TOWARDS THE DEVELOPMENT OF A MULTI-CRITERIA DECISION SUPPORT SYSTEM FOR SELECTING STORMWATER BEST MANAGEMENT PRACTICES

By

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Submitted in fulfilment of the academic requirements for the degree of

Master of Environment and Development

at the

Centre for Environment and Development

University of Natal

Pietermaritzburg

2001

ABSTRACT

The aim of this dissertation was to develop a multi-criteria decision support system (MCDSS) to allow a specified manager to select with confidence one or many of these BMPs for a particular site. The principal design approach was a review of South African and international literature pertaining to stormwater management techniques, in particular BMPs. This information was formulated into a primary matrix using a rank-and-weighting method. The scores were then checked against the literature to ensure that they were reasonable, culminating in the initial MCDSS. The MCDSS was then provided with seven scenarios, described in the literature, and the output reviewed. Although, the MCDSS would select appropriately when given few criteria for selection when these were increased, inappropriate outcomes resulted. Consequently, weighting factors were assigned to each criterion. The MCDSS was further tested using all the selection criteria and the output deemed satisfactory. The MCDSS was then tested in a case study of the Town Bush stream catchment at eleven sites along the river network and the results were adequate. Taking into consideration the economic aspects of BMP implementation a need also arose for the sites to be allocated to certain authorities depending upon ownership or responsibility. The sites were prioritised depending on potential threat to property and lastly by the hydrological nature of the stream at each site. A stormwater plan for the study area was also proposed. Although the MCDSS was functioning adequately it was not without its limitations. Limitations included the use of drainage areas as a surrogate measure for peak discharge thus, not allowing the user to design a series of BMPs or treatment chain. A second limitation was that initially the BMPs were designed as offline systems where stormwater is managed before entering the channel but in this study they were used as inline systems. Hence the ultimate selection was biased towards those BMPs able to deal with large drainage areas. Recommendations for further improvement include the development of a surrogate measure for drainage area thus allowing the user to design a treatment chain of BMPs; testing the MCDSS in more diverse circumstances; developing a more comprehensive set of selection criteria; and developing a clearer priority-setting model as the one used was rather simplistic. In conclusion the MCDSS provides the user with a useful tool where the selection and implementation of BMPs no longer has to take place in an ad hoc manner.

ACKNOWLEDGEMENTS

A study of this nature required support, guidance, patience and friendship of the people that were involved in my life during the period of the study. I wish to thank the staff and students at the Centre of Environment and Development, whom encouraged me and gave of their time.

A special note of thanks must go to my supervisor Dr Nevil Quinn who encouraged, and guided me through this period. To Michael Horswell, who gave willing of his time and without whom I would not have been able to complete this study. His knowledgeable experience with GIS saved me vast amounts of time and saved me from many sleepless nights. To David Catherine, who gave of his time even during his holiday this was greatly appreciated. He is unrivalled on Corel Draw!

Finally, I would like to express my thanks to my friends and family without whom this period would have been immensely harder.

PREFACE

The research described in this dissertation was carried out at the Centre for Environment and Development, University of Natal, Pietermaritzburg, under the supervision of Dr Nevil Quinn.

This dissertation represents original work by the author and has not otherwise been submitted in any form for any degree of diploma at any other University. Where the work of others has been used it has been duly acknowledged in the text.

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CHAPTER 1: OVERVIEW

INTRODUCTION

South Africa currently has one of the highest rates of urbanisation in the world (Braune & Wood 1999). It has been estimated that between 1999 and 2004 one million houses are to be built, covering an area of about 60 000 ha. Such an increase in impervious area will result in an increased volume and rate of runoff (EPA 1993), the consequences of which include an increased risk of flooding, streambank erosion, and a decline in groundwater recharge (Schueler 1987). Urbanisation also increases the type and amount of pollutants in surface runoff. Both Kibble (1987), and Huhn and Stecker (1997) state that polluted runoff from these modified surfaces pose one of the greatest threats to the quality of riverine systems. Unfortunately the control of such runoff (stormwater) is often neglected as a high priority issue (Braune & Wood 1999). In South Africa the problem of urban runoff is further compounded due to the presence of large informal (unserviced) developments (Braune & Wood 1999). Consequently the good management of urban stormwater runoff should be a major concern to those charged with its safe disposal.

1.1 PROBLEM STATEMENT

Conventional stormwater drainage systems designed to deal with the increased quantities of water resulting from urbanisation traditionally do so by providing the fastest possible transport of stormwater out of urban areas and into receiving waters (Jefferies *et al.* 1999; Warner 2000). However, what these systems do not factor in are the downstream consequences of increased quantities and decreased qualities of water. One such problem resulting from increased flows is that they tend to cause rivers to incise and result in bank stability problems (Rutherfurd, Jerie & Marsh 2000). In effect, this compromises the integrity of property and the environment.

Contemporary approaches to stormwater management seek to retain the natural features of drainage systems and provide onsite management to address water quality and quantity goals (EPA 1993; Argue 1995; Huhn & Stecker 1997; Warner 2000). This approach views stormwater as a resource to be used to recharge groundwater and to supply fresh water to surface waters, including wetlands. Properly managing stormwater can avoid problems with erosion, flooding, and adverse impacts on natural drainage features, including wetlands (EPA 1993).

To meet the above, a series of Best Management Practices (BMPs) were developed for urbanising areas (Schueler 1987; Urbanas 1997; Sieker 1998; Sieker & Klein 1998; Mehler & Ostrowski

1999). BMPs have allowed stormwater managers to determine how best to control the quality and quantity of surface waters within a watershed. BMPs attempt to mitigate against both the hydrological modifications and pollutant inputs that are inevitable results of urban and suburban development. These methods take into account ecological criteria and are potentially much closer to nature than the traditional methods are. Unfortunately, at the time of installation of the first systems, when knowledge of the detailed information needed for appropriate functioning was limited, a number of systems were constructed which were clearly not successful or suited to the environment in which they were placed (Jefferies *et al.* 1999).

The use and selection of specific BMPs depends on a variety of factors including site conditions, pollution source and site characteristics, management objectives and potential impact on the surrounding environment. In effect, a stormwater BMP plan may have many objectives but the ability of each specific BMP to meet these objectives in a cost effective manner thus depends on the careful selection of the appropriate BMP. To date there have been many attempts to synthesise the large body of information into one coherent decision tool for BMP selection (Azzout *et al.* 1995; Barraud *et al.* 1999; Schueler 1987, 2000; Urbanas 1997). However, in the process each of the authors has selected varying sets of criteria further complicating the selection process. Although the need for such alternative techniques has been highlighted by various South African authors (Green, Stephenson & Lambourne 1986; Stephenson 1989; Coleman 1990; Braune & Wood 1999) BMP implementation still seems to be lacking. Recently however, Braune & Wood (1999) have initiated such a process in South Africa, unfortunately they do not expand upon the original selection tool proposed by Urbanas (1997) but they do state that such a selection tool could be used in conjunction with a hazard assessment and biological indicator method. They stress the need to manage urban stormwater runoff on an integrated catchment basis and propose the use of BMPs to meet such a need. Thereby reducing the negative impact of urbanisation on the environment and quality of life.

Therefore a rigorous multi-criteria decision support system, which includes selection criteria from the various authors, for selecting the appropriate BMP for a specific set of circumstances and objectives is essential. In this way, it is hoped that a sustainable solution (balancing urbanisation and environmental protection) to the stormwater problem facing South Africa in the foreseeable future will be provided.

1.2 AIMS AND OBJECTIVES

The aim of this research project is to develop a multi-criteria decision support system that will allow a specified manager to select one or many BMPs for a particular site to accomplish the following:

- To reproduce, as closely as possible, the hydrological conditions in the stream to pre-development status or in other words to a natural regime.
- To provide some degree of pollutant removal.
- Be appropriate for site, given physical constraints.
- Be reasonably cost-effective in comparison to other BMPs or solutions to given management criteria.
- Have an acceptable future maintenance requirement.
- Have at least a neutral impact on the natural and human environment.

The objectives of this research project are to:

(i) Review the literature on stormwater management techniques with specific reference to BMPs. Particular attention will be given to the most recent techniques used in the UK, USA, and Australia.

(ii) Identify specific BMP selection criteria, advantages, as well as specific limitations of the various BMPs.

(iii) Consolidate and formulate the information to a multi-criteria decision support system.

(iv) Undertake testing of the support system in a case study and compare the results to other selection systems in order to evaluate its utility.

(v) In terms of the above, provide recommendations for further improvement and use.

1.3 METHODOLOGY

In view of the above aims and objectives, the principal approach adopted was a review of South African and international literature that pertained to stormwater management techniques and in particular BMPs. The purpose of the review was to establish the most common BMPs used worldwide and to determine how these were to be classified within the support system. Certain manuals, used previously in BMP selection, were used in the development of the MCDSS. Since neither tool was without its shortcomings (section 4.2.2), an inductive approach to the development of the MCDSS was adopted. A rank and weighting model was applied to the collected data, and as such resulted in the BMPs being awarded a score for each criterion. Certain aims and objectives common to stormwater management plans were also incorporated into the MCDSS (i.e. does the manager want to decrease erosion and pollution or increase ground water recharge?). Lastly financial constraints and potential threats of the BMPs were also factored into the MCDSS. This approach resulted in the formulation of a stormwater MCDSS for the selection of BMPs, thus concluding the initial phase of development.

The second phase of development resulted in the MCDSS being tested using case studies identified during the literature review. These studies ranged from simple (few criteria for selection) to complex (numerous criteria for selection). The outcomes of the MCDSS were compared to the results provided by the other tools.

After the completion of the above stages the MCDSS was then tested in a case study in the Town Bush catchment. However, limitations of time and finance resulted in a preliminary testing of the MCDSS only. Nevertheless, field study of the MCDSS enabled a review of the tool based on a practical exercise, and thus enabled the formulation of recommendations for stormwater management of the study area.

1.4 OVERVIEW OF THE DISSERTATION

Chapter two relates to issues surrounding watershed management. The chapter provides the reader with a better understanding of the impacts of urbanisation on urban watersheds. It introduces key concepts such as travel time, peak discharge, and the 'first flush' principal. It concludes by discussing certain tools that can be used for watershed management.

Chapter three provides an overview of the various categories of BMPs and discusses three methods of pollutant removal and the hydrological characteristics of different BMPs. This chapter also outlines the main objectives and issues that need to be considered when selecting a BMP plan or the selection of BMPs. It concludes with an example of a stormwater BMP plan from Canada that demonstrates the need for proper public consultation.

Chapter four details the methodology used in the formulation of the MCDSS. It begins by introducing the concept of decision support and the scope of such a tool before providing an outline of the process used for the development of the primary matrix and MCDSS. A critique of each selection tool used in the development of the MCDSS is provided before discussing in detail the various screening criteria that were incorporated into the model. The aim of this chapter is to take the reader through the step-wise process used in the development of the final MCDSS. In doing so detailed results and discussion of the MCDSS output has been provided.

Chapter five presents the results of applying the MCDSS in the case study of the Town Bush catchment, Pietermaritzburg, KwaZulu-Natal. Chapter six discusses the results and appraises the MCDSS. Chapter six also suggests priorities for stormwater management within the study area. Chapter seven concludes the study and provides recommendations for further improvement.

CHAPTER 2: WATERSHED MANAGEMENT

2.1 IMPACTS OF URBAN RUNOFF

Changes in land use within a watershed usually result in changes to stormwater runoff volume and quality. For example, urbanising watersheds are characterised by increases in impervious surfaces, which include roads, sidewalks, parking lots, and buildings, as compared to rural land uses (EPA 1996). Increased imperviousness leads to increased runoff volumes and velocities and higher pollutant loads (Argue 1995; EPA 1996; Sieker 1998). As the water moves readily and rapidly down roofs, pathways and roads into gutters and drains it is channelled directly to streams which as a consequence become more flashy. Runoff periods occur very soon after rainfall and because times of concentration are greatly reduced, resulting hydrographs increase in peakedness (Warner 2000). The flashy regime and the greater volume of water inject more energy into the system (Warner 2000). This has consequences for the removal of land-based and channel sediments and pollutants (Warner 2000).

2.1.1 Changes in watershed hydrology

The hydrology of a stream changes in response to initial site clearing and grading (Schueler 1987). Trees that had intercepted rainfall are felled (Figure 2.1 a), natural depressions which temporarily ponded water are graded to a uniform slope, and the thick humus layer that had absorbed rainfall erodes away (Schueler 1987). Having lost much of its natural storage capacity, the cleared and graded site can no longer prevent rainfall from being rapidly converted to runoff.

The situation worsens after construction is completed (Figure 2.1 a). Rooftops, roads, parking lots, sidewalks and driveways make much of the site impervious to rainfall. Unable to percolate into the soil, rainfall is almost completely converted into runoff. In effect, what has occurred is a disruption in the established rainfall-runoff relationship that exists in a watershed (EPA 1996). As stated, reduced infiltration occurs. There is also a subsequent reduction in the time of concentration (which is the time it takes surface runoff from the most distant point of a watershed to reach the first swale, sewer, or channel) (EPA 1996; Reeder 1996). Travel time, the time it takes flow to move through various conveyance elements (river reaches) to the next inlet or design point, may also be decreased by urbanisation.

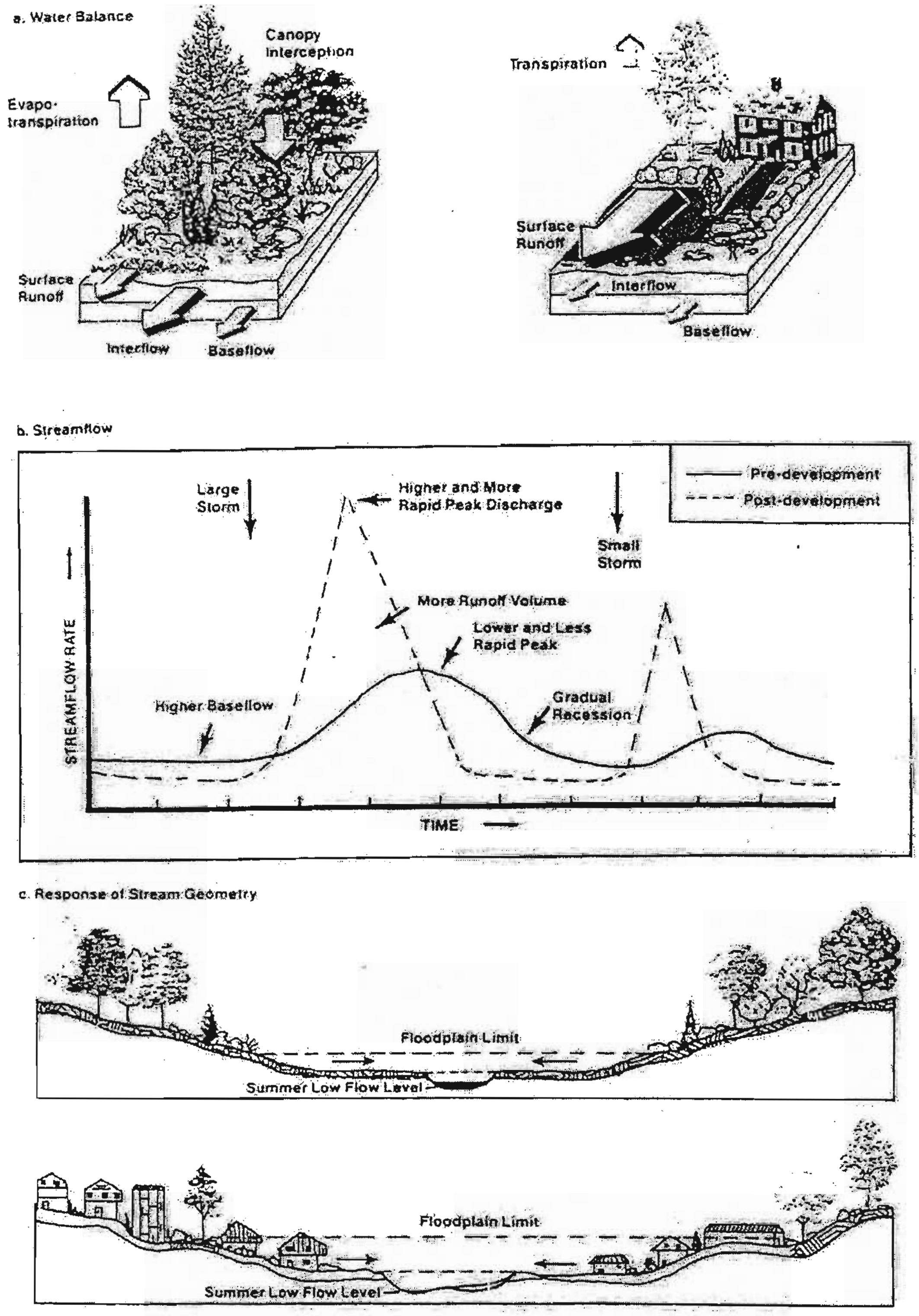

Figure 2.1: Changes in watershed hydrology as a result of urbanisation (Schueler 1987).

Both of these factors can significantly increase peak discharges and runoff (Figure 2.1 b). Box 1 lists various changes to the stream hydrology that occurred in a typical, moderately developed watershed.

Box 1: Various changes to the stream hydrology under a moderately developed watershed

- Increased peak discharges about two to five times higher than pre-development levels.
- Increased volume of storm runoff produced by each storm, in comparison to pre-development conditions. A moderately developed watershed may produce 50% more runoff volume than a forested watershed during the same storm (Schueler 1987).
- Decreased time needed for runoff to reach the stream (time of concentration) by as much as 50%, particularly if extensive drainage improvements are made.
- Increased frequency and severity of flooding. A short, intense summer thunderstorm that had only slightly raised water levels in the past now turns the stream into a torrent (Schueler 1987). In a natural state, a stream experiences bankfull discharges (i.e. runoff entirely fills the stream channel) only about once every two years. In moderately developed watersheds, bankfull discharges may occur as often as three or four times a year.
- Reduced streamflow during prolonged periods of dry weather due to the reduced level of infiltration in the watershed. In smaller, headwater streams, the reduction may be enough to cause a perennial stream to become seasonally dry.
- Greater runoff velocity during storms due to the combined effects of higher peak discharges, rapid time of concentration, and smoother hydraulic surfaces that occur as a result of development.

(a) **Travel time**

As mentioned above, travel time is the time it takes runoff to travel from the point where sheetflow enters a recognisable conveyance element, through the various conveyance elements, to a specified point in the watershed (EPA 1996). Travel time is principally a function of slope, length of flow path, depth of flow, and the roughness of the flow surfaces. As land uses in the watershed become smoother (e.g. imperviousness increases or forested land areas decrease), the velocity of runoff increases, which decreases travel time.

(b) **Peak discharge**

Peak discharge changes are often good indicators of changes in land use within a watershed (EPA 1996). The relationship between runoff volume, watershed drainage area, relative locations of urbanised areas, effectiveness of flood control structures or other storage structures, the time distribution of rainfall during a storm event, and travel time all determine peak discharge. The estimation of peak flows on small to medium sized watershed is said to be a common application of stormwater runoff estimation.

Mathematical relationships, or models, are used to approximate the relationship of rainfall to runoff. The results from modelling approximations used to predict runoff from a particular area are generally much better at indicating changes in runoff, rather than absolute runoff volume (EPA 1996). The United States Department of Agriculture's Soil Conservation Service (SCS) model has been used internationally and locally for the estimation of flood volume and peak discharge (Schmidt & Schulze 1987). However, this model has been specifically designed for use on small (30 km^2) catchments or less.

2.1.2 Changes in stream geometry

A growing body of literature documents substantial alterations in flow patterns, channel morphology, water quality, and biotic communities associated with watershed urbanisation (Ferguson and Suckling 1990; Booth & Jackson 1997; Wang, Lyons & Kanehl 2001). The primary adjustment to these new hydrological conditions is through channel widening (Figure 2.1 c) (Schueler 1987; Roesner, Bledsoe & Brashear 2001). Schueler (1987) mentions numerous surveys (Hammer 1972; Fox 1974; Robinson 1976) that have shown streams to widen two to four times their original size if post-development runoff is not effectively controlled. The resulting streambank erosion is usually severe since most floodplain soils are unconsolidated and highly erodible. The results of such erosion leads to a degradation of in-stream habitat (Roesner, Bledsoe & Brashear 2001). As eroded sediments are deposited downstream in slower moving reaches of the stream or at the entrance to lakes or estuaries the benthos is smothered thus harming the aquatic habitat (Roesner, Bledsoe & Brashear 2001; Wang, Lyons & Kanehl 2001).

Changes also occur in the elevation of the affected stream's flood level (Schueler 1987). The flood plain must therefore be elevated to accommodate the higher post-development peak discharge rate. If neglected, property and structures that had not previously been subject to flooding may now be at risk.

Streambanks are gradually undercut and slump into the channel. Trees that protected these banks are exposed at the roots, and are more likely to be windthrown, triggering a second phase of bank erosion. The large quantities of sediment eroded from streambanks and upland areas are seldom completely exported from the watershed and much of it remains as temporary channel storage in the form of sandbars or other sediment deposits. The amounts of sediment entering the river system must be taken into account when dealing with the type and functionality of BMPs (section 4.3.1 c 7: 61).

2.1.3 Stormwater quality

As Figure 2.2 demonstrates, the water quality aspects of the hydrobiological cycle are affected by both the rise in population and the increase in the extent of the impervious area. Since the volume of runoff becomes larger with the onset of development, the amount of soil moisture recharged is reduced. Consequently, less water is likely to percolate into any aquifer underlying an urban area. Between storm events, the baseflow within the natural drainage system is derived from such subsurface storages (Hall 1984). Low flows may therefore be expected to decrease as the urbanisation of an area increases (Hall 1984). Unfortunately, this decrease occurs simultaneously with the increase in the volume of waterborne wastes and the deterioration in the quality of stormwater runoff as contaminants are washed from streets, roofs and paved areas. The disposal of both solid and waterborne wastes may according to Hall (1984) and Ristenpart (1999) affect groundwater quality as well as having serious impacts on aquatic ecosystems.

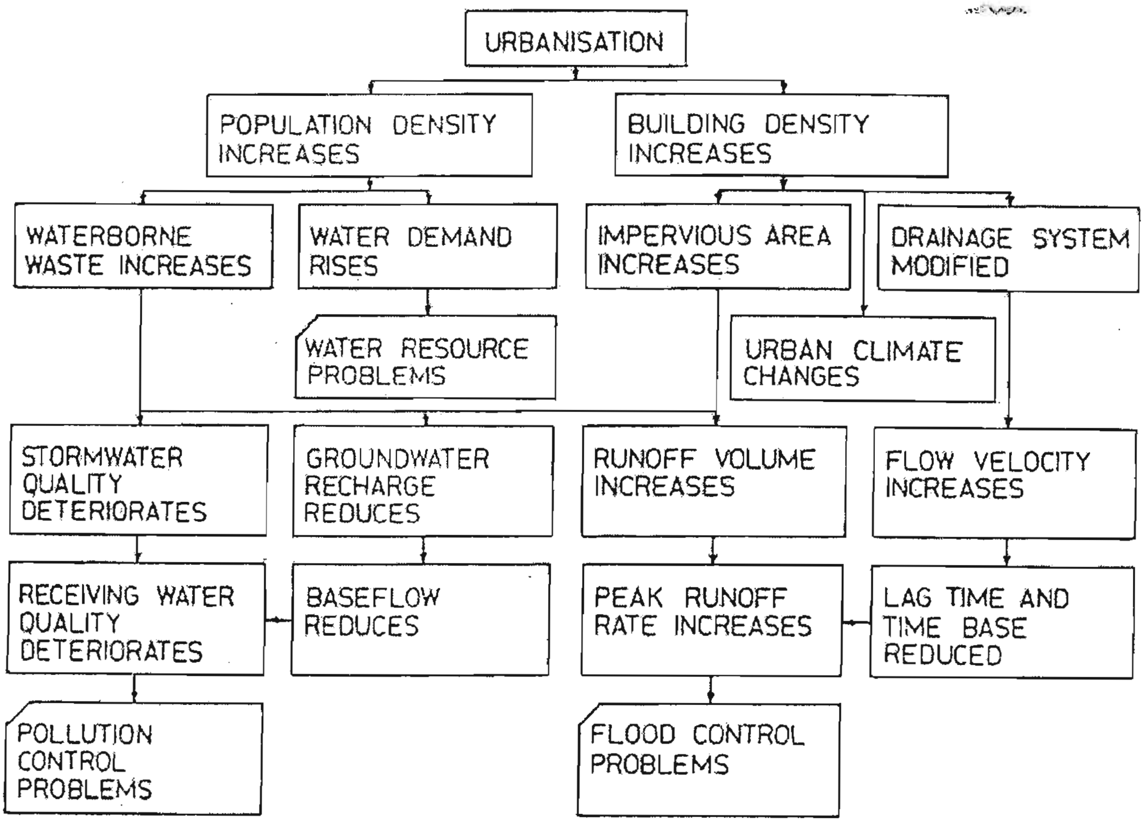

Figure 2.2: The effects of urbanisation on hydrological process (Hall 1984)

The principle types of pollutants found in urban runoff include sediment, oxygen-demanding substances, nutrients (phosphorous and nitrogen), heavy metals, pesticides, hydrocarbons, increased temperature, trash and debris (Corbit 1989; Coleman 1993; Mckissock, Jefferies & D'Arcy 1999).

A report by the Terrene Institute (Reeder 1996) mentions two principal phases from which pollutant problems arise. The first occurs during the construction phase where pollutant export increases dramatically both during and after development. Initial clearing and grading operations during construction expose much of the surface soils. Unless adequate erosion controls are implemented on site, enormous quantities of sediment can be delivered to the stream channel, along with attached soil nutrients and organic matter (Pitt 1985).

The second phase begins once the site has been stabilised (Schueler 1987; Reeder 1996). Pollutants accumulate rapidly on impervious surfaces and are easily washed off. The various surfaces of the urbanised area are said to be important sources of many pollutants. Trace metals, for example, are said to be a common component of many urban surfaces, such as roofing material, galvanised pipes, paints, wood preservatives, brake linings, and tires. Over time, these surfaces corrode, flake, decay, dissolve or leach out, enabling metals to wash away in urban runoff (Schueler 1987). Schueler (1987) also mentions that the above could be exacerbated by the acidity of urban rainfall.

(a) **The 'first flush' principle**

Various authors (Corbit 1989; Stanley 1996; Braune & Wood 1999) have acknowledged that pollution concentrations of storm flow are significantly higher than those of dry-weather flow. This occurrence is commonly known as the 'first flush' principle. According to Stanley (1997) the recognition of the "first flush" principle is important since it helps define the volume of runoff that must be captured and treated to remove a given percentage of pollutants from a storm event. Stahre and Urbanas (1990) suggest that if 20% of the storm runoff contains 80% or more of the pollutant load then a strong "first flush" is present.

2.1.4 Impacts of urban pollutants on receiving waters

The net effect of urbanisation is therefore to increase pollutant export to adjacent streams and to receiving waters such as lakes, rivers and estuaries (Scheuler 1987; Corbitt 1989; Stanley 1997; Mckissock, Jefferies & D'Arcy 1999). As mentioned previously, the aim of stormwater managers is to remove stormwater from the urban areas to the periphery as soon as possible. Therefore the aim of the following section is to highlight areas from which various pollutants originate and to show

how they impact on receiving waters. Planners and managers should be made aware of these and then choose the most appropriate BMPs for each site and situation.

(a) **Sediment**

Sediment from nonpoint sources is the most widespread pollutant of surface water (Hudson 1993). The consequences of high concentrations of suspended sediment in streams include increased turbidity, reduced light penetration, reduced prey capture for sight feeding predators, clogging of gills/filters of fish and aquatic invertebrates, reduced spawning and juvenile fish survival (Dallas, Day & Reynolds 1994). Changes in heat radiation due to turbidity has harmful effects on benthic fish and plants, and compromises most of water's major beneficial uses (Hudson 1993).

Additional impacts resulting from sediment accumulation include the smothering of the benthic community (Dallas, Day & Reynolds 1994), the filling in of small impoundments which create the need for costly dredging, and the reduction in aesthetic values.

The greatest sediment loads are exported during the construction phase of any development site. On stabilised development sites, the greatest sediment loads are exported from larger, intensively developed watersheds (Reeder 1996) that are not served by BMPs that effectively control streambank erosion (Scheuler 1987).

(b) **Nutrients**

Phosphorous and nitrogen, two of the most important plant nutrients, are typically reported in stormwater and base flow (Schueler 1987; Moore 1989; EPA 1996). Phosphorous is typically bound to sediments while nitrogen is dissolved in solution. An accumulation of these pollutants may lead to algal blooms in downstream receiving waters (also known as eutrophication). Kelbe and Germishuyse (1999) who examined the relationships between hydrological processes and water quality characteristics found that short duration, high intensity, storms resulted in a substantial rises in nitrate levels and a conservative increase in phosphorous. A reason for this observed difference may be a result of the land use of the study area. Shahane (1982) who developed a rank for average water quality loading during storms across southern Florida found that the most important source of nitrogen originated from agricultural lands while phosphorous originated from multifamily residential areas. This finding could be of some significance in Pietermaritzburg where the land use is comprised of both agricultural land and several residential areas. Thus the adequate detainment and treatment of runoff from these areas is essential.

(c) **Bacteria**

Bacteria levels in undiluted urban runoff almost always occur at levels well above drinking water standards (Schueler 1987; Moore 1989; Coleman & Simpson 1996). Because bacteria multiply faster during warm weather, it is not uncommon to find twenty-fold differences in bacteria levels between summer and winter (Schueler 1987). Sources of bacteria are largely dependent on the catchment and are generally human or animal faeces either deposited directly on the catchment surface or from sewage spills or leaks.

The majority of urban and suburban land uses export enough bacteria to violate various countries health standards, older and more intensively developed urban area produce the greatest export (Schueler 1987). The problem is especially significant in urban areas that experience combined sewer overflows that export bacteria derived from human waste (Moore 1989). The Msunduzi River, Pietermaritzburg, experiences such events annually during the rainy season where runoff generated from informal housing developments is channelled via sewer overflows to the river channel.

(d) **Oil and grease**

These compounds are universally found in stormwater (Moore 1989). Oil and grease contain a wide array of hydrocarbon compounds, some of which are toxic to aquatic life in low concentrations (Strenstrom, Silverman & Bursztynsky 1984). Many investigations have found a strong correlation between land use and the quantity of oil and grease generated during storms (Strenstrom, Silverman & Bursztynsky 1984). As might be expected hydrocarbon levels are highest in the runoff from parking lots, roads, and service stations. Hoffman *et al.* (1982) found that 64% of all settleable solids present in the 'first flush' consisted of hydrocarbons.

The correlation between land use and hydrocarbon production could provide an interesting scope of study for runoff managers. A simulation management technique developed by Strenstrom, Silverman and Bursztynsky (1984), for example, found that a 90% reduction in discharge from commercial properties and parking lots, representing only 9.6% of the total surface area of Richmond (USA), would result in a 53% reduction in total oil and grease runoff.

Such reductions would be of importance in cities were there is a considerable conversion from open land to commercial property.

Hydrocarbons are lighter than water and are initially found in the form of a rainbow coloured film on the water's surface. However, Schueler (1987) states that hydrocarbons have a strong affinity to sediment, once absorbed to these they tend to settle out. If hydrocarbons are not trapped by BMPs they tend to accumulate on the bottom sediments, where they persist for a long time, and exert negative impacts on the benthic community.

(e) **Thermal impacts**

For all organisms there is a temperature range, usually narrow, at which optimal growth, reproduction, and fitness occur and a wider temperature range in which they can survive (Dallas, Day & Reynolds 1994). Increases in water temperature reduce oxygen solubility, increase the toxicity of certain chemicals and lead to an increase in the metabolic rate of aquatic organisms (Dallas, Day & Reynolds 1994). Furthermore the findings of Vanwinkle *et al.* (1998) and Inoue and Nakanos (2001) concur with those of Dallas, Day and Reynolds (1994). Elevated water temperatures can have dire consequences for stream biota that are adapted to a coldwater environment. A rise in water temperature of a few degrees Celsius over ambient conditions can reduce or eliminate sensitive stream insects and fish species (Schueler 1987).

Anthropocentric changes in temperature in river systems may result from, for instance, thermal pollution by heated industrial or power station discharges, inter-basin transfers, alternations in the amount and type of riparian vegetation, and increases in artificial surfaces (asphalt, concrete). The following is a typical example how the various factors may interact with each other. Firstly, urban landscapes heat up on warm summer days, this imparts heat to runoff passing over it which then flows into receiving waters. Secondly, there are fewer trees on the streambanks to shade the stream channel, hence the stream is subject to greater exposure by sunlight. Finally, runoff stored in shallow ponds and other impoundments is heated between storms, and the water is released in a rapid pulse following a storm.

2.2 TOOLS FOR WATERSHED MANAGEMENT

2.2.1 Estimating annual pollutant loading

Loading estimates may focus on nutrient exports such as nitrogen or phosphorous from urban development sites. Loading estimates may also be useful for predicting changes in the export of various pollutants (sediments, oxygen-demanding substances or metals). They can also be used to analyse the effects of various BMPs. For example, as Reeder (1996) has suggested, a question may be asked how much would the sediment load decline if a buffer strip was installed to control erosion?

Pollutant export estimates for a variety of pollutants under different scenarios can be estimated using a tool called the Simple Method (Schueler 1987). Reeder (1996) states that the method is easy to use since it requires information that can be made readily available, and can be calculated without the use of computer models. However, she states that it is best limited to sites about two square kilometres in size.

The main aim of the Simple Method is to provide a quick, easy and versatile means for estimating pollutant loads (Schueler 1987). This method was successfully used by stormwater managers in Portland, Oregon to estimate pollutant loading from one of the catchments in the area (Hottenroth, Harper & Turner 1999). However, both Schueler (1987) and Hottenroth, Harper and Turner (1999) state that the method sacrifices some precision for the sake of simplicity and generality and cannot reflect detailed and unique characteristics of specific catchments. Despite its drawbacks, both authors consider the Simple Method precise enough to make reasonable and reliable non-point pollution management decisions at the site planning level especially when local data is available. Coleman and Simpson (1996) on the other hand state that results of this type of analysis have been conflicting and hence, one should be cautious when making pollution management decisions based on these data sets.

Storm pollutant export (L, in kg) from a development site can be determined by solving the following equation:

$$L = 0.23 * P * Pj * Rv * C * A$$ (Equation 1)

Where P = rainfall depth (cm) over the desired time interval

Pj = factor that corrects P for storms that produce no runoff

Rv = runoff coefficient, which expresses the fraction of rainfall Which is converted into runoff.

C = pollutant event mean concentration (EMC)

A = area of the development site (hectares)

0.23 = conversion factor

Where site-specific values for annual precipitation (P) are not available, they can be estimated from information on a national survey of storm event properties (Reeder 1996). The Correction Factor (Pj) is used to account for smaller storms that produce no runoff. The value Pj may be estimated at 0.9 where more precise data are unavailable. Schueler's (1987) rationale behind this value comes from the fact that in the Washington area of the United States only 90% of rainfall events produce any runoff. Therefore, Pj should be set at 0.9 for annual and seasonal calculations while for individual storms it should be set to 1.0 to avoid double counting.

The Runoff Coefficient (Rv) represents the fraction of precipitation that appears as runoff. The RV for a site depends on the nature of the soils, topography, and cover. However, the primary influence of the Rv is the degree of watershed imperviousness (Figure 2.3). The following equation represents the best-fit line through the data set of 47 small urban catchments monitored throughout the United States (Schueler 1987).

$$Rv = 0.05 + 0.009 (I)$$ (Equation 2)

Where I is the impervious area for the site expressed as a percent of the whole.

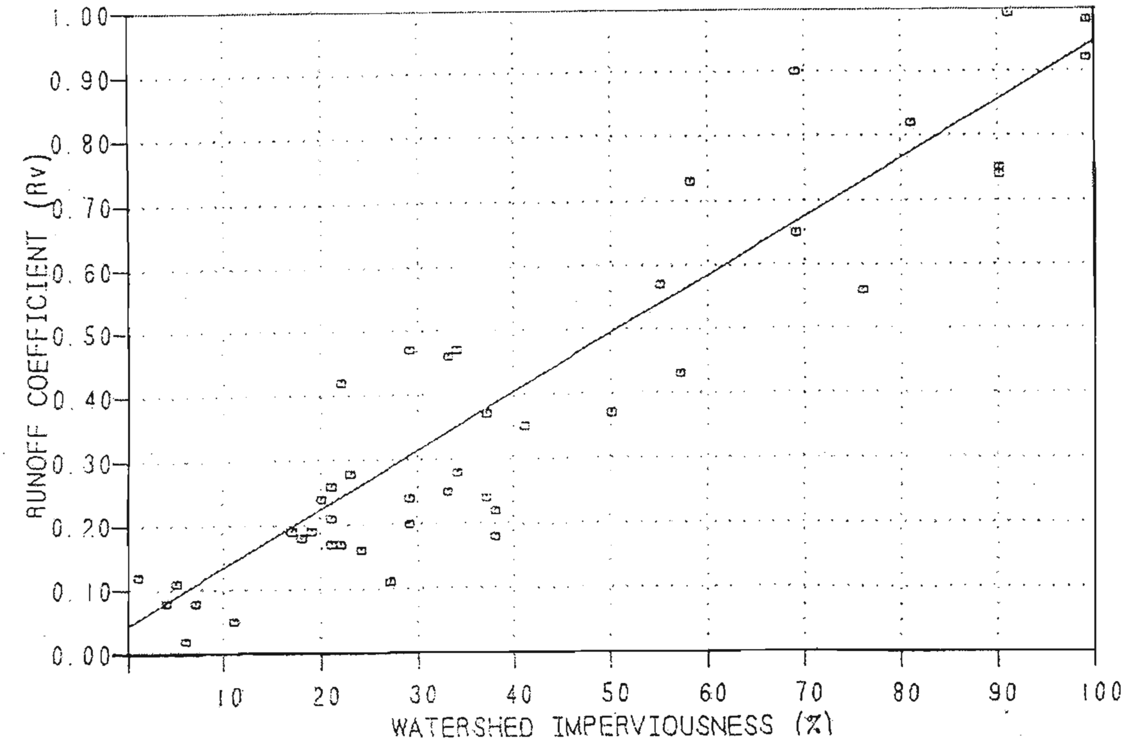

Figure 2.3: Relationship between watershed imperviousness (I) and the storm runoff coefficient (Rv) (Schueler 1987).

Values for I are readily obtained from site plans or accompanying hydrological computations (Reeder 1996). This is done by summing the area of the site covered by structures, sidewalks, driveways, parking lots, roads, patios and other impermeable areas and dividing it by the total site area.

The pollutant EMC (C) may be determined either from flow-weighted composite samples representative of annual average values in runoff from a given area and land use or they may be determined for each particular event. By dividing the total load for a particular event by the runoff volume for that event (Coleman & Simpson 1996).

A second approach that has been successfully employed and more widely used in urban drainage models is the deterministic approach (Coleman & Simpson 1996). In this approach the processes such as transport, erosion, and deposition occurring in the pollutant pathways through an urban catchment are modelled. Coleman and Simpson (1996) mention that if modelled correctly, this approach can account for the effects on the quality of the runoff due to change in the catchment characteristics, storm input, and management. To this degree a water quality model, WITQUAL, was developed for application to South African catchments and conditions. This model allows for the simulation of both nutrients and suspended solids as well as selected heavy metals. It also allows for the easy representation of catchment surfaces, drainage systems and stormwater management structures. The drainage system component of the model may be altered to allow for the inclusion of stormwater management structures at any point in the drainage system. This model enables the user to model dry weather flow found in most urban catchments (Coleman & Simpson 1996).

In testing the above model Coleman and Simpson (1996) found that it performed reasonably well considering certain simplifications they made in representing catchment dynamics and pollutant processes. An added benefit of the model is that it allows for "what if" scenarios for urban storm water drainage potions to be examined.

2.2.2 Design storms

Most rainfall-runoff methods require selection of a design storm having a specified recurrence interval. This method assumes that the probability or recurrence interval of the resulting surface runoff discharge or volume is equal to the probability or recurrence interval of the design storm (Walesh 1989). Estimates of high intensity rainfall are not only important for flood estimation, but are also important in the estimation of soil loss and vegetation damage resulting from high intensity storms (Smithers and Schulze 2001). In South Africa, RLMA (regional L-moment algorithm) has been applied to estimate short duration (≤ 24 h) design rainfall depths (Smithers & Schulze 2001). The benefit of this method is that it allows short duration design storms, through a process of regionalisation, to be estimated at ungauged sites in South Africa. According to Smithers and Schulze (2001) RLMA has many reported advantages, including robustness (model performs well even when not all of the assumptions are satisfied) and ease of use. The advantage of using a regionalised approach to design storm estimation is that at-site information is supplemented with information from the entire homogeneous region. As one can see from Figure 2.4, there seems to be an adequate agreement between quantiles estimated from the at-site data and from regional analysis for all durations and return periods. Hence this finding led Smithers and Schulze (2000) to assume that *prima facie* RLMA is capable of estimating design storms reliably.

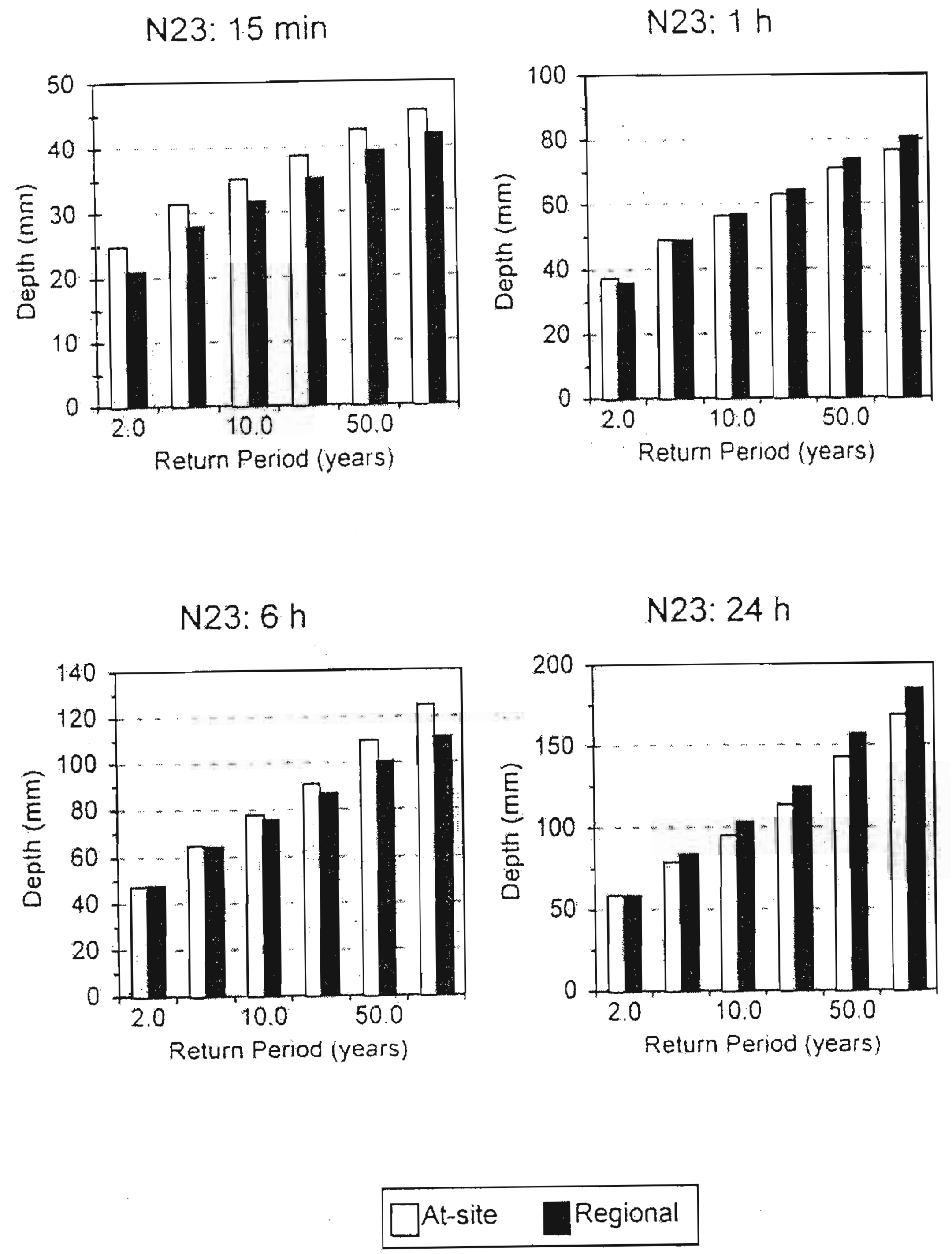

Figure 2.4: Comparison of design storms estimated using at-site data and regional analysis, Ntabamhlope Research Catchments (N23), KwaZulu-Natal (Smithers &Schulze 2000).

A second earlier method commonly used for estimation of flood volume and peak discharges for small catchments (< $30km^2$) is the SCS-SA method (Schmidt & Schulze 1987). Although mentioned earlier, Schmidt and Schulze (1987) state that this model's widespread use is due to the following reasons:

(i) The mathematical equations describing the model are simple to use.

(ii) The main inputs required for the model are obtained readily.

(iii) The technique is user orientated.

(iv) The technique provides realistic estimates of peak discharge and runoff volume when compared with observed data.

Stormflow depth (mm) can thus be determined by solving the following equation:

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \quad \textit{for } P > Ia \qquad \text{(Equation 3)}$$

Where:

Q = stormflow depth (mm)

P = design storm rainfall (mm)

S = potential maximum soil water retention under expected soil and land use conditions (mm)

Ia = initial abstractions (mm)

= cS or 0.1S

Where

C = a coefficient, accounting for initial losses prior to runoff occurring and which comprises depression storage, interception and initial infiltration.

According to Schmidt and Schulze (1987), the runoff equation only applies once rainfall has satisfied initial losses, i.e. when P > cS. Prior to this no runoff is assumed to occur hence Q is equal to zero. The coefficient is assumed to equal 0.1. Thus the equation becomes:

$$Q = \frac{(P - 0.1S)^2}{P + 0.9S} \qquad \text{(Equation 4)}$$

The potential maximum retention, S is related to soil properties, land-use conditions and the moisture content of the catchment, and is expressed as follows:

$$S = \frac{25\,400}{CN} - 254 \qquad \text{(Equation 5)}$$

Equation 2 allows for the transformation of S in mm to the dimensionless CN which ranges between 0 and 100.

Another important aspect to consider when dealing with urban runoff is peak discharge. In the SCS-SA method the determination of peak discharge is based on the triangular unit hydrograph. This unit hydrograph represents the temporal distribution of stormflow for an incremental unit depth of stormflow, ΔQ, occurring in a unit duration of time, ΔD (Schulze, Schmidt & Smithers 1992).

Peak discharge is thus defined by the equation:

$$\Delta q_p = \frac{0.2083\ A\ \Delta Q}{\Delta D/2 + L} \qquad \text{(Equation 6)}$$

Where

Δq_p = peak discharge of incremental unit hydrograph (m^3/s)

A = catchment area (km^2)

ΔQ = incremental stormflow depth (mm)

ΔD = unit duration of time (h), used with the distribution of daily rainfall to account for intensity variations

L = catchment lag (h), an index of the catchment's response time to the peak discharge

(a) **Runoff generation from urbanised areas**

In practice, runoff from an impervious area can be partitioned into that part which flows directly to streamflow or a stormwater system, and that part which flows initially onto a pervious area. Impervious areas are thus considered to be either:

1) *adjunct impervious areas*, these are directly adjacent to water courses or stormwater drains and channels, in such cases runoff from the impervious area contributes directly to streamflow, or
2) *disjunct impervious areas*, these are disconnected from the water courses and runoff from the impervious areas flows onto a pervious areas and thus contributed instead to the soil water budget (Schulze & Tarboton 1994).

The processes described above are conceptualised in Figure 2.5.

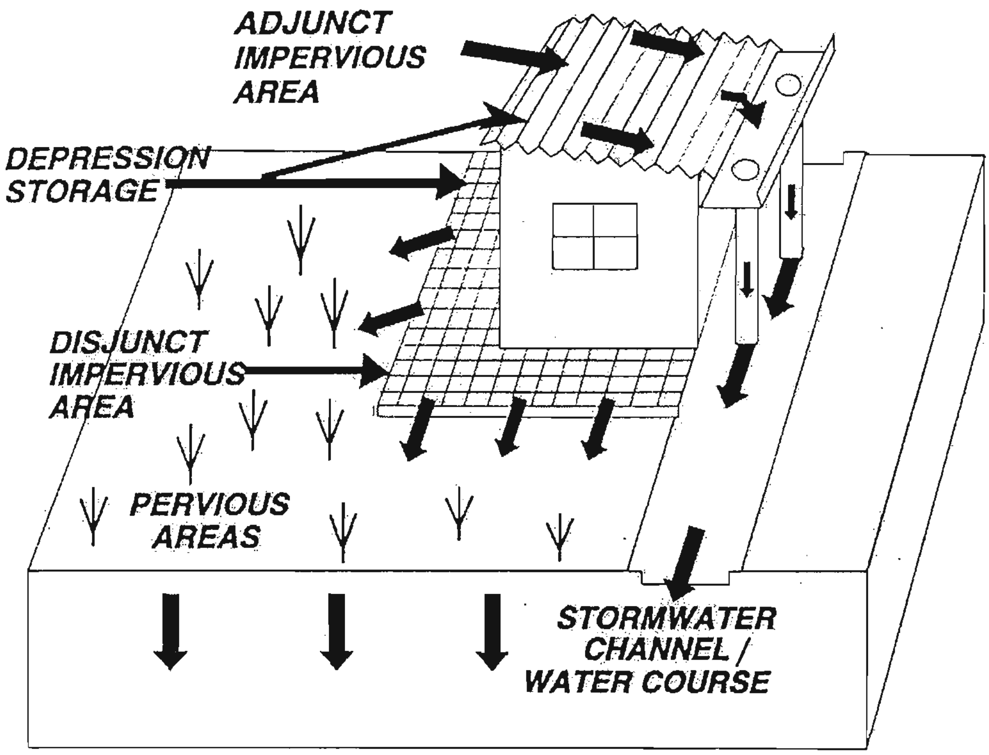

Figure 2.5: Conceptualisation of urban runoff generation (Schulze 1995).

This chapter has thus highlighted the various impacts of urbanisation on urban watersheds and has introduced key concepts in hydrology namely: travel, time, peak discharge, runoff volume and the first flush principal. It has thus concluded by discussing certain tools that can be used for watershed management. However, due to its ease of application the SCS-SA runoff programme shall be used in chapter five for the setting of priorities for land users. Although this does not mean that the programme will encompass all components mentioned up to this point. The following chapter will thus introduce best management practice (BMP) technology and discuss the three methods of pollutant removal and hydrological characteristics of the different BMPs. It is hoped that these methods could be a way of mitigating the impacts of urbanisation.

CHAPTER 3: CHOOSING THE RIGHT BMPS

3.1 BACKGROUND INFORMATION

Conventionally, stormwater drainage has been designed to provide the fastest possible transport of stormwater runoff out of the catchment into receiving waters (Seiker 1998; Ristenpart 1999). According to the combined and separated sewer principles, the sewer systems are designed to discharge all the rainwater up to an agreed limit without causing damage (Sieker 1998). Although this led to a high drainage efficiency (Seiker 1998), drastic results have been realised. These include, significant ecological damage, not only in urban areas but also in receiving waters, reduction of groundwater recharge, the increase in floods, and an increase in the severity of downstream erosion (Schuler 1987; Seiker and Klein 1998; Jefferies *et al.* 1999; Risternpart 1999; Schueler 2000). However, new concepts are combining infiltration, distributed storage and treatment as well as delayed runoff. In the sense of sustainable development, ecological criteria are also being taken into account in these modern drainage systems which are potentially much closer to nature than the traditional approaches have been.

Best management practices (BMPs), as they are known are becoming ever increasingly popular (Schuler 1987; Seiker & Klein 1998; Jefferies *et al.* 1999; Risternpart 1999; Schueler 2000). Stormwater BMPs are now widely used in drainage planning around the world. They have been used extensively in the UK (Clifforde, Morris & Crabtree 1995; Jefferies *et al.* 1999) and Germany (Sieker & Klein 1998; Sieker 1998; Risternpart 1999), in Canada (Wisner 1997), as well as in the US (Schueler 1987; Schueler 2000), and according to Risternpart (1999) in Australia as well.

Unfortunately, at the time of installation of the first systems when knowledge of the detailed information needed for appropriate functioning was limited, a number of systems were constructed which were clearly not successful or suited to the environment in which they were placed (Jefferies *et al.* 1999). The poor performance of the BMPs might have arisen from a number of factors including; the lack of sufficient land or space; bad design and construction; inadequate maintenance or incorrect choice of BMP for a particular function. This begs the question of how does one go about selecting the appropriate BMP for a specific function or site.

Therefore the aim of this section is to: introduce the various categories of BMPs; discuss the three methods of pollutant removal and hydrological characteristics of various types of BMPs; outline the main objectives of any BMP plan; and the issues that need to be examined when choosing a specific BMP. This section will conclude by highlighting the reasons for failure of many BMP plans and the various savings and tradeoffs of many BMPs especially when they function in conjunction with existing stormwater management systems.

3.2 CATEGORIES OF BMPS

There are essentially two broad categories of BMPs, namely non-structural and structural. Non-structural controls are techniques used to manage stormwater runoff that do not require physical alteration of the land. These include: pollution prevention and watershed management plans; preventive construction techniques; and outreach and educational programmes (EPA 1996). On the other hand, structural controls are methods for managing stormwater that involve altering the flow velocity, duration, and other characteristics of runoff by physical means (EPA 1996).

It must be stated that the aim of this dissertation is to address and mitigate the hydrological impacts of urbanisation using purely structural techniques. Therefore only structural BMPs will be described. Although, the author acknowledges the fact that non-structural techniques do have a place in the field of pollution control, especially in a preventive role by limiting the impacts of future development initiatives and in raising public awareness (Canadian example at section 3.5.1).

3.2.1 Structural controls

Structural BMPs can broadly be separated into three categories depending on method of pollutant removal or hydrological mitigation method. The three categories are: (i) infiltration (infiltration trenches/basins, porous pavement, porous pavement (reservoir design)), (ii) filtration (filter strips, grass swales, sand filters) and (iii) detention (extended detention basin wet/dry, wet ponds, constructed wetland; on-site-detention). For further more detailed information on the advantages and limitations of each specific BMP as well as a reading list, refer to Appendix 1.

(a) **Infiltration**

Three BMPs fall under this category namely: infiltration trenches/basins, porous pavement and porous pavement (reservoir design). The basic requirement is that infiltration has to take place obligatory through the active soil layer. In this way stormwater quality is enhanced by partial removal of solids (with absorbed chemicals) and dissolved chemicals (Sieker 1998). It must be stated that infiltration methods are not intended to trap coarse-grained sediments (aim of filtration methods) this must be achieved usually before the stormwater runoff reaches the infiltration BMPs. This may be achieved by pre-treating the water by way of a grass swale or filter strip. These systems require deep permeable soils at separation distances of at least one metre between the bottom of the structure and seasonal ground water levels (Barraud *et al.*

1999; Veldcamp *et al.* 1997; EPA 1999). Infiltration methods also provide some level of stormwater attenuation, the degree of which varies according to the particular BMP (Scheuler 1987, 2000; EPA 1996).

In Germany, filtration and infiltration methods have been used effectively in series. The so called "Mulden-Rigolen-System" (MR-System), which can be translated as the "Swale-Trench-System", uses the short-term storage and coarse sediment removal abilities of the Swale and the long-term storage, soluble and particulate removal abilities of the trench to achieve the highest possible infiltration and management of stormwater runoff (Sieker 1998) (Figures 3.1 and 3.2). Other benefits offered by infiltration BMPs include groundwater recharge, low flow augmentation, and streambank erosion control (Lindsey, Roberts & Page 1992a; EPA 1999). However, infiltration methods may be disqualified from selection if the groundwater supply requires protection (Azzout el al. 1995; Barraud *et al.* 1999). According to the EPA (1999), restrictions may also be applied to infiltration systems located above the sole drinking source aquifers. They further state that if infiltration methods are selected as the best available option, they should be incorporated with the recognition that periodic maintenance is necessary for these areas. To ensure the long-term viability of infiltration methods proper maintenance and operation of the entire system is essential.

Another application of infiltration devices is the supply of water for non-potable uses (Pratt 1999). To this end, Pratt (1999) decided to underseal the porous pavement BMP thus forming a reservoir. The water collected via such a system was then used in flushing toilets at a youth hostel in the United Kingdom. This adaptation could be particularly useful in areas where water is a limiting resource.

Lindsey, Roberts and Page (1992a) frequently observed clogging of infiltration facilities due to high levels of sediment in the stormwater. Hence infiltration systems, some filtration devices and sand filters should only be installed after construction has been completed and the site permanently stabilised. Lindsey, Roberts and Page (1992b), also mention that designers must give greater consideration to natural processes that govern erosion and sedimentation when implementing BMPs especially infiltration devices.

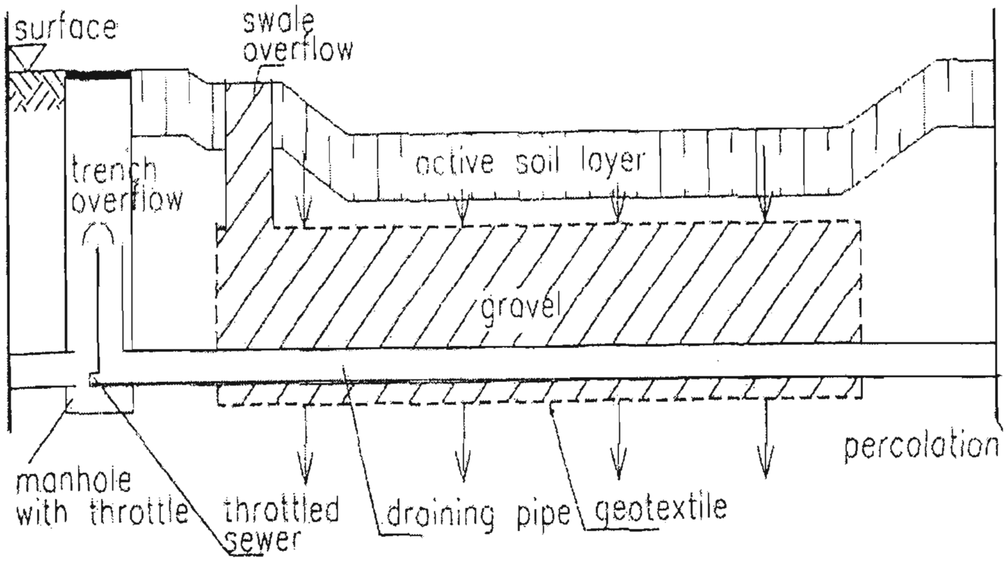

Figure 3.1: Longitudinal section of a standard element of the MR-system.

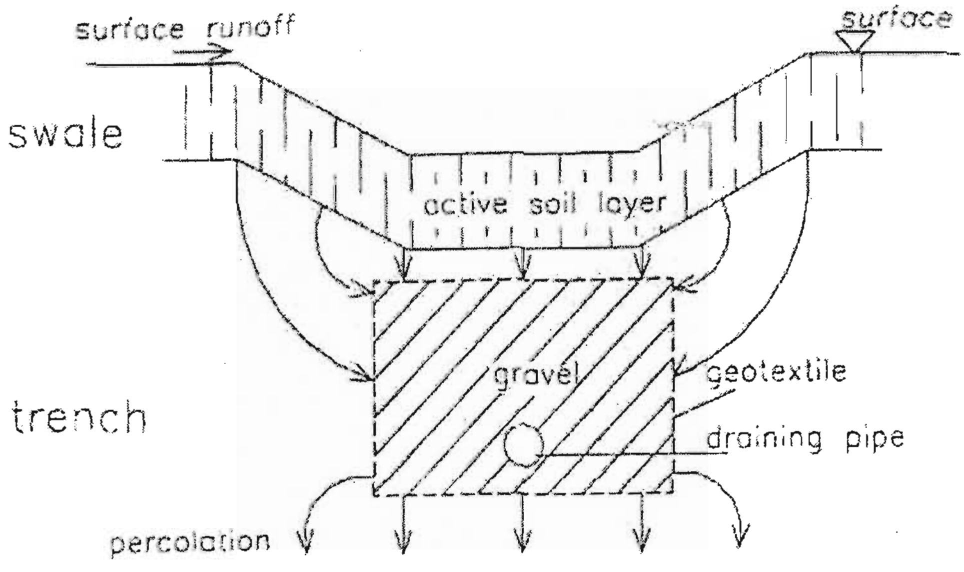

Figure 3.2: Cross section of a standard element of the MR-system.

(b) **Filtration**

BMPs that fall under this category include: vegetated filter strips/buffers, grassed swales, and sand filters. Vegetated methods such as filter strips/buffers and grass swales, use the ability of vegetation to reduce the flow velocities associated with concentrated runoff. By decreasing the flow velocities (depending on length and slope of vegetated or grassed area), they allow for removal of particulate contaminants through sedimentation, enhanced infiltration into the soil, and the reduction in the potential for downstream channel erosion, by attenuating the post-development peak discharge rate (Yu *et al.* 2001). However, vegetated methods are not generally capable of removing soluble pollutants such as nutrients (Schueler 1987; 2000; EPA 1996). Woodard (1988) contradicts this by stating that natural buffer strips do appear to be effective in reducing nutrients. He reports phosphorous removal rates of up to 99% from such structures. This finding may have been correct given his data but it may not be widely generalisable due to site-specific considerations since, reported ranges for nutrient removal rates for vegetative structures are said to range from 0-99% but on average nutrient removal rates are low, (20-40%) (Table 3.1). According to Yu *et al.* (2001), grass swales are an attractive option for transport departments since they are easily incorporated into the landscape, such as in highway medians. Swales require minimal routine maintenance such as mowing or periodic inspections to assess vegetative health and fill in eroded paths. Swale construction costs have been estimated at $50 per square meter and according to Yu *et al.* (2001), this makes them a cost effective option for stormwater management if performance is acceptable given the management requirements for the site.

A recent variation of vegetative methods especially filter strips has been developed to combat this inefficiency. The technology is referred to as bioretention. This approach is said to be suitable for managing runoff from small drainage areas using a mixture of plant materials and enriched soil composition. According to EPA (1996), bioretention can maximise nutrient uptake, evapo-transpiration, infiltration, microbial degradation of metals and carbon-based pollutants and storage to help reduce peak flows from the drainage area served to predevelopment levels. However, both EPA (1996) and PACD (2000) state that in order for this method to function properly conventional drainage conveyance methods such as pipe inlet systems need to be replaced with practices that promote sheet flow such as level spreaders.

Sand filters are systems of underground pipes beneath a self-contained bed of sand designed to treat urban stormwater. Runoff from a developed site is routed to the filters, infiltrated through the sand, then collected in the underground pipes and returned back to the stream or channel. Sand filters remove sediment, trace metals, nutrients, BOD, and faecal coliform from the initial pulse of stormwater from a development site (Schueler 1994; 1995). They provide significant pollutant removal, are useful for groundwater protection and have a limited ability to reduce peak discharges.

(c) **Detention**

BMPs that fall under this category include: extended detention basins (dry/wet), wet ponds, constructed wetlands, and oil/grit separators. BMPs in this category can be divided into those that primarily control stormwater runoff (quantity) (detention basins) and ones that aim to remove pollutants (constructed wetlands, wet ponds, oil/grit separators).

Dry/wet basins temporarily store stormwater runoff from a site and release it at a controlled rate by use of a fixed outlet. The idea behind these ponds is to replace the natural storage lost by development with artificial storage (Figure 3.3, Nix & Durrans 1996) insofar as doing so they are able to reduce peak-discharges to pre-development levels. A benefit of these methods is that they can reduce downstream erosion by reducing the frequency of bankfull and sub-bankfull flooding events (EPA 1996). Some dry extended basins are designed to incorporate vegetated areas which help to filter and absorb pollutants (Reeder 1996).

In both types of basins, pollutant removal results from the gravity settling of sediments/pollutants, the chemical transformation and biological uptake of nutrients (wet extended detention) while water is detained in the basin, and the infiltration of soluble nutrients through the soil profile (EPA 1996; Reeder 1996). Figure 3.4 demonstrates both the biotic and abiotic processes that occur in wetlands (Hellfield & Diamond 1997). Under favourable conditions these systems can play a ground water recharge function but according to Nix and Durrans (1996) this is usually the exception rather than the rule.

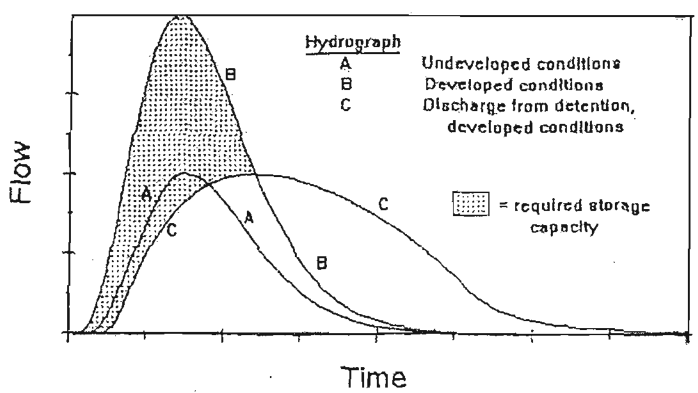

Figure 3.3: Typical hydrographs for natural and developed conditions, with and without detention (Nix & Durrans 1999).

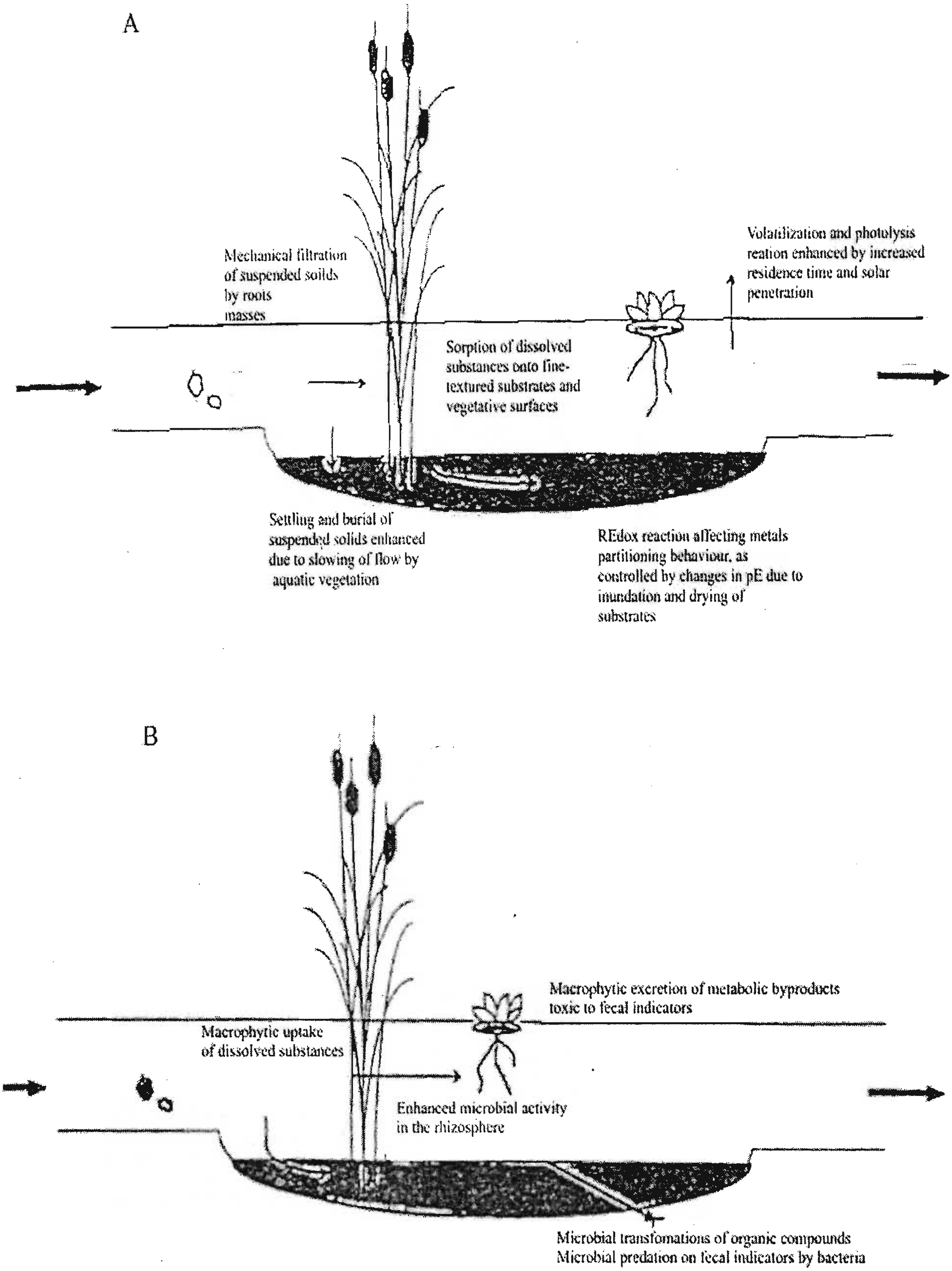

Figure 3.4: Wetland processes affecting water quality: (a) abiotic processes; (b) biotic processes (Hellfield & Diamond 1997).

Constructed wetlands (Plate 3.1) and wet ponds (Plate 3.2) are becoming widely used for the treatment of stormwater (Maristany & Bartel 1989; Wong *et al.* 1999) and combined sewer overflows (CSO) (Persson, Somes & Wong 1999). Persson, Somes and Wong (1999) state that all too often have both systems been broadly grouped together. However, ponds and wetlands differ significantly in their hydrologic and hydraulic characteristics and promote different water quality treatment processes. Ponds are generally small artificial bodies of open water with a small range of water level fluctuation. Perrson *et al.* (1999) state that emergent macrophytes are normally restricted to the margins because of water depth, although submerged plants may occur in the open water.

Constructed wetlands are shallow pools created on non-wetland sites as part of a stormwater collection and treatment system (EPA 1996). Essentially a wet pond with greater emphasis placed on vegetation and depth/area considerations (Schueler 1987, 2000; EPA 1996). Constructed wetlands regularly fill and drain and are typically extensively vegetated. It should also be noted that constructed wetlands are usually found in series with other types of BMPs especially ones aimed at sediment removal. These wetlands are designed to maximise removal of pollutants from stormwater through physical, chemical, and biological means and can be designed to temporarily store stormwater. Table 3.1 summarises the functions of vegetation during storm-event flow and baseflow conditions in wetlands.

Table 3.1: The functions of vegetation for stormwater control in constructed wetlands and wet ponds (Wong *et al.* 1999)

During baseflow	**During storm-event flow**
Provides surface area for epiphytes • epiphytes take up materials from the water and introduce them to sediments, as cells dislodge from plant surfaces and settle; this is a short-term process occurring over hours to weeks	Increased hydraulic roughness
Takes up nutrients from the sediments • nutrients in the sediment are transformed into plant biomass; this is a medium-term process occurring over weeks to years	Promotes uniform flow
Transforms absorbed materials into less available forms • plant biomass is returned to the sediment for storage as low-level biodegradable macrophyte litter; this is a long-term process occurring over years to decades	Enhances sedimentation of particles Provides surface area for small-particle adhesion
Control of surface sediment redox • plant root-zones generally help maintain an oxidised sediment surface layer preventing chemical transformation of settled pollutants	Protects sediments from erosion

Plate 3.1: Picture of a constructed wetland. Used primarily to treat stormwater and wastewater, constructed wetlands can also perform a utility function by providing habitat for various species and a place for humans to visit (Gelt 2000).

Plate 3.2: Picture of a wet pond situated near up market housing development, Austin, Texas (Watershed Protection Development Review 2001).

Oil/grit separators are mainly aimed at removing trash, debris, sediments and hydrocarbons from stormwater runoff associated with roads and parking lots before it is discharged into a conventional stormwater system or an infiltration BMP. These usually take the form of an underground concrete vault with several chambers. Oil/grit separators provide minimal groundwater recharge, low flow augmentation, peak runoff attenuation, or stream bank erosion control benefits. However, it must be stated that due to their inherent specificity for removing oil/grit from heavily trafficked areas such as gas stations, public works, transportation maintenance facilities, or other areas where hydrocarbon pollutant loads are expected to be significant they have not been considered in the remainder of the text.

3.3 OBJECTIVES IN BMP PLANNING

In order for a planner or engineer to select an appropriate BMP they would need to understand that that each BMP has both unique capabilities and persistent limitations. They would also need to balance these with both the physical constraints proposed by the development site and the overall objectives of the watershed in which they might be working.

During the review process it is critical that the overall objectives for managing runoff from a site are laid out. According to Schueler (1987; 2000); Argue (1995) and Jefferies *et al.* (1999) a BMP plan for a site should accomplish the following goals:

(i) To reproduce, as nearly as possible, the hydrological conditions in the stream to pre-development status or in other words to a natural regime.
(ii) To provide some degree of pollutant removal.
(iii) Be appropriate for site, given physical constraints.
(iv) Be reasonably cost-effective in comparison to other BMPs or solutions.
(v) Have an acceptable future maintenance requirement.
(vi) Have at least a neutral impact on the natural and human environment.

3.3.1 Reproduce natural flow regime

A prime function of BMP systems is the management of stormwater discharge in so far as reducing the frequency and severity of downstream floods. For design purposes most BMPs are designed to at least control the 2-year/24 hour storm event (Roesner, Bledsoe & Brashear 2001). This goal is usually achieved by controlling peak discharge computed for a specific design storm to pre-development levels (Argue 1995; Jefferies *et al.* 1999), commonly known as peak shaving. The basic effect of peak shaving on the outflow hydrograph is illustrated in Figure 3.5.

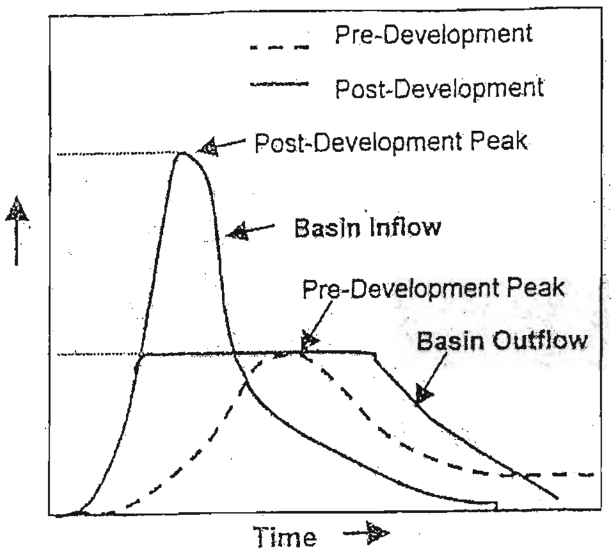

Figure 3.5: Effect of peak shaving on Detention Basin outflow hydrograph (Roesner, Bledsoe & Brashear 2001)

As mentioned previously floods are but one of the hydrological changes brought about by urbanisation. Other changes include impacts on aquatic biota as well as leading to an increase in severity of streambank erosion all of which can to some extent be mitigated by the appropriate choice of BMP. Some BMPs are able to achieve mitigation through either groundwater recharge or the control of small to medium storm events.

(a) **Design storm for BMPs**

For most BMPs, especially swales, infiltration basins, extended detention basins, constructed wetlands and wet ponds, the recommended design storm for sizing is the storm volume that is just greater than the 70-90% of the rainstorms (Roesner, Bledsoe & Brashear 2001).

3.3.2 Pollutant removal

Over the years, BMPs have been adapted to contain and manage pollution loads generated within a watershed to minimise conveyance downstream. According to Schueler (1987; 2000) BMPs differ markedly in their pollutant removal capabilities, and therefore planners and engineers must take cognisance of this fact. Table 3.2 taken from EPA (1999), lists detailed information on the removal efficiencies of various BMPs and the factors influencing their removal efficiencies.

Table 3.2: Effectiveness of management practices for control of runoff from newly developed areas (EPA 1999) TSS = total suspended solids; TP = total phosphorous; TN = total nitrogen; COD = chemical oxygen demand; PB = lead; ZN = zinc

	Average Removal Efficiencies (%)						
Management Practice	**TSS**	**TP**	**TN**	**COD**	**PB**	**ZN**	**Factors**
Infiltration Basin	75	65	60	65	65	65	• Soil percolation rates • Basin surface area • Storage volume
Infiltration Trench	75	60	55	65	65	65	• Same as above
Filter Strip	65	40	40	40	45	60	• Runoff volume • Slope • Soil infiltration rates • Vegetative cover • Buffer length
Grass Swale	60	20	10	25	70	60	• Same as above (except buffer length) • Swale Length • Swale Geometry
Porous Pavement	90	65	85	80	100	100	• Percolation rates • Storage volume
Sand Filter	80	50	35	55	60	65	• Treatment volume • Filtration media
Oil grit separator	15	5	5	5	15	5	• Sedimentation storage volume • Outlet configurations
Dry Extended Detention Basin	45	25	30	20	50	20	• Storage volume • Detention time • Basin shape
Wet ED Basin	80	65	55	NA	40	20	• Same as above
Wet Pond	60	45	35	40	75	60	• Pond volume • Pond shape
Constructed Wetland	65	25	20	50	65	35	• Storage volume • Detention time • Wetland shape • Wetland's biota • Seasonal variations

3.3.3 Site feasibility

According to Jefferies *et al.* (1999) one of the major contributing factors to BMP failure is the variability in site specifics. Site specifics include: lack of space set aside; steepness of the slope in the vicinity; lack of permeability of soil; soil type; depth of groundwater table and bedrock (Schueler 1987; 2000). In order to prevent these problems causing inefficiencies in a BMP, programme engineers and planners must consider the various site specifics and restrictions associated with each BMP.

3.3.4 Cost-effectiveness and maintenance burden

The construction costs for different BMPs can vary substantially, even on similar sites. When considering costs, the planers or engineers must include both the initial construction costs as well as the future maintenance costs (Mehler & Ostrowski 1999). Mehler and Ostrowski (1999) break costs down into four sections: planning costs (pre-planning and design); construction costs; material costs; and maintenance costs. For more detailed information on BMP costs, refer to Table 4.8.

Schueler (1987; 2000) mentions that in order for BMPs to continue to be effective they need to be regularly inspected and maintained. He also states that maintenance costs for BMPs are significant. Over a twenty-year period, maintenance costs will often equal or exceed the initial construction costs. Although these costs may run into the hundreds of thousands of Dollars they are yet only a fraction of the costs that may result from flooding. Ribaudo (1986) reports flood damages amounting to more than US$ 887 million in the United States of America. Hence, proper functioning and maintained BMP systems capable of detaining flood volumes to a manageable level are thus an essential requirement to any BMP plan.

3.3.5 Neutral impact on environment

The acceptance of BMPs by authorities and the public is strengthened by the amenity value of the specific BMP. According to Schueler (1987; 2000) as well as Mehler and Ostrowski (1999) the importance of enhancing the amenity values of a BMP cannot be overemphasized, as resident and local authorities perceptions of BMPs can play a crucial role in their acceptance and support.

3.4 SCREENING STEPS

In order to aid the planner or engineer in choosing the best or most appropriate BMP option for a site, a series of screening steps have been developed by various authors. What follows is a description of two methods that have been proposed for selecting the appropriate BMP option. The first selection method has been employed by the Barr Engineering Company in Maryland, USA to select BMPs. Theirs is a three-step process and guides the designer through three steps that progressively screen:

(i) Stormwater treatment suitability.
(ii) Physical feasibility factors.
(iii) Community and environmental factors.

Step one of the process is used by designers to answer the question: "Can the BMP meet the stormwater rate, volume, and water quality treatment requirements mandated by local regulations at the site or are a combination of BMPs needed?" At the end of this step, the designer can reduce the BMP options to a manageable number and determine if a single BMP or group of BMPs are needed to meet the management criteria.

Step two of the process allows the designers to answer the question: "Are there any physical constraints at the project site that may restrict or preclude the use of a particular BMP that has been selected from step one?" In this step, the designer screens BMPs to determine if soil type, infiltration rate, water table or drainage area present at the site may preclude or limit the use of a particular BMP.

The third and final step of the process allows the designer to answer the question: "Do the remaining BMPs have any important community or environmental benefits or drawbacks that might influence the selection process?"

The second series of screening steps has been developed by Schuler (1987; 2000) in order to compare the capabilities and limitations of each BMP. The following is an adapted list of the eight steps that should be followed (Figure 3.6):

The planner or engineer must take cognisance of the fact that these steps are merely guidelines to aid in deciding upon the most practical BMPs for a site. The sequence of steps might vary depending on how the planner or engineer weights the priority of each of these steps. Once these steps have been followed one still needs to factor in the cost of implementation and maintenance, this will have a discernible influence on the final choice of BMP for a particular site. What the engineer should also be aware of is the fact that a majority of BMPs may be marginally suited to a particular site but certain technical improvements may increase their applicability and functionality.

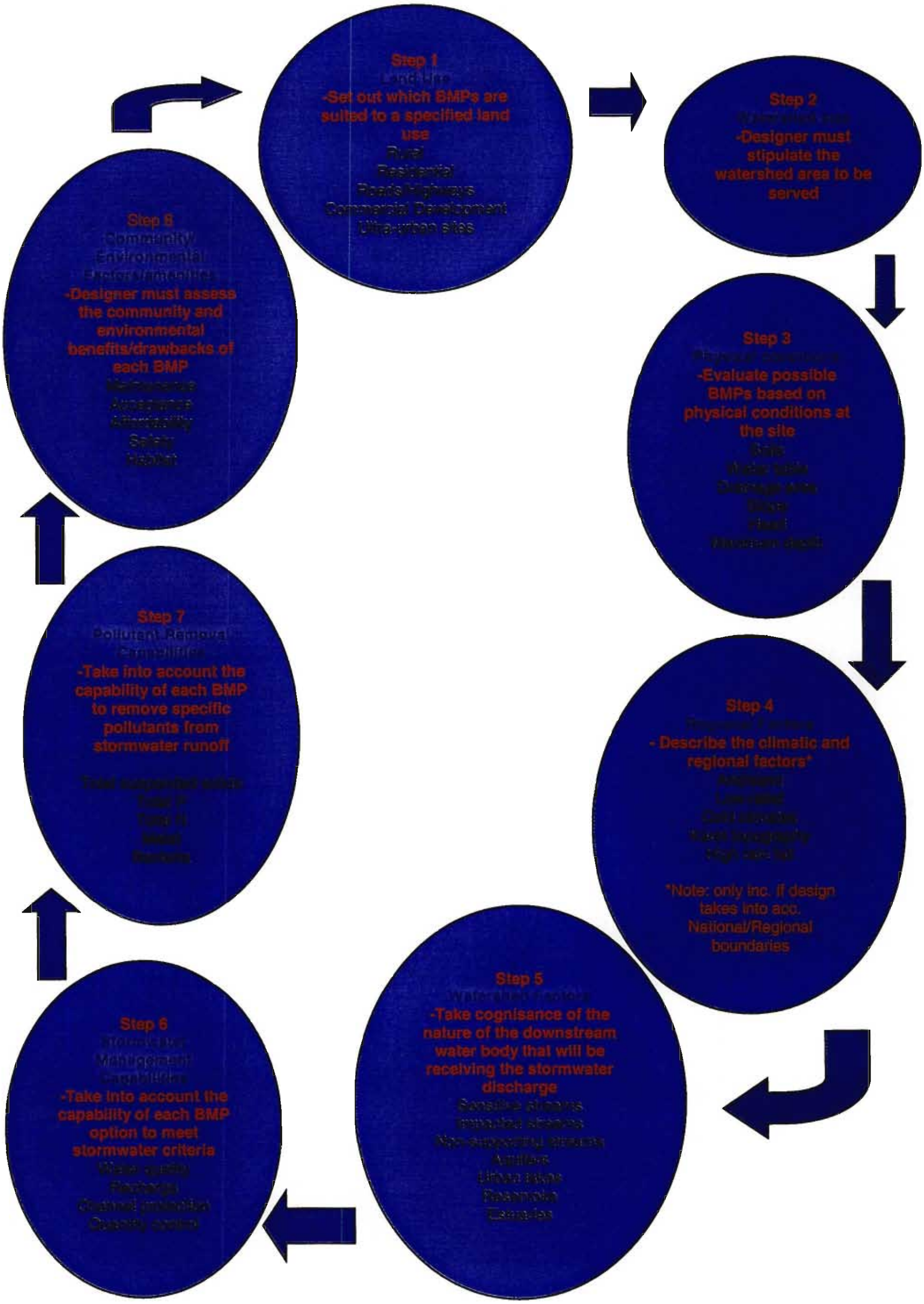

Figure 3.6: An eight-step procedure for determining BMPs for a particular set of circumstances. The sequence of the steps may differ according to their importance (After Schueler 2000).

3.5 OBTAINING ACCEPTANCE FOR BMPS AS DEVELOPMENT PRACTICES

Although many of the BMPs described in section 3.2.1 are being accepted by stormwater managers (water resource planners and engineers) for use in stormwater management programmes in many cities (Berlin-Mahlsdorf, Germany, Ristenpart 1999; Montreal, Canada, Wisner 1997, Adelaide, South Australia, Argue 1995) there are, however, many cases were failure to implement BMPs have occurred (Clifforde, Morris & Crabtree 1995; Wisner 1997; PACD 2000). The reasons given include the following:

(i) Many engineers and landscape architects have not been trained in non-traditional BMP approaches and consequently are reluctant to include them in site designs.

(ii) Many officials have not been convinced of the benefits, either locally or regionally, of alternative drainage and site design practices that incorporate BMPs.

(iii) Some BMPs especially wet ponds when implemented have been associated with negative public perception due to preconceived misperceptions (Wisner 1997).

(iv) Water quality issues have historically been given less emphasis than issues relating to flooding and drainage in the adoption of stormwater controls (Nix and Durrans 1996; Sieker 1998; Warner 2000).

(v) The voluntary nature of BMPs in local policies has minimised the urgency to implement them (PACD 2000)

Most of these objections to BMPs, and the concerns underlying them can be addressed by helping developers and government officials to understand the costs, benefits and tradeoffs associated with their technologies, as well as highlighting the rise in environmental awareness of the general public.

3.5.1 Costs, savings and tradeoffs

Stormwater must be managed from all developments, old and new. By using BMPs rather than traditional stormwater management systems (storm sewers, lined channels), development and stormwater costs can be lowered (Argue 1995; PACD 2000). Other aspects of the life-cycle cost of stormwater management programmes can be lowered by using BMPs effectively (PACD 2000) in other words benefits such as reduced costs of downstream maintenance such as streambank rehabilitation are usually not included in costing analysis of BMPs but are an added benefit of them. In Japan US$200 million was recently spent to restore the waterways of Tokyo for recreation purposes (Gippel & Fukutome 1998). While in the United States, the restoration of Biscayne Bay, a major Florida estuary is estimated to have cost in the region of US$ 24 million (Thorhaug, Man & Ruvin 1990). However, if stormwater issues have not been sufficiently addressed then these projects may be in jeopardy. For instance in the Florida estuary if suspended solids have not been adequately removed then the estuary may suffer from infilling once again. Although streambank erosion may be adequately addressed with large sums of money, these rehabilitation efforts may be blunted by the fact that increased runoff volumes reaching the receiving waters is the main cause of channel erosion. Hence streambank erosion will continue inevitably, a case of treating the symptom not the cause.

Savings of capital costs are increased through BMP use, such as:

(i) Vegetated swales are less costly to install than curb and gutter catch basins, and underground storm sewers (PACD 2000).

(ii) Directing flow to vegetated filter strips or infiltration devices to reduce runoff rates and volumes can reduce the size (and cost) of downstream conveyance and storage devices (storm sewers, culverts, and detention basins). and

(iii) Using upstream detention basins to reduce peak runoff can reduce the size (and cost) of major drainage and storm sewers.

According to PACD (2000) local officials need to fully understand the tradeoffs in selecting BMPs as alternatives to conventional drainage and stormwater management practices. They also state that many of the objections that are raised by local officials and the public are readily offset by specific advantages of particular BMPs. Table 3.3 lists commonly cited concerns and tradeoffs associated with incorporating BMPs into stormwater management systems (PACD 2000). PACD (2000) state that BMP programmes can improve the quality of lakes, streams, wetlands and detention basins further resulting in improved property values and increased recreational opportunities. It must be said in the same breath that if these BMPs are used in an urban context, informing the public about their functions is essential, as can be shown in the following example from Canada (Wisner 1997).

In Montreal, Canada stormwater management lakes were built with houses surrounding the lake. The idea was sold to the public on the supposition that they would increase recreational activities and property values. However, their specific function, stormwater control, was not mentioned and resulted in bad press. The reasons given were that the people had a 'Blue Lake' idea but due to the lakes specific function, it had to receive large quantities of sediment thus resulting in high turbidity values and thus fell short of the public idea. Secondly, due to the high levels of nutrients the lake was receiving from urban runoff, algae and weeds proliferated, resulting in a large percentage of the lake being covered. In this case it was found that at the public were not even aware of the large varieties of aquatic fauna and flora that were present. However, with "green thinking" on the rise public interest in the ecology of these waterscapes changed. Finally after being briefed on the objectives of the lakes and the various environmental functions they provided, the public accepted the lakes. What the above example shows is the need for adequate education to inform the public of the real objectives of the lakes and in doing so removes the potential for misconceptions to be formed. This lesson should be applied to all future projects were both the public and planners should be educated on the plethora of costs, savings, amenities and functions provided by BMPs.

Table 3.3: Concerns and Tradeoffs of BMPs (PACD 2000)

Category	Objections to BMPs	Tradeoffs
Environmental	Grass swales and wetlands may breed mosquitoes.	Natural, unmowed vegetation attracts song birds and other natural predators to mosquitoes. Demonstrate that mosquitoes are not a problem associated with stormwater wetlands.
	Wet detention ponds become eutrophic and choked with algae.	Properly designed wet ponds, particularly those protected by upstream pollutant trapping BMPs and incorporating wetland shelves, have reduced risk of eutrophication.
		BMPs protect downstream water quality.
		Vegetative BMPs protect open space, allow for attenuation of air pollutants and noise, and provide wildlife habitats.
Maintenance	Vegetated drainageways require more maintenance (mowing, trash removal) than their traditional storm drain counterparts.	Appropriately designed vegetated drainageways provide sufficient drainage capacity if left unmowed. Trash not controlled at the source will require collection–either from the drainageway, the catch basin, or somewhere downstream.Sediment and debris can be more readily removed from vegetated drainageways than from enclosed systems.
	Small detention pond outlets required for water quality enhancement are prone to clogging.	Innovative BMP design of forebays, detention pond outlets, particularly submerged outlets, can prevent small orifices from clogging and will make them self-cleaning.
		Incorporating filtering and trapping BMPs reduces downstream maintenance needs.
		Stabilization of stream flows through storage and infiltration BMPs reduces downstream scour and bank stabilization needs.
Aesthetics	Cattails and other wetland vegetation that develop in vegetated swales are unsightly.	Desirable species of prairie grasses and native vegetation can supplant nuisance species if encouraged through initial plantings and seasonal or annual, rather than weekly, cutting.
	Emergent vegetation in wet ponds is unsightly.	Desirable species of emergent vegetation (lily pads, flowering plants) can be planted and encouraged.
		Emergent vegetation provides habitat to waterfowl and mosquito predators.
	Wetlands are unsightly.	Wooded wetlands provide green space, habitat, and desirable open space.
		With minimal maintenance, prairie wetlands can be encouraged to provide wildlife habitat and grow a variety of flowering grasses.
	Residents object to "soggy spots" associated with vegetated filters and grassed swales.	Water detained in vegetated filters and grassed swales recharges groundwater.Well-designed swales should create ponding only for a short time.
		Vegetated filters and grassed swales retain pollutants that would otherwise pollute downstream waterways.

Conflicts with Existing Codes	Some municipal codes prohibit discharging downspouts and sump pumps onto lawns.	Discharging downspouts and sump pumps onto lawns: • Promotes groundwater recharge • Traps pollutants • Reduces downstream peak flows
	Some county and municipal codes require enclosed storm sewers.	Vegetated, open drainageways: • Promote groundwater recharge • Trap pollutants • Provide detention storage • Reduce velocities and downstream peak flows
	Storage release rates vary.	BMP benefits are maximized at release rates lower than those commonly in municipal flood-control programs. BMP benefits, however, require storage only for small (e.g., 2-year) storms. Hence, uniform low-flow release rates can achieve BMP benefits even with a variety of maximum 100-year release rates.

CHAPTER 4: FORMULATION OF MCDSS

4.1 INTRODUCTION

The choice of alternative techniques in urban stormwater drainage (infiltration, filtration and detention), in the past has often been made with a poor understanding of site constraints, and the possibilities afforded by these techniques (Azzout *et al.* 1995). This gives rise to extra costs and subsequent malfunctioning. To arrive at feasible choices one must formalise a large body of information into one coherent decision-making tool. Such a tool must take into account the multitude of selection criteria that should be considered when selecting BMPs. Possessing such a tool would assist 'decision makers' in choosing the correct urban stormwater drainage strategies. Decision tools have also been combined with geographic information systems (GIS) to aid planners in choosing the correct storm water management strategies (Sample *et al.* 2001). In other words it will allow them to make the right investments. The stakes are important and are not only economic: good management and therefore protection against the risks of flooding are also at stake (Barraud *et al.* 1999). Such a tool will also contribute to the proper management of water resources (protection of receiving waters), and will make technical investments pay (Azzout *et al.* 1995).

4.1.1 What is a decision support system?

Decision-making is a process of choosing among alternative courses of action for the purpose of attaining a goal or goals (Turban 1990). Hence a decision support system (DSS) is thus defined by Marakas (1999) as a system under the control of one or more decision makers that assists in the activity of decision making by providing an organised set of tools intended to impart structure to portions of the decision-making situation and to improve the ultimate effectiveness of the decision outcome. In its ultimate form it is a computer system aimed at using modelling to evaluate alternatives and to arrive at decisions. As one can see, a DSS is expected to serve the decision maker by extending his or her capacity to process the mountain of information encountered in the process of making a decision. To achieve any of the above potential benefits, the manager must understand not only the appropriate application of a particular DSS tool but also its limits (Marakas 1999).

No matter how well a DSS is designed, its value will be constrained by certain limitations. A DSS, like any other computer-based system, is only as good as the information that has been processed into it by its designers and programmers (Marakas 1999). As such it only possesses the 'skills' associated with its tool set.

In summary, DSS can make the decision process more effective and move it within the capabilities of the human decision maker. In order to achieve this goal such a system must be (i) simple, (ii) robust, (iii) easy to control, (iv) adaptive, (v) complete on important issues, and (vi) easy to communicate with (Turban 1990). Lastly, any manager must see a DSS as a tool in the decision-making process rather than as a mechanism that itself makes the decision.

4.1.2 User definition and scope of DSS use

Before moving onto the actual process of decision making it must be stated that before proceeding with the formulation of a DSS one must clearly determine who the users might be. In the words of Marakas (1999: 23): "No DSS can be considered functional or complete without the user". The user is commonly defined as the person, or persons, responsible for providing a solution to the problem at hand or for making a decision within the context for which the DSS will be designed to support. According to Stuth and Stafford-Smith (1993), the construction, design, presentation, database contents, and database management procedures should all be designed with the end user's requirements at the fore. To this degree the user group has been identified as either water resource planners or stormwater engineers. The DSS has not been designed for implementation by the individual landowner, due to the technical nature of the BMPs.

It is stressed though, that the introduction of a multi-criteria decision support system for selecting stormwater BMPs is not intended to replace professional judgement and intensive site-specific or area-specific investigations where they are required. Instead, it is intended to assist stormwater engineers or water resource planners to identify the optimal BMP technique for any particular set of circumstances and management goals. The DSS allows the user to set management goals, whatever they may be, select the necessary site information, and take cognisance of added benefits (environmental amenities) and potential threats (groundwater contamination or thermal impacts on receiving waters). Although the aim of this thesis is to develop a MCDSS for selecting BMPs, Sample *et al.* (2001) mention that DSS can be combined with GIS for use in urban stormwater modelling and management. When combined they could be used to explore more complex land use and BMP decisions. What this demonstrates is the powerful potential of future MCDSS.

4.1.3 The decision making process

For a decision to be taken, a certain process has to be followed if the outcome is to be sound and successful. According to Klein and Methlie (1995) a typical decision making process is to:

(i) Recognise a problem situation.
(ii) Diagnose a problem (assess what the problem is impacting upon and determine the cause)
(iii) Generate alternatives.
(iv) Compute criteria
(v) Evaluate alternatives
(vi) Select one alternative

Therefore the MCDSS has been developed to take into account the above decision process, albeit slightly modified. After the problem has been recognised and diagnosed, site-specific information and management goals will need to be fed into the MCDSS in order for the MCDSS to generate alternatives. Once this has taken place the user may evaluate the alternatives and select the appropriate one.

4.2 OUTLINE OF PRIMARY MATRIX AND MCDSS DEVELOPMENT

The MCDSS formulation took place via a series of phases (Figure 4.1). The three main forms of development were, literature reviews, testing and evaluation. As Figure 4.1 shows, the model was tested and evaluated four times coupled with precautionary literature checks to determine if the ranks and weights attached to each criterion were indeed correct. In order to help the reader understand this process and where each stage occurs in the text, section numbers have been included. The remainder of this chapter follows the path set out in Figure 4.1.

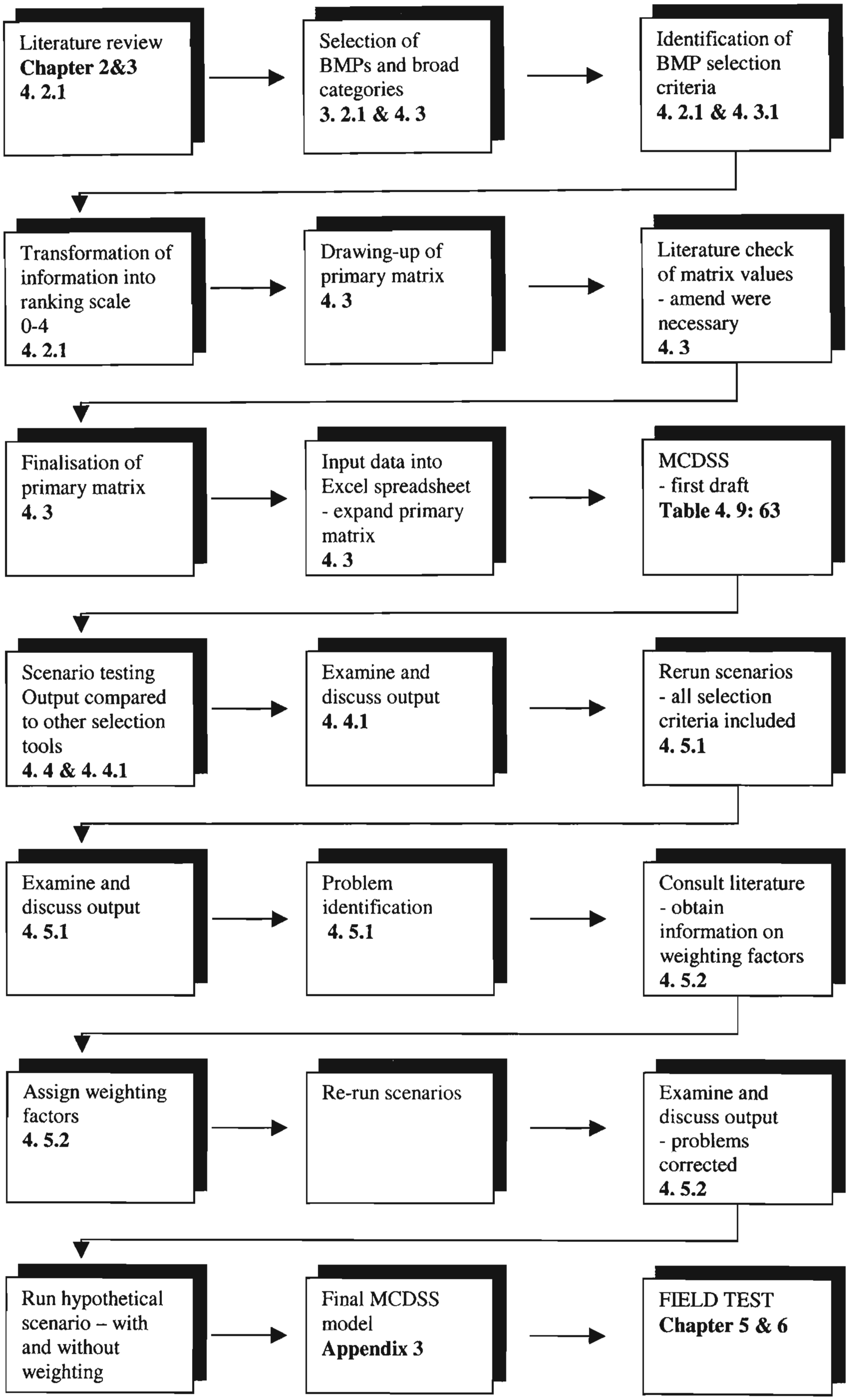

Figure 4.1: Outline and process of the primary matrix and MCDSS development. Section, table and chapter numbers have been included where possible.

4.2.1 Literature review and primary matrix development

As previously mentioned, a DSS is only as good as its "knowledge base" therefore an extensive literature review was conducted to meet this goal. This information was then used to develop the primary matrix.

The process of data collection took place via a series of steps. The first step was the general literature review where scientific papers, journals, and stormwater manuals were examined for information regarding BMPs and their use. In the process, other information such as generally accepted criteria for BMP selection and design were collected and collated. Once this stage was complete, the data collection form (Appendix 2) was developed. This form would thus provide a quick reference to the reviewed literature.

In the process of reviewing the literature, various selection tools were encountered (section 4.2.2). One such tool used a ranking scale to help the user in the selection process (Urbanas 1997). This idea formed the template for the collection of data and ultimately the formulation of the primary matrix. The primary matrix uses a rank and weighting method to assign scores to each BMP. Each BMP is scored from 0 – 4, with 4 being awarded to those BMPs that perform best in each of the selection criteria while zero was awarded to BMPs where functionality within a certain criterion was limited (Table 4.1) or when the BMP did not provide the particular function (Table 4.2).

The main reason for using this scale is the fact that it is a five-point scale and hence two was used as the mid point for data collection. For example when reviewing the literature, one would have to decide what score to assign to each BMP depending on the selection criteria. However, not all of the information collected from the literature was quantitative. A large portion was in fact qualitative. Therefore, in order to transform the data, descriptive terms such as optimal, sub-optimal, efficient, moderate, marginal as well as various other terms were awarded certain scores. For example optimal would have received a rating of four, efficient a value of three, moderate two, and sub-optimal or marginal one. If there was uncertainty on the exact rating, then the BMP was awarded the mid-point value. In such cases, these values were flagged for review once the remainder of the information had been collected and collated. A similar approach was applied to data presented in a visual format (Table 4.3). The visual data was then transformed into numerical format (Figure 4.2). A clear circle, representing a 'good option' would initially receive a value of three. This value could increase to four only after consultation with the literature. A half clear circle, depicting a suitable option under certain circumstances would initially receive a value of 2, the mid point. Again, after consultation with the literature, this value could go up or down depending on various other sources. Finally, a dark circle would receive a value of one, and may end up at zero, depending on the literature. This process thus culminated in the formulation of the primary matrix.

Table 4.1: Section of the final MCDSS relating to the slope (%) criterion. Each BMP has been awarded a value of 0-4 depending on the ability of the BMP to function under different slope conditions

BMP type	<5	5 to 10	10 to 15	>15
Infiltration Basin	4	3	2	1
Infiltration Trench	4	3	1	0
Porous Pavement	4	2	1	0
Porous Pavement (Reservoir Design)	4	2	1	0
Filter Strips	4	3	1	1
Grass Swale	4	2	1	1
Sand Filter	4	3	1	1
Extended Detention Basin	4	3	2	1
Wet Extended Detention Basin	4	3	2	1
Wet Ponds	4	3	2	1
Constructed Wetland	4	3	1	1
On-Site-Detention	4	3	3	2

Table 4.2: Section of the final MCDSS relating to the community and environmental factor criterion. Each BMP has been awarded a value of 0-4 depending on the ability of the BMP to perform each function

BMP type	Habitat creation	Aesthetics	Recreational Benefits	O & M	Relative Cost	Failure Rate/Risk	Potential for ground-water contamination.
Infiltration Basin	2	0	1	4	2	4	3
Infiltration Trench	0	0	0	4	2	2	4
Porous Pavement	0	0	0	3	4	3	4
Porous Pavement (Reservoir Design)	0	0	0	3	4	3	1
Filter Strips	3	3	0	2	1	1	1
Grass Swale	1	2	0	3	2	1	1
Sand Filter	0	0	0	3	4	2	1
Extended Detention Basin	2	2	0	3	2	1	1
Wet Extended Detention Basin	4	4	2	2	2	1	1
Wet Ponds	4	4	4	2	1	1	1
Constructed Wetland	4	4	4	4	3	1	1
On-Site-Detention	0	0	0	4	4	3	2

Table 4.3: Example of a BMP information sheet (after Schueler 1987).

	Peak Discharge control			**Volume control**	**Groundwater recharge**	**Streambank erosion control**
BMP	**2 yr storm**	**10 year storm**	**100 year storm**			
Dry extended detention basin	○	○	○	●	●	○
Wet extended detention basin	○	○	○	●	●	○
Wet pond	○	○	○	◗	●	◗
Infiltration trench	○	◗	●	○	○	◗
Infiltration basin	○	◗	●	○	○	○
Porous pavement	○	◗	●	○	○	◗
Grassed swale	◗	●	●	●	◗	●
Filter strip	◗	●	●	●	◗	●

Figure 4.2: Example of selection matrix occurring in various documents. The points awarded for each have been included.

4.2.2 Critique of selection tools

As mentioned previously, four other selection tools were used to compare those results given by the MCDSS to those of the other management tools. However, while using the other methods one came across certain limitations. What follows is a brief critique of each of the four methods.

(a) **Controlling urban runoff: A practical manual for planning and designing urban BMPs** (Schueler 1987)

This manual was one of the original attempts to categorise and collate the large body of BMP information into one coherent management tool. Although highly informative, it does have certain limitations. These include: difficulty in BMP choice and method of ranking.

The manual forces the decision maker to choose between one of three options: seldom provided, sometimes provided or usually provided. This method of selection thus leads to a tedious process of elimination. What might actually occur is a scenario where the decision maker has to choose between several BMPs and the only criteria he/she has at their disposal are vague descriptive terms. Although, this method finally produced an answer to the scenarios the process was tedious and sometimes confusing.

(b) **A stormwater manual toolbox** (Schueler 2000)
This manual was rather similar to the first although various other criteria were included. These included: Land use, climate & regional factors, and watershed factors. It is the point of view of the author that both climate and watershed factors have only been included to inform the decision maker of certain design modifications that might be necessary and do not ultimately alter the BMP selection process. Criticisms levelled against this model are similar to those of Schueler's first model.

(c) **Design and selection guidance for structural BMPs** (Urbanas 1997)
This method was not particularly user friendly since it did not allow the decision maker to select the specific site information as it only has one value called "sensitivity to site conditions". This tool lacked sufficient management criteria as it only lists three: water quality, flow rate control, and runoff volume reduction. This fact greatly increased the difficulty of BMP selection as many of the scenarios stipulated management criteria that were not present. Community and environmental factors of the specified BMPs were also omitted.

(d) **Barr engineering company** – Adapted from the *Maryland Stormwater Design Manual*, Maryland Department of the Environment.
This selection matrix follows a three-step process and begins by screening the BMPs for their suitability for stormwater treatment. After this has been preformed they are screened for their physical feasibility and lastly for their community and environmental amenities. This tool was one of the few that included costs in relative terms. This was very useful as the decision maker would be able to rapidly assess and compare costs of various BMPs. The water quality section of this method was detailed and useful. However, the management criteria section was limited to only two choices: rate control, and volume reduction. Other important benefits such a flood control or streambank erosion control, were omitted. This fact made the choice of appropriate BMPs extremely difficult.

4.3 THE PRIMARY MATRIX

The primary matrix (Table 4.9: 63) completes the first stage of the MCDSS development. It lists twelve different BMPs and their corresponding values for the various screening criteria. The twelve BMPs represent the most commonly used BMPs. However, design modifications may be made to each of the BMPs to suit individual requirements. It must be reiterated that the aim of this dissertation is to provide an engineer or water planner with a basic set of BMP options depending on the site constraints. Once this has been achieved, the user would then need to undertake a more detailed design and site inspection before the final modified BMP may be implemented. The BMPs listed here fall into three broad categories (section 3.2.1) namely: infiltration, filtration, and detention. Table 4.4 lists the twelve BMPs and their respective categories.

Table 4.4: List of twelve BMPs used in the final MCDSS and their corresponding category

BMP type	Category
Infiltration basin	Infiltration
Infiltration trench	Infiltration
Porous pavement	Infiltration
Porous Pavement (reservoir design)	Infiltration
Filter strips	Filtration
Grass swale	Filtration
Sand filter	Filtration
Extended detention basin	Detention
Wet extended detention basin	Detention
Wet ponds	Detention
Constructed wetland	Detention
On-site detention	Detention

Once the primary matrix was completed it was subjected to a review process. The rankings were checked with the literature to determine if they were correct. However, it was found that the set up of the first two criteria (soil infiltration rate and water table requirement) were incorrect as only zero or four was assigned to the various BMPs. Hence these criteria, through consultation with the literature, were expanded before the data was processed into the final MCDSS. An Excel spreadsheet was used for the model, into each cell the various ranks were added until all data had been transferred from the primary matrix to the final MCDSS.

Once completed the MCDSS was then tested using a variety of scenarios taken from manuals and other scientific papers. The aim of this phase of development was to assess the suitability of the MCDSS to select an appropriate management option given site constraints and user preferences. By comparing the options provided by the different stormwater manuals (Table 4.5) to the options provided by the MCDSS for the same scenario one was able to determine if the MCDSS was functioning sufficiently. However, before explaining the results of the testing phase and the reasons behind the subsequent assignment of weighting factors it is necessary to define the various terms used in the matrix.

Table 4.5: Stormwater manuals used in the development of the primary matrix

Manual	**Author/s**
Maryland Stormwater Design Manual, Maryland Department of the Environment	Barr Engineering Company
Design and Selection Guidance for Structural BMPs	Urbanas (1997)
Controlling Urban Runoff: A Practical Manuel for Planning and Designing Urban BMPs	Schueler (1987)
A Stormwater Manuel Toolbox	Schueler (2000)

4.3.1 The screening criteria

(a) **Screening BMPs based on treatment suitability (management options)**

Recall that in developing the MCDSS certain aims formed the backdrop to the formulation of any BMP plan. Two such aims were to reproduce, as nearly as possible, the hydrological conditions in the stream to pre-development status or in other words to a natural regime and to provide some degree of pollutant removal. This step thus allows the specified manager or designer to select the management goals for the particular BMP plan. The first management goal of reproducing pre-development hydrology can be achieved through a combination of peak discharge control, groundwater recharge, runoff volume reduction, streambank erosion control and flow rate control. As will be seen very few BMPs provide the full spectrum of management options. This is because a different flow condition and/or frequency must be controlled to provide each benefit. As an example, if the designer wants to control peak discharge then he/she must look to control very large, infrequent storms. However, if the designer wants to provide groundwater recharge he/she must look to control much smaller and more frequent storm events.

1) ***Flood control 'peak discharge control'***

As shown in the primary matrix as well as in the MCDSS, peak discharge will often be required for one or more design storms, the degree of which often depends on municipal guidelines or the degree of protection required by downstream developments. Peak discharge control is accomplished by temporarily detaining a large percentage of the runoff volume from the design storm and then releasing it at the lower pre-development rate. If a particular BMP cannot meet the full peak discharge requirement it should not necessarily be eliminated from consideration, but rather it is an indication that more than one practice may be needed at a site.

2) ***Runoff volume reduction***

This criterion relates to the relative effectiveness of a particular BMP to reduce the volume of stormwater runoff. Infiltration BMPs are highly effective in this regard, as a large percentage of the storm runoff volume is returned to the soil. Again, the fact that a particular BMP cannot fully meet the requirement does not necessarily mean that it should be eliminated from selection.

3) ***Groundwater recharge***

"Natural" levels of groundwater recharge can be achieved by diverting a significant fraction of the stormwater runoff from frequent small to moderate storms back into the soil. Infiltration BMPs are excellent in this regard. Vegetative methods, such as grassed swales and filter strips, and pond/detention BMPs have only a limited capacity.

4) ***Streambank erosion control***

All BMPs that provide an average (2) to high (4) peak discharge control for the 2-year design storm provide a degree of streambank erosion control. Note that the 2-year storm creates an erosive condition in natural channels (Rutherfurd, Jerie & Marsh 2000). Hence, in order to adequately protect downstream channels, it is necessary to control both the post-development increase in the 2-year bankfull flood and the increased frequency with which it occurs. According to Schueler (1987) this normally entails the control of storm events of intermediate size (less than the 2-year storm).

5) ***Flow rate control***

This criterion relates to the ability of a particular BMP to control the flow of stormwater once it has reached the management practice. For example, the design of the orifice of detention BMPs can determine the release rate of detained stormwater (Schueler 1987).

6) ***Pollution control***

The pollutant removal capability of a BMP is primarily determined by three interrelated factors:

(i) The removal mechanisms used.

(ii) The fraction of the annual runoff volume treated.

(iii) The nature of the pollutant being removed (Schueler 1987).

Although the removal rates discernibly differ in relation to BMP design and for each pollutant (Table 3.2), for ease of selection these percentages were converted into the five-point scale. Therefore, if the specified users require BMPs with pollutant removal capacities then they could refer to the MCDSS for a rapid assessment of those BMPs that provide water quality benefits. On the other hand, if the specified user requires more detailed information on particular removal rates then they could refer to Table 3.2. Other sources of detailed pollutant removal data include Schueler (1987), Urbanas (1994) and EPA (1999).

(b) **Screening BMPs based on site applicability**

The second step in selecting BMPs is to determine which BMPs are actually suited to the physical conditions at the site. Two of the more important factors to consider when selecting BMPs are infiltration rate and size of the drainage area. Veldcamp *et al.* (1997) state that if one was considering infiltration techniques then the soil infiltration rate as well various other factors are very important. While the EPA (1999) cite Schueler *et al.* (1992) who state that most BMPs can only be applied successfully in relatively narrow drainage areas. However, some leeway is warranted where a practice meets other management objectives. Other factors that need to be taken into consideration when selecting BMPs include the height of the water table, slope, runoff source/site characteristics.

(1) ***Infiltration rate / soil type***

The permeability of the underlying soil type has a profound influence on the functioning of certain BMPs. Infiltration BMPs are especially sensitive to infiltration rates and usually require deep permeable soils with an infiltration rate of no less than 0.25 $cm.h^{-1}$ (Velcamp *et al.* 1997; Alfakih, Barraud & Martinelli 1999). For simplicity, soil infiltration rate can be assumed from soil texture class (Table 4.6) since the percentages of sand, silt and clay have a profound influence on infiltration rate (Miller & Donahue 1995). The author recognizes the fact that soil infiltration rate is determined by a variety of other factors however as this MCDSS is a tool for decision making is aims to provide an initial range of BMPs. Before implementing any specific BMP more detailed geotechnical tests are required for infiltration feasibility and permeability. A second method assigns different soil forms and series to hydrological soil groups. The original system included four basic soil groups (A, B, C, D), although owing to the wide spectrum of soil properties displayed by southern African soils, three intermediate groups have been assigned (A/B, B/C, C/D; Schmidt & Schulze 1987). However, since the MCDSS has been developed as an initial selection tool, prior to more detailed analysis, only the original four groups were included in the MCDSS (Table 4.7).

Table 4.6: Four soil infiltration rates that have been classified by the National Cooperative Soil Survey (Miller & Donahue 1995)

Infiltration Class	**Infiltration Rate ($cm.h^{-1}$)**	**Infiltration Rate ($in.h^{-1}$)**	**Soil Texture Class**
Very Low	< 0.25	0.1	High percentage of clay
Low	0.25-1.25	0.1-0.5	High in clay, or low in organic matter
Medium	1.25-2.5	0.5-1.0	Loams and silts
High	> 2.5	1.0	Deep sands, deep well-aggregated silt loams

Table 4.7: Four basic hydrological soil groups (After Schmidt & Schulze 1987).

Soil Class	**Stormflow Potential**	**Infiltration Rate [1] ($cm.h^{-1}$)**	**Permeability Rate [2] ($cm.h^{-1}$)**
A	Low	> 2.5	>0.76
B	Moderately low	1.25-2.5	0.38–0.76
C	Moderately high	0.25-1.25	0.13-0.38
D	High	< 0.25	<0.13

[1] infiltration rates are controlled by surface conditions

[2] permeability rates are controlled by the soil profile

(2) ***Drainage area***

This criterion indicates the minimum or maximum drainage areas that are considered optimal for a practice. Pond and detention BMPs normally require significant drainage areas (greater than 10 acres) to ensure proper operation. The lower range for the above set of practices is set by the minimum orifice size. On the other hand, the majority of infiltration and vegetative BMPs are generally applicable on sites less than 5 hectares due either to space constraints (Azzout *et al.* 1995), economics (EPA 1999) or flow velocity constraints (Schueler 1987).

(3) ***Water table***

A high water table can seriously affect the functioning of infiltration BMPs. A general requirement to consider when selecting and designing BMPs is that the seasonally high water table should not extend to within one metre from the bottom of infiltration BMPs (Veldcamp *et al.* 1997; Schueler 2000).

(4) ***Slope***

Steep slopes can restrict the use of several BMPs. For example grass swales and filter strips do not effectively treat high-velocity flows (EPA 1999). Grass swales usually require a 5 % longitudinal gradient to function optimally (Yu *et al.* 2001) with filter strips requiring no more than 15 % slopes (EPA 1999).

(5) ***Runoff source/site characteristics***

This criterion relates to the suitability of BMPs to treat runoff from various areas. Choice of BMP is usually affected by area, type of runoff, and adaptability to conditions. For example, grass swales are favoured practices along highways as they require minimal space, are cost effective, and can be built to follow the path of the road (Yu *et al.* 2001). Infiltration practices are usually discouraged from implementation in rural areas. The main reason being the extremely high-suspended sediment levels in the water since slopes lack sufficient vegetative cover to protect the soil from the erosive effects of rainfall (pers. obs.). Consequently, these high-suspended sediment levels lead to rapid clogging of the infiltration surfaces (Livingston 2001).

For ease of selection, the following categories of urban land uses have been adapted from those present in *ACRU* (an agrohydrological modelling system) (Schulze & Tarboton 1994):

(i) Commercial high density (H-D); characterised by high runoff potential with approximately 85% of the surface area assumed to be impervious, any rain falling on these impervious areas is assumed to flow directly into stormwater drains or streamflow channels.

(ii) Roads/highways; same as above.

(iii) Residential medium to high density (M-H) or commercial medium density (M-D); this category consists primarily of housing with a high percentage of impervious surfaces (> 65%) present. This category also includes schools and shopping centres within urban areas.

(iv) Residential low to medium density (L-M); these areas are assumed to have impervious areas between 20 and 40%. Areas that fall under this category include newer suburbs with planted trees not fully established (impervious area of 40%) and well vegetated suburbs with large gardens consisting of trees, shrubs, lawns and gardens (impervious area of 20%).

(v) Rural low to medium density; a phenomenon of developing countries, often comprising small dwellings on the periphery of urban areas with no formal services are provided, this category of land use would include informal settlements. They have little or no vegetation.

(c) **Screening BMPs based on community and environmental factors**

The last step of the selection process assesses BMPs according to their community and environmental advantages and disadvantages. It must be stated that, in most cases, the environmental benefits are not automatically provided by any particular BMP when they are built. Rather, they are a result of thoughtful design, regular maintenance, and creative landscaping. Wisner (1997) relates a Canadian example where improper design, lack of public awareness, and infrequent maintenance led to a public outcry over the implementation of wet ponds due to macrophyte build-up. The author therefore concluded that besides water quality, water budget, and limnographic modeling BMP design studies should also include the participation of water recreational specialists, landscape architects, biologists, municipal officials, and representatives of the developer. The outcome of this process resulted in the rejection of the former economically prohibitive ideas such as increasing the depth of the lake in favour of adequate landscaping and educational programmes.

As the above example demonstrates, adequate foresight and planning is essential if public acceptance is to be achieved as such recreational benefits, aesthetics, and the potential for habitat creation have been included in the MCDSS as part of the selection process. It should also be noted that potential impacts of BMP implementation such as the potential for thermal increases, and groundwater contamination have also been included in the MCDSS, as the stormwater manager should be aware of such environmental impacts. Lastly, construction cost (relative to drainage area treated), operation and maintenance costs, and potential failure rates have been included to allow the designer to determine cost/benefit of any potential BMP.

(1) ***Habitat creation***

This criterion ranks BMPs according to their ability, assuming that an effort is made to landscape them appropriately, to provide wildlife habitat. As one can see from the matrix, BMPs that contain or detain water for long periods, score highly in this regard. The reason is that these BMPs provide refuges for both aquatic and terrestrial wildlife. Shallow designs (see Canadian example, section 3.5.1) are an attractive option for waterfowl, marsh birds and other wildlife (Schueler 1987; Marsalek, Watt & Henry 1992). Hellfield and Diamond (1997), also recommend marsh establishment for increasing the recruitment of fish and wading birds. However, they also discourage the dual use of aquatic wetlands i.e. pollutant removal and habitat enhancement. If ones goal is, first-and-foremost, to provide aquatic habitat or habitat enhancement then the toxicological effects and bioaccumulation of urban contaminants through the aquatic food web may ultimately prove detrimental to this long-term goal.

Vegetative BMPs such as grass swales and vegetated filter strips both provide a degree of wildlife habitat albeit limited in the case of grass swales. According to Schueler (1987), relatively diverse biological communities can be created through careful planting and selection of trees, shrubs, and grasses that provide food and cover for wildlife.

(2) ***Aesthetics***

As seen in the Canadian example, most pond BMPs have the potential to be either an attractive or unattractive addition to any community, depending on the attention given to planning, design and landscaping. According to the Greater Vancouver and Drainage District, *Liquid Waste Management Plan* landscape architects should be employed to integrate BMPs into neighbourhoods. For example, Hilding (1994) mentions that a lack of grass cover and the accumulation of trash and debris in infiltration devices may generate complaints from residents. Therefore, Schuler (1987) notes that they should be designed to be unobtrusive. Other design considerations include the concealment of control structures (low flow channels, riprap, and risers) by vegetation.

(3) ***Recreational benefits***

Although, Wisner (1997) and Hellfield and Diamond (1997) include the ability of wetlands and pond systems to provide recreational benefits as a management goal when selecting them for stormwater management neither author categorically lists the benefits. Hence, the reader is left to assume what they might be. Potential benefits could include, bird watching, fishing, general nature enjoyment, or water-skiing (only on large pond systems).

(4) ***Potential for groundwater contamination***

According to the EPA (1999), careful attention should be paid when selecting infiltration BMPs when groundwater requires protection. Restrictions or careful design considerations should also be applied to infiltration systems located above sole source (drinking water) aquifers. Where such devices are selected they should be implemented with the recognition that increased maintenance will be necessary. Although all systems have the potential to contaminate groundwater, infiltration devices by nature of their management processes pose the greatest threat. One must state however, that the potential for contamination must not disqualify a BMP from selection. It only means that careful design and effective maintenance will be needed to ensure the long-term success of such a system.

(5) ***Operation and maintenance***

This criterion assesses the relative operation and maintenance costs needed for a BMP. The term combines three criteria: frequency of inspection, scheduled maintenance and chronic maintenance problems (such as clogging). It should be noted that all BMPs require routine inspections and maintenance. Clogging of infiltration facilities and maintenance problems involving excessive growth of woody vegetation are common problems (Lindsey, Roberts & Page 1992b) leading to the malfunction of BMPs. Lindsey, Roberts and Page (1992b) list a variety of other faults that can occur when dealing with BMPs. This is an informative paper and is highly recommended for anyone seeking detailed information on maintenance requirements. Lastly, the authors of the above paper mention that BMPs should be inspected at least once every three years to ensure that they are operating as designed.

(6) ***Construction cost***

The BMPs are ranked according to their relative construction cost per impervious area treated. For more detailed information on costing equations of BMPs refer to Table 4.8.

(7) ***Failure rate/risk***

This criterion ranks BMPs according to their potential for failure. This criterion is subjective and has been developed from an extensive literature review process. The reason for the inclusion of such a criterion is that it allows the manager, engineer, or planner to view at a glance the risk involved when a BMP has been selected for implementation. This criterion does not disqualify any BMP from selection. Its only function is to inform the user that in order for the long-term success of the system to be assured he/she would need to carefully design, and manage such a system. If this is achieved then one will be able to substantially reduce any risk. For example, Urbonas (1994) cites Schueler *et al.* (1991) who found that due to groundwater build-up and the sealing of infiltrating surfaces due to sediment build-up (two major causes of failure), 90 % of infiltration basins and 50 % of infiltration trenches failed in the United States.

Table 4.8: Structural BMP cost/benefit overview for various specified developments (Costs in Canadian Dollars; 1$ = 1.5C$)

BMP	Construction Cost Equation	Construction Cost	Total Capital Cost [1]	Annual Maintenance Cost
15 ha Residential Development				
V_{wq} = water quality volume = 2,050 m^3				
V_t = total volume (V_{wq} + storage for flood control) = 3,610 m^3				
Extended Detention Basin	$ 11.65 $(35.31V_t)^{0.78}$	$112,000	$151,000	$1,100
Wet Pond	$ 28.90 $(35.31V_t)^{0.70}$	$108,000	$146,000	$4,900
Constructed Wetland	$ 34.70 $(35.31V_t)^{0.70}$	$130,000	$176,000	$5,900
Off-line Infiltration Basin	$44 V_{wq}	$90,200	$122,000	$4,500
Grass Swales	2,000 m^2 @ $ 50/m^2	$100,000	$135,000	$6,000
2 ha Municipal Office Complex				
Vwq = water quality volume = 410 m^3				
Sand Filter	$ 280 V_{wq}	$114,800	$155,000	$13,800
0.5 ha Municipal Repair Yard				
Grassed Filter Strip	425 m^2 @ $ 5/m^2	$2,125	$2,900	$1,000
Porous Pavement	5,000 m^2 @ $ 25/m^2	$125,000	$170,000	$35,000 (sweeping only)
Costs per Dwelling Unit				
On-Site Detention (O'loughlin et al. 1995)		$A5,000[2]		

[1] construction cost plus 35% for engineering, contingencies, sediment control, etc.

[2] 1$ = 2A$

Table 4.9: The primary matrix and scores awarded to each BMP in respect of the selection criteria. The main selection criteria are in red while those criteria in black are a subset of each. The values 0-4 represent scores awarded to each BMP. 4 = highest value; 0 = lowest value (section 4.2.1)

Structural BMP	Site Specific Sensitivity	Soil Infiltration Rate	Water Table Requirement	Slope	Size of Drainage Area	Stormwater Treatment Suitability	Water Quality Enhancement	Runoff Volume Reduction	Groundwater Recharge	Flood Control	Streambank Erosion Control	Flow rate Control	Runoff source/site characteristics	Roads/highways	Residential (M-H) or Com (M-D)	Commercial (H-D)	Rural	Residential (L-M)	Community/Environmental Factors	Habitat Creation	Aesthetics	Recreational Benefits	Operation & Maintenance	Cost (relative to drainage area)	Potential for Ground-water Contamination	Failure Rate/Risk
Infiltration Basin		4	4	2	3		3	4	4	4	3	3		1	3	2	1	4		2	0	1	4	2	3	4
Infiltration Trench		4	4	2	2		3	3	3	3	2	2		3	2	3	1	2		0	0	0	4	2	4	2
Porous Pavement		4	4	1	1		3	4	4	2	2	4		0	4	4	1	4		0	0	0	3	4	4	3
P Pav (Reservoir Design)		0	0	0	1		1	3	3	3	2	1		0	4	4	1	4		0	0	0	3	4	1	3
Filter Strips		0	0	1	1		2	2	2	1	0	2		2	3	0	2	4		3	3	0	2	1	1	1
Grass Swale		0	0	1	1		2	1	1	1	0	1		4	3	2	3	4		1	2	0	3	2	1	1
Sand Filter		0	0	1	0		3	0	1	0	0	1		4	2	4	2	1		0	0	0	3	4	1	2
ED Basin		0	0	0	3		3	0	1	3	3	3		3	3	2	2	3		2	2	0	3	2	1	1
Wet ED Basin		0	0	0	3		4	0	1	3	3	3		3	3	2	2	3		3	3	2	2	2	1	1
Wet Ponds		0	0	0	4		4	0	1	4	3	4		2	3	1	3	4		4	4	4	2	1	1	1
Constructed Wetland		0	0	0	3		4	0	1	3	3	3		0	3	2	4	4		4	4	4	4	3	1	1
On-Site-Detention		0	0	0	0		1	2	2	2	2	2		0	4	3	3	4		0	0	0	4	4	2	3

4.4 INITIAL TESTING OF THE MCDSS

This phase of testing deals with an evaluation of the MCDSS. The aim was to determine if the MCDSS was functioning correctly. This was determined by providing the MCDSS with certain scenarios and reviewing the output (BMP selection). If the BMP options provided by the MCDSS were similar to those mentioned by other management tools (section 4.2.2) for the same scenario then one could *prima facie* say that the MCDSS was functioning correctly. To reiterate, this was an initial stage of testing where outcomes (BMPs) and their corresponding scores were reviewed to determine firstly, if the original matrix values were correct and secondly, what weighting factors should be assigned to each criterion.

The MCDSS was given seven different scenarios, these scenarios were provided by the selection tools discussed in section 4.2.2, the Internet, and scientific papers. The source of each of the scenarios has been provided (Table 4.10). Before continuing with the scenario testing process, selection rules have to be stated. There are three sets of rules pertaining to different stages within the selection process. The first set relates to the correct selection of categories within the MCDSS. The second set of rules relate to certain precautions that need to be adhered to when BMPs have been chosen, these rules could improve BMP functioning. Lastly, the third set of rules is used if ties occur. This set of rules gives guidance on how to separate tied scores.

To reiterate the scores and ranks are only guides to decision making. The final decision ultimately rests in the hands of the decision maker. He/she might want to consider other information, for example, added benefits of certain BMPs or potential threats. To this degree, it should be mentioned that only the information supplied by the various authors, listed in Table 4.10, has been taken into account in the testing phase.

The first set of rules, for selecting categories within the MCDSS are as follows:

A)

(i) When choosing categories within either 'infiltration rate', 'drainage area', 'water table requirement' or 'slope' and the value is equal to the highest value of the one range and the lowest value of the other range, for example 5 ha is the highest value of the 2.5-5 ha range at the same time it is also the lowest value of the 5-7.5 ha range, the user must select the higher of the two ranges.

(ii) Office parks fall into the Residential (M-H) density category.

(iii) 'Cost' and 'Operation and Maintenance' criteria if selected, decrease the overall score by the amount indicated by their value.

(iv) A zero in any of the site screening criteria excludes that specific BMP from further selection.

The second set of rules relate to specific BMPs once they have been selected for implementation. These rules either help improve BMP functioning or negate the use of BMPs under conditions not incorporated into the MCDSS:

B)

(i) If infiltration trench or basin is selected then it is recommended that they should be pre-treated with either grass swales of vegetated filter strips. This will improve functioning and increase longevity.

(ii) High silt content of receiving waters negates the use of infiltration devices.

(iii) If porous pavement or porous pavement (reservoir design) are selected and are to be implemented in areas with either high traffic volumes or the occurrence of heavy vehicles then they should be designed to include a waterproof lining.

(iv) If on-site-detention is selected as an option then the following needs to be taken into consideration:

   a. If slopes are steep: then implement underground storage facilities

   b. If slopes are gradual: then ponding of water in parking lots and other open areas can occur.

The third set of rules relate to the occurrence of tied scores. If ties occur then: C)

(i) Look at the "Treatment Suitability Matrix" (Appendix 3). The BMP with the higher score achieves the higher rank.

(ii) If after (C i) the BMPs are still tie then look at the "Site Applicability" scores especially at the soil infiltration rate and drainage area columns.

(iii) If after (C ii) the BMPs are still tie then look at the "Community and Environmental Factor" column. The BMP that provides more environmental benefits achieves the higher rank.

4.4.1 The seven scenarios

Seven scenarios were used to test whether the initial MCDSS was functioning correctly. Each scenario will be presented in a similar fashion. The scenario number, source, site information, management objectives, scenario output, and MCDSS output have all been included (Table 4.10).

Table 4.10: Summary of the seven scenarios used in the development of the MCDSS. INF = infiltration rate; WT = water table; S = slope; DA = drainage area; RSC = runoff site characteristics; O & M = operation and maintenance costs. R1, R2 and R3 relate to the various ranks assigned by the MCDSS.

No.	Site information					Management objectives						Environmental and other considerations						
	INF	WT (m)	S (%)	DA (ha)	RSC	Water quality	Runoff volume reduction	Groundwater recharge	Flood control	Streambank erosion cont.	Flow rate control	Habitat creation	Aesthetics	Recreational benefits	O & M	Cost (relative to drainage area)	Choice according to the selected author for the given scenario	MCDSS output
1	Sandy loams			2.5	Office complex	✓		✓	✓			✓	✓	✓	✓	✓	I- trench (Schueler 1987)	R1) I- basin R2) I- trench R3) P-pavement
2	Sandy clay loams		5	20	H-D residential	✓			✓	✓		✓	✓	✓			Wet ED basin Dry ED basin Wet pond (Schueler 1987)	R1) Wet ED basin R2) Wet ponds R3) Dry ED basin
3	Sandy clay			16	H-D residential	✓			✓	✓							Wet ED basin (www.stormwatercentre.net)	R1) Wet ED basin R2) Wet pond R3) Dry ED basin
4	Sandy loam	3.5	<1	1.5	H-D residential	✓		✓									I-trench (www.stormwatercentre.net)	R1) P- pavement R2) I- basin R3) I- trench
5	Sandy clay	<5		2.5	M residential (High traffic volumes)		✓		✓								Detention porous pavement with waterproof lining (Pratt 1999)	R1) P – pavement (reservoir design)
6	Sandy clay	<5	<5	50	H-D Commercial	✓		✓	✓	✓		✓	✓				Constructed wetland (Helfield & Diamond 1999)	R1) Wet ponds R2) Constructed wetland R3) Wet ED- basin
7	Sand	5-8	<5	<2.5	Parking lots/Roads	✓	✓									✓	Swale-trench system (Sieker 1998)	R1) I- trench R2) Filter strips R3) Grass swale

The above set of scenarios has shown that the MCDSS was selecting the most appropriate BMPs according to the selections made by the individual authors. However, comparing the MCDSS output to one particular author might have introduced bias. Therefore, in order to reduce this bias the outputs made by the MCDSS were compared to other BMP selection tools. The results have been summarised in Table 4.11.

Table 4.11: An evaluation of the MCDSS ability to select BMPs suitability. The MCDSS was compared to four stormwater manuals (Table 4.5) in order to determine if the MCDSS was selecting the appropriate BMPs. The dark blue blocks represent the highest ranked BMP selected by the MCDSS for the given scenario. The light-blue blocks represent the BMP choice determined from the four manuals. The numbers within these blocks correspond with the key below and indicate why the option chosen by a particular manual is less favourable than the BMP recommended by the MCDSS

	SCENARIOS						
BMP type	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Infiltration Basin				2			
Infiltration Trench	1			1			
Porous Pavement							
Porous Pavement (Reservoir Design)							
Filter Strips					3		
Grass Swale					3		5
Sand Filter							
Extended Detention Basin		1	1				
Wet Extended Detention Basin							
Wet Ponds		1	1				
Constructed Wetland					4	3	
On-Site-Detention							

Key:

1) Lower Treatment Suitability Score
2) Limited Site Area, Porous Pavement out-scores I-Basin
3) Unable to meet management criteria
4) High area requirements
5) If area was a limiting factor then may select grass swale

4.5 FURTHER EVALUATION OF THE MCDSS

The following paragraphs relate to the evaluation of the MCDSS and the need to assign weighting factors to the various screening steps within the MCDSS. Various criticisms have been levelled against the selection tools used in the context of formulating and testing the MCDSS (section 4.2.2). However, in so doing one was able to highlight various shortcomings of the initial MCDSS. The details of which shall be discussed below. A copy of the completed MCDSS is contained in Appendix 3.

4.5.1 Critique of the initial MCDSS

In the initial testing phase of the MCDSS, it was found that the MCDSS would select appropriately when given few criteria for selection. However, if these were increased inappropriate outcomes resulted. For example, if the same set of scenarios where run, however this time one was to include all the available factors i.e. environmental and community benefits, potential threats, failure rates, and costs, quite a different picture occurred. Even though one BMP may have achieved a relatively high "Treatment Suitability" score it might have been surpassed by another BMP or BMPs. These BMPs although not registering high "Treatment Suitability" scores, might score highly in the various other selection criteria and particularly in the community and environmental section.

Table 4.12 shows the MCDSS output before and after the inclusion of all available selection criteria. As mentioned previously, only the specific information provided by the relevant scenarios where included in the initial testing phase. However, what can also been seen in Table 4.12 are the changes that occur in rank and score when all information is considered. The numbers in blue are those BMPs not considered for selection since they scored a zero in one or more of the site criteria (Refer to the rule A iv: 65).

Table 4.12: MCDSS output of scenario 4 before and after the inclusion of all selection criteria. Numbers in blue refer to those BMPs that scored a zero in any of the site applicability criteria thereby resulting in their disqualification. INF = infiltration rate; WT = water table; S = slope; DA = drainage area; RSC = runoff site characteristics; TSM = treatment suitability matrix; CEF = community and environmental factors

BMP	INF	WT	S	DA	RSC	TSM	Before SCORE	CEF	After SCORE
Infiltration Basin	4	1	4	2	3	7	21	-10	11
Infiltration Trench	4	1	4	4	2	6	21	-12	9
Porous Pavement	4	1	4	4	4	7	24	-14	10
Porous Pavement (Reservoir Design)	4	1	4	4	4	4	21	-11	10
Filter Strips	4	1	4	4	3	4	20	1	21
Grass Swale	4	1	4	4	3	3	19	-4	15
Sand Filter	1	1	4	4	2	4	16	-10	6
Extended Detention Basin	4	1	4	0	3	4	16	-3	13
Wet Extended Detention Basin	4	1	4	0	3	5	17	4	21
Wet Ponds	1	4	4	0	3	4	16	7	23
Constructed Wetland	1	4	4	0	3	5	17	4	21
On-Site-Detention	4	1	4	4	4	3	20	-13	7

Initially porous pavement (24 pts), infiltration basin (21 pts but higher TSM) and infiltration trench (21 pts) would have been selected. As one can see from the first score column, these BMPs achieved the highest TSM results hence their selection. However, when the "Community and Environmental Factors (CEF)" were considered in the selection process these three BMPs fell out of contention. Filter Strips and Grass swales were now ranked one and two respectively. The main reason for their superior CEF score was that they scored higher in the environmental benefits columns compared to porous pavement, infiltration basin, and infiltration trench. Other factors contributing to their remarkably superior CEF scores were that they both have lower operation and maintenance costs and overall costs, as well as having lower failure rates/risks and lower risks of groundwater contamination. Unfortunately, both filter strips and grass swales are nearly half as effective as the three original BMPs in terms meeting management criteria for this scenario indicated by their lower TSM values.

Overall costs relative to drainage area, and operation & maintenance costs are constants that are difficult to reduce, especially if one wants to ensure long-term success of any particular BMP. However, risk of groundwater contamination and failure rate can be minimised through proper selection and design of the appropriate BMPs. Alfakih *et al.* (1995) in their paper on the analysis of the failure of alternative techniques, discuss certain failure causes common to all alternative techniques. They state that the most serious faults, and consequently the most difficult to correct originate in the first phases of selection. According to Alfakih *et al.* (1995), these include the decision-making phase and subsequent BMP design. They go further by stating that besides common failure causes, specific failure causes occur for individual BMPs too. It should therefore be logical to assume that if one where to properly select and design BMPs, taking into account their specific limitations and criteria for improving longevity, one will be able to minimise failure and potential risk. Hence such criteria should not carry as much weight as other selection criteria, consequently weighting factors were applied to correct the above situation.

4.5.2 Weighting factors within the MCDSS

As mentioned above, the initial assumption of all selection criteria being equal was flawed and resulted in incorrect BMP selection when all criteria were included. Consequently, weighting factors need to be applied and additional selection rules included to help guide the decision maker in selecting the optimal BMP for a given set of criteria.

The total weighting value was set arbitrarily at ten points. Hence, if the individual weights are summed they will equal ten points (Table 4.13) the reason for this was to keep a constant scale. Hence, if in the future the weights were deemed incorrect it would be relatively simple to adjust the values accordingly without having to change any complex formulas.

Table 4.13: Summary of weighting factors assigned to various BMP selection criteria

BMP selection criteria	Weighting factors
Soil infiltration rate	1
Water table requirement	0.5
Slope	0.5
Size of drainage area	1
Stormwater treatment suitability	3
Runoff source/site characteristics	1
Habitat creation	0.5
Aesthetics	0.5
Recreational benefits	0.5
O & M	0.5
Cost relative to drainage area	0.5
Potential for groundwater contamination	0.25
Failure rate risk	0.25
TOTAL	**10**

To begin, the ranks were assigned using information and comments acquired during the literature review process. The ability of any BMP to meet specific management goals should be awarded. Since the main reason for the implementation of BMPs are to replace or improve upon the same goals being met by current engineering methods. As mentioned previously these newer approaches to stormwater management seek to retain natural features of drainage systems and provide onsite management to address water quality and quantity goals (EPA 1993; Argue 1995; Huhn and Stecker 1997; Warner 2000). Hence, the ability of any BMP to meet the specified management goals was assigned the highest rank of three.

In line with the initial rules, if ties did occur one was to look at the site applicability scores. Taking cognisance of the findings of both Veldcamp *et al.* (1997) and Schueler *et al.* (1992) who found that drainage areas and infiltration rates are two of the more important site factors to consider when selecting BMPs especially infiltration BMPs and detention BMPs (except on-site-detention). For example Brinson (1988) found that although basin wetlands normally possess a high capacity for assimilating nutrients, there might be little opportunity for this to happen if the catchment area is small and little water flows through them. Taking the above into account, both were assigned weighting factors of one. "Runoff source/site characteristics" was also assigned a weighting factor of one since certain BMPs are better suited to dealing with the runoff occurring from various sites, as well as their adaptability and ease of application to various conditions. Overall area requirements are also taken into account when considering source/site applicability. Water table requirements and site slope were thus deemed less important since in most cases design modifications may overcome any specific limitations. Hence, both of these criteria were assigned weighting factors of 0.5.

Lastly, ranks were assigned to the various community and environmental factors. The relationship between risk and potential threats and careful design has been mentioned. Therefore, both of these criteria were assigned weighting factors of 0.25 each and make up the risk column. Risk reduces the overall BMP score. Operation and maintenance costs as well as BMP cost (relative to drainage area) have also been discussed, since these are unavoidable and reduce the overall BMP score they were assigned weighting factors of 0.5 respectively. The assumption made here was that one did not want costs to interfere with the overall selection of the BMP. The overall cost score (COM), a combination of relative costs and operation and maintenance costs, is constant and will be included as a separate entity. The overall risk score (RISK), a combination of the potential risks of groundwater contamination and failure rates, as well as environmental benefits score (EB), have also been separated to allow the decision maker to assess these three criteria separately. Although important, habitat creation, aesthetics, and recreational benefits summed up as environmental benefits have each been assigned weighting factors of 0.5 each. The assumption here was although this specific matrix increases the BMP score one did not want to have a situation where environmental benefits provided by any particular BMP outweighed the ability of the BMP to meet the management goals for the site. If this situation were to occur, it would result in the MCDSS selecting inappropriate BMPs for the given management criteria (Table 4.14).

Table 4.14: MCDSS output of a hypothetical scenario, before and after the inclusion of all selection criteria

Scenario	INF	WT	S	DA	RSC	TSM	Before SCORE	CEF	After SCORE
Infiltration Basin	4	3	4	3	3	11	28	-10	18
Infiltration Trench	4	3	4	4	2	8	25	-12	13
Porous Pavement	4	3	4	3	4	8	26	-14	12
Porous Pavement (Reservoir Design)	4	3	4	3	4	8	26	-11	15
Filter Strips	4	3	4	2	3	3	19	1	20
Grass Swale	4	3	4	2	3	2	18	-4	14
Sand Filter	1	3	4	4	2	1	15	-10	5
Extended Detention Basin	4	3	4	2	3	7	23	-3	20
Wet Extended Detention Basin	4	3	4	2	3	7	23	4	27
Wet Ponds	1	2	4	1	3	8	19	7	26
Constructed Wetland	1	2	4	1	3	7	18	4	22
On-Site-Detention	4	3	4	4	4	6	25	-13	12

Initially the MCDSS would have selected infiltration basin, porous pavement (reservoir design), and porous pavement as its three most suitable BMPs given the relevant criteria. If the CEF column was taken into account (all weights are equal) then various changes occur. The two most significant being that infiltration basins fall out of contention even though it achieved by far the highest TSM value and filter strips are now ranked above infiltration trenches and basins even though it only achieved 3 out of a possible 12 in the TSM. In both cases, the MCDSS has incorrectly included certain BMPs. The last step then was to examine the output of the MCDSS after the inclusion of the weighting factors. A summary of the three scores has been included (Table 4.15), the values in orange are those scores given by the revised MCDSS (inclusion of weighting factors).

Table 4.15: A summary of the scores given by the original MCDSS before and after the inclusion of all selection criteria as well as the new scores given by the MCDSS after the weighting factors were included (orange values)

	Original MCDSS		Revised MCDSS
BMPs	**Before**	**After**	**Including weightings**
Infiltration Basin	28	18	43.25
Infiltration Trench	25	13	33
Porous Pavement	26	12	33.25
Porous Pavement (Reservoir Design)	26	15	34
Filter Strips	19	20	22.5
Grass Swale	18	14	17
Sand Filter	15	5	9.25
Extended Detention Basin	23	20	32.5
Wet Extended Detention Basin	23	27	36
Wet Ponds	18	22	36
Constructed Wetland	17	21	31

As one can see from Table 4.15 above and Table 4.17 below, the MCDSS has provided the user with a superior result in relation to the output summarised in Table 4.14. Firstly, infiltration basin retains the highest score and secondly both extended detention basins have been included in the selection process where initially they were excluded, as they were not in the top three ranked positions. Hence, the ability of both detention basins to meet the management criteria for the site was rewarded even though failure rates/risk, environmental benefits, and costs were taken into consideration. The output for the hypothetical scenario has been summarised below (Table 4.17). Before examining the results presented in Table 4.17 it is necessary to explain Table 4.16. The information portrayed in Table 4.16 helps the user to understand the scoring system. There are essentially five scores associated with each BMP. These include TSM (treatment suitability matrix score), which is the sum of the BMP scores for the number of management options chosen (max 6) multiplied by the weighting factor (3)

TSM = No. of options chosen (sum the individual scores for each option chosen) * TSMWF

Where TSMWF = criterion specific weighting factor (3)

The second factor is the SAS (site applicability score). This takes the site information scores for each BMP option and multiplies them by their relevant weighting factors. The maximum number of points available for this section is 16.

SAS = (INF * INFWF) + (WT * WTWF) + (S * SWF) + (DA * DAWF) + (RSC * RSCWF)

Where WF = criterion specific weighting factor
INF = Infiltration rate ($cm.h^{-1}$)
WT = Water Table (m)
S = Slope (%)
DA = Drainage area (ha)
RSC = Runoff source and site characteristics

The third factor is the EB (environmental benefits) score. The user is unable to choose his/her individual options. However this score is only a guide to decision making and does not exclude any BMP from selection. The maximum points available for this section is 6.

EB = (HC * 0.5) + (A * 0.5) + (RB * 0.5)

Where HC = Habitat creation
A = Aesthetics
RB = Recreational benefits

The last two scores relate to the overall operation and maintenance costs (COM) and the failure rate potential (RISK).

COM = (OM * 0.5) + (Cost * 0.5)

RISK = (GC * 0.25) + (FR * 0.25)

Where OM = Operational and maintenance costs

Cost = construction cost relative to drainage area

GC = Ground water contamination threat

FR = Failure rate

Again, the user is unable to select the individual options as the four options are used to derive the COM and RISK scores. These scores are always supplied as a guide to decision making. They also reduce the BMP score. It should be said that the final aim would have been to have a working model that colour codes the values in such a way as green would refer to the most applicable option (highest ability), orange intermediate, red the insufficient option and lastly blue not at all applicable. An example of this is demonstrated in Table 4.16. However, in the case of COM and RISK, red would refer to high cost or risk, orange medium, and green low cost or risk. The blue category was not needed as risk or cost could not have been inapplicable.

Table 4.16: A selection guide showing the relevant scores and the corresponding colours. The number of management criteria column refers to the TSM scoring system where the user has a choice of six criteria. The maximum points awarded to any one BMP will thus depend on the number of criteria selected.

Choice	Number of management criteria	Points (Max)	Blue (Insufficient option)	Red (Low ability)	Orange (Average ability)	Green (High ability)
TSM	1	12	<3	3-5	6-8	9-12
	2	24	<6	6-11	12-17	18-24
	3	36	<9	9-17	18-26	27-36
	4	48	<12	12-23	24-35	36-48
	5	60	<15	15-29	30-44	45-60
	6	72	<18	18-35	36-53	54-72
SAS		16	<4	4-7	8-11	12-16
EB		6	0	1-2	3-4	5-6
				High cost/risk	Medium cost/risk	Low cost/risk
COM		4		≥3.5	2-3	< 2
RISK		2		≥1.5	0.75-1.25	< 0.75

Table 4.17: Summary of the revised MCDSS output for a hypothetical scenario. TSM = Treatment suitability matrix, SAS = Site applicability score, EB = Environmental benefits, COM = overall cost and operation & maintenance costs, RISK = combination of failure rate and potential for groundwater contamination

Scenario	TSM	SAS	EB	COM	RISK	SCORE
MAX SCORE	**36**	**16**	**6**	**4**	**2**	**54**
Infiltration Basin	**33**	**13.5**	**1.5**	**3**	**1.75**	43.25
Infiltration Trench	**24**	**13.5**	**0**	**3**	**1.5**	33
Porous Pavement	**24**	**14.5**	**0**	**3.5**	**1.75**	33.25
Porous Pavement (Reservoir Design)	**24**	**14.5**	**0**	**3.5**	**1**	34
Filter Strips	**9**	**12.5**	**3**	**1.5**	**0.5**	22.5
Grass Swale	**6**	**12.5**	**1.5**	**2.5**	**0.5**	17
Sand Filter	**3**	**10.5**	**0**	**3.5**	**0.75**	9.25
Extended Detention Basin	**21**	**12.5**	**2**	**2.5**	**0.5**	32.5
Wet Extended Detention Basin	**21**	**12.5**	**5**	**2**	**0.5**	36
Wet Ponds	**24**	**8**	**6**	**1.5**	**0.5**	36
Constructed Wetland	**21**	**8**	**6**	**3.5**	**0.5**	31
On-Site-Detention	**18**	**15.5**	**0**	**4**	**1.25**	28.25

Note: Scenario information

INF	= Loamy sand
S	= 4%
RSC	= Residential (M-H density)
WT	= 8-12 m
DA	= 5-10 acres

Management Criteria

1) Groundwater recharge
2) Flood control
3) Streambank erosion

This chapter has thus detailed the methodology used in the formulation of the MCDSS. It has taken the reader through the step-wise process involved in designing a MCDSS of this nature. In so doing, results of the initial and final MCDSS have been discussed culminating in the testing of the MCDSS in a hypothetical scenario (Table 4.14). The completed MCDSS used for the hypothetical scenario can be found in Appendix 3. Chapter five and six thus details the testing of the MCDSS in its own case study.

CHAPTER 5: CASE STUDY

5.1 STUDY AREA

5.1.1 Geographic location

The Town Bush stream catchment forms part of the Dorpspruit catchment and lies between 30°18' and 30°24' east, and between 29°32' and 29°36' south. The catchment is orientated along a North West – South East axis. Its maximum length is 7.5 km and its maximum width is 4.5 km. The catchment is situated between Pietermaritzburg and Hilton and encompasses the residential areas of Athlone, Chasedene, Chase Valley, Hilton Gardens, Oak Park, Montrose, Mount Michael, Northern Park, and Woodlands (Figure 5.1). Two panoramic views (Plate 5.1a and 5.2b) provide a visual orientation of the catchment when used in conjunction with the 1:50 000 map (2930CB, Pietermaritzburg).

5.1.2 Stream network

The stream network consists primarily of the Town Bush stream with a few smaller tributaries entering at various points downstream. The Town Bush stream flows from the Town Hill escarpment through steep wooded areas through the Northern suburbs of Pietermaritzburg and into the Dorpspruit downstream from the Cascades shopping centre. The Town Bush stream has two tributaries, one on the left bank downstream from Oak Park and another on the right bank at Allerton veterinary station.

5.1.3 Relief

The altitude of the catchment varies between 1175m in the vicinity of Hilton and Edgehill and 675m at the confluence of the Dorpspruit. The dominant slope values are around 11% (Figure 5.2). High slope values ranging from between 50 and 78% are observed along the Town Hill escarpment and the Redcliffe/Ferncliffe escarpment along the northern edge (Biggs *et al.* 2001).

5.1.4 Land type

A section of the Land Type map 2930 Durban is depicted in Figure 5.3 (SIRI 1992). The study area has been delineated in black on the map. Land Types are identified on the map by different colours and a representative code. As one can see Land Type Unit Nos. Ab 116a, Ab 117a, Ab 118a, Ac 220a and Ac 221a are included within the selected area (Figure 5.3).

Upon examining the Land Type data sheet (SIRI 1992) one was able to obtain detailed information on soil series/land classes and soil depth ranges. Below is a description of how the Land Type data is presented according to terrain units. A sketch of the terrain type is provided at the bottom of each data sheet. Terrain units are described as follows:

a. represents a crest
b. a scarp
c. a midslope
d. a footslope
e. a valley bottom (SIRI 1992).

Information on clay content, soil texture and the nature of material which may be limiting soil depth is presented in the last three columns. A full description of the inventory can be obtained from published Land Types memoirs (SIRI 1992).

Before continuing with the methodology used during this section one needs to distinguish between the sources of the two types of site data used for determining the peak flows and runoff volumes and for use in the MCDSS.

The hydrological soil group, infiltration rates, and soil texture classes were acquired from the Land Type Maps (SIRI 1992). This data set was used for both purposes. Rainfall data, used in the determination of the peak flows and runoff volumes was acquired using the specific geographical co-ordinates for each site obtained using a geographical positioning system (GPS) and the corresponding altitude (m) value. These data sets allowed for the determination of the nearest five rainfall stations from which the user must then determine the most suitable option based on distance as well as mean annual precipitation. Land cover information, mean annual precipitation (MAP), catchment area of the eleven sites, and the average catchment slope of the eleven sites were determined from the data sets provided by the City Engineers Geographical Information Systems division. These data sets were again used for determining stormflow volumes and peak discharge. The site-specific land cover information was also processed into the MCDSS. It should be stated that data regarding mean annual precipitation could also have been obtained from Acocks (1988), Veld types of southern Africa. Each diagnostic Veld type has a MAP range attached to it. Although there is a range given one might take the mid point of the range and use this value in the SCS-SA programme. Another source of detailed rainfall data could also be obtained from Schulze, Schmidt and Smithers (1992).

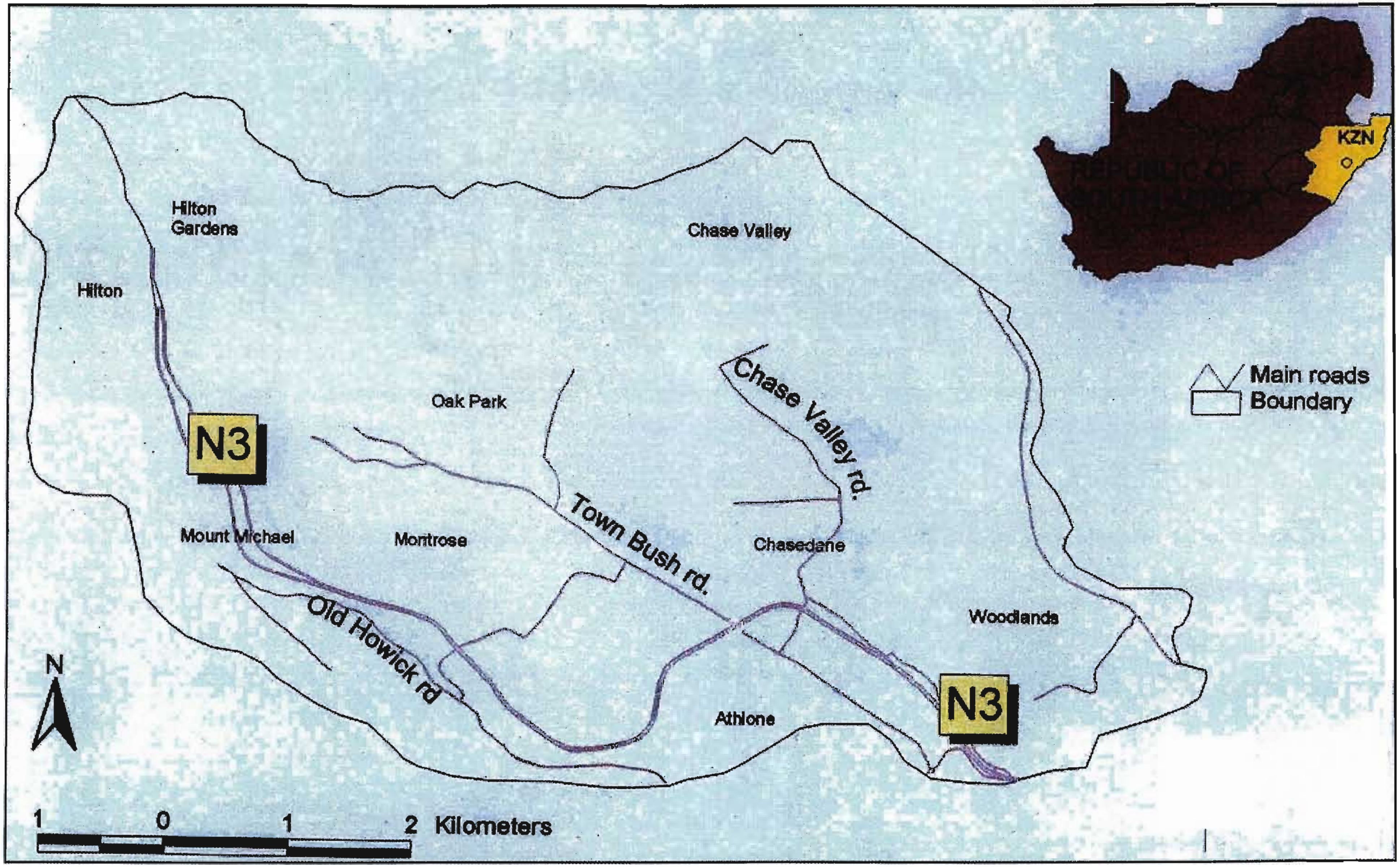

Figure 5.1: Map of the Town Bush stream catchment showing the position of the main roads and residential areas (After Nsanzya 2000).

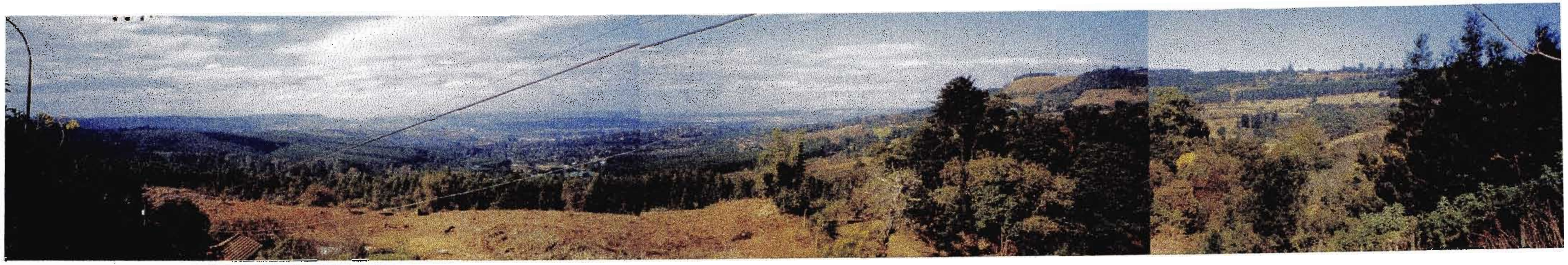

Plate 5.1(a): Panoramic view of the Town Bush stream catchment from D.V. Harris Waterworks down the Town Bush valley.

Plate 5.1(b): Panoramic view of the Town Bush stream catchment from Queen Elizabeth park across the Town Bush valley towards Ferncliffe and Oak Park.

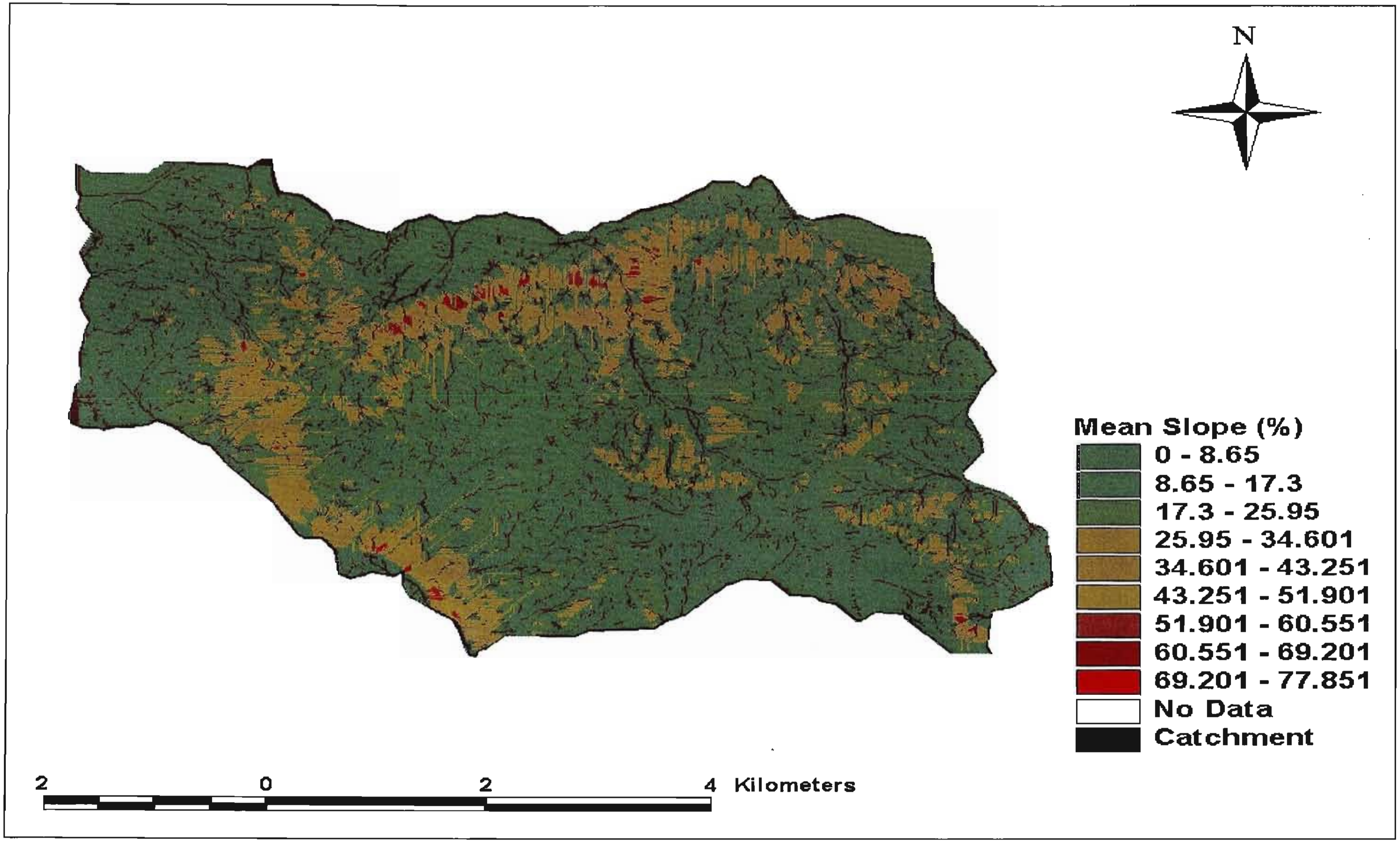

Figure 5.2: Slope map of the Town Bush catchment. Note the higher slope of the Town Hill escarpment (western boarder) and the Ferncliffe escarpment along the northern edge.

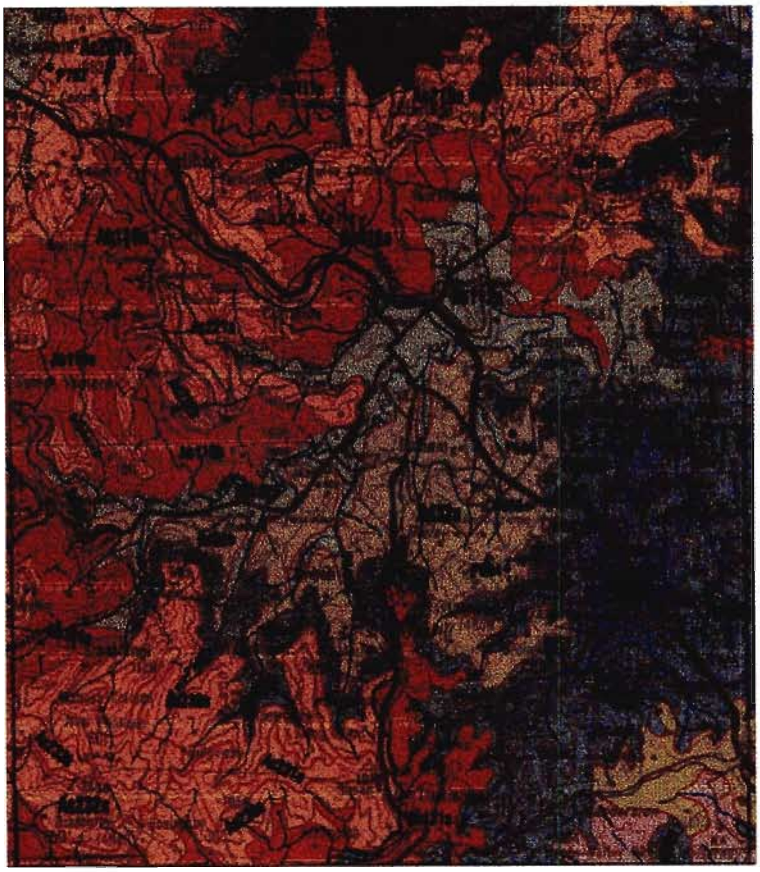

Figure 5.3: Section of the 1:250 000 land type map (SIRI 1992). The black outlined area refers to the study area.

5.2 METHODOLOGY

In order for the MCDSS to be used in the field study certain data sets were required. In order to obtain these data sets one had to first delineate the catchment on the 1:50 000 map (2930CB, Pietermaritzburg). Once this had been done, four 1:10 000 maps were obtained. Again the catchment was delineated, so too was the stream network. Three criteria were then used for the selection of sites within the study area. The first criterion was sites of major runoff generation were to be included. Therefore the National Highway met this criterion and was thus included in the study. Since detention BMPs require more than five hectares for proper implementation, open areas were highlighted on the map and the coordinates recorded using a GPS device. The third criterion for placement was that as these BMPs are relatively expensive one would want to place them in key areas such as sites where tributaries join. Thus if detention were to be selected as the most suitable option at these sites then the placement of BMPs in these areas would have the greatest effect.

The second stage of data collection took the form of obtaining certain data sets from the City Engineers GIS department. These data sets included, the two and ten metre contours, data on land use, slope data, river networks, as well as all the 1: 10 000 orthophotos of the study area. All these data sets were processed using ARCVIEW in order to obtain the relevant information required for the MCDSS. Unfortunately, no information regarding the depth of the water table at any of the sites was available and due to time and financial constraints a study of this nature was inappropriate and as such was omitted from the selection process. One should take note that this would not have eliminated any of the BMPs. However, before implementation of selected BMPs one would have to undertake a detailed site study to ensure that no specific design modifications are needed. Data regarding hydrological soil groups was obtained from the 1:250 000 land type map (SIRI 1992). Although this might be deemed an inappropriate scale for determining such groups when inputting the information into the MCDSS the fieldwork was undertaken at the 1:50 000 level.

After the completion of the above stage one had the problem of prioritising the eleven identified sites especially in light of the given financial considerations that are associated with BMP implementation. Therefore it was deemed necessary to separate the eleven sites depending upon land ownership or responsibility. Thus a priority-setting model was formulated (Figure 5.4). This model has three layers.

The first separates the BMPs on the grounds of ownership. The question was thus asked, "To whom, does the responsibility for implementation of the BMPs lie?" In order to answer this question data regarding land ownership was obtained from the Provincial Government Department.

The second layer separates BMPs according to the potential threat that may be posed to buildings or properties if they were not implemented. Thus if one had to choose between two sites where BMPs were to be implemented, the one where the integrity of buildings, houses, or bridges would be threatened receives the higher priority rating regardless of the third layer.

If it was deemed that no potential threat to property was foreseeable then one would still need another criterion to set priorities when any responsible party had to implement more than one BMP. For the third layer, hydrological analysis was used. The SCS-SA runoff model (Schulze, Schmidt & Smithers 1992) was run in order to obtain runoff volume and peak discharge values for the two, five, and ten-year storm events. Peak discharge allows the stormwater manager to quantify the magnitude of a flood while the runoff volume is the total volume of water expected for an individual storm event. According to Schulze & Schmidt (1994), for small catchments peak discharge is closely related to stormflow volume. This is demonstrated in Table 5.3 where, as stormflow volume increases so too does peak discharge. In the priority setting model preference is given to those sites with a higher peak discharge and stormflow volumes. As mentioned in Chapter two, greater stormflow volumes and peak discharges can result in channel widening and the results of such erosion can lead to the degradation of instream habitat. Results for the priority-setting phase have been summarised in Table 5.3.

Figure 5.4: Diagram showing the three layers of the priority-setting model.

The use of the priority-setting model would usually precede the use of the MCDSS, although this sequence is not obligatory. The two models although dealing with different sections of stormwater management are both essential. The MCDSS helps the user to select the appropriate BMPs for a given site and the priority-setting model prioritises the subsequent implementation of the BMP programme.

5.3 RESULTS

The results have been divided into two sections. The first section concerns the site information of the eleven sites that were recorded along the length of the Town Bush Stream. The second section concerns the setting of priorities. The position of each of the eleven sites within the study area can be seen in Figure 5.5. Although a summary of the site data i.e. geographical position and Land Type Unit specifications are shown in Table 5.1, each of the eleven sites will be dealt with in detail and all information that has been processed into the MCDSS shown. At the end of this section, a summary table of the MCDSS output for each of the eleven sites as well as all selected options has been provided (Table 5.2).

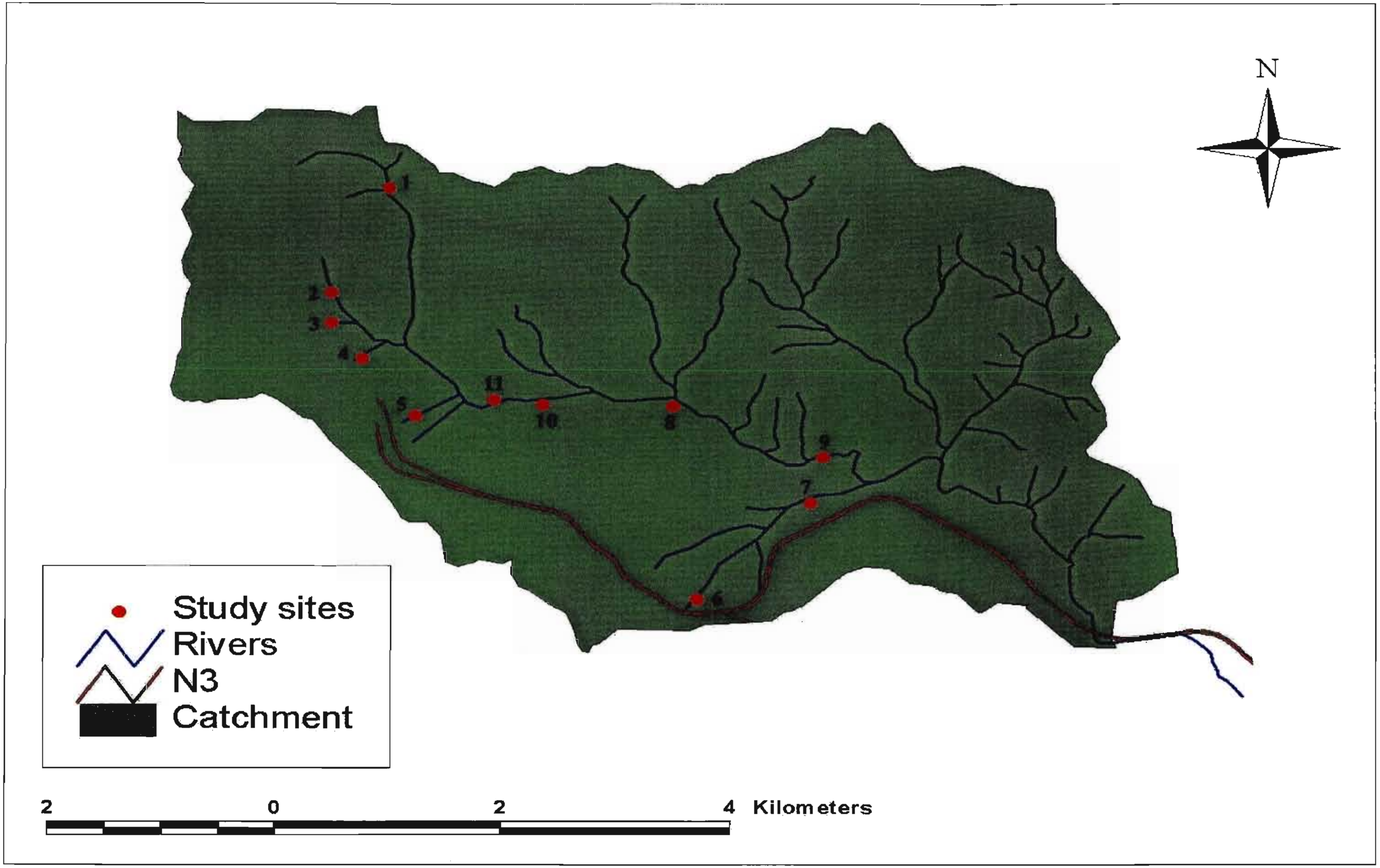

Figure 5.5: Map of the Town Bush stream catchment. Red circles show the position of the eleven study sites along the river network

Table 5.1: Summary of the site data for each of the 11 sites within the Town Bush Stream catchment

Site No.	Site description	GPS (S)	GPS (E)	Altitude (m)	Catchment area (km^2)[1]	Land Type	Hydrological soil group	Slope (%)	Runoff source/site
1	Wetland	29°32'41"	30°19'00"	1040	0.99	Ac 220	A	4	Res L-M
2	Stormwater pipe (N3)	29°33'14"	30°18'42"	1041	0.03	Ac 220	B	5	Road
3	Stormwater pipe (N3)	29°33'27"	20°18'41"	1059	0.18	Ac 220	B	5	Road
4	Stormwater pipe (N3)	29°33'38"	30°18'47"	1003	0.20	Ac 220	B	7	Road
5	Brick culvert QEP	29°33'49"	30°18'02"	926	0.22	Ac 220	B	4	Road
6	Concrete swales under N3	29°35'02"	30°20'31"	809	0.15	Ac 220	B	3	Road
7	Open park Cnr Frances Staniland/Mariott Rds	29°34'29"	30°21'01"	706	2.30	Ac 118	C	3	Res L-M
8	Open park Cnr Warick/Town Bush Rds	29°33'51"	30°21'03"	757	2.90	Ac 118	C	2	Res L-M
9	Car park – Cascades shopping centre	29°34'18"	30°21'19"	698	0.09	Ac 118D	D	1	Comm H-D
10	Open area along Town Bush Rd above Collen Ave	29°33'56"	30°19'53"	804	9.30	Ac 118	B	2	Res L-M
11	Waltdorf housing development	29°33'55"	30°19'37"	820	0.73	Ac 118	D	3	Res M-H

[1] to convert from km^2 to ha multiply by 100

Site 1. Wetland below Hilton Gardens

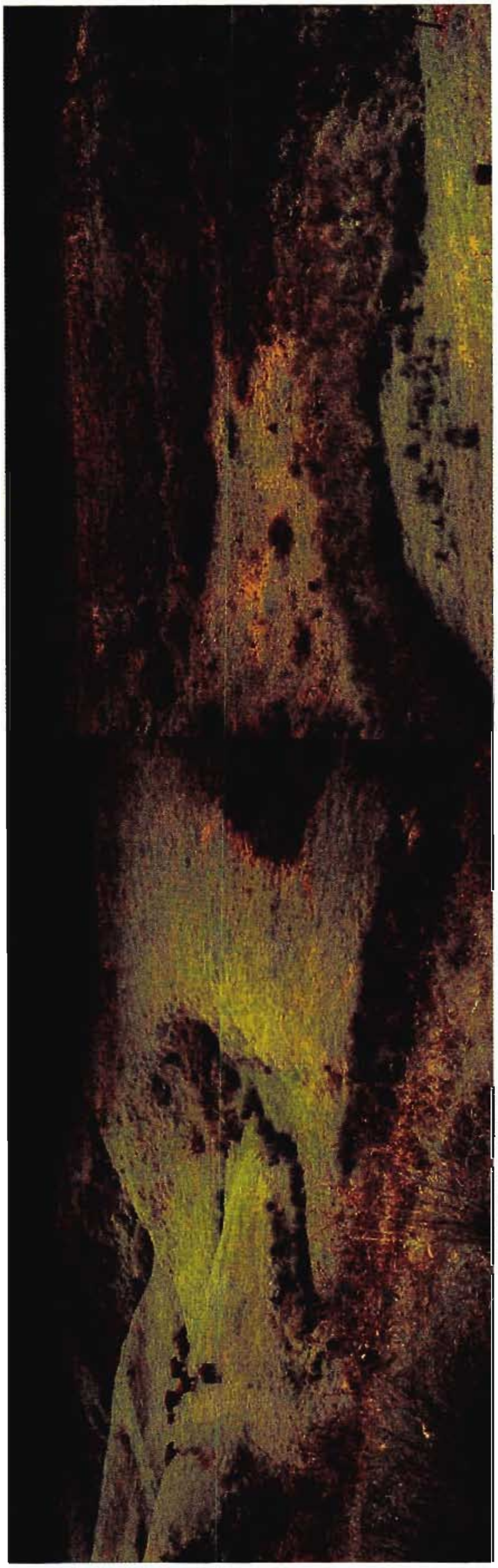

Plate 5.2: Photo taken below Hilton Gardens looking east towards Garlick Timber land.

1) *Site description*

This site occurs to the east of Hilton Gardens and is situated adjacent to Garlick Timber plantations. A temporary wetland seems to have already been initiated due to the presence of a concrete weir (pers. obs.). Taking cognisance of this fact, one could assume that if a wetland system were deemed to be the most suitable option for such a site then certain objectives namely: groundwater recharge, and runoff volume reduction would not usually form part of the management objectives since the wetland system has a low ability to meet this criteria. Hence, the selection of management objectives at aspect 3.

2) ***Site information data used for the MCDSS***

a. Hydrological soil group = A
b. Water table (m) = not available
c. Slope (%) = <5
d. Drainage area (ha) = 99
e. RSC = Low-medium residential

3) ***Management objectives***

a. Water quality improvement
b. Flood control
c. Streambank erosion control
d. Flow rate control

4) ***Environmental and other considerations***

As this site is near Hilton Gardens and already in a site applicable to the development of a wetland system it would be appropriate to develop a system that would incorporate various environmental considerations. The site should therefore be designed to provide habitat for both aquatic and terrestrial species, be aesthetically pleasing, and it should provide recreational benefits.

Site 2/3/4. Stormwater pipes and culverts along the N3

Plate 5.3: Photo of site 2 looking west towards the N3. This site is two metres below the asphalt.

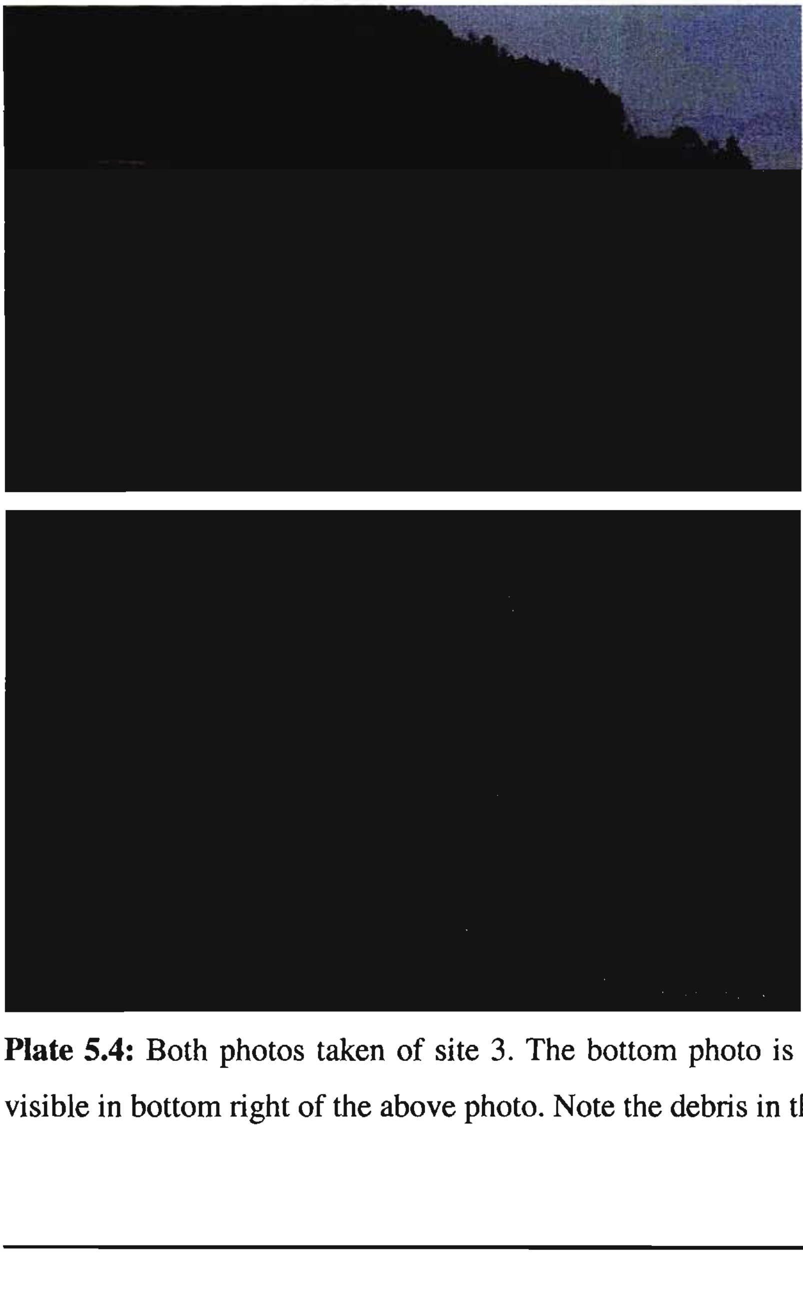

Plate 5.4: Both photos taken of site 3. The bottom photo is taken directly below the drain that is visible in bottom right of the above photo. Note the debris in the drainage course.

Plate 5.5: Photo taken inside the concrete culvert looking west towards the highway.

1) *Site description*

These sites occur along the National highway (N3) in the vicinity of Monzali's Castle. Stormwater runoff from the highway and from Hilton is channelled through these pipes. Below the outflows of each of these sites, stream channel widening was visible. This could be attributed to the increased velocities and volumes of runoff associated with urbanisation. As such, large amounts of sediment continue to be deposited in the Town Bush Stream (Biggs *et al.* 2001).

When management objectives for these sites were considered one had to take into account certain site limitations. One major limitation is the availability of space. Thus the design of certain systems would thus be limited. Hence even before the data is to be input into the MCDSS it should be noted that detention systems that are designed to control aspects such as flow rates and flood control were deemed to be inappropriate given the limits of space. As such only two management objectives were included.

2) *Site information data used for the MCDSS*

a. Hydrological soil group = B
b. Water table (m) = not available
c. Slope (%) = 5-7
d. Drainage area (ha)
   i. Site 2 = 03
   ii. Site 3 = 18
   iii. Site 4 = 20
e. RSC = Road/highway

3) *Management objectives*

a. Water quality improvement
b. Runoff volume reduction

4) *Environmental and other considerations*

As this site is close to the national road is might be applicable to design a system that provides some degree of environmental amenities.

Site 5. Constructed concrete and brick culvert on Queen Elizabeth property

Plate 5.6: Photo taken of the brick culvert looking west towards the highway.

1) ***Site description***

This site occurs on Queen Elizabeth Park (QEP) property. The runoff originating from the highway and Hilton is channelled into concrete swales that dump water into the natural river system. As such the water increases in velocity as it moves down the steep slopes above QEP. The results of such a process include fluvial undercutting, streambank erosion and channel widening. Previously the water from the upper reaches of the stream dumped directly onto an open field within the park bounds. The water would waterlog large areas of the park's nursery hence the park authorities have in fact created another brick culvert exacerbating the erosion problem.

When applicable management objectives for the site were chosen one was able to include all but one. This reason for this is due to the fact that there seem to be no site limitations but as the site is receiving water from other sources it would not be possible to reduce runoff in any way. Best management practices constructed at the point of runoff accumulation would be more suited to perform such an objective.

2) ***Site information data used for the MCDSS***

a. Hydrological soil group = B
b. Water table (m) = not available
c. Slope (%) = 4
d. Drainage area (ha) = 22
e. RSC = Road/highway

3) ***Management objectives***

a. Water quality improvement
b. Streambank erosion control
c. Flood control
d. Flow rate control
e. Groundwater recharge

4) ***Environmental and other considerations***

Some degree of environmental benefits should be incorporated into the design of any BMP system.

Site 6. Concrete swales draining underneath the N3

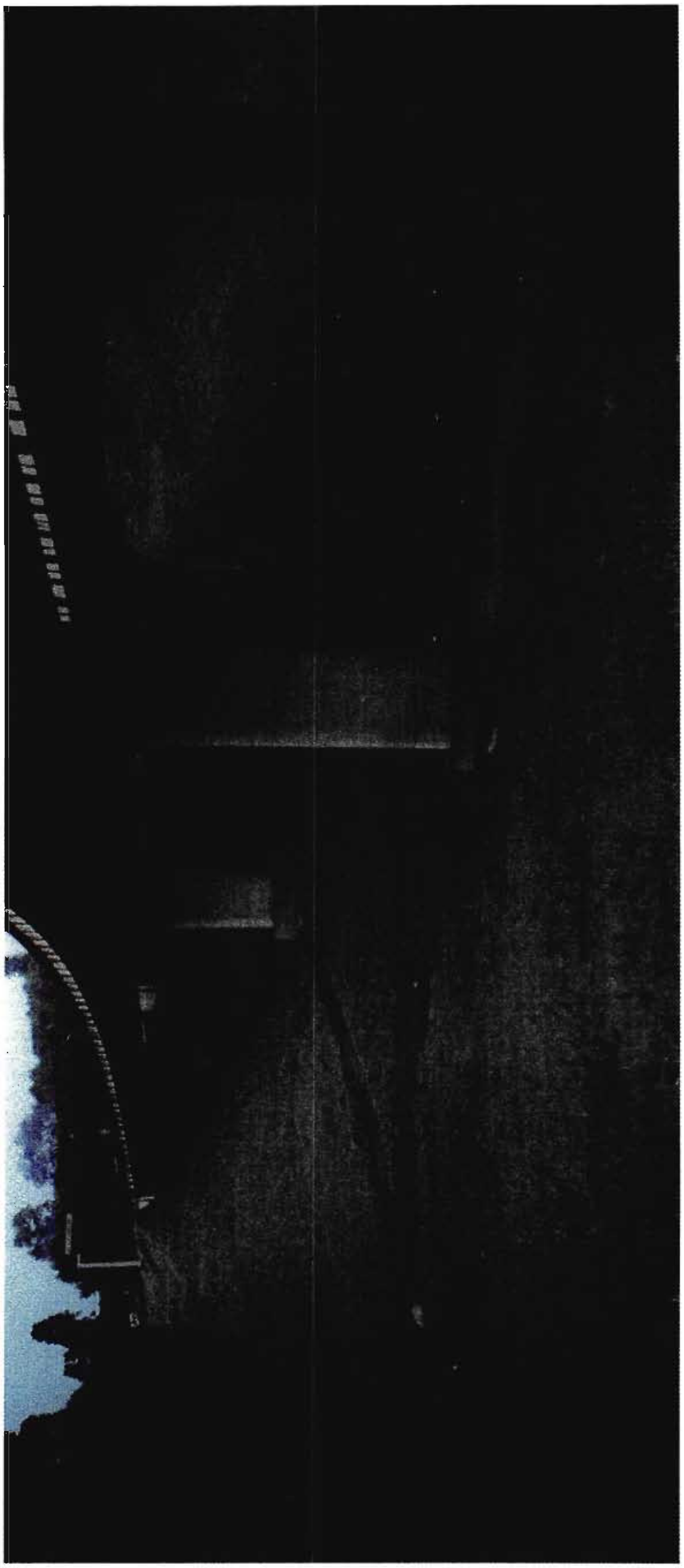

Plate 5.7: Photo taken underneath the N3 looking south towards Pietermaritzburg.

1) *Site description*

This site was directly underneath the N3. Several large concrete culverts were draining stormwater from various sections of the upper catchment. The culverts continued for approximately 50m before the stormwater was dumped into the river system. Due to the fact that this site is in the vicinity of the structural pillars of the national road it would be advisable to design a system that does not use infiltration as its main function for stormwater management. As the increased soil moisture content might affect the instability of the soil thus affecting the integrity of the pillars.

2) ***Site information data used for the MCDSS***

a. Hydrological soil group = B
b. Water table (m) = not available
c. Slope (%) = 3
d. Drainage area (ha) = 15
e. RSC = Road/highway

3) ***Management objectives***

a. Flood control
b. Streambank erosion control

4) ***Environmental and other considerations***

Some degree of environmental benefits should be incorporated into the design of any BMP system.

Site 7. Open park area. Corner of Frances Staniland and Mariott Rds.

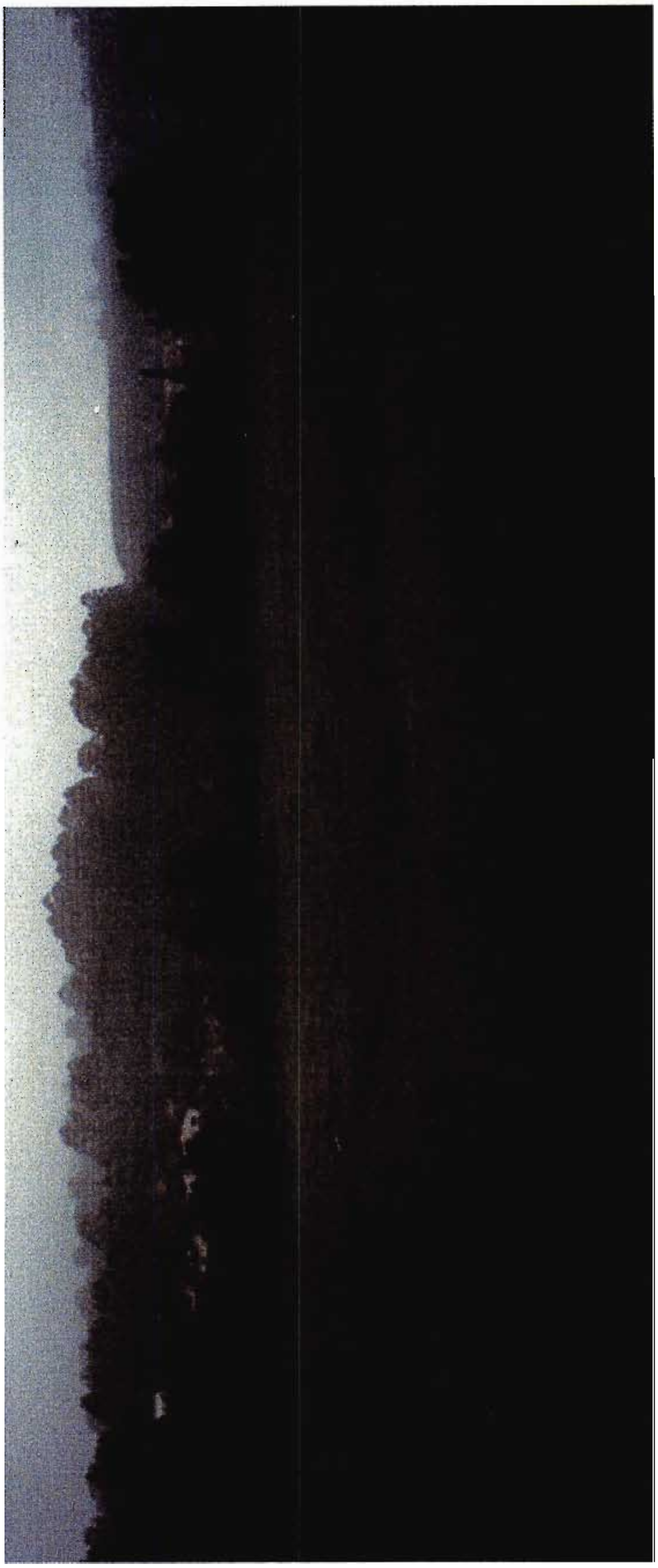

Plate 5.8: Photo taken on Mariott road looking east towards Cascades shopping centre.

1) *Site description*

This site was situated at the base of the southern tributary of the Town Bush steam. An open park would thus form the site where any BMP plan would be implemented. The reasons for this site being selected were that space would not be a limiting factor and secondly due to the vicinity of housing developments any BMP implemented could be designed with recreational benefits such as walking or bird watching in mind. The main aim would be to detain water as long as possible in order for settling of sediments and other nutrients to take place. As mentioned previously this site receives runoff from other areas hence it would not be possible to include the reduction of runoff as a management aim.

2) *Site information data used for the MCDSS*

a. Hydrological soil group = C
b. Water table (m) = not available
c. Slope (%) = 2
d. Drainage area (ha) = 230
e. RSC = Low-medium residential

3) *Management objectives*

a. Water quality improvement
b. Flood control
c. Streambank erosion control
d. Flow rate control

4) *Environmental and other considerations*

Any BMP that is selected should be designed to include the entire range of environmental benefits.

Site 8. Open park. Corner of Warwick and Town Bush Rds.

Plate 5.9 (a): Photo taken on Warwick road looking south towards Cascades shopping centre. Town Bush is to the right.

Plate 5.9 (b): Photo taken at (A) on Plate 5.8 (a). These pipes carry water of the Town Bush underneath the gravel road above.

Plate 5.9 (c): Photo taken to the right of plate 5.8 (b). Note how the river has incised.

1) ***Site description***

The reasons for the position of this site are similar to site 7 above. This site receives runoff from the Ferncliffe residential area. At the time of the field survey, channel widening and erosion were clearly visible. The outside meander of the river is adjacent to numerous properties. As this is a high-energy environment any widening of the stream channel will place the integrity of these properties in jeopardy. Hence, any development of this site would need to alter the stream channel to flow through the BMP plan. Management objectives for this site are similar to site 7.

2) ***Site information data used for the MCDSS***

a. Hydrological soil group = C
b. Water table (m) = not available
c. Slope (%) = 2
d. Drainage area (ha) = 290
e. RSC = Low-medium residential

3) ***Management objectives***

a. Water quality improvement
b. Flood control
c. Streambank erosion control
d. Flow rate control

4) ***Environmental and other considerations***

Any BMP that is selected should be designed to include the entire range of environmental benefits.

Site 9. Car park – Cascades shopping centre

Plate 5.10: Photo taken within the grounds of Cascades shopping centre. (A) refers to the Town Bush stream that flows through the centre.

1) ***Site description***

This site was situated within the bounds of the Cascades Shopping Centre. As plans have been passed for the further extension of the parking lot into the wetland it would be advisable to design this structure with detention storage in mind. The reason for the inclusion of this site was to examine if the MCDSS was functioning correctly. An educated guess would result in the developers designing the parking lot for detention of stormwater before allowing it to filter into the stream channel. However, other choices are available such as porous pavement or porous pavement (reservoir design). As such, it is an interesting scenario for the MCDSS to process.

2) ***Site information data used for the MCDSS***

a. Hydrological soil group = D

b. Water table (m) = not available

c. Slope (%) = 1

d. Drainage area (ha) = 0.9

e. RSC = High density commercial

3) ***Management objectives***

a. Runoff volume reduction

b. Flood control

c. Flow rate control

4) ***Environmental and other considerations***

Environmental considerations are always included in the MCDSS selection process. However, parking lots score zero under this section.

Site 10. Open area along Town bush Rd above Collen Ave

Plate 5.11 (a): This photo was taken along a dirt road looking towards the N3. The Waltdorf housing development is to the right and the Queen Elizabeth golf course to the left.

1) ***Site description***

This site is at a key position as it receives all runoff from the upper sections of the Town Bush stream catchment. Runoff generated from Hilton, Hilton Gardens, Montrose, QEP all filter through this site. Earlier in the year a collapsed slope was identified in the upper catchment, in the vicinity of the Monzali Castle property (Biggs *et al.* 2001). This has lead to high levels of sedimentation and turbidity. As a result, water quality samples taken by Mr Mark Graham of Umgeni Water in respect of the Town Bush stream on 31 May 2001, found no visible algae, limited primary biota, and all rocks covered in thick sediment. He thus concluded that severe damage had been caused to the riparian habitat. The development of a BMP at this site is thus crucial to limiting the damage caused by sediment in the stream channel. Plate (5.10 b & c) shows the contrast between the natural load in a tributary and the high sediment load in the Town bush stream. Other important aspects of this site include the vicinity of properties and the availability of space.

2) ***Site information data used for the MCDSS***

a. Hydrological soil group = B
b. Water table (m) = not available
c. Slope (%) = 2
d. Drainage area (ha) = 930
e. RSC = Low-medium residential

3) ***Management objectives***

a. Water quality improvement
b. Flood control
c. Streambank erosion control
d. Flow rate control

4) ***Environmental and other considerations***

Due to the vicinity of housing developments, any BMP implemented should be designed with recreational benefits such as walking or bird watching in mind.

Plate 5.11 (b): Tributary of the Town Bush stream flowing from the Queen Elizabeth golf course. Note the natural level of sediment.

Plate 5.11 (c): Main channel of the Town Bush stream draining from the northern areas. Note the high levels of sediment in the stream channel as a result of the collapsed slope in the vicinity of Monzali's Castle.

Site 11. Waltdorf housing development

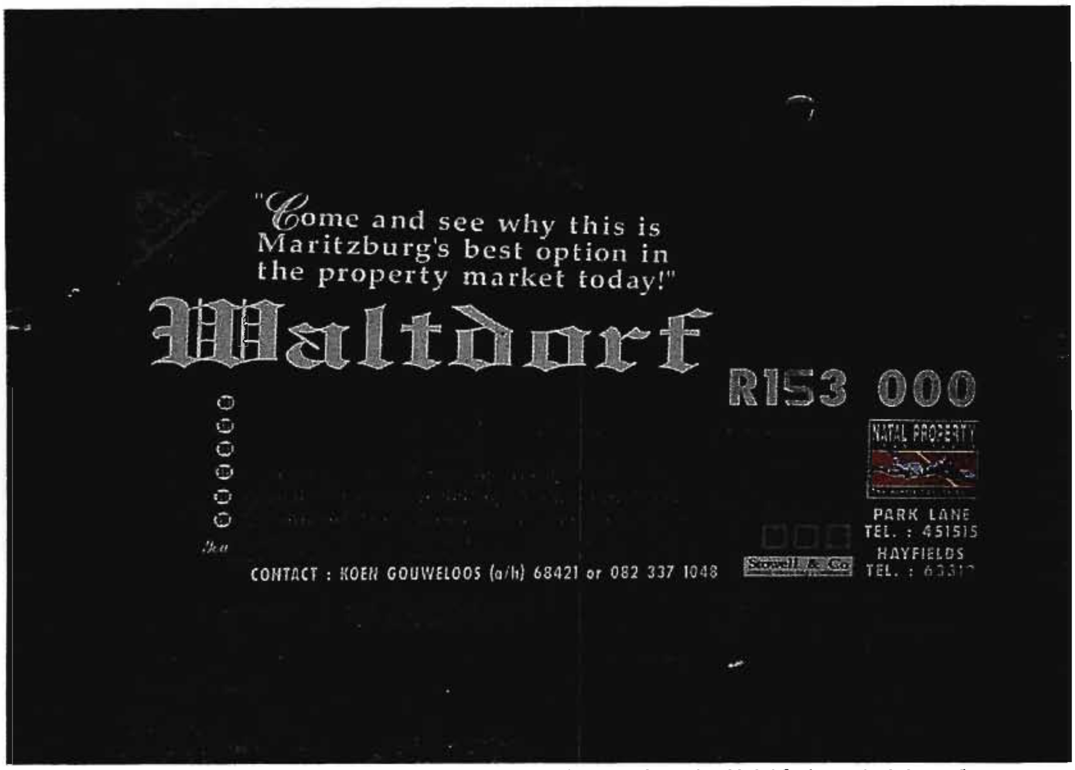

Plate 5.12 (a): The developers were only allowed to build if they initiated stormwater management techniques. They built grass swales and two dry detention basins thus, setting a precedent for further developments.

Plate 5.12 (b): View of the Waltdorf housing development. Note the concrete swale draining down the steep bank and the bare soil.

Plate 5.12 (c): Runoff from the swale is channelled through this pipe and into a detention basin. Note the erosion already taking place.

Plate 5.12 (d): Detention basin in the process of being constructed. Runoff from the upper section of the Waltdorf housing development is channelled into this basin and out through the pipes, labelled A.

Plate 5.12 (e): Grass swale that channels water into a completed dry detention basin (Plate 5.11 (d)).

Plate 5.12 (f): A dry detention basin developed specifically for the Waltdorf housing development. Note the outlet pipes at (A) and the erosion already taking place at (B).

1) ***Site description***

This site was included to test and compare the MCDSS. Although the developers have included certain BMPs such a grass swales (Plate 5.11 e) and two detention basins (Plate 5.11 d & f) it would be useful to examine the MCDSS output for this site.

2) ***Site information data used for the MCDSS***

a. Hydrological soil group = D
b. Water table (m) = not available
c. Slope (%) = 3
d. Drainage area (ha) = 73
e. RSC = Low-medium residential

3) ***Management objectives***

a. Flood control
b. Water quality improvement
c. Flow rate control
d. Streambank erosion control

4) ***Environmental and other considerations***

In terms of the environmental amenities, these structures should be designed to take into account the surrounding land features in order to lessen the visual impact. Harrison (pers. comm. 2000) stated that the residents have taken it upon themselves to maintain these systems i.e. mowing and removing sediment build-up. This practice would thus ensure the long-term success of these systems.

The above set of information was thus processed into the MCDSS in order to obtain the most suitable BMP options that could be implemented at each of the eleven sites (Table 5.2).

Table 5.2: MCDSS output for the eleven sites showing all selected options. INF = infiltration rate/ hydrological soil group; WT = water table; S = slope; DA = drainage area; RSC = runoff site characteristics; O & M = operation and maintenance costs. Note for selection process, if BMPs scored a zero in the TSM category they were not included. Especially sites 2,3 & 4 where runoff volume reduction was deemed a necessity.

No.	Site information					Management objectives						Environmental and other considerations					
	INF	WT (m)	S (%)	DA (ha)	RSC	Water quality	Runoff volume reduction	Groundwater recharge	Flood control	Streambank erosion cont.	Flow rate control	Habitat creation	Aesthetics	Recreational benefits	O & M	Cost (relative to drainage area)	MCDSS output
1	A	N/A	<5	99	L-M residential	✓			✓	✓	✓	✓	✓	✓	✓	✓	R1) Wet pond R2) Wet ED basin R3) Constructed wetland
2	B	N/A	5	3	Road	✓	✓					✓	✓	✓	✓	✓	R1) Infiltration basin R2) Infiltration trench R3) Filter strip
3	B	N/A	5	18	Road	✓	✓					✓	✓	✓	✓	✓	R1) Infiltration basin All other BMPs scored a zero in one or other category
4	B	N/A	7	20	Road	✓	✓					✓	✓	✓	✓	✓	R1) Infiltration basin All other BMPs scored a zero in one or other category
5	B	N/A	4	22	Road	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	R1) Wet pond R2) Wet ED basin R3) Infiltration basin
6	B	N/A	3	15	Road	✓			✓	✓	✓	✓	✓	✓	✓	✓	R1) Wet pond R2) Wet ED basin R3) Constructed wetland
7	C	N/A	3	230	L-M residential	✓			✓	✓	✓	✓	✓	✓	✓	✓	R1) Wet pond R2) Constructed wetland R3) Wet ED basin

Table 5.2: Continued.

No.	Site information					Management objectives						Environmental and other considerations					
	INF	WT (m)	S (%)	DA (ha)	RSC	Water quality	Runoff volume reduction	Groundwater recharge	Flood control	Streambank erosion cont.	Flow rate control	Habitat creation	Aesthetics	Recreational benefits	O & M	Cost (relative to drainage area)	MCDSS output
8	C	N/A	2	290	L-M residential	✓			✓	✓	✓	✓	✓	✓	✓	✓	R1) Wet pond R2) Constructed wetland R3) Wet ED basin
9	D	N/A	1	9	H-D commercial		✓		✓		✓	✓	✓	✓	✓	✓	R1) Porous pavement (reservoir design) R2) OSD
10	B	N/A	2	930	L-M residential	✓			✓	✓	✓	✓	✓	✓	✓	✓	R1) Wet pond R2) Wet ED basin R3) Constructed wetland
11	D	N/A	3	73	M-H residential	✓			✓	✓	✓	✓	✓	✓	✓	✓	R1) Wet pond R2) Constructed wetland R3) Wet ED basin

The results for the priority-setting model are summarised in Table 5.3. As mentioned earlier the sites were sorted firstly by land ownership (who is the responsible party), secondly by potential risk where the integrity of important structures were threatened (property, buildings, bridges), and lastly by the hydrological behaviour of stream at the site (peak discharge and runoff volume calculations).

Table 5.3: Results of the priority setting model for the eleven sites along the Town Bush stream catchment. Numbers in brackets represent the adjusted sequence of sites according to the SCS-SA runoff analysis

Responsible party	**Site No.**	**Ranking according to property threat**	**Ranking according to SCS-SA runoff (2, 5, 10 yr storm events)**					
			Runoff volume (thousand m^3)			**Peak discharge (m^3/s)**		
			2 yr	**5yr**	**10yr**	**2yr**	**5yr**	**10yr**
Garlick Timber (Pty) Ltd/ Mileca Prop. (Pty) Ltd	1	N/A	9	23	39	1.3	3.8	6.5
National Rds	2	N/A	(4) 12	17	21	3.4	4.8	5.9
	3	N/A	(3) 11	15	19	3.3	4.6	5.6
	4	N/A	(6) 9	13	16	2.5	3.6	4.4
	6	N/A	(2) 2	3	4	1.0	1.5	1.8
National Rds /QEP/Council	5	5	13	19	26	3.7	5.2	6.4
Msunduzi local council	7	10 & 8	(10)[1] .25	.44	.59	22.8	39.7	54.1
	8	7	(8) 134	205	261	19.0	29.0	36.8
	10		(7) 62	107	145	8.8	15.2	20.6
Old Mutual Property Developers	9	N/A	N/A[2]			N/A[2]		
Waltdorf Housing Complex Developers	11	N/A	N/A[2]			N/A[2]		

1 These values relate to runoff volume in million m^3

2 SCS-SA runoff analysis was not performed on these sites as they are offline systems and therefore there was no value for the hydraulic length catchment along the main channel in the peak discharge equation

CHAPTER 6: DISCUSSION

As the aim of MCDSS is to provide the user with a guide to decision making one would still need to examine the output before making the final decision. Although the MCDSS seemed to perform adequately, it is not with out its limitations. The aim of this chapter is thus two-fold firstly it will provide an appraisal of the MCDSS and secondly, after noting the limitations, an overall stormwater plan for the Town Bush stream catchment will be provided taking into account *inter alia* the MCDSS output, highlighted stakeholders, property threats, and SCS-SA runoff analysis results.

6.1 AN APPRAISAL OF THE MCDSS

To obtain recommendations for BMP implementation and to sufficiently test the performance of the MCDSS, a field study was thus a crucial part of the ongoing design process. This dissertation was only a preliminary investigation into BMP technology and aimed to develop a preliminary system for selecting BMPs. Hence it was clear from the start that the final product of this investigation would not be without its flaws given the scope of the study and limitations of time. The purposes of this appraisal are thus to discuss both the advantages and limitations of the MCDSS, and thus provide recommendations for further improvement and use.

The development of the MCDSS proceeded through various stages. Stage one could be seen as the literature review and culminated in the development of the primary matrix (Table 4.8). Stage two was the initial testing phase and the setting of weighting factors culminating in the final MCDSS. Stage three was thus the testing of the MCDSS in its own case study, the aim being to examine the process needed when dealing with catchment scale issues and to highlight potential benefits and drawbacks of the system. After completing all three stages a clear picture has developed where the practicality and usefulness of such a system can be sufficiently examined.

This appraisal will thus follow the same path as the entire design phase of the MCDSS. The three stages will be dealt with in a sequential manner with limitations and benefits of each being highlighted.

6.1.1 Appraisal of stage one (literature review to primary matrix development)

This stage held the key to the successful design of the MCDSS. A wide range of literature was consulted in order to form the primary matrix. During the literature review phase not a lot of consensus occurred among the authors in respect of BMP capability. Each author gave his or her own account of the usefulness and success rate of BMPs. One author might give a very good account of BMP use i.e. he/she might state, "Infiltration basins provide a high degree of flood control" whereas another might state only that infiltration basins provide and adequate or limited degree of flood control. However, the design of the primary matrix was made easier by the fact that design and selection manuals dealing with the entire range of BMPs and selection options were in print and available. A large body of information was also gleamed off the Internet.

A second problem encountered during this stage was the fact that BMPs were implemented in a wide range of countries and no detailed studies of successful implementation within southern Africa were available. Hence one could not be certain that the scores decided upon in the literature would hold true for South African conditions. The only respite is that a majority of the scores entered into the MCDSS where obtained from BMP projects implemented under conditions similar to those found in South Africa.

Taking into account the above set of obstacles one could not be certain that the values awarded to each BMP were reasonable. However, for a preliminary assessment of BMP technology it was adequate as the initial testing phase shows.

6.1.2 Appraisal of stage two (initial testing and weighting)

This stage was useful in determining how accurate the values in the primary matrix were. As mentioned in Chapter four, the primary matrix was the first stage of MCDSS development after a few literature checks the values were altered and then expanded into the MCDSS. The initial testing phase was successful as the MCDSS output for the seven scenarios were similar to those provided by the various authors and the other selection tools. However, at this stage only a handful of selection criteria were included in order to make the final selection. When environmental and cost criteria were included into the selection process, changes occurred (section 4.5.1). In order to correct these changes it was deemed necessary to implement a weighting scheme (section 4.5.2). Thus one could argue that another level of uncertainty was added to the process.

The literature was consulted at this point in order to determine what weights should be assigned to the selection factors. Again the final weights are subjective as each author's views were translated into weighting factors. The weights are also biased towards treatment suitability and management objectives as apposed to environmental benefits, BMP costs, and failure rates. Although the reasons given were that any BMP system that is to be implemented would need to perform the same functions as the engineering system it would replace.

Once the MCDSS was altered to include the weighing scheme, it was deemed to have improved the selection ability of the system, as now all criteria were taken into account. Unfortunately a few drawbacks of the weighting scheme are clear when it is used. The main problem is the fact that one is unable to place individual weights onto each of the management criteria. For instance one might want to improve water quality as well as reducing flooding but the system adds the scores for these criteria together and multiplies the total by the weighting factor. The same problem occurs with the environmental and cost/threat sections. Taking these issues into consideration, the MCDSS still performs relatively well.

A major drawback of the entire system it that is has been designed for use by professionals only. For example most of the data that needs to be processed into the system could only be obtained by technical means. A GIS technician was used to provide information regarding drainage areas and slope and soil analysis. Only after this process had been completed could one obtain the data necessary for the MCDSS. A second problem with the implementation of selected BMP options is the highly technical nature of the BMPs. Appendix 1, lists several references where detailed information on BMP design and costing can be acquired.

Before moving onto the last stage, it should be said that in the past BMP plans were implemented with the best intentions in mind (Jefferies *et al.* 1999). However, most of these failed due to several factors including bad design, poor site selection, insufficient funding, or incorrect choice for the management goals in question. Hence, this MCDSS has consolidated a large body of information into one tool for selection. Even though the final choice still rests in the hands of the developer, the reference list accompanying this dissertation could be a useful guide to detailed reports and technical design manuals regarding the successful implementation of BMPs.

6.1.3 Appraisal of stage three (field study)

This stage provided a successful means of examining the potential of the MCDSS through practical application. Most of the data needed for the study was obtainable except for information regarding water table depths. In hindsight, a surrogate criterion such as soil morpholoy should have been developed or maybe this criterion should have been omitted. The aim of this stage was to provide the means of taking obtainable data such a maps and GIS databases and using them to provide the necessary information needed for the MCDSS to make an appropriate selection. As stated many times this system is only a preliminary assessment and aims to provide the developer or user with a narrow choice regarding the plethora of BMPs that could be implemented. Although only the top three ranked BMPs were chosen for discussion one could examine the merits of maybe the top five. Beyond which large gaps occur between the BMP scores. What this model has succeeded in doing is that is does eliminate several BMPs from consideration. Thereby, providing the user with a narrow field of BMPs to choose from. Again, the BMPs included in this study are entry-level designs but more complicated designs, may be found in the literature accompanied by detailed sizing and hydrological design specifications.

Although the MCDSS has its advantages, the user should be cautioned against its limitations. These include the use of drainage areas as a surrogate measure for peak discharge. This limitation was quite severe, as it does not allow the user to design a series of BMPs or treatment chain. For example when one moves from the upper catchment at Hilton Gardens to the confluence of the southern tributary at the Allerton Veterinary Station the drainage area increases considerably. However, would this drainage area not decrease if one where to implement a detention system on the stream channel? Hence, the flow volumes, peak discharges, and drainage areas would then need to be recalculated for this change. In the MCDSS the drainage area criterion is biased towards small drainage areas as most of the BMPs function optimally below ten hectares. However, most of the sites had drainage areas greater than this value thereby eliminating several BMPs. If however, this adjustment could be made then several BMPs might be reinstated.

A second major limitation of this system relates to the actual usefulness of the BMPs. Most of these BMPs tend to be site specific or designed as offline systems to handle stormwater runoff from localised sites before allowing the water to reach the stream channel. In this study however, the BMPs were used as inline systems. Hence the ultimate selection of BMP options was biased towards those systems able to deal with large drainage areas.

Two other limitations of the MCDSS are that BMPs that score zero are not automatically flagged for user review. This would need to be factored into a working model if it were to be designed. Lastly, the colour coding system that was designed to aid the user in selecting BMPs was excluded, as a working model was not developed. Again, if a computer based MCDSS were to be developed this system would greatly add to the power of the MCDSS, as it provides a visual presentation of the outcomes.

Taking the above issues into consideration the MCDSS seemed to perform adequately, even though the wet pond, wet extended detention basin and constructed wetland BMPs were selected as the most appropriate BMPs for implementation at six of the eleven sties. However, the repetitive selection of these BMPs may be related to the site similarities and not to any inadequacy of the MCDSS. The reason for this is that the BMPs were used as inline systems. Hence, the majority of the drainage areas were greater than ten hectares thereby limiting the number of BMPs that could have been selected by the MCDSS.

6.2 A STORMWATER PLAN FOR THE TOWN BUSH STREAM CATCHMENT

Urbanisation and the effects thereof have been highlighted in Chapter two. What is required, however, is that consideration must be given to methods that mitigate the effects of increased run-off due to urbanisation. In this regard, the following suggestions are submitted.

South Africa's new water law provides a legal framework for the implementation of the recommendations that are to follow. The new National Water Act 36 of 1998 (here after referred to as the NWA) is intended to facilitate the achievement of environmentally sustainable, socially equitable and economically efficient use of the country's water resources. This is summed up by the Department of Water Affairs and Forestry's mission statement, "Some, for all, forever" (DWAF 1997). Thus the NWA represents a major shift in the philosophy and practice of water resource management. The explicit aim of the NWA is to balance the demands of resource protection with the demands of resource use in order to achieve long-term sustainability of the resource. This will require holistic, integrated and co-operative catchment management.

Integral to this purpose is the development of Catchment Management Strategies (CMS), which must contain sub-strategies for protecting and managing the biophysical aspects of the catchment. A catchment-based approach allows water managers to manage (or at least take cognisance of) all the components of the hydrological cycle within the catchment (Van Wyk *et al.* 2000). Thus people charged with managing the catchment need to understand the interactions and links between land uses and water quality in the catchment in order to manage in an integrated manner.

The Town Bush steam catchment is thus an ideal case study to examine the implications of the NWA. The catchment is divided up into two major land use sectors namely forestry and urban areas and as such the aim "…to balance the demands of resource protection with the demands for water use…" must be met if one hopes to achieve long-term sustainability. It is to the issue of resource protection were the stormwater plan will now focus.

One of the key problems in the Town Bush stream is sediment resulting from a collapsed slope in the vicinity of the Monzali castle property. Sediment is in terms of the NWA defined as a waste as:

> "…any solid material or material that is suspended, dissolved or transported in water (including sediment) and which is spilled or deposited on land or into a water resource in such volume, composition or manner as to cause, or to be reasonably likely to cause, the water resource to be polluted (Section 1(1) (xxiii)."

In terms of resource quality, and the impact of sediment thereon, if the character and condition of the instream and riparian habitat or the characteristics, conditions and distribution of the aquatic biota are affected in any way then pollution of the resource has occurred. Taking into account Mark Graham's observation of the Town Bush stream 31 May 2001 (pg 99), then one can *prima facie* deduce that pollution has taken place and hence the resource needs protection. Furthermore one can also state that the general obligation stipulated on persons to "…take all reasonable measures to prevent any such pollution from occurring, continuing or recurring (Section 19 (1))" has been violated. The persons in question include an owner of land, a person in control of land or a person who occupies, or has the right to use, land one which any activity that has been undertaken which causes, has caused or is likely to cause pollution of a water course. In concluding this section then failure of any such person to implement reasonable measures to prevent pollution shall be found to have transgressed the NWA (Section 151 (1) (h)). The NWA thus gives backing to relevant catchment management agencies to step in if these measures have not been taken, and direct the relevant persons to do so by a stipulated date (Section 19 (3)). If the person in question still does not comply, "… the catchment management agency may take measures it considers necessary to remedy the situation (Section 19(4))" and subject to Section (6) may recover all costs incurred in the process (Section 19 (5)).

The above set of legislation empowers the relevant catchment management authorities to take all measures possible to prevent or mitigate pollution to protect the water resource and to inform the relevant persons of their duty. The individual land owner although under certain circumstances may be one of the stipulated persons may also invoke their environmental right as set out in Section 24 of the Constitution of South Africa. As such one can see that legal backing could be invoked if relevant authorities do not act. Taking cognisance of the above issues the following suggestions are provided.

6.2.1 Stakeholder recommendations

Although there are several stakeholders involved within the bounds of the Town Bush stream catchment (Biggs *et al.* 2001), two main parties stand out. These include the National Roads Department and the Msunduzi Local Council. The details of the participative process followed by Biggs et al. (2001) can be found in their state of the environment report. However, as the aim of this section is to provide an holistic approach to stormwater management in the Town Bush stream catchment, all stakeholders and their responsibilities according to section 19 (1) of the NWA will be laid out. The proposals of the implementation of specific BMPs will begin from the top of the catchment to the Allerton Veterinary Station below Cascades shopping centre.

The first site of significance is site 1 on Garlick Timber property. The MCDSS chose the Wet pond as the preferred option. Examining the output (Appendix 4) one can see that this BMP met all the aims for the site. Bearing in mind the higher score of this BMP it also outscores wet ED basin in all environmental categories. Since this site is in the vicinity of Hilton Gardens, the potential is there for this site to become a community resource as well. If for instance there is a community action group they could help in the maintenance of the pond. This pond should be designed to contain the flood volume for at least the two-year storm event. This would limit the erosion potential downstream of this site.

Site 2, 3, 4 and 6 all occur along the National highway. Runoff from site 2 flows through the African Enterprise property, while runoff from site 3, 4 flows through Queen Elizabeth Park (QEP) and finally runoff from site 6 flows into a separate tributary which confluences with Town Bush stream at the Veterinary station. The National Roads Department has been identified as the responsible person for these sites. Runoff from the road has been channelled directly into the stream channels. Site 6 is particularly bad as three large concrete swales carry water into the stream tributary. These increased volumes of water, carried in narrow tributaries, have caused stream widening lower down. Although site 3 and 4 have priority over 6 and 2 it is necessary for practical reasons to deal with site 2, 3, and 4 as a unit. Site 6 as mentioned is on another tributary and as such will be dealt with separately.

Since site 2 is above 3 and 4 and has relatively small volumes of water and a peak di· passing through the pipe one would rather select the fourth option for this site narr swale option. This option was only fourth on the list due to the fact that only the information for this particular site was processed into the MCDSS. However, upon examining the SCS-SA output it would be advisable for the runoff from this site to be transported to the BMP that will need to be implemented below the site, to deal with the runoff generated from sites 3 and 4.

For site 3 and 4 only the infiltration basin option was viable given the site constraints and management options. All other BMPs scored a zero under one of the categories (Refer to Primary Matrix). Therefore, along the side of the highway an infiltration basin could be designed at an appropriate site as not to interfere with the stability of the highway. This basin might be limited by available space. Therefore, if the structure were to be designed to reduce runoff by 30 percent it would reduce the erosive effect of the stormwater in the river channels. It would also reduce the size of the BMPs downstream from this site especially the BMP that will need to be implemented at QEP. Note, that when infiltration BMPs are selected, one should implement either a grass swale or a filter strip as a pre-treatment mechanism to remove suspended particles thereby increasing longevity of the infiltration basin.

In order to mitigate the damaged caused by the several concrete swales at site 6 it would be necessary to implement a detention system to cope with the runoff. In this regard, the MCDSS proposed the use of a wet pond. However given the area constraints it would be wise to go with the wet ED system. This system also achieved a higher site applicability score. The concrete swales should also be replaced with grass ones that include stopping weirs to allow for the collection of sediment before it enters the detention system. These swales would also reduce to some degree the velocity of the runoff. It should be noted at this stage that the National Roads Department should make it common practice to design roads with grass runoff channels and hence move away from concrete swales. Yu *et al.* (2001), discuss the merits of such a system in detail.

The responsibility for the cost of implementing a BMP programme at site 5 rests in the hands of the National Roads Department, QEP, and the Msunduzi Local Council. The MCDSS option for this site was a wet pond system. Given the fact that this is the site of the Parks Board it would be appropriate to implement a system that provides maximum environmental benefits. As such the wet pond system achieved maximum points (6 out of 6) for the environmental benefit score. Although not scoring as high as some BMPs in the treatment suitability category it does have a low risk rating as well as being relatively inexpensive to implement and maintain. One would through consultation with stormwater planners and civil engineers decide upon the most suitable area for implementation.

Sites 7, 8, 10 are all key areas of concern for the Msunduzi local Council. Due to the ranking system employed site 10 was deemed to be the most important site followed by site 8 and 7. Due to the collapsed slope identified in the Monzali Castle Property large amounts of sediment have landed up in the stream. The impacts of which are rather serious (section 2.1.4). Thus, the implementation of a BMP at site 10 is crucial. According to the BMP output, the wet pond option was again selected as the superior choice. Although, the large amounts of sediment being carried in the stream could impair the ability of the pond to meet its other objectives the primary aim should be water quality improvement. Careful plant selection should take place to maximise sediment removal as well as reducing peak flood volumes. The remainder of the Town Bush stream below this point is highly eroded and its habitat in poor condition (Biggs *et al.* 2001). This system should also be designed to contain the two-year flood event. Thus by containing the runoff volume and subsequent release rate of the contained water one might reduce the downstream erosive effects and allow nature to recover and the streambanks to stabilise.

At this point it should be noted, that a specific rehabilitation programme needs to be implemented at the slope to prevent any further collapse thereby limiting the damage to the stream biota. This can be achieved by using eucalyptus logs to construct live cribwalls. In this regard, it is further suggested that a committee be established, consisting of the land owner, the lessee, representative of the Department of Water Affairs and Forestry, the Msunduzi Local Council and the Umgeni Municipality (previously Hilton TLC), and the Catchment Management Agency to consider the most appropriate actions needed to resolve this issues. It may also be of value to include a representative of the South African Roads Agency, who could possible provide financial assistance as any further collapse of the slope may adversely affect the hillside and hence the National Road.

According to the runoff analysis results, stage three of the priority-setting model (Figure 5.4 & Table 5.3), site 8 was deemed to be the second most important site where the council should implement a BMP. However in order to successfully implement such a scheme one would need to alter the course of the channel to flow through the BMP option thereby creating distance between the river channel and adjacent properties. This site receives all the runoff from the Ferncliffe residential area, and as such any BMP implemented would need to be able to, amongst others, improve water quality. The wet pond option was again selected as the most appropriate option taking into account site constraints. Careful plant selection as well as a rigorous maintenance schedule must be implemented when choosing such a system. This site could also become an area of recreation since when the field study was undertaken bird watchers where already present. The wet pond was also selected as the most appropriate option for site 7. The reason for the placement of such a site is that all runoff from the Montrose residential area as well as the highway would pass through this site. Hence its position is crucial for regulating stormflow and water quality. Again this site should at least be developed to control the two-year flood event. By reducing the peak flows in the river network one might be able to begin with other restoration projects that have been highlighted for this section of stream (Biggs *et al.* 2001).

Site 9 and 11 were included separately from the other nine sites. The main difference here is that the other systems have been developed for inline use, whereas these sites are offline systems. In a matter of fact, these sites are better suited for the implementation of stormwater management systems.

Site 9 relates to the Cascades Shopping centre. This site is of key importance given the fact that plans have been recently passed to allow the developers (Old Mutual Properties) to expand the parking lot into the adjacent wetland system. In this regard the MCDSS chose the most obvious solution that of porous pavement (reservoir design). Coupled with this, one can also use the parking area as an on-site-detention (OSD) system. Harrison (pers. comm. 2001) mentions various designs that could allow for a more pervious surface as well as providing the necessary storage. These include the use of bricks instead of asphalt and designing the parking lot in a bowl shape with a restricted outlet from the parking lot surface. Thus the flow of storm water reaching the river system could be controlled. One area could be designed for OSD as described above whilst another could be designed as a reservoir. The water that collects in this system could then be used for flushing of toilets within the Cascades centre and surrounding shops and businesses. Thereby making a large cost saving as well as preserving water.

Site 11 belongs to the Waltdorf housing development. According to Harrison (pers. comm. 2001), the developers were only allowed to build if they implemented runoff reductive measures. In fact, the residents of the development have taken to hand the responsibility of maintaining the grass swales and the one dry detention basin. It should be noted that according to the MCDSS the dry detention basin was the fourth ranked option. The developers could also have selected different management criteria and thus the choice of BMP would have been affected. Being that as it may, the MCDSS would again have selected wet pond as the most suitable option. However, due to the proximity of the BMP to the development one might choose the dry basin detention option (as chosen by the developers) as mosquitoes and odour could hinder the implementation of any wet systems. Therefore, this highlights another limitation of the MCDSS system, such negative aspects should have been included in the system. However, one could also argue that this could begin to complicate matters. However, all one would need to do before implementing any system would be to consult the literature. Various aspects such as these nuisance effects have been highlighted in Appendix 1 and references for further readings provided.

The majority of recommendations laid out above have been submitted to deal with the problem of stormwater on an instream basis and important government bodies highlighted as the responsible parties. However, one must not forget the important role that the individual landowner can play in catchment management. As stated in The Act there are general obligations placed upon persons to take reasonable measures to prevent pollution, in this regard sediment is defined as a pollutant. Thus the individual landowner should be encouraged to implement runoff-mitigating measures. These need not be as complex or expensive as the BMPs described above. One of the most simple and effective ways to mitigate urban runoff is through the harvesting of rain. In terms of this process, individual residences could harvest the rainfall from their house roofs to a water tank. The water collected in this manner could then be used for watering gardens or filling swimming pools. Not only does this assist in reducing urban runoff, it also reduces the demand for treated water.

CHAPTER 7:CONCLUSION AND RECOMMENDATIONS

7.1 CONCLUSION

At the beginning of this dissertation five objectives were set out. This conclusion will thus evaluate these individually and demonstrate to what degree each one was achieved. The first objective was to review the literature on stormwater management techniques with specific reference to BMPs. It was said that particular reference was to be given to the most recent techniques used in the UK, USA and Australia. During this phase of development a wide range of technical papers, and four manuals were reviewed. Unfortunately, the majority of papers were American of origin. However, this did not prove to be too much of a problem since reading the array of papers it was found that the BMP technology responded in a similar manner to a range of climatic conditions although, extreme climatic differences did have an influence on functionality. In general this objective was adequately achieved.

The second objective was to identify specific BMP selection criteria, advantages, as well as specific limitations of the various BMPs. Achieving this objective was helped along by the use of the four manuals (Table 4.5). Schueler (1987; 2000) seems to be an authority on BMPs in America. His manuals were invaluable in meeting this objective and in the design of the MCDSS. The four manuals formed the foundation of the MCDSS and were supplemented by the array of scientific papers. One drawback of these manuals was that they differed in the choice of BMPs discussed and the selection criteria used. It was at this stage that it was decided to list the most commonly used BMPs and selection criteria. Most BMPs have a basic design that can be implemented in an array of sites but these designs can also be altered depending on site specifics. These altered designs thus perform slightly differently in respect of the initial selection criteria as they are designed to address the original limitations of the core design. As such, only twelve of the most common core BMP designs were included in the MCDSS. By limiting the number of basic designs included within the MCDSS one was able to simplify the developmental process. The variations in BMP design are usually a function of unique site conditions whereas and the aim of this dissertation was to develop a MCDSS that could provide the user with a choice of BMPs that could be implemented, under general conditions, to an array of sites. Another drawback encountered during this phase was that there was limited information available on BMP implementation in South Africa and as such the MCDSS lacks a local aspect. If, in the future the design of the MCDSS is to be taken further it might be useful to address this aspect.

The third objective was to consolidate and formulate the information into an MCDSS. Chapter four of this dissertation discussed the vagaries of such an objective in detail. As mentioned a scoring system was applied to the information acquired during the literature review phase. It is in this aspect of the MCDSS design that the ultimate success or failure of the MCDSS lay. How can one ever be certain that the values awarded to each BMP for each selection criteria were reasonable? To this degree an initial testing phase was used and literature checks supplemented this process. Although, in hindsight, it might have been useful to subject each value awarded to a particular BMP for each criterion within the MCDSS to a sensitivity analysis. In spite of this the MCDSS performed adequately in both the initial testing phase and later in the case study.

The fourth objective was to evaluate the MCDSS in its own case study and compare the results to other support systems to evaluate its utility. Although the first part of this objective was met the second part was omitted. The reason for this was that the MCDSS was tested during the design phase to determine if it was selecting correctly. This phase of testing was not initially included in the design phase and was not without its difficulties. As previously mentioned, the four manuals differed widely in their choice of selection criteria and BMPs. During the design phase they were utilised since the MCDSS selections for given scenarios included only a limited amount of selection criteria. As such, the manuals were deemed to be satisfactory for this purpose. On the other hand, during the case study, the choice of BMPs made by the MCDSS was achieved by including the full array of selection criteria. Thus, the number of selection criteria used by the final MCDSS was far greater than the number of criteria used by any of the four manuals. As such any further comparison would have been inappropriate.

The last objective was to provide recommendations for further improvement and use. Although fairing adequately during the case study it was not without its limitations. However, the recommendations for further improvement and use have been listed in detail at the end of this section. However, one observation that can be made is that the MCDSS does provide the user with a useful tool for decision-making. Where in the past BMP selection and implementation was made in an ad hoc manner it can now be made with some confidence and in a more systematic manner.

In conclusion, section 24 of the Constitution of South Africa and the National Water Act are powerful tools that provide backing to the implementation of reasonable methods that can prevent or mitigate erosion, promote conservation, and secure ecologically sustainable development. It is hoped that BMPs that provide most of these will find favour with civil engineers and stormwater planners and that this dissertation has in some small way or another laid the groundwork for more detailed studies regarding BMPs and a new paradigm in stormwater management.

7.2 RECOMMENDATIONS

7.2.1 Further developments to the MCDSS

- A surrogate measure for drainage area should be sought and added into the MCDSS but it should not replace the original criterion. This surrogate measure would then allow the user to design a treatment chain of BMPs. The final MCDSS does not allow this management option to be implemented. As the system stands, it only allows for one BMP to be selected for inline use. Once the BMP has been chosen the original drainage area value is void and could not be used for selecting the second BMP in the chain. Originally BMP technology was designed as offline systems and in this study the technology was applied for inline use. Thus as one moved from the headwaters, the drainage area naturally increased thus limiting the range of BMP options available for selection. Therefore, if a surrogate measure was available then it could be used to help select the second BMP in the chain.
- The MCDSS needs to be tested in more diverse circumstances. As yet is has only been tested on one river and a tributary were site information tended to be quite similar.
- A more detailed priority-setting model should be designed, as the one used was rather simplistic.
- The MCDSS should be developed further into a computer based DSS this would make it a very powerful tool.
- The number of BMPs should be increased from the original twelve to a point where all possible design modifications are included.
- In the future a more comprehensive set of selection criteria should also be sought to make the selection process more accurate.
- In terms of the management objectives and the weighting thereof, one should alter the system to allow for a better weighting of individual priorities. At the moment all selected management objectives carry equal weighting.
- Finally, the MCDSS should be altered for use by non-professionals and as such it could then be implemented at an individual property scale. As such one would need to establish which criteria should be omitted and which ones should remain. For example land use type and size, could replace the drainage area criterion. As these BMP systems would be implemented as offline ones. Simple, cost effective, and easy to install BMPs should be included in such a system. For example, filter strips, grass swales, and rainwater harvesting techniques meet these requirements.

7.2.2 MCDSS implementation

- A detailed feasibility study of site 10 (open area along Town Bush road above colleen avenue) should be undertaken and the most suitable of the three BMP options selected by the MCDSS implemented. The City Engineers department has already identified this a key area for stormwater management. A study of this nature would provide an opportunity for the forging of a long-term partnership between the City Engineers Department and the University of Natal, Pietermaritzburg Water Resource Programme. The costs of implementation and maintenance over a period of five years should be noted as well as the change, if any, in public perception of such a project. A hydrological study of the stream should be undertaken before and after the implementation of any BMP as well as riparian and instream assessments. A study of this nature could be an invaluable asset in the future of stormwater management especially, as a study aid. It would also shift the study of BMPs from the hypothetical to the actual by providing the most critical test of this or any future MCDSS.
- Office complexes and high-density housing complexes should also be approached to implement the MCDSS and the financing of the selected BMP worked into the original construction and development costs. In the future, building plans should only be passed if stormwater management techniques are included. As mentioned such an incident occurred during the development of the Waltdorf housing complex. These office parks and housing complexes change sites from low to high runoff zones.

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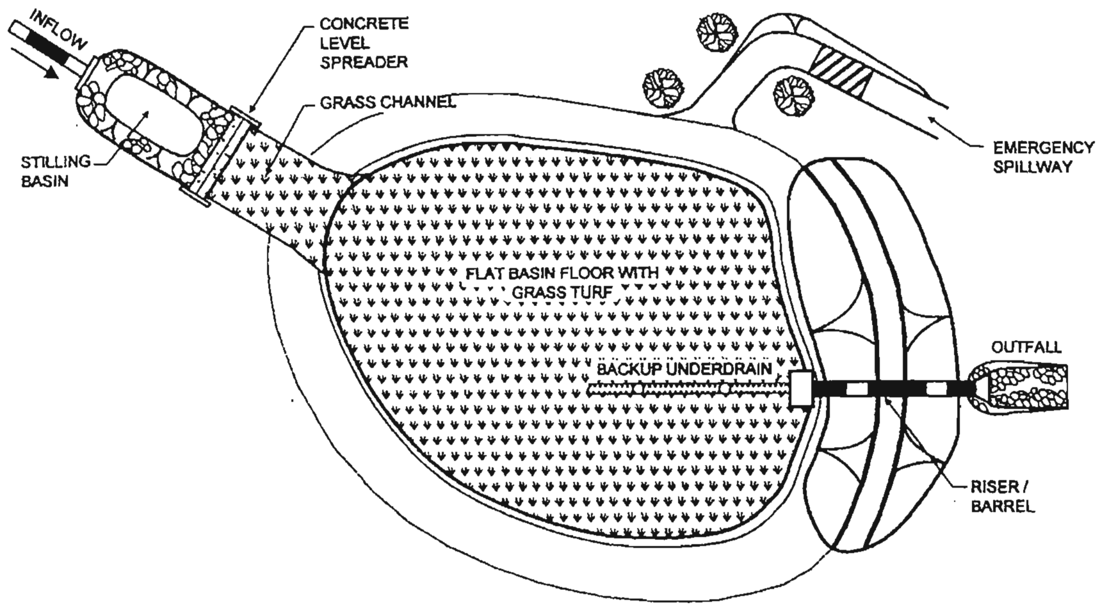
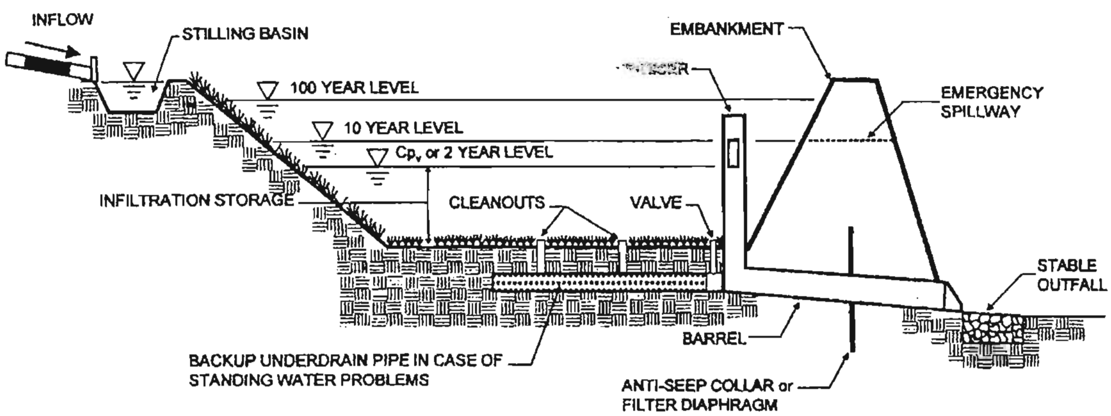
APPENDIX 1: BMP INFORMATION SHEETS

BMP Number 1: Infiltration basin



PLAN VIEW



PROFILE

Infiltration basins are stormwater impoundments that detain stormwater runoff and return it to the ground by allowing runoff to infiltrate gradually through the soils of the bed and sides of the basin. They are flat bottomed, usually have no outlet but an emergency underdrain may be implemented to channel filtrate to a specific area. Basins are usually located to collect stormwater runoff from adjacent drainage areas. Infiltration reduces both peak runoff rates and runoff volumes.

Applications and effectiveness

- Effective at removing both soluble and fine particulates found in stormwater runoff. (Coarse-grained pollutants should generally be removed before they enter an infiltration basin).
- Basins can be adapted to provide full control of peak discharges for large design storms.
- Depending on the degree of storage achieved in the basin, significant groundwater recharge, low flow augmentation, and localised streambank erosion control can be achieved.
- Suitable for residential areas, roads, municipal office complexes and maintenance yards as well as for new developments. Not suitable for ultra-urban areas.
- Suitable for drainage areas ranging from 2.5 to 25 ha.
- Infiltration facilities have high failure rates mainly due to clogging by fine sediment.

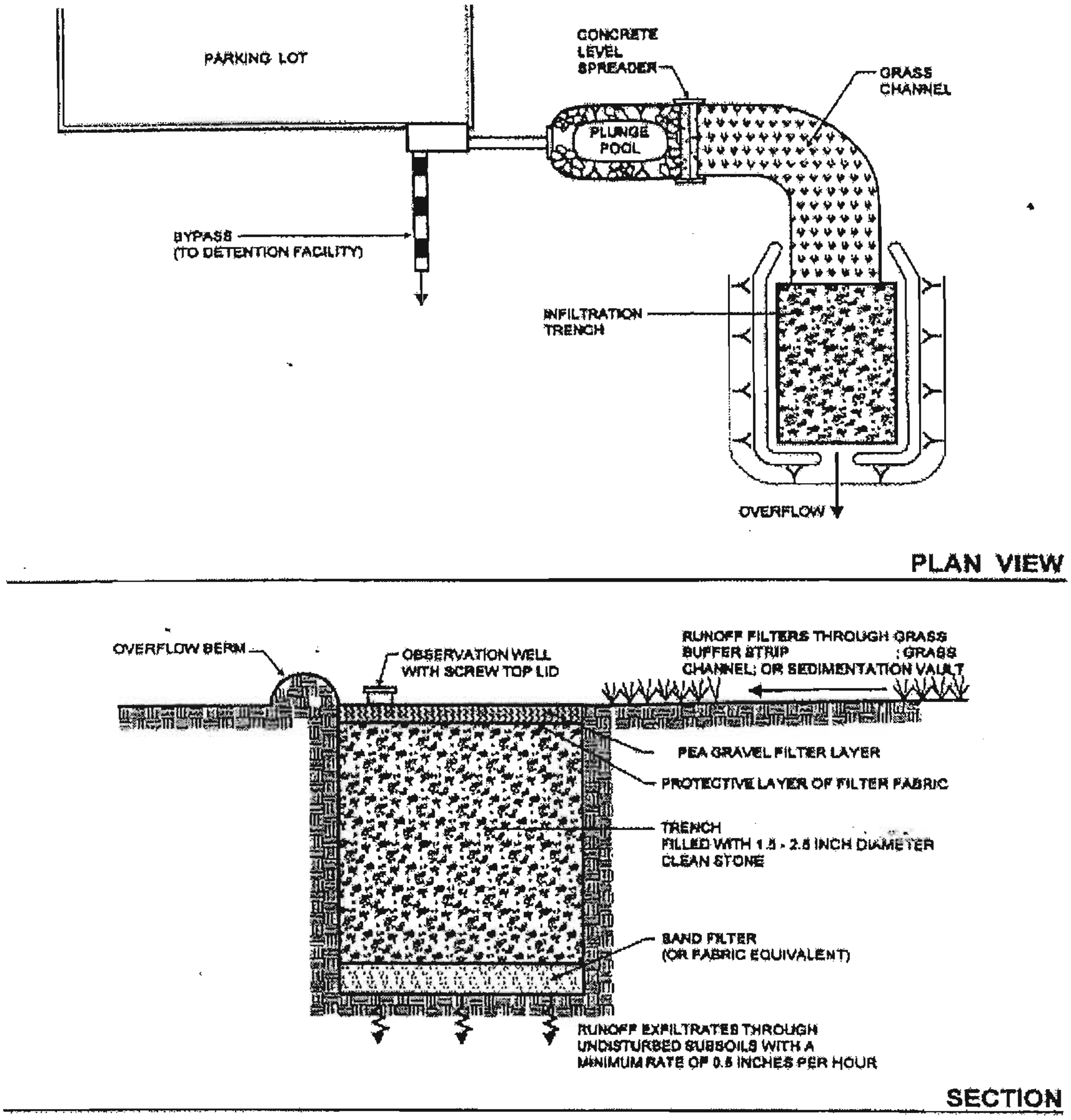
Limitations and drawbacks

- Relatively expensive to construct and maintain.
- Potential risk of groundwater contamination.
- May have short life span depending on long-term maintenance.

For more information consult:

1) EPA 1996. *Protecting Natural Wetlands: A Guide to Stormwater Best Management Practices*. Office of Water. Washington, D.C.
2) EPA 1999. Guidance Specifying Management Measures for Sources of Nonpoint Pollution in Coastal Waters. Office of Water. Washington, D.C. www.epa.gov/owow/nps/MMGI/Chapter4/index.htm
3) Greater Vancouver Regional District, Stormwater/Drainage Division. www.gvrd.bc.ca/services/sewers/drain/BestMgmtGuide.html
4) Schueler TR 1987. *Controlling Urban Runoff: A Practical Manuel For Planning and Designing Urban BMPs*. Metropolitan Washington Council of Governments, Washington, D.C.
5) Urbanas B 1997. Chief Master Planning and South Platte River Program Urban Drainage and Flood Control District: Design and Selection Guidance for Structural BMPs.
6) Urbonas B 1994. Assessment of Stormwater BMPs and Their Technology. *Water Science and Technology* 29 (1-2): 347-353.

BMP Number 2: Infiltration trench



Note: Grass channels or buffer strips have been implemented as a pre-treatment to remove excess sediment.

An infiltration trench is an excavated trench backfilled with clean, coarse aggregate to allow for the temporary storage of runoff. Runoff stored in the trench is allowed to infiltrate into the soil in the trench bottom or is conveyed from the trench by an outflow pipe to downstream detention systems. Infiltration trenches are designed to provide temporary storage and infiltration of stormwater associated with increasing development.

Applications and effectiveness

- Effectively removes both soluble and particulate pollutants. Not intended to trap course sediments, grass buffers or sand filters should be installed to capture sediment before it enters the trench.
- Trenches can provide groundwater recharge, low flow augmentation, as well as decreasing streambank erosion and bankfull flooding.
- Trenches are seldom practical or economically feasible on sites larger than 5 ha.
- Slopes should not be greater than 10%.
- Useful for providing containment for runoff generated from highways and roads.

Limitations and drawbacks

- High potential for groundwater contamination
- Moderate maintenance costs
- High clogging risk

For more information consult:

1) EPA 1996. *Protecting Natural Wetlands: A Guide to Stormwater Best Management Practices*. Office of Water. Washington, D.C.
2) EPA 1999. Guidance Specifying Management Measures for Sources of Nonpoint Pollution in Coastal Waters. Office of Water. Washington, D.C. www.epa.gov/owow/nps/MMGI/Chapter4/index.htm
3) Greater Vancouver Regional District, Stormwater/Drainage Division. www.gvrd.bc.ca/services/sewers/drain/BestMgmtGuide.html
4) Schueler TR 1987. *Controlling Urban Runoff: A Practical Manuel For Planning and Designing Urban BMPs*. Metropolitan Washington Council of Governments, Washington, D.C.
5) Urbanas B 1997. Chief Master Planning and South Platte River Program Urban Drainage and Flood Control District: Design and Selection Guidance for Structural BMPs.
6) Urbonas B 1994. Assessment of Stormwater BMPs and Their Technology. *Water Science and Technology* 29 (1-2): 347-353.
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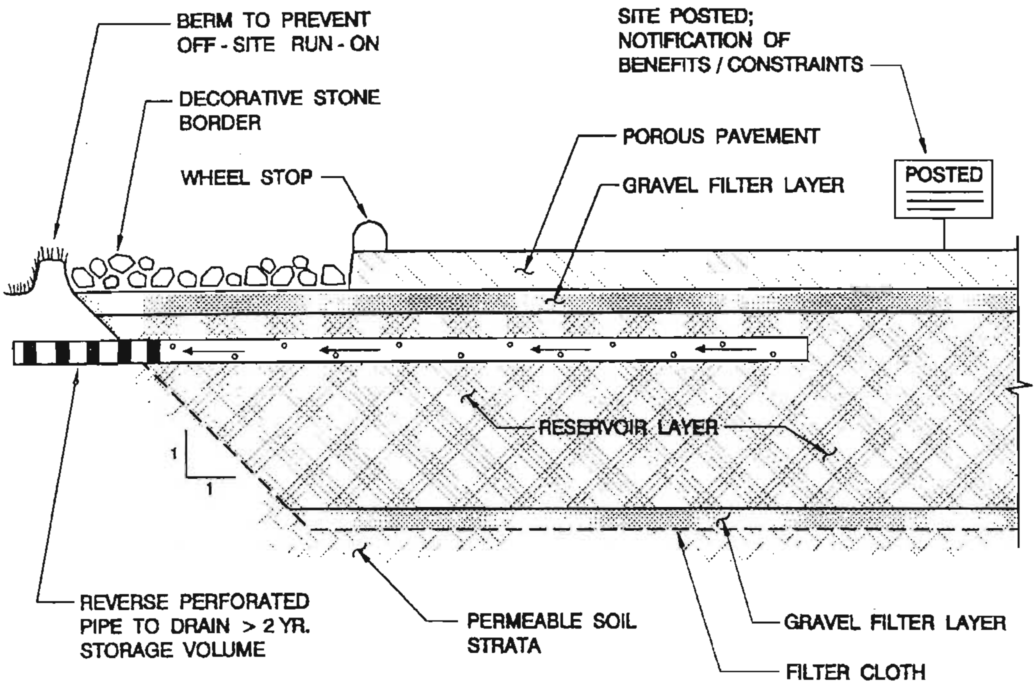
BMP Number 3: Porous pavement and reservoir porous pavement



Porous pavement is a permeable paving material that allows stormwater to percolate through the pavement to a gravel base. The pavement consists of a uniform, open graded coarse aggregate, cemented together with either concrete or asphalt. Water reaching the pavement infiltrates through the upper layer and into the soil layer below or is routed to conveyance systems via underdrains. Porous pavements provide similar water quality benefits to infiltration benefits.

Applications and effectiveness

- Only practical for low traffic volumes (parking lots, access roads, driveways, parking lanes)
- Suitable for runoff volume reduction, providing a degree of groundwater recharge, and water quality improvement.
- Limited provision of streambank erosion and flood control.
- By undersealing the original design to retain stormwater (Reservoir design), porous pavements could provide water for non-potable uses (Pratt 1999). Although this method sacrifices a number of the original applications it is useful in areas where water is a scarce resource. Stormwater control is a secondary aim.
- Applicable to developed urban areas.

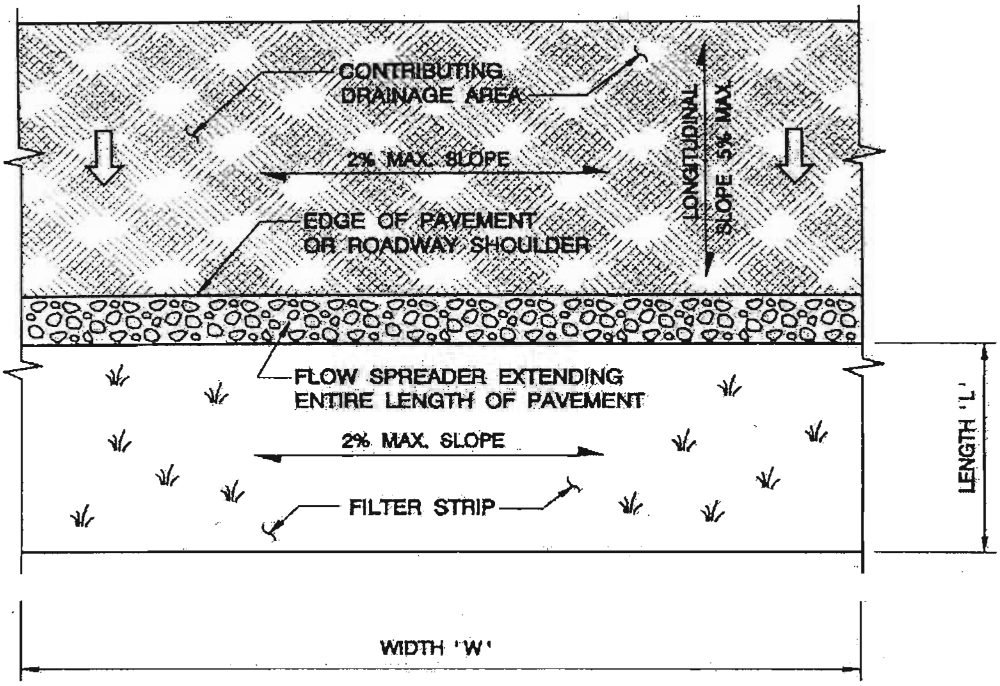
Limitations and drawbacks

- Both designs demand relatively high maintenance to ensure long-term viability
- High failure rate to clogging of pores
- Applicability limited to slopes of less than 5% after which functionality declines rapidly.
- Relatively expensive BMP to implement.

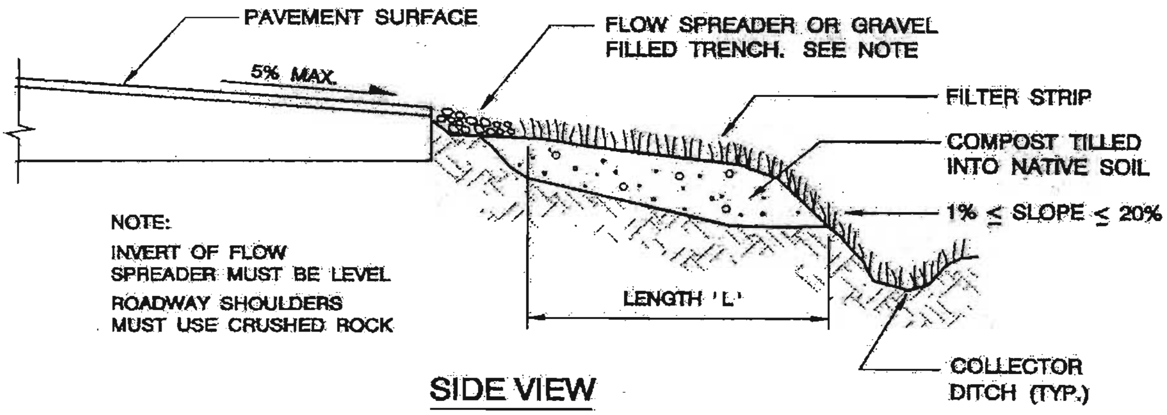
For more information consult:

1) EPA 1996. *Protecting Natural Wetlands: A Guide to Stormwater Best Management Practices*. Office of Water. Washington, D.C.
2) Greater Vancouver Regional District, Stormwater/Drainage Division. www.gvrd.bc.ca/services/sewers/drain/BestMgmtGuide.html
3) Pratt CJ 1999. Use of Permeable, Reservoir Pavement Constructions for Stormwater Treatment and Storage for Re-use. *Water Science and Technology* 39 (5):145-151.
4) Schueler TR 1987. *Controlling Urban Runoff: A Practical Manuel For Planning and Designing Urban BMPs*. Metropolitan Washington Council of Governments, Washington, D.C.

BMP Number 4: Filter strips



PLAN VIEW
NTS



SIDE VIEW
NTS

Filter strips are similar in many respects to grassed swales except that they are only designed to accept overland sheet flow. Runoff from an adjacent impervious area must be evenly distributed across the filter strips, usually be way of a level spreader. A recent variation of filter strips is a technology known as bioretention. This approach is suitable for managing runoff from small drainage areas using a mixture of upland plant materials and nutrient enriched soil composition. Bioretention can maximise nutrient uptake, evapo-transipration, microbial degradation of metals and carbon-based pollutants, and storage to reduce peak flows.

Applications and effectiveness

- Primarily function as water quality BMPs. However, reduction in flow velocities through the vegetation results in removal of particulate pollutants, enhanced infiltration into the soil and minimal groundwater recharge.
- At some sites, filter strips may help to reduce the size and cost of downstream control facilities.
- Help preserve the riparian zone and may stabilize streambanks.

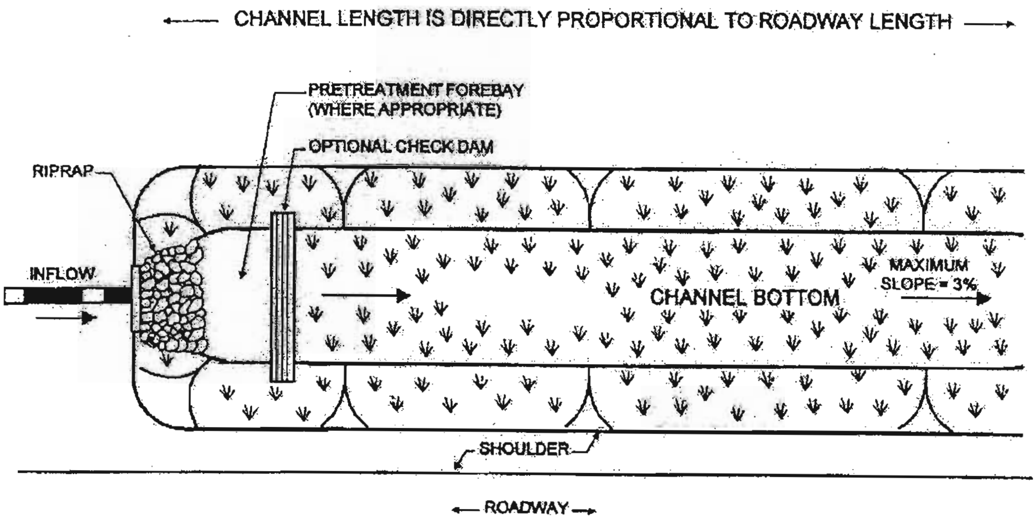
Limitations and drawbacks

- Not feasible in densely developed urban area.
- Not feasible on sites receiving runoff from more than five hectares.
- High flow velocities reduce effectiveness

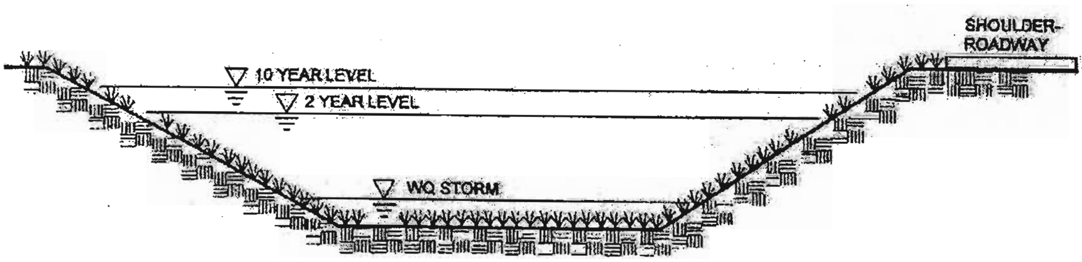
For more information consult:

1) EPA 1996. *Protecting Natural Wetlands: A Guide to Stormwater Best Management Practices*. Office of Water. Washington, D.C.
2) Greater Vancouver Regional District, Stormwater/Drainage Division. www.gvrd.bc.ca/services/sewers/drain/BestMgmtGuide.html
3) Schueler TR 1987. *Controlling Urban Runoff: A Practical Manuel For Planning and Designing Urban BMPs*. Metropolitan Washington Council of Governments, Washington, D.C.

BMP Number 5: Grass swale



PLAN VIEW



SECTION

Grass swales are typically applied in single family residential developments and highway medians as an alternative to curb, culvert and gutter drainage systems. They are essentially lined with either grass of other erosion-resistant species. They use the ability of vegetation to reduce the flow velocities associated with concentrated runoff. The added benefit of the vegetation is that it also limits the degree of soil erosion within the channel thereby, increasing BMP longevity.

Applications and effectiveness

- Decrease stormflow velocities and peak flow rates which in turn helps to reduce flooding and downstream erosion.
- Some of the flow may also infiltrate into the soil profile, reducing overall runoff volume and adding to groundwater recharge.
- Removal of pollutants can be accomplished through the filtration of plant stems, absorption to soil particles, and biological processes.
- Suitable for new developments – may be retro-fitted to existing developments.
- Suitable for residential areas, municipal office complexes, roadways, and municipal yards.

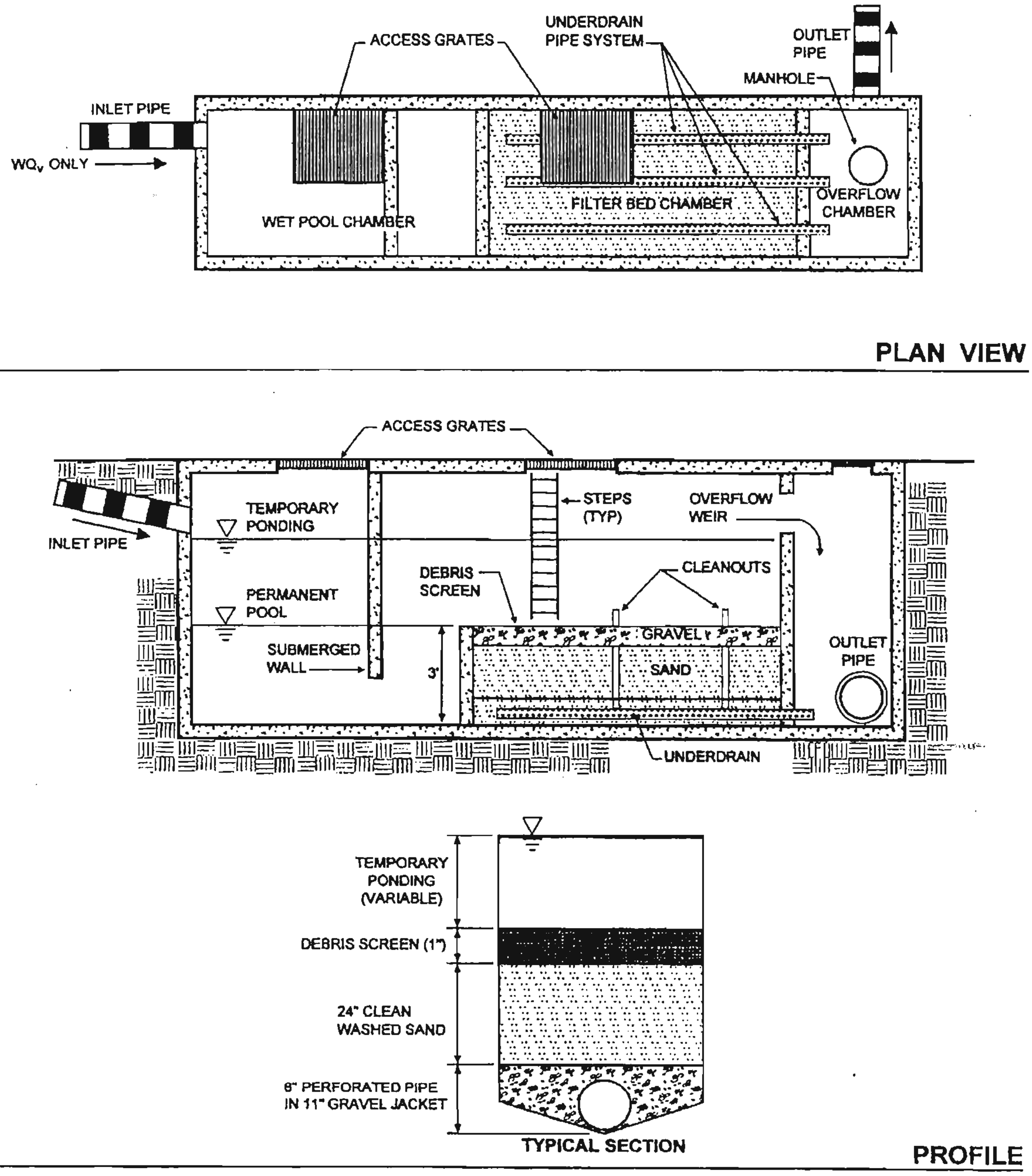
Limitations and drawbacks

- Not suitable for flow velocities greater than $5 m.s^{-1}$. Implementation of check dams may slow down velocity.
- Maximum contributing area 5 ha.
- Susceptible to erosion.
- Susceptible to sediment accumulation – provide pre-treatment if high sediment load expected.

For more information consult:

1) EPA 1996. *Protecting Natural Wetlands: A Guide to Stormwater Best Management Practices*. Office of Water. Washington, D.C.
2) Greater Vancouver Regional District, Stormwater/Drainage Division. www.gvrd.bc.ca/services/sewers/drain/BestMgmtGuide.html
3) Schueler TR 1987. *Controlling Urban Runoff: A Practical Manuel For Planning and Designing Urban BMPs*. Metropolitan Washington Council of Governments, Washington, D.C.
4) Yu SL, Kuo JT, Fassman EA & Pan H 2001. Field test of Grassed-Swale Performance in Removing Runoff Pollution. *Journal of Water Resources Planning and Management* 127 (3): 168-171.

BMP Number 6: Sand filter



Sand filter are systems of underground pipes beneath a self-contained bed of sand designed to treat urban stormwater. Water conducted to the BMP is filtered through various sand medias. The types of media used and its grain size distribution determine how small of a particle can be strained out. Coarser sands have larger pore spaces and as such have higher flow-through rates but pass larger suspended sediments and vice versa. Once filtrated through the bed, the water is collected in a series of underground pipes and returned to the stream or channel.

Applications and effectiveness

- Primarily a water quality BMP
- Provide a degree of groundwater recharge
- Sand filters may be used to retrofit existing stormwater management systems by locating them at the end of outlet pipes.
- Sand filter are an offline system (should be located outside the stream channel or drainage path)

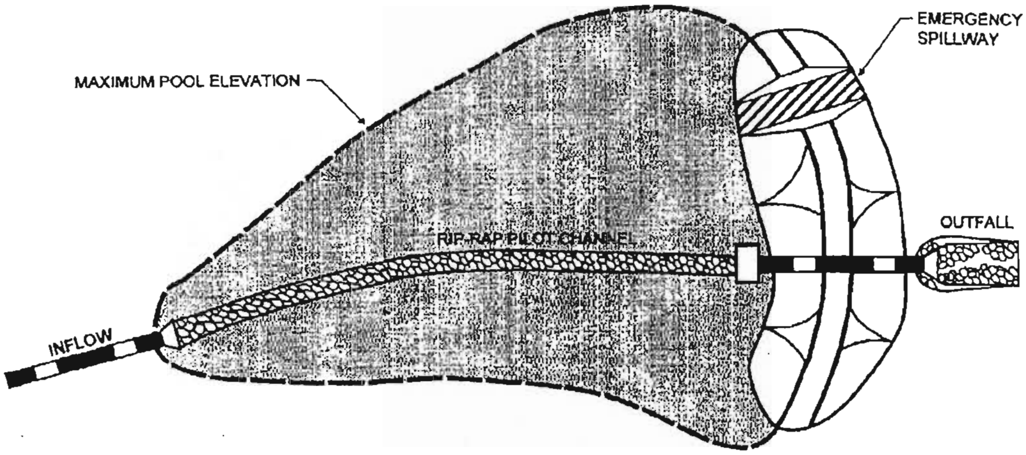
Limitations and drawbacks

- Do not provide runoff reduction or flood control.
- Must be protected from heavy sediment loading otherwise blockages will occur.
- More expensive to construct than other BMPs.
- Requires regular maintenance to ensure longevity.

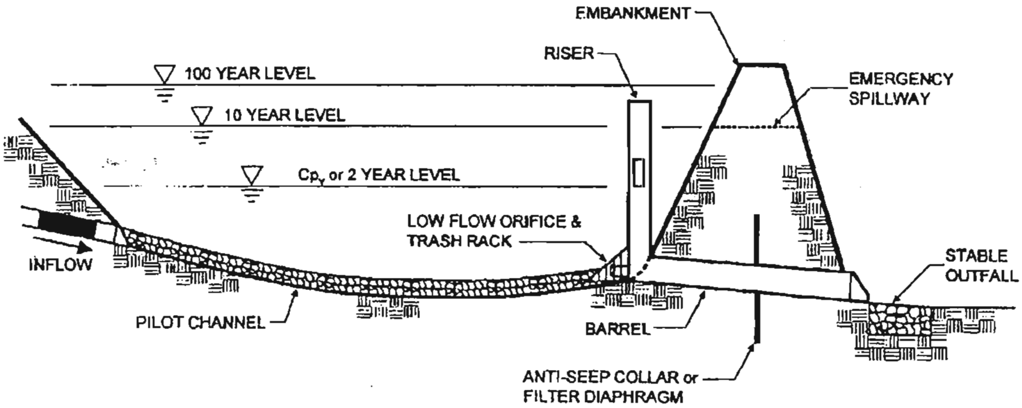
For more information consult:

1) EPA 1996. *Protecting Natural Wetlands: A Guide to Stormwater Best Management Practices*. Office of Water. Washington, D.C
2) Greater Vancouver Regional District, Stormwater/Drainage Division. www.gvrd.bc.ca/services/sewers/drain/BestMgmtGuide.html
3) Schueler T 1994. Developments in Sand Filter Technology to Improve Stormwater Runoff Quality. *Watershed Protection Techniques* 1 (2): 47-54.
4) Schueler T 1995. Performance of the Delaware Sand Filter Assessed. *Watershed Protection Techniques* 2 (1): 291-293.
5) Schueler TR 1987. *Controlling Urban Runoff: A Practical Manuel For Planning and Designing Urban BMPs*. Metropolitan Washington Council of Governments, Washington, D.C.
6) Urbonas BR 1999.Design of a Sand Filter for Stormwater Quality Enhancement. *Water Environment Research* 71 (1): 102- 113.

BMP Number 7: Dry and wet extended detention basins

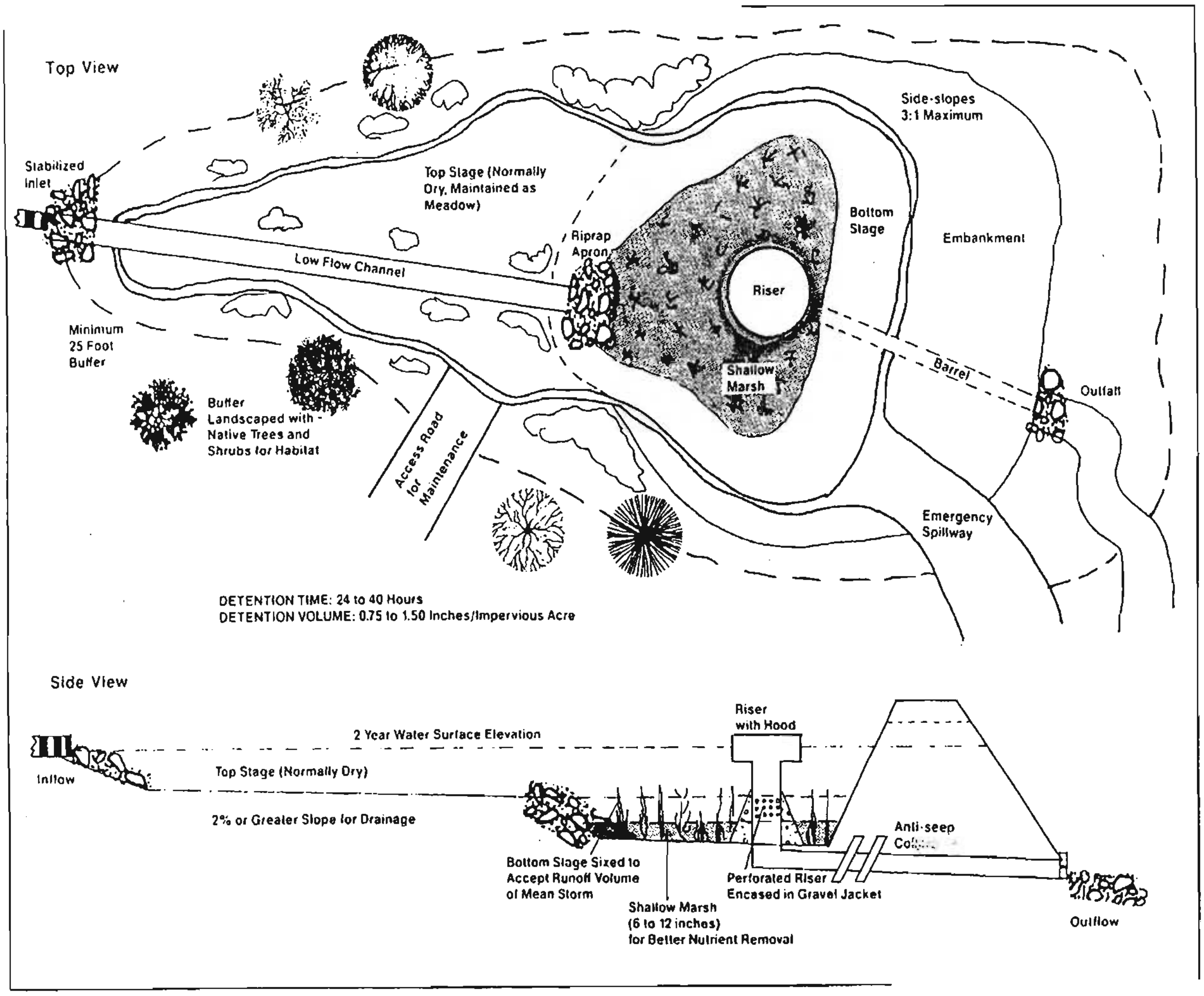


PLAN VIEW



PROFILE

Example of a dry extended detention basin.



Example of a wet extended detention basin.

Detention basins are designs to temporarily store collected runoff water, and to slowly release the stored water at a controlled rate through one or more orifices. Dry detention facilities are designed to empty completely between storm events whereas wet detention facilities maintain a body of water all year round. Dry and wet basins are similar in most regards except for the amount of habitat provided. Wet basins have a larger emphasis placed on vegetation and provide a degree of recreational benefits. Dry and wet basins should be designed according to the size of the storm volume and should contain the entire volume. Thus, avoiding the bypassing of the basin by pollutants.

Effectiveness and applications

- Limit peak runoff flow rate of developed conditions.
- Usually designed to control and detain the runoff from smaller, more frequent storms. Larger flows may be bypassed depending on the design.
- Designed to detain stormwater for up to 72 hours following a design event.
- Advantages of the longer detention time are two-fold
  - 1) The duration and frequency of bankfull flows can be reduced
  - 2) A significant reduction in particulate contaminants can be achieved.
- Suitable for new developments (Waltdorf housing development)
- Suitable for office complexes and municipal yards.
- Wet basins have higher pollutant removal capacities.

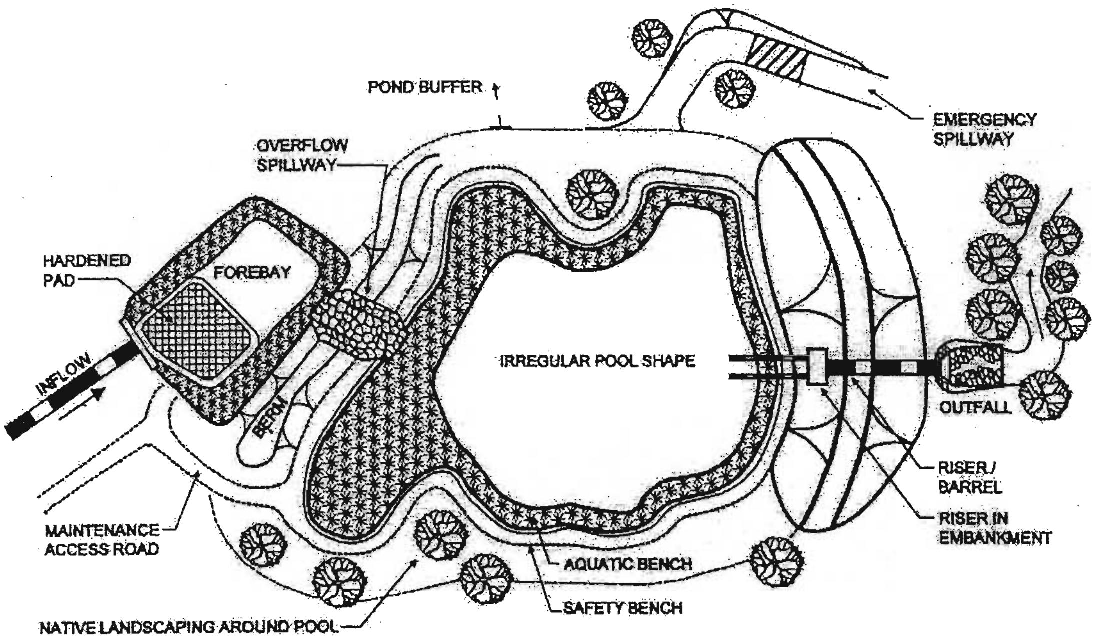
Limitations and drawbacks

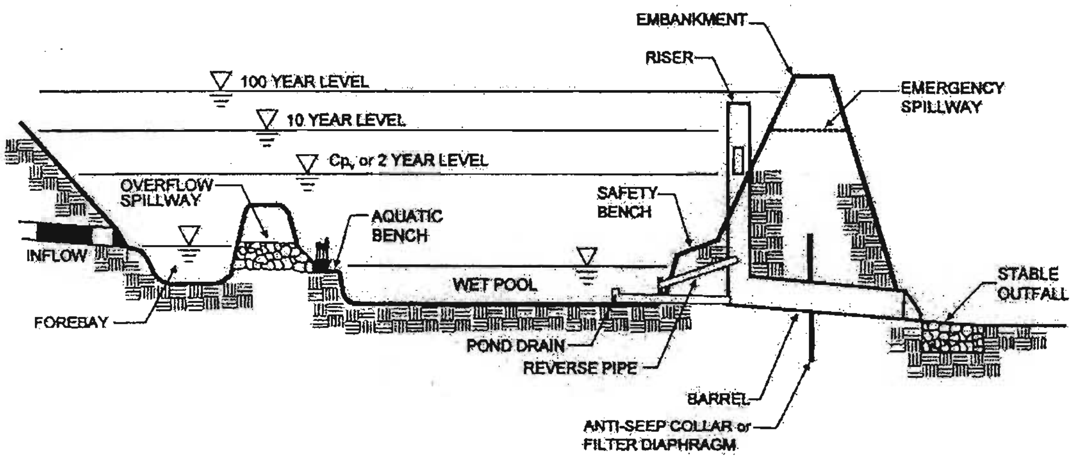
- Relatively high maintenance burdens and costs.
- Nuisance conditions can occur if the basin is not regularly maintained. Nuisances include odours, mosquitoes, and collection of trash and debris.
- Dry ponds have been perceived, as unattractive. Hence careful landscaping is needed to blend the BMP into the surroundings.

For more information consult:

1) EPA 1996. *Protecting Natural Wetlands: A Guide to Stormwater Best Management Practices*. Office of Water. Washington, D.C
2) Greater Vancouver Regional District, Stormwater/Drainage Division. www.gvrd.bc.ca/services/sewers/drain/BestMgmtGuide.html
3) Pettersson TJR 1998. Water Quality Improvement in a Small Stormwater Detention Pond. *Water Science and Technology* 36 (10) 115-122.
4) Schueler TR 1987. *Controlling Urban Runoff: A Practical Manuel For Planning and Designing Urban BMPs*. Metropolitan Washington Council of Governments, Washington, D.C.
5) Stanley DW 1996. Pollutant Removal by a Stormwater Dry Detention Pond. *Water Environment Research* 68 (6): 1076-1083.

BMP Number 9: Wet ponds





Wet ponds are an extremely effective water quality BMP. If properly sized and maintained, wet ponds can achieve a high removal rate of sediment, BOD, organic nutrients and trace metals. Biological processes within the pond also remove soluble nutrients. Wet ponds also provide flood control and streambank erosion protection. During runoff events, the permanent pool helps to minimize turbulence for enhanced settling of particulates, and helps to prevent scour and re-suspension of sediments.

Applications and effectiveness

- Provide water quality improvement, streambank erosion protection, flood and flow control.
- May be designed as offline facilities to contain the water quality volume (or streambank protection volume) while bypassing larger flows.
- Inline systems usually provide flood control as well.
- Provides a high degree of aquatic and terrestrial habitat.
- Aesthetically pleasing and can be used for various recreational activities.
- Suitable for new developments
- Suitable for small on-site facilities and large regional facilities.

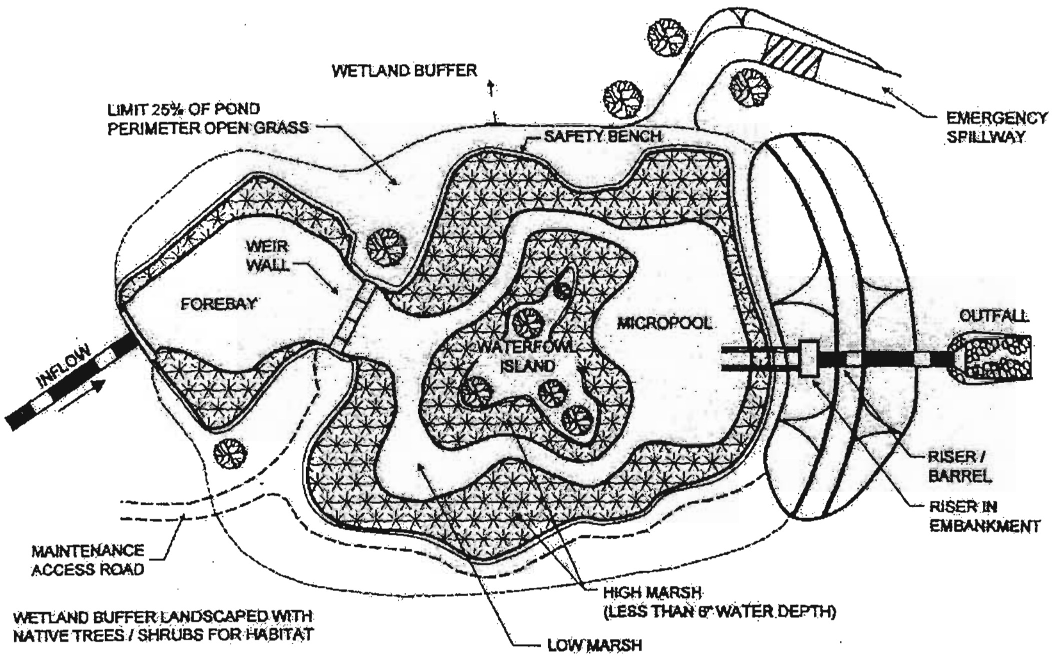
Limitations and drawbacks

- Nuisance problems of odours and mosquitoes.
- Thermal enhancement of downstream river systems. Particularly important for rivers in KwaZulu-Natal where trout are sensitive to thermal changes.
- Sediment build-up greatly reduces the effectiveness and dredging is rather costly.
- Maximum site slope 15%
- Maximum contributing drainage area typically 25km^2

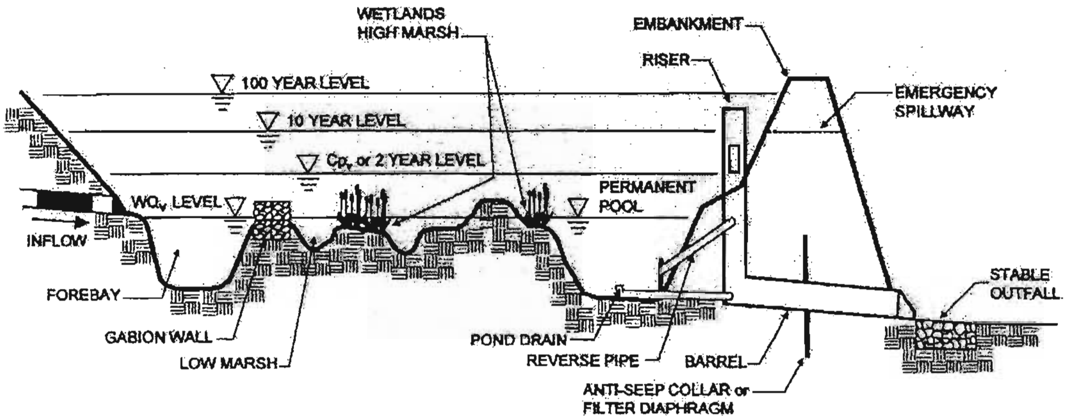
For more information consult:

1) EPA 1996. *Protecting Natural Wetlands: A Guide to Stormwater Best Management Practices*. Office of Water. Washington, D.C
2) Greater Vancouver Regional District, Stormwater/Drainage Division. www.gvrd.bc.ca/services/sewers/drain/BestMgmtGuide.html
3) Schueler TR 1987. *Controlling Urban Runoff: A Practical Manuel For Planning and Designing Urban BMPs*. Metropolitan Washington Council of Governments, Washington, D.C.

BMP Number 10: Constructed wetland



PLAN VIEW



PROFILE

Constructed wetlands are shallow pools constructed on non-wetland sites as part of a stormwater collection and treatment system. Essentially a wet pond with greater emphasis placed on vegetation and depth/area considerations. Constructed wetlands regularly fill and drain and are typically extensively vegetated. It should also be noted that constructed wetlands are usually found in series with other types of BMPs especially ones aimed at sediment removal. These wetlands are designed to maximise removal of pollutants from stormwater through physical, chemical, and biological means and can be designed to temporarily store stormwater.

Applications and effectiveness

- Reduces peakflow and provides streambank erosion protection.
- Provides water quality enhancement and community enhancement (recreation and aesthetic value).
- Suitable for small on-site facilities and large regional facilities.

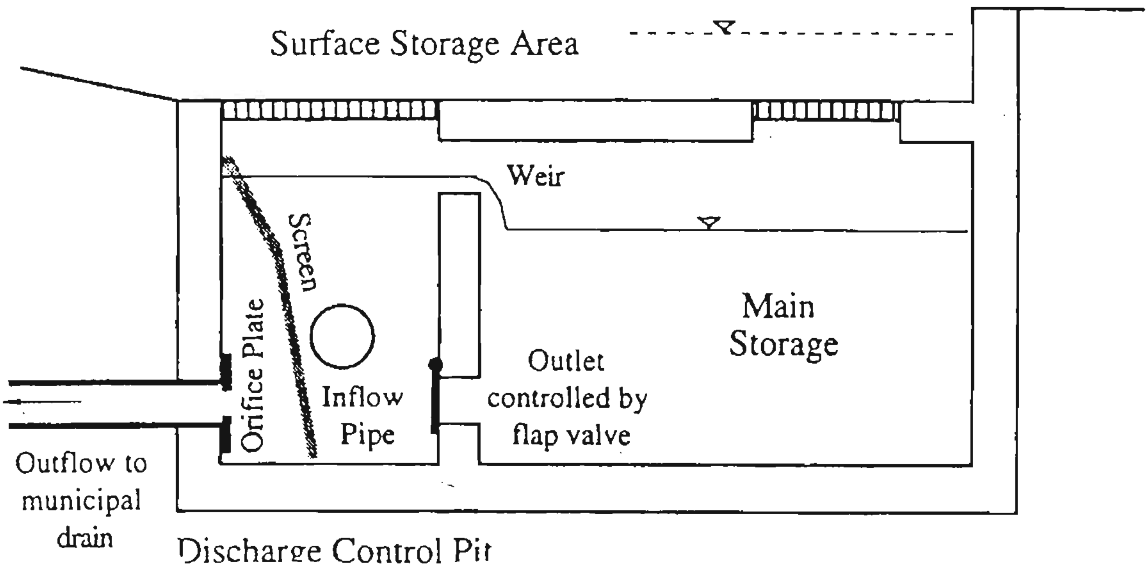
Limitations and drawbacks

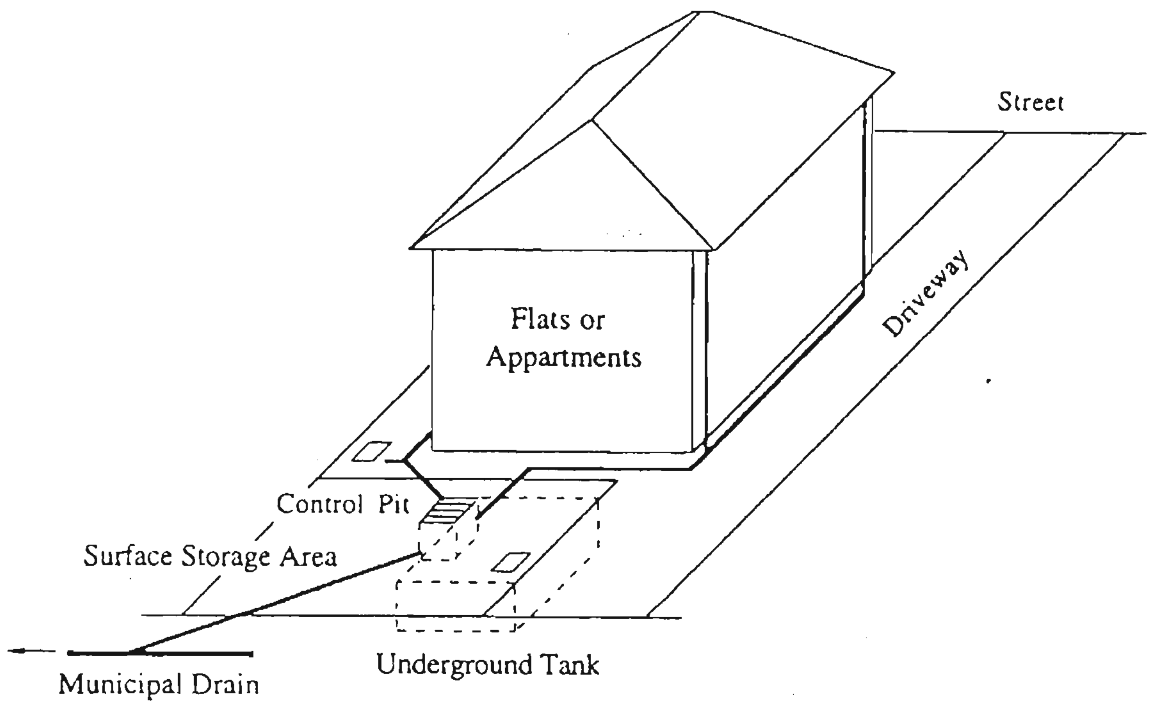
- Requires a site with adequate water supply to maintain permanent water pool.
- May require a liner to sustain permanent pool in very permeable soils.
- Thermal increases a concern for heat sensitive aquatic species.
- Inadequate maintenance may lead to nuisance problems. These include floating debris, algae, odours, and insects.
- Relatively large space requirement.

For more information consult:

1) EPA 1996. *Protecting Natural Wetlands: A Guide to Stormwater Best Management Practices*. Office of Water. Washington, D.C
2) Greater Vancouver Regional District, Stormwater/Drainage Division. www.gvrd.bc.ca/services/sewers/drain/BestMgmtGuide.html
3) Schueler TR 1987. *Controlling Urban Runoff: A Practical Manuel For Planning and Designing Urban BMPs*. Metropolitan Washington Council of Governments, Washington, D.C.

BMP Number 11: On-site-detention





On-site-detention systems usually take the form of pavements or parking lots. They have been used extensively in Australia. Usually occur were infiltration is not feasible. Other areas that have been used include school fields, floors of covered parking lots and lawns or gardens.

Application and effectiveness

- For a large development one large site can be used i.e. a single parking lot.
- Usually implemented in ultra urban areas. However, can be applicable to all conditions.
- OSD can also be implemented by the individual land user i.e. rainfall harvesting.

Limitations and drawbacks

- If slopes are steep greater than 15% then underground storage is needed.
- Underground storage is costly @ R 20 000 per unit.
- High maintenance cost
- Minimal water quality improvement

For more information consult:

1) Nicholas DI 1995. On-Site Stormwater Detention: Improved Implementation Techniques for Runoff Quantity and Quality Management in Sydney. *Water Science and Technology* 32 (1): 85-91.
2) O'Loughlin G, Beechan S, Lee S, Rose L & Nicholas 1995. On0Site Stormwater Detention Systems in Sydney. *Water Science and Technology* 32 (1): 169-175.

APPENDIX 2: EXAMPLE OF A DATA COLLECTION FORM

BMP Type: Infiltration trench							
Land use	**Soils**	**Water table**	**Drainage area**	**Slope (%)**	**Capability**	**Other**	**References**
Road networks	Permeable	1.5 metres from bottom of trench	Best below 7.5 ha	<5	Ground water recharge	Disadvantages – threat to groundwater -maintenance costs - rapid clogging	Veldcamp *et al.* (1997)
Urban type of environment	Same a I-basin	Deep water tables			Replicate pre-development hydrology		EPA (1996)
	Not good on clay				Decrease bankfull flooding frequency		Barraud *et al.* (1999)
	Soil hydraulic conductivity (10^{-6} to 10^{-3} $m.s^{-1}$)				Copes well with 2 yr design storm		Alfakih *et al.* (1999)
					Decreases streambank erosion		
					Runoff volume reduction		

APPENDIX 3: THE COMPLETED MCDSS IN EXCEL FORMAT

Spreadsheet of Stormwater Matrixes (1)

A/B/C/D refer to hydrological soil groups

Infiltration (cm.h^{-1})

[redacted]

0.1-0.5 inch.h^{-1} (L) **Sandy Clay Loam**
0.25-1.25 cm.h^{-1} (L) **Silty Loam**

0.5-1.0 inch.h^{-1} (M) **Loams, Silts**
1.25-2.5 cm.h^{-1} (M)

> 1.0 inch.h^{-1} (H) **Sandy Loam**
>2.5 cm.h^{-1} (H) **Loamy Sand**
Sand

	VL (D)	L (C)	M (B)	H (A)	Choice
BMP type	0.25	0.25-1.25	1.25-2.5	> 2.5	
Infiltration Basin	0	0	3	4	
Infiltration Trench	0	0	3	4	
Porous Pavement	0	0	3	4	
Porous Pavement (Reservoir Design)	4	4	4	4	
Filter Strips	1	3	3	4	
Grass Swale	1	3	3	4	
Sand Filter	3	4	2	1	
Extended Detention Basin	2	3	3	4	
Wet Extended Detention Basin	2	3	3	4	
Wet Ponds	4	4	2	1	
Constructed Wetland	4	4	2	1	
On-Site-Detention	1	2	3	4	

Water Table Requirement (m)

BMP type	<5	5 to 8	8 to 12	>12	Choice
Infiltration Basin	1	2	3	4	
Infiltration Trench	1	1	3	4	
Porous Pavement	1	2	3	4	
Porous Pavement (Reservoir Design)	1	2	3	4	
Filter Strips	1	2	3	4	
Grass Swale	1	2	3	4	
Sand Filter	1	2	3	4	
Extended Detention Basin	1	2	3	4	
Wet Extended Detention Basin	1	2	3	4	
Wet Ponds*	4	3	2	1	
Constructed Wetland	4	3	2	1	
On-Site-Detention	1	2	3	4	

Slope (%)

BMP type	<5	5 to 10	10 to 15	>15	Choice
Infiltration Basin	4	3	2	1	
Infiltration Trench	4	3	1	0	
Porous Pavement	4	2	1	0	
Porous Pavement (Reservoir Design)	4	2	1	0	
Filter Strips	4	3	1	1	
Grass Swale	4	2	1	1	
Sand Filter	4	3	1	1	
Extended Detention Basin	4	3	2	1	
Wet Extended Detention Basin	4	3	2	1	
Wet Ponds	4	3	2	1	
Constructed Wetland	4	3	1	1	
On-Site-Detention	4	3	3	2	

Size of Drainage Area (Hectares)

BMP type	2.5	2.5-5	5-7.5	7.5-10	>10	Choice
Infiltration Basin	2	3	4	4	2	
Infiltration Trench	4	4	1	0	0	
Porous Pavement	4	3	2	1	0	
Porous Pavement (Reservoir Design)	4	3	2	1	0	
Filter Strips	4	2	1	0	0	
Grass Swale	4	2	0	0	0	
Sand Filter	4	4	3	2	2	
Extended Detention Basin	0	2	3	4	4	
Wet Extended Detention Basin	0	2	3	4	4	
Wet Ponds	0	1	3	3	4	
Constructed Wetland	0	1	3	4	4	
On-Site-Detention	4	4	4	4	4	

Runoff source and site characteristics

BMP type	Roads/highways	Res (M-H) or Com (M-D)	Commercial (H-D)	Rural	Res (L-M)	Choice
Infiltration Basin	1	3	2	1	4	
Infiltration Trench	3	2	3	1	2	
Porous Pavement	0	4	4	1	4	
Porous Pavement (Reservoir Design)	0	4	4	1	4	
Filter Strips	2	3	0	2	4	
Grass Swale	4	3	2	3	4	
Sand Filter	4	2	4	2	1	
Extended Detention Basin	3	3	2	2	3	
Wet Extended Detention Basin	3	3	2	2	3	
Wet Ponds	2	3	1	3	4	
Constructed Wetland	0	3	2	4	4	
On-Site-Detention	0	4	3	3	4	

Stormwater treatment suitability matrix

BMP type	Water quality	Runoff vol red	Groundwater Recharge	Flood cont	Streambank erosion cont	Flow rate control	Choice
Infiltration Basin	3	4	4	4	3	3	
Infiltration Trench	3	3	3	3	2	2	
Porous Pavement	3	4	4	2	2	4	
Porous Pavement (Reservoir Design)	1	3	3	3	2	1	
Filter Strips	2	2	2	1	0	2	
Grass Swale	2	1	1	1	0	1	
Sand Filter	3	0	1	0	0	1	
Extended Detention Basin	3	0	1	3	3	3	
Wet Extended Detention Basin	4	0	1	3	3	3	
Wet Ponds	3	0	1	4	3	4	
Constructed Wetland	4	0	1	3	3	3	
On-Site-Detention	1	2	2	2	2	2	

Community and Environmental Factors

BMP type	Habitat creation	Aesthetics	Recreational Benefits	O & M	Cost (rel to drainage area)	Failure Rate/Risk	Potential for g-water cont.
Infiltration Basin	2	0	1	4	2	4	3
Infiltration Trench	0	0	0	4	2	2	4
Porous Pavement	0	0	0	3	4	3	4
Porous Pavement (Reservoir Design)	0	0	0	3	4	3	1
Filter Strips	3	3	0	2	1	1	1
Grass Swale	1	2	0	3	2	1	1
Sand Filter	0	0	0	3	4	2	1
Extended Detention Basin	2	2	0	3	2	1	1
Wet Extended Detention Basin	4	4	2	2	2	1	1
Wet Ponds	4	4	4	2	1	1	1
Constructed Wetland	4	4	4	4	3	1	1
On-Site-Detention	0	0	0	4	4	3	2

The total score sheet before the equations take effect

Scenario	INF	WT	S	DA	RSC	TSM	SCORE
Infiltration Basin							
Infiltration Trench							
Porous Pavement							
Porous Pavement (Reservoir Design)							
Filter Strips							
Grass Swale							
Sand Filter							
Extended Detention Basin							
Wet Extended Detention Basin							
Wet Ponds							
Constructed Wetland							
On-Site-Detention							

FINAL SCORE SHEET						A	B	C	D	E	F
Scenario	INF	WT	S	DA	RSC	SAS	TSM	EB	COM	RISK	SCORE
Infiltration Basin*	0	0	0	0	0			1.5	3	1.75	
Infiltration Trench*	0	0	0	0	0			0	3	1.5	
Porous Pavement**	0	0	0	0	0			0	3.5	1.75	
Porous Pavement (Reservoir Design)**	0	0	0	0	0			0	3.5	1	
Filter Strips	0	0	0	0	0			3	1.5	0.5	
Grass Swale	0	0	0	0	0			1.5	2.5	0.5	
Sand Filter	0	0	0	0	0			0	3.5	0.75	
Extended Detention Basin	0	0	0	0	0			2	2.5	0.5	
Wet Extended Detention Basin	0	0	0	0	0			5	2	0.5	
Wet Ponds***	0	0	0	0	0			6	1.5	0.5	
Constructed Wetland	0	0	0	0	0			6	3.5	0.5	
On-Site-Detention****	0	0	0	0	0			0	4	1.25	
MAX SCORE								6	4	2	

Equations used in the MCDSS

A) to get the SAS score = (INF * 1) + (WT * 0.5) + (S * 0.5) + (DA * 1) + (RSC * 1)

B) to get the TSM score = (Sum of initial TSM values * 3)

C) to get the EB score = (Habitat creation * 0.5) + (Aesthetics * 0.5) + (Recreational benefits * 0.5)

D) to get COM score = (O&M * 0.5) + (Cost * 0.5)

E) to get RISK score = (Failure rate * 0.25) + (Groundwater threat * 0.25)

F) to get SCORE = (Sum of all A…E)

Rules to consider when BMPs are selected

* If selected then should be pretreated with grass swale/filter strip to improve functioning

* High silt content of receiving water negates the use of infiltration devices

** Heavy vehicles and high traffic volumes - add waterproof lining

*** Wet pond require adequate base flow all year round

**** If slopes are steep then underground storage is needed otherwise ponding in parking lots and open areas can take place

APPENDIX 4: MCDSS OUTPUT FOR THE ELEVEN SITES

Results of MCDSS output for the 11 sites within the Town Bush stream catchment

* If selected then should be pretreated with grass swale/filter strip to improve functioning

* high silt content of receiving water negates the use of infiltration devices

** Heavy vehicles and high traffic volumes - add waterproof lining

*** Wet ponds require adequate base flow all year round

**** If slopes are steep then underground storage is needed otherwise ponding in parking lots and open areas can take place

NOTE: scores highlighted in yellow show that the BMP option scored a zero in either the TSM or SAS options. (Refer to primary matrix)

Site 1 output	TSM	SAS	EB	COM	RISK	SCORE
Infiltration Basin*	39	12	1.5	3	1.75	47.75
Infiltration Trench*	30	8	0	3	1.5	33.5
Porous Pavement**	33	9.5	0	3.5	1.75	37.25
Porous Pavement (Reservoir Design)**	21	9.5	0	3.5	1	26
Filter Strips	15	10	3	1.5	0.5	26
Grass Swale	12	9.5	1.5	2.5	0.5	20
Sand Filter	12	6	0	3.5	0.75	13.75
Extended Detention Basin	36	13	2	2.5	0.5	48
Wet Extended Detention Basin	39	13	5	2	0.5	54.5
Wet Ponds***	42	12.5	6	1.5	0.5	58.5
Constructed Wetland	39	12.5	6	3.5	0.5	53.5
On-Site-Detention****	21	14	0	4	1.25	29.75

Site 2 output	TSM	SAS	EB	COM	RISK	SCORE
Infiltration Basin*	21	7.5	1.5	3	1.75	26.25
Infiltration Trench*	18	11.5	0	3	1.5	25
Porous Pavement**	21	7	0	3.5	1.75	22.75
Porous Pavement (Reservoir Design)**	12	8	0	3.5	1	15.5
Filter Strips	12	8.5	3	1.5	0.5	21.5
Grass Swale	9	10	1.5	2.5	0.5	17.5
Sand Filter	9	11.5	0	3.5	0.75	16.25
Extended Detention Basin	9	9.5	2	2.5	0.5	17.5
Wet Extended Detention Basin	12	9.5	5	2	0.5	24
Wet Ponds***	9	6.5	6	1.5	0.5	19.5
Constructed Wetland	12	4.5	6	3.5	0.5	18.5
On-Site-Detention****	9	8.5	0	4	1.25	12.25

Site 3 output	TSM	SAS	EB	COM	RISK	SCORE
Infiltration Basin*	21	7.5	1.5	3	1.75	25.25
Infiltration Trench*	18	7.5	0	3	1.5	21
Porous Pavement**	21	4	0	3.5	1.75	19.75
Porous Pavement (Reservoir Design)**	12	5	0	3.5	1	12.5
Filter Strips	12	6.5	3	1.5	0.5	19.5
Grass Swale	9	8	1.5	2.5	0.5	15.5
Sand Filter	9	9.5	0	3.5	0.75	14.25
Extended Detention Basin	9	11.5	2	2.5	0.5	19.5
Wet Extended Detention Basin	12	11.5	5	2	0.5	26
Wet Ponds***	9	9.5	6	1.5	0.5	22.5
Constructed Wetland	12	7.5	6	3.5	0.5	21.5
On-Site-Detention***	9	8.5	0	4	1.25	12.25

Site 4 output

	TSM	SAS	EB	COM	RISK	SCORE
Infiltration Basin*	21	7.5	1.5	3	1.75	25.25
Infiltration Trench*	18	7.5	0	3	1.5	21
Porous Pavement**	21	4	0	3.5	1.75	19.75
Porous Pavement (Reservoir Design)**	12	5	0	3.5	1	12.5
Filter Strips	12	6.5	3	1.5	0.5	19.5
Grass Swale	9	8	1.5	2.5	0.5	15.5
Sand Filter	9	9.5	0	3.5	0.75	14.25
Extended Detention Basin	9	11.5	2	2.5	0.5	19.5
Wet Extended Detention Basin	12	11.5	5	2	0.5	26
Wet Ponds***	9	9.5	6	1.5	0.5	22.5
Constructed Wetland	12	7.5	6	3.5	0.5	21.5
On-Site-Detention****	9	8.5	0	4	1.25	12.25

Site 5 output

	TSM	SAS	EB	COM	RISK	SCORE
Infiltration Basin*	51	8	1.5	3	1.75	55.75
Infiltration Trench*	39	8	0	3	1.5	42.5
Porous Pavement**	45	5	0	3.5	1.75	44.75
Porous Pavement (Reservoir Design)**	30	6	0	3.5	1	31.5
Filter Strips	21	7	3	1.5	0.5	29
Grass Swale	15	9	1.5	2.5	0.5	22.5
Sand Filter	15	10	0	3.5	0.75	20.75
Extended Detention Basin	39	12	2	2.5	0.5	50
Wet Extended Detention Basin	42	12	5	2	0.5	56.5
Wet Ponds***	45	10	6	1.5	0.5	59
Constructed Wetland	42	8	6	3.5	0.5	52
On-Site-Detention****	27	9	0	4	1.25	30.75

Site 6 output

	TSM	SAS	EB	COM	RISK	SCORE
Infiltration Basin*	39	8	1.5	3	1.75	43.75
Infiltration Trench*	30	8	0	3	1.5	33.5
Porous Pavement**	33	5	0	3.5	1.75	32.75
Porous Pavement (Reservoir Design)**	21	6	0	3.5	1	22.5
Filter Strips	15	7	3	1.5	0.5	23
Grass Swale	12	9	1.5	2.5	0.5	19.5
Sand Filter	12	10	0	3.5	0.75	17.75
Extended Detention Basin	36	12	2	2.5	0.5	47
Wet Extended Detention Basin	39	12	5	2	0.5	53.5
Wet Ponds***	42	10	6	1.5	0.5	56
Constructed Wetland	39	8	6	3.5	0.5	49
On-Site-Detention****	21	9	0	4	1.25	24.75

Site 7 output	TSM	SAS	EB	COM	RISK	SCORE
Infiltration Basin*	39	8	1.5	3	1.75	43.75
Infiltration Trench*	30	4	0	3	1.5	29.5
Porous Pavement**	33	6	0	3.5	1.75	33.75
Porous Pavement (Reservoir Design)**	21	10	0	3.5	1	26.5
Filter Strips	15	9	3	1.5	0.5	25
Grass Swale	12	9	1.5	2.5	0.5	19.5
Sand Filter	12	9	0	3.5	0.75	16.75
Extended Detention Basin	36	12	2	2.5	0.5	47
Wet Extended Detention Basin	39	12	5	2	0.5	53.5
Wet Ponds***	42	14	6	1.5	0.5	60
Constructed Wetland	39	14	6	3.5	0.5	55
On-Site-Detention****	21	12	0	4	1.25	27.75

Site 8 output

	TSM	SAS	EB	COM	RISK	SCORE
Infiltration Basin*	39	8	1.5	3	1.75	43.75
Infiltration Trench*	30	4	0	3	1.5	29.5
Porous Pavement**	33	6	0	3.5	1.75	33.75
Porous Pavement (Reservoir Design)**	21	10	0	3.5	1	26.5
Filter Strips	15	9	3	1.5	0.5	25
Grass Swale	12	9	1.5	2.5	0.5	19.5
Sand Filter	12	9	0	3.5	0.75	16.75
Extended Detention Basin	36	12	2	2.5	0.5	47
Wet Extended Detention Basin	39	12	5	2	0.5	53.5
Wet Ponds***	42	14	6	1.5	0.5	60
Constructed Wetland	39	14	6	3.5	0.5	55
On-Site-Detention****	21	12	0	4	1.25	27.75

Site 9 output

	TSM	SAS	EB	COM	RISK	SCORE
Infiltration Basin*	33	8	1.5	3	1.75	37.75
Infiltration Trench*	24	5	0	3	1.5	24.5
Porous Pavement**	30	7	0	3.5	1.75	31.75
Porous Pavement (Reservoir Design)**	21	11	0	3.5	1	27.5
Filter Strips	15	5	3	1.5	0.5	21
Grass Swale	9	7	1.5	2.5	0.5	14.5
Sand Filter	3	12	0	3.5	0.75	10.75
Extended Detention Basin	18	11	2	2.5	0.5	28
Wet Extended Detention Basin	18	11	5	2	0.5	31.5
Wet Ponds***	24	10	6	1.5	0.5	38
Constructed Wetland	18	12	6	3.5	0.5	32
On-Site-Detention****	18	11	0	4	1.25	23.75

Site 10 output

	TSM	SAS	EB	COM	RISK	SCORE
Infiltration Basin*	39	11	1.5	3	1.75	46.75
Infiltration Trench*	39	7	0	3	1.5	41.5
Porous Pavement**	45	9	0	3.5	1.75	48.75
Porous Pavement (Reservoir Design)**	30	10	0	3.5	1	35.5
Filter Strips	21	9	3	1.5	0.5	31
Grass Swale	15	9	1.5	2.5	0.5	22.5
Sand Filter	15	7	0	3.5	0.75	17.75
Extended Detention Basin	39	12	2	2.5	0.5	50
Wet Extended Detention Basin	42	12	5	2	0.5	56.5
Wet Ponds***	45	12	6	1.5	0.5	61
Constructed Wetland	42	12	6	3.5	0.5	56
On-Site-Detention****	27	13	0	4	1.25	34.75

Site 11 output

	TSM	SAS	EB	COM	RISK	SCORE
Infiltration Basin*	39	8	1.5	3	1.75	43.75
Infiltration Trench*	39	4	0	3	1.5	38.5
Porous Pavement**	45	6	0	3.5	1.75	45.75
Porous Pavement (Reservoir Design)**	30	10	0	3.5	1	35.5
Filter Strips	21	7	3	1.5	0.5	29
Grass Swale	15	7	1.5	2.5	0.5	20.5
Sand Filter	15	8	0	3.5	0.75	18.75
Extended Detention Basin	39	11	2	2.5	0.5	49
Wet Extended Detention Basin	42	11	5	2	0.5	55.5
Wet Ponds***	45	14	6	1.5	0.5	63
Constructed Wetland	42	14	6	3.5	0.5	58
On-Site-Detention****	27	11	0	4	1.25	32.75