8.0	70-3000	1-3	10^4-10^7
			Low	1-5	4-18	8-180	180-3500	0.2-5.0	40-400	3-6	10^4-10^6
	Low Density	Low Cost	High	-	-	-	-	-	-	-	-
			Low	-	-	-	-	-	-	-	-

It may be concluded that, extensive monitoring of urban runoff discharges for the purpose of stormwater quality management is in its early stages of development in South Africa. Although many loading estimates have been reported for various land uses, high variability and inconsistencies exist among reported values. These differences may represent real variations or differences in sampling and analytical methods. This problem of little consistency or comparability among monitoring programs is further compounded by the absence of testing programs to evaluate urban runoff sampling strategies for effectiveness and efficiency; therefore, an optimal program has not been identified.

2.2 International case studies

Planning methodologies in Canada and the US uphold issues of water, development and the environment as an inseparable trinity (James and Niemczynowicz, 1992). Management of urban drainage in new developments without upsetting the existing aquatic ecosystems is prominent in their current planning methodologies (Ahmed, 1994; Bowen *et al.*, 1993). As a result, portability and recreational water usage are direct benefits of preserving aquatic ecosystem stability where the planning methodology is applied correctly throughout the catchment (Goyen and McLaughlin, 1978; Heathcote, 1987).

Stormwater management measures, which are also referred to as Best Management Practices (BMPs) in the USA, Alternative Technologies (AT) in France, and Sustainable Urban Drainage Systems (SUDS) in the UK, are often implemented in the form of treatment trains representing a sequence of BMPs. The use of BMPs has been the primary method to treat or control storm runoff quality in North America and Europe. These are a combination of practices for source control and for treatment (ASCE, 1998) but, the overall goals are to mitigate impacts resulting from storm runoff pollution. In North American terminologies, source control BMPs are practices that prevent pollution by reducing potential pollutants at their sources before they come into contact with stormwater, while treatment BMPs are methods to treat or remove pollutants from stormwater. Several studies have been undertaken to assess the ability of stormwater treatment BMPs e.g. wet ponds, grass swales, storm water wetlands, sand filters, dry detention, etc. to reduce pollutant concentrations and loadings in storm runoffs. Strecker et. al., 2001 reviewed many of these studies and reported that inconsistent study methods, lack of associated design information, and reporting protocols make-wide scale assessments difficult, if not impossible. For example, individual studies often included the analysis of different constituents and utilized different methods for data collection and analysis, as well as reported varying degrees of information of BMP design and inflow characteristics. The differences in monitoring strategies and data evaluation alone contribute significantly to the range of BMP effectiveness that has been reported.

Concerns with BMP performances is that it is difficult to link their installation to water quality improvements – receiving water quality at times seems unchanged before and after construction of BMP. Other major concerns are the degree to which pollutant removal associated with a particular BMP can be predicted and whether identical designs, not considering influent concentration characteristics can produce the same performance levels at different locations. Also there is a lack of methodologies or models to tell water quality managers where to place the BMP in the catchment to achieve optimal water quality results. Concerns about BMP performance calls for research program that addresses how the BMPs work, how to design for water quality control, what they cost, how effective they are, and where to best place them in the catchment.

BMPs are unit processes with key mechanisms working within them to reduce the effluent load. In Australia, criterion such as effectiveness of the BMP to remove pollutants, stormwater management goals, on-site vs. regional considerations, catchment and terrain factors, physical suitability factors, hydrological and climatic factors, community and environmental factors, location and permitting factors govern the selection of BMPs. Subjective rating systems are used to identify the optimum BMPs (NSWEPA, 1997).

Processes of stormwater treatment may be divided into four main groups:

1. Mechanical approaches, such as sieves, meshes or similar may provide better separation of solid particles from the liquid phase.
2. Physicochemical approaches, where chemical additives to improve separation characteristics for liquid and solid components may change the composition of stormwater runoff. The physical part will consist of sedimentation, flotation and filtration.
3. Biological approaches, where purification by a combination of physical, chemical and biological processes is achieved. The physical component is the necessary storage to provide adequate residence times for reactions and

biochemical degradation processes relying on digestion of micro organisms like fungi, algae, and bacteria.

4. Stormwater runoff reduction, where the formation of stormwater and the disconnection of impervious areas from the network lead to reduced stormwater flows and related pollution loads.

2.3 Non-structural control interventions

Stormwater management interventions require derivation of innovative approaches using a mix of strategies ranging from the basic principles of planning (to balance environmental and settlement characteristics), to technology choice, and to the operation and maintenance of the system. The interventions are combinations of practices for source control and for end-of-pipe treatment but, the overall goals are to mitigate impacts resulting from storm runoff pollution. Many end-of-pipe treatment controls are considered to be structural in that they involve some sort of earthen or concrete structure whereas source controls can be non-structural or structural. Treatment is only a part of management interventions, and is often at the end of the line of the stormwater or greywater waste stream. This section deals with non-structural control interventions, which are "apriori" to the occurrence of waste or pollutants (that is, avoidance or prevention, reducing, reusing and recycling of pollutants) before they are mobilised and delivered to receiving waters.

In response to Agenda 21 and other international framework of waste management and sustainable development, current practices have shifted away from a sole reliance on technological or end-of-pipe solutions to more proactive and integrated strategies that focus on changing the social and institutional relationships that have the power to both cause and minimize runoff quality and quantity problems. Non-structural control intervention is based on such strategies and aims at the production element of the pollution continuum (subsection 3.3.1). The National Strategy (DWAF, 1999) specifically emphasizes on non-structural source control in choosing appropriate interventions to manage the water quality effects of dense settlements.

Non-structural control interventions have many advantages including: long term sustainability due to its cost-effectiveness; preventive in nature and minimizes the need for treatment controls – “prevention is better than cure”; reduced ongoing operation or maintenance liability as compared with structural controls; creation of environmental awareness and; effective use of all resources including the involvement of community. Non-structural control interventions can be categorised into four main often inter-related undertakings namely: community education, Local Authority’s management activities, planning controls and, regulatory and enforcement policy.

2.3.1 Community education to manage water pollution

Stormwater runoff quality problems in urbanized areas are the result of many activities at various locations within the settlement. The impacts from the individual activities may be small but when aggregated over the whole settlement can become a very significant source of pollution to receiving waters. Often, people in developing areas are unaware that their actions and negligence have pronounced impact on stormwater quality. The willingness-to-pay surveys conducted by consultants and NGOs in urban areas of many countries of Africa revealed that many urban households were unaware that their own poorly functioning and overflowing septic tanks often caused health and sanitation problems (UNEP-ITEC, 2005). Once they are aware and have learnt simple solutions to reduce or avoid causing stormwater pollution, changes to their behaviour are more likely.

Community education is therefore an intervention designed to create awareness of stormwater and greywater issues to enhance community’s knowledge and understanding in order to encourage more responsible behaviour and improve their values and attitudes. The diverse background of a community with respect to age, gender, educational level, and other socio-economic factors imply that people will learn differently, hence a variety of techniques should be employed to achieve the desired objective. Such techniques may include:

- Talks, presentations and seminars
- Workshops

- Video and audio recordings and slides
- Courses and training through schools and colleges
- Mass media (radio and television) publicity
- Exhibitions, displays and print materials including brochures, posters, etc.
- Community clean-up days
- Community's *imbizos* (meetings)

It is important to give public education on the health implications of sanitary disposal of wastes and stormwater, and the role that the people are required to play. Broadly, the community would be educated on avoid/prevent, reduce/minimize, reuse, and recycle principles to manage stormwater runoff and greywater issues. These are detailed as below:

2.3.1.1 Avoidance or Prevention measures to manage water pollution

In low-income, high-density settlements the paths for the various waste streams are often merged; sewage, greywater, stormwater, and solid waste enter storm drains, which eventually discharge into receiving waters. This is caused by a general lack of understanding of the need to segregate different types of waste because of their different treatment requirements. There is also general lack knowledge about the destinations of the wastes and their impacts to the receiving environment. Significant improvements to water quality can be realized if communities are educated on the need to segregate various waste streams and use the services appropriately. Non-payment of services also limits the capacity of the Local Authority to effectively maintain services, which then leads to further failure of the services causing more pollution problems. Communities also need to be educated and empowered to initiate and undertake programs like planting (grass and tree) and clean-ups in their settlement. Generally, actions communities need to be educated on in order to prevent pollution include:

- Separate waste streams and appropriate use of available services
- Avoid littering and bush toileting
- Avoid illicit discharge connection into storm drains
- Avoid abuse or vandalism to service infrastructure

- Avoid non-payment of services
- Good house-keeping, planting and clean-up campaigns

In Phagameng, North West province (DWAF, 2001d), interventions focusing on awareness building, clean-ups, grass planting, provision of skips and litter bins resulted in a significantly pollution free environment. Also in Cairn, Mpumalanga province, the same study (DWAF, 2001d) used awareness campaigns to curtail the problem of bush toileting, illicit solid waste dumping, and non-payment of services. Similar interventions undertaken in Alexandra in Gauteng province (Van Veelen and Van Zyl, 1995) using mass media (radio and television), clean-up campaigns, etc. also achieved significant success with minimal costs.

2.3.1.2 Reduction or minimization measures to manage water pollution

Communities can be educated on interventions that aim at reducing the amount of pollutants that can reach the water environment. The role that the people are required to play to reduce pollution include:

- Water saving or conservation schemes (e.g. use of rainwater tanks)
- Impervious cover reduction
- Disconnection of roof-tops from storm drains
- Car washing in pervious areas
- Collection and proper disposal of domestic animals excreta
- Reduction of excessive fertilizer application in gardens, parks and other agricultural practices within and around the settlement

Water saving schemes that reduce the volume of greywater generated should form part community education particularly in settlements with larger water use in order to reduce pollutant loads entering the water environment. A test case study in Kilptown, Gauteng DWAF (2001d), found that one of the main pollution problem was the community often leave taps running unattended causing constant flow of greywater in the streets. Awareness campaign significantly reduced the greywater waste stream in Kliptown. Disconnecting rooftops from storm drains, a practice regulated in some advanced countries, can also reduce stormwater runoff volume and peak rate. Washing car on the street allow soapy water (rich in nutrients from the detergents), dirt, oils and grease to enter water environment. Community should be educated to use minimum amount of detergent to wash cars on the lawn or gravel. Household soapy water should also be directed towards the sink, toilet, lawn or pervious surfaces. A high number of domestic animals (including livestock) in settlements are a matter of concern as their excreta contribute to bacteria and nutrients in stormwater runoff if not properly managed. The total number of these animals in some settlements may out-number the population of human beings. Education on collection and proper disposal of animal excreta cannot be over emphasised.

Education should also focus on back-yard mechanics on the need to properly dispose of oil and grease. The need to grass or replant areas of disturbed soil to reduce erosion and sediment load is critically important especially in high slope areas.

2.3.1.3 Reuse and recycle measures to manage water pollution

Reuse involves using greywater and/or stormwater without any form of prior treatment whereas recycling involves some form of treatment before use. Awareness on options for community to reuse different waste needs to be promoted. Such options include separation of all wastes. Urine can be separately collected and stored for later use as a liquid fertiliser, rich in nitrogen, phosphorus and potassium. Toilet wastes can be composted and used as soil conditioner, rich in organic carbon, nitrogen and phosphorus. Greywater can be treated in constructed wetland or directly be used for sub-surface irrigation of the garden beds.

Stormwater can be reused at household or municipal levels. Households can use stormwater by collecting roof runoff in rainwater tanks for use as drinking water (after boiling), for flushing toilets or for irrigation of their gardens. Water from the roof can be directed to the garden directly or through a soak-away. At municipal level stormwater can be stored in ponds (for sedimentation) for use for irrigation of parks and gardens and for fire-fighting purposes. This is in addition to employing the ponds for flood control and for improving the visual amenity value of the water. Other uses of stormwater include recharge of groundwater, in particular to recharge groundwater to prevent seawater encroachment near the coast (Wright, 1991).

2.3.2 Local government/authority activities

The National Strategy (DWAF, 1999) emphasises the concept of institutional capacity building. This is defined in its broadest sense as including the agency's mandate, legislative instruments, organisational capacity, technical capacity (human resources, problem solving capacity and information systems), financial capacity, procedural capacity (policies, manuals, guidelines, codes of practice), and networking capacity (associations with other stakeholders). The constitution of South Africa indicates that local government has legislative and executive authority over *inter alia*; water and sanitation services, domestic waste water and sewerage disposal, pollution, cleaning, stormwater management, refuse removal and solid waste disposal. This mandate translates to provision of services – i.e. construction, operation and maintenance of services. Hence the degree of planning, management, operation and maintenance activities of local governments in terms of effectiveness and efficiency largely determine the pollution impacts arising from settlements.

2.3.2.1 Planning activities to manage water pollution

The process of influencing settlement planning in managing water quality effects is addressed in the National Strategy (DWAF, 1999). Opportunities exist for local government to plan settlements to influence water quality impacts on receiving waters in terms of settlement development type, positioning relative to sensitive water resources, size and density, service and maintenance levels. Pro-active interventions based on planning of settlements are most effective pollution management and are aimed at the production element of pollution continuum, and should therefore be considered as a first option. Planning should adopt a holistic approach to the four waste streams.

Good practice gives consideration to the following:

- Planning to formalise land-use or development type. Ashton and Bhagwan (2001) described a formal development as one that has been planned with laid out stands (i.e. one house per stand without backyard shacks) and a defined road network. A wastewater disposal system has been installed that consists of either a formal waterborne system, septic tanks and soak-away, or pit latrines. A formal development also has a piped water reticulation system into the house or at least a standpipe per stand. DWAF (2001a) proposes that low-income settlements should not be planned on slopes greater than 1:10. If this is unavoidable, roads should be tarred, and subsidised higher levels of services should be provided. High-density, low-income housing developments should be avoided near water resources with high or intermediate levels of protection, and where this is unavoidable, subsidised higher levels of services should be provided.
- Planning to select appropriate level of service that balances the size, density, and socio-economic status of the community to ensure long-term sustainability. Table 2-2 (DWAF, 2001a) provides appropriate levels of services and management practices required to minimise the pollution effects of dense settlements.
- Planning to educate the community on the appropriate use of services (to avoid abuse and vandalism) as well as other preventive measures.
- Planning of maintenance of services. The impact of pollution can be significantly reduced through better maintenance practices. Maintenance of services like all other preventive measures are ongoing and can be effective and sustainable if well planned.
- Planning of construction projects. In the planning of construction activities, it is important that consideration be given to the impact and potential effects of stormwater quality. Planning should therefore include treatments or operational methods to control erosion, sedimentation and pollution. The effectiveness of erosion and sediment control programs would be limited by construction sites that are not regulated, and by improper design and installation of practices at the site level. Building permits should therefore be regulated and regular inspection at construction sites would enforce compliance to erosion and sediment control programs.

- Settlement layout planning should give consideration to roads and drainage layout; creating space for stormwater runoff treatment facilities; providing visual amenity and landscape value of the stormwater systems; and reducing and/or disconnection of impervious areas. Settlement planning should take into account the natural drainage of the landscape to enable stormwater runoff to flow freely by gravity and minimize flooding. Water reuse as discussed above, should also be carefully planned and sufficient area must be set aside which can take the form of water for agriculture, aquaculture, and tree plantation or for irrigation of public parks and gardens.
- Slum networking (Parikh, 1999), i.e. planning of slums (high-density, low-income settlements) around cities and major urban centres. This concept exploits the linkage between the slums, natural drainage paths that influence the urban infrastructure and the environmental fabric of the city. Unconventional concepts such as topography management, earth regradation and constructive landscaping are applied to build low-cost service trunks, particularly for gravity based systems of sewerage and storm drainage, together with environmental improvements such as creation of fresh water bodies, cleaning up of polluted rivers, development of green pedestrian spines, and restoration of waterfront structures. Slum networking has been successfully applied in Indore, Baroda, Ahmedabad and Mumbai cities in India (Parikh, 1999).
- Preparation of catchment based stormwater management plans. This will provide an opportunity to involve all stakeholders, through structured-facilitated process, to develop an appropriate and coordinated mix of interventions to address specific management issues pertaining to each settlement or catchment as a whole. The concept of structured-facilitated process to manage water quality effects of settlements are well addressed in the National Strategy (DWAF, 1999; DWAF, 2001b,c.)

Table 2-3: Appropriate levels of services and management practices required to minimise the pollution effects of dense settlements (Source: DWAF, 2001a).

Size / Density (plot size)	**Sewage Waste**	**Grey Water**	**Storm Water**	**Litter and Household Waste**
< 5 dwellings / hectare (>2000m^2)	RDP levels of service (as stated in Red Book, 1990) will be sufficient to protect the water resource.		Erosion management is only required on steep slopes (>1:10)	Buried on-site. Waste pits should be covered or fenced.
5-10 dwellings / hectare (2000m^2-800m^2)	VIPs - may be unlined unless geotechnical conditions indicate a risk to the ground water	Soakaways must be installed at water collection points and standpipes	Erosion control measures necessary, irrespective of slopes	Buried on-site. Waste pits should be covered or fenced.
10-30 dwellings / hectare (800m^2-300m^2)	VIPs - may be unlined unless geotechnical conditions indicate a risk to groundwater. Access for desludging and regular desludging important.	Soakaways at water collection points - if in-home water supply, or yard connections - should be connected to on site disposal system.	Rudimentary stormwater systems required – channels may be open and unlined, swales could be considered in less dense areas.	Should be collected and safely disposed off-site. Community based systems preferable (communal pits etc.)
30-50 dwellings / hectare (300m^2-150m^2)	VIPs – should be lined. Access for desludging and regular desludging critical.	Yard connections preferred - should be connected to on site disposal system. If standpipes, formal washing up areas and disposal required.	Formal stormwater systems required. Channels lined with detention ponds. (detention time depends on the sensitivity of the resource)	Should be collected and safely disposed off-site, house to house systems recommended. Steer cleaning required.
50-80 dwellings / hectare (150m^2- 80m^2) Note: Dept Housing is unlikely to approve new plots which are < 150m^2	Preferably joint removal of sewage and grey water with off-site disposal of effluent. Intermediate levels of services for low income areas (i.e. low O&M costs). Demonstrated capacity with respect to the maintenance and operation of high levels of service is required.		Stormwater Management Plans are required which include detention ponds and litter traps.	Should be collected and safely disposed off-site, house to house systems recommended. Steer cleaning required.
> 80 dwellings / hectare (< 80m^2)	Some existing settlements are over 80 dw/ha. Long term planning should aim for providing less dense housing schemes, with more open spaces and adequate services. High-rise dwellings should be considered. At these densities encroachment in the riparian zone is a problem and de-densification should start along the rivers.			

Notes: 1) RDP levels of service are specified as a VIP, and 25L per person per day within 200m of the home.
2) On site refers to disposal on the individual property. Off site refers to disposal off the individual property, and may include condominial systems and communal septic tanks.
3) Levels of services higher than those proposed in the table should only be considered after financial viability (beyond capital requirements) has been proved. Levels of services lower than these may result in pollution problems.

2.3.2.2 Local government management activities

Local government should ensure that the planning activities as outlined above are implemented. In particular, the importance of provision of adequate and appropriate service levels and maintenance cannot be over emphasized.

Good practices of local government/authority management activities include the following:

- Monitoring the performance of stormwater management plans as well as other plans related to the four waste streams through inspections, interviews, reviewing the number and type of complaints, and operational and maintenance processes. This should result in the development of key performance indicators. There is also the need to monitor water quality information to aid decision-making. Good record keeping and the use of computer technology are important to be able to interpret the information. In most developing countries, the absence of or scarcity of information is a barrier to efforts in finding solutions to problems related to pollution management in settlements. Sometimes the available information is not in the right formats and is usually dispersed in piecemeal bits. This inability to acquire the right kind and form of information when it is needed usually leads to insufficient knowledge and inevitably results in poor management.
- The success of managing the water quality effects of settlements is largely contingent on the skills and commitment of staff in the local authority that performs the functions and services within this task. Undertaking internal education and training to technically enhance capacity building is efficient and cost effective to refine and improve local authority's management practices. The content of the training should be commensurate with level of staff and their specific needs. For example, conducting internal education programs can emphasise the relationship between pollution problems and operation and maintenance of services to the maintenance staff. Staff should be trained to routinely check activities and the waste stream systems and their work practices should be audited periodically.

- Effective communication within the local authority and coordination among all stakeholders is equally important to manage water quality effects of settlements. Local authority needs to define procedures: to communicate with stakeholders; for receiving, documenting and replying to communication from interested parties; for appropriate internal communication at all levels including operational staff; and reporting to the local community on management plans. Local authority should also ensure community participation (public involvement) from the planning stage to the implementation and maintenance stage in order to create a sense of ownership to the communities and to foster sustainability of the adopted management interventions.
- It is apparent that managing water quality effects of settlements is reliant upon supporting financial management arrangements for capital as well as operation and maintenance costs. However, lack of financial resources at local government level to implement and maintain even the most basic levels of services requires consideration to encourage cost effective solutions, such as non-structural source control interventions, to obtain better value from local government's overall financial strategy. Local government should endeavour to identify sources of funding such as: Consolidated Municipal Infrastructure Program (CMIP); Home owners subsidies; Pollution levies and catchment levies; Donor funds; Municipal Rates; Private-Public partnerships; and own funding. These funding sources and where these resources could be used to fund interventions are discussed in the National Strategy (DWAF, 1999). Local government should also explore community ability and willingness to pay for services to fund at least, operation and maintenance costs.

2.3.3 Regulatory and enforcement measures to manage water pollution

Many policies, legislation and regulation fit into this intervention including various scenarios discussed in Grobicki (2001) and Ashton & Bhagwan (2001). These may be detailed as follows:

Various scenarios of regulatory and enforcement as interventions to manage water quality effects of settlements are discussed in Grobicki (2001) and Ashton & Bhagwan (2001). These may be summarised as follows:

- Applying the principle of "polluter pays".
- Authorizations and site-specific water licenses as required by the National Water Act.
- Regulating and enforcing prohibition of development in flood plain (application of 50-year flood line).
- Regulating and enforcing prohibition of illicit connections to storm drains
- Regulating and enforcing prohibition of illicit dumping of solid waste, oil and grease.
- Regulating and enforcing disconnection roof gutters from urban drainage system.
- Regulating and enforcing the use of green fuel e.g. unleaded fuels to control vehicle emissions. Recent change from leaded to lead replacement fuel in South Africa is a positive move in a right direction.
- Regulating and enforcing prohibitions of other pollutions such as the use of excessive fertilizers and persistent pesticides.
- Regulating and enforcing the number of livestock kept in urban settlements
- Regulating and enforcing application of step or tier tariffs to water use to control greywater production.

2.4 Structural control interventions.

In the previous section, non-structural control interventions were shown to prevent and reduce pollution resulting from settlements. In bigger and denser settlements, the application of non-structural controls alone may not be adequate to manage the pollution and significant amount of pollutants may still reach the receiving water. This section therefore looks at structural controls, which may then be employed to treat the residual pollution that cannot be cost-effectively controlled by non-structural management strategies.

Many stormwater treatment measures are considered to be structural in that they involve some sort of mechanical devices and earthen or concrete structure. Structural source controls are normally distributed within the catchment at or close to the source of pollution whereas structural end-of-pipe controls are located at the outlet and are of bigger size. These are indicated schematically in Figure 2-1. Structural source controls have many advantages (compared to their counter part end-of-pipe controls), including:

- Greater water quality protections of downstream environment resulting in lower environmental and health impacts within the settlements.
- Smaller size and flows implies lower costs (capital, operation and maintenance) of individual treatment measures, although total system costs can be higher than single end-of-pipe control. Generally they are cost-effective for targeting particular site pollutants and 'hot spots'.
- Comparative lower flows may result in improved treatment efficiency
- Provides visual amenity value of the stormwater systems when they are properly integrated into settlement planning. In both developed and developing areas, some can be designed to fit aesthetically into open space landscaping.
- The probability that all the individual treatment measures will fail at a particular time is remote. Individual treatment measures have lower risk of failure.
- They can easily be retrofitted into existing settlements when space is available or can be created. Hence they lend themselves to staged approach of implementation.

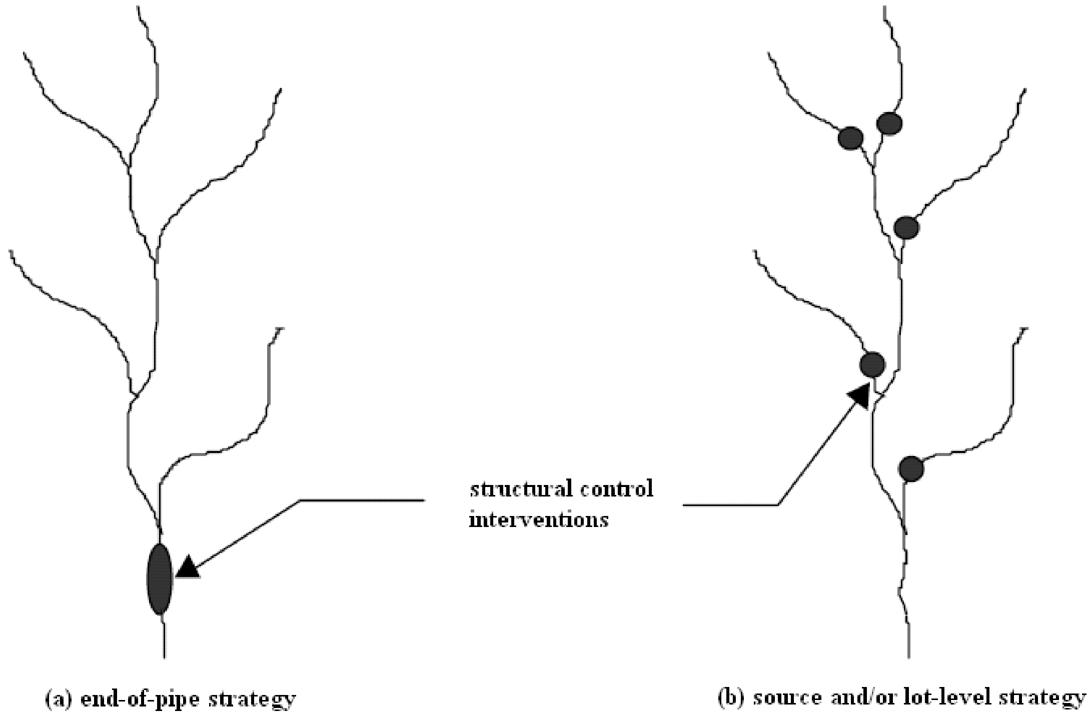

Figure 2-1: Location of stormwater treatment measures

On a finer scale of structural source controls are what is normally termed lot-level controls which represent minor measures implemented at lots to perform hydrologic functions such as: reduced lot grading to slow down runoff flow and enhance infiltration, redirecting roof leader discharges to ponding areas or soakaway pits, reduced imperviousness, functional (bioretention/filtration) landscaping, and open drainage swales. Lot-level controls are better achieved when incorporated into site design. However, some critics have found lot-level to be controversial, as it sometimes conflicts with building codes, challenges conventional stormwater management paradigms and is perceived by some to accommodate urban sprawl. In particular, Strecker (2002) questions the adequacy of the hydrological design procedures utilized to substantiate the effectiveness of lot-level controls.

Structural control interventions often referred to as “treatment BMPs, or treatment practices/measures/technologies” refers to physical structures designed for the purposes of: removing pollutants from stormwater runoff, reducing downstream erosion, providing flood control and promoting groundwater recharge. Fundamentally, they involve some engineering design and construction in contrast with non-structural controls. Some of the technologies (e.g. ponds and constructed wetlands) can be used to control both stormwater quantity and quality. In most instances, one technology predominates but, the trend is to combine the capabilities of two or more options by establishing “treatment trains” of complementary technologies in series to achieve the required stormwater quality and other benefits.

All of the structural control interventions require some sort of control over the flow rate of the water that flows through them. At high flows, options like ponds, wetlands and other vegetated infiltration measures are ineffective as the water is not retained long enough for biological and chemical reactions to take place. In addition, sedimentation and filtration of solids are also effective in quiescent conditions.

2.4.1 Treatment processes

Structural control interventions involve a variety of treatment processes. Water quality treatment can be provided by: 1) trap systems, such as racks, screens, sieves, meshes or similar to provide better separation of solid particles from the liquid phase; 2) settlement of contaminants, 3) filtering of contaminants by the passage of stormwater through a filter media or into the ground, or 4) gravity flotation for oil and litter. There are other treatment mechanisms such as attachment to plant material, biological uptake, bacterial decay, and precipitation. The water quality impacts, the pollutants that cause the impacts, the processes that may be involved in treating the pollutant and the treatment system in which the processes take place are summarized in Table 2-3.

The theoretical background of standard unit operations and processes employed in the treatment of wastewater are the same for stormwater treatment and are available in the literature, however, basic descriptions are provided below:

Table 2-4: Summary of water quality impacts, associated pollutants, and removal processes occurring in treatment technologies

Water quality Impact	Causative Pollutant	Treatment Processes	Possible treatment system
Sedimentation	Suspended solids	• Settle • Filter • Flocculate/settle	1. Pond/river system 2. Filter system 3. Wetlands 4. Swales/buffer strips 5. Chemical treatment
Oxygen depletion	Organic material BOD /COD	• Settle • Filter • Bacterial oxidation • Aeration	1. Pond/river system 2. Filter system 3. Wetlands 4. Swales/buffer strips
Eutrophication	Nitrogen NH_3	• Bacterial oxidation • Aeration • Filtration • Plant/algal uptake	1. Pond/river system 2. Wetlands 3. Filter system
	Organic N	• Settle • Hydrolysis • Filtration	1. Pond/river system 2. Filter system 3. Wetlands 4. Swales/buffer strips
	NO_3	• Plant and algal uptake • Bacterial conversion to N_2 (anaerobic)	1. Pond/river system 2. Swales/buffer strips 3. Wetlands
	NH_3	• Bacterial oxidation • Aeration • Filtration • Plant/algal uptake	1. Pond/river system 2. Wetlands 3. Filter system 4. Swales/buffer strips
	Organic P	• Settle • Filtration • Mineralization to PO_4	1. Pond/river system 2. Filter system 3. Swales/buffer strips 4. Wetlands
Toxicity	Heavy metals	• Precipitation • Settle • Filtration	1. Pond/river system 2. Filter system 3. Wetlands 4. Vegetated infiltration system 5. Chemical treatment systems
	Biocides	• Plant/algal uptake • Filtration • Bacterial oxidation • Settle	1. Pond/river system 2. Filter system 3. Wetlands 4. Swales/buffer strips
	Hydrocarbons	• Plant/algal uptake • Filtration • Bacterial oxidation • Settle	1. Pond/river system 2. Filter system 3. Wetlands 4. Swales/buffer strips
Health aspects	Bacteria, viruses and worms	• Settle • Filtration • Disinfection • Sunlight/UV radiation	1. Pond/river system 2. Filter system 3. Wetlands 4. Chemical treatment systems
Aesthetics	Litter, plastic bags, metal cans	• Filter • Settle	1. Filter systems 2. Pond systems/gross pollutant traps 3. Wetlands

2.4.1.1 Sedimentation

Sedimentation is the removal of suspended particulates from the water column by gravitational settling. The settling of discrete particles is dependent upon the particle velocity, the fluid density, the fluid viscosity, and the particle diameter and shape. Sedimentation can be a major mechanism of pollutant removal in structural control measures such as ponds and wetlands. Sedimentation can remove a variety of pollutants from storm water runoff. Pollutants such as metals, hydrocarbons, nutrients and oxygen demanding substances can become adsorbed or attached to particulate matter, particularly clay soils.

Removal of these particulates by sedimentation can therefore result in the removal of a large portion of these associated pollutants. The main factor governing the efficiency of a structural control intervention at removing suspended matter by sedimentation is the time available for particles to undergo settling. Fine particulates such as clay and silt can require detention times of days or even weeks to settle out of suspension. Therefore, it is important to evaluate the settling characteristics of the particulates in runoff before structural controls design in order to determine the detention time necessary for adequate settling to occur. The overall efficiency of a structural control in removing particulates by settling is also dependent upon the initial concentration of suspended solids in the runoff. In general, runoff with higher initial concentrations of suspended solids will have greater removal efficiency. In addition, some particles, such as fine clays, will not settle out of suspension without the aid of a coagulant. As a result there is usually a minimum practical limit of approximately 10 mg/l of TSS, below which additional TSS removal cannot be expected to occur (UDFCD, 1992).

2.4.1.2 Flotation

Flotation is the separation of particulates with a specific gravity less than that of water. Trash such as paper, styrofoam “peanuts” used for packaging, and other low-density materials can be removed from storm water by the mechanism of flotation. If the inlet area of the structure is designed to allow for the accumulation of floatable materials, then these accumulated materials can periodically be manually removed. Significant amounts of floatable can be removed from storm water in properly designed control measures in this manner. In addition, oils and hydrocarbons will frequently rise to the surface in storm water structural control measures. If the structure is designed with an area for these materials to accumulate, then significant removals of these pollutants can occur. Many modular or drop-in filtration systems incorporate an oil and grease or hydrocarbon trap with a submerged outlet pipe that allows these contaminants to accumulate and to be periodically removed.

2.4.1.3 Filtration

Filtration is the removal of particulates from water by passing the water through a porous media. Media commonly used in storm water structural control measures include soil, sand, gravel, peat, compost, and various combinations such as peat/sand, soil/sand and sand/gravel. Filtration is a complex process dependent on a number of variables. These include the particle shape and size, the size of the voids in the filter media, and the velocity at which the fluid moves through the media. Filtration can be used to remove solids and attached pollutants such as metals and nutrients. Organic filtration media such as peat or leaf compost can also be effective at removing soluble nutrients from urban runoff.

2.4.1.4 Infiltration

Infiltration is the most effective means of controlling storm water runoff since it reduces the volume of runoff that is discharged to receiving waters and the associated water quality and quantity impacts that runoff can cause. Infiltration is also an important mechanism for pollutant control. As runoff infiltrates into the ground, particulates and attached contaminants such as metals and nutrients are removed by filtration, and dissolved constituents can be removed by adsorption. However, infiltration is not appropriate in all areas, for example, where the soil is clayey and/or depth to bedrock is shallow.

2.4.1.5 Adsorption

Adsorption, while not a common mechanism used in stormwater structural control interventions, can occur in infiltration systems where the underlying soils contain appreciable amounts of clay. Dissolved metals that are contained in storm water runoff can be bound to the clay particles as storm water runoff percolates through clay soils in infiltration systems.

2.4.1.6 Biological Uptake

Biological uptake of nutrients is an important mechanism of nutrient control in structural control interventions. Urban runoff typically contains significant concentrations of nutrients. Ponds and wetlands can be useful for removing these nutrients through biological uptake. This occurs as aquatic plants, algae, microorganisms and phytoplankton utilize these nutrients for growth. Periodic harvesting of vegetation in structural controls allows for permanent removal of these nutrients. If plants are not harvested, however, nutrients can be re-released to the water column from plant tissue after the plants die.

2.4.1.7 Biological Conversion

Organic contaminants can be broken down by the action of aquatic microorganisms in storm water structural control interventions. Bacteria present in structural controls can degrade complex and/or toxic organic compounds into less harmful compounds that can reduce the toxicity of runoff to aquatic biota.

2.4.1.8 Degradation

Structural control interventions such as ponds and wetlands can provide the conditions necessary for the degradation of certain organic compounds, including certain pesticides and herbicides. Open pool technologies can provide the necessary conditions for volatilization, hydrolysis and photolysis of a variety of organic compounds to take place.

Pollutants exist in either particulate or soluble forms, but commonly they exist as a mix of both forms. Particulate pollutants, such as sediment and lead, are relatively easy to remove by common treatment processes, including settling and filtering. Soluble pollutant, such as nitrate and phosphate, are much more difficult to remove and settling and filtering processes have little or no effect, and biological mechanisms such as uptake by bacteria, algae, rooted aquatic plants or terrestrial vegetation must be used. Most structural control interventions can achieve an extremely high removal rate for suspended solids and trace metals that exist largely in particulate forms. Much lower removal rates are generally obtained for total phosphorus, oxygen-demanding materials and total nitrogen, since they exist as a mix of particulate and soluble forms (Schueler, 1987)

2.4.2 Typical structural control options

A number of structural alternatives are available for application depending on the characteristics of the upstream catchments and the requirements for water quality enhancement. Regardless of the type, structural control interventions are most effective when implemented as part of a comprehensive storm water management program that includes proper selection, design, construction, inspection and maintenance.

Structural control interventions can be grouped into several general categories. However, the distinction between the technologies types and the terminology used to group them is an area that needs standardization. In particular, the terms “retention” and “detention” are sometimes used interchangeably, although they do have distinct meanings. Storm water detention is usually defined as providing temporary storage of a runoff volume for subsequent release. Examples include detention basins, tanks or pipes, and deep tunnels, as well as temporary detention in parking lots, roof tops, depressed grassy areas, etc. Retention is generally defined as providing storage of storm water runoff without subsequent surface discharge. With the strict interpretation of this definition, retention practices would be limited to those practices that either infiltrate or evaporate runoff, such as infiltration trenches, wells or basins. However, retention is also commonly used to describe practices that retain a runoff volume (and hence have a permanent pool) until it is displaced in part or in total by the runoff event from the next storm. Examples include retention ponds, tanks, tunnels, and wetland basins. In being consistent with these definitions structural control interventions have been grouped and defined as follows:

- ***Infiltration systems*** capture a volume of runoff and infiltrate it into the ground. Environmental benefits in this system include filtration of pollutants through the underlying soil and adsorption of pollutants to the soil particle surfaces. Treatment facilities in this group include infiltration trenches, basins and porous pavements.
- ***Detention systems*** capture a volume of runoff and temporarily retain that volume for subsequent release into natural or artificial watercourses. Detention systems do not retain a significant permanent pool of water between runoff events. The environmental benefits of detention system are limited to sedimentation improving the water quality of flood peaks and the "first flush" effect, and habitat protection of aquatic ecosystems downstream through amelioration of flood peaks. Because detention ponds operating alone are ineffective, it is not appropriate to recommend them as a viable water quality control measure. However, they can be very effective when used in conjunction with other stormwater control practices.
- ***Retention systems*** capture a volume of runoff and retain that volume until it is displaced in part or in total by the next runoff event. Retention systems therefore maintain a significant permanent pool volume of water between runoff events. Environmental benefits of retention systems are much more wide-ranging, through improving water quality as wells as reducing the total volume of surface runoff. Retention ponds, in their similarity to natural and seasonal wetlands, encourage the development of chemical and bio-chemical activity, together with assimilation through established aquatic and bank side vegetation.
- ***Constructed wetland systems*** are similar to retention and detention systems, except that a major portion of the wetland contains vegetation. This group also includes wetland channels and provides filtering, settling, stabilizing, oxygenation and nutrient uptake.
- ***Filtration systems*** use some combination of a granular filtration media such as sand, soil, organic material, carbon or a membrane to remove constituents found in runoff. Examples in this group include sand filters and leaf compost filters.

- ***Vegetated systems*** (biofilters) such as swales and filter strips are designed to convey and treat either shallow flow (swales) or sheet flow (filter strips) runoff. The dense vegetative cover facilitates conventional pollutant removal through detention, filtration by vegetation, sediment deposition, infiltration and adsorption to the soil.
- ***Miscellaneous and vendor-supplied systems*** include a variety of proprietary and miscellaneous systems that do not fit under any of the above categories. These include trapping devices for litter, hydrodynamic devices, and filtration devices. Trapping devices and a number of additional designs were investigated for South African conditions by Armitage and Rooseboom (1998). The study surveyed international experience on litter trapping devices and together with laboratory experimentation; various trapping devices were compared in terms of operating efficiency and cost (installation and maintenance) to make recommendations for the South African context. As a result of this study, seven devices (composed of self-cleaning screens and in-line screens) were identified as showing the greatest promise in South Africa: Side-Entry Catchpit Traps (SECTs), The North Sydney Litter Control Device (LCD), The In-Line Litter Separator (ILLS), The Continuous Deflective Separator (CDS) device, The Stormwater Cleaning Systems (SCS) structure, The Baramy® Gross Pollutant Trap (BGPT) and, The Urban Water Environmental Management (UWEM) concept. A summary page of each device is presented in Appendix A which includes a brief description of the device, its application, patent holder or supplier, costs considerations, head requirements, size, trap efficiency, method of cleaning, potential advantages and disadvantages; and general comments about the device.

2.4.3 Effectiveness of structural control interventions

Rate of pollutant transport is a function of water depth, velocity and the degree of turbulence. Fine and dissolved pollutant may become attached to suspended solids; with the smaller sizes more implicated on account of their greater surface area relative to larger particles, and with improved ease of transport at lower velocities. Storage facilities (detention, retention and wetland systems) associated with urban drainage waterways reduces particle-associated pollutants through velocity reduction and subsequent settling; the efficiency of this accomplishment is a function of detention time. The controlling variables in storage facilities are:

- Inflow concentration. Structural control interventions do not function with a uniform percent removal across a wide range of influent water quality concentrations. For example, a treatment control that demonstrates a good percent removal under heavily polluted influent conditions may demonstrate poor percent removal when low influent concentration exists. For many constituents, there is a minimum concentration necessary to achieve any reduction.
- A design index that describes basin geometry, and
- Up-flow rate – a parameter based on annual runoff volume, storage area and catchment area (Chiew et al., 1997)

For particulate pollutants, inflow concentration and up-flow rate are identified as controlling parameters. If a treatment control relies heavily on particle settling for its effectiveness, the determination of particle-size-distribution of solids in the stormwater and analysis of various fractions of the sediment are necessary for selecting and designing an efficient treatment train system. Also if a treatment control relies on filtration, then it is important to use particle-size-distribution as an evaluation parameter.

The index is more important in the removal of dissolved pollutants. In the case of total phosphorus and total nitrogen, up to 70% removal is found to be achievable in good practice. Crucial to the success, therefore, are accurate estimations of runoff and pollutant load, and Chiew et al., (1997) suggests three different approaches: the Simple Method (Schueler, 1987); analysis of data from a good storm event monitoring program; and an appropriate runoff and water quality model. Methods for pollutant load estimation are extensively dealt with in chapters 4 and 5.

The goal of catchment management is to reduce the pollutant load either through source control (the most effective way to do it) or through multi-stage treatment (treatment trains). Although individual treatment controls may be less effective on percent basis, if they cumulatively still result in lower effluent concentration (or load), they benefit the catchment. Treatment controls should therefore not be designed for percent removal but for pollutant removal to achieve a given effluent level or water quality objective.

Review of structural control interventions effectiveness reveals the need for monitoring of performance over time and how performance are related to design method used (such as control of first flush, extended detention or retention, or peak discharge control), varying influent concentrations, different pollutants, large or small storm events and rainfall intensity. Some inferences adapted from Grobicki (2001) include:

Grass swales: performance is site-related. Minimum flow velocities and land slopes is necessary. Whalen and Callum (1998) report suspended solids removal rates in excess of 80%, but this is dependent on soil characteristics as this level of removal requires high infiltration capacity.

Porous pavements: asphaltic monolithic poured surfaces are known to seal over time with the accumulation of trapped solid material (Schueler et al. 1991) but modular block structures perform well (Pratt, 1990).

Percolation (infiltration) trenches: capable of removing up to 99% of solid particles but are failure prone, with groundwater mounding surfacing within the trench (Schueler *et al.* 1991).

Infiltration basins: capable of removing up to 99% of stormwater particulate matter depending on site conditions. Prone also to failure through sealing and groundwater mound build-up (Schueler *et al.* 1991).

Water quality inlets: evidence indicates poor performance of sand, silt and oil traps. These devices are expensive and appear to offer little water quality enhancement (Urbonas, 1994).

Trapping devices have been shown to have performance levels that vary from low for booms, to high for SEPTs and to very high for CDS devices. More detailed comparisons on the effectiveness of litter trapping devices are given in Armitage *et al.* (1994).

Extended detention basins: performance is governed by basin size, shape, and inlet/outlet geometry, with removal rates varying between 10% and 90%.

Wetlands: perform similarly to detention basins in sediment removal; nutrient uptake performance is thought to be dependent on maintenance measures e.g. crop harvesting.

Significant research has recently been conducted on the design, use and effectiveness of retention and detention pond features as structural control measures. Somes *et al*. (1998) discus the design of retention ponds, noting that because ponds are frequently designed as amenity features as well as having assimilation objectives, undesirable flow hydrodynamic conditions are frequently produced. They investigated a number of hypothetical designs focusing on inlet/outlet configurations and pond shape in terms of hydraulic efficiency to produce guidelines for most appropriate design shapes. Duncan (1998) presents an overview of urban stormwater treatment by detention in on-stream storage (ponds and wetlands), identifying relationships between quality improvement performance and a range of explanatory variables using data from international experience. The study reports that the best performance measure is percentage removal, estimated as output concentration as a percent of input concentration. Basin size measure is in terms of mean annual hydraulic loading rate. In terms of pollutants, suspended solids, nutrients, hydraulic loading and input concentrations are the most important explanatory variables. The study again notes that nutrient removal is poor with hydraulic loading rates greater than 100m/a, even with good design practice.

Lloyd *et al*. (1998) present a description of an investigation of retention basins and wetland systems for reducing sediment bound stormwater pollutants. They found that the removal efficiency of pollutants such as TSS, as well as sediment bound contaminants such as phosphorus is intrinsically related to the sediment characteristics of the sediment inflow into the wetland. These pollutants frequently have an affinity with the finer range of sediment sizes. They conclude that to achieve a high reduction in sediments and thus pollutants, a long retention time is required. Cognizance is also taken of the role wetland vegetation performs in reducing fine sediments, providing improved removal efficiency compared to an equally sized permanent (deep) pool. Of interest is the conclusion that differing sediment characteristics of catchments have important implications for the types of systems selected for pollutant reduction, and the sizing of these facilities. Because of these differing sediment characteristics, the authors call into question the suitability of directly transferring guidelines (e.g. Schueler, 1987) for appropriate sizes of wetlands for effective removal of pollutants such as TSS, TP and metals.

A brief review on the effectiveness of structural control interventions has been provided above but there is certainly no shortage of reference around this subject. For example, Schueler et al., (2007) have compiled an up-to-date pollutant removal rates (efficiencies) for each major group of stormwater treatment interventions by statistically analysing the updated database of the US *"National Pollutant Reduction Database for Stormwater Treatment Practices"* to derive new median and quartile values, that are presented in Table 2-5.

Table 2-5: Range of reported removal rates for major groups of stormwater structural control measures (Source: **Schueler et al., 2007)**

Pollutant	Dry Extended Detention Ponds			Wet Ponds			Stormwater Wetlands			Bioretention Areas		
	25th Quartiles	Median	75th Quartiles	25th Quartiles	Median	75th Quartiles	25th Quartiles	Median	75th Quartiles	25th Quartiles	Median	75th Quartiles
Total Suspended Solids (%)	20	50	70	60	80	90	45	70	85	15	60	75
Total Phosphorus (%)	15	20	25	40	50	75	15	50	75	-75	5	30
Soluble Phosphorus (%)	-10	-5	10	40	65	75	5	25	55	-10	5	50
Total Nitrogen (%)	5	25	30	15	30	40	0	25	55	40	45	55
Organic Carbon (%)	15	25	35	25	45	65	0	20	45	40	55	70
Total Zinc (%)	0	30	60	40	65	70	30	40	70	40	80	95
Total Copper (%)	20	30	40	45	60	75	20	50	65	40	80	95
Bacteria (%)	25	35	50	50	70	95	40	60	85	25	40	70
Hydrocarbons (%)	40	70	80	60	80	90	50	75	90	80	90	95
Chloride (%)	0	0	0	0	0	0	0	0	0	0	0	0
Trash/Debris (%)	65	80	85	75	90	95	75	90	95	80	90	95

Table 2-5: Range of reported removal rates for major groups of stormwater structural control measures (Source: Schueler et al., 2007) cont.

Pollutant	Stormwater Filters			Infiltration Practices			Swales		
	25th Quartiles	Median	75th Quartiles	25th Quartiles	Median	75th Quartiles	25th Quartiles	Median	75th Quartiles
Total Suspended Solids (%)	80	85	90	60	90	95	70	80	90
Total Phosphorus (%)	40	60	65	50	65	95	-15	25	45
Soluble Phosphorus (%)	-10	5	65	55	85	95	-95	-40	25
Total Nitrogen (%)	30	30	50	0	40	65	40	55	75
Organic Carbon (%)	40	55	70	80	90	95	55	70	85
Total Zinc (%)	70	90	90	65	65	85	60	70	80
Total Copper (%)	35	40	70	60	85	90	45	65	80
Bacteria (%)	25	40	70	25	40	70	-65	-25	25
Hydrocarbons (%)	80	85	95	60	90	95	70	80	90
Chloride (%)	0	0	0	0	0	0	0	0	0
Trash/Debris (%)	85	90	95	85	90	95	0	0	50

2.5 Urban stormwater quality management models

Due to the impacts on receiving waters and the expense involved in obtaining monitoring data on non-point source pollution data, interest has grown in compiling and analyzing existing data to develop predictive models for urban stormwater loads and concentrations. Such models aid planners and engineers to make loading estimates for unmonitored catchments. Compilation and analysis of data is a necessary step in the development of predictive models for estimating stormwater runoff loads. These sorts of data compilation and analysis have been done on a coarser scale, especially for the United States (USEPA, 1983; Driver and Tasker, 1990) and on a finer scale for several catchments and sites in them (Owusu and Stephenson, 2006; Coleman, 1990). The quality of urban runoffs is highly variable and site specific. This high range variability makes it difficult to predict impacts and design appropriate treatment measures without site-specific data.

Many methods exist to estimate stormwater runoff concentration and loading of pollutants. The process-based models typically simulate the dry weather accumulation of pollutants on the catchment surface and the subsequent wash off over storms (Heaney et al., 1976, Geiger and Dorsch, 1980; Huber and Dickinson, 1988). The process-based models require substantial data for calibration over the range of expected conditions but can be very effective when data exist and can simulate the most important physical, biological and/or chemical aspects of the problem. The regression equations empirically relate the event loads to the storm and catchment characteristics (Jewell and Adrian, 1981, 1982; Driver and Lystrom, 1986; Driver and Tasker, 1990, Owusu and Stephenson, 2006). This type of model can be used with little or no data but are very rough in their estimates. They are less effective for “what if” analysis, which may extend the situation beyond the limits of data bases, nor are they very accurate in prediction of acute or shock loadings. The relative merit of using regression models compared to process-based models is not clear, i.e., it is not evident whether the process-based models yield results that are worth the effort required to make them operational.

The main problem in modeling storm water pollution loads is the unavailability of event water quality data and the large variability in the pollutant concentration data that are available. Different opinions exist in the literature for explaining the pollutant buildup-wash off mechanisms and this focus on four explanatory variables: rainfall intensity (Sartor and Boyd, 1972; Yaziz et al., 1989), rainfall volume (Pravoshinsky and Gatillo, 1969), runoff rate (Lager et al., 1971; Ichikawa, 1981; Huber and Dickinson, 1988) and runoff volume (Diniz, 1979; Barbe et al., 1996), and two main processes, shear stress generated by flow (Nakamura, 1984; Akan, 1987; Deletic et al., 1997) and the energy input of rainfall (Coleman, 1990).

Extensive monitoring of urban runoff discharges for the purpose of stormwater quality management is in its early stages of development in South Africa. Studies locally undertaken involving the subject are indicated in Section 2.1. Although many loading estimates have been reported for various land uses in South Africa, high variability and inconsistencies exist among reported values. These differences may represent real variations or differences in sampling and analytical methods. In most of these studies also the monitoring point were located at the point of discharge to the watercourse and as result, site-specific causes of contamination of runoff were often overlooked.

In the developed countries, the modelling of stormwater management facilities for both quantity as well as quality control is often accomplished using event and/or continuous simulation analysis methods. Analytical probabilistic models, based on long-term rainfall statistics, have been developed as an alternative approach and have proven to be reliable when compared to continuous simulation models for the estimation of stormwater quantity control performance. As more emphasis has been placed on environmental impacts in the developed countries, and how non-point source pollution, namely urban runoff, can be mitigated, these analytical models have been extended for the prediction of water quality control performance of urban drainage systems as well. Papa *et al.*, 1997 found that, at planning stage of urban drainage systems, the analytical models can be employed with confidence to estimate system performance for pollution control for significantly less cost than their more expensive counterparts. This is especially more useful where the time and funding required to perform full scale simulations may not be available, as is in the case of this study. Analytical models are closed-form mathematical expressions requiring relatively few input parameters and, as a result, performance characteristics are computed. Table 2-4 compares analytical models with continuous simulation models. The advantages of using a continuous simulation model must be weighed against the problems (disadvantages) with such an approach.

Table 2-6: A comparison of analytical and continuous simulation models

	Advantages	Disadvantages
Analytical models	• Requires few input parameters. • Less complexity in setting up and executing the models. • Less knowledge base and skill of the user is not critical • More user-friendly	• Assumption of constant catchment parameters does not reflect reality. • Variability in input parameters cannot be captured. • Between storms pollutant loadings and stormwater treatment measures performance cannot be trapped
Continuous models	• Could capture some variability occurring with input parameters. • Can simulate inter-arrival time between storms and its impacts on trapping performance of stormwater treatment measures.	• More data set requirements. • Good catchment and climatic or hydrologic variables is required since algorithms within models are only as good as their inputs. • More complexity in setting up and executing the models. • More knowledge base and skill of the user is required • May not be user-friendly to an average user community

Wright et al., 1992 reports that, to date, hydrological modelling of South African township urban runoff (using hydrological models) could not be performed satisfactorily. This was because the data required for such an operation could not be collected from townships under the prevailing conditions. With the changing political and social climate in South Africa, such studies may become possible in the future. Even so, great care will still have to be taken in selecting a study area, as underground stormwater systems in low-cost, high-density type settlements provide unique problems with regard to flow gauging.

Hence continuous simulation offers possibilities for design and management that do not currently exist in South African low-cost, high-density settlements. However, widespread adoption of the National Strategy to manage water quality effects in dense settlements depends in part on the models becoming sufficiently user friendly and the input guidelines developed that the user community can execute the models with confidence and competence.

Urban water quality models and modelling are further reviewed in Appendix B to provide guidance for developing areas.

2.5.1 Model by Centre for Watershed Protection (CWP, 2001)

CWP (2001) is an analytical model for assessing various watershed treatment options. The model evaluates loads from a range of pollutant sources including urban runoff loads, dry weather loads, forest loads, farms and livestock loads, open water loads, road sanding loads, and point sources loads. It also includes a suite of watershed treatment options involving stormwater treatment practices and stormwater management programs as shown in Table 2-5.

Table 2-7: Menu of treatment options in CWP (2001)

Stormwater treatment practices	• Stormwater treatment practices for new development • Stormwater retrofits
Stormwater management programs	• Lawn care education • Pet waste education • Active construction erosion and sediment control • Street sweeping • Impervious cover disconnection • Land reclamation • Impervious cover reduction (Better site design) • Riparian buffers • Catch basin clean outs • Combine sewer overflow (CSO) repair/abatement • Sanitary sewer overflow (SSO) repair /abatement • Illicit connection removal • Septic system education • Septic system inspection/repair • Septic system upgrade • Marina pumpout • Point source treatment

Loads are estimated as a product of stormwater (or greywater/wastewater) volume and concentration. The volume of stormwater is estimated using The Simple Method (Schueler, 1987). Annual runoff is estimated as a product of annual rainfall volume, and runoff coefficient (eqn. 2-1); where runoff volume is estimated as:

$$R = P*P_f*R_v \qquad (2\text{-}1)$$

Where:

R = Annual runoff (mm)

P = Annual precipitation (mm)

P_f = Fraction of annual precipitation events that produce runoff (assumed to be 0.9)

R_v = mean runoff coefficient

Based on computed Rv's from 44 sites in the US, Schueler (1987) conducted linear regression analysis using the sites R_v as the dependent variable and watershed imperviousness (I) as the independent variable and obtained a relationship (eqn. 2-2) for estimating mean runoff coefficients. As the regression equation (eqn. 2-2) is empirical in nature, caution is noted in its application. Loads from urban catchments are estimated by CWP (2001) from impervious areas only.

$$R_v = 0.05+0.009(I) \qquad (2\text{-}2)$$

For all treatment options, the CWP (2001) assesses the treatment (i.e., load reduction) achieved by applying the practice efficiency to the treatable load, and then adjusting, or "discounting" the total treatment achieved to reflect the level of implementation throughout the watershed. Pollutants tracked in the model are nitrogen, phosphorus, solids and bacteria. The discount factors are described as: 1) treatability discount – the fraction of drainage area that can be treated the stormwater treatment practice; 2) capture discount – the fraction of annual rainfall captured by the practice; 3) design discount – the factor applied based on the adequacy of existing design standards; 4) maintenance discount – the factor applied based on the adequacy of maintenance conducted on treatment practice; 5) awareness discount – the fraction of people who remember educational messages; and 6) participation discount – the fraction of people who are willing to change their behaviour.

2.5.2 Model by Li et al., (1998)

Li *et al*., (1998) is an analytical probabilistic model for evaluating alternative stormwater management strategies with respect to their achievement of ecosystem and economic objectives. Treatment options in the model are downspout disconnection, stormwater exfiltration systems, and stormwater quantity and quality ponds. Adams et al., (1986) analysed long-term rainfall records across Canada and found that rainfall characteristics such as rainfall event volume *(v)*, duration *(t)*, and inter-event time *(b)* could be described by probability distribution functions (pdf's) which are exponentially distributed. With the exponentially distributed rainfall event volume, the pdf of runoff event volume were derived by Li et al., (1998) using the derived probability distribution theory. The annual runoff volume and pollution load were estimated as given in equations 2-3 and 2-4 respectively.

$$R = 10 * A * \left(\frac{\theta\phi}{\zeta}\right) e^{-\zeta S_d} \qquad (2\text{-}3)$$

$$L = \frac{R * C}{1000} \qquad (2\text{-}4)$$

where:

R = average annual runoff volume in m^3/yr,

A = drainage area in hectares,

θ = average annual number of rainfall events,

ϕ = area-weighted average runoff coefficient,

ζ = reciprocal of average rainfall event volume (1/mm)

S_d = area-weighted average depression storage (mm)

L = average annual runoff solids loading in kg/yr, and

C = average runoff solids concentration (mg/l).

Li *et al*., (1998) used a multi-efficiency model (based on the study by Weatherbe (1995)) to estimate the cumulative volume (N_v) and solids loading (N_s) reduction efficiencies of a series of treatment options as shown in equations 2-5 and 2-6 respectively.

$$N_v = \left[1 - \prod_i^n \left(1-\eta_v\right)\right] * 100\% \quad (2\text{-}5)$$

$$N_s = \left[1 - \prod_i^n \left(1-\eta_v\right)\left(1-\eta_s\right)\right] * 100\% \quad (2\text{-}6)$$

where:

- i = the i^{th} treatment option,
- n = total number of treatment options,
- η_v = runoff volume reduction efficiency of a treatment option, and
- η_s = solids concentration reduction efficiency of a treatment option

Li *et al*., (1998) notes that for a treatment option which reduces solids concentration only, (e.g., oil/grit separators, ponds), η_v is zero. For a treatment option which reduces runoff volume only, (e.g., downspout disconnection, stormwater exfiltration systems), η_s is zero. The latter implies that the model can only track particulate pollutants and not dissolved pollutants.

2.6 Hydrological design basis of structural stormwater control interventions

The design concepts in this sub-section form the basis for the water quality design of structural stormwater control interventions. Hydrologic data evaluated in order to propose or size management intervention include the amount and distribution of (1) rainfall volume; (2) rainfall intensity; (3) runoff volume and; (4) runoff intensity. Runoff volume and intensity are the most important hydrologic variables for water quality protection and design, and they are directly related to capture and treatment of mass load of pollutants. Maximum runoff intensity is the most commonly used hydrologic variable for drainage system and flood analysis in current design practices.

A common goal in all structural treatment interventions is not to effectively treat all catchment runoff but to provide effective treatment up to a certain flow level, with lower or negligible treatment provided for flows above this level. Most recurrent rainfall events are small (less than 25 mm of daily rainfall (USEPA, 2002)). For example, records of rainfall from Johannesburg International Airport (47 years of records), Pretoria University (68 years of records) and Roodepoort (33 years of records indicated that, 90% of the annual rainfall comes in storms smaller than 20 mm/day (see Figures B-1, B-2 and B-3 in Appendix B). Stormwater management professionals have come to realize that these small storms dominate catchment hydrologic parameters typically associated with water quality management issues and therefore the capture and treatment of these small storms will lead to improved water quality since the total pollutant load to receiving streams would be minimized. This new focus has given rise to concepts such as small storm hydrology in design and management of stormwater treatment measures in the United States (USEPA, 2002) and Australia (NSWEPA, 1997). In these countries, the use of small storms (those with return period under six months) approaches dominates design of stormwater treatment measures for pollutant removal. In particular, ASCE & WEF (1993) note that design events for runoff quality control are small frequent events (smaller than the 1 year average recurrence interval runoff event).

Large storms (i.e. storms ranging from 2 to 100 year return period) may contain significant pollutant loads (Chang et al., 1990) but their contribution to the annual average pollutant load is really quite small due to the infrequency of their occurrence. Besides, the infrequency of occurrence of large storms offers longer periods of recovery to receiving waters to flush themselves.

On the basis of this assertion, an approach from the small storm hydrology concept based on the work of Pitt (1994) for small urban catchments is proposed and consists essentially of:

- 90% rule regarding cumulative rainfall volume for water quality treatment. The rule simply reflects the risk decision-makers are prepared to take which will depend on the level of protection required for a particular resource class. For example, the 90% rule implies that 90% of the annual cumulative rainfall volume will be treated, and the rainfall volume corresponding to this 90% can be obtained from rainfall frequency spectrum.

- A method for estimating runoff water quality volume and peak discharge for structural treatment measure design using small storms. The water quality volume is 100% of the runoff volume produced by the 90% rain depth.

These translate to defining or specifying a rainfall volume such as the first 20 mm or other rainfall depth (that correlates to 90% of annual cumulative rainfall volume) or specifying the capture of stormwater runoff volume that corresponds to a design storm such as 3-month, 6-month or 1-year frequency storm. Several models are available to estimate runoff volume and peak rate however, the selection of the appropriate model will depend on the level of detail and rigour required as well as the amount of data available for the use of the model. The recurrence interval is commonly obtained from statistical analysis of rainfall data, since rainfall data is generally more readily available over a longer period.

By using resource directed measures as proposed in the National Strategy (DWAF, 1999), the local authority depending on the level of water resource protection required (or the established water resource class of the receiving water) can accordingly change the proposed 90% rule (e.g. to 70% rule for lower resource class) to optimize the attainment of the resource quality objectives. As mentioned above, the rule represents the risk decision-makers are prepared to take to protect their resource. However, the optimum rainfall depth from any rainfall frequency spectrum diagram occurs at a sharp upward inflection point, i.e., at the asymptote of the curve where it suddenly turns upward (see Figures B-1, B-2 and B-3 in Appendix B). At that point, small increase in the percent rainfall events results in disproportionately very high increase in rainfall depth which will in turn result in very high increase in the size and cost of treatment measure as well.

The above inference is applied in the SCS method to estimate stormwater quality volume and is described in Appendix B.

2.7 Discussion of literature survey

Informal settlements face serious urban water quality problems, the severity of which is related to several factors including population growth rates, living standards, rates of urbanization, level of services, types and densities of housing settlements. Key management issues that require attention in these areas include reduction in concentrations or loads of pollutants of concern such as nutrients, solids, bacteria, oxygen demanding compounds, metals, and litter. A balanced combination of sound stormwater and urban environmental management practices, active participation of affected parties and improved legislation (such as stormwater discharge permits) are identified as a requirements to achieve adequate reduction in pollution levels in discharges from informal settlements.

It was revealed that monitoring programs of urban runoff discharges for the purpose of stormwater quality management is in its early stages of development in South Africa. Loading estimates from existing monitoring studies in South Africa contain high variability and inconsistencies in reported values (Schoeman and MacKay (1995) and Campbel (2001), thus indicating the need for this research to identify optimal monitoring programs to characterise stormwater and greywater and also to define water quality management objectives. Synthesis of literature survey revealed that, appropriate solutions to urban runoff management problems are multi-faceted, reflecting the diversity and complexity of the problems themselves. Solutions proposed include control or reduction of pollution at source, through to interception and treatment of runoff prior to discharge to receiving water bodies. Socio-economic, environmental and technical aspects need to be integrated at the planning level when designing management options. Up to now, solutions are only proposed for developing areas. A way forward is a research like this study to develop a methodology to select potential interventions that are optimum for developing areas.

The models by CWP (2001) and Li *et al*., (1998) were designed for developed areas in the United States and Canada and have some setbacks in their applications in informal settlements in South Africa. These setbacks are discussed below.

The runoff volume estimated by Li *et al*., (1998) is based on derived probability distribution theory of Adams et al. (1986) (Section 2.5.2) which in turn, is based on rainfall records of Canada only. Significant contrast between climatic conditions and level of development in Canada and South Africa suggest that the empirical model of Li *et al*., (1998) is inadequate for use in South Africa's informal settlements. The model only tracks particulate solids which limit its application.

The model by CWP (2001) was considered good for adoption in this study but there was one fundamental setback in the estimate of runoff volume, i.e., the use of empirical regression equation (eqn. 2-2) based on the studies in the US to estimate runoff coefficient. Again, the contrast between climatic conditions and level of development in the US and South Africa suggest that the empirical regression equation (eqn. 2-2) is inadequate for use in South Africa's informal settlements. Again loads from urban catchments are estimated in CWP (2001) from impervious areas only. Studies such as Mackey (1993, 1994a,b), Grobicki (2001), van Ginkel et al. (1993) and Wright et al. (1993) have shown that pervious areas in developing areas contribute substantial loads to the receiving environments. Moreover, the defaults used in CWP (2001) model are based on highly developed catchments in the US.

This research therefore also aimed at improving CWP (2001) by undertaking the following modifications and additions:

- Modify the method to estimate runoff volume,
- Modify defaults and where possible, use data obtained in South Africa as defaults,
- Add implementation strategy to accommodate assessment of different management intervention scenarios,
- Add cost assessment in selecting strategies,
- Add a module to quantify water quality management objectives,
- Add interventions that are more suitable for informal settlements in South Africa,
- Add uncertainty/risk analysis, and
- Increase the number of pollutants tracked by the model.

3 DECISION MODELS TECHNOLOGY

3.1 Description

A decision model can be defined as any quantitative or logical abstraction of reality which is used to assist a body of persons in reaching an informed decision. The model developed must be appropriate to the users and the needs of the decision makers for which it is designed.

Decision models contain (Power, 2004):

a. System variables – that describes the environment,

b. Structural linkages – showing interdependencies among the system variables, and

c. Preferences – regarding the outcome of the decisions.

3.2 Decision support systems

Decision support system (DSS) practice, research and technology continue to evolve. By 1996, Holsapple and Whinton had identified five specialized types of DSS, including text-oriented DSS, database-oriented DSS, spreadsheet-oriented DSS, solver-oriented DSS, and rule-oriented DSS. These last four types of DSS match up with some of Alter's (1980) categories. Arnott and Pervan (2005) traced the evolution of DSS using seven sub-groupings of research and practice: personal DSS, group support systems, negotiation support systems, intelligent DSS, knowledge management-based DSS, executive information systems/business intelligence, and data warehousing. These sub-grouping overlap, but reflect the diverse evolution of prior research. The knowledge management-based DSS match up with Expert systems, a technique in artificial intelligence. In this thesis emphasis is placed on ***knowledge management-based DSS or expert systems***. Expert systems are presented in detail in Section 3.3.1.

A decision support system is defined as a tool which enables the decision makers to manipulate a decision model. In its simplest form the decision support system could be an EXCEL worksheet. The embedded formulae and relationships would form the decision model. It is therefore through the decision support system that the variables can be inspected and altered, the linkages created and deleted, and the preferences set out and evaluated. The methodology for carrying these processes out must be simple to use, versatile and allow for the majority of possible permutations and combinations. At all times the needs of the decision making body and the application of the system must be considered. The decision support system must in addition assist the decision makers in evaluating and interpreting the outcome of the analysis. This is crucial as many incorrect decisions could be made due to a misunderstanding of the variables and interdependencies involved.

3.3 Artificial Intelligence

Artificial Intelligence (AI) is a new and rapidly developing field of science. Many definitions for artificial intelligence exist in the literature. No single definition has achieved general acceptance. A simple definition was proposed by Rich (1983), in which he described the process as, *'How to make computers do things at which, at the moment, people are better at'*. This definition is obviously open to a wide field of interpretation.

A more detailed classification was proposed by Russell and Norvig (2003) and is adopted here, as it is more appropriate to the planning field. *'Artificial Intelligence aims to understand the nature of human intelligence through the construction of computer programs that initiate intelligent behaviour'*. This implies that the computer program arrives at a decision by calling on a wide range of reasoning processes incorporated into the program. Artificial intelligence techniques therefore offer a methodology of solving ill-structured problems, i.e. problems not having a clearly defined algorithmic solution.

Over the past 40 years artificial intelligence has received much attention, this is due to the increase in the speed and memory capabilities of computers, as well as the more readily available and more affordable computer hardware. During this period a wealth of articles, theses and books were published on AI in an attempt to formalize the approach to this relatively new science. Initially AI research concentrated on development of general laws of reasoning and progressed to a more detailed explanation of knowledge representation. Today the field has developed into a series of specialized areas of knowledge.

Russell and Norvig (2003) categorised the areas in which artificial intelligence has been developed as:

i. Problem solving – games requiring the ability to look ahead (chess);
ii. Logical reasoning – mathematical proofs and reductions;
iii. Language – understanding natural language and translating;
iv. Programming – developing automatic programming techniques;
v. Learning – systems that exhibit cognitive behaviour;
vi. Expertise – the use of an expert's knowledge and a data base to reach a solution;
vii. Robotics – repetitive performance of tasks.

The most promising of these areas and the most applicable to water resources is 'Expertise'.

3.3.1 Expert systems

An *expert system*, also known as a *knowledge based system*, is a computer program that contains the knowledge and analytical skills of one or more human experts, related to a specific subject. As an artificial intelligence (AI) technique, it has been applied by many of the more practical researchers, in an attempt to prove that AI is a valid science with practical applications. An Expert System provides professional advice through the gathering, codifying and application of accumulated human knowledge and experience in a specific field of expertise. The system developed has problem solving expertise which is tailored to the specialized problem to be solved.

A basic expert system consists of three sections, namely:

i. Knowledge base;
ii. Inference or Reasoning engine; and
iii. User interface.

The *knowledge base* of expert systems contains both factual and heuristic knowledge. *Factual knowledge* is that knowledge of the task domain that is widely shared, typically found in textbooks or journals, and commonly agreed upon by those knowledgeable in the particular field. *Heuristic knowledge* is the less rigorous, more experiential, more judgmental knowledge of performance. In contrast to factual knowledge, heuristic knowledge is rarely discussed, and is largely individualistic. It is the knowledge of good practice, good judgment, and plausible reasoning in the field. It is the knowledge that underlies the "art of good guessing."

The *problem-solving model* organizes and controls the steps taken to solve the problem. One common but powerful model involves chaining of IF-THEN rules to form a line of reasoning. If the chaining starts from a set of conditions and moves toward some conclusion, the method is called *forward chaining* (i.e. data → rules → conclusion). If the conclusion is known (for example, a goal to be achieved) but the path to that conclusion is not known, then reasoning backwards is called for, and the method is *backward chaining* (i.e. sub goals ← rules ← goals). These problem-solving methods are built into program modules called *inference engines* or *inference procedures* that manipulate and use knowledge in the knowledge base to form a line of reasoning.

User interface is the means of communication with the user, in other word, the code that controls the dialog between the user and the system. The user interface is generally not a part of the expert system technology, and was not given much attention in the past. However, it is now widely accepted that the user interface can make a critical difference in the perceived utility of a system regardless of the system's performance

The relationship between these sections is illustrated in Figure 3-1. A practical expert system is unlikely to follow this form exactly, but could if necessary, be reduced to fit this outline. Some practical applications will most likely contain more than one user interface.

Expert systems cover a wide range of detail or level of complexity. The basic definition of an expert system allows for the incorporation of simple coding programs, which offer advice on data entry, through to diagnostic packages providing professional advice.

Expert systems have been developed in order to address a variety of problems. Some of the more successful in general fields include (Giarratano and Riley, 2005):

DENDRAL	based on data obtained from mass spectrometer, this program determines the molecular structure of an unknown organic compound;
MYCIN	one of the best known, this application will analyze clinical data in order to identify bacterial diseases;
PROSPECTOR	based on geological data the program will give advice on discovering new ore deposits;
HYDRO	aids in the calibration of large watershed models by calculating the initial parameter values based on the catchment characteristics.

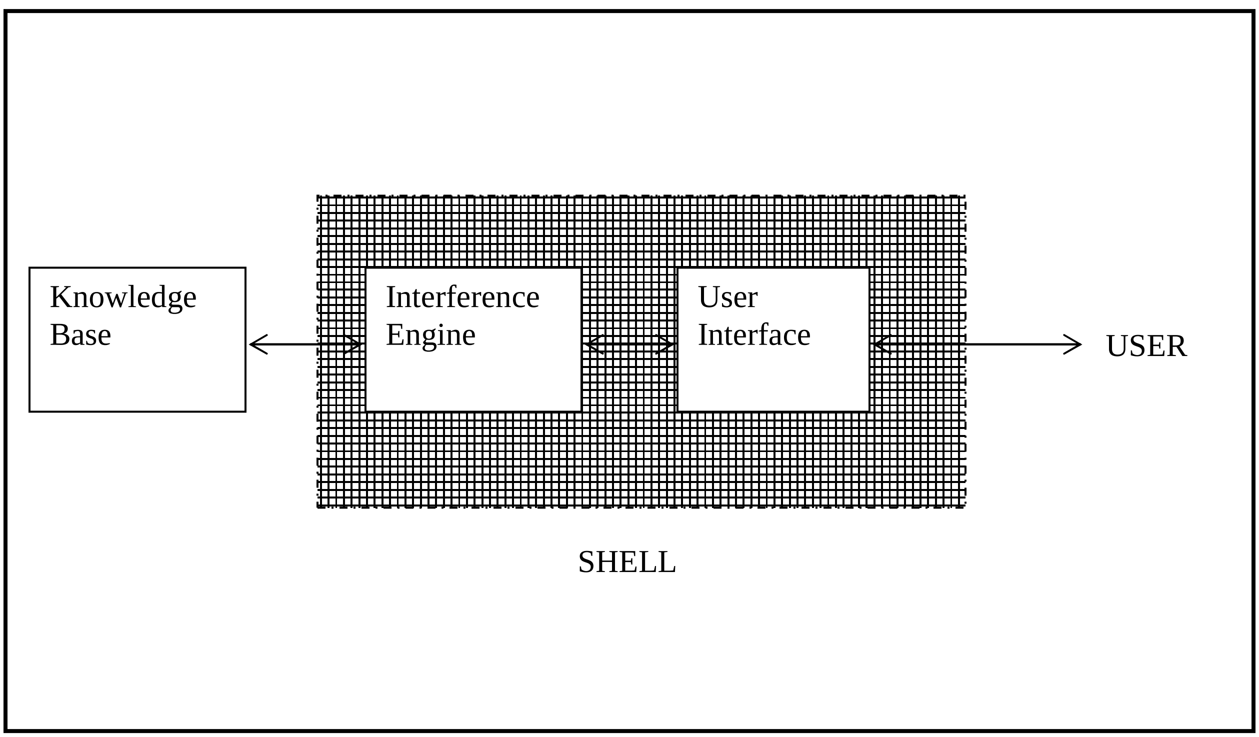

Figure 3-1: Typical Expert System Structure

In practice, Expert Systems have been most commonly used as interfaces between a user and a complex computer application model. This is particularly useful with inexperienced model users, as it provides the user with access to the accumulated knowledge of a collection of experts in a particular field of expertise. The investigation into expert systems has focused on the use of accumulated knowledge rather than formal reasoning processes. This has come about as it is envisaged that with the equivalent knowledge available to the expert system, it will be able to reach the same conclusions as its human counterpart. This empirical knowledge includes heuristic rules, expert opinions, inferences and rules of thumb. The storage of this expert knowledge in a database has an added advantage as the knowledge possesses an intrinsic value, which can be utilized if it is readily available.

A large gap has arisen between the system developers and the users of expert systems. This is due to the concern of model developers with the algorithmic areas of their programs. The expert rules are often poorly documented and not fully developed, in favour of a high level of refinement of the algorithmic section of the model. The knowledge in the expert system can be obtained from many sources, such as reports, case studies, empirical data, factual data bases and field experts. The most important source of knowledge is the field expert, yet this knowledge is the most difficult to extract and code. It is more efficient to observe the expert in a practical problem solving situation and note the methodologies used, than to attempt to extract the knowledge by question and answer methods.

An expert is defined as a person of experience, well versed in the field in question. For stormwater quality management, the expert would be an engineer, a natural scientist (hydrologist, environmentalist), social scientist, economist or an experienced planner, or more appropriately a combination of the five. All relevant expert knowledge, no matter how multi-disciplinary, should be included. An advantage of an expert system is the fact that the decision process can be made visible. The method by which the program reached its decision can be analysed, with the display of the decision path taken. It is therefore possible for the user or decision maker to evaluate the path chosen by the expert system in reaching the suggested solution. The decision maker is able to ascertain whether this was the most appropriate path for the case in question.

3.3.2 Applicability of expert systems to stormwater quality management

Many analytical tools have been developed for the manipulation and analysis of quantitative data. Issues which are not easily quantified, yet represent important aspects of the problem, are generally left unaccounted for due to the lack of appropriate tools for the analysis of qualitative data. This data is in the form of opinions, expert advice, qualitative evaluations, and a ‘feel’ for the nature of the problem. Artificial intelligence and related techniques (expert systems) allow planners to incorporate such qualitative data into a conventionally analytical analysis process.

To date the majority of stormwater quality management planning models have been algorithmic which has led to restrictions in the use of the model. The expert system allows for empirical rules, based on the experience of experts, to be incorporated into the computerized planning or management process. Figure 3-2 shows a typical planning process for stormwater quality management and the position of the expert therein.

It is obvious that the expert is an important factor in the planning/management process. In the developing countries the availability of experts on the required fields (e.g. stormwater quality management) is limited. It is at this point that one of the following three outcomes occurs:

i. The project is put on hold or cancelled,

ii. An external expert (from a developed country) is called in to assist, and

iii. The decision-making is undertaken by less-informed professionals.

All of the above cases may lead to expensive errors and a delay in the implementation of management interventions. Correctly designed expert systems can fulfil the need for experts in the developing areas and lead to timely provision of the correct stormwater quality management interventions.

Of concern about expert system is the fallibility of the expert opinion and/or whether the heuristics data will apply in all situations. The expert may introduce bias or inaccuracy, due to their own deficiencies and/or prejudices. This shortcoming is however, inevitable for even factual data are not free from uncertainties.

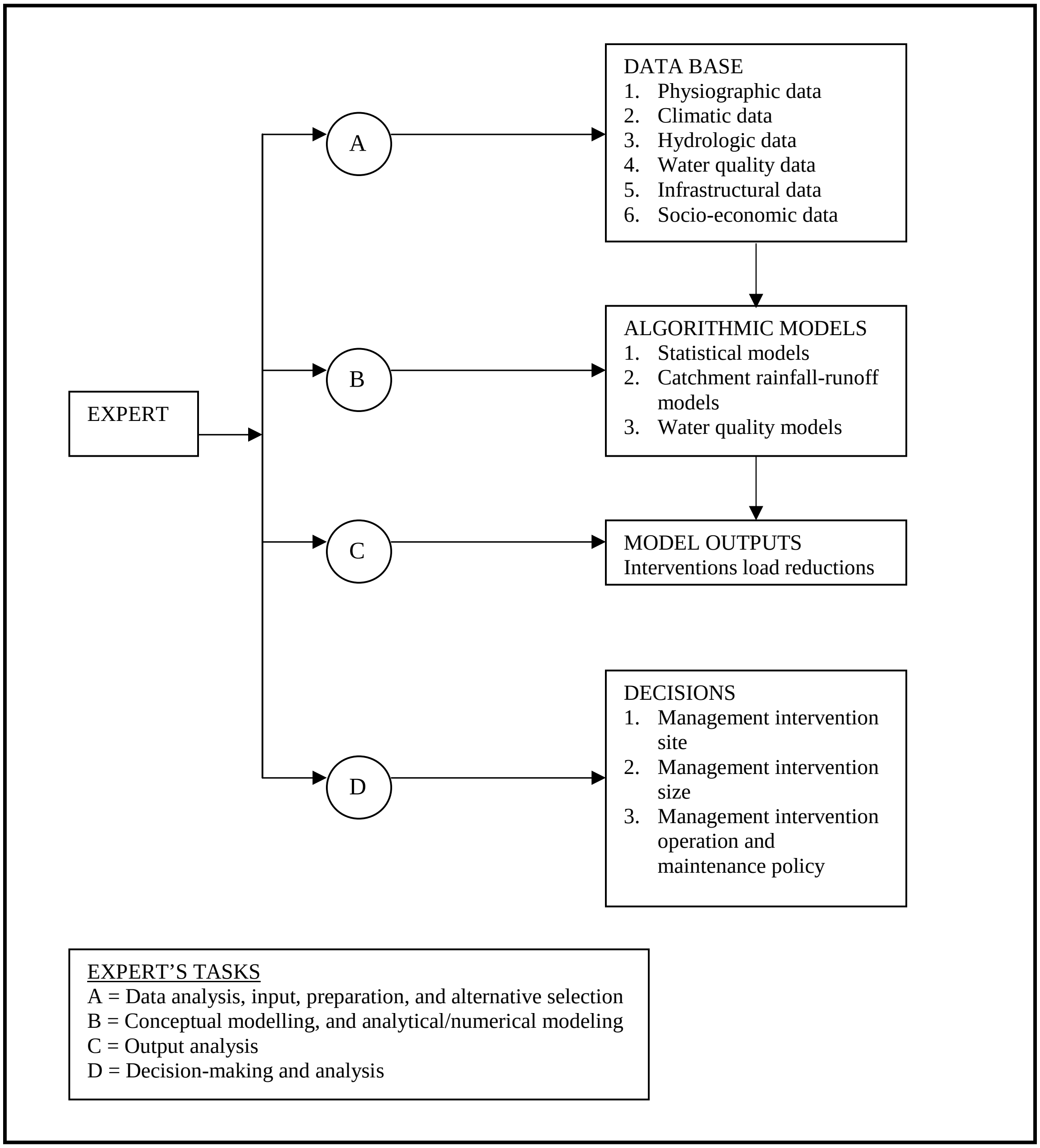

Figure 3-2: The expert in a typical planning process of stormwater quality management systems

3.3.3 Bayesian Networks

Bayesian networks (BNs), have been used routinely for many years in the fields of medicine (Chakraborty *et al*. 2005; Gaevaert 2006), computer science (Kao 2005; Robertson *et al*. 2007), and artificial intelligence (Kalacska *et al*. 2005; Prodanov and Drygajlo 2005). More recently have they been applied to the environmental and water resources fields (Ames 2002; Bromley 2004; Bromley 2006, Henriksen and Barlebo 2008; and Castelletti and Soncini-Sessa 2007).

BNs are used to evaluate the way in which the different variables that make up the system interact. These variables can represent any type of factor deemed to be relevant to the problem in hand; environmental, economic, social and so on. So in this sense they are ideally suited to represent complex water management issues where a whole range of multi-disciplinary variables often need to be taken into account. Furthermore BNs are able to use data sets that are incomplete and to use 'expert opinion' when little or no data is available. Moreover, the uncertainty of the data used in the network is explicitly represented by the way the results are expressed in the form of probability distributions. These characteristics of BNs make them an ideal instrument to help with decision-making in the field of water management, where problems are often complex, involve many different types of factor and where data is frequently scarce and unreliable.

A BN, also called a Bayesian belief network, is a type of decision support system or expert system based on probability theory which implements Bayes' rule of probability. This rule shows mathematically how existing beliefs can be modified with the input of new evidence.

BNs organise the body of knowledge in any given area by mapping out cause-and-effect relationships among key variables and encoding them with numbers that represent the extent to which one variable is likely to affect another (Jensen, 2002). Factors, associations and probabilities can be adjusted and validated and BNs are powerful for integrating data and knowledge from different sources and domains, e.g. domain models and are also capable of handling uncertain information in a practical and understandable way (Jensen, 2002; Henriksen et al., 2004, 2007a, b; Bromley, 2005).

BNs have gained a reputation of being powerful techniques for modelling complex problems involving uncertain knowledge and impacts of causes. BNs are a technique which is especially helpful when there is a scarcity and uncertainty in the data used in making the decision and the factors are interlinked, all of which makes the problem highly complex. The part of the net defined by variables and links is relatively easily communicated to stakeholders (Henriksen et al., 2007b). However the quantitative part, with the conditional probability tables (CPTs), the numbers, is the step where negotiation between parties involved will emerge and become more difficult. Encoding and populating BNs with numbers and CPTs are the most critical part of the construction process but at the same time the most important and powerful feature of BNs, compared to more soft tools for participatory integrated assessment e.g. 'brainstorming', 'multi-criteria techniques', 'consensus conferences' etc. (Hisschemoller et al., 2001). The weaknesses in BNs are:

- Probabilistic interdependencies: There have to be probabilistic interdependencies between all elements involved in the problem and data (or subjective estimate from experts have to be available) to populate the conditional probability tables.
- Computational complexity: Matthayu and Peng (2004) have expressed concerns about the problem of computational complexity of BN inference. They have noted that it may take time exponential to the network size, and thus computationally intractable for multi-criteria decision making problems involving large number of elements.
- Limited value as stand-alone DSSs: The value of BNs as stand-alone Decision Support Systems (DSSs) is limited, since it requires that all components of the problem domain be modelled with BNs, and since this application is definitively unsuitable when the reasonable alternative has to be determined via negotiations (Castelleti and Soncini-Sessa, 2007).

4 MODEL DEVELOPMENT

4.1 Summary

This Chapter presents the steps followed during the course of the research to develop a decision support system for rapid evaluation of stormwater quality management interventions. The literature was reviewed continuously throughout the research period to gather information to serve as the expert's knowledge base in the decision support system. In a study like this, the expert's knowledge base can best be deduced from a wide range of studies rather than on a single case study. Every step was performed keeping in mind the main objectives of the study given in Section 1.3 as:

- Review stormwater runoff quality and treatment practices and the extent of runoff and greywater management in rural and peri-urban areas of South Africa. The review was to also determine the extent of quality control awareness and experience among stormwater management professionals and collate information upon which present and future needs can be assessed and addressed.
- To develop a methodology to identify factors causing water quality management issues in low-cost, high-density settlements.
- To develop a methodology to characterize storm and grey water quality as well as setting ambient water quality and management objectives.
- To develop a methodology to identify and select potential non-structural and structural control interventions to manage storm and grey water quality.
- Based on the above, to develop a decision support system for evaluation of potential interventions for storm and grey water management at planning level.

The second objective was undertaken through desk-top study, field work and stakeholders' consultation to probe into processes that characterise pollution in settlements; into waste streams; and into other major factors that typically cause or contribute to pollution. Studies from South Africa relating to this objective are referenced to support the concepts proposed.

Management of non-point water quality impacts requires a more ambient-focused water quality management program. Literature survey (Schoeman and MacKay (1995) and Campbell (2001) revealed that loading estimates from existing monitoring studies in South Africa contain high variability and inconsistencies in reported values, thus indicating the need to identify optimal monitoring programs to characterise stormwater and greywater and also to define water quality management objectives. The need constitute the third objective, and was undertaken through literature review and discussions with stakeholders.

Development of comprehensive tools for selection and design of drainage management interventions even at planning levels is still at its early stage in South Africa. Hence planners and engineers are not equipped with the necessary knowledge and tools to deal with stormwater quality problems in informal settlements, as mentioned in the problem statement (Section 1.2). For this reason, the forth and fifth objectives of the study were defined: to develop a methodology to select interventions to manage runoff and grey water quality; and to develop a tool to evaluate the selected interventions respectively. The selection process involved identification (i.e. short listing potential interventions that can meet the stated objective given the pollutants of concern). The short-listed interventions were subjected to screening process to select the most efficient and effective intervention(s) based on factors such as site constraints, environmental impacts, and public acceptance. After identification and preliminary selection of suitable interventions, alternative stormwater quality management strategies were formulated by combining various mixes and magnitudes of interventions and a tentative timeframe for their implementation. These strategies were then evaluated to determine: 1) the loads reduced and 2) whether the management objectives are achieved. The computational description of the evaluation methods is presented in Chapter 5.

The summary of the model development process is presented in Figure 4-1 and is described Sections 4.2 to 4.4.

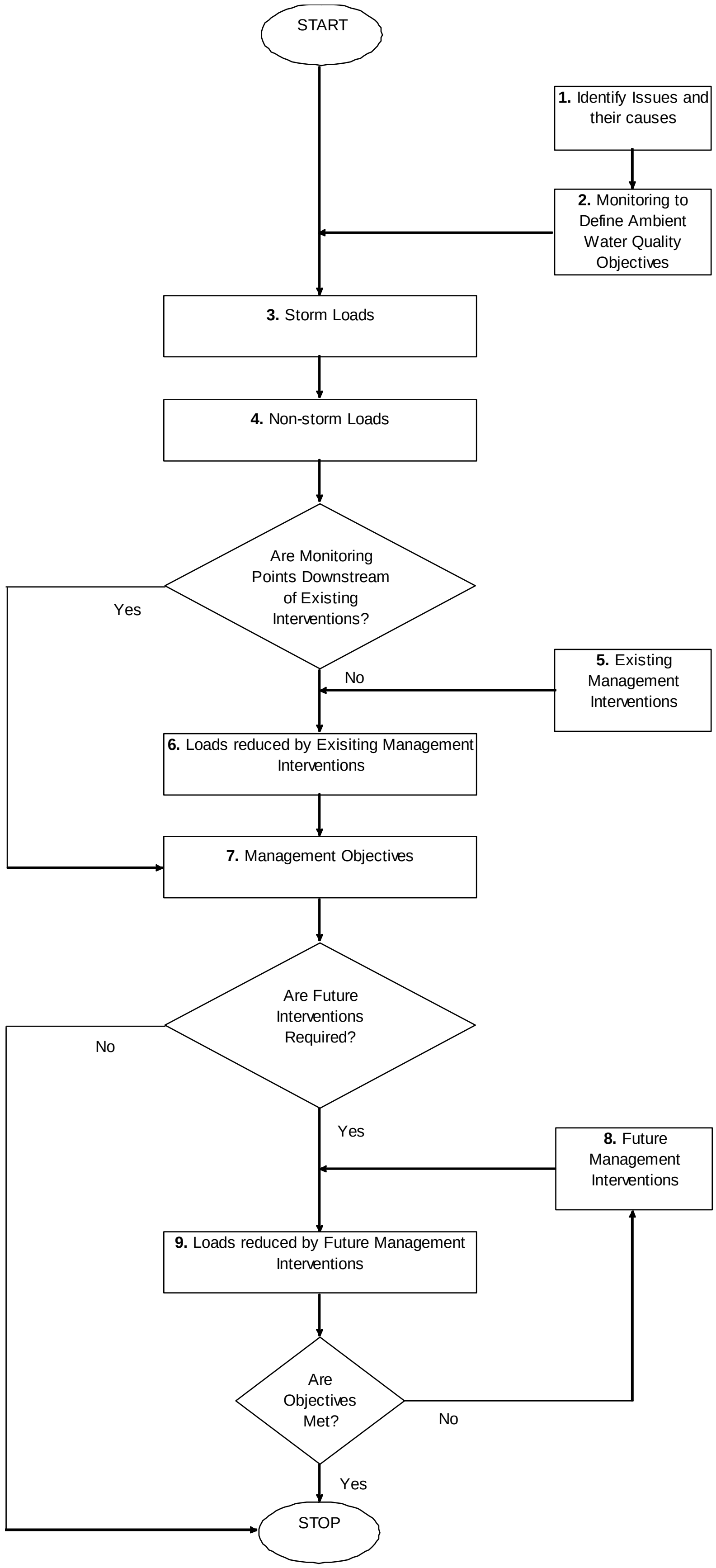

Figure 4-1: Model development process flow chart

4.2 Methods to identify factors causing water quality management issues

The aim of this section is to provide an understanding of the cause and effect relationships of pollution issues from informal settlements, as well as the type and detail of the information required to support the management decision-making process. Hence this section highlights on pollution continuum or pathways (production, delivery, transport and use), waste streams (greywater, stormwater runoff, sewage and solid waste), causes of pollution (physical, institutional and socio-economic), and other factors that exacerbates pollution from settlements. The significance of this section is to ensure that the right intervention is identified; selected and implemented that takes account of the identified problems and their root causes.

The problems and causes were identified through the structured facilitated approach proposed by the National Strategy (DWAF, 2001b). This basically involved the following:

a. A desk-top study to review existing information contained in reports, studies and monitoring programs to serve as expert's knowledge base in the decision support system. This was particularly useful for identifying water quality problems (e.g. nutrients, bacteria, and sediment).

b. Field work involving sampling and inspection of settlement. This was also useful for identifying water quality problems as well as some institutional and social problems and their causes.

c. Consultation involving community, Local Authority staff, and other stakeholders to obtain information on the range of water quality problems and causes.

4.2.1 The pollution continuum

Four important processes characterise impacts of urban pollution on receiving water namely: production, delivery, transport and use. These processes represent a conceptual continuum, which describes the pathway pollutants may follow from the point at which they are generated to the point at which they impact on the use of the water.

4.2.1.1 Production continuum

Production refers to the generation, deposition and build-up of pollutants within the settlement. This includes waste generated: as human excreta, as solid waste (litter), as greywater, as livestock wastes, from cultivated areas, from vehicles and from atmospheric deposition. Management (mainly waste prevention) requires the isolation, reduction, reuse, recycling or removal of pollutants before they are mobilized into a source or non-point source discharge (delivery).

4.2.1.2 Delivery continuum

Delivery refers to the movement of these wastes into the surface or groundwater environment, through surface wash-off, interflow and groundwater flow, with physical, chemical or biological attenuation and assimilation. This includes the breakdown of the sewerage system, stormwater runoff, direct disposal to the rivers, or seepage into the groundwater. Management (mainly waste and impact minimization) requires the interception, detention, treatment or assimilation of pollutants before they reach the surface water environment.

4.2.1.3 Transport continuum

Transport refers to the movement of waste once it has reached the water environment (i.e. rivers, wetlands, aquifers, impoundments, etc.), as well as physical, chemical and biological transformations that may occur in this process. Management requires enhancement of the natural assimilative functioning of the aquatic environment.

4.2.1.4 Use continuum

Use refers to the action of using the water for any purpose, either directly (e.g. recreation) or after abstraction (e.g. irrigation). Management requires reuse and recycle (treatment before use), or by restricting direct use of the water resource.

4.2.2 Waste streams

Wastes from settlements are associated with four waste streams:

4.2.2.1 Sewage waste

Sewage waste result from leaking or overflowing toilets or pit latrines, or broken or blocked sewerage pipes. Pollutants from this waste stream include mainly microbiological contamination, nutrients and organic matter.

4.2.2.2 Greywater or sullage

Greywater consist of water from laundry, bathroom, kitchen, or any combinations of these. Pollution result when dirty washing water thrown into streets is washed into nearby rivers when it rains, or when greywater is thrown directly into rivers. Pollutants from this waste stream include microbiological contamination, nutrients, solid waste or litter, and organic pollutants.

4.2.2.3 Stormwater

Pollution result when runoff washes soil, litter and other waste into the river. Pollutants from this waste stream include microbiological contamination, nutrients, solid waste or litter, sediment, metals and destruction of habitat.

4.2.2.4 Solid waste

Litter dropped in the streets, or household refuse that is thrown into the street or river. Pollutants from this waste stream include microbiological contamination, nutrients, solid waste or litter, sediment, and aesthetic destruction of habitat.

4.2.3 Major factors causing or contributing to pollution in settlements

The identification of the causes of water quality problems associated with the waste streams and the subsequent analysis of the problem using ‘structured facilitated approach’ is one the main theme of National Strategy to manage the water quality effects of settlements. This approach is detailed in “A guide to problem analysis”, which is one of the Water Quality Management Series of the National Strategy (DWAF, 2001b). Guidelines for determining causes and their linkages are also detailed in DWAF (2001b).

Generally, pollution from urban runoff is related to many variables among which are:

Physical causes include 1) population density and growth rates, 2) living standards, 3) rates of urbanization and extent of impervious areas, 4) types and density of housing or developments relative to the level of service, 5) none or inadequate or breakdown of sanitation services 6) encroachment onto, and destruction of riparian zones, 7) climatic and hydrologic factors, 8) topography, 9) geology and soils, 10) geomorphology and others. Management requires local council's planning and management activities and these have been reviewed earlier in Section 2.3.2.

Institutional causes include 1) operation and maintenance of service infrastructure for the various waste streams, 2) lack of capacity of Local Authority or Government to maintain services and 3) lack of or inadequate funding to address the problems. Management requires local council's planning and management activities and these have been reviewed earlier in Section 2.3.2.

Social causes include: 1) culture of non-payment of services, 2) illicit discharge connections 3) vandalism 4) poor hygiene and 5) lack of environmental awareness. Management requires community education and regulatory policies and these have been reviewed earlier in Sections 2.3.1 and 2.3.3 respectively.

Review and synthesis of literature reports on previous studies in South Africa support the relationships of pollution from urban areas with above variables. Generally, low-cost, high-density, informal housing types, poor living standards, and low levels of service and maintenance results in high pollution potential (Wimberley, 1992; Wright et al., 1992; MacKay, 1993; Archibald, 1994a, Grobicki, 2001; and others). Stephenson and Green (1998) and Wimberley and Coleman (1993) have also shown that, in general, the average pollutant load of runoff, expressed in terms of rainfall, varies with urban land-use, population density and the living standard of the population. In all cases, the higher the population density, or the lower the living standard of the community, the greater the resulting pollution load. Domestic animals (and their excreta) and informal trading also add considerably to pollution (Wright et al., 1992). Wimberley (1992); Van Ginkel et al., (1993); and Grobicki (2001) have also shown high pollution from urban areas associated with: low levels of sanitation and solid waste services, vandalism of these services by the communities, and low maintenance levels of these services.

Urbanization has been shown to increase the runoff resulting in higher flows and volumes (Dallas and Day, 1992; Archibald, 1994c; and others), higher erosion rates and larger pollutant loads being transported out of the catchment. Higher runoff volumes increase pollutant loads. Pressures for land particularly in informal low-cost, high-density settlements lead to encroachment onto, and destruction of riparian zone (which offers assimilation and attenuation of pollutants).

Natural factors such as climate and hydrology, topography, geology and soils, geomorphology and others normally define the background pollution levels. Rainfall, surface runoff, interflow and groundwater discharge are the driving hydrological forces causing water quality impacts from a non-point source. Rainfall depth and erosivity affect the mobilization of particulate contaminants, while its variability determines seasonal and "first flush" effects. Regional variations in urban runoff quality as observed in South African studies is summarised in Table 4.1 (Ashton and Bhagwan, 2001).

Table 4-1: Regional variations in urban runoff quality as observed in South African studies

Characteristics	**Rainfall pattern**		
	Summer rain High rainfall intensity	**Winter rain Low rainfall intensity**	**All year rain Low rainfall intensity**
Region	Highveld and KwaZulu Natal	South west Cape	South east Cape
Occurrence of first flush effect	Yes	Yes	Yes
Pollutant concentrations	High for first major wet season runoff, decreasing with time	Low for storm flow; high for low flow; maximum in summer	Low for storm flow; high for low flow; maximum in winter
Loads	High for summer; pollutant build-up on catchment in winter	High for storm flow; low for low flow; maximum in winter	High for storm flow; low for low flow; maximum in summer

The erosivity of rainfall can be described using the EI_{30} value. This is the product of the kinetic energy of a rainfall event and its maximum 30-minute intensity (Smithen and Schulze, 1982). Smithen and Schulze (1982) mapped average EI_{30} for South Africa, identifying nine EI_{30} zones in South Africa as shown in Table 4.2.

Table 4-2: Ratings of land cover erosion potential

LAND COVER CLASS	RATING
Cultivated: permanent – commercial dryland	3
Cultivated: permanent – commercial irrigated	2
Cultivated: temporary – commercial dryland	3
Cultivated: temporary – commercial irrigated	2
Cultivated: temporary – commercial semi-commercial/subsistence dryland	6
Degraded: forest and woodland	7
Degraded: thicket & bushland (etc)	7
Degraded: unimproved grassland	7
Dongas & sheet erosion scars	8
Forest	1
Forest and woodland	2
Forest plantations	3
Herbland	3
Improved grassland	2
Mines and quarries	7
Thicket & bushland (etc)	4
Unimproved grassland	5
Urban / built-up land: commercial	3
Urban / built-up land: industrial / transport	3
Urban / built-up land: residential	3
Urban / built-up land: residential (small holdings: grassland	3

The Department of Water Affairs and Forestry (1986) identified the following three rainfall classes in South Africa:

MAP	**Class**
<400 mm	1 (low)
400 – 800 mm	2 (medium)
>800 mm	3 (high)

Surface runoff washes off and delivers particulate and dissolved contaminants, but can also dilute their concentrations as runoff increases. Regional differences in rainfall intensity, soils and geomorphological characteristics in South Africa give rise to differences in dominant hydrological processes in different urban areas, and exert a great influence on the type of pollutants transported, the pathways by which these pollutants are transported and the magnitude of the loads that are transported. Studies in Cape Town (Wright et al., 1992 and Grobicki, 2001) where soils are sandy with high infiltration rate have shown that the major hydrological process is interflow and groundwater flow and pollution from storm runoff are fairly uniform throughout the year with low phosphate concentrations, due to adsorption during the passage through the sand. Interflow and groundwater discharge deliver dissolved contaminants, which have infiltrated and leached from the land, into the surface water environment. Hence, storm runoff flow, interflow and groundwater flow can all contribute to the pollution load exerted on South African rivers. The weathering of rocks and soils release various mineral salts and trace elements into surface streams and groundwater defining a characteristic chemical signature (MacKay, 1994a; Ashton et al., 1993; and Grobler and Silberbauer, 1985) of the water in the catchment.

Informal agricultural activities and excess fertiliser application in residential areas (as well as parks and gardens) can contribute excess loads of sediments and nutrients such as nitrogen and phosphorus.

In this section, the waste streams associated with water quality problems are identified together with the causes. In many instances, a cause to a particular problem is itself a problem due to another cause. For example, the problem of elevated nutrient may be caused by continuous sewer overflows, which in turn may be caused by low level of maintenance, which in turn may be caused by lack of capacity. There is therefore the need to probe deeper and deeper to uncover the root cause of the problem to ensure that the right intervention is identified; selected and implemented that takes account of the identified problems and their root causes. Table 4-3 presents possible (but not exhaustive) stormwater management problems and their causes.

Table 4-3: Possible stormwater management problems and their causes (adapted from NSWEPA, 1996)

Type	Issue	Possible Cause
Water Quality	Elevated nutrient concentrations	• Overflows from bucket toilets • Domestic animals droppings • Possible atmospheric deposition • Greywater from washings in households • Sewer overflows • Excess fertilizer application in residential areas, lawns and gardens • Washing of cars in streets
	Elevated suspended solids concentrations	• Litter from residential and commercial areas • Erosion from road surfaces and alleys • Erosion from construction sites • Channel erosion
	Elevated bacteria concentration	• Overflows from bucket toilets • Domestic animals droppings • Bush toileting in the reeds • Sewer overflows
	Litter in the environment	• Insufficient number of rubbish bins and skips • Infrequent emptying of bins and skips • Littering in residential, retail and commercial areas
Stream flow	Flooding and inappropriate stream flow regime	• Increased runoff flows due to impervious areas • Increased runoff flows from upstream • Lack of stormwater reuse • Litter in watercourse
Riparian vegetation	Degraded riparian vegetation	• Physical removal of vegetation • Introduction of exotic species • Encroachment of settlements in the flood plain and physical removal of vegetation
	Weed growth in riparian vegetation	• Nutrients from stormwater and greywater • Weed propagates from residential gardens • Removal of canopy vegetation
Social	Lack of integration of stormwater systems and recreational facilities	• No walking paths adjacent to watercourses • No fishing and swimming areas in watercourse due to pollution
	Lack of visual amenity and landscape value of the stormwater	• Litter, bush toileting and direct discharge of greywater in watercourses. • Concrete lined channels • Degraded 'natural' channels

Type	Issue	Possible Cause
	system	
	Lack of public involvement in stormwater management	• Lack of coordination and initiation abilities among community members with regards to stormwater and greywater management. • No catchment management committee • Community's development committee is not effective in drainage and water quality issues.
Managerial	Lack of drainage infrastructure	• Lack of funds from central government • Under spending of budget at municipality level • Lack of skills/capacity to initiate and implement projects
	Lack of funding for stormwater management	• No payment for services and hence cost recovery is a problem • No or insufficient allocation of funds for stormwater management
	Lack of coordination among community, council, DWAF and other stakeholders	• Poor communication between stakeholders • Poor integration of responsibilities across stakeholders
	Lack of effective control over operation and maintenance of basic services in place.	• No checks or monitoring of status of services and responsibilities • No repairs and maintenances • No regulatory policy to the use of stormwater systems and pollution production

4.3 Methods to develop water quality and management objectives

It was noted in Section 2.7 that loading estimates from existing monitoring studies in South Africa contain high variability and inconsistencies in reported values, thus indicating the need to identify optimal monitoring programs to characterise stormwater and greywater and also to define water quality management objectives. It goes without saying that the current water quality situation in informal settlements and the dynamics that affect water quality needs to be known. In this thesis, water quality objectives reflect the water quality criteria/standard/guideline set as ambient targets for a particular catchment, whereas water quality management objectives reflect load reduction targets set for management interventions to achieve. The development of water quality objectives is therefore a crucial step in the development of management objectives. The methods were developed as part of a co-operative and consultative process in order to ensure that they are realistic and what the communities and other stakeholders as a whole desire. The process followed in developing the methods is described in Figure 4-2.

Natural water bodies are able to serve many uses, including the transport and assimilation of waterborne wastes. But as natural water bodies assimilate these wastes, their quality changes. If the quality drops to the extent that other beneficial uses are adversely affected, the assimilative capacities of those water bodies have been exceeded with respect to those affected uses. Water quality management interventions are actions taken to ensure that the total pollutant loads discharged into receiving water bodies do not exceed the ability of those water bodies to assimilate those loads while maintaining the levels of quality specified by water quality objectives set for those waters.

Pollutant discharges originate from point and non-point sources. A common approach to controlling point source discharges, such as those from stormwater outfalls, municipal wastewater treatment plants or industries, is to impose standards specifying maximum allowable pollutant loads or concentrations in their effluents. This is often done in ways that are not economically efficient or even environmentally effective. Effluent standards typically do not take into account the particular assimilative capacities of the receiving water body (Loucks and Van Beek, 2005).

Non-point sources such as agricultural runoff or atmospheric deposition are less easily controlled, and hence it is difficult to apply effluent standards to non-point source pollutants, and their loadings can be much more significant than point source loadings. Management of non-point water quality impacts requires a more ambient-focused water quality management program.

The goal of an ambient water quality management program is to establish appropriate standards for water quality in water bodies receiving pollutant loads, and then to ensure that these standards are met. Realistic standard-setting takes into account the basin's hydrological, ecological and land use conditions, the potential uses of the receiving water body, and the institutional capacity to set and enforce water quality standards. For the purpose of this study, the standards for ambient water quality management will hence forth be referred to as *water quality objectives*.

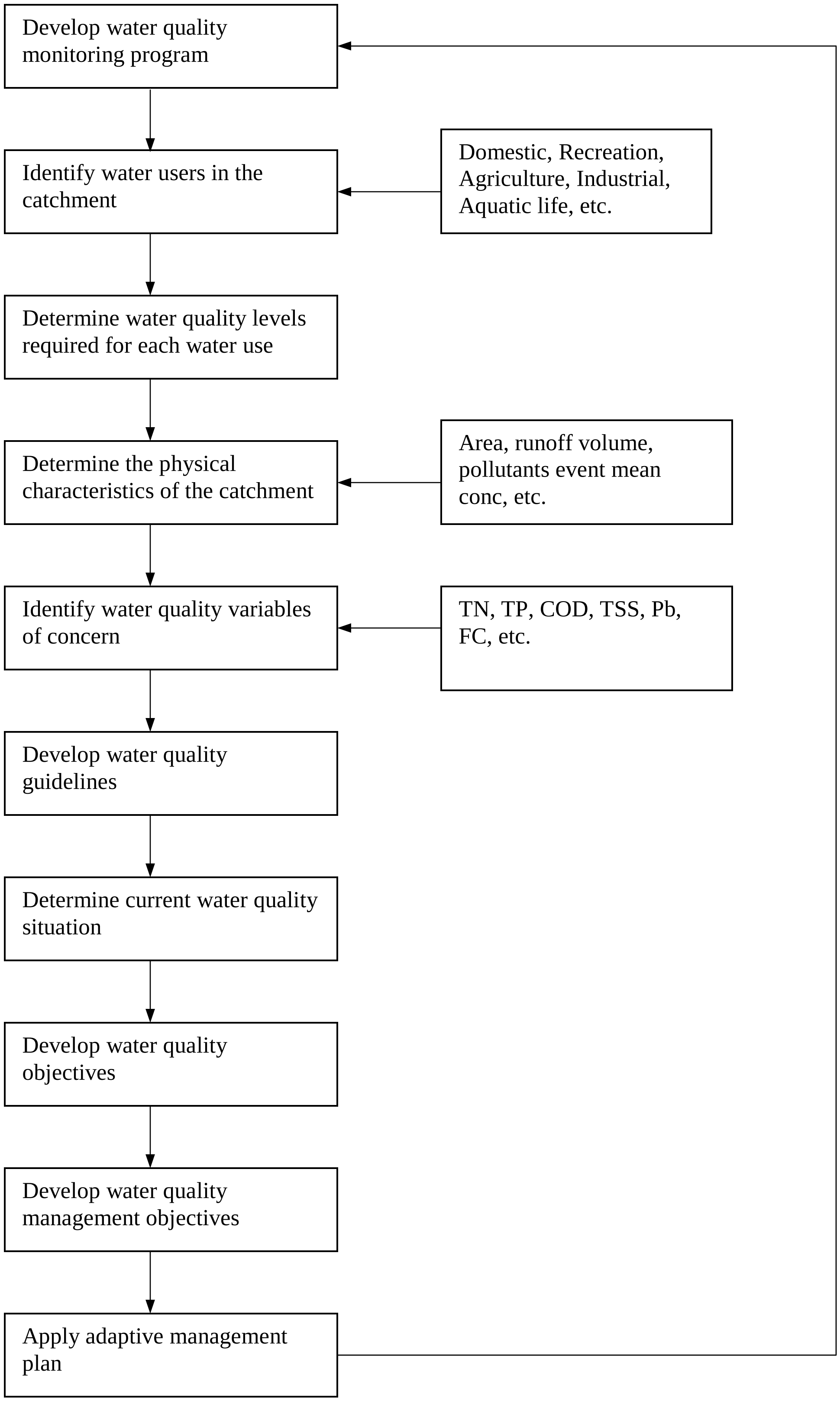

Figure 4-2: Flow chart for developing the water quality management objectives

4.3.1 Developing a water quality monitoring program.

Monitoring is the process of observing what is happening. Managers of water resources systems need to know what is taking place in their systems in terms of water quality, both over time and over space. This usually requires water quality sampling according to pre-arranged schedules and designs. Monitoring the impacts of pollution on receiving water bodies provides a way of assessing how well the water quality meets expectations. Monitoring also provides information on the state of water quality so that management action can be taken in response to that information with the aim of improving the water quality.

4.3.2 Identifying water users in the catchment

Identifying the intended uses of a water body (whether a lake, a section of a stream or an estuary) is a first step in setting water quality objectives for that body. The most restrictive of the specific desired uses of a water body is termed a *designated use*. Barriers to achieving the designated use are the presence of pollutants, or hydrological and geomorphic changes that affect the water quality.

For inland water use, five main users (designated use) are commonly recognised by the Department of Water Affairs and Forestry (DWAF, 1993a-d). These users are:

- Domestic
- Recreational
- Industrial
- Agricultural
- Natural environment

The designated use dictates the appropriate type of water quality objective. For example, a designated use of human recreation should protect humans from exposure to microbial pathogens while swimming, wading or boating. Other uses include those designed to protect humans and wildlife from consuming harmful substances in water, in fish and in shellfish. Aquatic-life uses include the protection and propagation of fish, shellfish and wildlife resources.

Water quality objectives set upstream may affect the uses of water downstream. For example, small headwater streams may have aesthetic value but may not be able to support extensive recreational uses. However, their condition may affect the ability of a downstream area to achieve a particular designated use such as 'fishable' or 'swimmable'. In this case, the designated use for the smaller upstream water body may be defined in terms of achieving the designated use of the larger downstream water body.

In many areas, human activities have altered the landscape and aquatic ecosystems to the point where they cannot be restored to their pre-disturbance condition. For example, someone's desire to establish a trout fish-farm in downtown Johannesburg or Pretoria may not be attainable because of the development history of these areas or the altered hydrological regimes of the rivers flowing through them. Similarly, someone might wish to designate an area near the outfall of a sewage treatment plant for shellfish harvesting, but health considerations would preclude any such use. Ambient water quality objectives must be realistic. Designating the appropriate use for a water body is a policy decision that can be informed by the use of water quality prediction models. However, the final objective selection should reflect a social consensus made while bearing in mind the current condition of the catchment, its pre-disturbance condition, the advantages derived from a certain designated use, and the costs of achieving that use.

4.3.3 Determining water quality levels required for each water user or designated use

Most users of water depend on adequate levels of water quality. When these levels are not met, these water users must either pay an additional cost for water treatment or incur at least increased risks of damage or loss. It is therefore important to determine the various water quality levels (acceptable and unacceptable) required for each user against which water quality guidelines can be developed. Nationally and internationally recognised list of water quality guidelines can often be used as the starting point for determining water quality levels required for each designated use. Risk assessment can also be used to set water quality levels on the basis of their physico-chemical and biological properties and toxicity. Although still to be developed, good water quality level determinations will include hazard identification, dose-effect relationships and risk characterization (both qualitative and quantitative).

4.3.4 Determining and describing physical characteristics of the catchment

The collection of existing data describing the characteristics of a catchment and its drainage courses is useful for a number of purposes, including:

- describing the existing conditions within the catchment
- enabling the values (e.g. aquatic and terrestrial fauna and flora, public health and safety, recreational use of water bodies, visual amenity of stormwater systems, water use, etc.) of the catchment to be determined, from which management objectives can be derived
- assisting with catchment audits, by prioritizing areas for investigation
- identifying constraints and opportunities for improved stormwater management practices, both structural and non-structural.

The data collected should be related to one of these purposes, to avoid collecting unnecessary data. For many catchments, a proportion of the potential data need noted below may not be readily available or cannot be quantified. It is difficult to provide a 'priority list' for identifying these characteristics, as their importance will vary between catchments. Items that may have a lower importance are italicised.

4.3.4.1 Physical characteristics:

- Soils, *including permeability, erodability and dispersivity*
- *Bedrock geology, including geochemical characteristics*
- Topography, including slope characteristics
- Climate, including rainfall, evaporation *and temperature distributions*
- Point sources of pollution (e.g. sewage treatment plants)
- Major sewer overflows

- Existing structural stormwater management practices (e.g. retarding basins, constructed wetlands).

4.3.4.2 Social characteristics:

- Regulating tools (e.g. Water Acts, Environmental Acts, Local Government Acts, legislations)
- *Population characteristics, including demographics and language characteristics*
- Recreational areas, including water related (e.g. riverside parks) and water based (e.g. swimming, boating, fishing) activities
- land use zoning
- Land use (e.g. commercial, residential, industrial, recreation) *and land ownership categories (e.g. private, local government, State Government).*
- Revenue from stormwater levy

4.3.4.3 Drainage course characteristics:

- Physical characteristics of the stormwater 'transport' system (e.g. piped, lined or natural channels)
- Physical characteristics of receiving water bodies (e.g. lakes, reservoirs, wetlands and estuaries)
- Fluvial geomorphology processes for natural (or modified natural) stormwater systems and receiving waters, *including erosion and sedimentation patterns*
- Surface hydrology, including flooding *and base flow characteristics*
- *Groundwater characteristics*
- Water quality in stormwater 'transport' systems and receiving water bodies, under wet and dry weather conditions (can be obtained from Section 4.3.1).
- *Costs, depreciation and upgrading costs (needed in formulation of subsequent stormwater management interventions strategies).*

4.3.4.4 Ecological characteristics:

- Aquatic fauna and flora characteristics (this applied to both the stormwater 'transport' system and receiving water bodies)

- Riparian zone fauna and flora characteristics
- Areas of urban bush land.

Using the available data, a description of existing catchment conditions can be undertaken. These conditions can include:

- topography, land use, soils
- hydrology (e.g. flooding and low flow characteristics)
- water quality (e.g. wet and dry weather, receiving water quality, major pollution sources). This will naturally come from Section 4.3.1
- watercourse and water body physical characteristics, and fluvial geomorphology (e.g. channel erosion, sediment transport)
- aquatic habitat characteristics
- riparian and foreshore vegetation.
- aquatic ecosystems

A comprehensive assessment of these characteristics could be an extensive exercise. Lack of detailed knowledge on these characteristics should not prevent the development of water quality management objectives.

4.3.5 Identifying water quality variables of concern

Efficient and effective drainage management in urban catchments from a water quality perspective as well as development of water quality objectives requires information about the water quality concerns of stormwater runoff and greywater as well as their characteristics. Providing this information is the role of pollution source and water quality impacts assessment through water quality monitoring programs, but this, in turn, implies an understanding of the cause and effect relationships between pollution source and water quality concerns, as well as the type and detail of the information required to support the management decision-making process.

The aim of this section is to identify water quality concerns and their characteristics based on previous studies in South Africa. Naturally, water quality concerns should be derived from the results of water quality monitoring programs (as discussed in section 4.3.1), if it has been undertaken.

Water quality is the term used to describe how well the physical, chemical and biological characteristics of water match the requirements for acceptable functioning of the aquatic environment and human uses, i.e. its fitness for use. Good water quality is acceptable for all uses, while water of poor quality has an adverse impact on the health of the aquatic environment or is not suitable for one or more users. A water quality concern is related to existing, threatened or perceived poor quality (Pegram and Gorgens, 2001). Assessment of the fitness for use of a water resource is not the subject of this study, and is dealt with extensively in the DWAF Water Quality Guidelines (DWAF, 1997).

Increased runoff volumes and velocities resulting from urbanization give rise to a wide variety of water quality problems that are linked to flooding and wash-off. The typical categories of problems that arise are: sedimentation, erosion (channel widening and streambed alteration) and habitat changes, as well as loss of aquatic or riparian habitats. The specific impacts that occur are the result of sediment transported from new developments and construction areas, toxic chemicals from automobiles and industry, nutrients and pesticides from gardening, heavy metals from industrial sites and bacteria and viruses from failing or inadequate sewage systems. Pollutant concentrations vary considerably during the course of a storm event and from one storm event to another at different sites in urban areas.

A number of water quality concerns associated with dense settlements include nutrients, sediments, pathogens, litter, organic matter, heavy metals, toxic organics, hydrocarbons, physical properties (e.g. pH, EC, etc), and in-stream and riparian habitat. Synthesis of literature reports on previous water quality monitoring work done in low-costs high-density settlements in South Africa reveals that the most important water quality concerns are microbiological pollutants, nutrients, suspended solids, and organic matter (Wimberley, 1992; Wright et. al., 1992, Van Veelen and DWAF, 1994a). Litter is the most visible and widespread symptom of pollution (Van der Merwe, 1993/4; Armitage et al., 1998; Marais and Armitage, 2003). Low-cost, high-density settlements usually produce low trace metal pollutant loads in contrast with high-cost, low-density type settlements (Kloppers, 1989; Wright et al., 1992) reflecting the lower income of residents and resultant decrease in traffic volumes; and also the fact that some the roads in these settlements are not surfaced to allow easy mobilization and delivery of the metals to the receiving waters. An overview of these most important water quality concerns is presented below:

4.3.5.1 Nutrients

Phosphorus and nitrogen are the main nutrients required for the normal growth and reproduction of plants. The inorganic forms of nitrogen and phosphorus are usually of concerned as they are responsible for eutrophication in streams and increased costs of treating water to potable standards. The nutrients mostly come from human and animal excreta and greywater as a result of failing or inadequate sanitation. The largest source of nutrients is the particulate and dissolved nutrients contained in the runoff. Phosphorus tends to be the limiting nutrient in South African fresh water system, the presence of which can contribute to excessive algal blooms.

4.3.5.2 Sediments (Suspended solids and Turbidity)

The sediments or solids may be organic or inorganic nature that is eroded and washed off the land surface from unpaved areas in the settlements by storms. It is the most widespread pollutant of surface water and has a negative effect on most water users. Increased turbidity and sedimentation affects the functioning and productivity of the aquatic environment, by decreasing light penetration for aquatic plants, and smothering aquatic habitat. Sedimentation of streams and impoundments decreases storage capacity, reduces recreational opportunities and can increase flooding. Many pathogens, nutrients, heavy metals and toxic substances are transported through the environment adsorbed on sediments. Sediment erosion occurs from all land uses, including natural vegetation, and is related to climate, soil and topographic conditions. However, increased erosion occurs where the vegetation cover is disturbed, such as agricultural crop and grazing lands, and construction sites in urban areas.

4.3.5.3 Microbiological pollutants - Pathogens

Microbiological contamination by pathogens has severe health implications for water users and the community. These mostly come from human excreta resulting from failing or inadequate sanitation services, animal excreta and greywater. Several diseases like cholera, dysentery, typhoid and gastro-enteritis are transmitted in the excreta of humans and animals. Pathogens such as faecal coliform and E.coli, are usually indicator organisms. The die-off rate for pathogens may vary from less than a day to a couple of weeks. Higher temperatures, solar radiation, nutrient deficiency, pH and predation increase bacteria die-off rates.

4.3.5.4 Litter and solid waste

Litter and solid waste impair the functioning of the aquatic environment and degrade the aesthetic quality of surface waters. It can pose serious health problems for recreational and domestic users of the water resource. It normally comes from poorly serviced commercial and residential areas and can also contribute to other water quality contaminants such as pathogens, nutrients and metals. Apart from its pollution impacts, blockages due litter and solid waste can cause failure of services such sanitation and stormwater infrastructure.

4.3.5.5 Organic pollutants

Organic pollutants are non-conservative in that they undergo some form of chemical or biological change. The major effect that organic pollutants have on the aquatic system is the depletion of the store of dissolved oxygen in the water due to numerous oxidation reactions taking place by means of various bacteria in the water. Organic pollutants include pesticides, oils, household use of organic products, debris from vegetation, etc. Organic pollution is quantified by Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD).

4.3.5.6 Habitat destruction - Riparian and in-stream

Habitat destruction mostly by building in the riparian zone affects the natural functioning of river ecosystems and allows waste to get into the rivers. Degradation of riparian and in-stream habitat exacerbates other water quality problems by reducing the attenuation and assimilation of contaminants during delivery and transport.

Monitoring water quality in the catchment through appropriate water quality indicators (physical, chemical, biological or ecological) or reviewing data where monitoring has been conducted will identify water quality concerns and characteristics. This provides an objective indication of the level of severity of water quality problems, which may be compared with receiving water desired resource state and/or fitness-for-use.

Water quality concerns, where water quality monitoring information are not available, can also be inferred from screening for symptoms (effects) of water quality problems associated with the receiving water environment, which is based on field surveys and data. This may include impacts on human health (from clinical data) associated with the use surface or ground water resources, degradation of the ecological health or aesthetic quality of the environment, eutrophication of downstream impoundments or slow flowing river reaches or siltation of river reaches and sedimentation of impoundments.

4.3.6 Developing water quality guidelines

Water quality guidelines for different user groups are not the same. Differences imply that water which would be ideally fit for use for one specific group may not ideally suit the other. In deciding whether or not water is fit for use, it necessary to establish whether the presence, or introduction of any material into the resource, would interfere with the water's intended use. It is consequently important to have a yardstick to measure the effect of changes in water quality on a specific water use. Water quality guidelines or criteria serve this purpose. They represent attempts to quantify water quality in terms of its physical, chemical, biological and aesthetic characteristics. Since guidelines or criteria are usually derived from data obtained from experimental or in-situ observations, they provide a scientific basis for the evaluation and assessment of water quality.

Setting water quality objectives requires an assessment of what constitutes "acceptable" and "unacceptable" water quality. Water quality guidelines, expressed as a range of values, where each range is associated with a description of the fitness for use, and where the total range extends from the most ideal to the point of unacceptableness, are best suited to supply the required information. In addition, guidelines also provide the necessary information for water users and other interested or affected parties to assess water quality in general, as well as to evaluate the acceptability of development on water quality.

Water quality guidelines are used to:

- Serve as the scientific basis for the development of water quality management objectives;
- Interpret data obtained from water quality monitoring programs;
- Assess the effect of human activities on water quality;
- Assess the effect of accidental spills; and
- Assess and evaluate water quality management performance

A water quality guideline can therefore be defined as *a set of criteria put together in such a way that they describe an increasing effect on the user the further the water quality deviates from the level at which there is no noticeable effect*. A guideline consists of a range of values, for each of which a qualitative or quantitative effect on a user (domestic, recreational, industrial, agricultural and natural environmental) can be described.

The connections among water bodies and segments must be considered when determining water quality criteria. For example, where a segment of a water body is designated as a mixing zone for a pollutant discharge, the criterion adopted should assure that the mixing zone use will not adversely affect the surrounding water body uses. Similarly, the desired condition of a small headwater stream may need to be specified in relation to other water bodies downstream; thus, an ambient nutrient criterion may be set in a small headwater stream to ensure a designated use in a downstream estuary, even if there are no local adverse impacts resulting from the nutrients in the small headwater stream. Conversely, a high fecal coliform criterion may be permitted upstream of a recreational area if the fecal load dissipates before the flow reaches that area.

4.3.7 Determining current water quality situation

Determining current water quality situation involve appraising water quality in the catchment by comparing current monitored water quality information with the water quality guideline developed for the catchment with regards to fitness for use, meeting standards and evaluating management performance. This appraisal will provide information on the status of water quality, detect changes and trends, and provide a basis to formulate or modify management objectives and strategies

4.3.8 Developing ambient water quality objectives

Ambient water quality objective should not be set as a single value, as this could lead to an on/off situation in which it will be difficult to measure success or to make decisions. The objectives should rather be a description of the general condition of the water body that has to be achieved, keeping in mind natural variations in water quality.

It is necessary to create a management model which takes into account various water quality conditions, each of which would lead to a very specific management action. This would not only serve to focus attention on priority areas and issues, but can also be used to gauge success. Figure 4-3 is a typical management model. The management ranges are described more fully in the paragraphs that follow.

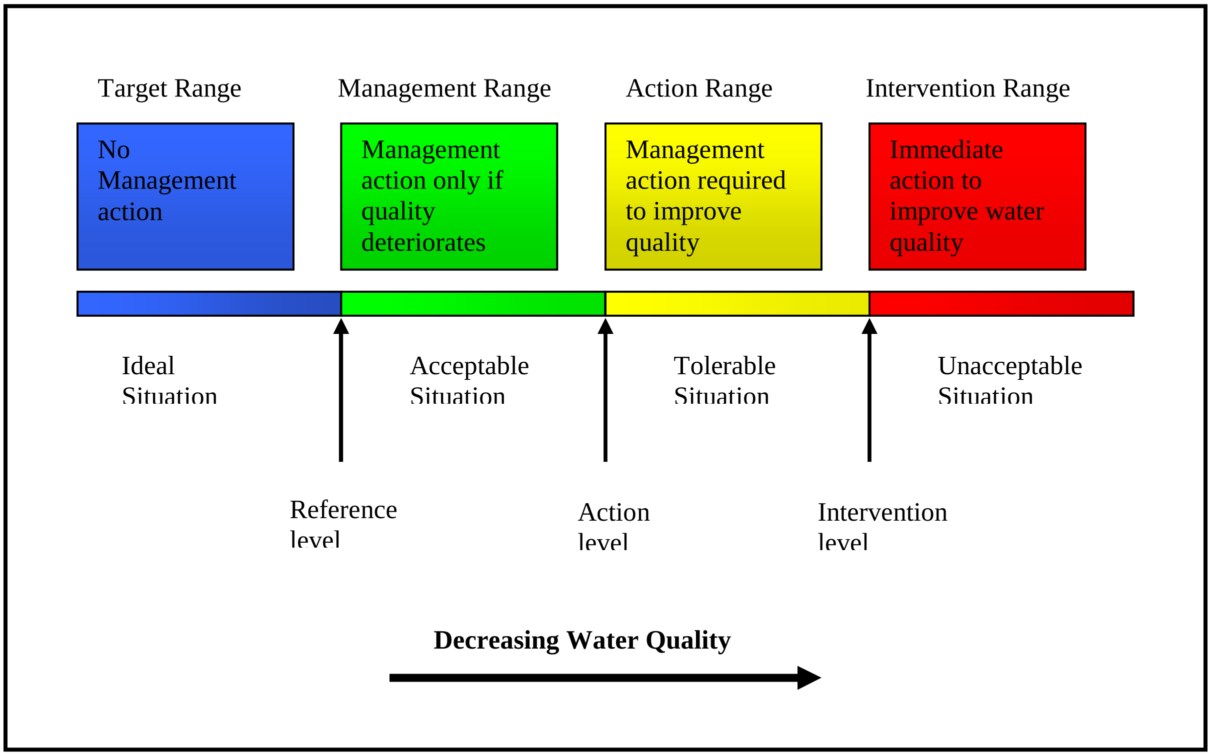

Figure 4-3: Typical ambient water quality management model (BKS, 1996)

4.3.8.1 Target Range

This is the desired state of water body that should be strived for, irrespective of any other consideration. This does not mean that this should be achieved at all costs, but merely that this should be kept in mind when making management decisions. However, should the present state of the water body fall within this range, then any deterioration should be allowed under extreme conditions and after careful consideration of the consequences. Other than this, no management action is required apart from monitoring the situation and ensuring that it does not deteriorate.

The situation here can be termed: Ideal. The upper bound of the target range is called the reference level

4.3.8.2 Management Range

When the state of the water body falls within this range, it means that in general none of the user groups is affected to a large extent, although the quality may occasionally fall outside the target guideline range. Should concentrations/values show an improvement in water quality or remain stable, then no management action is required other than to monitor the situation and to ensure that it does not deteriorate. Should there be a decline in water quality, then action should be initiated to identify the cause of the change, and to address the problem.

The situation here can be termed: Acceptable. The upper bound of the management range is called the action level.

4.3.8.3 Action Range

In this range some or all of the user groups will be noticeably affected, although the effects are not life-threatening or cause permanent damage. Should the water quality of the water body be in this range, management actions must be taken to address the situation as soon as possible. The objective would be to improve the water quality situation to acceptable, with the possible long-term goal to achieve an ideal situation. The time frame for this would depend on the nature of the problem and the seriousness of the situation. A leaking sewer can be fixed quickly, but it will take longer to implement costly changes at an industry to improve the quality of their effluent.

The situation here can be termed: Tolerable. The upper bound of the action range is called the intervention level.

4.3.8.4 Intervention Range

Should the state of the water body fall within this range, immediate and drastic action is required to address a situation that will have serious impacts on one or more of the user groups. The objective would be to improve the water quality situation to tolerable conditions in the shortest possible time, where after more permanent changes over a longer period can be made to achieve an acceptable situation.

The situation here can be termed: Unacceptable. The intervention range has no upper bound.

The ambient water quality objectives form the basis of water quality management, as they are used to determine what is acceptable and what not, and to what extent the water quality situation deviates from the ideal condition. The ambient water quality objectives therefore correspond to the reference value, the action level and the intervention level as depicted in Figure 4-3.

The ambient water quality objectives are derived from the water quality guidelines, and where a variable only affects one user group, the upper values of the ranges described as fit for use, acceptable and tolerable form the water quality objectives. The relationship between water quality guidelines and ambient water quality objectives is shown in Table 4-4.

Table 4-4: Comparison of water quality guidelines and ambient water quality objectives

Guideline category	Ambient Water Quality Objective Range	Upper Value of Range
Fit for use	Ideal	Reference level
Acceptable	Acceptable	Action level
Tolerable	Tolerable	Intervention level
Not fit for use	Unacceptable	

Where a variable impacts on more than one user group, the water quality guidelines for those user groups must be combined into a single set of ambient water quality objectives. The principle that is applied is that the most sensitive user is used to determine the various ranges. This is depicted graphically in Figure 4-4.

4.3.8.5 Water Quality Classification

The condition of a water body cannot be described on the basis of a single measurement, but should be based on a long term average or the central tendency of the water quality. A two-weekly sampling interval yields statistically independent measurements (BKS, 1996), while a period of 12 months will include both wet and dry periods. The statistical distribution of two-weekly measurements obtained from grab samples over a period of one year can therefore be used to determine into which management range the water quality falls.

Water quality measurements seldom follow a normal distribution and tend to be skewed. For this reason non-parametric statistics are often used to describe the central tendency of the measurements. The percentile values that can be used are the 50^{th}, 75^{th} and 95^{th} percentile values, where these values define a level that is not exceeded for that percentage of measurements.

The classification of the water quality of a water body will be based on the statistical distribution of the water quality measurements. Depending on which range the median, the 75^{th} and the 95^{th} percentile values for a variable measured over a one year time period falls, the water quality situation will be classified as ideal, acceptable, tolerable or unacceptable, as shown in Figure 4-5.

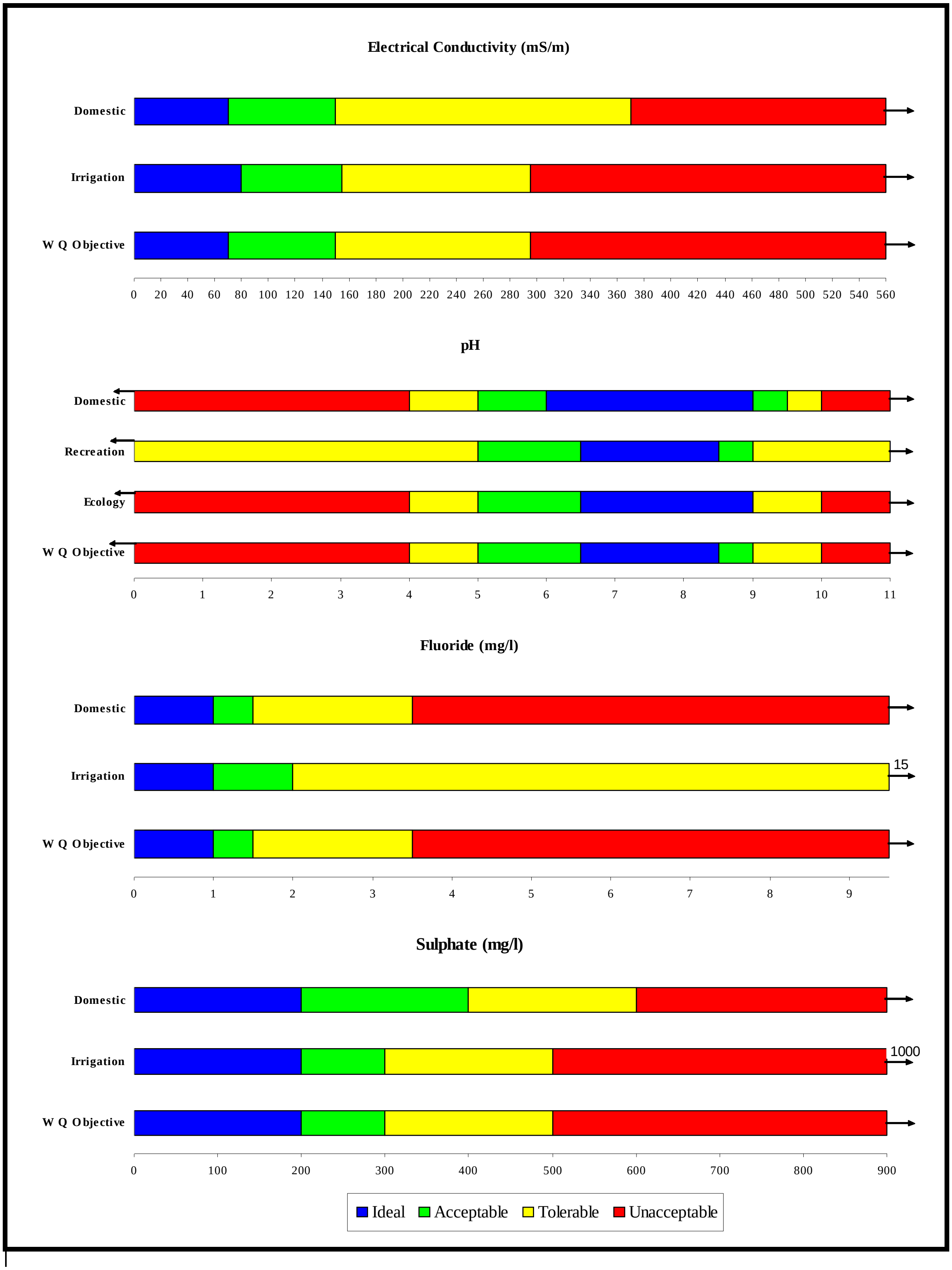

Figure 4-4: Example of combination of water quality guidelines into ambient water quality objective (BKS, 1996).

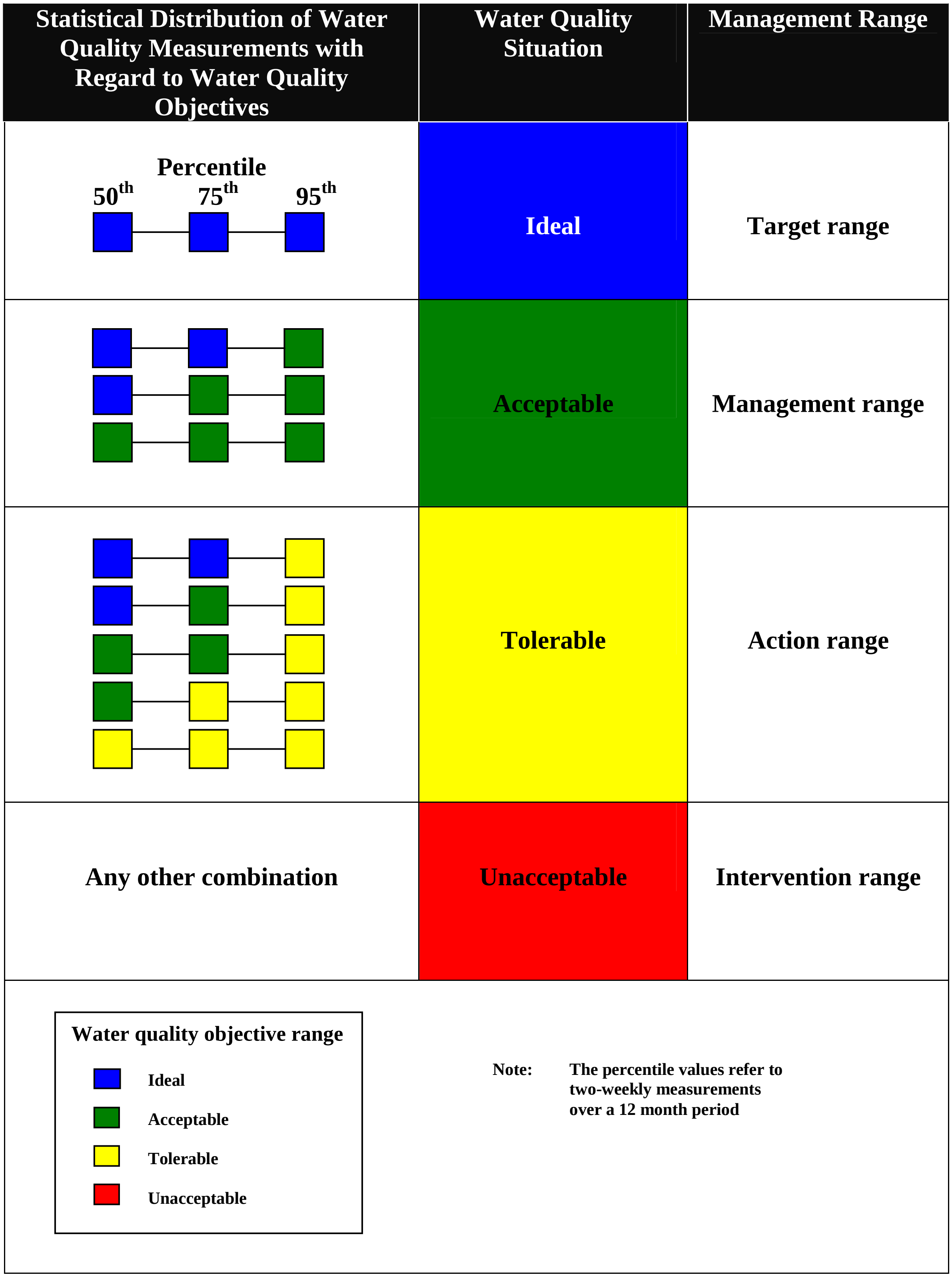

Figure 4-5: Classification of water quality situation into ambient water quality objective (BKS, 1996).

4.3.9 Developing stormwater quality management objectives – load reduction targets

Following the water quality monitoring program, identification of designated users and water quality variables of concern, development of water quality guidelines and ambient water quality objectives, stormwater management objectives can be developed to protect the designated users and also to comply with the set ambient water quality objectives. These objectives are directed towards the stormwater interventions (non-structural and structural) to alleviate pollution to the receiving environments.

Usually two sets of objectives are set. The first may be long-term objectives (effectively a 'vision' or 'aim' or 'goal' for the catchment) and the second being more short term, quantifiable objectives. The short term objectives can be the basis for evaluating the performance of the interventions at the end of a certain period (e.g. 5 years).

The objectives (particularly the short-term objectives) will differ from catchment to catchment but should be based on ecologically sustainable development which is one of the fundamental principles guiding this study (Section 1.5).

Long-term objectives for stormwater quality management may include the following:

- Water quality in the catchment is to meet ambient water quality objectives.
- The value of indigenous riparian, floodplain and foreshore vegetation is to be optimized.
- The value of physical habitats for aquatic fauna within the stormwater system is to be optimized.
- The impact of stormwater on public health and safety is to be optimized.

Short-term objectives for stormwater quality management may include the following:

- The ambient concentrations of each pollutant within the catchment are to be reduced by a specified amount for each pollutant

- Litter is to be trapped from high litter generation areas in the settlement, including residential, commercial or industrial areas, streets with strip shopping, major active recreation areas
- The erosion problem in a specific watercourse is to be reduced, to create a watercourse in a state of dynamic equilibrium
- The physical habitats for aquatic fauna in a specific watercourse are to be restored.

An example of stormwater intervention objectives that could be adopted is presented in Table 4-5. The short-term objective is based on what is currently considered to be a cost-effective level of stormwater treatment.

Table 4-5: Example of potential stormwater treatment objectives

Pollutants	Long-term objectives (Aim/Goal/Vision)	Short-term Objectives
SS	Suspended solids loads equal to that of pre-development catchment	75% retention of the average annual load
TP	The load of phosphorus from the catchment that results in the attainment of the ambient water quality concentration objective	50% retention of the average annual load
TN	The load of nitrogen from the catchment that results in the attainment of the ambient water quality concentration objective	50% retention of the average annual load
Litter	No anthropogenic litter in water bodies. Input of organic litter equal to that which would have occurred from the equivalent forested catchment	Retention of litter greater than 50 mm for flows up to 6 months return period peak flow

The percentage retentions *(R)* quantified in the short-term objectives is estimated as in equation (4-1).

$$R = \frac{(C_l - A_l)}{C_l} \times 100 \qquad (4\text{-}1)$$

Where:

C_l = Average annual load from the catchment estimated using the current average pollutant concentration.

A_l = Average annual load from the catchment estimated using the ambient water quality objective pollutant concentration.

4.3.10 Applying adaptive management plan

Actions taken to manage the water quality in the catchment more effectively on the basis of new information from monitoring program may lead to changes in the information needs. As information needs change, the chain of activities in Figure 4-1 will repeat itself. Each component of the flow chart is subject to change and enhancement over time, reflecting changes in knowledge or goals, improvements in methods and instrumentation, and budgets.

Management decisions will always be made on the basis of uncertain information. These uncertainties in our ability to predict the impacts of our management decisions motivate the use of adaptive approaches to management. Adaptive management is the process by which management policies change in response to new knowledge gained from research and new information obtained from monitored data about the system being managed. Adaptive management requires a monitoring program to detect changes in the system, the ability to evaluate trends in system performance and, finally, the authority and willingness to modify management decisions in response to those trends in an effort to improve system performance.

The development of stormwater quality management objectives has to be based on the information available, which in turn is obtained from the monitoring program. As monitoring programs are iterative in character, so should development of stormwater management objectives. The development of future stormwater quality management objectives should be based on information collected by the existing monitoring program. Monitoring programs and stormwater quality management objectives must be constantly ‘designed’, specified, detailed, described, or documented and updated to be sure that the system continually produces the information desired.

4.4 Methods to select and evaluate stormwater quality management interventions

Development of comprehensive tools for selection and design of drainage management interventions even at planning levels is still at its early stage in South Africa. Hence planners and engineers are not equipped with the necessary knowledge and tools to deal with stormwater quality problems in informal settlements. For this reason, one of the objectives of the study was defined to develop a methodology to select interventions to manage runoff and grey water. The selection process involves identification (i.e. short listing potential interventions that can meet the stated objective given the pollutants of concern). Given the adverse effects of urban stormwater (from informal settlements) impacts on receiving waters quality, the selection of stormwater quality management interventions must be efficient and effective. Efficient and effective selection requires that various alternative interventions be identified and evaluated at planning stage based on the following fundamental principles:

- **Sustainability** which recognizes the need to balance the economic, social and environmental needs and to protect resources for future generations, when planning, constructing and operating infrastructure;
- **Hierarchical Management Approach** which requires stormwater quality management to be carried out firstly at source, and thereafter proceeding down to the end-of-pipe, and in each case employing firstly non-structural and thereafter proceeding to structural technologies if necessary;
- **Public Consultation** which enables all affected stakeholders to be consulted and given the opportunity to provide input to decisions; and
- **Adaptive Management** which recognizes we are dealing with very complex natural and man-made systems whose responses is not fully predictable with the currently available science-based tools. Best practice therefore requires selecting and designing technologies on the basis of best available data, ongoing

monitoring and data collection, and revisiting decisions to produce improved technology selections and designs.

It is always desirable to control stormwater at its source, or as close as possible before other drainage systems and downstream control measures are considered. This preferred hierarchy of stormwater management measures has advantages over the traditional downstream end-of-pipe control techniques (e.g., ponds) because it can maintain the spatial and temporal characteristics of the natural hydrologic cycle. Additionally, the preferred hierarchy, which emphasizes low cost source controls, allows stormwater management interventions to integrate with municipal capital and operating programs gradually.

4.4.1 Methods to select and evaluate non-structural control interventions

Generally, stormwater management programs employ non-structural control interventions while treatment practices are dependent on structural control measures. Management programs that address source and/or on-site controls should be a component of any stormwater quality management plan. Non-structural control interventions can have a significant effect on the total pollutant load discharged to a receiving environment and are characterized by the following advantages:

- Least cost.
- Potentially available for early action or implementation.
- Medium to long-term financial rewards of non-structural control measures are their effect on decreasing the size of structural control measures, leading to lower levels of investment.
- No maintenance requirements.
- Potential site constraints are not worrying.
- Offers good house-keeping practices and overall environmental and health being of settlement residents.
- Creates and sustains awareness of the need for stormwater management.

Their payback is significant, depending on their level of success, in terms of the sustainability of the urban environment. Figure 4-6 shows a flow chart of the selection process of non-structural control measures. Figures 4-6 and 4-7 are basically an elaboration of activities or components involved in steps 8 and 9 in Figure 4-1. The first step in the selection process (Figure 4-6) is to identify issues and causes of pollution and this has been dealt with in detail in Section 4.2. The second step is to define management objectives (or load reduction targets) which has also been described in detail in Section 4.3. The third step is the identification of non-structural interventions. A number of non-structural control interventions involving community education, management activities, planning controls and regulatory policies have been reviewed in Section 2.3. These non-structural interventions are re-categorised in accordance with the hierarchical management approach of stormwater quality as presented in Table 4-6. In step four, the identified interventions are further subjected to screening process to select (preliminary only at this stage) the most effective and efficient one(s). In order to select or consider a non-structural control intervention, implementation requirements (or 'critical screening variables') were developed. The implementation requirements for the various interventions are summarised in Table 4-7. For an intervention to be considered, one or more of the implementation requirements have to be satisfied. The selection is based on the pollution hierarchical management approach (i.e. going from prevention – reduction – reuse/recycle – treatment). Step five involves formulation of alternative stormwater quality management strategy and is described later in Section 4.4.3.

The sixth step involves evaluation of the interventions (strategy) to estimate load reductions that can be achieved. A computational description of the evaluation methods for each intervention is presented in Chapter 5. If the loads reduced by non-structural interventions do not meet management objectives, then structural control interventions are considered in Section 4.4.2. If the loads reduced meet management objectives, then the last two steps involving selection of preferred interventions (strategy) and soliciting stakeholders input and acceptance complete the process. Stakeholders who may be involved include stormwater managers, consultants, community, coordination groups such as catchment management committees, local municipalities, and state government departments. These stakeholders have a crucial role to play if the non-structural control measures are to be successful. In particular, it is important that the community be encouraged to accept a degree of ‘ownership’ of the selected interventions that will be implemented, as the community is responsible for many of the water quality problems within a catchment.

Table 4-6: Non-structural control measures for various stormwater quality management approaches

Hierarchical Management Approach	Non-Structural Control Measures
Prevention/Avoidance Technologies	1. Formalise land-use or development type 2. Planning controls (described in chapter 5) 3. Local authority's management activities (described in chapter 5) 4. Regulatory and enforcement policy (described in chapter 5) 5. Separate waste streams and appropriate use of services 6. Avoid littering and bush toileting 7. Avoid illicit discharge connection into storm drains* 8. Avoid abuse or vandalism to service infrastructure 9. Avoid non-payment of services 10. Good house-keeping, planting and clean-up campaigns
Reduction/Minimization Technologies	1. Water saving or conservation schemes 2. Use of rainwater tanks* 3. Reduce impervious cover* 4. Disconnection of roof-tops from storm drains* 5. Car washing in pervious areas 6. Collection and proper disposal of domestic animals excreta* 7. Reduction of excessive fertilizer application in gardens, parks and lawns* 8. Street Sweeping* 9. Erosion and sediment control* 10. Repair/abatement of failing sanitary services including septic system* 11. Control of sanitary sewer blockages and overflows*
Reuse and Recycle Technologies	1. Urine can be reused as liquid fertiliser 2. Composted toilet waste can be recycled as soil conditioner 3. Greywater can be re used as sub-surface irrigation of garden beds 4. Rainwater at household level can be reused for non-potable domestic use 5. Stormwater at municipal level can be reused for irrigation of parks, lawns and fire-fighting 6. Stormwater can be reused for recharge of groundwater

* Measures included in the model. Others are not included in the model because either they do not readily lend themselves to quantification of their load reductions or data are not available locally and internationally for this process.

Table 4-7: Implementation requirements for non-structural measures

Non-structural Control Measure	Implementation requirements
Lawn Care Education	Occurrence of lawns and gardens in settlement
	Over fertilization of lawns and gardens
Domestic Animal Waste Education	Domestic animals roam in settlement
	Owners don't cleanup their animal’s droppings
Septic System Education and Repair	Sanitation includes septic systems
	Failing septic systems are not regularly maintained
Erosion and Sediment Control	Occurrence of erosion of sediment from bare earth areas
	Erosion control has not been regulated at construction sites
	Low levels of compliance of regulated erosion controls at construction sites
	Installation and maintenance of erosion control measures are poor.
	Soil and sand stockpiles are unprotected
	Grading and excavation projects in wet weather periods
Street sweeping (and waste removal)	Infrequent or non-existence of street sweeping practice
	Minimum sweeping frequencies have not been established or not followed
	Littering is a common problem in urban catchment
	Solid waste collection is not regular
Sewer Overflow Repair/Abatement	Occurrence of sewer overflows in the settlement
	Sewer overflows are not timely reported or attended to
Illicit Connection Removal	Sewer line does not carry grey or sullage water
	Grey or sullage water enters storm drain
Impervious Cover Reduction	High impervious cover in the settlement
	Formalization of settlement is feasible
	Relocation of households or reducing impervious cover is feasible
Impervious Cover (Downspouts) Disconnection	Low-to-Medium-density settlement
	Site depth to bedrock is not a constraint
	Site depth to water table is not a constraint
	Site Slope is not a constraint (flatter lot grading)
	Site concentrated flow erosion hazard is low
	Site soil hydrologic group is either A or B (Schueler, 1987)
	Community acceptance is high. Community is willing to use rainwater tanks as alternative
	Occurrence of lots with downspouts connected to storm drains
	Roof to lot area ratio < 0.5 (Li, et. al., 1997a) i.e. sufficient lawn area

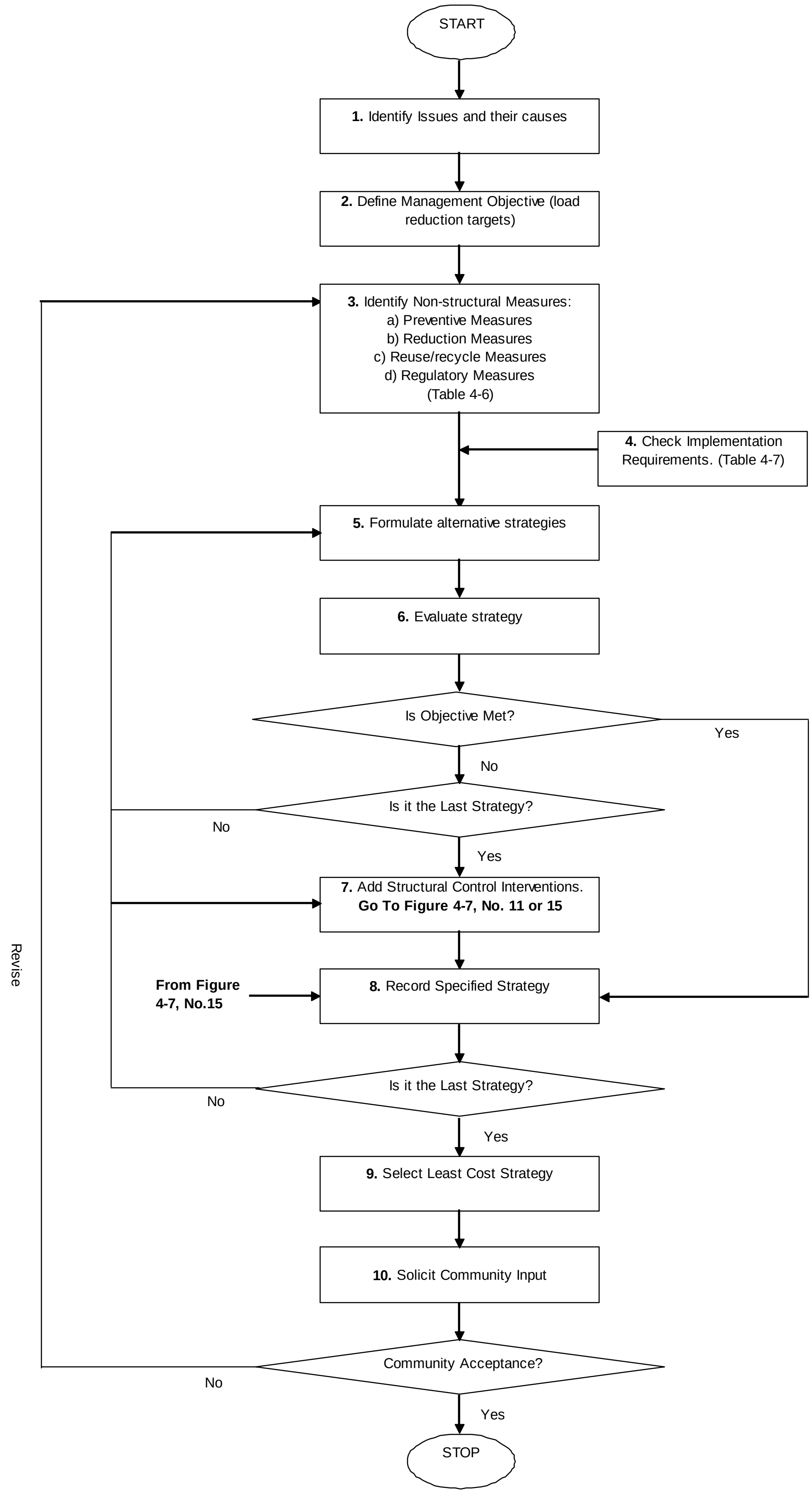

Figure 4-6: Selection Process Flow Chart for Non-Structural Control Technologies1

4.4.2 Methods to select and evaluate structural control interventions

Non-structural control interventions alone may not be able to reduce the total pollutant loads to acceptable levels in many settlements. In such situations, it is important to consider further stormwater quality treatment using structural control interventions. The outcomes in the case of structural control interventions are subject to conventional cost-benefit appraisal. Since the benefits are mostly difficult to quantify, least-cost analysis is often preferred. The selection process for structural control interventions is summarized in a flow chart shown in Figure 4-6. The first step is to identify or short list the most suitable interventions based on pollutants each intervention typically removes and the range of removal efficiencies through literature reviews. Planners can screen the effectiveness of structural technology list using Table 2-5, obtained through comprehensive literature review on the performance of structural measures, to determine the likelihood of a particular control intervention to meet the load reduction target. The second step is to identify potential sites for implementation of each structural control intervention.

The most important criterion governing selection of structural control interventions for water quality improvement is the effectiveness of the technology to remove pollutants. Other important criteria include maintenance requirements; potential site constraints; site soils; environmental and community impacts. A comprehensive list of criteria to be considered in selection of structural control technologies comprises:

- Area served
- level of service
- Regulatory requirement
- Effectiveness of technology
- Land use
- Slope
- Hydraulic head
- Depth to water table
- Depth to bedrock
- Area needed

- Need for pretreatment
- Soil type
- Environmental impacts
- Public acceptance
- Water requirement
- Maintenance requirement
- Capital cost
- Operation and maintenance cost
- Aquatic habitat enhancement
- Thermal impact
- Wildlife habitat enhancement
- Soil contamination
- Base flow support
- Peak discharge control
- Stormwater volume control
- Bank erosion control
- Water conservancy
- Active recreation
- Passive recreation
- Aesthetic appeal
- Safety hazards
- Sensitive environmental features

Some of these criteria are not critical to selection process as their impacts can be accommodated in the design. The critical ones can be formulated as implementation requirements, as presented in Table 4-9. The use of implementation requirements to further short list potential structural control interventions is the third step in Figure 4-7. For an intervention to be considered, all of its implementation requirements have to be satisfied, either with or without implementation of engineering measures designed to remedy the associated impacts. If there are additional environmental and community impacts associated with the engineering remedial measures, then the technology or intervention is not suitable for the site of interest.

Also in step three, the suitability of each site is assessed and, environmental and community impacts, as well as sensitive environmental features are identified. The screening process is done using Table 4-9 to answer questions like:

- Do any physical constraints at the project site restrict or preclude the use of a particular intervention?
- Do the remaining structural control interventions have any important community or environmental benefits or drawbacks that might influence the selection process?

The first question will enable the planner to screen the structural control interventions listed in Table 4-9 to determine if the soils, water table, drainage area, slope, headwater conditions, land use, and ownership present at a particular development site might limit the use of an intervention. In answering the second question, options are compared against each other with regard to operation and maintenance, riparian/aquatic habitat, community acceptance, cost, health and safety issues, and other environmental and social factors.

Structural control interventions have the potential to create adverse environmental impacts at the installation site, such as:

- Outflows from structural control interventions under low flow conditions having poorer water quality than inflows.
- Reduced downstream dissolved oxygen concentrations.
- Loss of aquatic habitat and riparian vegetation.
- Retention of sediment to below pre-development levels, potentially causing sediment starvation and downstream watercourse erosion.

Health and safety issues associated with most structural control interventions should be considered during the selection and design process and they include the potential for:

- Infiltrated water to contaminate potable groundwater wells and cause structural problems to building foundations.
- Mosquito-borne diseases.
- Odours.
- Drowning.
- Diseases and infections from pathogens and from other pollutants trapped in the structural control interventions.

However, most of the safety issues could be addressed during the design stage. Capital costs are difficult to compare among structural control interventions as the actual costs will be dependent on the site characteristics and the design of the control measures. Actual maintenance costs are also difficult to determine, as they depend on the nature of inflows, the type of maintenance equipment and the control technology design. Further, information on these costs is hard to obtain in South Africa if at all they exist, and very limited monitoring of maintenance costs information exists even internationally.

Step four is to evaluate and select the site(s). This is achieved through site (detailed geological and/or geotechnical) investigation to characterise the site and access its suitability. Sites are then compared against each other to select technically suitable and economically feasible ones. Step five involves formulation of alternative stormwater quality management strategies, detailed in Section 4.4.3. The last step is to evaluate interventions (strategy) to quantify expected load reductions.

Table 4-8: Implementation Requirements for Structural Technologies

Structural Technology	Implementation requirements
Riparian Buffers	Riparian zones or adequate space exist in catchment
	Site location is outside flood plain
Wet Ponds	A minimum contributing drainage area of 4 to 10 ha. (Schueler et al., 2007)
	Site without shallow water table or bedrock (Schueler et al., 2007)
	Surface area of pond at least, 1 to 3% of contributing drainage area depending on the pond's depth (Schueler et al., 2007)
	Utility relocation is not a constraint. (Schueler et al., 2007)
	Facility located at least, 3m from property lines, 8m from building foundations, 15m from septic system fields, and 30m from private wells (Schueler et al., 2007)
	Road access for construction and maintenance
	Community acceptance is assured
	Site location is outside flood plain
	No community and environmental concerns (or they can be addressed)
	Adequate head (minimum 1.8 to 2.5 m). (Schueler et al., 2007)
	Potential for low sediment trap
Water Quality Swales and Filter Strips	Permeable soils for dry and grass swales (groups A and B) (Schueler et al., 2007)
	Site without shallow bedrock
	Depth to water table is not less 0.6m (Schueler et al., 2007)
	Relatively flat site slope, e.g. < 5% for grass channels and 2% for dry swales (Schueler et al., 2007)
	Enough head exist. Dry swales require 1 to 1.5m, and grass swales require 0.3m of head (Schueler et al., 2007)
	Adequate space. Swales usually consume about 15% of contributing area (Schueler et al., 2007)
	Maximum contributing drainage area of 2 ha (Schueler et al., 2007)
	Community acceptance is assured
Sand Filters	Potential for low sediment input
	Adequate hydraulic head and space exist
	Maximum contributing drainage area of 2 ha (Schueler et al., 2007)
	No community and environmental concerns (or they can be addressed)
	Community acceptance is assured
Infiltration Basins	Minimum infiltration rate of at least 13 mm/h (Schueler et al., 2007)
	Depth to bedrock and water table at least 1m. (Schueler et al., 2007)
	Facility located at least, 3m from property lines, 8m from building foundations, 30m from septic system fields, 30m from private wells, 30m from surface waters, 122m from surface drinking water sources, and 365m from public water supply wells (Schueler et al., 2007)
	Contributing drainage area close to 100% imperviousness, else pervious areas are properly stabilized by dense vegetation to avoid frequent clogging (Schueler et al.,

Structural Technology	Implementation requirements
	2007)
	Maximum contributing drainage area to infiltration trench of 0.4 ha to avoid clogging (Schueler et al., 2007).
	Adequate space
	Potential for low to medium sediment input
	No community and environmental concerns (or they can be addressed)
	Community acceptance is assured
	For residential land use only
Constructed Wetlands	Adequate contributing drainage area to sustain a permanent water level
	Adequate space for pond. (Typically between 3 and 5% of the contributing drainage area, depending on the average depth of the wetland and the extent of its deep pool features. Schueler et al., 2007).
	Without shallow bedrock
	Adequate hydraulic head exist. (Typically a minimum of 0.6 to 1.2m needed, Schueler et al., 2007).
	Utility relocation is not a constraint (Schueler et al., 2007)
	Facility located at least, 3m from property lines, 8m from building foundations, 15m from septic system fields, and 30m from private wells (Schueler et al., 2007)
	Road access for construction and maintenance
	No community and environmental concerns (or they can be addressed)
	Community acceptance is assured
	Site location is outside flood plain
	Adequate public safety provisions
	Low site slopes
	Low evapotranspiration and presence of base flow into wetland
	Potential for low sediment trap
Porous Pavements	Not suitable for soils with infiltration rates less than 7 mm/h (D soils) or soils with clay content greater than 30%. Generally ideal within the range of 13 to 25 mm/h. (Schueler, 1987)
	Site without shallow bedrock and water table
	Site slope less than 5%. (Schueler, 1987)
	Generally for parking lots and lightly used access roads. (Schueler, 1987)
	Located more than 30m from drinking wells; at least 3m down-gradient and 30m up-gradient from building foundations. (Schueler, 1987)
	Contributing area restricted to 0.1 - 4 ha. (Schueler, 1987)

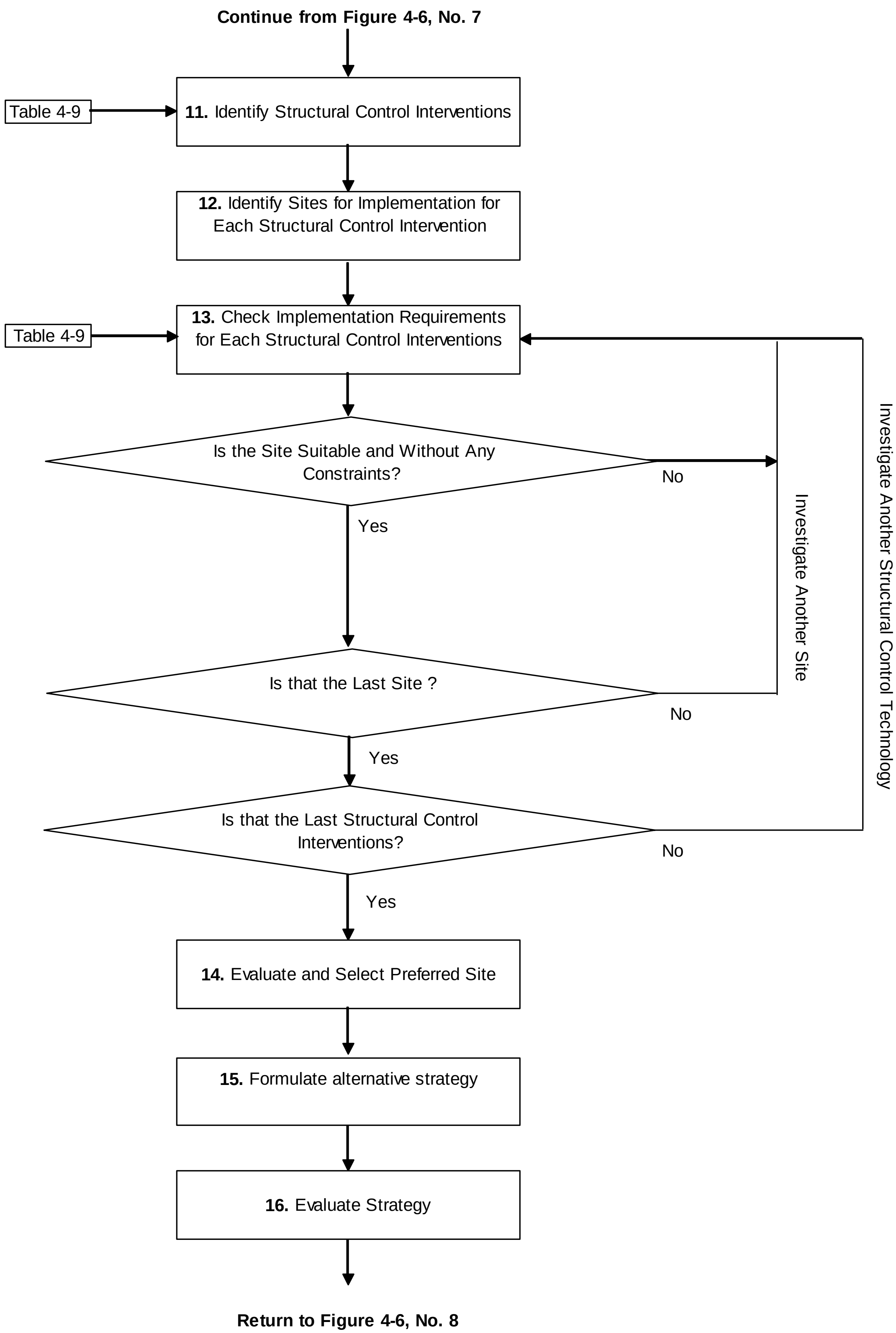

Figure 4-7: Selection Process Flow Chart for Structural Control Technologies

4.4.3 Formulation of alternative management strategies

Upon identification and preliminary selection or screening of suitable control technologies, alternative stormwater quality management strategies can be formulated by combining various mixes and magnitudes of non-structural and structural control measures in accordance with the preferred stormwater management hierarchy. This hierarchy emphasizes the use of non-structural source and drainage system controls before downstream structural treatment controls. However, the cost and effectiveness of many of the non-structural technologies depends largely on the commitment of the community as well as the institutional capacity of the local government planning and management activities. Each strategy should include prioritization of specific management actions to be implemented in the catchment and a tentative timeframe for their implementation. An optimum strategy would be the one that meets water quality objectives at minimum cost.

The broad prioritization of actions should be aimed at facilitating the incorporation of proposed measures into local governments' development of Management Plans and budget. Thus, both short- and long-term strategies could be formulated as follows:

- Short-term strategies (e.g., 2 year implementation) may use non-structural technologies.
- Medium to long-term strategies (e.g., 5 to 15 year implementation) may in addition to non-structural control measures, incorporate structural control measures which are not yet widely practiced and/or monitored in developing countries.

5 QUANTITATIVE DESCRIPTION OF MODEL COMPONENTS

The fifth objective of the study states:

- To develop a decision support system for evaluation of potential interventions for storm and grey water management at planning level.

This objective was undertaken as presented in Chapter 4, Sections 4.4.1 to 4.4.3. The model acts as a starting point from which stormwater management professionals can evaluate various management interventions. In this chapter the computations used to evaluate storm loads, non-storm loads, and load reductions by the various management interventions are described in detail. Literature review and computational methods were used in this part of the research. The chapter is divided into the following five sections:

i. Computation methods of storm loads
ii. Computation methods of non-storm loads
iii. Computation methods of structural control interventions
iv. Computation methods of non-structural control interventions
v. Computation of measure of assuredness (reliability)

A flow chart showing the sequence of the computations is presented in Figure 5-1. The computations in the model consist of additions and modifications to the model developed by CWP (2001). The modifications consisted of:

a. Modification in the estimate of runoff volume and load (presented in Section 5.1)
b. Modification in the estimate of interventions load reductions (presented in Section 5.4)
c. Modification in defaults used in the knowledge-base of the expert system or decision support system, which was based on South African studies (presented in Section 6.2)
d. Coding in Visual Basic for Application (presented in Section 6.1)

The additions included:

a. A module to estimate load reduction targets of pollutants of concern (presented in Section 4.3.9)

b. Addition of four management interventions (presented in Sections 5.4.12 to 5.4.15)

c. Addition of two pollutants tracked by the model (presented in Section 5.6)

d. A module to formulate implementation strategy (presented in Section 4.4.3 and 5.4)

e. Costing to select the optimum management strategy (presented in Section 5.7)

f. Estimation and inclusion of uncertainties (presented in Section 5.3)

The main features of this Chapter is summarised in Table 5-6.

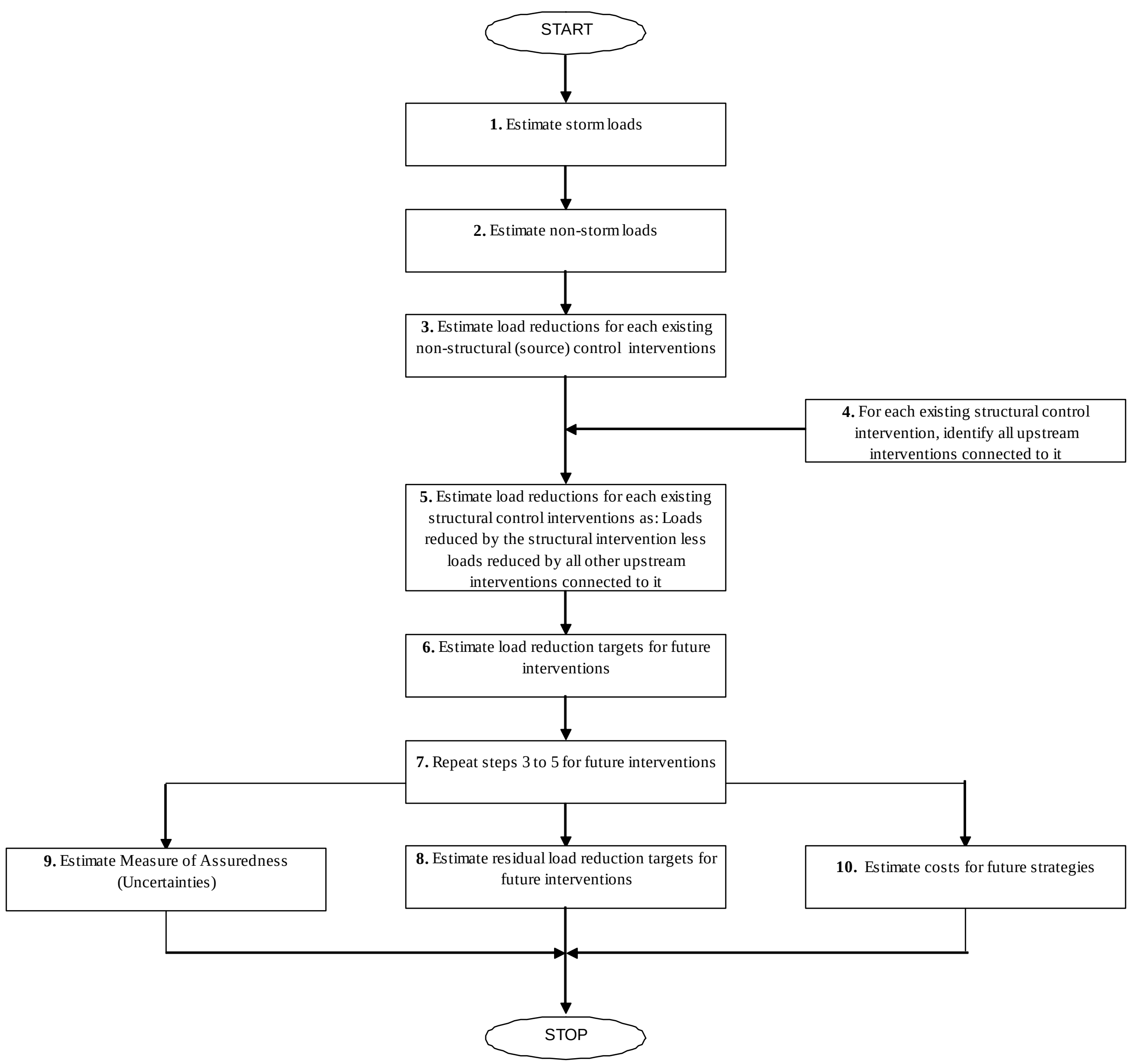

Figure 5-1: Model computations flow chart

5.1 Computation methods of storm loads

A different approach was used to estimate runoff volume and pollutant loads compared to the Simple Method used in CWP (2001). In the Simple Method (Schueler, 1987), empirical regression equation (eqn. 2-2) in Section 2.5.1 was used to estimate runoff coefficient. The empirical equation was based on studies in the US. The contrast between climatic conditions and level of development in the US and South Africa suggest that the empirical regression equation (eqn. 2-2) is inadequate for use in South Africa's informal settlements. The implication in the Simple Method that runoff loads is proportional to the percent impervious areas has been found to be flawed in South African conditions. For example, Coleman (1990a) found that stormwater runoff loads from Alexandra, an informal settlement north of Johannesburg far exceeded those from Hillbrow, a residential and commercial district in Johannesburg where percent imperviousness far exceed that of Alexandra. Again loads from urban catchments are assumed in CWP (2001) to be equal to loads from impervious surfaces only. Such an assumption will rarely apply in typical South African rural settlements where considerable runoff and soil erosion (loads) occurs in pervious areas due to one or combination of several of the following factors, viz.:

- Arid climatic conditions
- Intense thunderstorm activity with inherent high rainfall erosivity
- Shallow erodible soils
- Limited vegetation cover and/or
- Poor conservation management techniques.

Studies by Mackey (1993, 1994a,b), Grobicki (2001), van Ginkel et al. (1993) and Wright et al. (1993) have shown that pervious areas in South Africa contribute substantial loads to the receiving environments.

To overcome these flaws for South African conditions, the use of runoff coefficients recommended by DWAF (Alexander, 1990) was used to estimate runoff volume. Runoff coefficients are recommended for different catchments and land uses in South Africa as shown in Table B-2 in Section B4.1.1, Appendix B. By replacing the mean runoff coefficients (Rv's) in the Simple Method by the recommended coefficients for South African conditions, the model could estimate loads and load reductions for both impervious and pervious areas, and the method is henceforth referred to as *'The Simple Modelling Method'*.

Loads from primary sources, L_{ps}, (i.e. storm or wet weather loads) were estimated by categorizing the catchment into three land uses, namely: residential, commercial and industrial. The Simple Modelling Method estimates pollutant loads as a product of annual runoff volume and pollutant concentration and is described in detail in Appendix B, Section B7.1. The load is estimated as aggregate loads from pervious and impervious surface areas.

5.2 Computation methods of non-storm loads

Loads from secondary sources (i.e. non-storm or dry weather loads) are estimated as a product of flow and concentration, the same basic methodology of the Simple Modelling Method. Because flows from secondary sources are location-specific, the accuracy of estimates improves with additional information about the system being studied. For example, the estimates of flow (or load) generated from septic systems within an urban catchment will depend on the accuracy of septic system inventories available. From these inventories, unconventional base unit of measurements such as, length of sewer and number of septic systems can be formulated to estimate flows and loads. Local data may substantially improve these estimates. Non-storm loads included in the model are loads from septic systems, sanitary sewer overflows (SSOs), and illicit connections to storm drain. The computation methods for these are presented below.

5.2.1 Septic systems

Load from septic systems is the sum of loads from working septic systems and failing septic systems. The model estimates loads from septic systems as a product of flow and concentrations. The flow is the product of the number of septic systems functioning, number of persons per household and per capita wastewater generation. Pollution from failing septic systems can either be on the surface by means of overland flow or the subsurface. Pollutant transport varies considerably depending on the soil characteristics, catchment characteristics, and the site of the systems. Water pollution risk from overland flow is determined from delivery ratio which depends on soil absorption ability and surface runoff rates.

The equations for estimating septic system annual load of each pollutant are defined by equation 5-1, 5-2, and 5-3. The effluent concentrations of septic tank at the tank site are attenuated as the pollutants are transported to streams. Hence a delivery ratio is applied to account for this attenuation process. The concentrations of working septic system *(C_{ws})* at catchment outfall are estimated from equation 5-2. Defining a failing septic systems load is a difficult task in view of the fact that the definition of failure varies. Failing systems will result in subsurface loads but a complete failure will surely result in untreated surface loads. Hence the model uses a weighted average concentration based on the fraction of complete failures that essentially result in a direct wastewater discharge, and the fraction that contributes to subsurface flow only. The effluent concentration from failing septic systems is estimated from equation 5-3.

$$L_{sep} = 0.365 D_u D_f P_u W_u \left[S_f C_{fs} + (1 - S_f) C_{ws} \right] \qquad (5\text{-}1)$$

and

$$C_{ws} = \textit{effluent concentration of septic tank at the tank site} * D_r \qquad (5\text{-}2)$$

$$C_{fs} = F_f * C_{ww} + (1 - F_f) * C_{ww} * D_r \qquad (5\text{-}3)$$

The notations in equations 5-1 to 5-3 are defined as:

L_{sep} = Annual pollutant load from septic system (kg/yr)

0.365 = A conversion factor. (For bacteria, conversion factor = 3.65×10^{-8} and Load is in million count/year)

D_u = Number of dwelling units

D_f = Fraction of dwelling unit with septic system

P_u = Persons per dwelling units

W_u = Water use (m^3/c/d)

S_f = Fraction of septic systems failing

C_{fs} = Effluent concentration from failing septic systems (mg/l, for bacteria count/100ml)

C_{ws} = Effluent concentration from working septic systems (mg/l, for bacteria count/100ml)

F_f = fraction of complete failures of septic systems

C_{ww} = wastewater concentration (mg/l)

D_r = delivery ratio (fraction)

5.2.2 Sanitary Sewer Overflows

Sanitary Sewer Overflows (SSOs) occur both during and between storms, that is, it contributes to both storm and non-storm loads. Non-storm loads are caused by breakages and blockages while the storm loads are caused by lack of capacity due to infiltration of rainfall into the sewer pipes (Stephenson and Barta, 2005). SSOs loads are estimated in the model as a product of total flow from SSOs and concentrations for raw sewage. The flow is estimated as a product of number of SSOs per unit kilometer of sewer length *(N_o)* by a typical SSO volume *(V)*.

The resulting equation for estimating SSOs annual load is given by equation 5-4.

$$L_{sso} = 10^{-3} * l * N_o * V * C_{ww} \qquad (5\text{-}4)$$

Where:

L_{sso} = Annual pollutant load from sanitary sewer overflows (kg/yr)

10^{-3} = A conversion factor. (For bacteria, conversion factor = 10^{-2} and Load is in million count/year)

l = Length of sanitary sewer (km)

N_o = Number of annual overflows per km (#/km/yr)

V = Typical volume per sanitary sewer overflow (m^3)

C_{ww} = Concentration of wastewater characteristics (mg/l), (for bacteria, count/100ml)

Typical SSO volume per day may be estimated from equation 5-5 as:

$V = D_u * P_u * Per\ capita\ sewer\ generation * t/24$ (5-5)

Where:

D_u = Number of dwelling units

P_u = Persons per dwelling units

t = typical duration of an overflow in a day (hrs)

5.2.3 Illicit Connections (IC)

Contribution of loads from illicit connections to storm drains can be assumed to result from residential and business connections and both are estimated from the product of flow and concentration. For residential connections, the flow is obtained as equation 5-6 and the number of illicit connections obtained from equation 5-7.

*Flow = Person per dwelling unit * Water use * Number of illicit connections* (5-6)

And:

*Number of Illicit connections = fraction illicitly connected (1%) * Number of Sewered dwelling units* (5-7)

For businesses, illicit connections are composed of wash water connections and complete wastewater connections. Total flow concentrations are a flow weighted average of wash water and raw sewage data which is evaluated from equation 5-8:

$C_t = (C_w F_w + C_{ww} F_{ww}) / (F_w + F_{ww})$ (5-8)

Where:

C_t = Total flow concentration (mg/l)

C_w = wash water concentration (mg/l, for bacteria count/100ml)

C_{ww} = wastewater or raw sewage concentration (mg/l, for bacteria count/100ml)

F_w = wash water flow (m^3/connection/day)

F_{ww} = raw sewage flow (m^3/connection/day)

The annual loads from residential, business wash-water and business complete wastewater are summed in equation 5-9 to obtain an equation for estimating total illicit connections annual pollutant load.

$$L_{ill} = 0.365\{P_u*W_u*I_r*D_u*C_{ww} + B_u*I_b(B_w*F_w*C_w + (1-B_w)F_t*C_t)\} \quad (5\text{-}9)$$

Where:

L_{ill} = Annual pollutant load from Illicit connections (kg/yr)

0.365 = conversion factor, (For bacteria, conversion factor = $3.65x10^{-8}$ and Load is in million count/year)

P_u = persons per dwelling unit

W_u = water use (m^3/c/d)

I_r = fraction of households illicitly connected

D_u = Number of dwelling units

C_{ww} = wastewater concentration pollutant (mg/l, for bacteria count/100ml)

B_u = number of businesses

B_w = fraction business connections that are wash water only

I_b = fraction of businesses with illicit connections

F_w = wash water flow from business illicit connection (m^3/d)

F_t = total flow per business illicit connection (m^3/d)

C_w = wash water pollutant concentration from business illicit connection (mg/l, for bacteria count/100ml)

C_t = combined wash water and wastewater pollutant concentration from business illicit connection (mg/l, for bacteria count/100ml)

5.2.4 Subsurface and base flow from lawns and gardens

Imperviousness due to urbanization results in reduced subsurface or base flow. The pollutant concentrations in subsurface flow are relatively low due to filtration, adsorption, and biodegradation processes which occur within the soil. However, concentrations of nutrients (nitrogen and phosphorus) are of concern as a result of leachate from backyard gardens in informal and rural settlements. Nutrients annual load is estimated as a product of its concentration and annual infiltration volume. The model approximates the volume of infiltrated water as a fraction of annual rainfall, based on soil type as classified by U.S. Soil Conservation Service (National Engineering Handbook, 1972) in terms of their absorbing capacities. The lawn subsurface flow annual load of nutrient is estimated from equation 5-10:

$$L_{lawn} = (A_{SA}*F_{IA} + A_{SB}*F_{IB} + A_{SC}*F_{IC} + A_{SD}*F_{ID})\ P*C*A_L*K_c \qquad (5\text{-}10)$$

Where:

L_{lawn} = Annual pollutant load from lawn or subsurface flow (kg/yr)

P = Mean annual precipitation (mm/yr)

A_{SA}…A_{SD} = Proportion of area covered by Hydrologic Soil Groups A…D

F_{IA}…F_{ID} = Fraction of infiltrated rainfall into Hydrologic Soil Groups A…D

C = nutrient concentration in leachate or subsurface flow (mg/l)

A_L = Lawn area (km^2)

K_c = Factor to account for compaction of urban soils

5.3 "Subjective risk assessment" in estimating load reductions

Ambient water quality prediction and management involves considerable uncertainty. No one can accurately predict what pollutant loads will occur in the future, especially from area-wide non-point sources. In addition to uncertainties inherent in measuring the attainment of water quality objectives, there are uncertainties in models used to determine pollution loads, and to predict the effectiveness of actions taken to meet water quality objectives. The models available to help managers predict water quality impacts are relatively simple compared with the complexities of actual water quality systems. These limitations and uncertainties should be understood and addressed as water quality management decisions are based on their outputs.

The mean or median pollutant removal efficiencies usually quoted in the literature (e.g. Schueler, 1987) as well as those derived from analytical calculations and simulation model predictions can rarely be achieved on a catchment-wide basis for a variety of reasons. The reasons are based on the fact that, treatment measures operate in an environment of change and uncertainty described below and in Appendix A, Section A6.1.

Outcomes or events that cannot be predicted with certainty are often called risky or uncertain. Some individuals draw a special and interesting distinction between risk and uncertainty. In particular, the term *risk* is often reserved to describe situations for which probabilities are available to describe the likelihood of various events or outcomes. If probabilities of various events or outcomes cannot be quantified, or if the events themselves are unpredictable, some would say the problem is then one of *uncertainty*, and not of risk. In this section, what is not certain is considered uncertain. When the ranges of possible events are known and their probabilities are measurable, risk is called *objective risk*. If the probabilities are based solely on human judgement, the risk is called *subjective risk*.

Such distinctions between objective and subjective risk, and between risk and uncertainty, rarely serve any useful purpose to those developing and using models. Likewise, the distinctions are often unimportant to those who should be aware of the risks or uncertainties associated with system performance indicator values.

Uncertainty in information is inherent in future-oriented planning efforts. It stems from inadequate information and inappropriate assumptions, as well as from the variability of natural processes. Stormwater managers often need to identify the uncertainty of, or changes in system performance indicator values from what was predicted due to any changes in input data and parameter values. They need to reduce this level of uncertainty to the extent practicable. Finally, they need to communicate the uncertainties clearly so that decisions can be made with this knowledge and understanding.

There are knowledge uncertainty and natural variability uncertainties. Knowledge uncertainties include lack of sufficient data to estimate probabilities of various events that might happen; imprecision in input data measurements; and imprecision in our understanding of all the treatment processes occurring in the treatment control measures. Natural variability includes temporal and spatial variability in hydrological and meteorological input series (e.g. amounts of rainfall, evaporation, land cover and topography), to which model input values may be subject. Other uncertainties may include variability in water use; return flows from settlements, atmospheric deposition of pollutants, design, maintenance and operation of stormwater control interventions, all resulting in changes of flows, and their qualities, and consequently changes in the affected ecosystems. There is also uncertainty with respect to human behaviour and reactions related to non-structural interventions (e.g. educational programs) to reduce pollutant loads. Social uncertainty may often be the most significant component of the total uncertainty associated with just how a treatment control measure will perform (Loucks and Beek, 2005).

In this section, the goal of the 'subjective risk assessment' is to evaluate the likelihood of a scenario/factor occurring for which the consequence results in some level of ineffectiveness in management intervention performance. All scenarios that lead to this common outcome (ineffectiveness) - for a specific intervention - can then be combined to determine a single 'subjective risk' of arriving at that outcome. In stormwater control interventions, six scenarios were identified to be associated with risk which can influence the estimate of load reductions or the ineffectiveness of the interventions. These are:

a. A fraction of catchment area that can be treated by an intervention *(η_a)*
b. A fraction of annual rainfall that can be captured by control intervention *(η_b)*
c. A factor to reflect design adequacy of interventions *(η_c)*
d. A factor to reflect maintenance level of interventions *(η_d)*
e. A fraction of population that can be reached with education programs *(η_e)*
f. A fraction of population that will change behaviour or participate in the program or comply with the set standard *(η_f)*

CWP (2001) also used these six factors to *'discount'* load reductions achieved by various interventions.

Only rain that falls on area(s) contributing to intervention(s) can be treated. Runoff from outside the contributing areas will end up in rivers untreated. The factor, η_a, is generally the area captured by the control measure divided by the area of the catchment as given in equation 5-11.

$$\eta_a = \frac{A_i}{A_c} \quad (5\text{-}11)$$

Where:

A_i = Areas captured by intervention (km^2).

A_c = Total area of catchment (km^2)

The factor, η_b, is the fraction of annual rainfall captured by the treatment control intervention. This value is determined by analysing local rainfall records to develop a rainfall frequency spectrum. The rainfall frequency spectrum represents the statistical distribution of 24-hour rainfall events.

The removal efficiencies to be used in the model are those quoted from literature as well as those derived from analytical calculations and simulation model predictions and it is uncertain that these values would be achieved in every location. The factor, η_c, accounts for the design features incorporated into treatment control measures to enhance pollutant load reductions. It also accounts for design shortcomings and is estimated based on adequacy of existing design practice or standard. This factor is very subjective and depends on engineering or professional judgement.

The performance of structural treatment control measures will deteriorate with time unless adequate operation and maintenance procedures are put in place. The factor, η_d, accounts for the temporal variability of treatment control measures load reductions capabilities that stems from the effectiveness of operation and maintenance practices. The factor, η_d, is estimated based on adequacy of maintenance undertaken and is very subjective and depends on engineering or professional judgement.

Some management programs involve community education and the success of those programs depends on fraction of population that can be educated. The factor, η_e, is the fraction of population reached with education programs and it depends on the type of media (e.g. radio, television, and community meetings) used to distribute information and the impact it creates which in turn, depends on the fraction who remember the educational information on a long term basis. Even if educational programs reach some population, not all those population will be willing to change behaviour or participate or comply with the programs. The factor, η_f, accounts for the fraction of population willing to change behaviour or comply. For each intervention, some combinations of the six factors (η_a, η_b, η_c, η_d, η_e, and η_f) apply as shown by a tick (√) in Table 5-1.

Table 5-1: Risk factors applicable to interventions

Interventions	**Risk factors (η)**					
	η_a	η_b	η_c	η_d	η_e	η_f
Lawn care education	√				√	√
Septic systems education					√	√
Domestic animal waste education	√[1]				√	√
Erosion and Sediment control from active construction sites	√			√		√[2]
Street Sweeping	√				√[3]	√[4]
Downspout Disconnection	√				√	√
Riparian Buffers	√		√	√		
Impervious Cover Reduction	√					
Illicit Connection Removal	√					
SSO Repair/Abatement	√					
Septic System Inspection/Repair				√[5]		√
Erosion and Sediment control from catchment pervious surface	√			√		√[2]
Rainwater Tanks	√	√		√	√	√
Exfiltration systems	√	√	√	√		
River assimilative capacity			√	√		
Other Structural control interventions	√	√	√	√		

Note: 1 = fraction of animal waste that is treatable; 2 = compliance factor; 3 = sweeping efficiency factor; 4 = sweeping frequency factor; 5 = fraction of septic systems that will inspected/repaired.

A *'measure of assuredness' (ξ)*, which reflects the proportion of pollutant loads that can '*reliably'* be reduced by an intervention *under the prevailing conditions*, can be estimated to account for 'subjective uncertainties/risk' in load reductions. The prevailing conditions include, for example, fraction of annual rainfall (which have been adopted) to be treated based on water quality protection required, the standard of design and maintenance practices (low, high), and the fraction of community willing to participate in a program.

The six factors can be assumed as independent random variables, i.e., the value of any one factor is not influenced by the value taken by other factors. The measure of assuredness would then be the joint proportions of the random variables, i.e., the product of the six factors (η_a, η_b, …, and η_f) as given by equation 5-12.

$$\xi = \eta_a * \eta_b * \ldots\ldots * \eta_f \quad (5\text{-}12)$$

The above deductions indicate that, to have minimum 'subjective risk' in future control interventions, the stormwater manager should maximize the six factors (viz. η_a, η_b, η_c, η_d, η_e, and η_f), that is, increase the faction of contributing areas to treatment control measures, capture and treat more annual cumulative rainfall, institute high standard of design, institute high operation and maintenance schedules of treatment control measures, ensure educational programs reach greater proportion of population, and also ensure greater proportion of population participate in the programs. Model outputs of 'measure of assurednesses is discussed in Appendix C, Section C.3.4.

5.4 Computation methods to estimate load reductions by interventions

This section describes the computation methods for estimating pollutant load reductions by various interventions included in the model. Many of the interventions (e.g. Lawn care education program, Active construction's erosion and sediment control program, downspout disconnection program and Impervious cover reduction program) may not be applicable in certain townships or rural settlements. Given the fact that some settlements, (e.g. Alexandra and Soweto cluster in Gauteng; Swartkops in the Eastern Cape; and Khayelitsha and Cape Flats in the Western Cape) have mixed development types - involving formal to informal, high to low density, high to low income; and high to low level of services- it was felt appropriate to identify and include a comprehensive list of interventions to provide a wider spectrum for selection of measures suitable for a particular settlement. The onus is therefore on the user to identify and select program(s) that will best suit the catchment under his/her study, and the methodology to do this is described in Chapter 4. For each intervention, the timeframe for completion as well as the magnitude of implementation (or implementation factor), as described in Section 4.4.3, must be formulated. The implementation factors *(ω)* represent the proportion of the intervention that can be implemented based on local governments' Management Plans and budget.

Computational methods to estimate the best possible pollutant removal for each intervention is presented below.

5.4.1 Fertilizer Use Education (FUE) Intervention Load Reduction

Fertilizer use education (FUE) program is targeted to reduce nutrient loads resulting from over-fertilization of lawns and gardens. The procedure was to estimate the load associated with excess fertilizers applied to lawns and gardens, and then apply equation 5-12 – which reflect the proportion of pollutant loads that can '*reliably*' be reduced by an intervention. By adding the implementation factor *(ω)*, the annual pollutant load reduction from FUE program as given by CWP (2001) is modified to equation 5-13:

$$L_{lce} = A_L K_{app} * K_r * K_l * \xi_1 * \omega_1 \tag{5-13}$$

And A_L is given by equation 5-14

$$A_L = \varepsilon\left[A_{res} - \left(A_{res} * I_{res}\right)\right] \tag{5-14}$$

Where:

L_{fue} = Annual pollutant load reduction from Fertilizer Use Education program (kg/yr)

A_L = Lawn area (km^2)

A_{res} = Residential area (km^2)

I_{res} = Impervious cover in residential area (%)

K_{app} = Typical Fertilizer application rates (kg/km^2/year)

K_r = Fertilizer application reduction (fraction)

K_l = Fraction of fertilizer lost to the environment

ε = Proportion of residential pervious surfaces in lawns

$\xi_1 = \eta_a * \eta_e * \eta_f$ (obtained from equation 5-12 and Table 5-1)

ω_1 = Implementation factor for fertilizer use education program

5.4.2 Septic System Education (SSE) Intervention Load Reduction

Annual load from septic systems *(L_{sep})* was estimated in Section 5.2.1 (equation 5-1) as the sum of loads from working septic systems and failing septic systems. Ideally, septic system education (SSE) would eliminate all failing septic systems *associated with behaviour*. Hence the loads reduced will correspond to the annual load from septic systems *(L_{sep})* less the annual load for which there are no failing systems. In other words, after SSE intervention, $S_f = 0$ and $C_{fs} = C_{ws}$ such that equation 5-1 will reduce to equation 5-15:

$$L'_{sep} = 0.365 D_u D_f P_u W_u C_{ws} \qquad (5\text{-}15)$$

Hence loads reduced prior to the application of risk and implementation factors are simply equation 5-1 minus equation 5-15 as provided in equation 5-16.

$$L'_{sse} = 0.365 D_u D_f P_u W_u \lfloor S_f C_{fs} + (1 - S_f) C_{ws} \rfloor - 0.365 D_u D_f P_u W_u C_{ws}$$
$$= L_{sep}\left[1 - \frac{C_{ws}}{C_{fs} * S_f + (1 - S_f) C_{ws}}\right] \qquad (5\text{-}16)$$

By applying equation 5-12 and the implementation factor *(ω)*, the resulting annual load reduction from septic system education program is then given by equation 5-17:

$$L_{sse} = L_{sep}\left[1 - \frac{C_{ws}}{C_{fs} * S_f + (1 - S_f) C_{ws}}\right] \xi_2 * \omega_2 \qquad (5\text{-}17)$$

Where:

L_{sse} = annual pollutant load reduction from septic system education program (kg/yr; for bacteria million count/yr)

L_{sep} = annual pollutant load from septic system (kg/yr)

S_f = Fraction of septic systems failing

C_{fs} = Effluent concentration from failing septic systems (mg/l, for bacteria count/100ml)

C_{ws} = Effluent concentration from working septic systems (mg/l, for bacteria count/100ml)

$\xi_2 = \eta_e * \eta_f$ (obtained from equation 5-12 and Table 5-1)

ω_2 = Implementation factor for septic system education program

5.4.3 Domestic Animal Waste Education (DAWE) Intervention Load Reduction

A common problem in low-income high density settlements in developing countries in terms of pollution to receiving water environment is defecation from domestic animals such as dogs, sheep, goats, cattle, pigs, chickens, ducks, turkeys, donkeys, horses, and others. Many of these animals roam about in the settlements while some of them are kept in smallholdings at backyards. The loads reduced are estimated based on the fraction of owners who clean up their animal waste.

The factor η_a for domestic animal waste education (DAWE) program is estimated from equation 5-18.

$$\eta_a = P_{rdaw} * (1 - P_{cdaw}) \quad 5\text{-}18$$

Where:

P_{rdaw} = Fraction of population or owners whose domestic animals roam in the settlement

P_{cdaw} = Fraction of population or owners who clean their domestic animals waste

By applying equation 5-12 and the implementation factor *(ω),* the load reduction resulting from DAWE program is given by equation 5-19.

$$L_{dawe} = \lfloor 365 * D_u * W_{pro} * C_{daw} * D_{da} * F_{pw} \rfloor * \xi_3 * \omega_3 \quad (5\text{-}19)$$

Where:

L_{dawe} = Annual pollutant load reduction from domestic animal waste education program (kg/yr, for bacteria million count/yr)

D_u = Number of dwelling units or households

W_{pro} = Domestic animal waste production (kg/animal/day; colonies or count/kg)

C_{daw} = Concentration of a pollutant in domestic animal waste (kgs/kg; colonies/kg)

D_{da} = Fraction of households with domestic animal

F_{pw} = Fraction of pollutant delivered to water course

$\xi_3 = \eta_a * \eta_e * \eta_f$ (obtained from equation 5-12 and Table 5-1)

ω_3 = Implementation factor for domestic animal waste education program

5.4.4 Active Construction Erosion and Sediment Control (ACESC) Intervention Load Reduction

Construction and urban development sites represent the greatest source of sediment loads in urban areas; often an order of magnitude higher than other land uses. This also results in an increase in adsorbed contaminants, such as nutrients and heavy metals, particularly where the construction is in an area with high atmospheric deposition rates. Loads from active construction erosion and sediment control (ACESC) program are storm loads and are estimated using the Simple Modelling Method described in Section 5.1 and adjusting the runoff coefficient to reflect the bare compacted ground typically found at construction sites. The equation for estimating sediment annual load reduction from active construction site is given equation 5-20.

$$L_{acss} = PR_f C_r A_{ac} C_{ss} \qquad (5\text{-}20)$$

Where:

L_{acss} = Annual sediment (SS) load from active construction site (kg/yr)

P = Mean Annual Precipitation (mm/yr)

R_f = Fraction of annual rainfall that produces runoff

C_r = Runoff coefficient for cleared land (dimensionless)

A_{ac} = Area of construction site (km^2)

C_{ss} = Concentration of sediment (SS) (mg/l)

Nitrogen and phosphorus loads are obtained by multiplying the soil content ($S_{n/p}$) of these constituents by annual sediment load, and by enrichment factor ($E_{n/p}$). The enrichment factor is generally defined as the ratio of the abundance of a particular constituent in an enriched material to its abundance in the original material. For bacteria, the *potency factor* defined as the number of bacteria count per ton of sediment, is used in the model instead of enrichment factor. The equation for estimating annual load of nutrients from active construction site is given by equation 5-21:

$$L_{acn} = L_{acss}S_{n/p}E_{n/p} \quad (5\text{-}21)$$

Where:

L_{acn} = Annual nutrients load from active construction site (kg/yr)

$S_{n/p}$ = Soil content of nitrogen or phosphorus (% by weight)

$E_{n/p}$ = Enrichment factor of nitrogen or phosphorus. For bacteria, potency factor is used.

L_{acss} is defined in equation 5-20

By applying equation 5-12 and the implementation factor *(ω)*, the annual sediment load reduction from ACESC program is estimated from equation 5-22:

$$L_{escs} = L_{acss} * P_{eff} * \xi_4 * \omega_4 \quad (5\text{-}22)$$

And the nutrient load reduction from ACESC is given by equation 5-23:

$$L_{escn} = L_{escs} * S_{n/p} * E_{n/p} \quad (5\text{-}23)$$

Where

L_{escs} = Sediment annual pollutant load reduction from ACESC program (kg/yr)

L_{escn} = Nutrient annual pollutant load reduction from ACESC program (kg/yr)

P_{eff} = Assumed ACESC program efficiency

$\xi_4 = \eta_a * \eta_d * \eta_f$ (obtained from equation 5-12 and Table 5-1)

ω_4 = Implementation factor for ACESC program

5.4.5 Street Sweeping (SS) Intervention Load Reduction

The load from each street type is estimated by multiplying the total load from the associated land use and the fraction of impervious area swept in that land use, equation 5-24. The total load from the associated land use *(L_{ps})* is the storm load estimated using the Simple Modelling Method in Section 5.1. The loads reduced from each street type are the product of the street load and efficiency of street sweeping. The efficiency depends on the sweeping technique. The efficiency of sweeping is reduced if the sweeper is unable to sweep the entire road surface principally due to cars parked on streets and also due to the fact that the operators may not be well trained. The total load reduction from street sweeping is the sum of load reductions from streets associated with each particular land use. By applying equation 5-12 and the implementation factor *(ω)*, the resulting equation for estimating annual pollutant load reduction from street sweeping is given by equation 5-25:

$$L_{st} = \sum_{i-1}^{n}\left[L_i^{ps}\left(\frac{A_i^{st}}{A_i * I_i}\right)\right] \qquad (5\text{-}24)$$

$$L_{ss} = \sum_{i-1}^{n}\left[L_i^{ps}\left(\frac{A_i^{st}}{A_i * I_i}\right)E_i^{s}\right] * \xi_5 * \omega_5 \qquad (5\text{-}25)$$

The notations in equations 5-24 and 5-25 are defined as:

i = the i^{th} land use

n = total number of land uses

L_{st} = Annual load from streets (kg/yr)

L_{ss} = Annual pollutant load reduction from street sweeping program (kg/yr)

$L^{ps}{}_i$ = total annual storm load from land use *i* (kg/yr), obtained from equation B-2 in Appendix B.

$A^{st}{}_i$ = Total street area swept in land use *i* (km^2)

A_i = Total area in land use *i* (km^2)

$E^{s}{}_i$ = Efficiency of sweeping in land use *i* (%)

I_i = Fraction of total impervious cover in land use *i* (%)

$\xi_5 = \eta_a * \eta_e * \eta_f$ (obtained from equation 5-12 and Table 5-1)

ω_5 = Implementation factor for street sweeping program

5.4.6 Downspout Disconnection Intervention Load Reduction

Downspout or Impervious Cover Disconnection (ICD) is a logical stormwater management practice but was not explicitly required until recently in the United States and Europe. The method is not practiced in many countries. It involves disconnection of downspout and redirection of roof runoff to lawn or pervious areas. By returning the roof runoff to soils through infiltration, this control technology reduces runoff volume and pollutant loadings. This control measure is suitable where the local site grading is gentle and sufficient lawn or pervious areas are available. It is also desirable to have sandy soils and a low groundwater table on site so that the diverted runoff will not be detained on the lawn over extended periods of time. Residents may participate in a disconnection program when a municipal bylaw is enacted. For voluntary downspout disconnection programs, public participation may be improved by education and financial subsidy. The downspout disconnection program in the model is aimed at both residential and commercial rooftops.

Impervious cover disconnection load reduction in residential areas is estimated based on a proportion of rooftop area $(D_{icd}*R_{pt})$ to the total impervious cover in the residential area $(A_{res}*I_{res})$. By applying equation 5-12 and the implementation factor (ω), the resulting equation for estimating annual pollutant load reduction from downspout disconnection is given by equation 5-26:

$$L_r^{icd} = 10^6 \frac{D_{icd} * R_{pt}}{A_{res} * I_{res}} L_{ir}^{ps} * \xi_6 * \omega_6 \quad (5\text{-}26)$$

Where:

$L^{icd}{}_r$ = Annual pollutant load reduction from ICD in residential area (kg/yr, for bacteria million count/yr)

10^6 = Conversion factor (m^2/km^2)

D_{icd} = Total number of homes disconnected or to be disconnected

R_{pt}= Typical roof area

A_{res} = Total residential area (km^2)

I_{res} = Fraction of impervious cover of residential land use (%)

$L^{ps}{}_{ir}$ = Total primary source pollutant annual storm load from impervious residential land use only (kg/yr)

$\xi_6 = \eta_a * \eta_e * \eta_f$ (obtained from equation 5-12 and Table 5-1)

ω_6 = Implementation factor for downspout disconnection program

Similarly, impervious cover disconnection load reduction in commercial areas is estimated as given in equation 5-27:

$$L_c^{icd} = \frac{U_t}{(A_{com} I_{com})} L_{ic}^{ps} * \xi_6 * \omega_6 \quad (5\text{-}27)$$

For existing and future management programs, the parameter U_t is estimated from equations 5-28 and 5-29 respectively.

$$U_t = F_{com} * F_{bus}(A_{com} * \mathrm{I}_{com}) \quad (5\text{-}28)$$

$$U_t = F_{com}(A_{com} * \mathrm{I}_{com})) \quad (5\text{-}29)$$

Where:

$L^{icd}{}_c$ = Annual pollutant load reduction from ICD in commercial areas (kg/yr)

U_t = Total disconnected impervious cover area (km^2)

F_{com} = Fraction of commercial imperviousness as rooftop

F_{bus} = Fraction of businesses disconnected

A_{com} = Total commercial area (km^2)

I_{com} = Fraction of impervious cover in commercial land use (%)

$L^{ps}{}_{ic}$ = Total primary source pollutant annual storm load from impervious commercial land use (kg/yr, for bacteria million count/yr)

$\xi_6 = \eta_a * \eta_e * \eta_f$ (obtained from equation 5-12 and Table 5-1)

ω_6 = Implementation factor for downspout disconnection program

The total load reduction from impervious cover disconnection *(L_{icd})* is then calculated from equation 5-30 as:

$$L_{icd} = L^{icd}{}_r + L^{icd}{}_c \quad (5\text{-}30)$$

5.4.7 Riparian Buffers (RB) Intervention Load Reduction

The total riparian buffers (RB) load reduction is obtained by direct application of removal efficiencies *(E_{rb})* to the total urban primary and secondary sources annual load *($L^{ps+secs}$)*. By applying equation 5-12 and the implementation factor *(ω)*, the resulting equation for estimating annual pollutant load reduction from riparian buffer intervention is given by equation 5-31:

$$L_{rb} = E_{rb} * L^{ps+\sec s} * \xi_7 * \omega_7 \quad (5\text{-}31)$$

Where:

L_{rb} = Annual pollutant load reduction from riparian buffers program (kg/yr).

$L^{ps+secs}$ = Total pollutant annual load from primary and secondary sources (kg/yr).

($L^{ps+secs} = L^{ps}+L^{secs}$, *and* $L^{secs} = L_{sep}+L_{sso}+L_{ill}+L_{lawn}$)

E_{rb} = Removal efficiency of riparian buffer (%).

$\xi_7 = \eta_a * \eta_c * \eta_f$ (obtained from equation 5-12 and Table 5-1)

ω_7 = Implementation factor for riparian buffers intervention

5.4.8 Impervious Cover Reduction (ICR) Intervention Load Reduction

Impervious cover reduction (ICR) is also a logical stormwater management program but not explicitly required until recently in the United States and Europe. The method is not practiced in many countries but is included here for completeness. Better site design techniques such as narrowing street widths and reducing the number and size of parking spaces can reduce the total impervious cover in urban catchments. Reduction of impervious cover reduces the amount of runoff which in turn, reduces the catchment pollutant loads delivered to streams. ICR is assumed in the model as a future management intervention only.

By applying equation 5-12 and the implementation factor *(ω),* the resulting equation for estimating annual pollutant load reduction from ICR intervention is given by equation 5-32:

$$L_{icr} = L_{ps} * \xi_8 * \omega_8 \quad (5\text{-}32)$$

Where:

L_{icr} = Annual pollutant load reduction from impervious cover reduction program (kg/yr, for bacteria million count/yr).

L_{ps} = Total pollutant annual storm load from primary sources (residential + commercial + industrial) (kg/yr).

$\xi_8 = \eta_a$ (obtained from equation 5-12 and Table 5-1)

ω_8 = Implementation factor for impervious cover reduction intervention

5.4.9 Future Illicit Connection Removal (FICR) Intervention Load Reduction

Future illicit connection removal (FICR) intervention is targeted to remove all of illicit connection load *(L_{ill})* estimated in Section 5.2.3. The resulting FICR load reduction equation is given by equation 5-33:

$$L_{ficr} = L_{ill} * \xi_9 * \omega_9 \qquad (5\text{-}33)$$

Where:

L_{ficr} = Annual pollutant load reduction from FICR program (kg/yr, for bacteria million count/yr).

L_{ill} = Annual pollutant load from all illicit connections (kg/yr).

$\xi_9 = \eta_a$ (obtained from equation 5-12 and Table 5-1)

ω_9 = Implementation factor for illicit connection removal intervention

5.4.10 Sanitary Sewer Overflow Repair/Abatement (SSOR) Intervention Load Reduction

Load reduction from sanitary sewer overflow repair/abatement (SSOR) program may include measures such as repairing blockages, increasing the capacity of sewers, and lining pipes to prevent inflow/infiltration. The intervention is targeted to remove all of sanitary sewer overflows load *(L_{sso})* estimated in Section 5.2.2. The SSOR load reduction equation is given by equation 5-34:

$$L_{ssor} = L_{sso} * \xi_{10} * \omega_{10} \qquad (5\text{-}34)$$

Where:

L_{ssor} = Annual pollutant load reduction from SSOR program (kg/yr, for bacteria million count/yr).

L_{sso} = Annual pollutant load from sanitary sewer overflows (kg/yr, for bacteria million count/yr).

$\xi_{10} = \eta_a$ (obtained from equation 5-12 and Table 5-1)

ω_{10} = Implementation factor for sanitary sewer overflow repair intervention

5.4.11 Septic System Inspection/Repair (SSR) Intervention Load Reduction

This intervention is intended for local municipality to inspect septic systems and ensure the 'failing' systems are repaired by the owners and that effluent from all septic systems to the receiving environment are that of a 'working' system. The procedure for estimating load reduction for SSR intervention is the same as described in Section 5.4.2 and the resulting equation is given by equation 5-35. The derivation of equation 5-35 is the same as provided in equation 5-17.

$$L_{ssr} = L_{sep}\left[1 - \frac{C_{ws}}{C_{fs} * S_f + (1 - S_f)C_{ws}}\right] * \xi_{11} * \omega_{11} \qquad (5\text{-}35)$$

Where:

L_{ssr} = Annual pollutant load from SSR program (kg/yr, for bacteria million count/yr)

L_{sep} = Annual pollutant load from septic systems before repairs (kg/yr, for bacteria million count/yr)

S_f = Fraction of septic systems failing

C_{fs} = Effluent concentration from failing septic systems (mg/l, for bacteria count/100ml)

C_{ws} =Effluent concentration from working septic systems (mg/l, for bacteria count/100ml).

$\xi_{11} = \eta_d * \eta_f$ (obtained from equation 5-12 and Table 5-1)

ω_{11} = Implementation factor for septic system repair intervention

5.4.12 Catchment Surface Erosion and Sediment Control (CatchESC) Intervention Load Reduction

The loss of top soil from catchment surface, the sediment yield carried by rivers and the decrease in storage capacity or reservoirs, together with the environmental degradation associated with soil erosion and sediment transportation, remain one of the major problems facing the development of the water resources of Southern Africa (Schulze, 1995). The Universal Soil Loss Equation (USLE) given by Wischmeier and Smith (1978) provides for an estimate of the long-term average annual soil loss resulting from sheet and rill erosion. It thus excludes the soil loss resulting from concentrated flow and gully formation and if used for sediment yield estimations requires the inclusion of a separate term to represent the delivery ratio, which accounts for the portion of eroded soil which leaves the catchment. The USLE is described by equation 5-36:

$$L_{usle} = 10^5 * D_r * A_c * R * K * LS * CP \qquad (5\text{-}36)$$

Where:

L_{usle} = Annual sediment yield (kg/yr)

D_r = Delivery ratio

A_c = Total catchment area (km^2)

R = Annual rainfall erosivity (N/h/yr)

K = Soil erodibility (ton.h/N/ha)

LS = Slope length and gradient factor

CP = Land use related factors (cover and management factor)

The delivery ratio may be related to catchment drainage density (McElroy et al, 1976, quoted in Quibell et al, 2003). Drainage density may be estimated for each sub-catchment, based on the total length of rivers in the sub-catchment divided by the total area.

The factor R in equation 5-36 is referred to in South Africa as EI_{30} and is defined in Section 4.2.3 as the product of the kinetic energy of a rainfall event and its maximum 30-minute intensity (Smithen and Schulze, 1982) to describe erosivity of rainfall. Smithen and Schulze (1982) estimated long-term average annual EI_{30} values and plotted them on a map of South Africa. Lines of equal rainfall erosivity known as iso-erodent lines, expressed in EI_{30} units were drawn. From this map (Figure 5-2), EI_{30} can be estimated for any location in South Africa.

The soil erodibility factor, K, is defined as the rate of soil loss per rainfall erosion index unit as measured on a standard plot (Renard et al, 1991, quoted in Schulze, 1995). The K-factor thus represents the processes of soil detachment and transport by raindrop impact and surface flow, localized deposition due to topography and tillage induced roughness, as well as rain water infiltration into the soil profile. Approximate K-factor values can thus be allocated by first determining the soil erodibility potential/class of the soil series. The erodibility potential/class of all 501 soil series identified in the Binomial Soil Classification in South Africa is given in Chapter 6 of the ACRU User Manual (Schulze, 1990). The K-factor is then estimated from Table 5-2.

Table 5-2: Erodibility factors for various soil erodibility classes

Soil Erodibility Class	**Soil K-factor**
Very High	> 0.7
High	0.50 - 0.70
Moderate	0.25 - 0.50
Low	0.13 - 0.25
Very Low	< 0.13

The length of a slope of land and its gradient affect the rate of soil erosion by water substantially. Slope length is defined as the distance from the point of origin of overland flow to the point where either the slope gradient decreases sufficiently for deposition to take place, or the runoff enters a well defined natural or artificially constructed channel. The slope length is difficult to estimate and involves considerable judgement. Two guidelines for this estimation are provided:

- In the case where detailed information on the catchment topography is not available, Schulze (1995) estimates slope length (S_{lf}) as in equations 5-37 and 5-38:

  $$S_{lf} = -3.0S_{\%} + 100 \qquad for\ S_{\%} < 25\% \qquad (5\text{-}37)$$

  and

  $$S_{lf} = 25 \qquad for\ S_{\%} \geq 25\% \qquad (5\text{-}38)$$

  Where $S_{\%}$ = slope gradient in per cent.

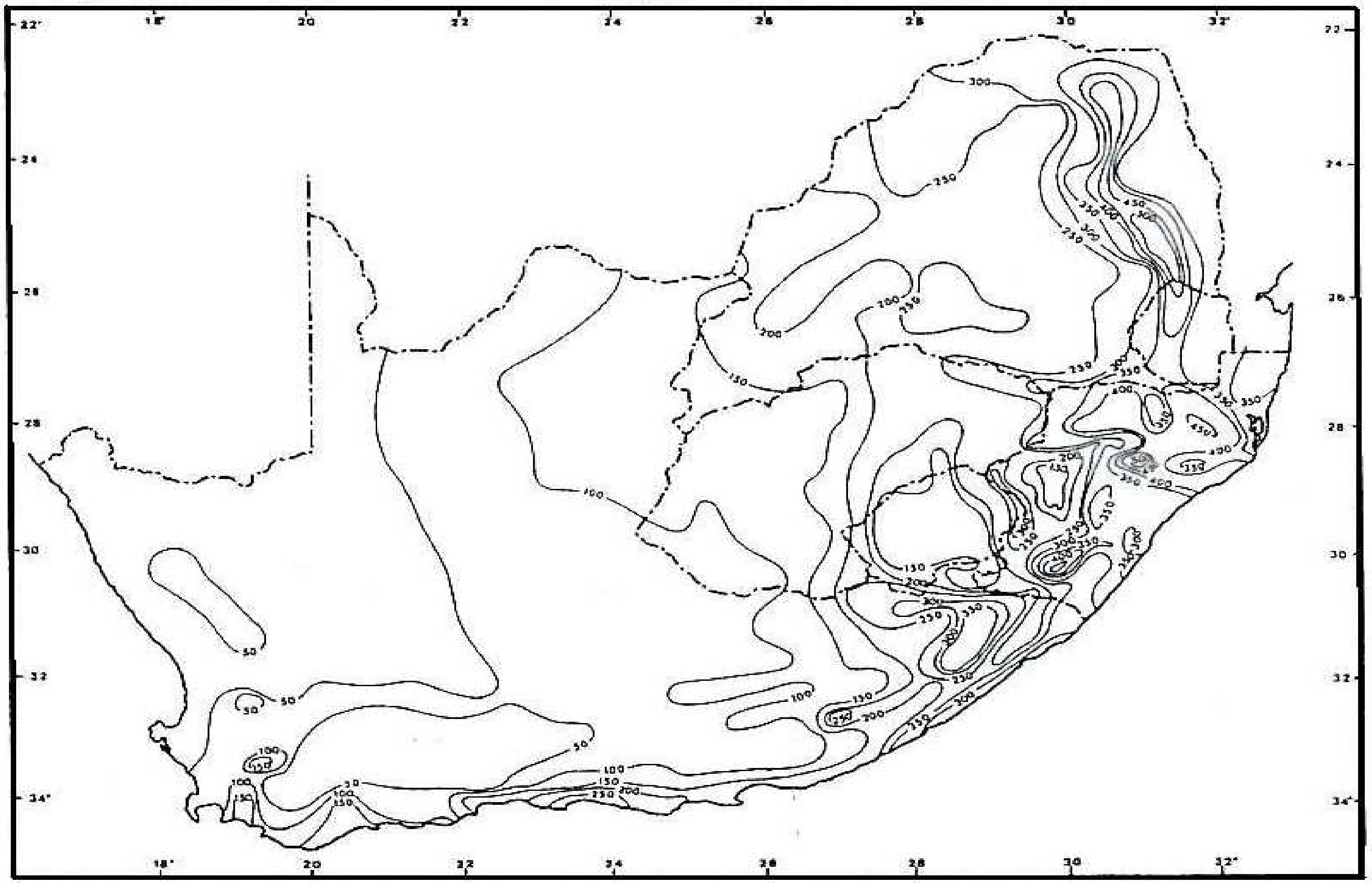

Figure 5-2: Estimated average annual EI_{30} for South Africa (Source: Smithen and Schulze, 1982)

- Soil loss increases more rapidly with slope steepness than it does with slope length. The slope steepness factor (S_{sf}) is given by McCool et al, 1987, (quoted in Schulze, 1995) as in equations 5-39 and 5-40:

$$S_{sf} = 10.8 \sin S_{deg} + 0.03 \qquad \text{for } S\% < 9\% \qquad (5\text{-}39)$$

and

$$S_{sf} = 16.8 \sin S_{deg} - 0.05 \qquad \text{for } S\% \geq 9\%. \qquad (5\text{-}40)$$

where:

S_{deg} = slope angle in degrees.

For slopes shorter than 5m the equation 5-41 should be used to evaluate S_{sf} (McCool et al, 1987, quoted in Schulze, 1995).

$$S_{sf} = 3.0(\sin S_{deg})^{0.8} + 0.56. \qquad (5\text{-}41)$$

The factor *LS* in the equation 5-36 is the product of the slope length (S_{lf}) and slope steepness (S_{sf}) factors described above. Table 5-3 presents the land use related factors (CP) for South African conditions

Table 5-3: Land use related factors with different land use categories (adapted from Quibell et al, 2003)

Land use	Riparian	Grass	Dryland	Rural	Informal	Urban
CP-factor	0.028	0.028	0.15	0.1	0.2	0.15

By applying equation 5-12 and the implementation factor *(ω),* the resulting equation for estimating annual pollutant load reduction from CatchESC intervention is given by equation 5-42 and 5-43.

$$L_{catchescs} = L_{catchss} * P_{eff} * \xi_{12} * \omega_{12} \qquad (5\text{-}42)$$

Where: $L_{catchss} = L_{usle}$ (5-43)

Where enough data is not available to estimate L_{usle}, $L_{catchss}$ can be approximated to equation 5-44.

$$L_{catchss} = L_{ps} - L_{psi} \qquad (5\text{-}44)$$

And the nutrient load reduction resulting from CatchESC intervention is given by equation 5-45:

$$L_{catchescn} = L_{catchescs} * S_{n/p} * E_{n/p} \quad (5\text{-}45)$$

Where

$L_{catchescs}$ = Sediment annual pollutant load reduction from CatchESC intervention (kg/yr)

$L_{catchescn}$ = Nutrient annual pollutant load reduction from CatchESC intervention (kg/yr)

L_{ps} = Total primary source pollutant annual load from both pervious and impervious areas (kg/yr)

L_{psi} = Total primary source pollutant annual load from impervious areas (kg/yr)

P_{eff} = Assumed CatchESC intervention efficiency

$S_{n/p}$ = Soil content of nitrogen or phosphorus (% by weight)

$E_{n/p}$ = Enrichment factor of nitrogen or phosphorus

$\xi_{12} = \eta_a * \eta_d * \eta_f$ (obtained from equation 5-12 and Table 5-1)

ω_{12} = Implementation factor for CatchESC intervention

5.4.13 Rainwater Tanks (RT) Intervention Load Reduction

Use of rainwater tanks as structural control intervention, allow for the modelling of stormwater harvesting and re-use strategies, which may have benefits both for potable water conservation, and also for reduction of runoff volume. The reduction in runoff volume, in turn reduces pollutant loads washed off from the catchment surface. The rainwater tanks control intervention is suitable especially in high-density residential settlements where downspout disconnection is not suitable. It can also be used in conjunction with downspout disconnection in medium and low-density settlements. Rainwater tank intervention may receive greater participation by residents if municipal bylaw is enacted. For voluntary use of rainwater tanks, public participation may be improved by education and financial subsidy (e.g. in the purchase of the tanks).

Rainwater tanks intervention load reduction in residential areas is estimated based on a proportion of rooftop area captured to the total impervious cover in the residential area. Thus, applying equation 5-12 and the implementation factor *(ω)*, the resulting equation for estimating annual pollutant load reduction from rainwater tanks intervention is given by equation 5-46:

$$L_{rt} = 10^6 \frac{D_u * R_{pt}}{A_{res} * I_{res}} L_{ir}^{ps} * \xi_{13} * \omega_{13} \tag{5-46}$$

Where:

L_{rt} = Annual pollutant load reduction from RT intervention in residential area (kg/yr, for bacteria million count/yr)

10^6 = Conversion factor (m^2/km^2)

D_u = Number of dwelling units

R_{pt}= Typical roof area (m^2)

A_{res} = Total residential area (km^2)

I_{res} = Fraction of impervious cover of residential land use

L^{ps}_{ir} = Total primary source pollutant annual load from impervious residential land use only (kg/yr)

$\xi_{13} = \eta_a * \eta_b * \eta_d * \eta_e * \eta_f$ (obtained from equation 5-12 and Table 5-1)

ω_{13} = Implementation factor for rainwater tanks intervention

5.4.14 Exfiltration System (ExS) Intervention Load Reduction

Stormwater exfiltration systems were developed to improve the stormwater quality from fully urbanized areas (Li and Koo, 1994; Tran, 1995). The system consists of two 200 mm perforated pipes, plugged at the downstream end which are laid below the storm sewer at the upstream section of the sewer system. The sewer and the perforated pipes are encased in a granular stone trench wrapped with filter fabric. Figure 5-3 shows a typical cross-section of an exfiltration system. The first flush of runoff will be directed to the perforated pipes with plugged ends. Together with the surrounding granular bedding, this pipe-trench system can store the runoff of a 15 mm rainfall event and allow exfiltration within a certain period of time depending on the permeability of the host soil. Excess runoff will bypass the perforated pipe system and travel through the storm sewer. The perforated pipes can be cleaned by a hydraulic nozzle. Pretreatment of storm runoff using screening at the perforated pipe inlet can also reduce the maintenance requirements.

The stormwater exfiltration system can be constructed within the right-of-way and integrated with storm sewer replacement or road rehabilitation projects. Although the construction of stormwater exfiltration system is generally only cost-effective when road and/or sewer is rehabilitated or replaced, there are circumstances where stormwater exfiltration system may be appropriate for good-conditioned residential road and sewer systems.

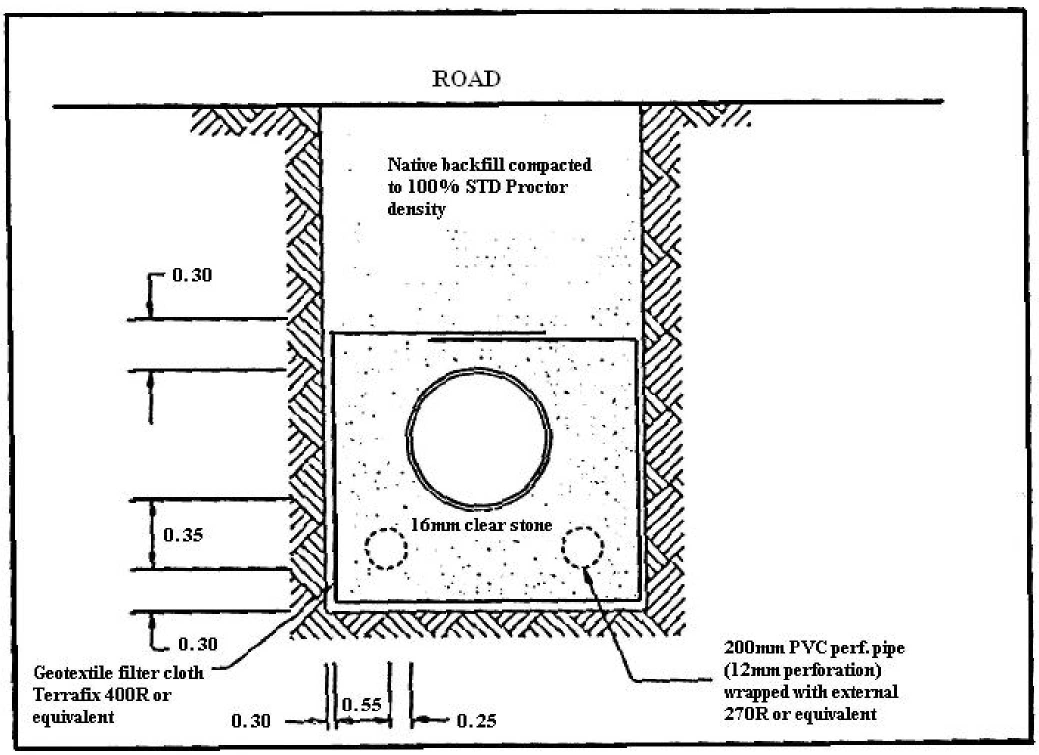

Figure 5-3: Cross-section of exfiltration systems (adapted from Candaras et al.; 1995)

Load reductions are estimated by applying the interventions efficiency *(P_{eff})* to the fraction of storm load from the contributing area $(A_{si}/A_c)L_{ps}$. By applying equation 5-12 and the implementation factor *(ω)*, the resulting equation for estimating annual pollutant load reduction from exfiltration systems intervention is given by equation 5-47:

$$L_{exs} = \left(\frac{A_{si}}{A_c}\right)\left(L^{ps} - L_{ups}\right) * P_{eff} * \xi_{14} * \omega_{14} \qquad (5\text{-}47)$$

The notations in equation 5-47 are defined below

L_{exs} = Annual pollutant load reduction from exfiltration system program (kg/yr)

L^{ps} = Total pollutant annual load from primary sources (kg/yr)

L_{ups} = Total pollutant annual storm load reduction from all upstream interventions (kg/yr)

A_{si} = Area surveyed or inventoried for exfiltration systems retrofit (km^2)

A_c = Total area of catchment (km^2)

P_{eff} = Assumed exfiltration systems intervention efficiency

$\xi_{14} = \eta_a * \eta_b * \eta_c * \eta_d$ (obtained from equation 5-12 and Table 5-1)

ω_{14} = Implementation factor for exfiltration systems intervention

In many cases the same runoff will receive the benefit of non-structural control interventions before being treated by structural control intervention. In this regard, structural control interventions do not act on uncontrolled load, but on this load minus the load removed by upstream non-structural control interventions. Since exfiltration systems are structural control interventions, there is the need to account for load reductions resulting from all upstream non-structural control interventions (e.g. Lawn Care Education, Domestic Animal Waste Education, Street Sweeping, and Downspout Disconnection) that reduce storm loads.

5.4.15 River Assimilative Capacity (RAC) Program Load Reduction

Natural water bodies are able to serve many uses, including the transport and assimilation of waterborne wastes. But as natural water bodies assimilate these wastes, their quality changes. If the quality drops to the extent that other beneficial uses are adversely affected, the assimilative capacities of those water bodies have been exceeded with respect to those affected uses. Water quality management measures are actions taken to ensure that the total pollutant loads discharged into receiving water bodies do not exceed the ability of those water bodies to assimilate those loads while maintaining the levels of quality specified by quality objectives set for those waters.

Natural in-stream processes such as sedimentation, adsorption, aeration and biological degradation are typical removal mechanisms. Providing opportunities for turbulent flow can enhance aeration. Cascades and small weirs can help to increase physical entrainment of oxygen into the water column, and the inclusion of riverine habitats with significant roughness will also promote turbulence and aeration. The efficiency of the pollutant load reduction will depend on factors such as: type and depth of river bed material; river longitudinal slope; river bed roughness and cross-sectional area; flow and initial concentrations. Synthesis of data from a study by Campbell (2001) on the fate of urban runoff from Alexandra in the Jukskei river provides efficiencies of river assimilative capacity of selected pollutants indicated in Table 5-4 for monitoring point at Frankenwald, 2km downstream from the Alexandra weir.

Table 5-4: Jukskei river assimilative capacity efficiency for storm and low flows

Pollutants	TN	PO_4	TP	COD	SS	FC
Storm flow	64%	40%	47%	20%	29%	45%
Low flow	80%	67%	74%	67%	67%	17%

The resulting equation for estimating annual pollutant load reduction from river assimilative capacity is given by equation 5-48:

$$L_{rac} = \lfloor L_{ps} * P_{eff\,1} \rfloor \xi_{15} + \lfloor L_{\sec s} * P_{eff\,2} \rfloor \xi_{15} \qquad (5\text{-}48)$$

Where:

L_{rac} = Annual pollutant load reduction from river assimilative capacity (kg/yr)

L_{ps} = Total pollutant annual load from primary sources (kg/yr)

L_{secs} = Total pollutant annual load from secondary sources (kg/yr)

P_{eff1} = Assumed river assimilative capacity efficiency for storm flow (%)

P_{eff2} = Assumed river assimilative capacity efficiency for low flow (%)

$\xi_{15} = \eta_c * \eta_d$ (obtained from equation 5-12 and Table 5-1)

5.4.16 Other structural control interventions load reduction

Other structural control interventions other than riparian buffers, rainwater tanks, and exfiltration systems fall into this group. They are categorised together because the method of estimating their load reductions are the same but different from the other three structural interventions mentioned above. Also each intervention in this group can not be implemented in phases, for example, 30% of a pond or wetland cannot be implemented to commence operation. Hence the implementation strategy conceptualized in this research (Section 4.4.3) cannot be applied to this group of structural control interventions. The interventions in this group include dry water quality pond, dry extended detention pond, wet pond, wetlands, sand filters, and infiltration basins. Load reductions are estimated by applying interventions efficiency *(T_{eff})* to the storm load (after accounting for load reductions by all upstream interventions) from the contributing area and then apply also equation 5-12. For an existing structural control intervention or a retrofit, load reductions are given by equation 5-549:

$$L_{stm} = \left(L^{ps} - L_{ups}\right)T_{eff} * \xi_{16} \quad (5\text{-}49)$$

Where

L_{stm} = structural treatment control measure annual pollutant load reduction (kg/yr)

L_{ups} = Total pollutant annual storm load reduction from all upstream interventions (kg/yr)

L^{ps} = total pollutant annual storm load from primary sources (kg/yr)

T_{eff} = pollutant removal efficiency of structural intervention in the group (%)

$\xi_{16} = \eta_a * \eta_b * \eta_c * \eta_d$ (obtained from equation 5-12 and Table 5-1)

5.5 Interventions in series

Section 5.4 described the various computation methods to estimate load reductions from non-structural and structural control interventions. Often, the same runoff will receive treatment from two interventions that are in series. For example, non-structural control interventions may reduce runoff loads, and then this same runoff may be directed to structural control interventions. Thus, the treatment from structural control interventions will be the treatment from uncontrolled runoff minus the load removed by all upstream non-structural control interventions that treat storm loads, as described in Sections 5.4.14 and 5.4.16. The only exception of structural control interventions is rainwater tank as it is normally situated at the beginning of the series.

Non-structural control interventions were assumed to be distributed evenly throughout settlement or catchment so that the loads reduced by them can be subtracted from the total catchment load to obtain influent loads to structural control interventions. The model in its current form is not programmed to simulate structural control interventions in series, and it's an area in the model recommended for future improvement. Given the nature of housing developments in informal settlements (high density), it could be expected that structural control retrofits may be only feasible at settlements outlets and thus the need for these interventions to act in series would be minimal.

5.6 Target pollutants in the model

The most important water quality concerns can be categorised into the following groupings: microbiological pollutants, nutrients, sediments, metals, and organic matter (Section 4.3.5). Typical pollutants under each group are shown in Table 5-5.

Table 5-5: Typical pollutants in stormwater runoff

Stormwater quality group	Typical pollutants
Nutrients	Nitrogen and Phosphorus
Sediments	Suspended solids, turbidity, total solids, filterable solids
Pathogens	Fecal coliform, E-coli, fecal streptococci, enterococci
Organic pollutants	BOD, COD, dissolved oxygen (DO)
Metals	Lead, Iron, Copper, Boron

In order to cover all the groupings in the model, at least a pollutant was selected from each group namely:

i. Nitrogen,
ii. Phosphorus,
iii. Suspended solids,
iv. Fecal coliform,
v. COD, and
vi. Lead.

The pollutants were selected to coincide with typical pollutants that have been monitored (e.g. Wimberley, 1992; Wright et. al., 1992, Kloppers, 1989, Van Veelen and DWAF, 1994a) in informal settlements in South Africa. In fact, existing data on stormwater and greywater quality are by and large, on these six selected pollutants.

Comprehensive literature review was then carried out to determine the pollutants that are typically removed by each intervention considered under Section 5.4. The target pollutants (from the six selected pollutants) for each intervention are shown in Table 5-6. Table 5.6 summarises the main features of the interventions used in the model including type of load (storm or non-storm) reduced by each intervention and the factors used in determining pollution reductions.

5.7 Costs of strategies

The model compares the cost of different strategies to select the least cost. The cost of an intervention (Ω) is given by equation 5-50 as a product of its total annualized cost (C_a) and implementation factor (ω). Annual costs (expressed as unit treatment costs) include capital, operation and maintenance costs. Schueler et al (2007) and USEPA (1998) describes methods of estimating capital, operation, and maintenance costs of interventions for point and non-point source pollution control interventions.

$$\Omega = C_a * \omega \qquad (5\text{-}50)$$

The cost of a strategy (Є) consisting of a number of interventions is given by equation 5-51 as the sum of the costs of the interventions.

$$Є = \Omega_1 + \Omega_2 + \Omega_3 + \ldots + \Omega_n \qquad (5\text{-}51)$$

The least cost strategy out of a number of strategies is the one with minimum cost.

5.8 Summary

The principal statement of the problem of this research (Section 1.2) states that: development of comprehensive tools for selection and design of drainage management interventions even at planning levels is still at its early stage in South Africa. Hence planners and engineers are not equipped with the necessary knowledge and tools to deal with stormwater quality problems in informal settlements. For this reason, the forth and fifth objectives of the study were defined: to develop a methodology to select interventions to manage runoff and grey water quality; and to develop a tool to evaluate the selected interventions respectively.

The previous Chapter presented the steps followed during the course of the research to develop a DSS for rapid evaluation of stormwater quality management interventions and the various computations involved were presented in this Chapter.

The main distinguishing features of the DSS compared to a similar model by CWP (2001) are:

- Storm loads estimated in the DSS are loads derived from both pervious and impervious areas whereas CWP (2001) model deals with storm loads only from impervious areas. Studies such as Mackey (1993, 1994a,b), Grobicki (2001), van Ginkel et al. (1993) and Wright et al. (1993) have shown that pervious areas in developing areas contribute substantial loads to the receiving environments.
- The defaults in the DSS were based on studies on water quality management in South African situations. The literature was reviewed extensively to gather information to serve as the expert's knowledge base in the DSS.
- A module to formulate implementation strategies which accommodate assessment of different management intervention scenarios. This will allow a stormwater manager to assess different scenarios by combining different mixes of control interventions at different levels of implementation to meet management objectives.
- Costing to select the optimum management strategy.
- A module to quantify water quality management objectives (load reduction targets) of pollutants of concern.
- Addition of four new interventions (rainwater tanks, catchment erosion and sediment control, exfiltration systems, and river assimilation) that is more suitable for informal settlements in South Africa.

- Estimation and inclusion of ‘subjective risk assessment’. Stormwater managers often need to identify the risk of, or changes in system performance indicator values from what was predicted due to any changes in input data and parameter values. They need to reduce this level of risk to the extent practicable and to communicate the risks clearly so that decisions can be made with this knowledge and understanding

Table 5-6: Main features of interventions used in the model

Interventions	**Type of load** (storm or non-storm)	**Target pollutants**	**Main factors determining pollution reduction**	**Risk factors**
Lawn care education	Storm and non-storm	TN, TP	Typical fertilizer application rate, fraction of fertilizers reduced	η_a, η_e, η_f
Septic systems education	Storm and non-storm	TN, TP, COD, Pb, SS, FC	Fraction of septic systems failing	η_e, η_f
Domestic animal waste education	Storm and non-storm	TN, TP, FC	Proportion of households with domestic animals	η_a, η_e, η_f
Erosion and Sediment control from active construction sites	Storm	TN, TP, SS, FC	Program efficiency, delivery ratio	η_a, η_d, η_f
Street Sweeping	Storm	TN, TP, COD, Pb, SS	Program efficiency, proportion of street area swept	η_a
Downspout Disconnection	Storm	TN, TP, COD, Pb, SS, FC	Proportion of impervious area as rooftop	η_a, η_e, η_f
Riparian Buffers	Storm	TN, TP, COD, Pb, SS	Program efficiency	η_a, η_c, η_d
Impervious Cover Reduction	Storm	TN, TP, COD, Pb, SS, FC	Proportion of impervious area to be reduced	η_a
Illicit Connection Removal	Non-storm	TN, TP, COD, Pb, SS, FC	Number and flow of all illicit connections	η_a
SSO Repair/Abatement	Storm and non-storm	TN, TP, COD, Pb, SS, FC	Average number of annual overflows, volume per overflow	η_a
Septic System Inspection/Repair	Non-storm	TN, TP, COD, Pb, SS, FC	Fraction of septic systems failing	η_d, η_f
Erosion and Sediment control from catchment pervious areas	Storm	TN, TP, SS, FC	Program efficiency, delivery ratio	η_a, η_d, η_f
Rainwater Tanks	Storm	TN, TP, COD, Pb, SS, FC	Proportion of impervious area as rooftop	η_a, η_b, η_d, η_e, η_f
Exfiltration systems	Storm	TN, TP, COD, Pb, SS, FC	Program efficiency, contributing area	η_a, η_b, η_c, η_d
River assimilative capacity	Storm and non-storm	TN, TP, COD, Pb, SS, FC	River assimilation efficiency based on monitored data	η_c, η_d
Other Structural control interventions	Storm	TN, TP, COD, Pb, SS, FC	Treatment measure efficiency	η_a, η_b, η_c, η_d

Note: η_a = fraction of catchment area that can be treated by an intervention; η_b = fraction of annual rainfall that can be captured by control intervention; η_c = factor to reflect design adequacy of interventions; η_d = factor to reflect maintenance level of interventions; η_e = fraction of population that can be reached with education programs; η_f = fraction of population that will change behaviour or participate in the program or comply with standard.

6 MODEL IMPLEMENTATION

A background on the structure of decision models was presented in Chapter 3 and the model development process was presented in Chapter 4. The quantification of the pollution reduction levels by the interventions included in the model were presented in Chapter 5. It is now necessary to clarify how the model was implemented as a decision support system. This Chapter is therefore a logical follow up to Chapters 3, 4 and 5 to achieve the forth objective of the research that states:

- To develop a decision support system for evaluation of potential interventions for storm and grey water management at planning level.

This chapter is divided into four sections, described as below:

Section 6.1 deals with the coding of the model which reflects the *inference engine* and the *user interface* of the expert or decision support system. Section 6.2 presents the model defaults which describe the *knowledge base* of the expert or decision support system. Additional information obtained from literature review of South African studies is added to provide background knowledge and information to help users formulate their own heuristics and alter the defaults. Section 6.3 describes the data requirements and the general application of the model. Section 6.4 presents the summary of the Chapter.

6.1 Model coding

In Section 3.3.1, the structure of the expert or decision support system was presented as consisting of basically the knowledge base, inference engine, and the user interface. The shell of the system was described to consist of the inference engine and the user interface (Figure 3-1). This section of the thesis presents the shell of the expert or decision support system and it is preceded with reasons to support the adopted shell and its trend of developments.

There is a tendency towards computer modeling in civil engineering as an end to a means. Large and sophisticated computer packages have the ability to produce comprehensive reports with supporting data, graphs and files. Compatibility of data files between programs is useful and common. For example, field data can be logged with

GPS, fed to a GIS program, analysed for design, sent to CAD for engineering drawing and reports published. A professional looking engineering end product is achieved. But do engineers and clients always want to go that far and pay for the sophistication?

Software for most engineering calculations is available and used in most design offices. The language of the software is of no concern to the user as sophisticated interfaces facilitate use. But the assumptions and defaults in the software and indeed the method of calculation are often not known by the user. It is no longer possible to step into the calculations and check or follow the calculations. The code is generally inaccessible. The language of programming in most cases is unfamiliar to the engineer. Most engineers now confine their computation ability to spreadsheet type calculations or use a user-friendly package.

When computers became available to engineers around the 1960s, the programming language of the engineer was FORTRAN (Formula translation). The Language had a resemblance to the way engineers were accustomed to setting down their calculations. Other languages appealed to financers, e.g. COBOL. Then BASIC, very similar to FORTRAN, received a boost with HP computers with built-in BASIC compilers. PCs also made BASIC available via DOS. Then GWBasic, QuickBasic, and Widows Orientated Basic became successively more available to the engineer. Older languages became obsolete with changes in machines and operating systems. It required an effort to stay abreast of computer programming. Software development was left to researchers and professional programmers. The more sophisticated input/output coding lost many more practitioners with the introduction of Visual Basic.

With a desire not to lose perspective and not to lose sight of what the end product of software should be, many researchers e.g. Stephenson (2003) have skirted the fringe of computational developments and fortunately software developments have again merged with engineering know-how through Visual Basic for Application in Excel.

Microsoft has introduced the possibility of writing macros in Visual Basic for Application (VBA). VBA provides an opportunity to use the most common Windows programming language, Visual Basic, and apply it to Excel problems. This means that a program can be written in the same easy Basic language that was available with earlier computers, and the program can interface input and output with an Excel spreadsheet to get full value. Not only is data input and output simple and attractive, data is transportable and in recognizable format. For the simple user all he will see is the spreadsheet with input forms, and output in graphical or tabular form. He/she can take the sheets into reports or transmit to clients. For the more sophisticated user he can inspect and modify and add programs with the VBA editor. This type of software occupies very little computer space and can be sent via email because the VBA/Excel software does not need to be transferred.

In keeping with the above trend of developments, the model code was written using macros (procedures) in Visual Basic Application and the model is interfaced with an Excel spreadsheet for its input data and output results. The programming approach was based on the Visual Basic programming language with extensions that enable it to control the different types of objects in Excel. In principle, the programming can be viewed as having two components – the Visual Basic language portion and the Excel object model. The Visual basic portion contains statements that are part of the Visual Basic language. *Statements* are commands that produce some action such as controlling the flow of the program. One such statements is *If…Then…Else*. This tests whether a condition is true. *If* that condition is true, *Then* do some action. *If* it is not true (Else), do a different action. The Excel object models contain objects and properties that describe Excel and its contents. Excel objects are items in Excel that can be changed, such as a workbook, worksheet, and range on a worksheet. Each object has its own set of properties that describe it. These properties are its attributes or characteristics. For example, if you want to set a value of cell D3 to 8, you use a line like

Range ("D3").value = 8

In this example, *value* is a property of *Range.*

The code organizes and controls the steps taken to evaluate the management interventions. The code involves forward chaining of *If-Then* rules (Section 3.3.1) to form a line of reasoning. The code was built into modules with the VBA editor that manipulates and uses data in the knowledge base (Section 6.2) in the EXCEL spreadsheet to evaluate management interventions. The advantage of the EXCEL interface is that, it presents all the model defaults to the user, and the defaults can be changed at the user's discretion.

6.2 Description of model defaults

This Section describes the model defaults, that is, the knowledge base of the decision support system. Often, data from developing areas to run or implement water quality management models are either not available or difficult to obtain. Therefore it becomes necessary to apply heuristic data (Section 3.3.1) rather than attempting to implement a complex model requiring data that do not exist or are expensive to obtain. The description of the defaults presented below are categorised according to each intervention considered in the decision support system, and ***all the defaults can be changed in the model at the user's discretion***.

6.2.1 Defaults in the estimate non-storm loads from secondary sources

Model default values for individual per household, sewer use (per capita wastewater generation), and wastewater concentrations are presented in Table 6-1.

Table 6-1: Wastewater Use and Concentration Data (Typical South African data)

Parameter	Model Default	Source
Individuals per household	6	RED BOOK, 1995
Sewer use (Per capita wastewater generation)	125 l/c/d (0.125m^3/c/d)	RED BOOK, 1995
TN	105 mg/l (as total of TKN = 65 mg/l and NH_4 = 40 mg/l)	IWPC (1984)
TP	13 mg/l	IWPC (1984)
COD	600 mg/l	IWPC (1984)
Pb	0.1 mg/l	IWPC (1984)
SS	350 mg/l	IWPC (1984)
FC	10^7	IWPC (1984)

6.2.1.1 Septic systems

The defaults and other information for septic systems relate to equations 5-1 to 5-3 in Section 5.2.1. A Water Research Commission study by Wright (1995) investigated the situation of septic systems in South Africa and established the following baseline information:

- The septic tank system is the most commonly used method of domestic wastewater treatment in the coastal zone of South Africa. The design and management of these systems vary greatly within the region and differences even occur within single local authority areas.
- Wastewater disposal by means of septic tank systems is a well-established technology and a wealth of technical information is available on design criteria. There is, however, a general lack of technical knowledge at the "user" level and lack of legislation pertaining specifically to septic tank systems.
- Lack of a sufficiently thick, unsaturated zone is the greatest problem encountered in the coastal zone leading to horizontal flow at shallow depths, water-logged conditions and return flow.
- The pollutants of greatest concern in the coastal context are nutrients (nitrogen and phosphorus) and biological contaminants (bacteria, parasites and viruses). Field studies indicated that a correctly designed and constructed drainage field effectively

retains these pollutants within a radius of 20 to 50m of the discharge point. Nitrogen does, however, have the potential to contaminate groundwater and should be regarded as a conservative constituent. Ideally the drainage field should be 5m above any impermeable layer and/or water table and 30m away from any surface water body. The distance from a groundwater supply point should be at least 50m and ideally 100m.

- There is an urgent need for greater control in the use of septic tank systems within the coastal zone. Greater attention must be given to the drainage field component of septic tank systems, as this currently receives minimal attention and is the cause of most pollution problems.
- The septic tank system remains the most cost efficient means of domestic wastewater disposal for the coastal zone. The systems must, however, be correctly designed, constructed and maintained.

Results from Wright (1999) clearly indicate how effective the coastal sands are in purifying the effluent. The working septic system effluent concentrations at the catchment outfall (C_{ws}) can be estimated as typical septic tank effluent concentrations at tank site multiplied by delivery ratios, as given by equation 5-2. The effluent concentrations shown in Table 6-2 are concentrations at the site of the septic systems while the delivery ratios in Table 6-3 are for estimating pollutant transport to streams.

The derivation of the model defaults (i.e. working septic system effluent concentrations) assumed a value for the delivery ratio as presented in Table 6.3. It’s unlikely the assumptions will apply in all situations, thus site specific data (where available) may be substituted for the defaults in Table 6-3.

Table 6-2: Septic tank effluent quality (adapted from Wright, 1999)

Determinant	Normal domestic septic tank effluent, monitored at tank site (mg/l)
K	23.9
Na	101.0
Ca	18.5
Mg	7.9
NH_4-N	8.2
SO_4	2.8
Cl	141.0
Alk ($CaCO_3$)	363.0
NO_x-N	<0.1
PO_4-P	14.2
DOC	26.0
EC	126.0
pH	6.8
Faecal Coliform	3.6×10^6

Table 6-3: Attenuated effluent concentrations from working septic systems

Parameter	Model default	Assumptions
Failure rate	50%	
TN	20 mg/l	Assume a 50% delivery ratio and a tank site effluent conc. of 40 mg/l
TP	0 mg/l	Assume 0% delivery ratio
COD	0 mg/l	Assume 0% delivery ratio
Pb	0 mg/l	Assume 0% delivery ratio
SS	0 mg/l	Assume 0% delivery ratio
FC	0 count/100ml	Assume 0% delivery ratio

Hence the model uses a weighted average concentration for each constituent based on the assumption that of all septic system failures, 10% are complete failures, essentially resulting in a direct wastewater discharge, and the remainder contribute to subsurface flow only. Table 6-4 presents the default concentrations used in the model which were derived by application of equation 5-3 in Section 5.2.1.

Table 6-4: Effluent concentrations from failing septic systems

Parameter	Model default	Assumptions
TN	30 mg/l	Assume a 50% delivery ratio for subsurface flow
TP	2 mg/l	Assume 0% delivery ratio for subsurface flow
COD	60 mg/l	Assume 0% delivery ratio for subsurface flow
Pb	0.1 mg/l	Assume 0% delivery ratio for subsurface flow
SS	40 mg/l	Assume 0% delivery ratio for subsurface flow
FC	1.0×10^6 count/100ml	Assume 0% delivery ratio for subsurface flow

6.2.1.2 Sanitary Sewer Overflows (SSOs)

The defaults and other information in this subsection relate to equations 5-4 and 5-5 in Section 5.2.2. Based on information from AMSA (1994), eighty-seven SSOs occur per 1000km of sewer per year. Johannesburg Water scorecard indicates that 80% of sewer burst are restored within 24 hours (Johannesburg IDP, 2003). If an average time of 18 hours (default) is accepted as the duration of overflow then using the information on sewer use, and individual per household from Table 6-1, typical SSO volume may be estimated from the equation 5-5. Site-specific knowledge about the number and frequency of overflows on an annual basis, coupled with detailed system inventory information greatly improves the flow estimate. The model defaults 50% of the SSOs load for each storm and non-storm loads.

6.2.1.3 Illicit Connections (IC)

The defaults and other information in this subsection relate to equations 5-6 to 5-9 in Section 5.2.3. For residential connections, the model's default is that 1% of sewered dwelling units are illicitly connected to storm drains. For businesses, default wash water and total flow characteristics are shown in Table 6-5. The defaults for businesses having illicit connections are 10% and 90% respectively.

Table 6-5: Defaults for Business Illicit Connections

		Connection Type	
		Wash water [a]	**Total flow concentration**[b]
Flow (m^3/connection/day)		0.76	1.14
Pollutant concentrations	**TN (mg/l)**	15	69
	TP (mg/l)	10	12
	COD (mg/l)		
	Pb (mg/l)		
	SS (mg/l)	150	270
	FC (count/100ml)	0	6,000,000

a: Concentrations derived from U.S. EPA, 1980
b: Total flow concentration is a combined wastewater and wash water concentrations

6.2.1.4 Lawns - subsurface or base flow

The defaults and other information in this subsection relate to equations 5-10 in Section 5.2.4. The default fraction of rainfall infiltrated for each soil group is indicated in Table 6-6. Concentration data of nutrients in urban subsurface flow are highly variable, and depend on the type and amount of fertilizer used, timing of fertilization, and soil types (Petrovic, 1990; Schueler, 1995a). Table 6-7 presents typical ranges of values for nutrient concentrations of leachate associated with different land uses in South Africa based on a synthesis of values from NSI (1996), Novotny and Olem (1994), Pegram and Gorgens (2001), and Mills et al. (1985). The model uses default value of 3 mg/l for nitrogen and 0.1 mg/l for phosphorus for informal settlement.

Table 6-6: Fraction of rainfall infiltrated in different hydrologic soil group (Horsley, 1996)

Hydrologic Soil Group	Default fraction of rainfall infiltrated
A	0.45
B	0.3
C	0.15
D	0.075

Table 6-7: Nutrient concentrations of leachate for different rural land uses in South Africa.

Land use type	Nitrogen (mg/l)	Phosphorus (mg/l)
Undisturbed (grassland and woodland)	0.01 – 0.03	0.005 – 0.02
Livestock	0.05 – 0.1	0.01 – 0.03
Crop land	0.05 – 0.5	0.01 – 0.02
Forestry	0.01 – 0.02	0.005 – 0.01
Settlement (informal)	1 - 5	0.05 – 0.5

6.2.2 Defaults in the estimate risk factors

The defaults and other information in this subsection relate to equation 5-12 in Section 5.3 as well as to equations 5-13 to 5-49 in Section 5.4.

6.2.2.1 Defaults in the estimate of η_b

The factor η_b reflects a fraction of annual rainfall that can be captured by the control intervention and the default is 90%.

6.2.2.2 Defaults in the estimate of η_c

The factor η_c reflects design adequacy of management interventions. No data is available in South Africa to propose or quantify these values. However, the values suggested by CWP (2001) in Table 6-8 are used as defaults in the model.

Table 6-8: Defaults for η_c (source: CWP, 2001)

Description of existing design practice	η_c
Specific design standards, including location, and performance enhancing features. Legally binding and enforced.	1.2
Same as 1, but not legally binding.	1.0
Legally binding design standards exist, but do not specify site restrictions for treatment control measures, or do not explicitly define design features to enhance performance.	1.0
No design standards.	0.8

6.2.2.3 Defaults in the estimate of η_d

The factor η_d reflects maintenance adequacy of management interventions. No data is available in South Africa to propose or quantify these values, however, the values shown in Table 6-9 are used as defaluts in the model.

Table 6-9: Defaults for η_d (source: CWP, 2001)

Description of design practice	η_d
Regular maintenance is specified in design guidance, and is regularly conducted by the community. Alternatively, a private owner conducts regular maintenance, and the community regularly inspects practices and has an enforcement mechanism.	0.9
Regular maintenance is specified in design guidance, but the community has a poor tracking system or limited staff to ensure that maintenance occurs.	0.6
There is no guidance specifying when and how maintenance will occur.	0.5

6.2.2.4 Defaults in the estimate of η_e and η_f

The factors η_e and η_f represent the fraction of population that can be reached with educational programs and the fraction of population that will change behaviour respectively. The screening of "Soul City" (series 1 to 3) in South Africa between 1994 and 1997 as an educational vehicle was part of "multi-media health promotion strategy" campaign to make appropriate use of radio, television and print media for health promotion. This took the form of a 13-part television drama; a 15 minute radio drama in 8 languages; and serialised booklets as inserts in 10 newspapers. The central message conveyed was that clean water and good sanitation are central to good health and hygiene practices. A pilot study of "the use of multi-medias an educational tool" in Mamelodi (Skosana, 2001) was done to establish whether the messages of "Soul City" had a long-term impact. The results revealed that respondents mostly viewed the television series as fictional entertainment (may be due to lack of education as well as inadequate access to appropriate services). The respondents were asked to rate the method that may have greater impact in the lives of people in respect of the daily health issues that affect them. Table 6-10 presents results for each media type which were used as defaults in the model.

Table 6-10: Defaults for η_e (adapted from Skosana, 2001)

Media Type	η_e
Spiritual healers/sangomas/traditional leaders	12%
Churches	2%
Community meetings	1%
Women societies and groups	17%
Health campaigns at local clinics	5%
Advertisements (e.g. billboards)	22%
Education of child-care minders	25%
Television	16%

The deduction by Skosana (2001) was that 84% of the respondents took messages seriously and changed behaviour. The model therefore defaults η_f to be equal to 0.84. Taylor and Wong (2002) provide a critical evaluation of translation of awareness through to attitude change through to behaviour change. Their study has found major differences or incongruities between people's attitude and their actual behaviour. They also note that there is uncertainty over the transferability of the results obtained from some evaluation exercises, as the value of some interventions depends on the *context* within which they are applied. For example, an education and enforcement program in a high density residential area may produce a reduction in the percentage of the population that wash their car on the street (rather than in a sewered wash bay) from 80% to 40%. An identical campaign may be run in another part of the city with similar land use, but if affordable wash bays were not as readily available, it is unlikely this magnitude of behavioural change would result. The user is therefore encouraged to substitute these defaults with site specific information.

6.2.3 Defaults in Fertilizer Use Education Intervention Load Reduction

The defaults and other information in this subsection relate to equation 5-13 and 5-14 in Section 5.4.1. There is very little information on nutrient cycle and fate in settlement gardens or lawns and citizen behaviour is quite variable as well. Defaults presented below were made in the model based on broad generalizations (heuristics) derived from a review of scientific literature (Starr and DeRoo, 1981; Petrovik, 1990; Schueler, 1995a):

- Residents apply approximately 168.14 kg/km^2-year of nitrogen, and 16.81 kg/km^2-year of phosphorus.
- Community will reduce this application rate by 50%.
- 25% of the reduction in application of nitrogen would have been lost in runoff or infiltration. Little data are available on the fate of phosphorus applied to lawn, thus it was assumed that only 5% of applied phosphorus is lost to the environment.
- 60% of residential pervious surface are managed as lawns and/or gardens. However, in townships and rural areas, this value may be low and can be changed in the model at the user's discretion.
- The load reduction is partitioned between surface and subsurface reductions, depending on the soil type. Data from Nizeyimana et al. (1997), suggests that the surface load component of fertilizer lost to the environment is 3%, 10%, 30% and 90% for soil type A, B, C, and D respectively. For phosphorus, the same factors are 10%, 35%, 80%, and 95%.

Motaung (2001) conducted a household survey for environmental baseline assessment in four villages in Eastern Cape of South Africa and found that 86% of households use a portion of the land on which they built as a garden for growing crops or vegetables or both. It is defaulted that this fraction (86%) represents individuals that fertilize their gardens and/or lawns, and that 65% of these people 'over-fertilize'. Hence, the $\boldsymbol{\eta_a}$ for lawn care education program, which is given by the product of the fraction of individuals that fertilize and fraction that 'over-fertilize' is 0.56 (i.e. 0.86 x 0.65). All defaults can be changed in the model at the user's discretion.

6.2.4 Defaults in Septic System Education Intervention Load Reduction

The defaults and other information in this subsection relate to equation 5-17 in Section 5.4.2. Ideally, septic system education would eliminate all failing septic systems. It is assumed that the owners of all failing septic systems do not conduct proper maintenance and hence they are all target audience in SSE. Defaults for η_a and η_e in the model are therefore both equal to 1. All defaults can be changed in the model at the user's discretion.

6.2.5 Defaults in Domestic Animal Waste Education Intervention Load Reduction

The defaults and other information in this subsection relate to equations 5-18 and 5-19 in Section 5.4.3. Domestic animal waste production *(W_{pro})* refers to the mass of faeces produced (daily or annually) by a particular domestic animal. Concentration or mass of pollutant in domestic animal waste *(C_{daw})* refers to the mass of a pollutant in a unit mass of feaces. Few South African data are given in Tables 6-11 and 6-12:

Table 6-11: Domestic animal waste mass

Animal	[1]Mass of faeces, W_{pro} (ton animal^{-1} year^{-1})	[2]Mean daily wet mass of faeces, W_{pro} (kg animal^{-1} day^{-1})
Cattle	0.63 – 0.73	23.6
Chickens	0.038	0.182
Ducks	0.038	0.336
Geese	0.040	
Turkeys	0.040	0.448
Horses	0.35 – 0.39	
Pigs	0.100	2.7
Sheep	0.035	1.13

Note: 1 Tshiteya (1985), quoted in Kolbe (1990). It is not stated whether the data refer to wet or dry mass.
2 Reddy et al. (1981)

Table 6-12: Domestic animal waste characteristics (Petersen et al., 1956)

Animal	Concentration of pollutant in domestic animal waste *(C_{daw})*		
	Nitrogen (kgs/kg)	Phosphorus (kgs/kg)	Fecal Coliform (10^6 colonies/kg)
Cattle	0.0057	0.0013	230
Sheep	-	-	16000
Pigs	-	-	3300
Chickens	-	-	1300
Turkeys	-	-	290
Ducks	-	-	33000

6.2.6 Defaults in Active Construction Erosion and Sediment Control Intervention Load Reduction

The defaults and other information in this subsection relate to equations 5-20 to 5-23 in Section 5.4.4. The default runoff coefficient for pervious surface at construction sites is 0.5. Schueler and Lugbill (1990) estimated average concentration of sediment from construction sites to be 680 mg/l and this value is used as a default in the model. Nitrogen and phosphorus concentrations may be estimated based on sampling of the in-situ soil or existing local soil surveys. If sediment samples are used, this already reflects the nutrient enrichment and the enrichment ratio is equal to 1. A default enrichment factor of 2 is used as per the suggestion for nutrient modeling reported in Haith *et al*. (1992). The default for the potency factor is 10^{12} MPN/ton. Typical nitrogen content in soils is 500mg/kg to 2000mg/kg, while typical phosphorus content is between 250mg/kg to 1000mg/kg (Pegram and Gorgens, 2001). The default efficiency for ACESC intervention is 50%. The default for the factor to reflect maintenance level of interventions (η_d), fraction that will comply with standard (η_f) are based on a study by Patterson (1994) and are shown in Table 6-13.

Table 6-13: Risk factors for active construction erosion and sediment control (adapted from CWP, 2001)

Risk factors	Description	Value
η_f	Few inspectors; no preconstruction meeting, poor practices allowed by codes and regulations.	0.4
	Inspectors can visit sites monthly; pre-construction required for larger sites.	0.7
	Inspectors visit sites weekly or on-site or certified inspectors; education programs for inspectors and contractors.	0.9
η_d	Few inspectors; no preconstruction meeting, poor practices allowed by codes and regulations.	0.3
	Inspectors can visit sites monthly; pre-construction required for larger sites; regulations prohibit least effective practices.	0.6
	Inspectors visit sites weekly or on-site or certified inspectors are used; education programs for inspectors and contractors; practices that perform poorly are not permitted	0.9

6.2.7 Defaults in Street Sweeping Intervention Load Reduction

The defaults and other information in this subsection relate to equations 5-24 and 5-25 in Section 5.4.5. Efficiencies depend on pollutant type, type of sweeping technique and frequency of sweeping.

Broom (Wanielista (1978)

Broom type mechanical sweepers remove litter, dust and dirt from city streets. They are relatively inefficient for the removal of the fine solids fraction of street materials. Efficiencies are: Solids – 87%, BOD_5 – 20%, N – 10-25%, and P – 2-30%.

Advanced sweeping (Wanielista (1978)

These are brush and vacuum mechanical sweeping. A greater portion of the finer solids fraction of the street surface contaminants is removed. Efficiencies are approximately: solids (dry weight) – 90%, BOD_5 – 60%, PO_4-P – 2-30% and Heavy Metals – 85%.

The frequency of sweeping affects the effectiveness of the intervention to reduce pollutant load. The factor η_f is applied to account for the uncertainty associated with frequency of sweeping. Street sweeping efficiency depends on the sweeping technique. The efficiency of sweeping is reduced if the sweeper is unable to sweep the entire road surface principally due to cars parked on streets and also due to the fact that the operators may not be well trained. Hence, a factor η_e is applied to the efficiencies to account for these deficiencies. Default values for η_e and η_f are shown in Table 6-14.

Table 6-14: Suggested values for frequency and efficiency for street sweeping program (adapted from Wanielista, 1978)

Risk factors	Description	Value
η_f	Weekly	1.0
	Monthly	0.6
η_e	No parking restrictions; no operator training	0.5
	Parking restrictions; no operator training	0.75
	Parking restrictions; Operator training	1.0

6.2.8 Defaults in Downspout Disconnection Intervention Load Reduction

The defaults and other information in this subsection relate to equations 5-26 to 5-30 in Section 5.4.6. The following defaults were used in the model:

- Typical roof area = 186m^2
- Fraction of commercial land use imperviousness as rooftop = 0.3
- Fraction of commercial land applicable for downspout disconnection = 0.25

6.2.9 Defaults in River Assimilative Capacity Intervention Load Reduction

The defaults and other information in this subsection relate to equation 5-48 in Section 5.4.15. The defaults for river assimilation efficiency are presented in Table 6-15 and were adapted from the study by Campbell (2001). In the study, a 6km stretch of the Jukskei River just downstream of Alexandra settlement was used to determine the different biological, physical and chemical processes that pollutants undergo during natural assimilation, their rates and efficiencies of assimilation in rivers and their impact on the environment downstream of the area. “Grab” samples were taken (2km intervals) over the study period which included both low-flow and storm events

Table 6-15: River assimilation efficiency (adapted from Campbell, 2001)

Type of flow	River assimilation efficiency (%)					
	TN	TP	COD	Pb	SS	FC
Storm	64	47	20	10	29	45
Non-storm	80	74	67	10	67	17

6.2.10 Defaults in Catchment Erosion and Sediment Control Intervention Load Reduction

The defaults in this subsection relate to equations 5-36 and 45 in Section 5.4.12. The default efficiency for catchment erosion and sediment control intervention is 50%.

6.2.11 Defaults in Riparian Buffer Intervention Load Reduction

The defaults in this subsection relate to equation 5-31 in Section 5.4.7. The default efficiencies for riparian buffer intervention are presented in Table 6-15.

Table 6-16: Riparian buffers efficiency (from Schueler et al. 2007*)

Pollutants	TN	TP	COD	Pb	SS
Efficiency (%)	30	10	40	70	70

* The efficiencies are for water quality swales

6.2.12 Defaults in Other Structural Control Interventions Load Reduction

The defaults in this subsection relate to equation 5-49 in Section 5.4.16. The default efficiencies for the interventions are presented in Table 6-17.

Table 6-17: Other Structural Control Interventions efficiency (from Schueler et al. 2007)

Type of intervention	**Efficiency (%)**				
	TN	TP	COD	Pb	SS
Dry water quantity pond	5	19	1	3	10
Dry extended detention pond	25	19	2	47	60
Wet pond	33	51	60	80	70
Wetland	30	49	70	76	78
Water quality swales	38	34	60	81	10
Filters	38	59	67	86	37
Infiltration basin	51	70	60	90	90

6.3 Evaluation approach

The ultimate objective of this research was to develop a decision support system which is able to assist the decision making body in evaluating various catchment storm and grey water quality management interventions in the most efficient and effective manner. The process of the evaluation must be appropriate to the application in question and to the level of answers required.

6.3.1 Decision making process

A decision making process is complex and in order to implement a decision support system it is necessary to define the decision making beforehand in a context. Decision making is defined as the assessment of ill-structured (unstructured) problems (Simon and Newll, 1958). Unstructured decisions involve heuristics, trial-and-error, intuition, and common sense in addition to logic; the relevant factors and outcomes are somewhat vague and tend to be more qualitative than quantitative. The uncertainty involved in unstructured problems makes the decision making process unique and requires an evaluation of the decision maker's preference.

The decision support system assists the decision maker in evaluating all the options via five steps (shown in Figure 6-1). A user selects interventions and formulates independent strategies. Information on each strategy is input into the model at a time/run. A strategy is a combination of different mixes of interventions. The model then evaluates the strategy and if the water quality objectives are met optimally, the strategy is recorded else, the implementation factors of the strategy are successively adjusted/improved until objectives are met optimally. The process is repeated for different independent strategies and the best (having least cost) of all recorded strategies is selected.

In using a model to formalize the decision making process, two benefits are gained regardless of whether the final outcome meets the set objective or not. The first benefit is a 'structurization' of the problem. i.e., the water quality problems and the causes of the problems must be clearly defined following which the management interventions must be identified and screened to satisfy all implementation requirements before they can be incorporated into the model. This clarifies the problem in the planners' minds, eliminates inconsistencies, allows for hierarchical pollution management application, and allows the decision makers to more clearly assess the solution possibilities. The second benefit lies in the elicitation of the preference strategy of the decision makers, permitting an insight into the implementation of the various strategies. Particular biases and specific interests become more apparent and can be dealt with. This process must be carried out successively in order to reach an acceptable preference strategy.

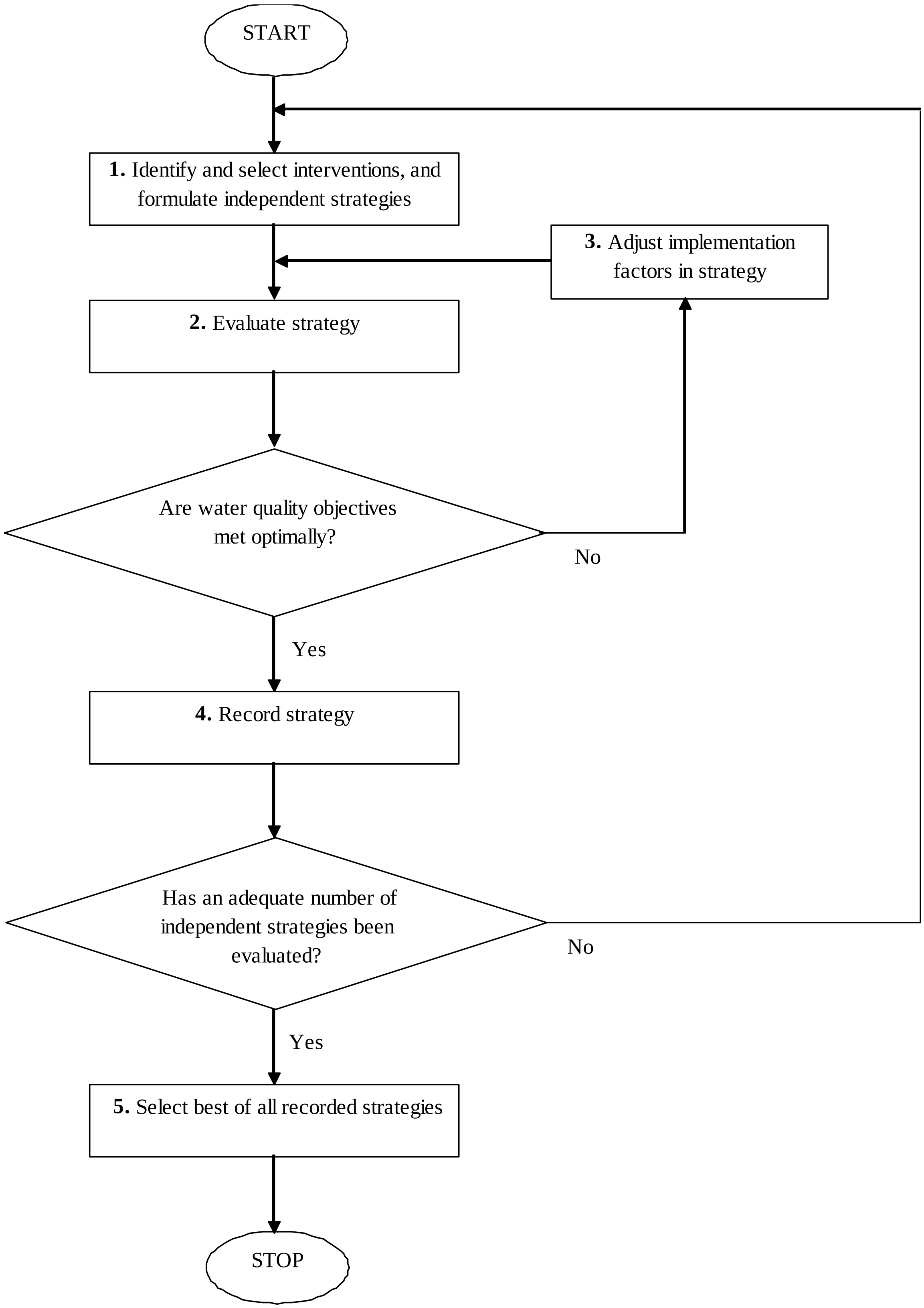

Figure 6-1: Illustration of the decision making process

6.3.2 Data requirements and model operation

6.3.2.1 Data requirements

One of the intentions of the model implementation has been to provide an appropriate level of analysis without demanding a lot of input data. This was achieved by capturing factual and heuristics data in the knowledge base of the expert systems that are used as defaults. As the number of identified or preferred management interventions increase the demand for data increases. Each management intervention requires data specific to its evaluation. The data is entered under the five categories namely: catchment data, storm load data, non-storm load data, existing intervention data, and future intervention data.

Under the catchment data category, catchment MAP, area, planning horizon, and ambient water quality objectives are entered. All the data in this category need to be filled out to prevent errors as they are used frequently in different modules to estimate loads and load reductions. The planning horizon in the model is the maximum period the set management objectives are expected to be achieved. When the model is run, the implementation timeframe of the future management interventions are compared to the planning horizon. A management intervention is excluded in the analysis if its implementation timeframe is more than the planning horizon. The storm load data category requires data on land use types and their associated: fraction of impervious areas, runoff coefficients (for both pervious and impervious areas), and event mean concentrations. Data required for non-storm load category depend on the sources of non-storm loads present. Data required for each source are:

- Sewage use data: – dwelling units or number of households
- Septic systems data: – fraction of dwelling units using septic systems
- Illicit connections data: – number of businesses
- Sanitary sewer overflows data: – total length of sanitary sewer
- Nutrients and bacteria in urban soil data: – soil content of nitrogen and phosphorus (% by weight)
- Active construction erosion and sediment control data: – area of active construction

- Catchment erosion and sediment control data: - annual rainfall erosivity, soil erodibility, slope length and gradient factor, cover and management factor, and delivery factor. These data are discussed in Section 5.4.12.
- Lawns data: - fraction of the soil in the catchment that are Hydrologic soil group A, B, C, and D.

Similarly data required for existing and future interventions categories depend on the number interventions existing or planned for implementation. Data required for each intervention are:

- Active construction erosion and sediment control intervention: - fraction of building or construction sites that are regulated and unit treatment cost
- Catchment erosion and sediment control intervention: - fraction of pervious areas controlled or planned for implementation and unit treatment cost
- Street sweeping: - area swept, frequency of sweeping and unit treatment cost
- Downspout disconnection intervention: - fraction of residential land where the intervention is applicable, fraction of homes or businesses disconnected and unit treatment cost
- Rainwater tanks intervention: - fraction of residential land where the intervention is applicable, fraction of homes with rainwater tanks and unit treatment cost
- Impervious cover reduction: - area of impervious land to be redeveloped, fraction of impervious cover reduced and unit treatment cost
- Illicit connection removal intervention: - fraction of drainage system surveyed or inventoried and unit treatment cost
- Sanitary sewer overflows repair intervention: - fraction aimed to be reduced, and fraction completed and unit treatment cost
- Septic system repair: - fraction of the system inspected, and fraction of population with septic system willing to repair and unit treatment cost
- Riparian buffers intervention: - buffer length, buffer width and unit treatment cost
- Exfiltration systems: - area of land surveyed for the implementation of the intervention, fraction of that area that is applicable for the intervention and unit treatment cost

- Other structural control interventions: - for the existing ones, the data required include contributing areas to the interventions. For retrofits, data required include area surveyed for the retrofits, fraction of that area treatable, fraction of the area as impervious cover, number of retrofits built per year and unit treatment cost.

For future interventions, data on implementation timeframe and magnitude must be provided for each intervention. The onus is on the user to estimate the unit treatment cost of each interventions.

The cost data category is the only place in the output sheet where the user inputs data. For a strategy that achieves management objectives, the total cost of the strategy and the implementation factors (i.e. magnitude of implementation) of the interventions should be recorded in the corresponding fields in the cost data category.

6.3.2.2 Model application

The model is a decision support system for rapid assessment of various catchment water quality management interventions. Although a simple model, it requires significant data input depending on the number of management interventions existing or planned for implementation. The model is primarily targeted at those who are involved or are likely to be involved in stormwater quality management including catchment managers, local governments or municipalities, catchment management agencies, private consultants and researchers. The model is not a design tool; does not contain the algorithms necessary for design of structural stormwater quality facilities and it should therefore be viewed as conceptual evaluation and selection tool at planning level.

The model application flowchart is presented in Figure 6-2 and the sequential steps involved are described below. A detailed description of the operation of the model (DSS) is given in the user manual in Appendix C.

The first step in the model application is catchment data input. Data required in each input category is described in Section 6.3.2.1. The second step is input of water quality objectives for pollutants of concern. At this point, it is assumed that the water quality objectives for the catchment would have been established and pollutants of concern have been defined. The methods to establish water quality objectives and identify pollutants of concern are described in Chapter 4, Sections 4.3.5 through to 4.3.9. The third step involves input of data on existing management interventions also described in Section 6.3.2.1. To estimate the load reduction target, one has to compare the load from monitored data (less the load reduced from existing interventions) with the load from set water quality objectives. Hence the third step is not required if the monitoring point is downstream the existing interventions as the load estimated from the monitoring data would have already accounted for the load reduced by the existing interventions. The forth step is to run the model to evaluate the existing interventions and determine the catchment load reduction targets or management objectives. Computational methods to estimate load reductions are described in Section 5.4. Load reduction targets for storm and non-storm loads are estimated as given by equations 6-1 and 6-2 respectively.

$$T_{red} = \frac{T_{sl} - T_{sl}^{'} - T_{slext}}{T_{sl} - T_{slext}} \times 100 \qquad (6\text{-}1)$$

$$T_{red}^{'} = \frac{T_{nsl} - T_{nsl}^{'} - T_{nslext}}{T_{nsl} - T_{nslext}} \times 100 \qquad (6\text{-}2)$$

Where:

T_{red} = Pollutant storm load reduction target

T_{sl} = Pollutant storm load from monitored concentrations

T'_{sl} = Pollutant storm load from ambient water quality objectives' concentrations

T_{slext} = Pollutant storm load reduced by existing interventions. If monitoring was undertaken downstream of interventions then $T_{slext} = 0$

T'_{red} = Pollutant non-storm load reduction target

T_{nsl} = Pollutant non-storm load from monitored concentrations

T'_{nsl} = Pollutant non-storm load from ambient water quality objectives' concentrations

T_{nslext} = Pollutant non-storm load reduced by existing interventions. If monitoring was undertaken downstream of interventions then $T_{nslext} = 0$

Step 5 consists of input of data on future management interventions. This is preceded by identification of interventions and formulation of alternative management strategies, described in Sections 4.4.1 to 4.4.3. Step six is to run the model to: a) evaluate future interventions strategy, and b) estimate residual load reduction targets. If the objective is met, that is, the residual load reduction targets are zero, the strategy (implementation factors and cost) is recorded in the seventh step. Steps five to seven is repeated for different strategies formulated. In the last step, the strategy with the minimum cost is selected.

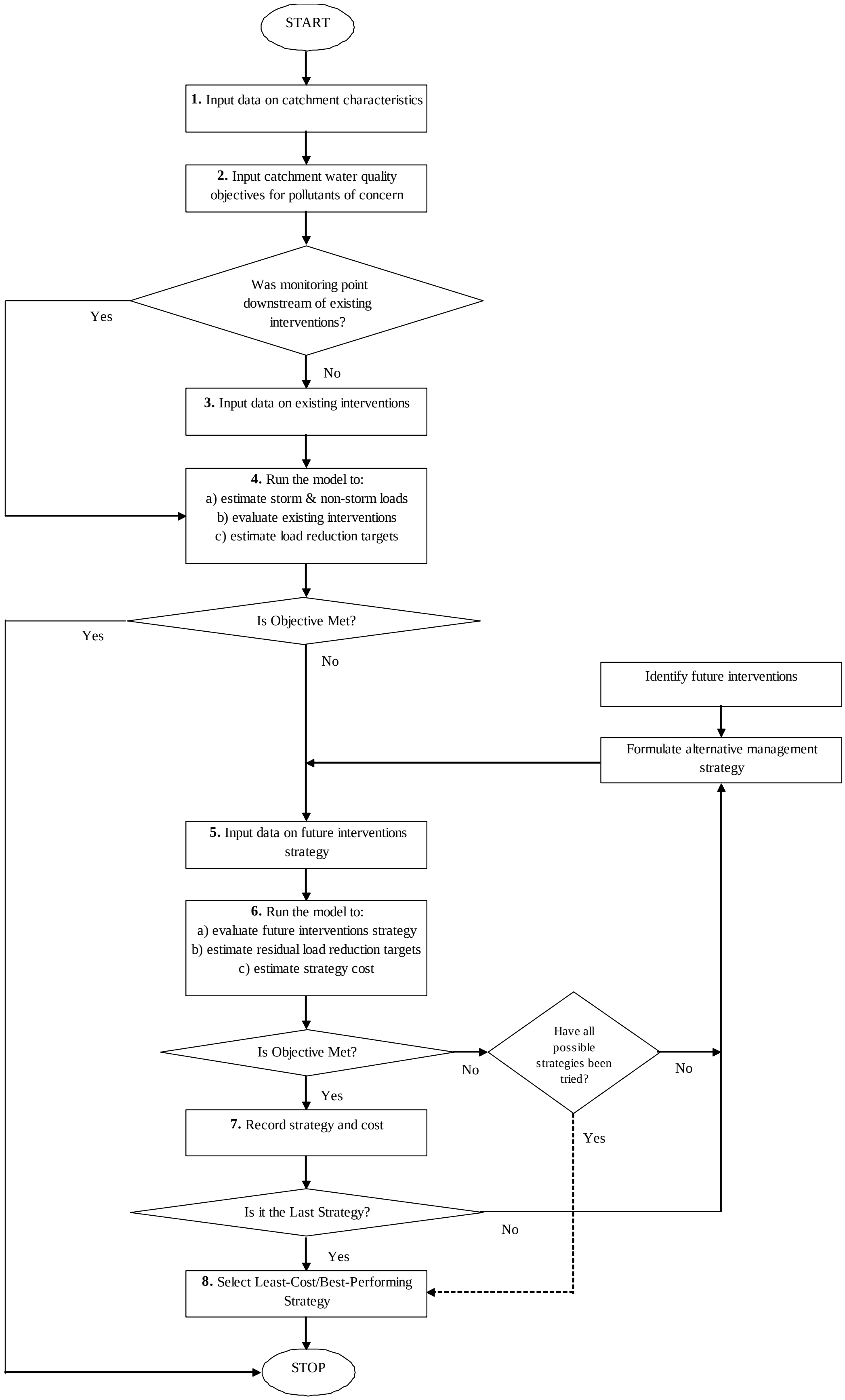

Figure 6-2: Model application flow chart

6.3.3 Model limitations

There are a number of challenges in quantifying stormwater treatment likely to occur in a catchment. These include:

- Uncertainty that exists in estimating both pollutant loads and interventions' load reductions. Regardless the efforts given to estimate 'qualitative uncertainties/risks' in the model, uncertainties still remain (resulting from the many input data) and can be reduced by additional research and data collection and analysis. Hence output values are subject to imprecision.
- Pollutant loads and treatment effectiveness vary both in time and space. Some pollutant sources are episodic in nature, while others are more continuous; some occur in storm flows, while others occur in base flows and dry weather flows.
- Proper estimation of catchment treatment must include socio-economic factors (e.g. human behaviour) and management activities which are difficult to quantify.
- For a wide range of treatment options available, little or no monitoring data exist especially in developing countries, to assist in evaluating their effectiveness. Without this information, it becomes difficult to estimate the benefit of many programs and treatment measures.
- Estimating the level of implementation and maintenance is also another challenge. The performance of a treatment option will often depend on operation and maintenance procedures, availability of funds, human resources capacity and technical know-how.

The main limitations of the model are:

- The model is analytical based on lumped parameters which are subject to many assumptions and limitation as against continuous modelling. The limitations and advantages of analytical and continuous modelling are described in Table 2-5 in Section 2-5.
- Schueler (1987) recommends the application of the Simple Method (for which this model was based on) to catchment size up to 50 km^2. No reason was provided for this upper limit. Hence the best application of the model is on a small catchment (e.g. up to 50 km^2) unless the larger catchment is broken into smaller

sub-catchments. This will reduce uncertainties associated with variability of data input measurements.

- The model provides estimates of many source loads and load reductions for which reliable monitoring or performance data is not yet available especially in developing areas. It must be recognized, however, that the model defaults are nothing more than informed judgments or heuristics based on literature review. They have been included in the framework to help stormwater managers who would otherwise not have access to these data to evaluate as many sources and treatment/management options as possible.
- The model makes simplified assumptions and employs analytical methods for the calculation of loads and load reductions for which much more complicated analyses may be conducted.
- The simplifications in the model lead to 'uncertainty' in the results. While measures of assuredness have been included in the estimation of load reductions, it may also be necessary to assign an explicit margin of safety in cases where a specific target needs to be met, such as in meeting water quality objectives for a catchment that requires high protection of water resources.
- Although most of the data input into the model is quantitative, some parameters require user discretion. In particular, the stormwater manager is required to make judgments regarding the long-term performance or public participation associated with various measures or programs.
- The model tracks only six pollutants: nitrogen, phosphorous, chemical oxygen demand, lead, suspended solids and fecal coliform.

6.4 Summary

The following summarises the approach adopted in the implementation of the DSS outlined in this Chapter. The guiding philosophy was to follow a pragmatic approach to the problem of water quality issues in informal settlements. The model was interfaced with Microsoft Excel. The user interface has been kept simple, in order to ensure easy and practical application of the DSS. The biggest cost of modelling is often in learning the details and complexities of a model, and its principles and limitations. Time away from sophisticated models also causes users to forget aspects, and it is the ease of initial access or re-access which can inspire confidence in the user and enable the model to be used to its fullest. With the Excel interface, a user can inspect, modify and add programs with the VBA editor thus giving the model the flexibility to allow updates and improvements as appropriate based on new research, management objectives, and monitoring data.

One of the intentions of the model implementation has been to provide an appropriate level of analysis without demanding a lot of input data. Often, data from developing areas to run or implement models are either not available or difficult to obtain. Therefore it becomes necessary to apply heuristic data rather than attempting to implement a complex model requiring data that do not exist or are expensive to obtain. Hence, this Chapter also described the model defaults (consisting of both factual and heuristic data), which form the knowledge base of the decision support system.

The methods set out in Section 6.3.2.2 serve as the basis for the use of the DSS. A summary of the process is outlined below.

i. The first step in the model application is catchment data input.
ii. The second step input for ambient water quality objectives for pollutants of concern.
iii. The third step involves input of data on existing management interventions.
iv. The forth step is to run the model to evaluate the existing interventions and determine the catchment load reduction targets or management objectives.
v. Step 5 consists of input of data on future management interventions. This is preceded by identification of interventions and formulation of alternative management strategies.
vi. Step six is to run the model to: a) evaluate future interventions strategy, and b) estimate residual load reduction targets.

vii. If the objective is met, the strategy is recorded in the seventh step. The strategy is recorded by entering the implementation factors of each intervention and the cost of the strategy in the *cost data category* in the output sheet. Steps five to seven is repeated for different strategies formulated.

viii. In the last step, the strategy with the minimum cost is selected.

7 ALEXANDRA TOWNSHIP CASE STUDY

The decision support system was developed in Chapters 3 and 4, the various computations in the model development described in Chapter 5 and the implementation of the DSS was presented in Chapter 6.

In this chapter, the DSS is applied using Alexandra Township in Johannesburg as a case study. The sequential steps of model application described in Section 6.3.2.2 was used as a modus operandi. Section 7.1 presents physical characteristics of Alexandra catchment which is a basic input to all the modules (categories) in the DSS. The ambient water quality objectives and pollutants of concern are defined in Section 7.2. Section 7.3 describes causes of water quality issues in Alexandra catchment. Estimates of storm loads, non-storm loads, and load reduction targets are presented in Section 7.5. Potential management interventions are identified in Section 7.5 and it is followed by formulation of alternative management strategies in Section 7.6. Section 7.7 presents evaluation of future management interventions (estimates of load reductions). Recommendation of the preferred strategy is provided in Section 7.8 and it is followed by conclusions and recommendations in Section 7.9.

The Water Research Commission of South Africa, City of Johannesburg, and the Water System Research Group of the University of the Witwatersrand conducted a lot of research in Alexandra on water quality and quantity issues, and as a result a great wealth of data exists in the literature (e.g. Wimberley (1992), Campbell (2001), Owusu and Stephenson (2006), Stephenson and Associates (2002), and Stephenson et al. (2003)). This data formed the main core of data input into the model.

7.1 Details of the Study Area

7.1.1 Locality

The Alexandra township is located 12 km north-east of central Johannesburg and 4 km east of Sandton central business district, between the eastern bypass (N3) and the old Pretoria road. The township is flanked by the suburban areas of Lombardy to the south, Wynberg to the west, and Marlboro to the north. The township is split into west and east bank by the Jukskei River. The west bank measures about 350 ha and is completely developed as high density residential area with small commercial and industrial areas. The east bank measures approximately 140 ha and is predominantly undeveloped. Details of this geographical layout are shown in Figure 7-1. The west bank is principally the focus of this study.

7.1.2 Population and density

The official population of Alexandra was estimated as 166 971 according to the 2001 population census of South Africa. This translates to a population density of 477 persons/ha and 80 dwelling units/ha (assuming 6 persons/dwelling unit). This suggests that every person in Alexandra has, on average, about 16 m^2 of living space, assuming that 20% of the area is taken up by roads, business, schools, and other open spaces. If the relatively small number of storey buildings in Alexandra is further taken into consideration, this figure becomes even more alarming.

7.1.3 Topography and Morphology

The area slopes steeply in a west-east direction towards the Jukskei River, with slopes varying from 12.5% in the western sections to 3.3% in the sections closer to the Jukskei River.

The Jukskei River is the largest of the three Rivers draining the northern and north-eastern suburbs of the Witwatersrand. The source of Jukskei River is in Bezuidenhout valley, east of Johannesburg. The highest point in the Jukskei River itself is at 1695 mamsl. The River loses 475m in height over its length of 66 km. This yields an average slope of 7.3 m/km, which, although by no means exceptional for South African Rivers, makes it a fast flowing River. The tributaries are even steeper and therefore faster flowing than the Jukskei River itself. Flow is initially in north-easterly direction for about seven kilometres, until the Gillooly's Farm interchange, where the River swings northwards. Eight kilometres downstream of this point, the River begins to flow past Alexandra Township. The catchment area of Jukskei River is about 92.4 km^2 upstream and 102.0 km^2 downstream of Alexandra. Downstream of Alexandra, the Jukskei River flows through the residential areas of northern Johannesburg, and is joined by the Braamfontein, Sand and Modderfontein spruits before the confluence with the Crocodile River.

The Jukskei River and its tributaries are not deeply incised and because they run fast and shallow, they are for the most part well aerated and well mixed. As a result a higher organic load can be tolerated before anaerobic conditions occur. Due to relatively high velocities, the streams can carry a relatively high suspended load. However, any drop in velocity will cause the coarser material to settle out. The various weirs in the Jukskei River therefore tend to silt up rapidly.

Three small tributaries of the Jukskei River rise on the west bank of Alexandra forming the main stormwater drainage systems (channelled into rectangular culverts). The middle and northern drainage systems merge just before joining the Jukskei River. These three stormwater drainage systems divide the area into three subcatchments as shown in Figure 7-2. For the purpose of this study, the drainage lines and their associated catchments are called northern, middle and southern.

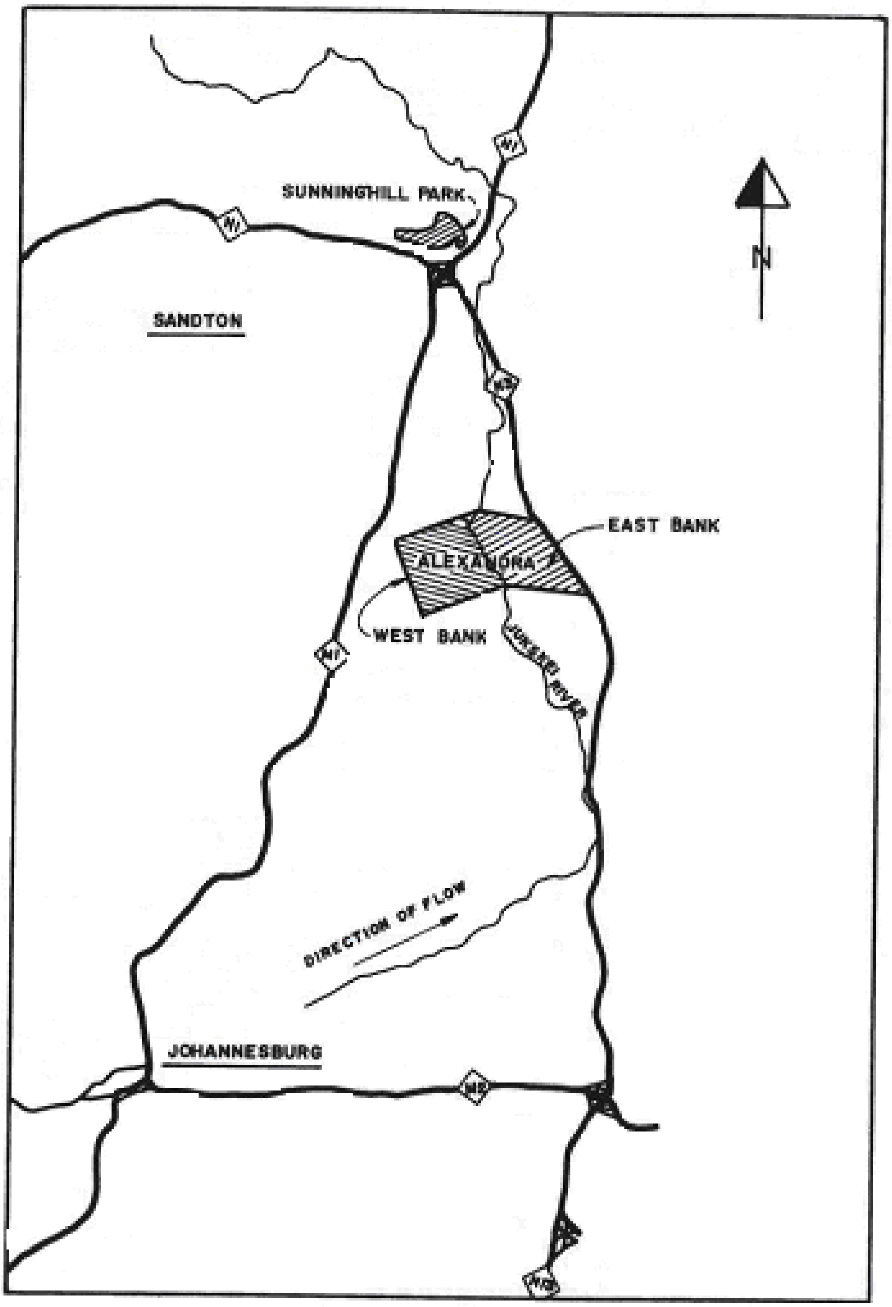

Figure 7-1: Alexandra Locality Plan

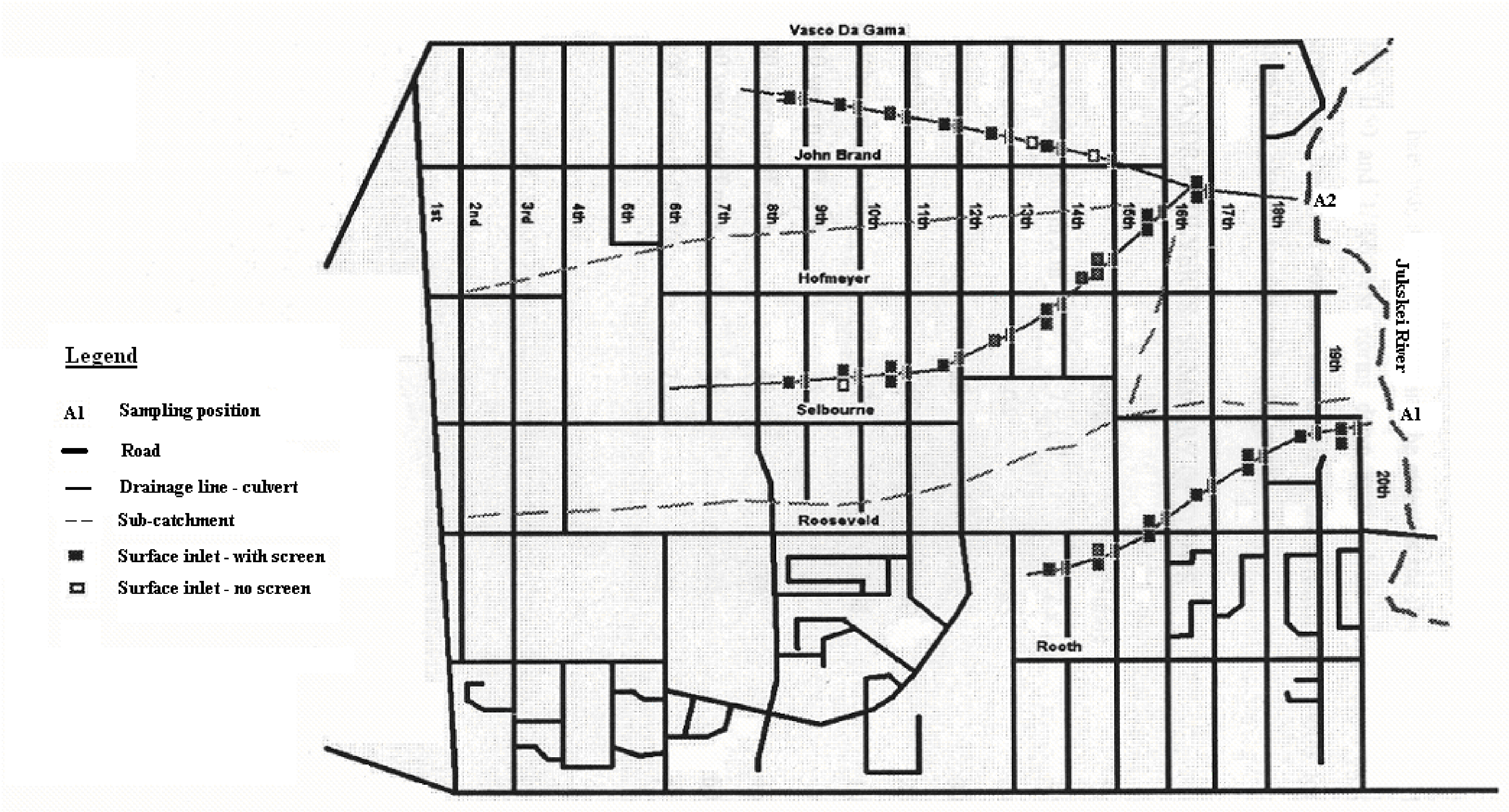

Figure 7-2: Current Layout of Alexandra West Bank Settlement

7.1.4 Geology and soils

Alexandra Township is underlain by highly weathered and decomposed rocks of the Achaean granite, forming the Johannesburg/Pretoria dome. Outcrops of granite occur in places, especially in the Riverbed of the Jukskei River. The granite is, in its fresh state, a medium to coarse textured pink or grey rock. The rock has decomposed to form a residual soil layer of loamy sand which varies in depth between 0.5 to 6.0 metres. Overlying this residual soil are various transported soils, as well as unconsolidated fill material in some areas. Alluvial wash material occurs in the gully and flood plain of the Jukskei River.

7.1.5 Land use and Services

Land-use characteristics are being dominated by a high-density residential development. Alexandra consists of a combination of formal and informal settlements. The formal settlement has full engineering services, including a water reticulation system, water-borne sewage, electrical reticulation, and non-stand ablution facilities. The informal settlement comprising shacks and "make-shift" houses are spaced close to each other with a maze of narrow alleys between them, and has developed on previously vacant land and in low lying areas, some demarcated as flood zones. There are also many areas where the two settlement types overlap, with one house and any number of back-yard shacks being situated on a stand. The informal settlement was not planned for, and is thus operating on very rudimentary services such as public stand-pipes and portable toilets. These toilets are serviced by the Alexandra Town Council on a daily basis. The portable toilet system is regarded by the Council as a temporary and emergency measure to meet the sanitary crisis, in operation only until the sewer system is upgraded to accommodate the residents of the informal developments. The sewage system in Alexandra is in a poor state, and overflowing sewers are a common sight. This is partly due to overloading of the system and incorrect use, but also due to poor maintenance. Until 1987 sewage from Alexandra was treated at the Alexandra Sewage Works. After these works were decommissioned, sewage is treated at the Johannesburg Northern Works.

Refuse removal in the informal areas presents a serious problem as refuse are dumped in the River and the main streets. Some success has been achieved by placing waste removal skips provided by the City of Johannesburg at strategic points, but more education is required to gain the cooperation of the residents in order that they place their refuse in the skips, which may require them to walk a short distance. A crucial factor in this is the removal of refuse by contractors, which is not always carried out in accordance with the contract.

The township is serviced by stormwater drains. Most of the drainage network consists of culverts and underground pipe network. The main drainage facilities are three tributaries (rectangular culverts) draining the west bank. The culverts were constructed underground to carry stormwater to the Jukskei River. The culverts, up to 1.7m high by 3.9m wide were designed to take a 10 year storm, it appears, and surplus water for larger storms was intended to flow over ground. There are no roads down the gullies or culverts, but the area above the culverts was intended to be parkland. However, with the migration of thousands of people to the Alexandra area, land for building was at premium and informal houses sprung up along the previously open land to the extent that the land around and on top of the culverts is very densely populated with shacks. Apart from stormwater, the culverts also receive greywater, which are general wash water from kitchen, bathroom, car-wash, and garages. Water is transferred into the stormwater system via a series of surface inlets. These inlets are in the form of kerb inlets that divert runoff from the road surface into the stormwater systems, and surface inlets that divert overland flow, between the streets, into the system.

The commercial areas comprise of schools, an old age home, a veterinary clinic, a community centre, hostels, police station, taxi ranks, and shopping areas.

7.1.6 Climate and Hydrology

Alexandra and the catchment of Jukskei River situated on the Transvaal Highveld experience warm summers and cool winters. The climate is relatively dry, with very low humidity in winter. The weather station in Kempton Park at OR Tambo International

Airport is sufficiently close to Alexandra for all climatic data analysis. Alexandra and the Jukskei River catchment falls in the summer rainfall area, and receives almost 50% of its rainfall from November to January, the highest rainfall occurring in January. As can be expected, thunderstorm activity is highest in November to January, with some activity in October, February and March. The average annual rainfall in the area is about 750 mm. Hail occurs on average 2 or 3 times per year, while it hardly ever snows.

Evaporation in the catchment is much higher than the rainfall, as is the case in most places in South Africa. The Symons Pan evaporation is about 1700 mm/a. As with the rainfall, most of evaporation occurs in summer.

As Alexandra is highly urbanised, runoff is mainly urban runoff. The impervious surfaces created by roads, pavements and roofs means that less rainfall infiltrates the ground and that more runoff is generated. There is no flow gauge that measures flow from Alexandra Township into the Jukskei River.

7.2 Water quality objectives and pollutants of concern in Alexandra

The water quality guidelines and objectives for the Jukskei River for the different user groups have been developed by BKS (1996). Table 7-1 presents a summary of the various guideline ranges and their associated colour codes. Narrative description for the colour codes are: Blue – fit for use; Green – acceptable; Yellow – tolerable; Red – not fit for use; Purple – totally unfit for use.

The water quality objectives were derived from the water quality guidelines, and where a variable only affects one user group, the upper values of the ranges described as fit for use, acceptable and tolerable (see Table 7-2) form the water quality objectives. The detail of the water quality objectives derivation is presented in BKS (1996) and the result is summarised in Table 7-2.

Table 7-1: Water quality guideline ranges and colour coding (BKS, 1996)

User category	Variable	Range				
		Fit for use	Acceptable	Tolerable	Unacceptable	Totally unfit for use
Domestic	EC (mS/m)	<70	70-150	150-370	370-1500	>1500
	pH (pH units at $25^{o}C$)	6-9	9-9.5:5-6	9.5-10:4-	<10: <4	
	Turbidity (NTU)	<1	1-5	5	10-50	>50
	Odour (category)	1	2	5-10		
	Colour (category)	1	2			
	Sulphate (mg/l)	<200	200-400	400-600	600-700	>700
	Nitrate (mg/l)	<6	6-10	10-20	<20	
	Fluoride (mg/l)	<1.0	1.0-1.5	1.5-3.5	3.5-100	>100
Recreation	pH (pH units at $25^{o}C$)	6.5-8.5	5.05-6.5:8.5-9.0	<9: <5		
	Turbidity (NTU)	<10	10-20	20-25	<25	
	Odour (category)	1	2			
	Colour (category)	1	2			
	Litter (category)	1	2			
	F. Coli (CFU/100ml)	<150	150-600	600-2000	2000-100000	>100000
	E. Coli (CFU/100ml)	<126	126-200	200-400	400-100000	>100000
Agriculture (Irrigation)	EC (mS/m)	<60	80-155	155-295	295-1000	>1000
	SAR	>3	3.0-5.0	5.0-10.0	>10.0	
	Fluoride (mg/l)	<1.0	1.0-2.0	2.0-15.0	>15.0-100	>100
	Sulphate (mg/l)	<200	200-300	300-500	500-1000	>1000
Environment	pH (pH units at $25^{o}C$)	6.5-9.0	5-6.5	4-5:9-10	<4: >10	
	Tot Ammonia (mg/l)	<0.16	0.18-0.40	0.4-2.6	2.6-5	>5
	Nitrite (mg/l)	<0.03	0.03-0.15	0.15-5.0	5.0-10	>10
	Turbidity (NTU)	<16	16-25	25-35	>35	
	Chlorine (ug/l)	<0.2	0.2-0.35	0.35-5	5-100	100
Other	Phosphate (mg/l)	<0.05	0.05-0.1	0.1-0.5	0.5-1.0	>1.0
	COD (mg/l)	<15	15-30	30-80	80-170	>170

The water quality objective formed the basis of the stormwater management strategy, as they were used to determine what is acceptable in terms of pollution levels and what is not, and to what extent the runoff quality situation in Alexandra deviates from the ideal condition as well as the extent of pollution load reduction target required. Assessment of the fitness for use of a water resource is currently being extended for implementation of the National Water Act, particularly in terms of the Water Resource Classification System and Resource Quality Objectives. These reflect the sensitivity of the receiving water environment and users in a catchment, and indicate the resource quality required for the level of protection associated with an acceptable degree of risk (Pegram and Gorgens, 2001). In this case study, the risk taken is to treat 90% of cumulative annual rainfall to meet the water quality objectives of Jukskei River catchment. This risk factor was defined in Section 5.3 as a fraction of annual rainfall that can be captured by a control intervention (η_b).

Table 7-2: Water quality objectives for the Jukskei River catchment (BKS, 1996)

Variable	Units	Range		
		Reference Level	Action Level	Intervention Level
EC	mS/m	70[1]	150	295
pH (at 25°C)		6.5-8.5	5.0-6.5; 8.5-9.0	4.9-5.0; 9.0-10
Turbidity*	NTU	16[1]	25	35
Litter	Category	1	2	3
SAR	-	3.0	5.0	10
Nitrate	mg/l	6	10	20
Nitrite	mg/l	0.03	0.15	5.0
Tot Ammonia**	mg/l	0.16	0.40	2.6
Fluoride	mg/l	1.0	1.5	3.5
Sulphate	mg/l	200	300	500
Chlorine	ug/l	0.2	0.35	5.0
E.Coli	CFU/100ml	126	200	400
Faecal coliform	CFU/100ml	150	600	2 000
Phosphate	(mg/l)	0.05	0.1	0.5
COD	(mg/l)	15	80	80

Notes: * The value for turbidity are determined by the guideline for the aquatic ecology
** At 20°C and pH 8
1 A value approaching 0 is not desirable.

The Water Research Commission of South Africa, and the then Water System Research Group of the University of the Witwatersrand have conducted a lot of research in Alexandra on water quality issues (e.g. Wimberley (1992), Campbell (2001), Owusu and Stephenson (2006),). These studies revealed six pollutants of concern and their concentrations are presented in Table 7-3.

Table 7-3: Characteristics of pollutants of concern in Alexandra catchment

TN (mg/l)	TP* (mg/l)	COD (mg/l)	Pb (mg/l)	SS (mg/l)	FC (count/100ml)
43	25	378	0.8	2219	10^6

Notes: * Total phosphates only

7.3 Causes of water quality issues

This aspect of the work involved identifying factors that currently prevent, or may prevent, water quality objectives from being satisfied, that is, factors resulting in water pollution. These issues have been identified by a combination of:

- Desk-top study, involving a review of existing information contained in reports, studies and monitoring programs.
- Field-work involving an inspection of the settlement.
- Discussions, involving interviewing community representatives to obtain information on issues.

These problems or issues are mainly environmental pollution, flooding, social and managerial. These issues are described below.

Most of the community does washing at the standpipes, resulting in constant flow of greywater on the roads and culverts to the River. The community often leaves taps running to rinse the clothes, which further exacerbates the problem. People doing the washing at their houses put their dirty washing water onto the street.

Of considerable concern also is the bucket sanitation system. Each of the toilet stands serves about 5 families and emptying is not frequent and as a result, they are often full. Often, there is spillage from overfull buckets and many buckets and toilets are broken. Sewer blockages and overflows are also common.

The high density of the houses also results in a problem of excess solid waste, and the solid waste containers often overflow. Littering is also a significant problem. Table 7-4 presents a summary of the causes of management issues.

Table 7-4: Summary of the causes of management issues in Alexandra

Category of issues	Issue	Possible Cause
Environmental (Water Quality)	Elevated nutrient concentrations	• Overflows from sewers and bucket toilets due to overcrowding • Domestic animals droppings • Fertilizers and herbicides applied to lawns (minimal) • Greywater from washings in residential and commercial land uses
	Elevated suspended solids concentrations	• Litter from residential and commercial areas • Erosion from road surfaces and construction sites
	Elevated bacteria concentration	• Overflows from sewers and bucket toilets due to overcrowding • Domestic animals droppings • Bush toileting in the reeds
	Litter in the environment	• Insufficient number of rubbish bins and skips • Infrequent emptying of bins and skips • Littering in residential, retail and commercial areas
Stream flow	Flooding	• Increased runoff flows due to increased imperviousness resulting from high density housing. • Lack of stormwater reuse (e.g. rainwater tanks) • Blockages of inlets • Litter in watercourse • Encroachment into the flood zones
Riparian vegetation	Degraded riparian vegetation	• Direct greywater discharge • Encroachment of settlements in the flood plain • Physical removal of riparian vegetation
	Weed growth in riparian vegetation	• Nutrients from stormwater and greywater
Social	Lack of integration of stormwater systems and	• Overcrowding • No walking paths adjacent to watercourses

Category of issues	Issue	Possible Cause
	recreational facilities	• No fishing and swimming areas in Jukskei River due to pollution
	Lack of visual amenity and landscape value of the stormwater system	• Litter, veld-toileting and discharge of greywater in the streets and into Jukskei River. • Overcrowding
	Lack of public involvement in stormwater management	• Lack of coordination and initiation abilities among community members with regards to stormwater and greywater management. • Community's development committee is not effective in drainage and water quality issues. • Lack of education and public awareness on stormwater issues.
Managerial	Lack of funding for stormwater management	• Non payment for services and hence cost recovery is a problem • Willingness and ability to pay is marginal as most people live under the poverty line due to unemployment.
	Lack of coordination among community, catchment management council, DWAF and other stakeholders	• Poor communication between stakeholders • Poor integration of responsibilities across stakeholders
	Lack of effective control over operation and maintenance of basic services in place.	• No checks or monitoring of status of services and responsibilities • No scheduled repairs and maintenance

7.4 Estimate of loads and load reduction targets

The data requirement to estimate storm and non-storm loads are described in Section 6.3.2.1. These data were obtained for Alexandra as presented in Table 7-5 and were input into the DSS. The defaults described in Sections 6.2.1 to 6.2.2.4 were also used unchanged. There are no management interventions existing in Alexandra besides the river systems (i.e. river assimilation capacity).

Table 7-5: Alexandra catchment storm and non-storm loads data input

Parameters	Values						Source
Catchment MAP (mm)	750						Estimated
Total urban catchment area (km^2)	3.5						Estimated
Planning horizon (yrs)	20						Assumed
Impervious residential areas (%)	70						Estimated
Impervious commercial areas (%)	70						Estimated
Runoff coefficient of pervious areas	0.25						Estimated
Runoff coefficient of impervious areas	0.85						Estimated
Dwelling Units	10 000						Estimated
Number of businesses	200						Estimated
Total length of sanitary sewer (km)	20						Estimated
Soil (%)	0.2						Quibell et al. (2003)
Soil (%)	0.3						Quibell et al. (2003)
Annual rainfall erosivity (N/h/yr)	320						Smithen and Schulze (1982)
Soil erodibility (ton.h/N/ha)	0.5						Schulze (1995)
Slope length and gradient factor	0.2						Schulze (1995)
Cover and management factor	0.1						Quibell et al. (2003)
Delivery factor	0.2						Estimated
Ambient water quality objective characteristics (mg/l; count/100ml)	TN	TP	COD	Pb	SS	FC	BKS (1992)
	10.55	0.1	80	0.1	80*	600	
Storm flow characteristics (mg/l; count/100ml)	TN	TP	COD	Pb	SS	FC	Owusu and Stephenson (2006) and Wimberley (1992)
	43	2.5	378	0.8	2219	10^6	

Note: * Obtained from DEAT (1982)

The results after running the model are presented in Tables 7-6 and 7-7. Table 7-6 presents loads from primary sources (i.e. urban land) and secondary sources (i.e. sewer overflows and illicit connections). The loads from these two sources are disaggregated into storm and non-storm loads. Table 7-6 also indicates that on annual basis, a greater proportion of loads exiting Alexandra catchment are non-storm loads (mostly from illicit connections). The objectives' target loads indicated in Table 7-7 are loads obtained should existing storm and non-storm flow concentrations be equal to that of the water quality objectives concentrations. The load reduction targets represent the proportion of storm and non-storm loads that need to be reduced in order to meet management objectives. Section 7.5 identifies potential management interventions to meet these load reduction targets.

Table 7-6: Summary of existing loads in Alexandra

	TN (kg/yr)	TP (kg/yr)	COD (kg/yr)	Pb (kg/yr)	TSS (kg/yr)	FC (million/yr)
Urban Land	24,475	2,079	473,763	1,128	2,468,281	8.62E+09
Active Construction	-	-			-	0.00E+00
SSOs	6	0	12	0	40	1.00E+06
Illicit Connections	1,747,512	517,573	10,929,793	16,634	17,446,000	1.96E+03
TOTAL LOAD*	373,979	136,648	4,080,598	16,099	8,225,474	8.62E+09
Storm Load	24,255	2,076	473,769	1,128	2,468,301	8.62E+09
Non-Storm Load	349,724	134,572	3,606,830	14,971	5,757,173	3.32E+05

Note: * Total load reflect the sum of loads from primary and secondary sources less loads reduced by exiting interventions. Loads reduced by existing interventions are not shown in the table.

Table 7-7: Alexandra management objectives – existing load reduction targets

	TN	TP	COD	Pb	TSS	FC
Objectives' target loads for storm flow (kg/yr)	5,951	83	100,271	141	88,991	5.17E+06
Objectives' target loads for non-storm flow (kg/yr)	231,412	2,852	2,892,610	9,861	2,892,610	2.03E+02
Objectives' total target loads (kg/yr)	237,363	2,935	2,992,881	10,002	2,981,601	5.17E+06
Load ReductionTarget for storm flow (%)	75	96	79	88	96	99.94
Load ReductionTarget for non-storm flow (%)	34	98	20	34	50	99.94
Load ReductionTarget for total flow (%)	37	98	27	38	64	99.94

7.5 Potential future management intervention

Potential management options identified for Alexandra settlement include: de-densification of settlement, domestic animal waste education, erosion and sediment control, frequent street sweeping, impervious cover reduction, downspout disconnection, use of riparian buffers, illicit connection removal, sanitary sewer overflows abatement, use of rainwater tanks and exfiltration systems. These interventions are reviewed in

Sections 2.3 and 2.4 and the methods followed in identifying them are outlined in Sections 4.4.1 and 4.4.2. The interventions were selected to deal with the causes of the water quality issues in the catchment as defined in Table 7-4 in Section 7-3, bearing in mind that the identified interventions also have to meet their implementation requirements as defined in Table 4-7 and 4-9 in Sections 4.4.1 and 4.4.2 respectively.

Formalization of Alexandra settlement would require de-densification and upgrading. These would involve: provision of a public spatial structure to provide relief from overcrowding; creation of public gathering places; and improvement of engineering services such as potable water and electricity into the settlement; and sewage, refuse, stormwater and wastewater removal from the settlement. These can be achieved through negotiated relocation of residents and informal economic activities (such as back-yard mechanics and poultry farms) to create spatial structures consistent with formal settlements.

Stephenson and Associates (2002) investigated stormwater culverts in Alexandra township and reported that some 4 500 informal dwellings are constructed in the public areas along the waterways intended as green strips. About 2 000 of these homes are on the flood path, the others on the fringes. Some of these are block construction, but the majority is dwelling units made of corrugated iron sheets. They estimated that, at a guess estimate of R20 000 per house, it would cost R40 million to rebuild the houses on the flood path only.

7.6 Formulation of alternative management strategies

The identified interventions were used to formulate alternative strategies. The strategies were formulated by a combination of different mixes of interventions. For instance, a strategy was formulated as:

- 50% clean-up and education interventions (to emphasize more importantly on domestic animal waste education) to be completed in the next 2 years;
- 70% of catchment erosion and sediment control interventions to be completed in the next 2 years;

- 60% of regular street sweeping and refuse removal to be accomplished in the next 2 years;
- 100 % maintenance and repair of all broken, blocked, and overflow sewers and other sewage systems to be achieved in the next 2 years.
- 90% de-densification by relocation of some residents to be completed in the next 10 years. The programme of de-densification has already commenced five years ago;
- 90% of impervious cover reduction to be completed in the next 10 years. Impervious cover reduction by demolishing shacks and converting the resulting area into pervious surface. These areas should in turn provide space for the formal houses downspouts to be disconnected and discharged onto.
- Downspout disconnection – 90% of feasible areas to be completed in the next 10 years;
- Use of rainwater tanks – 90% of feasible areas to be completed in the next 5 years;
- Illicit connection removal – 50% of feasible areas to be completed in the next 10 years;
- Riparian buffers along Jukskei river and tributaries – 40% to be completed in the next 7 years;
- Exfiltration systems retrofit – 60% of feasible areas to be completed in the next 15 years.

Different strategies were formulated by altering the implementation magnitude (factor) and timeframe of some or all of the interventions shown in the above strategy.

7.7 Evaluation of future management interventions

The data requirement to evaluate future management interventions are described in Section 6.3.2.1. Table 7-8 presents the parameters used to determine the pollutant load reduction of each intervention. The parameters for impervious cover reduction and downspout disconnection are described below.

Impervious cover reduction.

Mtshelwane (2002) estimated that, there are 34 000 shacks and 4 060 formal houses in Alexandra. Based on this information and assuming that the average shack roof print area is 60 m^2 then the total area occupied by shacks to be redeveloped is 2.04 km^2, that is 83% of total Alexandra impervious areas. It was further assumed that, by demolishing 69% shacks and converting the resulting area into pervious surface, these areas would in turn provide space for the formal houses downspouts to be disconnected and discharged onto.

Impervious cover disconnection.

Provision of rain water tanks can also be used to augment the downspout disconnection intervention. In the estimation of load reduction by impervious cover disconnection, it was assumed that formalization of Alexandra settlement will result in about 10 000 formal houses with average roof print area of 186 m^2. It was also assumed that 70% of residential land will be applicable for this intervention and 70% of the people in this area will be willing to participate in disconnecting their downspouts or use rain water tanks. In the commercial areas, it was assumed that; a) 30% of the impervious area is roof tops; b) a further 25% of this area applicable for this intervention and, c) 60% of commercial units will be willing to disconnect downspouts.

The interventions defaults described in Sections 6.2.2 to 6.2.9 were also used unchanged. The procedure applied in evaluating future management interventions (strategies) is in accordance with the sequential steps (steps 5 to 7) presented in the model application flow chart, Figure 6-8 in Section 6.3.2.2. After the interventions data and strategy were input into the model, the model was run to estimate load reductions and residual load reductions. If the objective is met, that is, the residual load reduction targets are zero, the strategy is recorded. The process is repeated for a different number of strategies. A number of strategies were evaluated and those which achieved the management objectives are shown in Table 7-9 indicating the magnitude of implementation of each intervention.

Table 7-8: Data for interventions used for the Alexandra Township case study in the model

Parameters	Values	Source
Illicit Connection Removal Intervention		
Fraction of drainage system surveyed (%)	100	Estimated
Unit treatment cost (R/m^3)	0.02	Assumed
SSO Repair Intervention		
Fraction of repairs completed (%)	100	Estimated
Unit treatment cost (R/m^3)	0.5	Assumed
Catchment Erosion & Sediment Control Intervention		
Fraction of pervious surface treatable	0.7	Estimated
Unit treatment cost (R/m^3)	0.3	Assumed
Street Sweeping Intervention		
Street sweeping area: Brush-type mechanical (km^2)	0.035	Estimated
Street sweeping area: Broom (km^2)	0.021	Estimated
Street sweeping area: Vacuum assisted (km^2)	0.5	Estimated
Unit treatment cost (R/m^2)	0.05	Assumed
Riparian Buffers Intervention		
Buffer Length (km)	3	Estimated
Buffer Width (km)	0.02	Assumed
Unit treatment cost (R/m^3)	0.25	Schueler et al. (2007)
Impervious Cover Reduction Intervention		
Land to be redeveloped (km^2)	2.04	Assumed
Average impervious cover reduction (%)	20	Assumed
Unit treatment cost (R/m^3)	679*	Deduced from Mtshelwane (2002)
Downspout (Impervious Cover) Disconnection Intervention		
Typical house roof area (square meter)	186	Assumed
Fraction of residential land applicable	70	Assumed
Unit treatment cost (R/m^3)	0.1	Assumed
Rainwater Tanks Intervention		
Fraction of Residential Land where Applicable	0.7	Assumed
Unit treatment cost (R/m^3)	0.5	Schueler et al. (2007)
Exfiltration System Intervention		
Area surveyed for application (km^2)	3	Estimated
Fraction of area “treatable” (%)	80	Assumed
Unit treatment cost (R/m^3)	630	Li et al (1998)
Domestic Animal Waste Education		
Unit treatment cost (Lump Sum)	20 000	Assumed

Note: * Includes relocation of households and provision of houses

The unit treatment cost cited from Schueler et al. (2007) and Li et al. (1998) in Table 7-8 were converted from US dollars and Canadian dollars respectively (at rates of 1US$ = 1C$ = R7 South African).

Table 7-9: Alternative stormwater quality management strategies evaluated

Strategy		Interventions									
		DAWE	CESC	SS	SSOR	ICR	ICD	ILL	RB	RT	EXS
		Timeframe of implementation (yrs)									
		2	5	2	2	10	10	10	7	5	15
		Magnitudes of implementation (%)									
S-1		20	60	100	100	100	100	35	20	90	90
S-2		50	70	60	100	90	90	50	40	90	60
S-3		30	90	100	100	100	100	40	50	100	10
S-4		0	45	50	100	70	90	40	30	100	40
S-5		0	100	50	100	40	35	40	0	100	100

Note:
DAWE = Domestic animal waste education
CESC = Catchment erosion and sediment control
SS = Street sweeping
SSOR = Sanitary sewer overflow repairs
ICR = Impervious cover reduction
ICD = Impervious cover (Downspout) disconnection
ILL = Illicit connection removal
RB = Riparian buffers
RT = Rainwater Tanks
EXS = Exfiltration system

The results from the modelling and evaluation of strategies are presented in Appendix D, Tables D-1 to D-5. Jukskei River system is very effective in assimilating the pollutants from Alexandra catchment. The river assimilative capacity is more efficient than any of the interventions simulated, as shown in Table D-1 to D-5 under *'Load reductions from future intervention'* categories. For storm loads, interventions found to be most effective are: use of rainwater tanks, impervious cover reduction, downspouts disconnection, exfiltration systems, and catchment erosion and sediment control. Non-storm loads from Alexandra results mostly from illicit connections to the drainage system and hence are reduced effectively by illicit connection removal intervention.

7.8 Selecting the preferred strategy

Any of the five strategies shown in Table 7-9 achieves the desired objectives and can be selected. The local authority can select from these strategies the one that fit into their developments or management plans in terms of budget or cash flow constraints. The preferred strategy was obtained through cost optimization analysis as presented in Table 7-10. For the five strategies that achieved management objectives, the implementation factors and the total cost of the strategies were recorded in cost category data in the output sheet of the model. The fifth strategy (S-5) came out with the minimum cost and hence, represents the optimum strategy. Most of the unit treatment costs were assumed in the analysis hence the cost figures could be taken as indicative only.

Table 7-10: Strategies cost optimization

COSTS CATEGORY											
STRATEGY	**COST OF STRATEGY**	**INTERVENTIONS**									
		DAWE	CESC	SS	ICD	RT	RB	ICR	EXS	ILL	SSOR
		IMPLEMENTATION FACTORS (%)									
S-1	R 45,519,668	20%	60%	100%	100%	90%	20%	100%	90%	35%	100%
S-2	R 41,359,892	50%	70%	60%	90%	90%	40%	90%	60%	50%	100%
S-3	R 45,422,272	30%	90%	100%	100%	100%	50%	100%	10%	40%	100%
S-4	R 32,303,010	0%	45%	50%	90%	100%	30%	70%	40%	40%	100%
S-5	R 19,292,802	0%	100%	50%	35%	100%	0%	40%	100%	40%	100%

7.9 Summary and recommendations

There have been a number of studies on stormwater quality from Alexandra catchment and its pollution threat to the receiving environment. These studies mostly identify the pollutants of concern; source and causes of pollution; and threats of the pollution to aquatic environment and health of the residents of Alexandra as well as other users of water from the Jukskei River. The case study presented in this chapter uses mostly the information from the previous studies to apply the DSS developed in this research. In this chapter, the DSS was used to:

a. Estimate storm and non-storm loads for Alexandra catchment
b. Quantify water quality management objectives (load reduction targets) for Alexandra catchment
c. Identify potential future management interventions to control the pollution
d. Formulate alternative management strategies involving different mixes of interventions
e. Evaluate the strategies by quantifying their load reductions
f. Select the optimum strategy based on cost analysis.

This chapter brings together all the theoretical development that has come before it, into suitably challenging case study to assess whether the hypotheses and research questions put forward in Section 1.3 were proven to be correct or false, and to what extent the research questions had been answered. The hypotheses namely:

- pollution problems from informal settlements reflect local conditions with respect to the economic development, the level of environmental protection practice (including the associated infrastructures), institutional arrangements, social factors, and public awareness;
- Given these adverse effects on receiving waters, the selection of stormwater quality management interventions must be efficient and effective. Efficient and effective selection requires that various alternative interventions be identified and evaluated at planning stage based on the principles of sustainability, hierarchical management approach, public consultation, and adaptive management;

had been proven to be correct.

All the research questions namely:

- Which area or land use within an urban catchment has the greatest potential or need for stormwater quality improvement?
- How critical are pollutants from secondary sources such as sanitary sewer overflows, illicit connections, and active construction in an urban catchment, which are often overlooked in simple or complex models?
- How to meet specified target load reduction as required?
- What interventions should be considered to treat/manage current and future contaminant sources to a receiving river body?
- Which combination of interventions (or strategies) would produce a minimum cost in meeting a community's stormwater quality management objectives?
- What pollutant reduction has been achieved by current or existing programs?
- What level of assuredness/risk does the estimated load reduced by an intervention represent?
- How effective are investments in educational and other non-structural control programs to manage stormwater quality?

had also been answered.

A sequence of actions that the municipality may implement to improve and manage stormwater quality as part of capital and operational projects include:

a. Non-structural and operational controls such as educational programs (lawn care education, domestic animal waste education, septic system education); erosion and sediment control; frequent street sweeping and refuse removal; and maintenance operations should be an on-going procedure since they are preventive measures, cost-effective and good house-keeping.
b. As part of de-densification and relocation of dwellings projects, feasible residential and commercial areas should have impervious cover areas reduced and downspouts disconnected gradually. Ways to achieve higher percent coverage of impervious cover reduction, downspouts disconnection, and rainwater tanks should also be investigated, including combinations of subsidies, regulatory measures and

application of additional technologies such as soak-away pits. Better site design techniques such as porous pavements, narrowing street widths and reducing the number and size of parking spaces can be used to also reduce imperviousness. It will take time to de-densify and formalize Alexandra settlement and also to confirm the cost and effectiveness of exfiltration systems, impervious cover reduction, downspout disconnection, illicit connection removal, and riparian buffers interventions. Thus, they should be implemented gradually over a long period of time.

c. If Jukskei River water quality objectives are to be strictly met by Alexandra catchment, then the only feasible solution is to allow the tributaries to drain only storm flows and add non-storm flows to the sewage lines. Sewerage construction and upgrade after formalization of Alexandra is part of Alexandra Renewal Project. The possibility of adding all greywater and other illicit connections to the sewage lines should be investigated.

d. A methodology for measuring the benefits of the interventions on Jukskei River, health and well being of the people in Alexandra should be developed. This would also require continuous performance monitoring to access the actual performance of the interventions relative to their expected performance.

e. Most of the data and defaults used in the model were assumed and sourced from other international studies. It is recommended that future data capture should be encouraged and substituted in the model to enhance measure of assuredness in the parameter estimations.

f. The recommended management strategy should be reviewed and updated periodically as part of the capital and operational budget process.

The usefulness of the DSS was demonstrated by the Alexandra catchment case study. Not all the necessary information was available at the time of this study. Thus, the study's recommendations are only preliminary and should be examined rigorously before adoption.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

High-density low-income settlements in developing countries have backlog in sanitation and drainage. This includes sewage, greywater and severely contaminated stormwater runoff. In low-income areas the paths are often merged; sewage, greywater, solid waste and contaminated runoff enter surface drains, which eventually discharges into streams, rivers and impoundments that are used for drinking water supply and recreation. Hence discharges from these settlements cause numerous adverse water quality effects on urban areas and on receiving waters, including erosion, sedimentation, dissolved oxygen depletion, nutrient enrichment and eutrophication, toxicity, reduced biodiversity, high drinking water purification costs, and the associated impacts on beneficial water uses. These problems reflect local conditions with respect to the climate, economic development, the level of environmental protection practice (including the associated infrastructures), institutional arrangements and public awareness. Also the development of comprehensive tools for selection of drainage management interventions even at planning levels is still at its early stage in South Africa. Hence planners and engineers are not equipped with the necessary knowledge and tools to deal with stormwater quality problems especially in informal settlements.

The above constituted the problem statement of the research whose primary aim was to develop a general guideline for effective management of urban runoff and greywater quality in South Africa with particular reference to low-income, high-density urban developments. To achieve this, the following specific objectives were set:

- Review stormwater runoff quality and treatment practices and the extent of runoff and greywater management in rural and peri-urban areas of South Africa. Determine the extent of quality control awareness and experience among stormwater management professionals and collate information upon which present and future needs can be assessed and addressed.
- To develop a methodology to identify factors causing water quality management issues in low-cost, high-density settlements.

- To develop a methodology to characterize storm and grey water quality as well as setting ambient water quality and management objectives.
- To develop a methodology to identify and select potential non-structural and structural control interventions to manage storm and grey water quality.
- Based on the above, to develop a decision support system for evaluation of potential interventions for storm and grey water management at planning level.

The methodologies used to achieve the above objectives consisted of: literature review; consultations with stakeholders; data analysis and computations; model development; and model application.

The literature review of South African case studies presented in Chapter 2 revealed that, contaminations of urban runoff water quality are related principally to: predominant type of land use activity (residential, industrial, commercial and agricultural); development type (formal versus informal); development density (expressed as number of people or dwelling units per unit area); standard or cost of development (low-cost high-density versus high-cost low-density); level of services provided and degree of service maintenance. The review also highlighted key management issues that require attention in catchment stormwater quality management including the reduction of pollutant concentrations of nutrients; suspended solids; bacteria; toxic chemicals including pesticides and metals; and oxygen demanding parameters to meet water quality objectives. Although many loading estimates have been reported for various land uses, high variability and inconsistencies exist among reported values. These differences may represent real variations or differences in sampling and analytical methods. This problem of little consistency or comparability among monitoring programs is further compounded by the absence of testing programs to evaluate urban runoff sampling strategies for effectiveness and efficiency; therefore, an optimal monitoring program has not been identified.

The solution appeared to lie with the development of guideline and a user friendly model to manage water quality effects in informal settlements. It was determined that this model should be able to account for social (non-structural) interventions and be applicable to developing areas with their history of limited data collection.

The model development was presented in Chapter 4, and the various computations involved were presented in Chapter 5. The model implementation was presented in Chapter 6. The model is a decision support system for rapid assessment of various water quality management interventions. The model was implemented using macros in Visual Basic for Application (VBA) in Excel. Although a simple model, it requires significant data input depending on the number of management interventions existing or to be implemented.

The model estimates storm loads, non-storm loads, and management objectives, and evaluates management interventions by estimating their load reductions. The load reductions are estimated by applying the intervention's efficiency to the total load from the catchment, and then apply a measure of assuredness to account for uncertainties. The model is primarily targeted at those who are involved or are likely to be involved in stormwater quality management including catchment managers, local governments or municipalities, catchment management agencies, private consultants and researchers. The model helps to answer the following questions:

- How to meet specified target load reduction as required?
- What interventions should be considered to treat/manage current and future contaminant sources to a receiving river body?
- Which combination of interventions (or strategies) would produce a minimum cost in meeting a community's stormwater quality management objectives?
- What pollutant reduction has been achieved by current or existing programs?
- What level of assuredness/risk does the estimated load reduced by an intervention represent?
- How effective are investments in educational and outreach programs to manage stormwater quality?
- Which area or land use within an urban catchment has the greatest potential or need for stormwater quality improvement?

- How do nutrient loads in a community that relies on septic systems compare to a sewered one, given the expected rates of maintenance?
- How serious does active construction impact the stormwater quality, and what measures to take to control impacts in the face of growing urbanization?
- How critical are pollutants from secondary sources such as sanitary sewer overflows, illicit connections, and active construction in an urban catchment, which are often overlooked in simple or complex models?

This research has explored decision support systems for stormwater and greywater quality management in developing areas. The investigation involved developing methodologies to: 1) identify factors causing water quality management issues, 2) set ambient water quality and management objectives, and 3) select potential management interventions. These methods were assimilated in the model development in Chapter 4. The decision support system and the related methodologies have been shown through a case study of Alexandra Township located north of Johannesburg to be versatile and to provide a good rapid assessment of various water quality management strategies. The decision support system and the related methodologies satisfy all the objectives set out in the introduction (Section 1.4).

The main distinguishing features of the DSS compared to a similar model by CWP (2001) are:

- Storm loads estimated in the DSS are loads derived from both pervious and impervious areas whereas CWP (2001) model deals with storm loads only from impervious areas. Studies such as Mackey (1993, 1994a,b), Grobicki (2001), van Ginkel et al. (1993) and Wright et al. (1993) have shown that pervious areas in developing areas contribute substantial loads to the receiving environments.
- The defaults in the DSS were mostly based on studies on water quality management in South African situations. The literature was reviewed extensively to gather information to serve as the expert's knowledge base in the DSS.
- A module to formulate implementation strategies which accommodate assessment of different management intervention scenarios. This will allow a stormwater

manager to assess different scenarios by combining different mixes of control interventions at different levels of implementation to meet management objectives.

- Costing to select the optimum management strategy.
- A module to quantify water quality management objectives (load reduction targets) of pollutants of concern.
- Addition of four new interventions (rainwater tanks, catchment erosion and sediment control, exfiltration systems, and river assimilation) that is more suitable for informal settlements in South Africa.
- Six pollutants (nitrogen, phosphorus, COD, lead, suspended solids, and faecal coliform) are tracked in the model as compared to four in the CWP (2001) model.
- Estimation and inclusion of uncertainties. Stormwater managers often need to identify the uncertainty of, or changes in system performance indicator values from what was predicted due to any changes in input data and parameter values. They need to reduce this level of uncertainty to the extent practicable and to communicate the uncertainties clearly so that decisions can be made with this knowledge and understanding.

8.2 Recommendations

The following recommendations are made towards enhancement of the DSS developed under this research:

- The general scarcity of appropriate quantitative information on urban water quality characteristics and management interventions (including design parameters, costs, and removal effectiveness) hampers the selection of suitable management interventions that can be deployed to manage or control the impacts of urban water quality pollution. Consequently, it is essential that carefully targeted research should be conducted to fill these information gaps. The input parameters into the decision support system can be used to guide the type of information needs.

- Development of a database to capture all monitored information is crucial to water quality management in settlements. This should include a database on structural treatment measures performance to help establish their important design parameters and elucidate the parameter effects on the structural treatment measure performance. A database on non-structural programs will help to establish the factors that are critical to their effectiveness and sustainability. Any developed database should be readily available to the public or at least all stakeholders and should be a driving force of knowledge sharing.
- The original research proposal included an undertaking of field treatability tests of some interventions as a case study. This action was initiated in Kliptown, a township in Johannesburg but, could not be completed due to financial constraints. Hence all the interventions identified and included in the model are not tested to ascertain their applicability and suitability. It is therefore recommended to test the model using actual monitored data from a selected settlement. This will require a long-term data collection programme.
- The extent to which geographic information systems (GIS) can be used as appropriate management and communications technologies to quantify urban runoff, identify and select appropriate management interventions and to communicate choices to decision-makers needs further research.
- The structural control interventions in the DSS (excluding rainwater tanks and exfiltration systems) are not programmed to act in series to themselves. Modifications to allow the structural controls to act in series will enhance the DSS and it is recommended.
- The DSS would be greatly enhanced if it could be re-designed to run continuous simulation to accommodate temporal and spatial variation of input parameters.
- Selection of least cost strategy with the DSS is presently achieved by trial and error process. The selection process can be improved if the DSS can be linked to an optimizer and a research into this is recommended.
- The DSS has enormous input data requirements, each with their own uncertainties. Classical uncertainty analysis may not be feasible for this type of

model but further elucidation of how uncertainty can be accounted for remains an important research gap and should remain on the agenda as an important issue.

Extensive literature review revealed certain aspects of water quality management in settlements which require research but were beyond the limits of the undertaking in this research. A research into these aspects will in no doubt complement this study and are summarised below.

- Research on the sustainability of management interventions is in its infancy even in the developed world. So far, broadly accepted sustainability criteria, which would allow measurement of the sustainability of individual interventions or projects, have not been established. More research is needed on the interaction of technical and social issues, including social marketing of stormwater management and public education and participation in this process.
- The sustainable operation of stormwater management systems requires sound financing for both the initial implementation and for continuous maintenance. In new areas, stormwater management financing is relatively easy – through lot levies and similar development fees. In the existing areas, the financing of retrofitted stormwater management systems is much more difficult and this may be a major reason why progress in stormwater management in older areas with sound but possibly outdated infrastructures is rather slow. The old way of financing drainage services from the general municipal tax revenue is a common norm in South Africa, but other models are being developed as well. Financing of drainage and stormwater management systems by promoting the user pay principle and collecting drainage fees are potential innovative concepts. Drainage fees may be link to the user's generation of runoff, which may be considered to be proportional to the impervious area directly occupied by the user. A research into this for possible application in South Africa is recommended.
- Literature review has indicated that there is an ongoing change in the ownership and operation of stormwater management systems. While traditionally the drainage systems were publicly owned and operated, there is trend towards other modes of ownership and operation, involving the private sector – that is

privatization. Towards this end, stormwater utility companies (both public and private) are being set up and these then provide stormwater management services. Typically, these stormwater utilities operate within larger water companies, which can provide integrated services to urban populations. Operation of new stormwater management systems requires dedicated agencies, preferably operating within the integrated water management authorities. In this system, various mixes of public and private sector partnership are promoted, to find the best combination fitting the local conditions. Furthermore, these agencies should be locally based and responsible to their local clientele, whose interests they have to serve. Whether these concepts of privatization and partnership are conducive for application in informal settlements requires research.

- Urban drainage infrastructures are significantly changing from the older systems with pipes only, to new, more cost effective and environmentally friendly systems (green infrastructures) encompassing attractively landscaped ponds, natural channels, wetlands, infiltration sites and swales. The application, effectiveness and sustainability of these green infrastructures in informal settlements require further research. The ability of these green infrastructures to with stand vandalism and abuse would also have to be looked at.
- Finally, settlement drainage touches the lives of practically all settlement dwellers. It is therefore important to keep public awareness, education and participation in the forefront of all stormwater management activities, recognizing that the success of stormwater management depends on public support and participation.

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APPENDIX A OVERVIEW OF TRAPPING SYSTEMS

A.1 Introduction to Trap systems

This Appendix was adapted from Armitage et. al., 1998. Of all the structural technologies, the trapping systems are the only technology that has recently received considerable local research (Armitage et. al., 1998) in the context of stormwater runoff treatment. As a result of this study, seven devices (composed of self-cleaning screens and in-line screens) were identified as showing the greatest promise in South Africa:

- Side-entry catchpit traps (SECTs)
- The North Sydney Litter Control Device (LCD)
- The In-line Litter Separator (ILLS)
- The Continuous Deflective Separator (CDS) device
- The Stormwater Cleaning Systems (SCS) structure
- The Baramy® Gross Pollutant Trap (BGPT) and
- The Urban Water Environmental Management (UWEM) concept.

Many of these structures are Australian and their main features are summarised in Table A-1. The study also revealed that fences, nets, booms or baffles might also be successfully used to intercept litter in streams provided the peak flow velocity is not too high.

Screens, racks, booms and baffles are most appropriate and cost-effective methods of removing litter from drainage systems. Screens (and racks) consist of a series of vertical and horizontal bars or wires that trap litter while allowing water to pass through the openings between the bars or wires. Screens (and racks) can be used effectively to capture significant amount of aesthetically undesirable litter contained in storm runoff. Finer screens have higher removal efficiencies, but are more susceptible to clogging and tearing and may require maintenance after each overflow event. The effectiveness of screening units is reduced significantly by the presence of oil and grease in the flow.

Booms are containment systems that use specially fabricated floatation structures with suspended curtains designed to capture buoyant materials. Booms can also be designed to absorb oils and grease.

The trapping systems are sized based upon the expected volume of litter released during a design-storm event. After a storm event, material captured in the systems can be removed manually. Trapping systems can easily be retrofitted to existing or developing settlements. Removal efficiencies are tied closely to the design size, whereas the main selection criteria of these systems at any particular location depend on

- Maximum flow rate
- Allowable head loss
- Relative size of the structure
- Litter removal efficiency
- Reliability (structural and hydrological)
- Ease of cleaning and maintenance
- Cost-effectiveness.

Often, traps arranged in series yields better treatment performance than a single trap serving the whole the catchment. For this reason, many traps are designed to handle peak flow rates in the region 1-month to 2 years recurrence interval (Armitage et al., 1998), as all treatment measures are seldom designed to handle the maximum expected flood peak.

A summary page is provided below for each of the seven devices identified by Armitage et al., 1998 as showing the greatest potential for use in South African condition.

Table A- 1: Summary of litter trapping devices – adapted from Allison, 1997 (quoted in Armitage et al., 1998)

Devices	Typical catchment area (ha)	Typical cleaning frequency	Head requirement	Maximum efficiency (%)	Comments on performance
SECT	0.1 – 1	Monthly or after every major storm	Low (effectively)	59 – 76 (50 – 100% coverage respectively)	Need to be able to target the catchpits with the highest loads. The efficiency of the unit is strongly affected by the number of untrapped catchpits and the cleaning frequency
LCD	20 – 150	Monthly or after every major storm	High	25	Inefficient in high flows but collects most material at low to medium flows. Likely to be a relatively expensive option. Relatively easy to clean.
ILLS	5 – 25	Monthly or after every major storm	Low	25	Little data available. Likely a relatively expensive option. Moving parts may cause problems.
CDS	10 – 200	4 times a year	Low	99	Very efficient trapping device, but very expensive to install and tedious to clean.
Baramy®	10 – 500	4 times a year	High	95	Little prototype data available, but shows considerable promise. Compact. Easy to clean.
SCS	>1	Monthly or after every major storm	High	95	Works well provided the head is available. Easy to clean.
UWEM	>400	After every major storm	Low (effectively the head is generated by a sluice gate)	90	The concept of generating head in-situ via a hydraulically actuated sluice shows considerable promise for use with other structures e.g. Baramy®, SCS.
Fences, nets, weirs, booms or baffles	>400	Depends on structure and location. Could vary from weekly to annually	Low	Varies. Could approach 100% with very low peak velocities.	Efficiency unpredictable – depends on structure and location. Generally the cheapest solution.

A.2 Side-Entry Catchpit Traps - SECTs

Description: In it most basic form, a wire mesh or plastic perforated tray is mounted on metal supports embedded in the catchpit sidewalls next to, and immediately underneath, the catchpit opening. Stormwater either flows through the perforations (which are typically between 5 and 20 mm in diameter) leaving the litter behind, or, if the perforations are blocked and/or the tray full, the stormwater flows over the back wall of the tray. A schematic cross section of a typical side-entry catchpit trap is shown in Figure A-1.

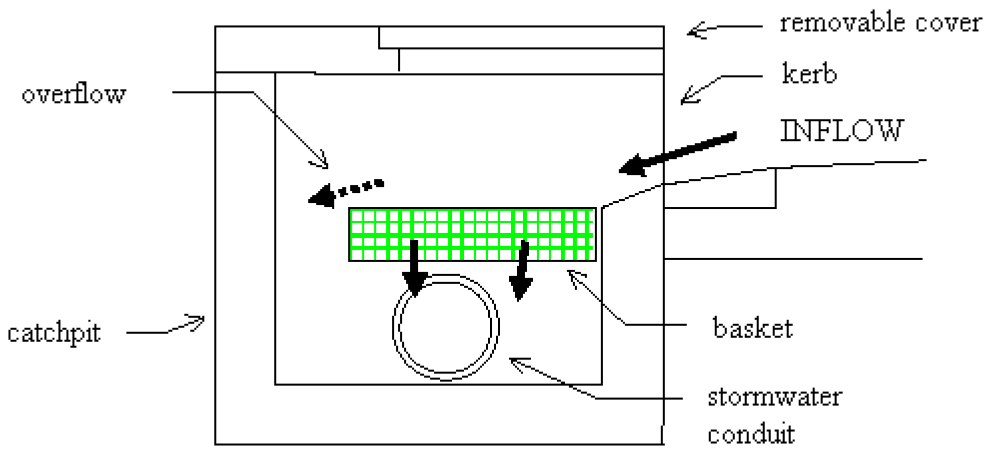

Figure A- 1: Cross-section through a typical side-entry catchpit trap

Application: side-entry catchpits. SECTs can be custom made to suit virtually any side-entry catchpit.

Patent holder: Various Ausralian designers and/or patent holders including the following:

- Banyule City Council
  275 Upper Heidelberg Road
  Ivanhoe, Victoria Australia
  Phone: [++61] (3) 9490 4222

- Pitclear Industries

38 McGlynn Avenue
South Morang, Victoria, 3752
Australia

- Dencal Industries
  24 halcyon Way
  Narre warren South, Victoria, 3805
  Australia

Installation costs: A$60 – 150 per catchpit (Allison, 1997).

Cleaning costs: A$5 – 10 per catchpit per clean (Allison, 1997). Typically a catchpit would be cleaned at monthly intervals or after every major storm.

Head requirement: A minimum of 500 mm (includes the depth of the basket and diameter of the stormwater conduit) – but this is generally already available within the side-entry catchpit.

Size: fit within almost all existing side-entry catchpits

Trap efficiency: the basket mesh size varies between 5 and 20 mm. Particle samller than this are often trapped as a result of the "filter" that starts to form on the basket following deposition. If the baskets are not cleaned often enough, litter will pass over the overflow. According to Allison, 1997 (quoted in Armitage et al., 1998) the maximum trap efficiency is about 76%. If not all the catchpit are fitted with baskets, the overall efficiency will obviously drop. Allison, 1997 showed that for Coburg, if the engineer correctly selected the catchpits carrying the higher loads, the net efficiency could be predicted from:

$$E = 1.18 \times 10^{-4} * T^3 - 2.58\times10^{-2} * T^2 + 2.184 * T \qquad (R^2 = 0.91)$$

where E = net trap efficiency (%)

T = trap coverage (%)

Method of cleaning: By hand or with a vacuum eductor (truck fitted with a suction hose. The basket then washed with water under high pressure.

Advantages (after Melbourne Water Waterways and Drainage Group, 1995 (quoted in Armitage et al., 1998)):

- Quick and easy to install.
- Collection of litter is easily integrated into catchpit maintenance program.
- Prevents transfer of kerb-side litter into drains and waterways.
- Litter trap basket can be easily removed for maintenance purposes.
- Litter trap basket has been designed to capture debris while still allowing water to pass into the drainage system.
- Can be used to identify the main sources of litter as part of catchment management progromme.

Disadvantages (after Melbourne Water Waterways and Drainage Group, 1995 (quoted in Armitage et al., 1998)):

- High cost of acquiring a special vacuum track for litter collection
- The catchpit covers are heavy and need to be removed using safe lifting techniques.
- A large number of units are required in litter prone areas.

Comments: Only cost-effective in high litter producing areas such as Central Business Districts (CBD). Additional traps might be required downstream to catch bypass material. Most effective when used in conjunction with a catchment management program.

A.3 The North Sydney Litter Control Device - LCD

Description: The device consist of a pre-cast or in-situ concrete pit located downstream of a stormwater drainage pipe or culvert. A drop is provided in the pit between the invert of the inlet and the floor of the outlet structure. This drop is in the order of a metre, which caters for the 635 – 850 mm deep removable baskets and a 150 – 300 mm gap below the outlet structure. Above the removable litter basket is an inclined trash rack with vertical bars spaced every 50 mm. The trash rack is inclined towards the litter baskets to prevent the inflow from scouring out previously deposited litter. It is hinged so that it can be pushed back to enable easy removal of the litter baskets (Brownlee, 1994). A schematic cross section of a typical LCD is shown in Figure A-2.

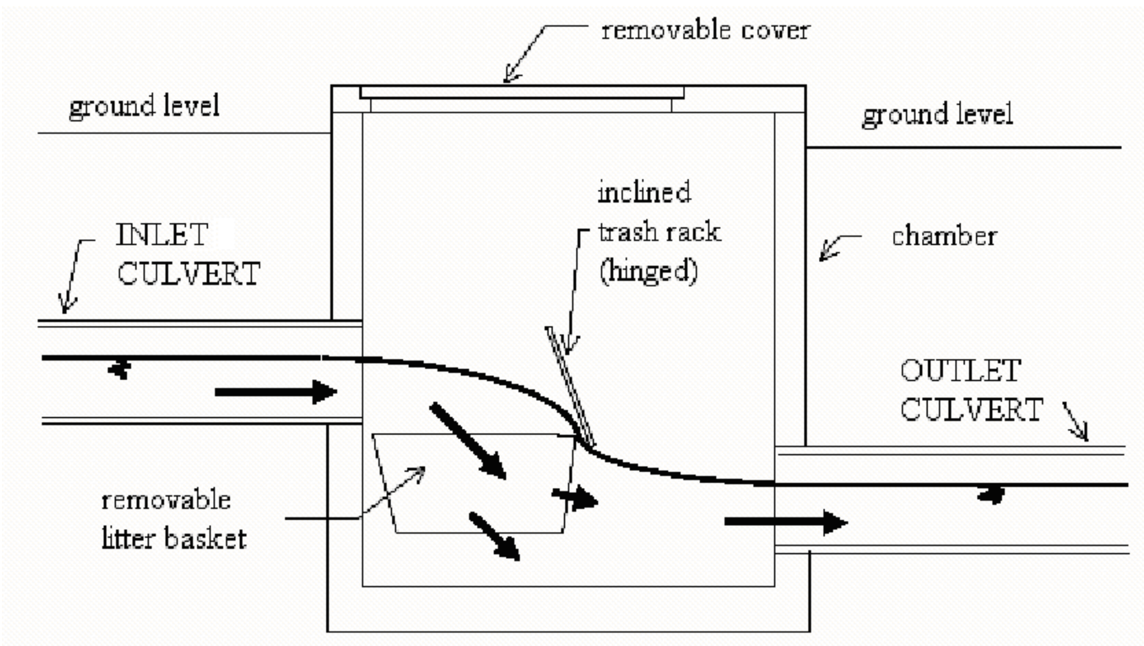

Figure A- 2: Section through a typical North Sydney Litter Control Device (LCD) (after Brownlee, 1995 and Hocking, 1996 (both quoted in Armitage et al., 1998))

Application: On conduits up to about 1 500 mm diameter.

Patent holder: Attention: Mr Ray Brownlee

North Sydney Council

200 Miller Street

Australia

Phone [++61] (2) 9936 8231

Fax [++6] (2) 9936 8203

Installation costs: The existing data is given in Table A-2.

Table A- 2: Capital Costs of Litter Control Devices (Brownlee, 1995)

Location	**Cost (A$)**	**Catchment Area (Ha)**
Willoughby Street	100 000	8.92
Walker Street	120 000	16.76
Smoothey Park	120 000	16.48
Waverton Park	120 000	30.01
Crows Nest Road	120 000	25.27
Ellamang Street	50 000	1.71
Honda Road	100 000	40.20
Grafton Road	130 000	144.74
Hayes Street	80 000	38.40
TOTAL	**940 000**	**322.50**

.

The average installation cost is A$2 900 per hectare.

Cleaning costs: The average cleaning costs are estimated to be in the order of A$2.67 per hectare per clean (Allison, 1997)

Head requirement: 650 – 1 000 mm.

Size: A LCD typically has external dimensions in the order of 3.5 x 3 x 3 m deep.

Trap efficiency: The baskets are generally constructed from 5 mm thick punched sheet metal with staggered 30 mm diameter holes (Hocking, 1996 (quoted in Armitage et al., 1998)). Sometimes 20 mm holes are used (Brownlee, 1995 (quoted in Armitage et al., 1998)). Studies have shown that finer material than this is often bound up in the matrix of coarse material that is soon trapped by the baskets. Trap efficiency is however strongly related to cleaning frequency. Increasing the cleaning frequency from monthly to after every storm (approximately weekly), increased the quantity of litter trapped at the

Smoothey Park LCD by 192% (Hocking, 1996 (quoted in Armitage et al., 1998)). The device is considered to be generally less than 30% efficient with monthly cleaning (Allison, 1997 (quoted in Armitage et al., 1998)).

Method of cleaning: The litter is retrieved by lifting the baskets out of the LCD and depositing the litter into the rear of a 6 tonne haulage unit. This takes a two person maintenance crew approximately 35 minutes (Hocking, 1996 (quoted in Armitage et al., 1998)).

Advantages:

- Simple operation
- May be installed under road surfaces
- Relatively easy to clean.

Disadvantages:

- Extensive
- Inefficient
- Requires a relatively high head for operation.

Comments: Only likely to find application in high density commercial areas where there is insufficient room to install more efficient device. Although the LCD is probably the least efficient of the seven devices described here, it is considerably better than many other similar devices which are currently on the market. This illustrates the difficulties facing the designers of litter control devices.

A.4 The In-Line Litter Separator - ILLS

Description: A carefully shaped boom situated in the separator pit deflects the flow into the holding pit. Once in the holding pit, the flow is forced down under a suspended baffle wall and up over a weir before being returned to the separator pit downstream of the boom. The relatively large plan area of the holding pit ensures that the average vertical flow velocities are low enough to prevent carry-through of those objects, such as plastic bags, that have a negligible settling velocity (positive or negative) (Figure A-3).

In the event of particularly high flows through the stormwater conduit, the increased water levels on both sides of the boom causes it to float out of the way, ensuring that upstream flood levels are not affected by the structure, and the litter already trapped in the holding pit is not washed out. The boom is restrained by rods, which are attached to its upper surface and the walls of the chamber above the pipe inlet, in such a way that the boom is free to rotate about a hinge at the wall (Swinburne University of Technology, 1996 (quoted in Armitage et al., 1998)). The plan of and cross-sections through the In-line Litter Separator (ILLS) is shown in Figure A-3.

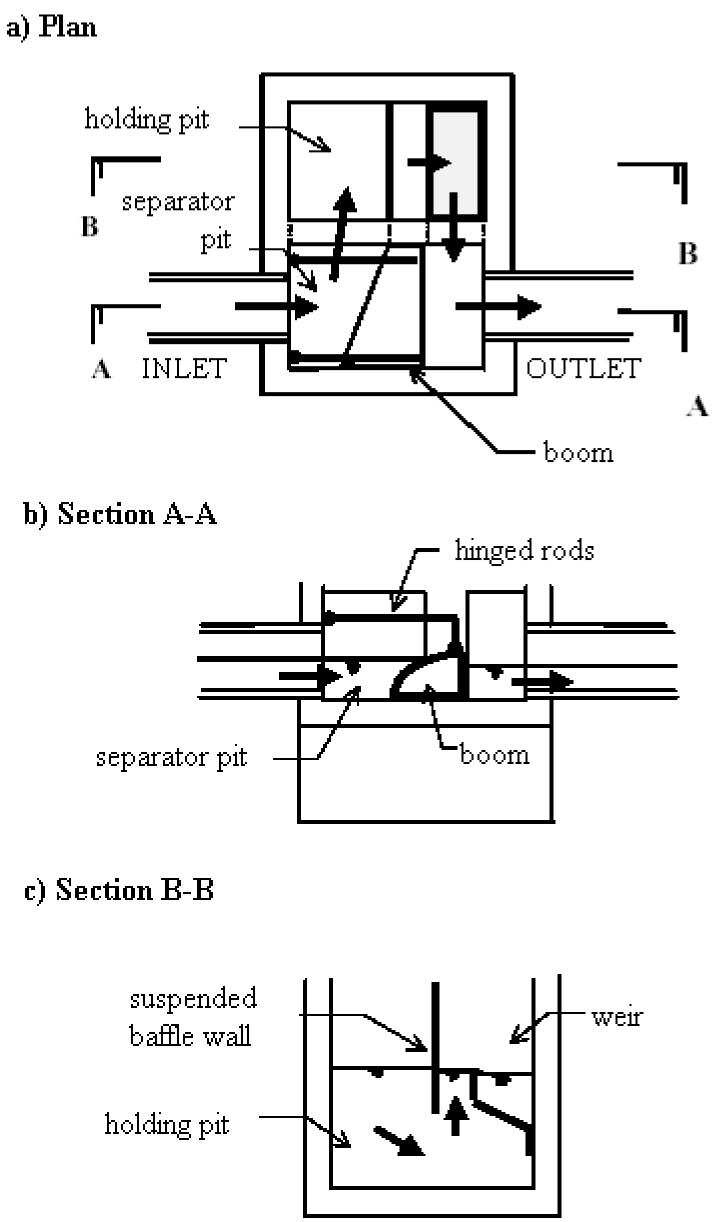

Figure A- 3: Plan of and cross-sections through the In-line Litter Separator (ILLS)

Application: On conduits up to about 900 mm in diameter.

Supplier: marketed under the name “Litterguard” and supplied by:

CSR Humes

122a Doherty’s Road

Laverton North, Victoria

Australia
Phone [++6] (3) 9360 3888
Fax: [++6] (3) 9360 3887

Installation costs: A$4 000 – A$8 000 depending on the pit size, depth of pipe and type of pit cover required.

Cleaning costs: No information available. Will probably be in the order of R50 per unit per clean. The unit will probably have to be cleaned monthly or after every major storm.

Head requirement: Less than 200 mm.

Size: While considerably smaller than the CDS unit, the ILLS nevertheless extends from one and a half to two metres from one wall of the pipe.

Trap efficiency: Little information is available. Likely to be a very inefficient with polyethylene sheeting - for example in the form of shopping bags. This is problematic as shopping bags make up a large percentage of water-borne litter. By-passing also commences at a fairly low flow rate to keep the head requirement to a minimum. As considerable quantities of litter are carried in high flows, the overall efficiency of the device is likely to be low.

Method of cleaning: Hand-held scoop or vacuum eduction.

Advantages:

- Fairly easily retro-fitted to existing stormwater systems.
- Very low head requirement means that it has great flexibility.
- Can also trap oils and grease.
- Retains previously trapped litter during periods of bypass
- Relatively easy to clean

Disadvantages:

- Unreliable trapping performance.
- Boom might be damaged by fast moving heavy objects.
- Boom hinging mechanism might be damaged causing flooding during periods of high flow, or loss of liter once flows have dropped.
- Lack of field data

Comments: The ILLS is probably only viable as a retro-fit system in situations where flat gradients and lack of space preclude other options.

A.5 The Continuous Deflective Separation - CDS - Device

Description:

The flow in a stormwater conduit is deflected into a circular pollutant separation and containment chamber. Gross pollutants are separated within the upper separation portion of the inner chamber with the aid of a perforated plate screen which allows the filtered water to pass through to a volute return system and back to the outlet pipe. The water and associated pollutant contained within the inner chamber are kept in continuous motion by the vortex action generated by the incoming flow. This has the effect of keeping the gross pollutant in the containment chamber from blocking the perforated plate screen. The heavier pollutants ultimately settle into the lower solids collection sump, whilst the flotsam floats on the surface of the containment chamber (Wong and Wooton, 1995 (quoted in Armitage et al., 1998)) Horizontal and vertical sections through the CDS device are shown in Figure A-4.

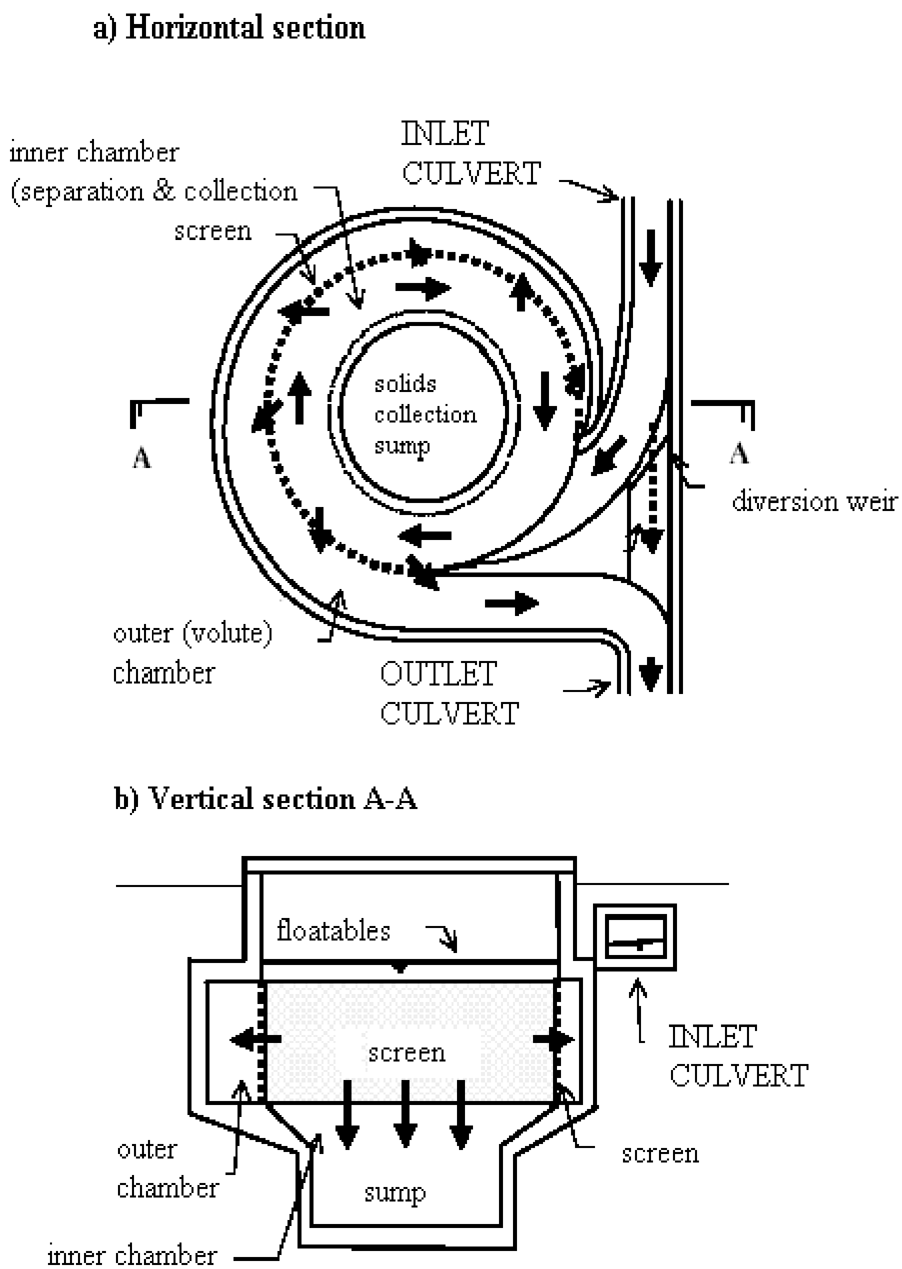

Figure A- 4: Horizontal and vertical sections through the CDS device

Application: Typically on conduits greater than one meter diameter. They can be installed in open channels carrying flows up to about 50 m^3/s provided a high bypass ratio (during floods) is acceptable.

Patent holder: CDS Technologies Pty Ltd
1140 Nepean Highway

Mornington, Victoria, 3931
Australia
Phone: [++6] (3) 5977 0305
Fax: [++6] (3) 5977 0302
Email: info@cdstech.com.au
Internet: http://www.cdstech.com.au

Installation costs: Little data currently exists. The three meter diameter unit constructed in Coburg, Australia, which is capable of treating 550 liters per second, costs A$230 000, but this including many extra costs associated with construction including realignment of power, water, telephone and gas lines, and strengthening of the covers to allow the passage of large trucks. The cost of the unit excluding site works was about A$100 000 (Allison, 1997 (quoted in Armitage et al., 1998)). CDS Technologies have recently installed units treating from 0.8 – 1.75 m3/s for costs in the range of A$140 000 – A$160 000. These prices might be reduced by 15 – 20% once precast units become available (CDS Technologies, 1997 (quoted in Armitage et al., 1998)). Further information regarding costs should be obtained from CDS Technologies Pty Ltd.

Cleaning costs: Little data currently exists. The Coburg unit costs about A$1 000 per clean. In Australia, these units are cleaned about four times a year (Allison, 1997 (quoted in Armitage et al., 1998)). In South Africa, with much higher litter loads, cleaning might be required more frequently.

Head requirement: Approximately 400 mm at commencement of bypass flow (Allison, 1997 (quoted in Armitage et al., 1998)).

Size: A large off-channel structure. The Coburg unit required a 6 x 6 x 4 m excavation. The unit may however be installed underneath road surfaces (Allison, 1997 (quoted in Armitage et al., 1998)).

Trap efficiency: A typical screen has a 5 mm opening. Studies by Wong et al., 1995 (quoted in Armitage et al., 1998) indicate that approximately 95% of material down to 50% of the separation screen aperture size is also trapped. Litter loss is predominantly as a result of bypass during high flows. The litter already trapped in the unit is unaffected by bypass.

Method of cleaning: CDS Technologies Pty Ltd has designed a 'basket' that fits within the sump of the unit. This basket can be raised by means of an external crane, and the contents deposited into waiting trucks (Blanche and Crompton, 1996 (quoted in Armitage et al., 1998)). In Melbourne, the CDS Technologies have invested in a truck mounted telescoping grab to achieve fast and cost effective mechanical without dewatering (CDS Technologies, 1997 (quoted in Armitage et al., 1998)). Alternatively the unit can be pumped dry using a specially designed eductor truck that strips the litter off and returns the liquid to the conduit downstream of the bypass weir. If the unit is cleaned manually, special training and equipment is required – but this method of cleaning is not recommended (Allison, 1997 (quoted in Armitage et al., 1998)).

Advantages (after Melbourne Water Waterways and Drainage Group, 1995 (quoted in Armitage et al., 1998)):

- High percentage removal of litter.
- Will not block (except if the unit is complete full of litter).
- Minimal maintenance
- Can be located anywhere in the drainage system.
- Effective even in high flows – a bypass operates if the system is overloaded.

Disadvantages (after Melbourne Water Waterways and Drainage Group, 1995 (quoted in Armitage et al., 1998)):

- Very high capital cost.
- High cost of acquiring a special truck designed for litter collection from the unit.
- May require annual eduction of sediments from the sump.

- Trapped material might ferment to produce toxic substances.

Comments: Although an extremely efficient device from a hydraulic point of view, the high installation and cleaning costs make this unit suitable only for high value land and where there is limited space for alternatives.

A.6 The Baramy® Gross Pollutant Trap - BGPT

Description: Application: on pipes or channels from 300 mm diameter upwards. The direct flow version has no particular upper flow limit as long as there is sufficient space and drop available (as much as 4.5 m is required in some instances). It is unlikely that a BGPT would ever be installed on a channel with a maximum flow in excess of 50 m^3/s.

Patent holder: Baramy Engineering Pty Ltd
P. O. Box 357
Katoomba, New South Wales, 2780
Australia
Phone: [++6] (47) 82 5741
Fax: [++6] (47) 82 3430
Email: Baramy@Lisp.com.au

Installation costs: depends on size and layout. The estimated costs of the basic units (they are usually prefabricated and delivered to site for installation) are given Table A-3.

Table A- 3: The basic installation cost of Baramy® Gross Pollutant Traps

Pipe diameter (mm)	**Installation Cost (A$)**
300 – 450	6 000 – 8 000
525 – 900	12 000 – 16 000
1 000 – 1 500	20 000 – 24 000
Multiple pipes	From 34 000

Flow in excess of 30 cumecs	From 40 000

To the above must be added site costs which would be site specific and could double the cost of the installation (Baramy, 1997 (quoted in Armitage et al., 1998)).

Cleaning costs: little data currently exists. Seeing that the device is cleaned in much the same way as the SCS structure, the cleaning costs are probably of the same order of magnitude i.e. R35/m^3 litter.

Head requirement: typically between 700 mm and 1.5 m (Baramy, 1997 (quoted in Armitage et al., 1998)). However, some units require as little as 350 mm, whilst others require as much as 4.5 m (Baramy, 1997 (quoted in Armitage et al., 1998)).

Size: the relative size of the structure varies from installation to installation. The smallest units for installation on pipes are about 3 m wide including the access ramp. The larger units are typically three times the width of the channel. Installations on very wide channels may only be 50% wider than the channels.

Trap efficiency: The screen opening is typically 15 mm and, since the trap is usually designed to intercept the entire flow range, the trap would thus be expected to catch virtually all material with a minimum dimension larger than this. If a bypass is provided, litter carried over the bypass would naturally be lost.

Advantages:

- Generally designed to remove litter over the entire flow range.
- Can handle relatively high flows (up to say 30 m3/s) with ease.
- Negligible maintenance.
- Easy to clean.
- Little risk of toxic fermentation.
- Relatively safe for public and workers.

Disadvantages:

- High head requirement.
- Requires a large amount of ground that must generally be fenced off to prevent the public from coming into contact with trapped litter.

Comments: If it were not for its high head requirement, this device would be the first choice in most situations. Head may however be created by means of an hydraulically actuated sluice gate as with the UWEM concept. In some instances, the drop in trapping efficiency occasioned by the use of a sluice gate may be more than compensated for by the hydraulic efficiency of the structure.

APPENDIX B WATER QUALITY MODELS AND MODELLING

B1. Use of models in water quality management

Monitoring data are the preferred form of information for identifying impaired waters. Model predictions might be used in addition to or instead of monitoring data for several reasons:

- Modelling might be feasible in some situations where monitoring is not.
- Integrated monitoring and modelling systems could provide better information than one or the other alone for the same total cost. For example, regression analyses that correlate pollutant concentration with some more easily measurable factor (such as stream flow) could be used to extend monitoring data for preliminary listing (of impaired status) purposes. Models can also be used in a Bayesian framework to determine preliminary probability distributions of impairment that can help direct monitoring efforts and reduce the quantity of monitoring data needed for making listing decisions at a given level of reliability (Loucks and Beek, 2005).
- Modelling can be used to assess (predict) future water quality situations resulting from different management strategies. For example, assessing the improvement in water quality after a new stormwater treatment measure is built, or the effect of increased informal settlement growth and effluent discharges.

Combined runoff and water quality prediction models link stressors (sources of pollutants and pollution) to responses. Stressors include human activities likely to cause impairment, such as the presence of impervious surfaces in a watershed, cultivation of fields close to the stream, over-irrigation of crops with resulting polluted return flows, the discharge of domestic and industrial effluents into water bodies. Indirect effects of humans include land cover changes that alter the rates of delivery of water, pollutants and sediment to water bodies.

A review of direct and indirect effects of human activities suggests five major types of environmental stressors:

- alterations in physical habitat

- modifications in the seasonal flow of water
- changes in the food base of the system
- changes in interactions within the stream biota
- release of contaminants (conventional pollutants)
  (Karr, 1990; NRC, 1992, 2001).

Ideally, models designed to manage water quality should consider all five types of alternative management measures. A broad-based approach that considers these five features provides a more integrative approach to reduce the cause or causes of degradation (NRC, 1992).

Models that relate stressors to responses can be of varying levels of complexity. Sometimes, they are simple qualitative conceptual representations of the relationships among important variables and indicators of those variables, such as the statement 'informal dense settlements in a catchment highly affect water quality, including the condition of the river biota'. More quantitative models can be used to make predictions about the assimilative capacity of a water body, the movement of a pollutant from various point and non-point sources through a catchment, or the effectiveness of certain structural stormwater treatment measures (best management practices).

Predicting the water quality impacts of a proposed urban development can only be undertaken by some form of modelling. Modelling can comprise both source-modelling, to estimate the likely pollutant loads from existing and/or proposed land uses, and control-modelling, to estimate the ability of stormwater treatment measures such as constructed wetlands to reduce pollutant levels.

Ideally, water quality models should be calibrated using appropriate monitored data. The accuracy of models can be enhanced by calibration based on local or on-site monitoring of water quality and flow events. An alternative approach in the absence of on-site monitoring can be to use the results from studies at sites with similar characteristics. However, measured in-stream water quality is a function of both pollutants exported and in-stream processes, and it is difficult to separate these influences. Such monitoring alone, however, cannot be used to predict the expected impacts of a new development.

Current techniques for water quality modelling do not provide reliable estimates of the relationship between land use activities and ambient receiving water quality. This is partially due to the complexity of the physical, chemical and biological processes in a water body, and our lack of understanding of the relationship between intermittent stormwater discharge quality and ambient water quality. Therefore, in general it is currently not possible to accurately relate changes in pollutant loads or runoff concentrations to the achievement of ambient water quality objectives for rivers and streams.

Stormwater quality modelling involves significant uncertainty and variability associated with:

- rainfall temporal and spatial distribution across a catchment;
- rainfall/runoff relationships for catchments;
- pollutant export relationships;
- pollutant behaviour in waterways;
- estimation of pollutant retention in stormwater treatment measures; and
- monitoring errors.

This variability and uncertainty needs to be acknowledged when model results are being assessed.

B2. Modelling techniques

Three levels of detail can be employed in urban stormwater quality modelling to estimate stormwater pollutant loads:

Level 1: Average Annual Storm Load

This prediction level estimates the average annual pollution loads from stormwater, commonly expressed in kilograms of pollutant exported per year. These are relatively simple modelling techniques, which may relate land use, annual rainfall, catchment runoff characteristics and average pollutant concentrations to estimate the annual pollutant load.

Level 2: Actual Event Load

This level assesses the pollutant loads from a storm event or on a daily basis. These models use daily or event rainfall data and catchment runoff characteristics to generate daily or event runoff, which is then used to calculate pollutant loads.

Level 3: Actual Distribution of Concentrations and Load within Events

This level estimates actual pollutant concentrations and loads, as a function of time, within each storm event. This form of modelling uses relatively short duration rainfall data (e.g. 5 - 60 minutes) and complex modelling of runoff characteristics from pervious and impervious areas to generate runoff hydrographs. The runoff characteristics are then used to generate pollutographs, which indicate variations in pollutant concentration over time.

Further details on modelling techniques can be found in Huber (1992) and O-Loughlin and Goyen (1995).

Huber (1992) identifies total storm load (Level 2) as usually being sufficient to estimate the likely change in pollutant loads following a land use change. Further, Huber (1992) notes that detailed simulation of short term incremental changes in concentrations/loads (Level 3 detail) is generally only necessary for analysis of some control options, whose effectiveness may be a function of the transient behaviour of pollutants. The assessment of any first flush effects, for example, would be determined by Level 3 modelling, although such detailed assessment is not normally required.

The modelling approach adopted can be related to the size or significance of the development. Simple modelling analyses are likely to be reasonable for small scale developments, while more sophisticated modelling should be undertaken for major development proposals. A suggested modelling approach is provided in Table B.1, for ranges of development areas.

Table B- 1: Suggested Modelling Approaches (adapted from NSWEPA, 1996)

Total Development Area	Potential Modelling Approach
Small (< 10 ha)	Level 1
Medium (10 -50 ha)	Level 2
Large (>50 ha)	Level 2 (or 3) (with on-site calibration)

Water quality modelling should generally address suspended solids (SS), total phosphorus (TP) and total nitrogen (TN), in addition to runoff volume, as a minimum.

An example of Level 1 modelling technique is described in Section B.7.1. The event mean concentration (EMC) parameters for pollutants contained in this Appendix can also be used for Level 2 modelling. The use of EMCs for Level 2 modelling is preferred over non-linear pollutant export coefficients (regression equations), on the basis that EMCs have been found to be generally independent of event runoff volumes (US EPA 1983, Duncan 1995).

B3. Model selection criteria

Water quality predictive models described above include both mathematical expressions and expert scientific judgement. They include process-based (deterministic) models and data-based (statistical) models. The models should link management options to meaningful response variables (such as pollutant sources and water quality standard parameters). They should incorporate the entire ‘chain’ from stressors to responses. Process-based models should be consistent with scientific theory. Model prediction uncertainty should be reported. This provides decision makers with estimates of the risks of options. To do this requires prediction error estimates.

Water quality management models should be appropriate to the complexity of the situation and to the available data. Simple water quality problems can be addressed with simple models, while complex ones may or may not require the use of more complex models. Models requiring large amounts of monitoring data should not be used in situations where such data are unavailable. Models should be flexible enough to allow updates and improvements as appropriate based on new research and monitoring data.

Stakeholders need to accept the models proposed for use in any water quality management study. Given the increasing role of stakeholders in water management decision processes, they need to understand and accept the models being used, at least to the extent they wish to do so. Finally, the cost of maintaining and updating the model over time must be acceptable.

Although predictions are typically made with the aid of mathematical models, there are certainly situations where expert judgement can be just as good. Reliance on professional judgement and simpler models is often acceptable, especially when data are limited.

Highly detailed models require more time and are more expensive to develop and apply. Effective and efficient modelling for water quality management may dictate the use of simpler models. Complex modelling studies should be undertaken only if warranted by the complexity of the management problem. More complex modelling will not necessarily ensure that uncertainty is reduced, and in fact added complexity can compound problems of uncertainty analyses.

Placing a priority on process description usually leads to the development and use of complex deterministic models rather than simpler deterministic or empirical models. In some cases this may result in unnecessarily costly analyses. In addition, physical, chemical and biological processes in terrestrial and aquatic environments are far too complex to be fully represented in even the most complicated models. For water quality management, the primary purpose of modelling should be to support decision-making. The inability to describe all relevant processes completely contributes to the uncertainty in the model predictions.

B4. Model data and methods

Data availability and accuracy are sources of concern in the development and use of models for water quality management. The complexity of models used for water quality management should be compatible with the quantity and quality of available data. The use of complex deterministic models for water quality prediction in situations with little useful water quality data does not compensate for that lack of data. Model complexity can give the impression of credibility, but this is usually misleading.

It is often preferable to begin with simple models and then, over time, adds additional complexity as justified by the collection and analysis of additional data. This strategy makes efficient use of resources. It targets the effort toward information and models that will reduce the uncertainty as the analysis proceeds. Models should be selected (simple versus complex) in part on the basis of the data available to support their use.

Water quality models of water bodies receiving pollutant discharges require those pollutant loadings as input data. These pollutant discharges can be from point and non-point sources. Point source discharges are much easier to measure, monitor and estimate than non-point source inputs. Non-point discharge data often come from rainfall–runoff models that attempt to predict the quantity of runoff and its constituent concentrations. The reliability of the predictions from these models is not very good, especially if short time periods (e.g. each day or week) are being simulated. Their average values over longer time periods (e.g. a month or year) tend to be more reliable. This is mainly because the short-term inputs to those models, such as constituent loadings on the land and the rainfall within an area, can vary over space and time within the area and time period being simulated, and are typically not known with any precision.

B4.1 Parameters for modelling pollutants and runoff

There are a range of options for estimating pollutant concentrations and runoff parameters (or coefficients) for use in water quality modelling. These options include obtaining pollutant concentration and flow data from:

- studies of other catchments (e.g. as reported in the literature);

- monitoring of the development site (to characterise existing conditions – Section 4.3.1); or
- additional monitoring from a catchment in the region with similar land use to that proposed for the development. This data can be used to predict post-development conditions.

Reasonably conservative parameters should be used where there is uncertainty associated with model parameters obtained from other catchments, or where the level of modelling is lower than that contained in Table A.1. This would involve the use of relatively low predevelopment EMCs, runoff parameters or other forms of export rates, and relatively high post-development parameters.

The accuracy of the modelling will increase with the amount of monitoring data used to calibrate the model parameters. The decision on the need for, and level of water quality and flow monitoring can be based on an economic comparison of the monitoring costs against the potential benefit of improved model accuracy. These benefits may include a more intense land use change or the reduced size of stormwater treatment measures.

The estimated retention of pollutants by any proposed stormwater treatment measure will also need to be modelled to estimate the effectiveness of the mitigation measures.

B4.1.1 Runoff volume (rainfall-runoff relationships)

Runoff coefficients from non-urban catchments will have a high degree of variability, depending on factors such as soils, vegetation, topography and rainfall patterns. Department of Water Affairs and Forestry (DWAF) determine the runoff coefficient by sub-dividing the runoff coefficient into components. Evapo-transpiration losses are low during storm, but a portion of the total rainfall does not reach the river channel due to infiltration into the soil or damming up behind vegetation, in natural ponds or artificial dams.

Steep slopes also cause more rainfall to run off, thus steep slopes behave more like impervious areas than flat areas. Natural ponds also decrease with increase in slope. Thus the slope of catchment has a significant contribution to the runoff. The smaller the annual exceedence probability the larger the runoff coefficient will be, this is to accommodate the variation of known effects which also increase with rainfall intensity but are not accounted for in the calculations. These include: shortened time of concentration, higher percentage runoff, and greater possibility of saturated catchment prior to the storm. Generalized values of runoff coefficients recommended by DWAF for hydrological studies are given in Table B-2 as guidance.

Table B- 2: Recommended values of Runoff coefficients (Alexandra, 1990).

Rural catchments: $C_1 = C_Y + C_P + C_V$						**Urban Catchments C_2 for T <=20**	
Component		**Category**	**MAP**			**Land use**	**C_2**
			<600	**600-900**	**>900**		
C_Y	Steepness in %	Y<3	0.01	0.03	0.05	**Lawns:**	
		3-10	0.06	0.08	0.11	Sandy, flat <2%	0.005-0.10
		10-30	0.12	0.16	0.20	Sandy, steep >7%	0.15-0.20
		30-50	0.22	0.26	0.30	Heavy soil, flat <2%	0.13-0.17
		Y>50	0.26	0.30	0.34	Heavy soil, steep >7%	0.25-0.35
C_P	Permeability of soil (%)	Soil A: very permeable.	0.03	0.04	0.05	**Residential:**	
		Soil B: permeable.	0.06	0.08	0.10	Single family area.	0.30-0.50
		Soil C: semi-permeable.	0.12	0.16	0.20	Apartment unit.	0.50-0.70
		Soil D: impermeable.	0.21	0.26	0.30	**Industrial:**	
C_V	Vegetation	Dense bush, forest.	0.03	0.04	0.05	Light areas.	0.50-0.80
		Thin bush, cultivate land.	0.07	0.11	0.15	Heavy areas.	0.60-0.90
		Grass land.	0.17	0.21	0.25	**Business:**	
		Bare surface.	0.26	0.28	0.30	Downtown.	0.70-0.95
						Neighbourhood.	0.50-0.70
						Streets.	0.70-0.95

Probability of exceedence	50	20	10	5	2	1	0.5	**Urban Catchments C_2 for 20<T <=50**	
	0.50	0.55	0.60	0.67	0.83	1.00	1.20	Lawns	0.35-0.50
								Other	0.70-1.00
Rural condition: $C_1 = C_Y + C_{Pmax} + C_{Vmax}$								**Urban Catchments C_2 for T >50**	1

Note: T = Return Period

The runoff coefficient C is determined by computing coefficient values for the impervious and pervious catchment surfaces. The percentage impervious area is then used to compute a weighted runoff coefficient for the catchment. If a value of 1 is assumed for the runoff coefficient for the impervious areas then a weighted value of C is then given by:

$$C = P_{imp} . 1 + (1 - P_{imp}) C_{per} \qquad \text{(B-1)}$$

Where:

P_{imp} = Percentage impervious area

C_{per} = Computed runoff coefficient for the pervious areas

B4.1.2 Pollutant Concentration Parameters

Site-specific pollutant concentrations obtained through a well-planned monitoring program is recommended for use. Where time and funds do not warrant such monitoring exercise, Table B-3 can be used as a guide for planning purposes. Table B-3 indicates expected concentration ranges of various water quality constituents based on a review of South African studies. Although the categorisation of land-use should be seen as qualitative only, it is nevertheless a useful indication of when and where to expect pollution problems, and the likely nature of those problems (Ashton and Bhagwan, 2001). Catchments having sparse vegetation cover, poor standard of services and low levels of service maintenance are categorised as high pollution potential, whereas those having good vegetation cover, high standard of services, and high level of service maintenance are categorised as low pollution potential. Development type, density and costs as used in Table B-3 are also described in Ashton and Bhagwan, 2001.

The concentrations shown in Table B-3 are for "urban runoff" monitored at the outfalls, and are assumed to represent composite concentrations that include other sources such as illicit connections (greywater, etc), sanitary overflows, and so on.

EMCs for different pollutants should not generally be sourced from different catchments or studies, as there is often a relationship between the pollutant generation processes in the catchment and the type of land use. The actual data on runoff and pollutant concentration will be catchment specific but a guide can be obtained from this data.

Table B- 3: Expected pollutant concentration ranges for categories of residential catchments in South Africa (Coleman, 2001).

Development type	Development density	Development costs	Pollution potential	NH_4 (mg/l as N)	TKN (mg/l as N)	EC (mS/m)	SS (mg/l)	PO_4 (mg/l as P)	COD (mg/l)	DO (mg/l)	Feacal Coliform (/100 ml)
Formal	High Density	High Cost	High	3-7	4-14	13-100	20-1000	0.2-6.0	60-500	3-6	10000-100000
			Low	1-3	2-8	12-50	40-150	0.2-3.0	40-300	3-6	1000-10000
		Low Cost	High	1-30	10-40	70-2500	40-1850	0.4-14.0	150-400	1-6	10000-1000000
			Low	1-5	2-8	15-200	21-400	0.2-3.0	15-70	3-6	10000-1000000
	Low Density	High Cost	High	1-21	1-16	30-200	1-2500	0.1-6.0	5-800	3-6	1000-10000
			Low	0-3	1-5	10-50	21-350	0.0-3.0	20-80	1-6	0-1000
		Low Cost	High	-	-	-	-	-	-	-	-
			Low	-	-	-	-	-	-	-	-
Informal	High Density	Low Cost	High	5-24	7-103	25-700	800-8000	1.0-8.0	70-3000	1-3	10000-10000000
			Low	1-5	4-18	8-180	180-3500	0.2-5.0	40-400	3-6	10000-1000000
	Low Density	Low Cost	High	-	-	-	-	-	-	-	-
			Low	-	-	-	-	-	-	-	-

B5. Water quality model processes

Water quality models can be applied to many different types of water system, including streams, rivers, lakes, reservoirs, estuaries, coastal waters and oceans. The models describe the main water quality processes, and typically require the hydrological and constituent inputs (the water flows or volumes and the pollutant loadings). These models include terms for dispersive and/or advective transport depending on the hydrological and hydrodynamic characteristics of the water body, and terms for the biological, chemical and physical reactions among constituents. Advective transport dominates in flowing rivers. Dispersion is the predominant transport phenomenon in estuaries subject to tidal action. Lake-water quality prediction is complicated by the influence of random wind directions and velocities that often affect surface mixing, currents and stratification. For this and other reasons, obtaining reliable quality predictions for lakes is often more difficult than for streams, rivers and estuaries. In coastal waters and oceans, large-scale flow patterns and tide are the most important transport mechanisms.

The development and application of water quality models is both a science and an art. Each model reflects the creativity of its developer, the particular water quality management problems and issues being addressed, the available data for model parameter calibration and verification, the time available for modelling and associated uncertainty, and other considerations. The fact that most, if not all, water quality models cannot accurately predict what actually happens does not detract from their value. Even relatively simple models can help managers understand the real world prototype and estimate at least the relative, if not actual, change in water quality associated with given changes in the inputs resulting from management policies or practices.

Detailed principles and equations describing advective and dispersive transport are available in the literature.

B6. Simulation methods

Most of those who will be using water quality models will be using simulation models that are commonly available from the market, governmental agencies (e.g. USEPA), universities, or private consulting and research institutions such as the Danish Hydraulics Institute, Wallingford software or WL | Delft Hydraulics (Ambrose et al., 1996; Brown and Barnwell, 1987; Cerco and Cole, 1995; DeMarchi et al., 1999; Ivanov et al., 1996; Reichert, 1994; USEPA, 2001; WL | Delft Hydraulics, 2003; Wong et al., 2005).

These simulation models are typically based on numerical methods that incorporate a combination of plug flow and continuously stirred reactor approaches to pollutant transport. Users must divide streams, rivers, and lakes and reservoirs into a series of well-mixed segments or volume elements. A hydrological or hydrodynamic model calculates the flow of water between all of these. In each simulation time step, plug flow enters these segments or volume elements from upstream segments or elements. Flow also exits from them to downstream segments or elements. During this time the constituents can decay or grow, as appropriate, depending on the conditions in those segments or volume elements. At the end of each time-step, the volumes and their constituents within each segment or element are fully mixed. The length of each segment or the volume in each element reflects the extent of dispersion in the system.

B6.1 Model Uncertainty

There are two significant sources of uncertainty in water quality management models. One stems from incomplete knowledge or lack of sufficient data to estimate the probabilities of various events that might happen. Sometimes it is difficult to even identify possible future events. This type of uncertainty stems from our incomplete conceptual understanding of the systems under study, by models that are necessarily simplified representations of the complexity of the natural and socio-economic systems, as well as by limited data for testing hypotheses and/or simulating the systems.

Limited conceptual understanding leads to parameter uncertainty. For example, there is an ongoing debate about the parameters that can best represent the fate and transfer of pollutants through watersheds and water bodies. Arguably, more complete data and more work on model development can reduce this uncertainty. Thus, a goal of water quality management should be to increase the availability of data, improve their reliabilities and advance our modelling capabilities.

However, even if it were possible to eliminate knowledge uncertainty, complete certainty in support of water quality management decisions will probably never be achieved until we can predict the variability of natural processes. This type of uncertainty arises in systems characterized by randomness. Assuming past observations are indicative of what might happen in the future and with the same frequency – in other words, assuming stationary stochastic processes – we can estimate from these past observations the possible future events or outcomes that could occur and their probabilities. Even if we think we can estimate how likely any possible type of event may be in the future, we cannot predict precisely when or to what extent that event will occur.

For ecosystems, we cannot be certain even what events may occur in the future, let alone their probabilities. Ecosystems are open systems in which it is not possible to know in advance what all the possible biological outcomes will be. Surprises are not only possible, but likely; hence, neither type of uncertainty – knowledge uncertainty nor unpredictable variability or randomness – can be eliminated.

Thus, uncertainty is a reality of water quantity and quality management. This must be recognized when considering the results of water quality management models that relate to actions taken to meet the desired water quality criteria and designated uses of water bodies.

B7. Examples of models to estimate runoff volume and pollutant loads

B7.1 The Simple Modelling Method

The Simple Modelling Method is a modified version of The Simple Method (Schueler, 1987). This model estimates the average annual pollution load of stormwater, commonly expressed in kilograms of pollutant exported per year. It is a relatively simple modeling technique, which relates land use, annual rainfall, catchment runoff characteristics and average pollutant concentrations to estimate the annual pollutant load. This modeling technique can also be used to estimate the reduction in load achieved by treatment measures. In the Simple Modelling Method, the runoff coefficient is estimated as a weighted value of runoff coefficient of pervious and impervious areas (see section B4.1.1). Runoff coefficients of pervious and impervious areas are estimated from recommendations given by Alexandra (1990) for Southern African conditions (Table B-2).

The Simple Modelling Method for estimating storm runoff loads requires little information, including the sub-catchment area and runoff coefficient (a weighted average of pervious and impervious areas), stormwater runoff pollutant concentrations, and annual precipitation. The Simple Modelling Method estimates pollutant loads as a product of annual runoff volume and pollutant concentration, as:

$$L^{ps} = RC_oA \qquad \text{(B-2)}$$

Where:

L^{ps} = Annual load (kg/yr)

R = Annual runoff (mm/yr)

C_o = Pollutant concentration (mg/l).

A = Area (km^2)

For bacteria, the conversion factor is modified, so that the loading equation is:

$$L^{ps} = 10\, RC_bA \qquad \text{(B-3)}$$

Where:

L = Annual load (million count/yr)

R = Annual runoff (mm/yr)

C_b = Bacteria concentration (million count/100ml).

A = Area (km^2)

10 = A conversion factor

Annual Runoff

Annual runoff is estimated as a product of annual runoff volume, and runoff coefficient; where runoff volume is estimated as:

$$R = PP_fC \qquad \text{(B-4)}$$

Where:

R = Annual runoff (mm/yr)

P = Annual precipitation (mm/yr)

P_f = Fraction of annual precipitation events that produce runoff (assume 0.9)

C = Runoff coefficient (weighted average of pervious and impervious areas, see section B4.1.1)

The Simple Modelling Method can also be used to estimate the reduction in load achieved by a constructed wetland, or other structural treatment measures. The average runoff depth, be estimated as the product of the annual rainfall and the volumetric runoff coefficient, can be combined with the known wetland area to estimate likely pollutant retention.

B7.2 Cumulative Rainfall Method

In many instances it may be necessary to estimate pollutant exported from urban areas based on daily rainfall records rather than data for discrete storm events. The cumulative rainfall method is suitable for estimating pollutant loads captured by a design rainfall depth (say 20mm/day). The design rainfall depth may be defined from the rainfall frequency spectrum prepared from rainfall records for a given catchment (described in Section 2.6). The rainfall frequency spectrum represents a statistical distribution of 24-hour rainfall events (rainfall depth vs. frequency/percent value is less than) and provides decision makers a means to choose a risk. For water quality treatment, the risk represents a rainfall depth or a design storm corresponding to a chosen frequency (or percentage of time the rainfall depth value is not exceeded). The design rainfall depth normally targets frequent storms which constitute greater percentage of cumulative rainfall in many catchments. The frequent storms often wash down catchment surfaces, generating a relatively high 'first flush' concentration of pollutants. Thus for rainfall in excess of design rainfall depth, only that rainfall up to the design rainfall depth is considered in the calculation of pollutant loads, while the total rainfall is considered for the calculation of runoff volumes. Based upon these observations and assumptions the methodology of using cumulative rainfall method for estimation of pollutants exported from urban catchments is described below:

a. Examine historical rainfall data for the area and select a rainfall year approximating median rainfall conditions.

b. Determine the number of days, and cumulative rainfall on those days, when less than say, 20 mm (or any design rainfall depth) of rainfall occurred.

c. Estimate the cumulative runoff volume from the catchment for those days of less than 20 mm rainfall by multiplying the cumulative rainfall by the catchment runoff coefficient. The runoff coefficient is determined as described in Section B4.1.1.

d. Estimate the cumulative pollutant load for those days of less than 20 mm rainfall by multiplying the runoff volume estimated in (c) by the pollutant event mean concentration provided in Table B-3 in Section B4.1.2. For example, if less than

20 mm rainfall occurred on 60 days over the year and the cumulative rainfall on those days was 350 mm, and the catchment runoff coefficient (weighted value of pervious and impervious areas) is 55%, and suspended solids concentration is 100 mg/l, then;

Runoff volume = 0.55 x 350 = 192.5 mm = 192.5 ML/km^2

Suspended solids load = 192.5 ML/km^2 x 100 mg/l = 19250 kg/km^2

e. Determine the number of days, and cumulative rainfall on those days, when rainfall was 20 mm or greater.

f. Estimate the pollutant load for those days of 20 mm or greater rainfall. For example, if more than 20 mm of rainfall occurred on 12 days, and the cumulative rainfall on those days was 450 mm, then;

Runoff volume applicable = 0.55 x 12 x 20 = 132 mm = 132 ML/km^2

Suspended solids load = 132 ML/km2 x 100 mg/l = 13 200 kg/km^2

g. Sum the pollutant (suspended solids) loads calculated in steps (d) and (f) to determine the total estimated load exported from the catchment or (to be treated by the treatment measure).

B7.3 Estimation of Runoff Volume Based On SCS Method

The SCS method is an easy approach for determining the water quality volumes. The concept and general procedure used in estimating volume and rate of runoff in small catchments in South Africa, based on the SCS technique is presented in Schmidt and Schulze (1987).

Water quality treatment measures are sized based on Water Quality Volume (WQV). The WQV is an empirical measure based on the stormwater quality design rainfall depth, P_d and the areas of development (be they impervious and/or pervious), draining to the water quality treatment device and the associated Curve Numbers relating to those contributing areas. The areas of development contributing to the water quality treatment measure are those areas, be they impervious or pervious that contribute runoff whether or not it needs to be treated. The Curve Numbers represent runoff from various surfaces or land-uses overlying various soil types and are obtained from Table B-4 for typical South African conditions.

The stormwater quality design rainfall depth, P_d is the rainfall depth that corresponds to design rainfall depth regarding the cumulative rainfall volume for water quality treatment. This rainfall depth can be estimated from rainfall frequency spectrum as described above in section B7-2. For example, the rainfall frequency spectrum for Johannesburg, Pretoria and Roodepoort are prepared and are shown in Figures B-1, B-2 and B-3 respectively. These rainfall frequency spectra indicate that 90% of all rainfall recorded in the two rain gauge stations are less than 20 mm. This analysis yields a stormwater quality design rainfall depth, P_d of 20 mm in and around Johannesburg and Pretoria (if 90% of all rainfalls are to be treated).

Alternatively, Smithers and Schulze (2003) also describe a method to estimate design rainfall depth for South Africa. The procedure for using the SCS method to estimate runoff volume is as follows:

a. Design rainfall depth, P_d

   Use rainfall frequency spectrum or Smithers and Schulze (2003) to obtain the 24 hour design rainfall depth

b. Runoff Curve Numbers

   Identify the soil types for the site and its associated land cover to select the associated curve number. Use Table B-4 for curve numbers.

c. Calculate storage (S) individually for both pervious and impervious area

   $S = (25400/CN) - 254 =$ mm (B-5)

   Estimate separately for pervious and impervious areas.

d. Initial Abstraction

Initial abstraction, I_a, consists mainly of interception, infiltration and surface storage, all of which occur before runoff begins, and it can be estimated by the empirical relation:

I_a (mm) = cS, (B-6)

where c is the coefficient of initial abstraction.

Arnold and Schulze (1979) conducted research in agricultural catchments in South Africa and indicated that the coefficient of abstraction is dependent on season and antecedent moisture condition, and a value of c = 0.10 was estimated for general application irrespective of season. The value of c will however approach a value of zero as imperviousness increases. It may be assumed that for 98% imperviousness, c = 0.

e. Runoff depth

Runoff depth, R_d (mm) = $(P_d - I_a)^2 / ((P_d - I_a) + S)$ (B-7)

Estimate runoff depth separately for pervious and impervious areas

f. Runoff volume

Runoff volume, R_v (m^3) = $1000 R_d A$ (B-8)

A (km^2) is the pervious or impervious area. Estimate runoff volume separately for pervious and impervious areas.

g. Water quality volume is summation of both R_v's

h. The load is estimated from the product of runoff volume and event mean concentration of the catchment.

Designers are also referred to Schmidt and Schulze (1987) for application of the SCS method in South African conditions.

B7.4 Rational Method

For the water quality treatment practices, storms and issues such as timing or response time (peak flow) are not important as for other devices for flood control. However, if flood control is to be considered then the SCS or rational method can be used to determine the peak flow rate from a small catchment. The application of SCS method in South African conditions is detailed in Schmidt and Schulze (1987). The rational formula for use in South Africa is generally expressed as:

$$Q = \frac{1000CIA}{3.6}$$

Where:

Q (l/s) is the peak flow rate

I (mm/h) is the average rainfall intensity

A (km^2) is the catchment area

C is the dimensionless runoff coefficient

The rainfall intensity is determined using one of the following equations (Op ten Noort and Stephenson, 1982):

Inland region:

$$I = \frac{(7.5 + 0.034MAP)R^{0.3}}{(0.24 + t_d)^{0.89}}$$

Coastal region:

$$I = \frac{(3.4 + 0.023MAP)R^{0.3}}{(0.2 + t_d)^{0.75}}$$

Where: MAP (mm) is the mean annual precipitation, R (yrs) is the recurrence interval, and t_d (hours) is the storm duration. By applying the small storm concept, the recurrence interval should not exceed 1-year.

The storm duration t_d is determined using the formula for the time of concentration t_c (hours) given as

$$t_d = t_c = \left[\frac{0.87L^3}{H} \right]^{0.385}$$

Where: L (km) is the length of catchment and H (m) is the elevation difference

Table B- 4: Runoff Curve Numbers for selected suburban and urban land uses for typical South African conditions. (adapted from Schmidt and Schulze, 1987)

LAND USE	DESCRIPTION		HYDROLOGIC SOIL GROUP CURVE NUMBERS A	B	C	D
Urban / Suburban Land Uses	Open spaces, parks, cemetries	Good (>75% grass cover)	39	61	74	80
		Fair (50-75% grass cover)	49	69	79	84
	Commercial / business areas	85% impervious	89	92	94	95
	industrial districts	72% impervious	81	88	91	93
	Residential: lot size 500 m^2	65% impervious	77	85	90	92
	1000 m^2	38% impervious	61	75	83	87
	1350 m^2	30% impervious	57	72	81	86
	2000 m^2	25% impervious	54	70	80	85
	4000 m^2	20% impervious	51	68	78	84
	Paved parking lots, roofs, etc.		98	98	98	98
	Streets/Roads: tarred		98	98	98	98
	gravel		76	85	89	91
	dirt		72	82	87	89
	dirt-hard surface		74	84	90	92

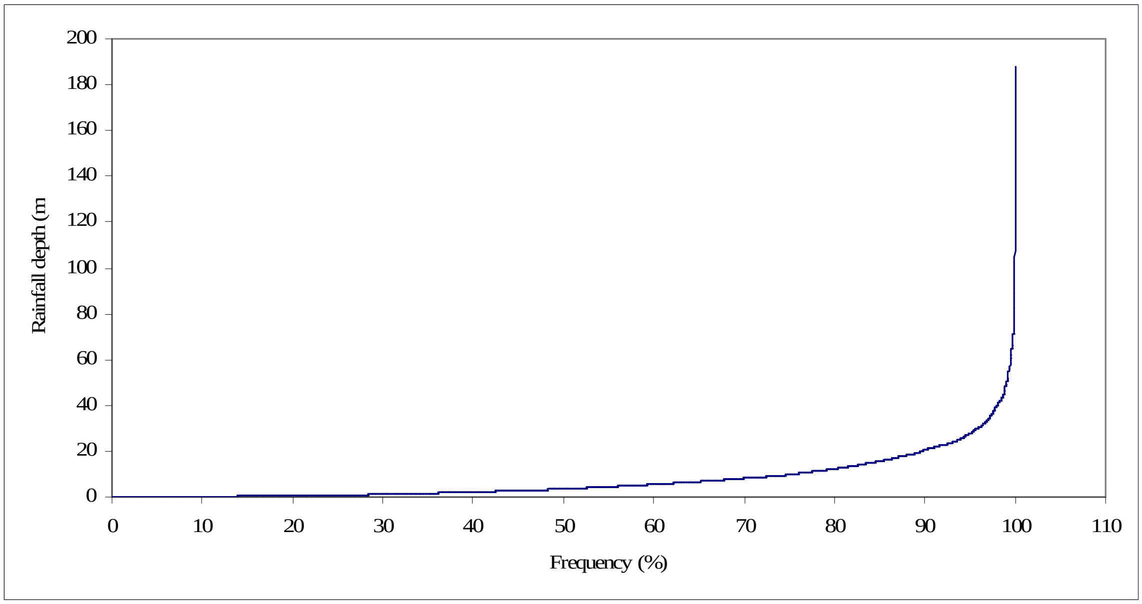

Figure B- 1: Rainfall Frequency Spectrum for Johannesburg (DWAF Station: A2E009)

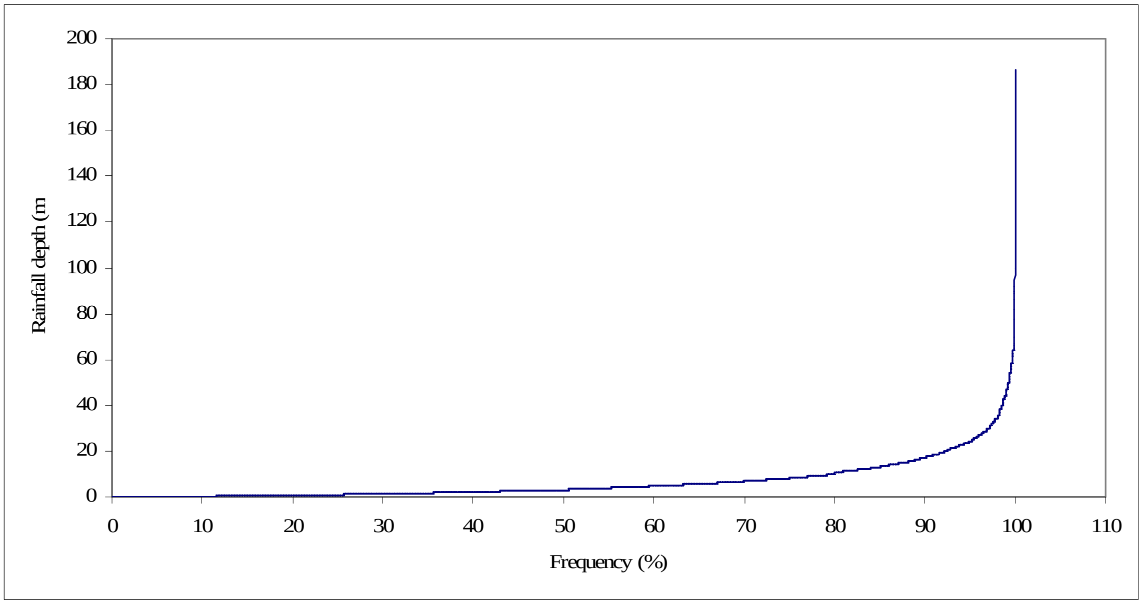

Figure B- 2: Rainfall Frequency Spectrum for Pretoria (DWAF Station: A2E003)

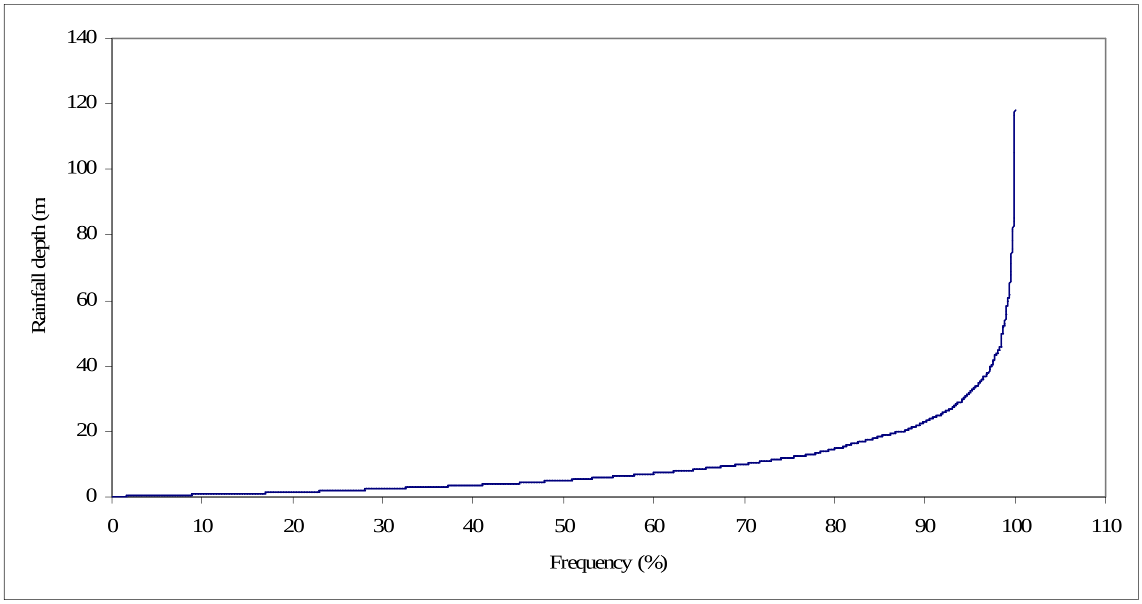

Figure B- 3: Rainfall Frequency Spectrum for Roodepoort (DWAF Station: 04758185)

APPENDIX C PROGRAM USER MANUAL

C.1 Introduction

The program is designed to simulate stormwater and greywater quality management interventions and to operate at a range of spatial scales. It is a deterministic model and it allows rigorous analysis of the merit of the existing and future management interventions on annual basis.

Whether to justify existing interventions, develop future ones, or evaluate their progress, catchment managers are frequently confronted with the question about the effectiveness of their programs to improve water quality. This calls for the need to define the benefit or quantify load reduction of the interventions put in place. Load reductions need to be defined amongst the following:

- How to meet specified target load reduction as regulated?
- What interventions should be considered to treat/manage current and future contaminant sources to a receiving river body?
- Which combination of interventions (or strategies) would produce a minimum cost in meeting a community's stormwater quality management objectives?
- What pollutant reduction has been achieved by current or existing programs?
- What level of assuredness/risk does the estimated load reduced by an intervention represent?
- How effective are investments in educational and outreach programs to manage stormwater quality?
- Which area or land use within an urban catchment has the greatest potential or need for stormwater quality improvement?

- How do nutrient loads in a community that relies on septic systems compare to a sewered one, given the expected rates of maintenance?
- How serious does active construction impact the stormwater quality, and what measures need to be taken to control impacts in the face of growing urbanization?
- How critical are pollutants from secondary sources such as sanitary sewer overflows, illicit connections, and active construction in an urban catchment, which are often overlooked in simple or complex models?

Answers to these questions require accurate estimation of pollutant loadings and determination of how conditions will improve in response to various treatment options. The model, an aid to decision making, enables users to evaluate the effectiveness of existing and future interventions in order to improve or maintain stormwater quality. The model therefore helps to answer all of the above questions. In contrast to most models, simple or complex (e.g. SWMM and MUSIC (2005)), the model takes into account the efforts and staffing (e.g. in educational interventions), design, maintenance, and the inherent treatability of the different sources and each of these factors have profound influence in evaluating interventions load reductions. The model is primarily targeted at those who are involved or are likely to be involved in stormwater quality management including catchment managers, local governments or municipalities, catchment management agencies, private consultants and researchers.

The program is written in Visual Basic as a macro to an Excel spreadsheet. The programming code is not apparent and the user needs only work with the spreadsheets for Input and Results. Thus two sheets named Input and Output are available on opening of the program. To run the program, fill in all the required data on the Input sheet and press

Run. When the simulation ends, the program automatically presents the results on the output sheets.

In order to make data entry easier, cells are shaded in light gray and dark gray colours in the input sheet. Light gray cells must be filled out, unless a pollutant source or treatment option is not being considered. For example, the areas of industrial land only need to be filled out only if industrial land is in the catchment. Dark gray cells represent model defaults that a user may want to modify. Black cells contain formulas, and typically should not be overwritten.

C.2 Model input sheet

Data entry into the input sheet is categorized into: catchment data input, storm load data input, non-storm load data input, existing interventions data input, and future intervention data input. These categories are explained as below:

C.2.1 Catchment data input category

Under the catchment data category (Table C-1), catchment annual precipitation, total area, planning horizon, and ambient water quality objectives are entered. All the data in this category need to be filled out to prevent errors as they are used frequently in different modules to estimate loads and load reductions.

Table C- 1: Catchment data input

CATCHMENT DATA						
MAP (mm)	750					
Catchment Area (km^2)	3.5					
Planning Horizons (yrs)	10					
Ambient water quality objectives	TN (mg/l)	TP (mg/l)	COD (mg/l)	Pb (mg/l)	SS (mg/l)	FC (count /100ml)
Storm	10.6	0.1	75	0.1	80	130
non-storm	10.6	0.1	75	0.1	80	130

C.2.2 Storm load data input category

The storm load data category (Table C-2) requires data on land use types and their associated: fraction of impervious areas, runoff coefficients (for both pervious and impervious areas), and event mean concentrations.

Table C- 2: Storm loads data input

STORM LOADS DATA												
Land Use		Area	Fraction of imperv. Area	Runoff coeff. for pervious areas	Runoff coeff. for imperv. areas	Event Mean Concentrations					
						TN	TP	COD	Pb	SS	FC
		km^2				mg/l	mg/l	mg/l	mg/l	mg/l	count /100ml
Residential	LD	2	0.7	0.25	0.85	43	2.5	378	0.8	2219	10^6
	MD	1	0.7	0.25	0.85	43	2.5	378	0.8	2219	10^6
	HD										
Commercial		0.3	0.7	0.25	0.85	43	2.5	378	0.8	2219	10^6
Industrial		0.2	0.5	0.25	0.85	43	2.5	378	0.8	2219	10^6

Each land use is divided into three: low density, medium density, and high density. All the cells in this category, with the exception of land uses that are not the in the catchment, need to be filled out. For example, if a catchment consists of only low density residential land use, then only the first row needs to be filled out.

C.2.3 Non-storm data input category

The non-storm data category requires data from secondary sources including general sewage use data, septic systems, illicit connections to stormwater drains, sanitary sewer overflows, nutrients and bacteria in urban soil, active construction erosion and sediment control, and catchment erosion and sediment control to calculate loads from secondary sources (i.e. non-storm loads). All the cells in General sewage use must be filled out as they are used frequently in different modules to estimate loads and load reductions. Data required for non-storm load category depend on the sources of non-storm loads present. Data required for each source are:

C.2.3.1General Sewage use

A user should enter data for dwelling units or number of households as shown in Table C-3.

Table C- 3: General sewage use data input

General Sewage Use Data						
Dwelling Units	10000					
Individuals per Dwelling Unit	6					
Water Use (m^3/c/d)	0.264978					
Wastewater Characteristics:	**TN (mg/l)**	**TP (mg/l)**	**COD (mg/l)**	**Pb (mg/l)**	**SS (mg/l)**	**FC (count/100ml)**
	60	3	120	1	400	1,000,000

The defaults (dark gray cells) are: individuals per household, water use (i.e. per capita wastewater generation), and wastewater characteristics. The defaults may be substituted with local data if available.

C.2.3.2Septic systems

If septic systems exist in the catchment, a user should enter data on fraction of dwelling units using septic systems as shown in Table C-4. The defaults (dark gray cells) are: fraction of septics failing, characteristics of effluent from working septics, characteristics of effluent from failing septics. The defaults may be substituted with local data if available.

Table C- 4: Septic systems data input

Septic Systems						
Septic Dwelling Units(% of total)	0					
Fraction of Septics Failing	50%					
Characteristics of Effluent from Working Septics	TN (mg/l)	TP (mg/l)	COD (mg/l)	Pb (mg/l)	SS (mg/l)	FC (count/100ml)
	20	0	60	0.2	0	1,000
Characteristics of Effluent from Failing Septics	TN (mg/l)	TP (mg/l)	COD (mg/l)	Pb (mg/l)	SS (mg/l)	FC (count/100ml)
	33	1	100	0.7	40	1,000,000

C.2.3.3Illicit connections

User should enter data on soil content of nitrogen and phosphorus (% by weight) as shown in Table C-5. The defaults (dark gray cells) are: phosphorus enrichment factor, nitrogen enrichment factor, and bacteria potency factor. The defaults may be substituted with local data if available.

Table C- 5: Illicit connections data input

Illicit Connections						
Fraction of Residential Population Illicitly Connected	0.8					
Number of Businesses	200					
Fraction of Businesses with Illicit Connections	0.5					
Fraction of Businness Connections that are Wash Water Only	0.9					
Wash Water Flow (m^3/d)	2737.8					
Total Flow/business (m^3/d)	4106.7					
	TN	TP	COD (mg/l)	Pb (mg/l)	SS	FC
Wash Water Concentrations	10	5	80	0.1	150	0
Total Flow Concentrations	38	3.6	212	0.2	140	1,000,000

C.2.3.4 Sanitary sewer overflows

If sanitary sewer overflows occur in the catchment, a user should enter data on total length of sanitary sewer in the settlement as shown in Table C-6. The defaults (dark gray cells) are: fraction of load as storm flow, annual overflows per kilometer of sewer of length, typical volume of overflow. The defaults may be substituted with local data if available.

Table C- 6: Sanitary sewer overflows data input

Sanitary Sewer Overflows	
Length of Sanitary Sewer (km)	20
Fraction of Load as Storm Flow	50%
Overflows/1km of Sewer/yr	0.5
Volume per Overflow (m^3)	10

C.2.3.5 Nutrients and bacteria in urban soil

A user should enter data on soil content of nitrogen and phosphorus (% by weight) as shown in Table C-7. The defaults (dark gray cells) are: phosphorus enrichment factor, nitrogen enrichment factor, and bacteria potency factor.

Table C- 7: Nutrients and bacteria in urban soil data input

Nutrients and Bacteria in Urban Soil	
Soil P (%)	0.2
Soil TN (%)	0.3
P Enrichment Factor	2
N Enrichment Factor	2
Bacteria potency factor (10^6 MPN/ton)	1,000,000

C.2.3.6 Active construction erosion and sediment

If active construction occurs in the catchment, a user should enter data on total area of active construction sites as shown in Table C-8. The defaults (dark gray cells) are: runoff coefficient at construction sites, and typical sediment concentration from construction site. The defaults may be substituted with local data if available.

Table C- 8: Active construction erosion and sediment data input

Active Construction	
Area (km^2) of Active Construction	0.0025
Runoff Coefficient for Cleared Land	0.5
TSS from Construction Sites (mgl)	680

C.2.3.7 Catchment erosion and sediment

A user should enter data on: annual rainfall erosivity, soil erodibility, slope length and gradient factor, cover and management factor, and delivery factor as shown in Table C-9. These data are discussed in Section 5.4.12.

Table C- 9: Catchment erosion and sediment data input

Catchment Sediment Yield	
Annual rainfall erosivity (N/h/yr)	320
Soil erodibility (ton.h/N/ha)	0.5
Slope length and gradient factor	0.2
Cover and management factor	0.1
Delivery factor	0.2

C.2.3.8 Lawns or subsurface flow data

If fertilization of lawns, garden, and parks occurs in the catchment, a user should enter data on fraction of the soil in the catchment that are Hydrologic soil group A, B, C, and D as shown in Table C-10.

Table C- 10: Lawns or subsurface flow data input

Lawns (Subsurface Flow)		
	%	Infiltration Rate (fraction of rainfall)
A-Soils	40%	0.45
B-Soils	50%	0.3
C-Soils	9%	0.15
D-Soils	1%	0.075
N in Leachate (mg/l)	2	
P in Leachate (mg/L)	0.03	
Compaction Factor	0.8	

The defaults (dark gray cells) are: nutrients concentration, compaction factor, and fraction of rainfall that infiltrate. The defaults may be substituted with local data if available.

C.2.4 Existing intervention data input category

The existing management intervention category reflects interventions currently in place to control loads from urban land. The data required depend on the number of interventions existing. In all cases, the program asks *whether* a particular intervention exist (*Intervention?)*. If the answer is yes the user simply enter the number 1, if not the number 0 is entered in the light gray cell. When the program runs, only the interventions with the *Intervention?* cell value equal to 1 will be included in the simulation. It should be noted that, even if all the data is filled and the *Intervention?* cell value is not equal to 1, that particular intervention will not be evaluated. Data input for each intervention are described below:

C.2.4.1Existing lawn care education intervention

The user needs only to indicate if the intervention exists or not by entering the number 1 or 0 in the light gray cell (Table C-11). The rest of the data shown in Table C-11 are defaults and can be changed at the user's discretion.

Table C- 11: Existing lawn care education intervention data input

Existing Lawn Care Education				
			Nutrient Characteristics	
Intervention? (Y=1/N=0)	0		Nitrogen	Phosphorous
		Typical Application Rates (kg/km^2-year)	168.14	16.81
Intervention risk factors		Fertilizer Reduction (Fraction)	0.5	0.5
Fertilizers (fraction)	0.86	Fraction "Lost" to the Environment	0.25	0.05
"Overfertilizers" (fraction of fertilizers)	0.8	Fraction of Above Lost as Surface Runoff		
Awareness of Message (Fraction of Population)	0.4	A Soils	0.03	0.1
Fraction willing to change behavior	0.6	B Soils	0.1	0.35
		C Soils	0.3	0.8
		D Soils	0.9	0.95

C.2.4.2Existing domestic animal waste education intervention

The user needs only to indicate if the intervention exists or not by entering the number 1 or 0 in the light gray cell (Table C-12). The rest of the data shown in Table C-12 are defaults and can be changed at the user's discretion.

Table C- 12: Existing domestic animal waste education intervention data input

Existing Domestic Animal Waste Education			
Intervention? (Y=1/N=0)	0		
Intervention risk factors		Waste Characteristics	
Fraction of Households with a domestic animal	0.6	Waste Production (kg/animal-day)	1
Owners who roam their animal (fraction)	0.8	N Concentration (kg/kg)	0.0057
Owners who Clean Up (fraction)	0.2	N Delivery Factor	0.25
Fraction willing to change behaviour	0.6	P Concentration (kg/kg)	0.0013
Awareness of Message (Fraction of Population)	0.4	P Delivery Factor	0.75
		Bacteria Concentration(million/kg)	230
		Bacteria Delivery Factor	0.05

C.2.4.3Existing active construction erosion and sediment control intervention

The user needs to indicate whether the intervention exists or not by entering the number 1 or 0 in the *Intervention?* light gray cell (Table C-13). The *fraction of building permits that are regulated* should also be entered in the corresponding light gray cell. The rest of the data shown in Table C-13 are defaults and can be changed at the user's discretion.

Table C- 13: Existing active construction erosion and sediment control intervention data input

Existing Active Construction Erosion and Sediment Control	
Intervention? (Y=1/N=0)	0
Intervention Efficiency	70%
Fraction of Building Permits Regulated	0.7
Compliance risk factor	0.7
Installation/ Maintenance risk factor	0.9

C.2.4.4Existing catchment erosion and sediment control intervention

The user needs to indicate whether the intervention exists or not by entering the number 1 or 0 in the *Intervention?* light gray cell (Table C-14).

Table C- 14: Existing catchment erosion and sediment control intervention data input

Existing Catchment Erosion and Sediment Control	
Intervention? (Y=1/N=0)	0
Intervention Efficiency	20%
Fraction of catchment controlled (%)	0.3
Design risk factor	0.5
Maintenance risk factor	0.4

The *fraction of catchment (i.e. pervious areas) controlled* should also be entered in the corresponding light gray cell. The rest of the data shown in Table C-14 are defaults and can be changed at the user's discretion.

C.2.4.5Existing street sweeping intervention

The user needs to indicate whether the intervention exists or not by entering the number 1 or 0 in the *Intervention?* light gray cell in Table C-15. The *area swept in residential, parking lots and other streets* for each sweeping technique should also be entered in the corresponding light gray cells. The rest of the data shown in Table C-15 are defaults and can be changed at the user's discretion.

Table C- 15: Existing street sweeping intervention data input

Existing Street Sweeping											
Intervention? (Y=1/N=0)	0										
	Streets Swept (km^2)		Parking Lots Swept	Efficiencies - Residential				Efficiencies - Other roads			
Sweeper Type	Residential	Other Streets	(km^2)	Nutrients	COD	Pb	TSS	Nutrients	COD	Pb	TSS
Brush-type Mechanical	0.005	0.015	0.015	24%	20%	40%	30%	4%	20%	40%	5%
Broom	0.004	0.007	0.01	51%	26%	45%	64%	18%	26%	45%	22%
Vacuum Assisted	0.003	0.008	0.01	62%	30%	50%	78%	63%	30%	50%	79%
Sweeping Frequency risk factor	1	1	1								
Technique risk factor	0.5										

C.2.4.6 Existing downspout disconnection intervention

The input data is divided into two: residential and commercial and both needs to be filled out. The user needs to indicate whether the intervention exists or not by entering the number 1 or 0 in the *Intervention?* light gray cell in Tables C-16a and C-16b. The *fraction of residential land where the intervention is applicable* and *fraction of homes or businesses disconnected* should also be entered in the corresponding light gray cells. The rest of the data are defaults and can be changed at the user's discretion. The data required in Tables C-16a and 16b are for both existing and future downspout disconnection.

Table C- 16a: Existing residential downspout disconnection intervention data input

Existing Downspout (Impervious Cover) Disconnection - Residential	
Intervention? (Y=1/N=0)	0
Typical Roof Footprint (square meter)	186
Fraction of Homes Disconnected (%)	10%
Fraction of Residential Land where Applicable	0.45
Fraction of Population Reached	1
Fraction Willing to Participate	0.7

Table C-16b: Existing commercial downspout disconnection intervention data input

Existing Downspout (Impervious Cover) Disconnection - Commercial	
Intervention? (Y=1/N=0)	0
Fraction of Businesses Disconnected (%)	70%
Fraction of Commercial Imperviousness as Rooftop	0.3
Fraction of Land where Applicable	0.25
Fraction of Population Reached	1
Fraction Willing to Participate	0.8

Existing intervention require: typical roof area (default), fraction of homes disconnected, fraction of businesses disconnected, and fraction of commercial imperviousness as roof top (default). The rest of the data shown in Tables C-16a and C-16b (including typical roof area) are for future downspout disconnection intervention described in Section 2.5.5.

C.2.4.7Existing river assimilation intervention

The user needs to indicate whether the intervention exists or not by entering the number 1 or 0 in the *Intervention?* light gray cell (Table C-17). The rest of the data shown in Table C-17 are defaults and can be changed at the user's discretion.

Table C- 17: Existing river assimilation intervention data input

Existing River Assimilative Capacity						
Intervention? (Y=1/N=0)	1					
Efficiency						
	TN	TP	COD	Pb	TSS	FC
Storm flow assimilation (%)	64%	47%	20%	10%	29%	45%
Non-Storm flow assimilation (%)	80%	74%	67%	10%	67%	17%
Design risk factor	0.7					
Maintenance risk factor	0.6					

C.2.4.8Existing rainwater tanks intervention

The user needs to indicate whether the intervention exists or not by entering the number 1 or 0 in the *Intervention?* light gray cell in Table C-18. The fraction of homes with rainwater tanks should also be entered in the corresponding light gray cell. The rest of the data shown in Table C-18 are defaults and can be changed at the user's discretion.

Table C- 18: Existing rainwater tanks intervention data input

Existing Rainwater Tanks	
Intervention? (Y=1/N=0)	0
Typical Roof Footprint (square meter)	186
Fraction of Homes with rainwater tanks (%)	20%
Fraction of annual rainfall captured	0.9

C.2.4.9 Existing riparian buffers intervention

The user needs to indicate whether the intervention exists or not by entering the number 1 or 0 in the *Intervention?* light gray cell in Table C-19. The buffer length and width should also be entered in the corresponding light gray cell. The rest of the data shown in Table C-19 are defaults and can be changed at the user's discretion.

Table C- 19: Existing riparian buffers intervention data input

Existing Riparian Buffers				
Intervention? (Y=1/N=0)	0			
Buffer Length (km)	3			
Buffer Width (km)	0.02			
Efficiency				
TN	TP	COD	Pb	TSS
30%	10%	40%	70%	70%
Design risk factor	0.7			
Maintenance risk factor	0.6			

C.2.4.10 Other existing structural control interventions

The user needs to indicate whether other structural control intervention(s) exists or not by entering the number 1 or 0 in the *Intervention?* light gray cell in Table C-20. For the existing ones, contributing areas to the interventions should also be entered in the corresponding light gray cells. The red cells contain formulas and should not be overwritten or changed. The rest of the data shown in Table C-20 are defaults and can be changed at the user's discretion.

Table C- 20: Other existing structural control interventions data input

Other Existing Structural Control Interventions							
Intervention? (Y=1/N=0)	0						
	Area Captured						
	(km^2)	Efficiency					
BMP Type		TN	TP	COD	Pb	TSS	FC
Dry Water Quantity Pond	0.2	5%	19%	1%	17%	3%	10%
Dry Facilities	0.09	25%	19%	2%	17%	47%	60%
Wet Pond	0.3	33%	51%	60%	60%	80%	70%
Wetland	0.7	30%	49%	70%	81%	76%	78%
WQ Swale	0.001	38%	34%	60%	75%	81%	10%
Filters	0.01	38%	59%	67%	89%	86%	37%
Infiltration	0.01	51%	70%	60%	88%	90%	90%
Total	0	0%	0%	0%	0%	0%	0%
	Capture risk factor	Design risk factor	Maintenance risk factor				
	0.9	0.8	0.5				

C.2.5 Future intervention data input category

The last category is the future management intervention and it reflects the planned interventions to be implemented to control loads from settlement. The future management intervention category is a continuation of existing management intervention category, that is, the data reflect both current interventions and interventions planned to be implemented, unless a current intervention will be discontinued or modified in the future. For future interventions, data on *implementation timeframe* and *magnitude* must be provided for each intervention. In all cases, the program asks (*Intervention?)* whether a particular intervention exist. If the answer is yes the user simply enters the number 1, if not the number 0 is entered in the light gray cell as described in Section C.2.5. The data requirements for this category depend on the number of interventions planned for implementation. Data input for each intervention are described below:

C.2.5.1Future lawn care education intervention

The user needs to indicate whether the intervention is planned for implementation or not by entering the number 1 or 0 in the *Intervention?* light gray cell in Table C-21. Make sure to fill in all the details of exiting lawn care education intervention in Table C-11, Section C.2.4.1. Those data are used in the future intervention as well. The implementation factor, implementation timeframe and cost of the educational program should also be entered in the corresponding light gray cell.

Table C- 21: Future lawn care education intervention data input

Future Lawn Care Education	
Intervention? (Y=1/N=0)	0
Implementation Factor (%)	100%
Implementation Timeframe	5
Cost (Lump Sum per community)	

C.2.5.2Future domestic animal waste education intervention

The user needs to indicate whether the intervention is planned for implementation or not by entering the number 1 or 0 in the *Intervention?* light gray cell in Table C-22. Make sure to fill in all the details of exiting domestic animal waste education intervention in Table C-12, Section C.2.4.2. Those data are used in the future intervention as well. The implementation factor, implementation timeframe and cost of the educational program should also be entered in the corresponding light gray cell.

Table C- 22: Future domestic animal waste education intervention data input

Future Domestic Animal Waste Education	
Intervention? (Y=1/N=0)	1
Implementation Factor (%)	0%
Implementation Timeframe (yrs)	5
Cost (Lump Sum per community)	

C.2.5.3Future active construction erosion and sediment control intervention

The user needs to indicate whether the intervention is planned for implementation or not by entering the number 1 or 0 in the *Intervention?* light gray cell in Table C-23. Make sure to fill in all the details of exiting active construction erosion and sediment control intervention in Table C-13, Section C.2.4.3. Those data are used in the future intervention as well. The implementation factor, implementation timeframe and unit treatment cost of the intervention should also be entered in the corresponding light gray cell.

Table C- 23: Future active construction erosion and sediment control intervention data input

Future Active Construction Erosion and Sediment Control	
Intervention? (Y=1/N=0)	0
Implementation Factor (%)	100%
Implementation Timeframe (yrs)	5
Unit Treatment Cost (R/m^3)	

C.2.5.4Future street sweeping intervention

The user needs to indicate whether the intervention is planned for implementation or not by entering the number 1 or 0 in the *Intervention?* light gray cell in Table C-24. Make sure to fill in all the details of exiting street sweeping intervention in Table C-15 in Section C.2.4.5. Those data are used in the future intervention as well. The implementation factor, implementation timeframe and unit treatment cost of the intervention should also be entered in the corresponding light gray cell.

Table C- 24: Future street sweeping intervention data input

Street Sweeping	
Intervention? (Y=1/N=0)	1
Implementation Factor (%)	50%
Implementation Timeframe (yrs)	5
Unit Treatment Cost (R/m^2)	

C.2.5.5Future downspout disconnection intervention

The user needs to indicate whether the intervention is planned for implementation or not by entering the number 1 or 0 in the *Intervention?* light gray cell in Table C-25. Make sure to fill in all the details of exiting downspout disconnection intervention in Tables C-16a and 16b in Section C.2.4.6. Those data are used in the future intervention as well. Future intervention require fraction of residential land applicable as input data, and the defaults namely: typical roof area, fraction of population reached, fraction willing to participate, fraction commercial land as roof top, and fraction of commercial land applicable. The implementation factor, implementation timeframe and unit treatment cost of the intervention should also be entered in the corresponding light gray cell.

Table C- 25: Future downspout disconnection intervention data input

Future Downspout (Impervious Cover) Disconnection	
Intervention? (Y=1/N=0)	1
Implementation Factor (%)	35%
Implementation Timeframe (yrs)	5
Unit Treatment Cost (R/m^3)	

C.2.5.6 Rainwater tanks intervention

The user needs to indicate whether the intervention is planned for implementation or not by entering the number 1 or 0 in the *Intervention?* light gray cell in Table C-26. The data on: fraction of residential land where the intervention is applicable, implementation factor, implementation timeframe and unit treatment cost of the intervention should also be entered in the corresponding light gray cell. The rest of the data shown in Table C-26 are defaults and can be changed at the user's discretion.

Table C- 26: Future rainwater tanks intervention data input

Future Rainwater Tanks	
Intervention? (Y=1/N=0)	1
Typical Roof Footprint (square meter)	186
Fraction of Residential Land where Applicable	0.7
Fraction of Population Reached	1
Fraction Willing to Participate	0.9
Fraction of annual rainfall captured	0.9
Implementation Factor (%)	100%
Implementation Timeframe (yrs)	5
Unit Treatment Cost (R/m^3)	

C.2.5.7 Future catchment erosion and sediment control intervention

The user needs to indicate whether the intervention is planned for implementation or not by entering the number 1 or 0 in the *Intervention?* light gray cell in Table C-27. The data on: fraction of pervious surface that can be treated, implementation factor, implementation timeframe and unit treatment cost of the intervention should also be entered in the corresponding light gray cell. The rest of the data shown in Table C-27 are defaults and can be changed at the user's discretion.

Table C- 27: Future catchment erosion and sediment control intervention data input

Future Catchment Erosion and Sediment Control	
Intervention? (Y=1/N=0)	1
Intervention Efficiency (%)	70%
Fraction of pervious surface treatable	0.7
Installation/Design Risk factor	0.7
Maintenance Risk factor	0.5
Implementation Factor (%)	100%
Implementation Timeframe (yrs)	5
Unit Treatment Cost (R/m^3)	

C.2.5.8Future exfiltration systems intervention

The user needs to indicate whether the intervention is planned for implementation or not by entering the number 1 or 0 in the *Intervention?* light gray cell in Table C-28. The following data should also be entered in the corresponding light gray cell: area surveyed for the implementation of the intervention, fraction of that area that is treatable, implementation factor, implementation timeframe and unit treatment cost. The rest of the data shown in Table C-28 are defaults and can be changed at the user's discretion.

Table C- 28: Future exfiltration systems intervention data input

Future Exfiltration Systems	
Intervention? (Y=1/N=0)	1
Intervention Efficiency (%)	60%
Area Surveyed (km^2)	3
Fraction of area "treatable"	80%
Capture risk factor	0.9
Design risk factor	1
Maintenance risk factor	0.5
Implementation Factor (%)	100%
Implementation Timeframe (yrs)	10
Unit Treatment Cost (R/m^3)	

C.2.5.9 Future riparian buffers intervention

The user needs to indicate whether the intervention is planned for implementation or not by entering the number 1 or 0 in the *Intervention?* light gray cell in Table C-29. The following data should also be entered in the corresponding light gray cell: implementation factor, implementation timeframe and unit treatment cost. Make sure to fill in all the details of exiting riparian buffers intervention in Table C-19 in Section C.2.4.9. Those data are used in the future intervention as well.

Table C- 29: Future riparian buffers intervention data input

Future Riparian Buffers	
Intervention? (Y=1/N=0)	1
Implementation Factor (%)	0%
Implementation Timeframe (yrs)	5
Unit Treatment Cost (R/m^3)	

C.2.5.10 Future river assimilation intervention

The user needs to indicate whether the intervention exists or not by entering the number 1 or 0 in the *Intervention?* light gray cell in Table C-30. The rest of the data shown in Table C-30 are defaults and can be changed at the user's discretion.

Table C- 30: Future river assimilation intervention data input

Future River Assimilative Capacity						
Intervention? (Y=1/N=0)	1					
Efficiency						
	TN	TP	COD	Pb	TSS	FC
Storm flow assimilation (%)	64%	47%	20%	10%	29%	45%
Non-Storm flow assimilation (%)	80%	74%	67%	10%	67%	17%
Design risk factor	0.7					
Maintenance risk factor	0.6					

C.2.5.11 Septic system education intervention

The user needs to indicate whether the intervention is planned for implementation or not by entering the number 1 or 0 in the *Intervention?* light gray cell in Table C-31. The following data should also be entered in the corresponding light gray cell: implementation factor, implementation timeframe and unit treatment cost. The rest of the data shown in Table C-31 are defaults and can be changed at the user's discretion.

Table C- 31: Septic system education intervention data input

Septic System Education	
Intervention? (Y/N)	0
Awareness of Message (Fraction of Population)	0.4
Fraction willing to change behavior	0.6
Implementation Factor (%)	100%
Implementation Timeframe (yrs)	5
Unit Treatment Cost (R/m^3)	

C.2.5.12 Impervious cover reduction intervention

The user needs to indicate whether the intervention is planned for implementation or not by entering the number 1 or 0 in the *Intervention?* light gray cell in Table C-32.

Table C- 32: Impervious cover reduction intervention data input

Impervious Cover Reduction	
Intervention? (Y=1/N=0)	1
Impervious Land to Be Redeveloped (km^2)	2.04
Average Impervious Cover Reduction (%)	20%
Implementation Factor (%)	35%
Implementation Timeframe (yrs)	5
Unit Treatment Cost (R/m^3)	

The following data should also be entered in the corresponding light gray cell: area of impervious land to be redeveloped, fraction of impervious cover reduced, implementation factor, implementation timeframe, and unit treatment cost.

C.2.4.13 Other future structural control interventions

The user needs to indicate whether other structural control intervention(s) exists or not by entering the number 1 or 0 in the *Intervention?* light gray cell in Table C-33. The following data should also be entered in the corresponding light gray cell: area surveyed for the retrofits, fraction of that area treatable, fraction of the area as impervious cover, number of retrofits built per year, implementation factor, implementation timeframe, fraction of retrofits, and unit treatment cost. The fraction of retrofits is used to calculate the number of BMP type (e.g. the number of wet pond) in the catchment. The black cells contain formulas and should not be overwritten or changed. The rest of the data shown in Table C-33 are defaults and can be changed at the user's discretion.

Table C- 33: Other future structural control interventions data input

Other Structural Control Retrofits								
Intervention? (Y=1/N=0)	0							
Area Surveyed (km^2)	3.5							
Impervious Cover in Surveyed Area	80%							
Fraction of area "treatable"	25%							
Number of Retrofits Built Per Year	1							
Typical Retrofit Drainage (km^2)	0.0875							
Implementation Factor (%)	100%							
Implementation Timeframe (yrs)	5							
		Efficiency						
BMP Type	Fraction of Retrofits	TN	TP	COD	Pb	TSS	FC	Unit Treatment Cost (R/m^3)
Dry Water Quantity Pond	0%	5%	19%	1%	17%	3%	10%	
Dry Extended Detention Pond	0%	25%	19%	2%	17%	47%	60%	
Wet Pond	100%	33%	51%	60%	60%	80%	70%	
Wetland	0%	30%	49%	70%	81%	76%	78%	
WQ Swale	0%	38%	34%	60%	75%	81%	0%	
Filters	0%	38%	59%	67%	89%	86%	37%	
Infiltration	0%	51%	70%	60%	88%	90%	90%	
Total		33%	33%	33%	33%	33%	33%	
	Capture risk factor		Design risk factor		Maintenance risk factor			
	0.5		1		0.5			

C.2.5.14 Illicit connection removal intervention

The user needs to indicate whether the intervention is planned for implementation or not by entering the number 1 or 0 in the *Intervention?* light gray cell in Table C-34. The following data should also be entered in the corresponding light gray cell: fraction of drainage system surveyed for the implementation of the intervention, implementation factor, implementation timeframe, and unit treatment cost.

Table C- 34: Illicit connection removal intervention data input

Illicit Connection Removal	
Intervention? (Y=1/N=0)	1
Fraction of System Surveyed	100%
Implementation Factor (%)	40%
Implementation Timeframe (yrs)	5
Unit Treatment Cost (R/m^3)	

C.2.5.15 Sanitary sewer overflows repair intervention

The user needs to indicate whether the intervention is planned for implementation or not by entering the number 1 or 0 in the *Intervention?* light gray cell in Table C-35. The following data should also be entered in the corresponding light gray cell: implementation factor, implementation timeframe, and unit treatment cost, and fraction of the goal completed.

Table C- 35: Sanitary sewer overflows repair intervention data input

Sanitary Sewer Overflow Repair/ Abatement	
Intervention? (Y=1/N=0)	1
Fraction Complete	100%
Implementation Factor (%)	100%
Implementation Timeframe (yrs)	5
Unit Treatment Cost (R/m^3)	

C.2.5.16 Septic system repair intervention

The user needs to indicate whether the intervention is planned for implementation or not by entering the number 1 or 0 in the *Intervention?* light gray cell in Table C-36. The following data should also be entered in the corresponding light gray cell: fraction of the system inspected, fraction of population with septic system willing to repair, implementation factor, implementation timeframe, and unit treatment cost.

Table C- 36: Septic system repair intervention data input

Septic System Repair	
Intervention? (Y=1/N=0)	0
Fraction Inspected	60%
Fraction Willing to Repair	90%
Implementation Factor (%)	100%
Implementation Timeframe (yrs)	5
Unit Treatment Cost (R/m^3)	

C.3 Model Output Sheet

Each time the program runs, the program prints the results onto the output sheet. The categories in the output sheet are described below:

C.3.1 Storm loads output category

The results for storm load module in the input sheet are printed onto the storm load category in the output sheet. The storm loads output category is shown in Table C-37.

Table C- 37: Storm loads output category

STORM LOADS								
Land Use		Annual (Impervious and Pervious) Loads					
		TN (kg/yr)	TP (kg/yr)	COD (kg/yr)	Pb (kg/yr)	SS (kg/yr)	FC (Million count/yr)
Residential	LDR	38,894	2,261	341,901	724	2,007,086	9.05E+09
	MDR	19,447	1,131	170,951	362	1,003,543	4.52E+09
	HDR	0	0	0	0	0	0.00E+00
Commercial		5,834	339	51,285	109	301,063	1.36E+09
		0	0	0	0	0	0.00E+00
		0	0	0	0	0	0.00E+00
Industrial		3,193	186	28,067	59	164,761	7.43E+08
		0	0	0	0	0	0.00E+00
		0	0	0	0	0	0.00E+00
Total (Urban Land)		**67,367**	**3,917**	**592,203**	**1,253**	**3,476,452**	**1.57E+10**

C.3.2 Non-storm loads output category

The results for non-storm load module in the input sheet are printed onto the non-storm load category in the output sheet. The non-storm loads output category is shown in Table C-38.

Table C- 38: Non-storm loads output category

NON-STORM LOADS						
Secondary sources	Total Annual Loads					
	TN (kg/yr)	TP (kg/yr)	COD (kg/yr)	Pb (kg/yr)	SS (kg/yr)	FC (million/yr)
Septic Systems	0	0	0	0	0	0.00E+00
Active Construction	344	230			573,750	
SSOs	6	0	12	0	40	1.00E+06
Illicit Connections	1,747,512	517,573	10,929,793	16,634	17,446,000	1.96E+03
Lawns (Subsurface Flow)	223	3				
Total Secondary Load	**1,748,085**	**517,806**	**10,929,805**	**16,634**	**17,446,614**	**1.00E+06**

C.3.3 Existing interventions output category

The results for existing intervention module in the input sheet are printed onto the existing intervention load reduction category in the output sheet. The existing intervention output category is shown in Table C-39.

Table C- 39: Existing interventions output category

LOAD REDUCTION FROM EXISTING INTERVENTIONS						
	TN (kg/yr)	**TP (kg/yr)**	**COD (kg/yr)**	**Pb (kg/yr)**	**TSS (kg/yr)**	**FC (million/yr)**
Lawn Care Education	0	0				
Domestic Animal Waste Education	0	0				0.00E+00
AC Erosion and Sediment Control	0	0			0	0.00E+00
Catchment Erosion and Sediment Control	0	0			0	0.00E+00
Street Sweeping	0	0	0	0	0	
Impervious Cover Disconnection	0	0	0	0	0	0.00E+00
Rainwater Tanks	0	0	0	0	0	0.00E+00
Other Existing Structural Controls	0	0	0	0	0	0.00E+00
Riparian Buffers	0	0	0	0	0	
River Assimilative Capacity	1,441,129	384,845	7,441,410	1,789	12,697,018	7.05E+09
Total Reduction	**1,441,129**	**384,845**	**7,441,410**	**1,789**	**12,697,018**	**7.05E+09**

C.3.4 Future interventions output category

The results for future intervention module in the input sheet are printed onto the future intervention load reduction category in the output sheet. The future intervention output category is presented in Table C-40 showing the loads reduced by each intervention, the measure of assuredness and the cost of each intervention. The estimated load reductions represent a proportion of actual load that can be reduced if all conditions (risk factors) are perfect, and that proportion is the value of the measure of assuredness. Hence a smaller value of the measure of assuredness indicates a conservative value (or a bigger margin of safety) of the load reduction estimated.

Table C- 40: Future interventions output category

LOAD REDUCTION FROM FUTURE INTERVENTIONS								
	TN (kg/yr)	**TP (kg/yr)**	**COD (kg/yr)**	**Pb (kg/yr)**	**TSS (kg/yr)**	**FC (million/yr)**	**Measure of Assuredness (%)**	**Costs (R/yr)**
Lawn Care Education	0	0					17	-
Domestic Animal Waste Education	0	0				0.00E+00	15	4,000
AC Erosion and Sediment Control	0	0			0	0.00E+00	44	-
Catchment Erosion and Sediment Control	41,999	28,000			69,999	7.00E+07	24	14,884
Street Sweeping	128	98	257	177	2,157		50	3,850
Impervious Cover (Downspout) Disconnection	3,648	212	32,069	68	188,254	8.48E+08	31	40,399
Rainwater Tanks	26,019	1,513	228,723	484	1,342,691	6.05E+09	57	320,341
Other Existing Structural Controls	0	0	0	0	0	0.00E+00	13	-
Riparian Buffers	0	0	0	0	0		1	66,938
Septic System Education	0	0	0	0	0	0.00E+00	24	-
Impervious Cover Reduction	2,485	144	21,846	46	128,242	5.78E+08	17	44,000,000
Exfiltration Systems	12,473	725	109,642	232	643,640	2.90E+09	36	283,500
Other Structural Control Retrofits	0	0	0	0	0	0.00E+00	-	-
Illicit Connection Removal	699,005	207,029	4,371,918	6,654	6,978,400	7.85E+02	100	766,980
SSO Repair/Abatement	6	0	12	0	40	1.00E+06	100	50,000
Septic System Inspection/Repair	0	0	0	0	0	0.00E+00	54	-
River Assimilative Capacity	1,441,129	384,845	7,441,410	1,789	12,697,018	7.05E+09	100	-
Totals	**2,226,891**	**622,567**	**12,205,876**	**9,450**	**22,050,442**	**1.75E+10**	**-**	**45,519,668**

C.3.5 Existing interventions load reduction summary category

Load reductions for existing interventions are disaggregated into storm and non-storm loads during simulation run. The results are output onto existing interventions load reduction summary category in the output sheet. Existing interventions load reduction summary category is shown in Table C-41.

Table C- 41: Existing interventions load reduction summary category

LOADS WITH EXISTING INTERVENTIONS SUMMARY						
	TN (kg/yr)	**TP (kg/yr)**	**COD (kg/yr)**	**Pb (kg/yr)**	**TSS (kg/yr)**	**FC (million/yr)**
Urban Land	24,475	2,079	473,763	1,128	2,468,281	8.62E+09
Active Construction	344	230			574	5.74E+05
SSOs	6	0	12	0	40	1.00E+06
Illicit Connections	1,747,512	517,573	10,929,793	16,634	17,446,000	1.96E+03
TOTAL LOAD	**374,323**	**136,878**	**4,080,598**	**16,099**	**8,226,048**	**8.62E+09**
Storm Load	24,599	2,305	473,769	1,128	2,468,875	8.62E+09
Non-Storm Load	349,724	134,572	3,606,830	14,971	5,757,173	3.32E+05

C.3.6 Future interventions load reduction summary category

Load reductions for future intervention are disaggregated into storm and non-storm loads during simulation run. The results are output onto future interventions load reduction summary category in the output sheet. Future interventions load reduction summary category is shown in Table C-42.

Table C- 42: Future interventions load reduction summary category

LOADS WITH FUTURE INTERVENTIONS SUMMARY						
	TN (kg/yr)	TP (kg/yr)	COD (kg/yr)	Pb (kg/yr)	TSS (kg/yr)	FC (million/yr)
Urban Land	-62,499	-28,616	81,226	120	93,298	-1.83E+09
Active Construction	344	230		0	574	5.74E+05
SSOs	0	0	0	0	0	0.00E+00
Illicit Connections	1,048,507	310,544	6,557,876	9,980	10,467,600	1.18E+03
TOTAL LOAD	**-411,662**	**-100,847**	**-683,868**	**8,437**	**-1,127,376**	**-1.83E+09**
Storm Load	-62,378	-28,390	81,226	120	93,871	-1.83E+09
Non-Storm Load	-349,284	-72,457	-765,094	8,317	-1,221,247	-1.69E+05

C.3.7 Existing load reduction targets category

The existing load reduction targets define the management objectives. This category (Table C-43) consists of objectives' target loads for storm, non-storm and total flows (total flow = storm + non-storm flows).

Table C- 43: Existing load reduction targets category

MANAGEMENT OBJECTIVES - EXISITING LOAD REDUCTION TARGETS						
	TN	**TP**	**COD**	**Pb**	**TSS**	**FC**
Objectives' target loads for storm flow (kg/yr)	6,244	313	94,004	141	89,565	1.69E+06
Objectives' target loads for non-storm flow (kg/yr)	229,440	2,852	2,711,821	9,861	2,892,610	4.41E+01
Objectives' total target loads (kg/yr)	235,685	3,165	2,805,826	10,002	2,982,175	1.69E+06
Load ReductionTarget for storm flow (%)	75	96	79	88	96	100
Load ReductionTarget for non-storm flow (%)	34	98	20	34	50	100
Load ReductionTarget for total flow (%)	37	98	27	38	64	100

The objectives' target loads define the loads that will exit the catchment if concentrations of storm and non-storm flows are the same as the set ambient water quality objectives. When the program runs, the objectives' target loads are compared with the existing storm and non-storm loads (in Table C-41) to estimate the load reduction targets.

C.3.8 Residual load reduction targets category

The residual load reduction targets define whether management objectives are met or not. The objective is met if the residual load reduction target is zero (i.e. 0%) or less. When the program runs, the loads reduced by future interventions are compared with the load reduction targets to estimate the residual load reduction targets.

Table C- 44: Residual load reduction targets category

RESIDUAL LOAD REDUCTION TARGETS AFTER APPLICATION OF FUTURE INTERVENTIONS						
	TN	**TP**	**COD**	**Pb**	**TSS**	**FC**
Residual Load Reduction Target for storm flow (%)	0	0	0	0	0	0
Residual Load Reduction Target for non-storm flow (%)	0	0	0	0	0	0
Residual Load Reduction Target for total flow (%)	0	0	0	0	0	0

C.3.9 Cost category

The cost category (Table C-45) is the only place in the output sheet where the user inputs data. For the strategies that achieve the management objectives, the implementation factors and the costs of strategies are *recorded* in the corresponding light gray cells in Table C-45. The optimum strategy is the one with the minimum cost.

Table C- 45: Cost data category

COSTS CATEGORY										
INTERVENTIONS	**STRATEGIES**									
	Strategy-1	Strategy-2	Strategy-3	Strategy-4	Strategy-5	Strategy-6	Strategy-7	Strategy-8	Strategy-9	Strategy-10
	IMPLEMENTATION FACTORS (%)									
Lawn Care Education										
Domestic Animal Waste Education	20%	50%	30%	0%	0%					
AC Erosion and Sediment Control										
Catchment Erosion and Sediment Control	60%	70%	90%	45%	100%					
Street Sweeping	100%	60%	100%	50%	50%					
Impervious Cover Disconnection	100%	90%	100%	90%	35%					
Rainwater Tanks	90%	90%	100%	100%	100%					
Other Existing Structural Controls										
Riparian Buffers	20%	40%	50%	30%	0%					
Septic System Education										
Impervious Cover Reduction	100%	90%	100%	70%	40%					
Exfiltration Systems	90%	60%	10%	40%	100%					
Other Structural Control Retrofits										
Illicit Connection Removal	35%	50%	40%	40%	40%					
SSO Repair/ Abatement	100%	100%	100%	100%	100%					
Septic System Inspection/Repair										
River Assimilative Capacity										
COST OF STRATEGIES	**R 45,519,668**	**R 41,359,892**	**R 45,422,272**	**R 32,303,010**	**R 19,292,802**					

APPENDIX D: RESULTS FROM EVALUATION OF FUTURE MANAGEMENT INTERVENTIONS FOR ALEXANDRA TOWNSHIP CASE STUDY

Table D- 1: Results from evaluation of first strategy

STORM LOADS							
		TN (kg/yr)	TP (kg/yr)	COD (kg/yr)	Pb (kg/yr)	SS (kg/yr)	FC (Million count/yr)
Residential	HDR	38,894	2,261	341,901	724	2,007,086	9,045,000,192
	MDR	19,447	1,131	170,951	362	1,003,543	4,522,500,096
	LDR	0	0	0	0	0	0
Commercial		5,834	339	51,285	109	301,063	1,356,750,080
		0	0	0	0	0	0
		0	0	0	0	0	0
Industrial		3,193	186	28,067	59	164,761	742,500,032
		0	0	0	0	0	0
		0	0	0	0	0	0
Total (Urban Land)		**67,367**	**3,917**	**592,203**	**1,253**	**3,476,452**	**15,666,750,464**

NON-STORM LOADS						
Secondary sources	TN (kg/yr)	TP (kg/yr)	COD (kg/yr)	Pb (kg/yr)	SS (kg/yr)	FC (Million count/yr)
Septic Systems	0	0	0	0	0	0
Active Construction	0	0			0	
SSOs	6	0	12	0	40	1,000,000
Illicit Connections	1,747,512	517,573	10,929,793	16,634	17,446,000	1,963
Lawns (Subsurface Flow)	223	3				
Total Secondary Load	**1,747,741**	**517,577**	**10,929,805**	**16,634**	**17,446,040**	**1,001,963**

Table D-1: Results from evaluation of first strategy (cont.)

LOAD REDUCTION FROM EXISTING INTERVENTIONS						
Interventions	TN (kg/year)	TP (kg/year)	COD (kg/year)	Pb (kg/year)	SS (kg/year)	FC (million/year)
Lawn Care Education	0	0				
Domestic Animal Waste Education	0	0				0
AC Erosion and Sediment Control	0	0			0	0
Catchment Erosion and Sediment Control	0	0			0	0
Street Sweeping	0	0	0	0	0	
Impervious Cover Disconnection	0	0	0	0	0	0
Rainwater Tanks	0	0	0	0	0	0
Structural Stormwater Management Practices	0	0	0	0	0	0
Riparian Buffers	0	0	0	0	0	
River Assimilative Capacity	1,441,129	384,845	7,441,410	1,789	12,697,018	7,050,208,256
Total Reduction	**1,441,129**	**384,845**	**7,441,410**	**1,789**	**12,697,018**	**7,050,208,256**

Table D-1: Results from evaluation of first strategy (cont.)

LOAD REDUCTION FROM FUTURE INTERVENTIONS								
	TN (kg/yr)	**TP (kg/yr)**	**COD (kg/yr)**	**Pb (kg/yr)**	**SS (kg/yr)**	**FC(million/yr)**	**Measure of Assuredness (%)**	**Costs (R/yr)**
Lawn Care Education	0	0					17%	0
Domestic Animal Waste Education	96	66				773,683	15%	4,000
AC Erosion and Sediment Control	0	0			0	0	44%	0
Catchment Erosion and Sediment Control	25,200	16,800			41,999	41,999,380	24%	14,884
Street Sweeping	255	196	514	355	4,314		50%	3,850
Impervious Cover Disconnection	10,423	606	91,624	194	537,869	2,423,925,248	31%	40,399
Rainwater Tanks	23,417	1,361	205,851	436	1,208,422	5,445,793,792	57%	320,341
Other Existing Structural Controls	0	0	0	0	0	0	13%	0
Riparian Buffers	28	1	328	1	3,046		1%	66,938
Septic System Education	0	0	0	0	0	0	24%	0
Impervious Cover Reduction	7,105	413	62,461	132	366,668	1,652,400,256	17%	43,968,776
Exfiltration Systems	11,225	653	98,678	209	579,276	2,610,528,256	36%	283,500
Other Structural Control Retrofits	0	0	0	0	0	0	0%	0
Illicit Connection Removal	611,629	181,151	3,825,428	5,822	6,106,100	687	100%	766,980
SSO Repair/ Abatement	6	0	12	0	40	1,000,000	100%	50,000
Septic System Inspection/Repair	0	0	0	0	0	0	54%	0
River Assimilative Capacity	1,441,129	384,845	7,441,410	1,789	12,697,018	7,050,208,256	100%	0
TOTALS	**2,130,513**	**586,091**	**11,726,305**	**8,937**	**21,544,752**	**19,226,630,144**	**-**	**45,519,668**

Table D-1: Results from evaluation of first strategy (cont.)

LOADS WITH EXISTING INTERVENTIONS SUMMARY						
	TN (kg/year)	TP (kg/year)	COD (kg/year)	Pb (kg/year)	SS (kg/year)	FC (million/year)
Urban Land	24,475	2,079	473,763	1,128	2,468,281	8,616,712,192
Active Construction	-	-			-	-
SSOs	6	0	12	0	40	1,000,000
Illicit Connections	1,747,512	517,573	10,929,793	16,634	17,446,000	1,963
TOTAL LOAD	373,979	136,648	4,080,598	16,099	8,225,474	8,617,543,680
Storm Load	24,255	2,076	473,769	1,128	2,468,301	8,617,211,904
Non-Storm Load	349,724	134,572	3,606,830	14,971	5,757,173	331,629
LOADS WITH FUTURE INTERVENTIONS SUMMARY						
	TN (kg/year)	TP (kg/year)	COD (kg/year)	Pb (kg/year)	SS (kg/year)	FC (million/year)
Urban Land	-53,497	-18,019	14,307	-198	-273,313	-3,558,707,968
Active Construction	0	0			0	0
SSOs	0	0	0	0	0	0
Illicit Connections	1,135,883	336,422	7,104,366	10,812	11,339,900	1,276
TOTAL LOAD	-315,629	-64,601	-204,297	8,950	-622,260	-3,558,876,928
Storm Load	-53,720	-18,023	14,307	-198	-273,313	-3,558,707,968
Non-Storm Load	-261,909	-46,578	-218,604	9,149	-348,947	-169,058
MANAGEMENT OBJECTIVES - EXISITING LOAD REDUCTION TARGETS						
	TN	**TP**	**COD**	**Pb**	**SS**	**FC**
Objectives' target loads for storm flow (kg/yr)	5,951	83	100,271	141	88,991	5,170,328
Objectives' target loads for non-storm flow (kg/yr)	231,412	2,852	2,892,610	9,861	2,892,610	203
Objectives' total target loads (kg/yr)	237,363	2,935	2,992,881	10,002	2,981,601	5,170,531
Load ReductionTarget for storm flow (%)	75	96	79	88	96	100
Load ReductionTarget for non-storm flow (%)	34	98	20	34	50	100
Load ReductionTarget for total flow (%)	37	98	27	38	64	100
MANAGEMENT OBJECTIVES - RESIDUAL LOAD REDUCTION TARGETS AFTER APPLICATION OF FUTURE INTERVENTIONS						
	TN	**TP**	**COD**	**Pb**	**SS**	**FC**
Residual Load Reduction Target for storm flow(%)	0	0	0	0	0	0
Residual Load Reduction Target for non-storm flow(%)	0	0	0	0	0	0
Residual Load Reduction Target for total flow(%)	0	0	0	0	0	0

Table D- 2: Results from evaluation of second strategy

LOAD REDUCTION FROM FUTURE INTERVENTIONS								
	TN (kg/yr)	**TP (kg/yr)**	**COD (kg/yr)**	**Pb (kg/yr)**	**SS (kg/yr)**	**FC(million/yr)**	**Measure of Assuredness (%)**	**Costs (R/yr)**
Lawn Care Education	0	0					17%	0
Domestic Animal Waste Education	240	164				1,934,208	15%	10,000
AC Erosion and Sediment Control	0	0			0	0	44%	0
Catchment Erosion and Sediment Control	29,400	19,600			48,999	48,999,272	24%	17,364
Street Sweeping	153	118	308	213	2,588		50%	2,310
Impervious Cover Disconnection	9,381	545	82,462	175	484,082	2,181,532,672	31%	36,359
Rainwater Tanks	23,417	1,361	205,851	436	1,208,422	5,445,793,792	57%	320,341
Other Existing Structural Controls	0	0	0	0	0	0	13%	0
Riparian Buffers	56	1	658	2	6,184		1%	66,938
Septic System Education	0	0	0	0	0	0	24%	0
Impervious Cover Reduction	6,395	372	56,215	119	330,001	1,487,160,192	17%	39,571,896
Exfiltration Systems	7,484	435	65,785	139	386,184	1,740,352,256	36%	189,000
Other Structural Control Retrofits	0	0	0	0	0	0	0%	0
Illicit Connection Removal	873,756	258,786	5,464,897	8,317	8,723,000	982	100%	1,095,686
SSO Repair/ Abatement	6	0	12	0	40	1,000,000	100%	50,000
Septic System Inspection/Repair	0	0	0	0	0	0	54%	0
River Assimilative Capacity	1,441,129	384,845	7,441,410	1,789	12,697,018	7,050,208,256	100%	0
TOTALS	**2,391,415**	**666,228**	**13,317,598**	**11,189**	**23,886,518**	**17,956,980,736**	**-**	**41,359,892**

Table D-2: Results from evaluation of second strategy (cont.)

LOADS WITH FUTURE INTERVENTIONS SUMMARY						
	TN (kg/year)	TP (kg/year)	COD (kg/year)	Pb (kg/year)	SS (kg/year)	FC (million/year)
Urban Land	-52,272	-20,520	62,483	44	1,820	-2,289,059,584
Active Construction	0	0			0	0
SSOs	0	0	0	0	0	0
Illicit Connections	873,756	258,786	5,464,897	8,317	8,723,000	982
TOTAL LOAD	-576,530	-144,738	-1,795,590	6,698	-2,964,027	-2,289,229,056
Storm Load	-52,495	-20,524	62,483	44	1,820	-2,289,059,584
Non-Storm Load	-524,035	-124,214	-1,858,073	6,654	-2,965,847	-169,352
MANAGEMENT OBJECTIVES - RESIDUAL LOAD REDUCTION TARGETS AFTER APPLICATION OF FUTURE INTERVENTIONS						
	TN	**TP**	**COD**	**Pb**	**SS**	**FC**
Residual Load Reduction Target for storm flow(%)	0	0	0	0	0	0
Residual Load Reduction Target for non-storm flow(%)	0	0	0	0	0	0
Residual Load Reduction Target for total flow(%)	0	0	0	0	0	0

Table D- 3: Results from evaluation of third strategy

LOAD REDUCTION FROM FUTURE INTERVENTIONS								
	TN (kg/yr)	**TP (kg/yr)**	**COD (kg/yr)**	**Pb (kg/yr)**	**SS (kg/yr)**	**FC(million/yr)**	**Measure of Assuredness (%)**	**Costs (R/yr)**
Lawn Care Education	0	0					17%	0
Domestic Animal Waste Education	144	98				1,160,525	15%	6,000
AC Erosion and Sediment Control	0	0			0	0	44%	0
Catchment Erosion and Sediment Control	37,799	25,200			62,999	62,999,068	24%	22,326
Street Sweeping	255	196	514	355	4,314		50%	3,850
Impervious Cover Disconnection	10,423	606	91,624	194	537,869	2,423,925,248	31%	40,399
Rainwater Tanks	26,019	1,513	228,723	484	1,342,691	6,050,882,560	57%	355,934
Other Existing Structural Controls	0	0	0	0	0	0	13%	0
Riparian Buffers	69	1	824	3	7,765		1%	66,938
Septic System Education	0	0	0	0	0	0	24%	0
Impervious Cover Reduction	7,105	413	62,461	132	366,668	1,652,400,256	17%	43,968,776
Exfiltration Systems	1,247	73	10,964	23	64,364	290,058,720	36%	31,500
Other Structural Control Retrofits	0	0	0	0	0	0	0%	0
Illicit Connection Removal	699,005	207,029	4,371,918	6,654	6,978,400	785	100%	876,549
SSO Repair/ Abatement	6	0	12	0	40	1,000,000	100%	50,000
Septic System Inspection/Repair	0	0	0	0	0	0	54%	0
River Assimilative Capacity	1,441,129	384,845	7,441,410	1,789	12,697,018	7,050,208,256	100%	0
TOTALS	**2,223,202**	**619,974**	**12,208,450**	**9,633**	**22,062,126**	**17,532,635,136**	**-**	**45,422,272**

Table D-3: Results from evaluation of third strategy (cont.)

LOADS WITH FUTURE INTERVENTIONS SUMMARY						
	TN (kg/year)	TP (kg/year)	COD (kg/year)	Pb (kg/year)	SS (kg/year)	FC (million/year)
Urban Land	-58,810	-26,024	78,652	-63	81,612	-1,864,713,728
Active Construction	0	0			0	0
SSOs	0	0	0	0	0	0
Illicit Connections	1,048,507	310,544	6,557,876	9,980	10,467,600	1,178
TOTAL LOAD	-408,317	-98,484	-686,442	8,254	-1,139,635	-1,864,882,944
Storm Load	-59,033	-26,027	78,652	-63	-1,139,635	-1,864,713,728
Non-Storm Load	-349,284	-72,457	-765,094	8,317	-1,139,635	-169,156
MANAGEMENT OBJECTIVES - RESIDUAL LOAD REDUCTION TARGETS AFTER APPLICATION OF FUTURE INTERVENTIONS						
	TN	**TP**	**COD**	**Pb**	**SS**	**FC**
Residual Load Reduction Target for storm flow(%)	0	0	0	0	0	0
Residual Load Reduction Target for non-storm flow(%)	0	0	0	0	0	0
Residual Load Reduction Target for total flow(%)	0	0	0	0	0	0

Table D- 4: Results from evaluation of forth strategy

LOAD REDUCTION FROM FUTURE INTERVENTIONS								
	TN (kg/yr)	**TP (kg/yr)**	**COD (kg/yr)**	**Pb (kg/yr)**	**SS (kg/yr)**	**FC(million/yr)**	**Measure of Assuredness (%)**	**Costs (R/yr)**
Lawn Care Education	0	0					17%	0
Domestic Animal Waste Education	0	0				0	15%	0
AC Erosion and Sediment Control	0	0			0	0	44%	0
Catchment Erosion and Sediment Control	18,900	12,600			31,500	31,499,534	24%	11,163
Street Sweeping	128	98	257	177	2,157		50%	1,925
Impervious Cover Disconnection	9,381	545	82,462	175	484,082	2,181,532,672	31%	36,359
Rainwater Tanks	26,019	1,513	228,723	484	1,342,691	6,050,882,560	57%	355,934
Other Existing Structural Controls	0	0	0	0	0	0	13%	0
Riparian Buffers	42	1	494	2	4,660		1%	66,938
Septic System Education	0	0	0	0	0	0	24%	0
Impervious Cover Reduction	4,974	289	43,723	93	256,667	1,156,680,192	17%	30,778,142
Exfiltration Systems	4,989	290	43,857	93	257,456	1,160,234,880	36%	126,000
Other Structural Control Retrofits	0	0	0	0	0	0	0%	0
Illicit Connection Removal	699,005	207,029	4,371,918	6,654	6,978,400	785	100%	876,549
SSO Repair/ Abatement	6	0	12	0	40	1,000,000	100%	50,000
Septic System Inspection/Repair	0	0	0	0	0	0	54%	0
River Assimilative Capacity	1,441,129	384,845	7,441,410	1,789	12,697,018	7,050,208,256	100%	0
TOTALS	**2,204,571**	**607,211**	**12,212,855**	**9,465**	**22,054,670**	**17,632,038,912**	**-**	**32,303,010**

Table D-4: Results from evaluation of forth strategy (cont.)

LOADS WITH FUTURE INTERVENTIONS SUMMARY						
	TN (kg/year)	TP (kg/year)	COD (kg/year)	Pb (kg/year)	SS (kg/year)	FC (million/year)
Urban Land	-40,179	-13,260	74,247	105	89,068	-1,964,117,120
Active Construction	0	0			0	0
SSOs	0	0	0	0	0	0
Illicit Connections	1,048,507	310,544	6,557,876	9,980	10,467,600	1,178
TOTAL LOAD	-389,687	-85,721	-690,847	8,422	-1,132,179	-1,964,286,336
Storm Load	-40,403	-13,264	74,247	105	89,068	-1,964,117,120
Non-Storm Load	-349,284	-72,457	-765,094	8,317	-1,221,247	-169,156
MANAGEMENT OBJECTIVES - RESIDUAL LOAD REDUCTION TARGETS AFTER APPLICATION OF FUTURE INTERVENTIONS						
	TN	**TP**	**COD**	**Pb**	**SS**	**FC**
Residual Load Reduction Target for storm flow(%)	0	0	0	0	0	0
Residual Load Reduction Target for non-storm flow(%)	0	0	0	0	0	0
Residual Load Reduction Target for total flow(%)	0	0	0	0	0	0

Table D- 5: Results from evaluation of fifth strategy

LOAD REDUCTION FROM FUTURE INTERVENTIONS								
	TN (kg/yr)	**TP (kg/yr)**	**COD (kg/yr)**	**Pb (kg/yr)**	**SS (kg/yr)**	**FC(million/yr)**	**Measure of Assuredness (%)**	**Costs (R/yr)**
Lawn Care Education	0	0					17%	0
Domestic Animal Waste Education	0	0				0	15%	0
AC Erosion and Sediment Control	0	0			0	0	44%	0
Catchment Erosion and Sediment Control	41,999	28,000			69,999	69,998,960	24%	24,806
Street Sweeping	128	98	257	177	2,157		50%	1,925
Impervious Cover Disconnection	3,648	212	32,069	68	188,254	848,373,824	31%	14,140
Rainwater Tanks	26,019	1,513	228,723	484	1,342,691	6,050,882,560	57%	355,934
Other Existing Structural Controls	0	0	0	0	0	0	13%	0
Riparian Buffers	0	0	0	0	0		1%	66,938
Septic System Education	0	0	0	0	0	0	24%	0
Impervious Cover Reduction	2,842	165	24,984	53	146,667	660,960,128	17%	17,587,510
Exfiltration Systems	12,473	725	109,642	232	643,640	2,900,587,008	36%	315,000
Other Structural Control Retrofits	0	0	0	0	0	0	0%	0
Illicit Connection Removal	699,005	207,029	4,371,918	6,654	6,978,400	785	100%	876,549
SSO Repair/ Abatement	6	0	12	0	40	1,000,000	100%	50,000
Septic System Inspection/Repair	0	0	0	0	0	0	54%	0
River Assimilative Capacity	1,441,129	384,845	7,441,410	1,789	12,697,018	7,050,208,256	100%	0
TOTALS	**2,227,248**	**622,587**	**12,209,015**	**9,457**	**22,068,866**	**17,582,012,416**	**-**	**19,292,802**

Table D-5: Results from evaluation of fifth strategy (cont.)

LOADS WITH FUTURE INTERVENTIONS SUMMARY						
	TN (kg/year)	TP (kg/year)	COD (kg/year)	Pb (kg/year)	SS (kg/year)	FC (million/year)
Urban Land	-62,856	-28,637	78,087	114	74,873	-1,914,089,728
Active Construction	0	0			0	0
SSOs	0	0	0	0	0	0
Illicit Connections	1,048,507	310,544	6,557,876	9,980	10,467,600	1,178
TOTAL LOAD	-412,364	-101,097	-687,007	8,431	-1,146,374	-1,914,258,944
Storm Load	-63,079	-28,640	78,087	114	74,873	-1,914,089,728
Non-Storm Load	-349,284	-72,457	-765,094	8,317	-1,221,247	-169,156
MANAGEMENT OBJECTIVES - RESIDUAL LOAD REDUCTION TARGETS AFTER APPLICATION OF FUTURE INTERVENTIONS						
	TN	**TP**	**COD**	**Pb**	**SS**	**FC**
Residual Load Reduction Target for storm flow(%)	0	0	0	0	0	0
Residual Load Reduction Target for non-storm flow(%)	0	0	0	0	0	0
Residual Load Reduction Target for total flow(%)	0	0	0	0	0	0