THE USE OF EROSION MODELS TO PREDICT THE INFLUENCE OF LAND USE CHANGES ON URBAN IMPOUNDMENTS

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DECLARATION

I certify that this thesis is my own unaided work. It is being submitted to the Degree of Master of Science to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

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ABSTRACT

The impact of soil loss from urban erosion processes is a major problem confronting decision makers on a national and local level. One such resource is the Boksburg Lake in the Eastern Service Delivery Region of the Ekurhuleni Metropolitan Municipality of the Gauteng Province, South Africa.

The purpose of the study was to quantify what impact soil erosion, as a result of changes in land-use, had on the urban impoundment. There is a close relationship between how land is managed and the impact erosion may have on in-stream health. Increased erosion as a result of catchment changes increases the loads of phosphorus introduced into streams (Croke, 2002) and subsequently increases the occurrence of eutrophication. The management of sediment levels combined with reduced catchment phosphorus load is viewed as the most viable option in eutrophication abatement.

Available soil erosion models and methods were compared and the most suited selected for the study. The study used a modified approach of the Universal Soil Loss Equation and the Soil Loss Estimation Model for Southern Africa. These were adjusted for urban conditions. Various simulation models were run and the results presented.

Results from five of the models yielded results within 15%, or 85% confidence, of the measured results. Four of these models are however not generally accepted methods and can only be used as indication. The USLE method utilizing the Vanoni SDR equation is the preferred method and was applied in subsequent modelling.

The simulation results of the phosphorus loading, although not within a 10% accuracy, relates to the observed loadings of 2008. By observing a similar trend as the sediment loadings, as a result of the development, it was concluded that the phosphorus loadings relate to the soil loss models which was related to changes in the catchments as a result of changes in land usage (imperviousness as indicator).

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LIST OF SYMBOLS

MUSLE model parameter	a
Mean Annual soil loss from land	Aa
Area	A
MUSLE model parameter	b
Crop management factor	C
Long term average SCS curve number	CN
Percentage of clay in sediment	C_{sed}
Percentage of clay in soil	C_{soil}
Rainfall Kinetic Energy	E
Soil Erodibility Index	F
Percent Effective Vegetation Cover	I
Rainfall Intensity (30 minutes)	IE_{30}
imperviousness (%)	Imp
Soil-erodibility factor	K
baseline rill erodibility parameter	Kr
Slope Length (m) or Length of watershed (m)	L
Slope length and slope gradient factor	LS
Product of the primary particle size fraction	M
exponent related to slope gradient (to calculate LS)	n
Percentage of organic matter	OM%
percent silt plus very fine sand	SS%
Support Practice Factor	P
Population Density in developed portions of urbanised areas	PD_d
Mean Annual Rainfall (mm)	Pm
Permeability Code	Ps

Rainfall volume (m^3) from individual events	Q
Peak Flow rate	q_p
Rainfall Erosivity	R
Recurrence interval	R_c
Relief of watershed	Rr
Peak rainfall excess rate	R_{ep}
Slope Length/steepness (%)	S
Percent sand	Sa
Structure code	S_s
Sensitivity Index	SI
Sediment yield from an individual storm	SY
Storm duration (hr)	T_d
Topographic factor (Steepness factor)	X
Sediment yield (MUSLE)	Y
Relief-Length ratio in m/km	ZL

LIST OF ABBREVIATIONS

ACRU	Agricultural Catchment Research Unit
AGNPS	Agricultural Non-Point Source Pollution
AMSL	Average Meters above Sea Level
ANSWERS	Areal Non-point Source Watershed Environment
ARI	Annual Recurrence Interval
BHA	Boksburg Historical Association
CLC	Contribution Life Cycle
COD	Chemical Oxygen Demand
CORINE	Coordination of Information on the Environment
CREAMS	Chemical Runoff and Erosion from Agricultural Management Systems
DATS	Department of Agriculture Technical Services
DTM	Digital Terrain Model
ECC	Effective Contributing Catchment
ECOHAM1	Ecological North Sea Model Hamburg
EMM	Ekurhuleni Metropolitan Municipality
EPA	Environmental Protection Agency
EUROSEM	European Soil Erosion Model
FSL	Full Supply Level
GIS	Geographic Information System
HEM3D	Hydrodynamic Eutrophication Model
IWR	Institute of Water Research
KE	Kinetic Energy
KINEROS	Kinematic Runoff and Erosion Model
LISEM	Limburg Soil Erosion Model
MAP	Mean Annual Precipitation

MMF	Morgan and Finney Model
MUSLE	Modified Universal Soil Loss Equation
NEUTRO	Princeton Eutrophication Model
OECD	Organization for Economic Cooperation and Development
OPUS	Advanced simulation model for non-point source pollution transport
pH	Measure of hydrogen ion concentration
PCSWMM	Personal Computer Stormwater Management Model
PEM	Potomac Eutrophication Model
PEPP	Process-oriented Erosion Prognosis Program
PSIAC	Pacific Southwest Interagency Committee
REM	Reservoir Eutrophication Model
RSEM	Reservoir Specific Eutrophication Model
RUSLE	Revised Universal Soil Loss Equation
SAWB	South African Weather Bureau
SCS	Soil Conservation Services
SDF	Spatial Development Framework
SDR	Sediment Delivery Ratio
SLEMSA	Soil Loss Estimator for Southern Africa
SRB	Sediment Retention Basin
SRP	Soluble Reactive Phosphorus
SS	Suspended Solids
SWAT	Soil and Water Assessment Tool
SWMM	Stormwater Management Model
US	United States
USDA	United States Department of Agriculture
USLE	Universal Soil Loss Equation

VIMS	Virginia Institute of Marine Science
WASP	Water Quality Analysis Simulation Program
WEPP	Water Erosion Prediction Project
WRC	Water Research Commission
WSUD	Water Sensitive Urban Design

1 INTRODUCTION

1.1 Significance of study and research question

Impoundments in urban areas of South Africa, either natural or artificial, are popular recreational attractions that add to the quality of life, increase property value and are increasingly built as focal points for commercial developments. More regularly such impoundments acts as receptacles for polluted runoff, resulting in water quality problems which ultimately reduce the aesthetic value and undermine their recreational value and function as originally envisaged (Freeman *et al*, 2000).

The impact of soil loss from erosion processes is a major problem confronting decision makers on a national and local level due to the impact on local resources (Le Roux *et al*, 2007). One such resource is the Boksburg Lake in the Eastern Service Delivery Region of the Ekurhuleni Metropolitan Municipality of the Gauteng Province, South Africa. The Problem is due, in part to the reluctance of municipal officials primarily involved with storm water infrastructure and catchment management to undertake seemingly non-technical issues such as dealing with causes of erosion in the urban environment and partly because it is viewed as a social behaviour and environmental management problem rather than an engineering consideration (Armitage & Marais, 2003).

The purpose of the study is to quantify what impact soil erosion processes, as a result of changes in land-use, will have on urban impoundments, Boksburg Lake in this case study. The impact is assessed through the compilation of a computer based simulation model.

Boksburg Lake, located in Boksburg, a service delivery centre of the Ekurhuleni Metropolitan Municipality within the Gauteng provinces is a shallow, urban hypertrophic dam as per OECD (Organization for Economic Cooperation and Development) classification (Annex 1, p 92) (Vollenweider & Kerekes, 1980). The dam has been in a polluted state for at least two decades with an increase in fish mortality rates (South Africa. Ndumo Group Projects, 2008). This is primarily as a result of pollution.

There is a close relationship between how land is managed and the impact erosion (and hence phosphorus) may have on in-stream health. Increased erosion as a result of catchment changes increases the possible loads of phosphorus introduced into streams (Croke, 2002) and subsequently increases the occurrence of eutrophication. Recent research has discovered that existing stores of sediment, resulting from previous erosion (mid–to-long term), are responsible for the delivery of additional phosphorus to waterways and reservoirs (Croke, 2002). The management of sediment levels combined with reduced catchment phosphorus load is viewed as the most viable option in eutrophication abatement. This is due to phosphorus release from low-oxygen sediments in riverbeds and reservoir sediment layers (Croke, 2002).

The aim of the study is to identify the impact changes in urban catchments will have on sediment loadings and what the impact (over time) will be on the volume of the capacity of the urban impoundments. This will be achieved through the compilation of a soil loss model using a similar methodology proposed by Moojong *et al* (2008), applying a modified approach of a soil loss model (in Moojong's case, the Revised Universal Soil Loss Equation), suited for urban conditions. This approach will be adopted for South African rainfall and soil conditions. Considerations and recommendations for the reduction of the external nutrient loads (specifically phosphorus) will be presented.

The main question to be answered is thus:

- What impact does land use change in urban catchments have on sediment loadings (yields) of impoundments?

The following secondary questions are also raised:

- What linkage exists between the sedimentation as a result of erosion and phosphorus loadings, and can the occurrence of eutrophication be reduced as a result of this linkage?

It is important to have a basic understanding of eutrophication processes (and hence the phosphorus) as this study assumes that the limitation of phosphorus will limit eutrophication and that a considerable portion of the phosphorus load in deposited impoundments originates from detached sediments which are transported by urban storm water systems. The following sections will focus on soil erosion dynamics, models to predict soil loss, eutrophication and phosphorus loads and their associated prediction models and limitations and gaps of the existing knowledge base concerned with urban soil loss estimation.

1.2 Key gaps in knowledge and data

Soil loss models mostly focus on large scale catchments for water resources and soil conservation activities. Where such models have been tailored to look at urban environments, they are often only aimed at combined sewer applications within first world developed countries. There exists a limitation and need of urban soil loss models modelling within developing countries using limited data.

1.3 Objectives of the study

Sedimentation in urban impoundments is a consequence of soil erosion brought about by land use changes in the catchment. As a result of these catchment changes, experienced when urban areas go through cycles of renewal and degradation, sediment loadings on urban impoundments increase periodically, resulting in water quality problems. It is the aim of this study to assess the impact such land use changes will have on sediment loads in the Boksburg Lake. Secondly, it is recognized that phosphorus availability in reservoirs results from immense sediment reserves and storages from the catchments and streams. These sediment reserves originate from upstream urban catchments and are transported through a complex transportation system. By limiting the detachment and transport of sediment, through the limiting of erosion, a reduction of eutrophication can be brought about in the Boksburg Lake. This can only be achieved using a simulation model and a proper management system by answering the appropriate management questions.

2 BACKGROUND

2.1 Introduction

Soil erosion is affected by many factors, these include; climate erosivity (also referred to as rainfall erosivity), soil erodibility, topography of the affected site, vegetation cover practices (management strategies) and conservation measures applied. Each of these factors affects soil erosion in one of a three-phase process, involving the detachment, transportation and deposition processes of sediment.

A brief introduction on the types of water erosion (only erosion process considered for this study), namely sheet, rill, gully, and stream erosion is provided. Models on the quantification of these processes are discussed in section 2.7.

2.2 Extent of soil degradation by erosion

It is estimated that the total land area subjected to human-induced soil degradation to be two billion hectares with an estimated land area of 1100 Mha affected by water erosion (Lal, 2001). The global extent of human-induced soil degradation is summarised in the table below. Africa has the second largest degradation after Asia.

Table 1 Global extent of human-induced soil degradation (Lal, 2001)

World Region	Total Land area (10 ha)	Human induced soil degradation (10 ha)	Soil Erosion	
			Water	Wind
Africa	**2966**	**494**	**227**	**186**
Asia	4256	748	441	222
South America	1768	243	123	42
Central America	306	63	46	5
North America	1885	95	60	35
Europe	950	219	114	42
Oceania	882	103	83	16
World Total	**13013**	**1965**	**1094**	**548**

2.2.1 Soil erosion as contributor to water quality problems

Soil loss and sediment yield are two terms that have distinct meanings in erosion technology. Soil loss refers to the removal of soil material from its original position (Lentsoane, 2005), i.e., a particular slope or development. It can be defined as the detachment and movement of soil particles on a landscape profile or land facet distinguishing it from deposition and sediment transport in catchment (Nearing *et al*, 1994). The total sediment outflow from a catchment during any given time is the sediment yield of that catchment. It is that proportion of the soil loss that is not deposited before the catchment outflow or designated area or area of interest in the catchment (Lentsoane, 2005). It is therefore a net result of the complex process of detachment and transport by raindrops and flowing water (Nearing *et al*, 1994). It is thus acceptable to assume that for small catchments, or facets, the soil loss corresponds with sediment yield and is proportional for bigger catchments (Nearing *et al*, 1994). This is due to temporal and permanent deposition taking place within the catchment.

A major contributor to adverse water quality issues is soil erosion. It is estimated that over 70% of South Africa's surface has been affected by varying intensities and types of soil erosion (Le Roux *et al*, 2007). Sediments are intricately linked to both the supply and transfer of phosphorus. Managing of diffuse sources (such as fertilizer rich soils) of sediment and phosphorus is a key priority for land managers in controlling the delivery to streams (Croke, 2002). The focus in urban management is different compared to that for rural areas, with sources in urban areas (especially South Africa) more regularly being from sewer discharges than anything else (Wiechers and Heynike, 1986).

Recent research in Australia has also discovered the significance of existing stores of sediment in supplying nutrients for algal growth (Karssies and Prosser, 2001). This is the result of long term deposition of phosphor rich sediment in waterways and reservoirs. The research has shown that phosphorus release from low-oxygen sediments in riverbeds is an important factor in the on-set of major algal bloom breakouts.

Sediments can act as phosphorus sinks under aerobic conditions because oxygen is freely available to the microbes living in the sediments. The release of phosphorus is affected by their respiration which reduces oxygen concentrations in bottom waters during periods of temperature stratification. A similar process is experienced when there are high organic loadings (e.g. dead and rotting plant matter).

Management practices aimed at minimizing and intercepting erosion are also likely to minimize the phosphorus transport. Management practices for the reduction of the generation and delivery of phosphorus, linked to erosion, in our catchments include (Croke, 2002):

- Focus on control of diffuse sources
- Stabilizing stream banks
- Development of engineering structures (e.g. contour banks, gully sediment traps, artificial wetlands, farm dams) to reduce on site erosion and sediment delivery
- Management of erosion in high flow events
- Reducing flood peaks. This can be achieved by building appropriate conservation structures such as surface retention basins to retain rainfall in the landscape and by managing ground cover during wet seasons.

2.3 Principles of eutrophication

The word *'eutrophic'* comes from the Greek word *'eutrophos'* meaning well-fed. While an enormous amount of literature has been published on this topic (South Africa. Department of Water Affairs and Forestry, 2002), a detailed treatment is outside the scope of this report.

Eutrophication refers to the enrichment of a water body with plant nutrients such as phosphates and nitrogen, resulting in the excessive growth of algae or other plants (Freeman *et al*, 2000). This excessive growth interferes with the desirable uses of the water. Over the past few decades, starting in the early 1980s already, the word "eutrophication" has been used more often to denote the undesirable addition of nutrients and the effect this has on the impoundment (Meyer and Rossouw, 1992).

The causes and effects of eutrophication are complex. With natural lakes a distinction is often made between what is termed natural and cultural eutrophication (anthropogenic) processes (Rast and Thornton. 2000). According to this distinction natural eutrophication depends only on the local geology and natural features of the catchment whilst cultural eutrophication is associated with human activities which accelerate the eutrophication process beyond the rate of the natural process. The difference between the two distinctions in South Africa seems irrelevant as South African impoundments are manmade with the exception of a few natural pans. The following schematic illustrates some of the factors that drive the eutrophication process in an impoundment. Important to notice is the increased nutrient enrichment that can arise from both point and non-point sources external to the impoundment as well as internal sources like the impoundment's own geology that can release nutrients, but specifically phosphate (Rast and Thornton, 2000).

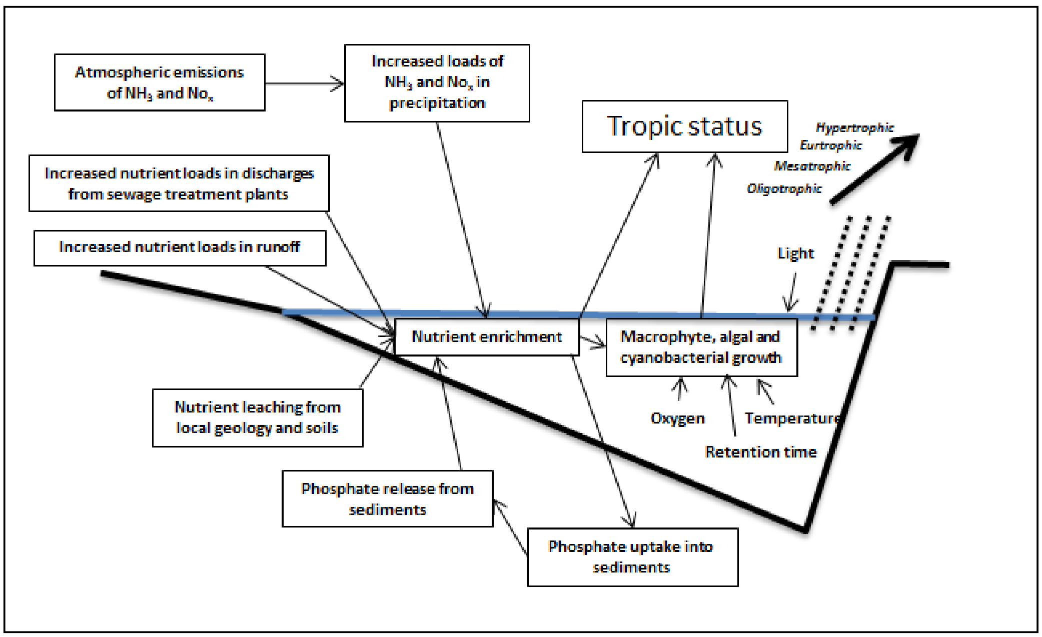

Figure 1 Simplified schematic illustration of the most important factors driving eutrophication (South Africa. Department of Water Affairs and Forestry, 2002)

Eutrophication is a concern because of its numerous negative impacts. The detailed impact is complex and inter related. It is beyond the scope of this study to do an in-depth study on eutrophication as the purpose is only to investigate the sediment related sources of phosphorus and to identify the typical loads expected from urbanised related areas.

The potential impacts of eutrophication are summarised and illustrated in Figure 2, extracted from the draft report for the national eutrophication monitoring programme of the then Department of Water Affairs and Forestry (South Africa. Department of Water Affairs and Forestry, 2002).

Impacts of eutrophication generally include:

- Ecological impacts (in this case e.g. fish mortalities)
- Aesthetic (algal growth and smells)
- Human health impacts associated with recreational activities and sanitation
- Recreational impacts
- Economic impacts (loss of income due to recreational facilities not being used)

All these impacts are associated with the Boksburg Lake.

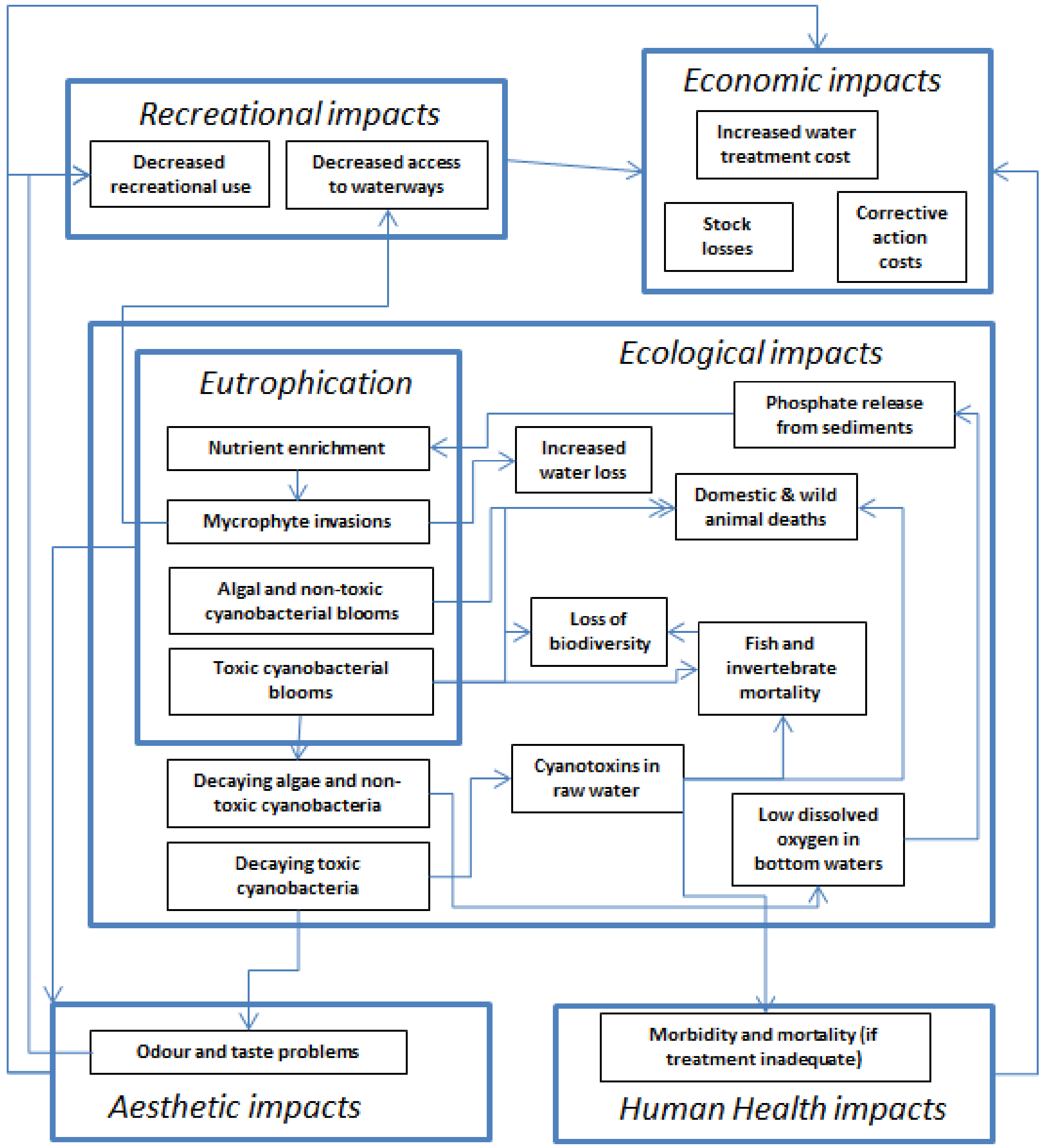

Figure 2 Potential negative impacts of eutrophication (South Africa. Department of Water Affairs and Forestry, 2002)

2.3.1 Eutrophication models

Various models have been developed to predict future eutrophication levels in reservoirs. The reservoir eutrophication model (REM) was used to simulate the tropic status of South African reservoirs (Meyer and Rossouw, 1992). The model assumes that only phosphorus limits eutrophication and that chlorophyll II concentration is a suitable measure for assessing tropic status of a water body (Meyer and Rossouw, 1992). The model simulates the export of non-point source and point source phosphorus from catchments as well as the phosphorus mass balance and resulting chlorophyll concentrations of the water body. The model has three sub-models as illustrated in Figure 3.

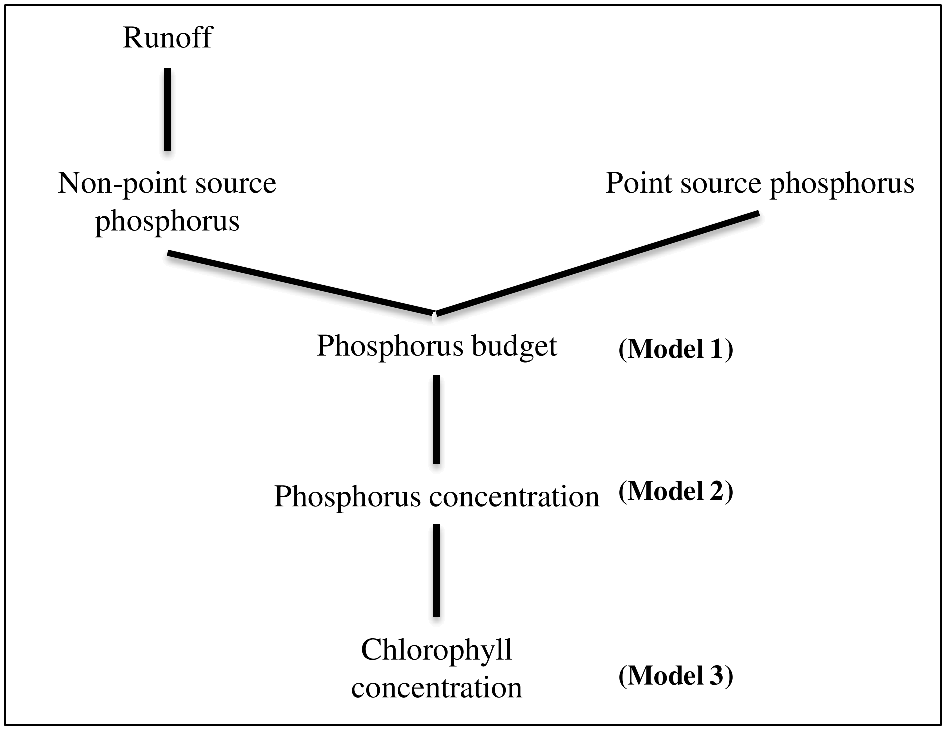

Figure 3 REM Model Layers (Meyer and Rossouw, 1992)

The reservoir eutrophication model is an empirical model and simulates the eutrophication levels that can be expected as the result of different water quality management strategies for the control of point source phosphorus (Meyer and Rossouw, 1992). Meyer and Rossouw (1992) found that the REM model to be too simple and too inflexible to accurately characterise the behaviour of individual South African reservoirs. They therefore developed a more accurate and reservoir specific eutrophication model (RSEM). RSEM is more complicated than REM and accounts for more variables and has to be calibrated individually for each reservoir (Meyer and Rossouw, 1992). The study however indicated that the conventional REM model should not be used to simulate the tropic status of dams as the chemical and physical characteristics of dams differ too much but also that the RSEM model also still need to be tested and further developed (Meyer and Rossouw, 1992). No proof of further enhancements or development of the model could be found.

Scientists at the Virginia Institute of Marine Science (VIMS), Department of Physical Sciences, have developed a general purpose, three-dimensional numerical model which is an integration of a hydrodynamic model, a sediment transport model, and a water quality (eutrophication) model called HEM3D (Park *et al*, 2005). The model can be applied to a wide variety of environmental problems and can operate at a variety of temporal and spatial scales in coastal embayments, estuaries and tributaries. HEM3D is a general-purpose modelling package for simulation of the flow field, transport, and eutrophication processes throughout the water column and of diagenetic processes in the benthic sediment (Park *et al*, 2005).

There are several commercial and research codes available for eutrophication modelling (Tkalich *et al*, 2002) other than those discussed in the preceding section. A few is listed in Table 2.

Table 2 Eutrophication models

Model	**Developed by**	**Approximate Year**
Reservoir Eutrophication Model (REM)**	Grobler	1985
Reservoir Specific Eutrophication Model (RSEM)**	Meyer	1992
HEM3D*	VIMS	2005
WASP*	Ambrose	2001
Potomac Eutrophication Model (PEM)*	Thomann and Fitzpatrick	1982
Ecological North Sea Model Hamburg (ECOHAM1)*	Andreas	1997
Princeton Eutrophication Model (NEUTRO)*	Princeton	

*(Tkalich *et al*, 2002) ** (Meyer and Rossouw, 1992)

From the assessment of these models it is clear that they cannot be grouped into specific types as each model is problem specifically developed. In many instances the models are coupled with water quality models, as is the case with WASP and NEUTRO.

2.3.2 Phosphorus

Phosphorus is an essential element for all life and in aquatic ecosystems it is considered the growth limiting nutrient (Heynike and Wiechers, 1986). For this reason phosphorus must be controlled and by doing so, it provides a means of controlling the deleterious effects of eutrophication, viz. excessive and unwanted algal and plant growth (Walker, 1983).

Phosphorus is a chemical that serves as an important nutrient in surface water. Phosphorus naturally complexes with other molecules to form organic and in-organic phosphates (Perry *et al*, 2008). It is present in stormwater in both the dissolved (measured as orthophosphate or Soluble Reactive Phosphorus (SRP)) and particulate-bound phase adsorbed to sediment particles (Perry *et al*, 2008). The presence of phosphorus in the environment is cyclic where under natural conditions it migrates from rock and sediment deposits and a small portion being metabolized into the tissue of living organisms (Perry *et al*, 2008).

High levels of phosphorus lead to excessive algal growth, which can decrease light penetration and cause oxygen depletion when the algae die off. These conditions interfere with recreational and aquatic life uses and reduce the aesthetic quality of receiving waters. Severe phosphorus concentrations can result in concentrations of blue-green algae that are toxic to wildlife, pets and humans.

There are many sources of phosphorus in urban stormwater, including fertilizer, vegetation, soil and dust, and animal waste. In urban areas, phosphorus concentrations are related to intensity of land use (Bannerman *et al*, 1999), with loads being highest from urban lawns and streets (Bannerman *et al*, 1999). Human activities accelerate the slow phosphorus cycle and it is estimated that they increase the load in phosphorus by about 300% in surface water systems (Perry *et al*, 2009).

Water quality degradation as a result of increased phosphorus loading is beginning to be acknowledged by policy makers in the form of the National Eutrophication Monitoring Programme within the South African National Water Quality Monitoring Programme Series, a product of the Department of Water Affairs.

2.3.3 Sources of phosphorus in urban catchments

Phosphorus inputs in water courses and urban lakes can come from both natural processes and human activities. Natural sources of phosphorus include weathering

processes of rock, decomposition of organic material, and soil leaching. Sources from human activities include fertilisers, pet waste, and detergents from car washing, vehicle emissions, industrial discharge and sewage (Khwanboonbumpen, 2006).
A study was compiled by the office of the US Geological Survey to investigate the sources of phosphorus in stormwater from two residential catchments in Madison, Wisconsin (Bannerman *et al*, 1999). Although spanning a period of only two years (1994 to 1995), the relative sources remained the same over the period, but changes in the concentrations were observed. The study identified concentrations of suspended solids, total phosphorus, and dissolved phosphorus mainly from source areas which included lawns, streets (feeders, collectors and arterials), driveways, parking lots, and roofs (pitched and flat). The source-area concentrations as the geometric means of the combined concentration data were incorporated into the urban-runoff model, called SLAMM or Surface Loading and Management Model (Bannerman *et al*, 1999).

Streets and lawns were found to be the largest contributors of total and suspended phosphorus loads in residential areas. Of these lawns are the largest contributors of total and dissolved phosphorus (presumably from fertilizer application); streets contributing approximately only 40 percent of the catchment load (Bannerman *et al*, 1999). Streets were found to be the largest contributor to suspended solid loadings.

A study in 2006 by Khwanboonbumpen found the major phosphorus sources within two urban areas of Perth Australia were also from fertiliser application on lawns at both sites with the monthly total TP input load of 0.07 ± 0.01 g m^{-2} at Bannister Creek, and 0.13 ± 0.05 g m^{-2} at Wanneroo.

The total quantity of phosphorus loss through surface entrainment is through three processes namely attachment to sediment, dissolved in the runoff, and dissolved in Leachate (Khwanboonbumpen, 2006). The US Department of Agriculture found that as much as 56.2% of tons of sediment are lost through the attachment through waterborne sediment (United States Department of Agriculture, 2006). This figure can be as high as 90% on agricultural watersheds (Zhang *et al*, 2008). Small percentages are lost through leaching and it was assumed that the remainder is dissolved in the runoff.

2.4 Water Erosion Principles

Phosphorus gets into water in both urban and agricultural settings and tends to attach to soil particles and thereby gets transported to water bodies from runoff (United States Geological Survey, 2014). These soil particles are often the result of erosion.

Soil erosion is but one form of soil degradation and is a naturally occurring process on all land with the two major contributing agents of water and wind. Erosion models are a simplified representation of erosion in reality (Lentsoane, 2005). In order to evaluate erosion prediction tools and methods it is important to have an understanding of the underlying principles.

The magnitude and rate of soil erosion by water is controlled by the following factors:

- Rainfall intensity and run-off (climate erosivity)
- Soil erodibility
- Slope gradient and length
- Vegetation or cover practices
- Conservation measures

2.4.1 Erosion process

Soil erosion by water is a basic three-phase process, involving the detachment, transportation and deposition processes of sediment by the erosive agents (American Association of Civil Engineers, 1975). Phase one, or detachment, refers to the dislodging of soil particles from soil mass whereas transportation refers to the entrainment and movement of the soil particle from its original position to a downstream point where phase three occurs. Phase three, or deposition, occurs when there's no longer sufficient energy to transport the particles (Morgan, 2005).

2.5 Types of Water Erosion

Water erosion causes an on-site loss of soil through the loss of the nutrient rich soil layer, and causes an off-site effect of movement of sediment causing silting of reservoirs. In this study the case of Boksburg Lake is considered. The following types of water erosion are found as illustrated in Figure 4.

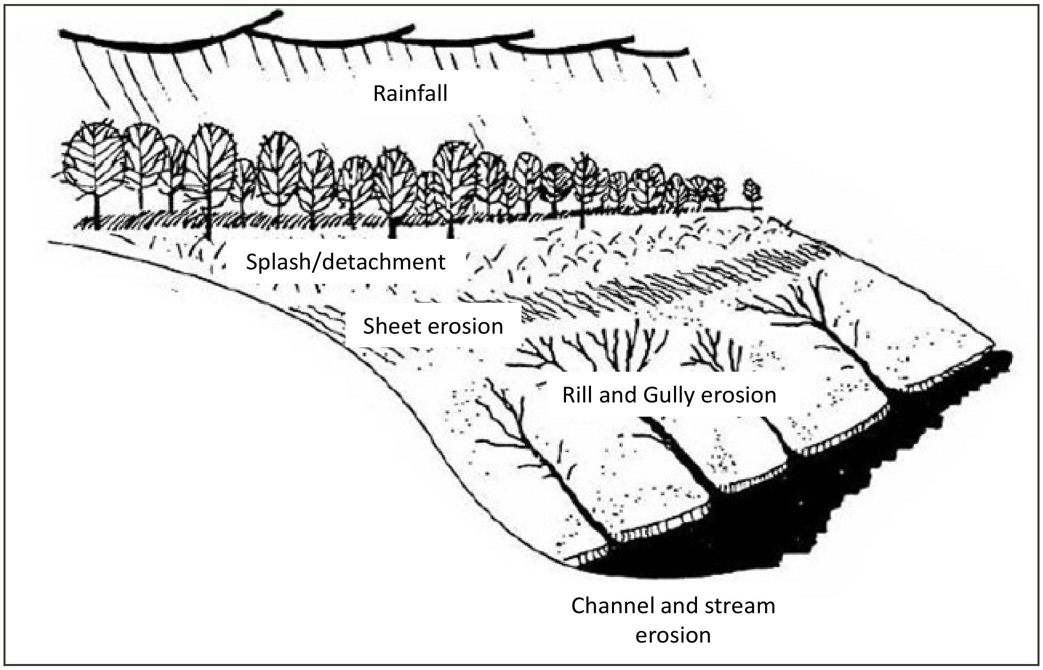

Figure 4 Four types of soil erosion (erosion mechanics) (http://www.cep.unep.org/pubs/Techreports/tr32en/content.html)

2.5.1 Sheet erosion or inter-rill erosion

Sheet erosion is characterized by the detachment of soil particles from the soil matrix and down slope removal of soil particles within a thin sheet of water occurring when the entire surface of a field or plot is gradually eroded in a uniform way (Directorate Agriculture Information Services, 2008; Lentsoane, 2005). Sheet erosion occurs over an extended timeframe with no immediate indication that soil is being lost.

2.5.2 Rill erosion or channel erosion

There are always irregularities in a field or plot and when shallow inter-rill flows concentrate into flow paths, small channels are formed. Particles are detached when the transport capacity is more than the sediment load and when shear stresses exceed the natural soil resistance (Lentsoane, 2005). As the soil is washed away, miniature dongas are formed (Directorate Agriculture Information Services, 2008).

2.5.3 Gully erosion (Dongas)

Gullies formed by erosion are dynamically similar to channel erosion except for their ephemeral flow and supply of sediment to the waterways, being either artificial or natural. Sediment is produced by either scouring of the base of the scarp, supercritical flow at the heads of the depression, and by scouring action of running water on the banks of the gully channel (Lentsoane, 2005).

2.5.4 Stream Channel erosion

Stream channel erosion, which closely resembles rill erosion, has two components namely;

(i) Bank erosion and

(ii) Bed load erosion and occurs due to side slope instability. Bank erosion occur when the channel boundaries are eroded whilst bed load erosion occurring as a result of transported sediment at the base of the stream channel interacting with the bed (Lentsoane, 2005).

2.6 Erosion Factors

All erosion factors controlling the magnitude and rate of erosion can be grouped into the following categories: climate erosivity, soil erodibility, and topography. A combination of these three factors can be used to create potential soil erosion risk maps because it indicates the susceptibility of the soil to rainfall erosion, irrespective of the vegetation cover and land use (Le Roux, 2010). The remaining two factors are conservation measures and land cover practices. The effect of bio-physical processes governing soil erosion is influenced by economic, social and political causes. These are summarized in Figure 5, as expressed by Lal in 2001.

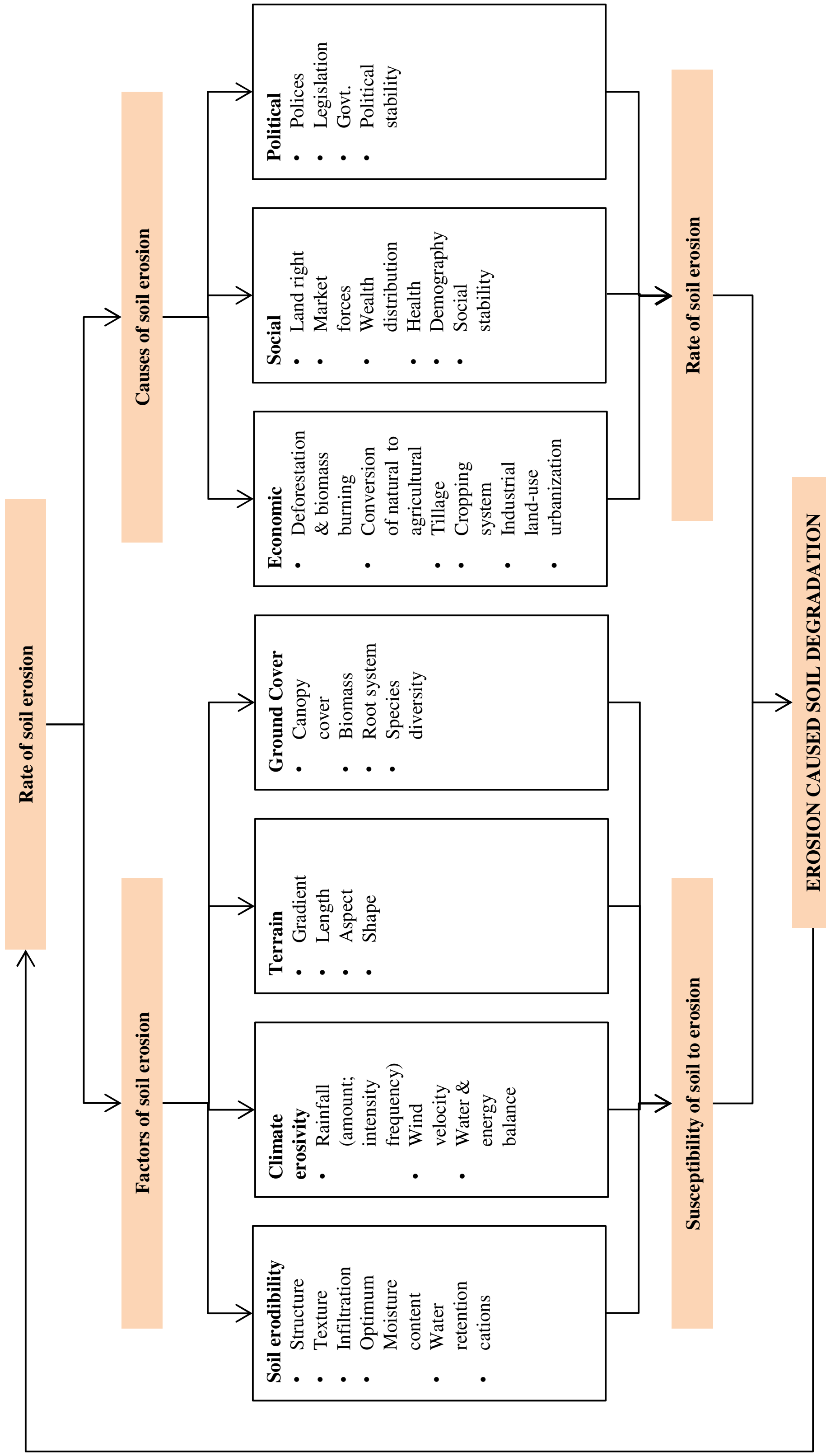

Figure 5 Factors of soil erosion; causes of soil erosion and interactions between them (Lal, 2001)

2.6.1 Climate Erosivity (Rainfall erosivity)

Climate erosivity can in brief be defined as the ability or power of rain to cause soil loss (Nearing *et al*, 2004). The rainfall erosivity is generally thought of in terms of the R-factor in the case of the Universal Soil Loss Equation (USLE), which will be discussed in detail in section 5.5.1, and was derived based on data from natural runoff plots located throughout the eastern parts of the United States (Nearing *et al*, 2004). It is a function of two rainfall characteristics, intensity and kinetic energy (Lentsoane, 2005) where the rainfall intensity is related to two types of rain events: the short-lived intense storms (typically in the Highveld) with the infiltration capacity of the soil exceeded, and the prolonged storms of low intensity that saturates the soil (Lentsoane, 2005). Soil detachment and dispersal of the soil particles is initiated by the kinetic energy (KE) of the raindrops and is a function of the raindrop size and its terminal velocity (Morgan, 2005). Most studies use the 30 minute rainfall intensity (IE_{30}) to define the combined effect of 30 minute-intensity and kinetic energy of the rainfall (Lentsoane, 2005). In a study by Msadala *et al* (2010) daily rainfall was used as input to the daily rainfall erosivity model developed by Rosewell (1996) in a study for Australia in the mid-1990s. Monthly EI_{30} surfaces were developed for the entire South Africa. In addition, an interpolation method was developed instead of using a pure inverse distance weight technique as in previous studies. The resulting R-factor map is shown in Figure 6 (Msadala *et al*, 2010).

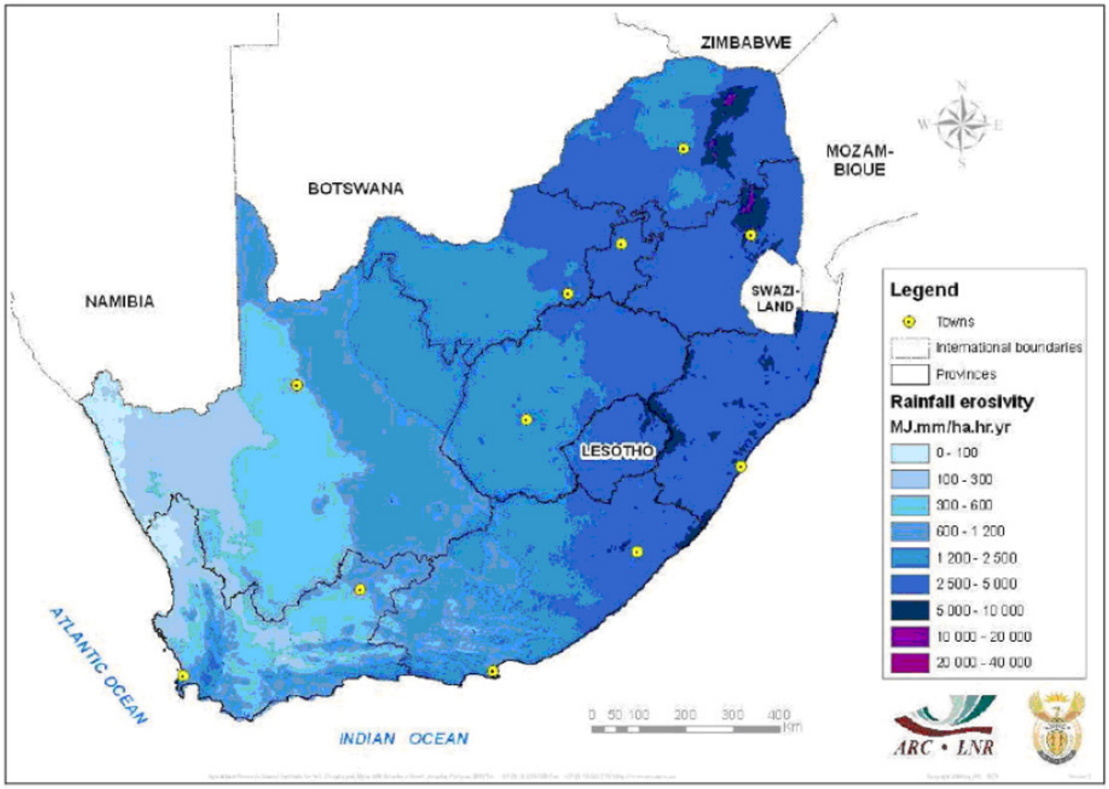

Figure 6 Rainfall erosivity map for South Africa (Msadala et al, 2010, pp 214)

The rainfall erosivity value, measured in MJ.mm/ha.hr.yr, ranges between 1 200 and 6 000.

2.6.2 Soil erodibility

Soil erodibility (K) depends on soil, and geological characteristics such as parent material, texture, structure, organic matter content, porosity, catena and many more (Owusu, 2011). It represents the susceptibility of soil or surface material to i) erosion, ii) transportability of the sediment, iii) amount and rate of runoff given a particular rainfall input. K values reflect the rate of soil loss per rainfall runoff erosivity (R) index (Kim, 2006). The K-factor may be estimated from data on the soil's particle size distribution, organic matter content, surface structure and profile permeability using the soil erodibility monograph (Kim, 2006). Soil data are limited especially on sub-catchment level and even on country level with no digital data available (Msadala *et al*, 2010). The soil erodibility maps produced in the study by Msadala *et al* (2010) used an alternative method derived from a similar study conducted in Australia. In this study with the absence of soil analytical and experimental data 1: 50 000 and 1: 250 000 soil maps were used for the period 1973 – 1987 (soil erodibility ratings were derived for the individual soil series of the binomial Soil Classification System) as well as erodibility values which were linked to corresponding soil series. The results were used to produce the map presented in Figure 7.

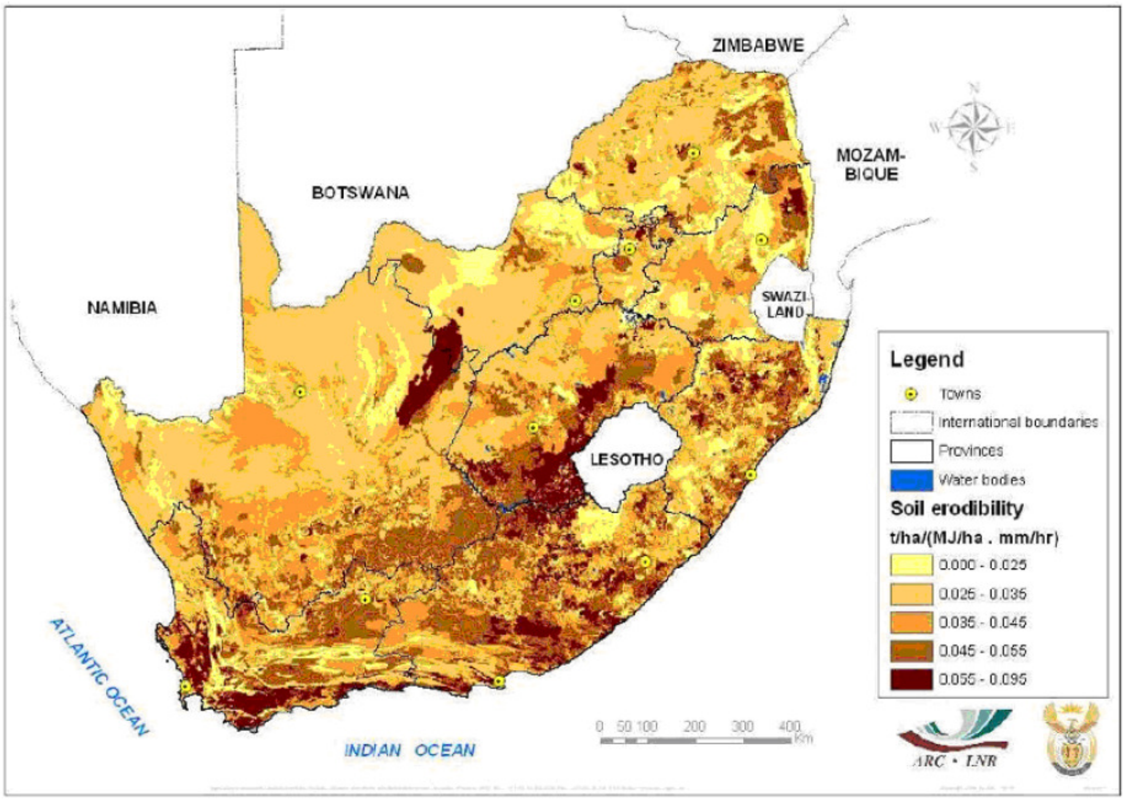

Figure 7 Soil Erodibility map for South Africa (Msadala *et al*, 2010, pp 215)

2.6.3 Topography

Topography influences velocity and volume of the surface runoff (Lentsoane, 2005) and often applies at an essentially local level, erosion being initiated at specific locations on the slope, or in association with minor topographic variations (Le Roux, 2010). Erosion is expected to increase with slope length and slope steepness (Lentsoane, 2005).

Soil loss increases as the slope steepens (reaching a maximum on slopes of approximately 8 – 10°) (Lentsoane, 2005). Increased slope length limits erosion as the rate of detachment by shallow overland flow decreases down slope and flow becomes concentrated (Abrahams *et al*, 1991).

2.6.4 Vegetation Cover Practices

The cover management factor (C) represents the effect of vegetation, management and erosion control practices on soil loss (Kim, 2006). The value represents a ratio comparing the existing surface conditions at a site to the standard conditions of the unit plot (Kim, 2006). The aboveground components of vegetation reduce the energy of raindrops and velocity of runoff to reduce the quantity directed to the soil (Lentsoane, 2005).

The density of the above ground cover, height and continuity of the canopy determines the effectiveness of the vegetation cover in reducing detachment by raindrop impact and hence dissipating the impact energy (Morgan, 2005). Other than dissipating the impact, vegetation cover also reduce the flow velocity by imparting roughness to the flow, filters sediment from the runoff and increases infiltration (Morgan, 2005).

The mechanical strength of soil against mass movement and stability depends on the below ground components of the vegetation (Lentsoane, 2005).

2.6.5 Conservation measures (or support practices)

The conservation measure or support practice factor (P) is the ratio of soil loss for the specific support practice and the corresponding soil loss with straight row upslope and down slope tillage (Kim, 2006). The factor accounts for control practices that reduce the erosion potential of the runoff by their influence on the drainage pattern, runoff concentration, runoff velocity, and hydraulic forces exerted by runoff on soil (Kim, 2006).

2.7 Water Erosion Models

The underlying fundamentals of erosion processes have been investigated for many decades and are still on-going and increasingly focus on very detailed topics. A model is a simulation of reality and is a scientific technique used to predict outcomes and conditions, in this instance, soil erosion under a wide range of conditions. Erosion prediction methods and models are primarily used to evaluate agricultural and crop related activities, development of land-use strategies, determine sediment yield indices, and guide government policies on soil conservation.

Since the recognition of erosion as a serious agricultural problem in the late 1920s soil erosion prediction models have evolved from early qualitative to complex physically based estimates (Lentsoane, 2005) but following extensive periods of research, more improved models were developed. Soil Loss models were strictly based on quantifying the on-site impact of erosion. Non-point source pollution became more evident in the late 1970s placing an emphasis on the development of models with greater prediction accuracy, hence leading to the development of physically based models that incorporate spatial distribution of runoff and sediment over the land surface and during single events (Lentsoane, 2005). Figure 8 summarises the history of the development of the main model types since the early 1900s.

Most prediction models are empirical in nature and are becoming more spatially and temporally distributed as more erosion mechanics are reflected. There are various models, each developed with a specific aim and condition and for the purpose of this study it is important to know the basis and limitations, and applicability of each. Morgan (2005) states the following, "Any attempt to use a model for conditions other than those specified should be viewed as bad practice and, at best, speculative". Differentiating between these classes of models, as reflected in Figure 8, usually rests on the level of complexity used to represent the soil erosion process (Le Roux *et al*, 2007).

There are basically three types of erosion models: empirical, conceptual, and stochastic and physically based with stochastic models being the latest and most difficult to use as they are heavily dependent on data and a thorough knowledge of statistical analysis (Lentsoane, 2005).

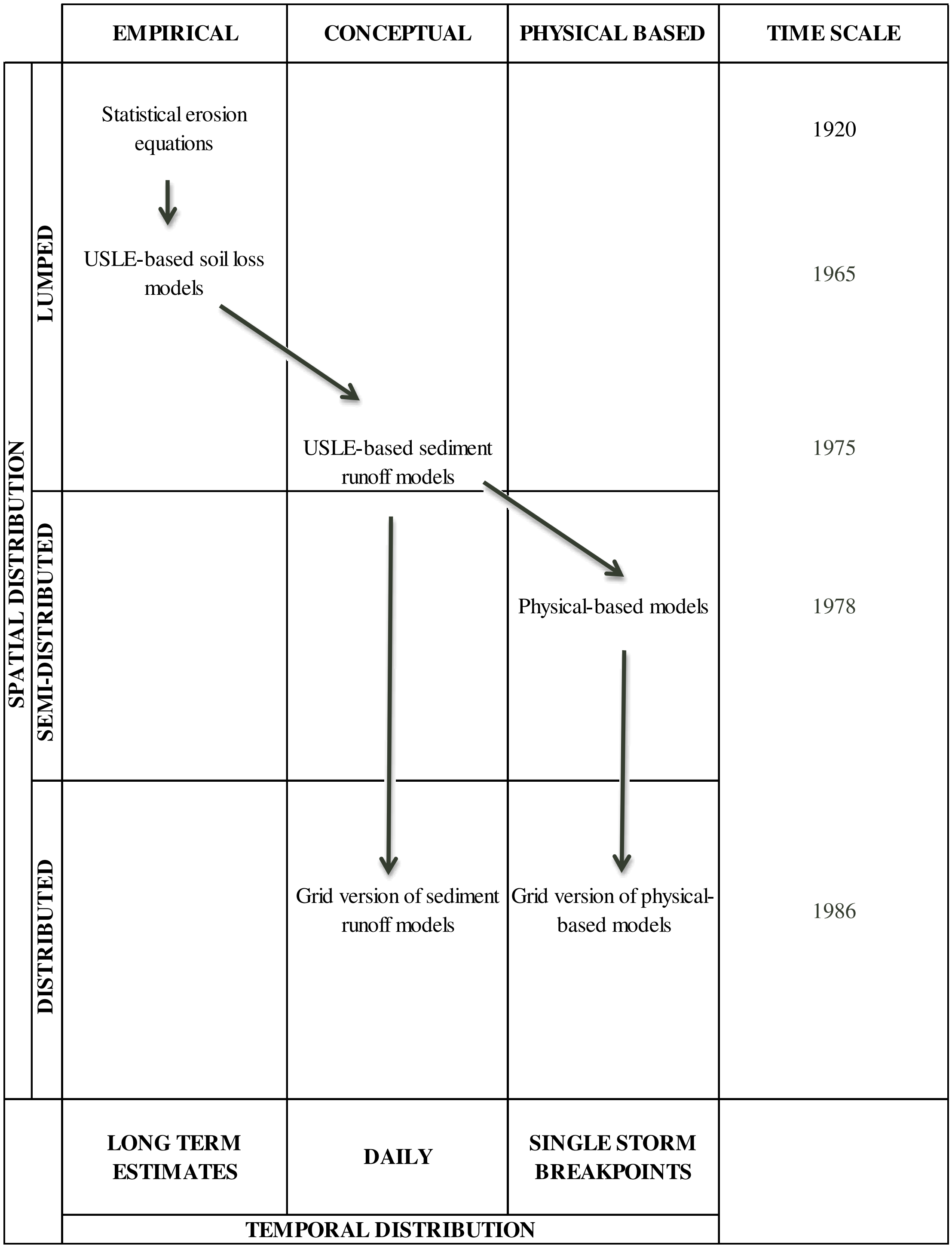

Figure 8 History of erosion models development (Van Zyl and Lorentz, 2003)

2.7.1 Empirical Models (Generally referred to as Soil Loss models)

Empirical models are simplified representations of natural processes based on observations (Thiemann, 2006) and are statistical in nature representing a group of models that are based on defining and identifying soil loss and sediment yield as the products of individual factors influencing erosion and hence ignoring the actual mechanisms of erosion (Lentsoane, 2005).

Empirical models are often used to model complex processes and are particularly useful in identifying sources of sediment. These models range from simple statistical equations to complex relationships, yielding results which are difficult to compare. Table 3, lists some of the most common empirical models and their sources as derived from the comparison of Thiemann (2006).

Table 3 Empirical Models (Thiemann, 2006)

Model	Development	Approximate Year
Musgrave Equation	Musgrave	1947
Pacific Southwest Interagency Committee (PSIAC)	PSIAC	1968
Denby-Bolton Method Flaxman Method	Flaxman	1972
Sediment Equation	Renfro	1975
Delivery Ratio Method	Denby and Bolton	1976
Universal Soil Loss Equation (USLE)	Wischmeier and Smith	1978
Soil Loss Estimation Model for South Africa (SLEMSA)	Elwell	1978
Coordination of Information on the Environment (CORINE)	European Community	1977
Revised Universal Soil Loss Equation (RUSLE)	Wischmeier and Smith,	1980
SOILLOSS (modified RUSLE)	SCS New South Wales	1993

Empirical soil loss models are applied to differentiate between areas of high and low erosion potential and target efforts for conservation purposes (Lentsoane, 2005). Their weaknesses include the following:

- They do not account for why and how erosion occurs.
- They cannot be easily extrapolated beyond the data range.
- They only predict gross erosion (soil loss) over a long-term period from rill and inter-rill areas.
- They fail to predict sediment yield and gully erosion.

In order for empirical soil loss models (e.g. RUSLE) to determine the sediment yield, the gross erosion (soil loss) is multiplied by a sediment delivery ratio. The application of sediment delivery ratios should be applied with extreme caution because of the empirical nature of these methods (Lentsoane, 2005). To overcome the problems of determining a delivery ratio sediment-runoff models (conceptual models) were developed.

Semi-empirical models in use are listed in Table 4.

Table 4 Semi-empirical Models (Saha, 2003)

Model	Development	Approximate Year
Modified Universal Soil Loss Equation (MUSLE)	Williams	1975
Morgan and Finney Model (MMF)	Morgan	1984

Empirical based methods use variations of a basic equation (known as the Universal Soil Loss Equation) namely:

$$Aa = R.K.(LS).C. \qquad (2.1)$$

Where:

Aa = the mean annual soil loss from the land (in tons.ha-1.yr-1)

R = Rainfall Erosivity factor

K = Soil-erodibility factor

LS = Slope Length and Slope Gradient factor

C = Crop management factor

P = Erosion-control practice factor

Both the USLE and RUSLE methods estimate average annual gross erosion as a function of rainfall energy (Zhang *et al*, 2009).The sediment yield production is improved using MUSLE by replacing the rainfall energy factor with a rainfall factor. This eliminates the need for delivery ratios, and allows the equation to be applied to the individual storm events (Zhang *et al*, 2009). In general, MUSLE is expressed as follows:

$$Y = 11{,}8\ (Q \cdot q_p)0{,}56 \cdot K \cdot LS \cdot C \cdot P \qquad (2.2)$$

Where:

Y = the sediment yield, t

Q = Rainfall volume from individual event, m^3

q_p = peak flow rate, m^3/s

K,LS,C,P = Same factors as USLE and RUSLE

2.7.2 Conceptual Models (Generally referred to as Sediment-runoff models)

Conceptual models usually incorporate general descriptions of catchment processes and mostly do not include specifications on the process interaction which would require detailed catchment information. These models are a mixture of empirical and physically based models and therefore provide an indication of quantitative and qualitative processes within a watershed. The most common conceptual models and their sources are presented in Table 5 (Thiemann, 2006).

Table 5 Conceptual Models (Thiemann, 2006)

Model	Development	Approximate Year
Sediment Concentration Graph	Johnson	1943
Renard-Lauren Model	Renard and Lauren	1975
Unit Sediment Graph	Rendon-Herrero	1978

Instantaneous Unit Sediment Graph	Williams	1978
Sediment routing Model	Williams and Hann	1978
Discrete Dynamics Models	Sharma and Dickenson	1979
Agricultural Catchment Research Unit (ACRU)*	Schulze	1995
Hydrologic Simulation Programme	Walton and hunter	1996
Soil and Water Assessment Tool (SWAT)	US-ARS	1984
Agricultural Non-point source Pollution (AGNPS)	US-ARS	1985

*The ACRU model uses the Modified Universal Soil Loss Equation (MUSLE) for the estimation of sediment yield (Msadala *et al*, 2010).

Conceptual models describe what happens in small catchments and have the same weaknesses as soil loss models, but they have the advantage of being able to predict sediment yield on a daily basis (Lentsoane, 2005). Sediment-runoff models can be considered as spatially lumped models but have lately become grid-based (See Figure 8). The fundamental equation describing the basis on which sediment-runoff models rely is given as:

$$SY = a\,(Q/q_p)^{b}\,KLSCP \qquad (2.3)$$

Where,
- SY = sediment yield from an individual storm in metric tons
- Q = storm runoff volume in m^3
- q_p = peak runoff rate in m^3/s
- K = USLE soil-erodibility factor
- LS = USLE slope length and slope gradient factor
- C = USLE crop management factor
- P = USLE erosion-control practice factor
- a, b = model parameters (constants)

2.7.3 Physically-based Models

Physically-based models (also referred to as process based models) have been developed to represent natural processes and describe each individual physical process of the system in one complex model (Thiemann, 2006). These models require high resolution spatial and temporal input data and are therefore often custom developed with a specific application in mind and are therefore not intended for universal utilisation (Thiemann, 2006). Physically-based models represent a synthesis of the individual components that affect erosion including the spatial variability of important land surface characteristics such as topography, slope aspect, vegetation, and soil as well as climate parameters. These models do not consider erosion occurring in large gullies, perennial streams, stream banks and erosion from wave action (Lentsoane, 2005). The most common physically-based models are summarised in Table 6.

Table 6 Physically-based Models (Thiemann, 2006)

Model	Development	Approximate Year
Erosion Kinematic Wave Models	Hjelmfelt, Piest and Saxton	1975
Quasi-steady State model	Foster, Meyer and Onstad	1977
Areal Non-point Source Watershed Environment Response Simulation (ANSWERS)	Beasley et.al	1982
Chemical Runoff and Erosion from Agricultural Management Systems (CREAMS)	Knisel	1980
Water Erosion Prediction Project (WEPP)	Laflen et al.	1991
European Soil Erosion Model (EUROSEM)	Morgan	1994
Kinematic Runoff and Erosion Model (KINEROS)	European Union	>2000
Limburg Soil Erosion Models (LISEM)	De Roo et al.	1996
Process-oriented Erosion Prognosis Program (PEPP)	Schramm	1994
Erosion2/3D	Schmidt	1999
Advanced simulation model for non-point source pollution transport (OPUS)	Ferreira and Smith	1992

Physically-based models provide several advantages over empirical and conceptual models, including (Lentsoane, 2005):

- More reliable extrapolation to un-gauged areas

- Capabilities for estimating spatial and temporal distributions of net soil loss and sediment yield
- Ability to predict off-site delivery of sediment
- Can calculate erosion from concentrated flows in ephemeral gullies, deposition in backwater and impoundments, deposition in concave slopes, and the enrichment of the fines caused by deposition

3 MODEL SELECTION

3.1 Erosion Model Selection

Various erosion models exist and have been in use, but not all are suited to the application and intended purpose of this study. An evaluation of adequate erosion models is required to select those models suitable as soil evaluation tool for use in urban environments and for use by municipal managers. Section 2.7 summarised available models. These will be further evaluated for suitability to this study.

A suitable model for this study should at least be able to meet the following requirements:

- Simulate erosion processes occurring in the study area to an acceptable level
- Use available data and data formats
- Be simple to apply
- Assess the impact of land-use changes
- Assess influence and application of management practices
- Be scalable (be able to predict losses from small to large areas without the need for excessive calibration)

Because of the wide range of available models and in order to evaluate the different types of models, potential models were selected based on a criteria set of which the results are summarised in Table 7. Not all models listed in section 2.7 were assessed. Only i) most recent, ii) widely used, iii) applicable (not project specific), and iv) locally available, models were selected. Another consideration was the use of available data sources.

Table 7 serves as a summary of possible models. This is still too broad a range and further assessment is required. Also, a major consideration is the implementation and use of such a system at local municipal level. A quick and easy method is required which will not require excessive data entry and studies.

Table 7 Potential erosion models assessed for suitability

Type of Model		Model Acronym	Applicable to study	Complex (medium to high)
Factor based models	Empirical soil loss	USLE	Yes	No
		SLEMSA	Yes	No
		CORINE	No	No
	Conceptual soil loss	RUSLE	Yes	No
	Semi-empirical models (Sediment-runoff)	MUSLE	No	Yes
		ACRU	No	Yes
Mechanistic models	Physical based	CREAMS	Yes	Yes
		ANSWERS	No	Yes
		EUROSEM		Yes
		LISEM		Yes
		Erosion2D	No	Yes
	Process based	WEPP	Yes	Yes

3.2 Evaluation of Models

In order to evaluate the different types of erosion models a more detailed assessment method was used.

The models were evaluated according to the following criteria (summarised in Appendix E: Summary of model evaluation):

1. The kind of erosion that is predicted. Is soil loss or sediment yield or both predicted (yield versus event based)
2. Type of erosion that is simulated (e.g. inter-rill, rill, gully, bed load). The method must be able to model inter-rill and rill erosion.

3. Erosion processes simulated and factors that is accounted for e.g. detachment and transport by rainfall. For this study detachment and transport by rainfall will be apply.
4. Type of model (factor or mechanistic based).
5. The purpose the model was developed for.
6. Adaptations of the models to other purposes.
7. Use of data (spatial and temporal distribution).

The simple statistical/empirical models (USLE, RUSLE, CORINE and SLEMSA) can only be used in instances where the data ranges from which it was developed can be calibrated for use in other geographical areas and the use thereof requires caution. The datasets for the USLE and RUSLE methods have been extrapolated for Southern Africa by McPhee and Smithen (1984). Empirical methods give no indication of why erosion takes place beyond rill and inter-rill processes. This is however within the context of this study.

The appeal to using SLEMSA is found in its relative ease of use and limited data requirements. According to Somayeh (2012) SLEMSA has various other advantages for developing countries, in that:

- It combines accuracy without the need for excessive field experiments.
- Maintains flexibility by the use of easily measurable parameters.
- Ease of data updating and entering.

Somayeh (2012) stated that the use of complex mathematical equation to derive soil loss values makes the model difficult to apply.

CORINE (Coordination Information Environment), which includes a geographical information system interface, was specifically developed by European Community DG XI and was primarily focussed on European conditions (Giordano, 2014) although a North American application was also attempted as reported by Giordano. The model is based on the Universal Soil Loss Equation. The CORINE project team endeavoured to modify the model to meet the requirements of the project which relates to agricultural practices on a local scale. The model includes two different indices of soil erosion risk namely: a) potential soil erosion risk which is derived from the basic physical factors of soil climate and topography, and b) Actual soil erosion risk which refers to the risk of erosion under current land use conditions as well as vegetation.

The potential soil erosion risk factors is derived from a soil erodibility index (same as USLE), climate index which is suited for Europe and a slope or topographical index. The model is suited for European conditions but specifically the southern mountainous areas (Giordano, 2014). CORINE was not further considered for this study.

Factor based methods simulate erosion processes (inter-rill and rill) in a lumped manner by using variations of one standard equation. Semi-empirical on the other hand take sediment deposition and movement into account.

Semi-empirical mathematical models (MUSLE, ACRU and MMF) have primarily been developed for the estimation of sediment yield for basin sized catchments in excess of 1 000 hectares (>10 km^2) (Lentsoane, 2005) computed from daily storm events. Modifications are made to the erosivity factor in the case of MUSLE and CREAMS where USLE was split to represent inter-rill and rill erosion separately (Lal, 2001). CREAMS is complex and was not further considered for this study.

Physical and process based (mechanistic) models simulate erosion processes more realistically than factor based models. Additionally these models take account of runoff and peak discharge in addition to the rainfall erosivity factor to estimate both soil loss and sediment yield. The application of mechanistic models has an advantage over factor-based models because of the off-site effects (sediment yield) (Giordano, 2014).

LISEM and Erosion 2/3D are raster based models for single storm events but do describe the same processes as KINEROS and EUROSEM. EUROSEM, like KINEROS is single event with LINEROS being based on SCS Curve number method (similar to ACRU) and uses a segment based 1D Hortonian overland flow. KINEROS is kinematic based (Matthies, 2007).

Mechanistic models require adequate, reliable, spatially distributed data which aren't often available. This poses a major constraint on model application and is the primary reason why factor based methods is preferred in Southern African regions (Lentsoane, 2005). Most of the mechanistic models were not tested and researched in Africa with the exception of WEPP.

WEPP partially incorporates equations from CREAMS and includes gully erosion and channel transport.

3.3 Selected model

From assessing the models it is clear that the process and physically based models is very complex, combining high temporal resolution with capacity to simulate runoff on watershed scales. Because of the spatial requirements, results are often doubtful and varying. For this reason an empirical and conceptual model were selected for suitability to the study. The models selected are SLEMSA and USLE. Also considered were CORINE and MUSLE but were excluded because of the European based climate indices used by CORINE and the complexity of data requirements of MUSLE.

Both SLEMSA and USLE have been previously applied in South Africa as long term annual estimates of soil loss and sufficient data should be available for the simulations. The flexibility of USLE makes it possible to evaluate conditions not possible by SLEMSA.

Although RUSLE retains the core formula of USLE it does incorporate concepts from process based models. These include changes in climate erosivity, cover management factors and the soil's erodibility (Lentsoane, 2005). Attempts have been made to predict sediment yield using similar concepts to that of sediment runoff models. USLE is considered the best conceptual model to predict soil loss from rill and inter-rill erosion (Lentsoane, 2005).

USLE is also considered the most applicable and dynamic model applicable to a wide range of conditions whereas SLEMSA requires less input and is relatively easier to apply than USLE. SLEMSA is however sensitive to minor changes which makes it less reliable than USLE (Lentsoane, 2005).

3.3.1 Data input requirements

The input requirements for complete model compilation are presented in Table 8. Not all data fields are available and assumptions will be made. The assumptions will be discussed in chapter 5.

Table 8 Selected models: input requirements

	FIELD	SLEMSA	USLE
1.	**Climate**		
	Rainfall runoff erosivity	X	X
2.	**Soil**	X	X
	Depth of soil	X	X
	% organic matter	X	X
	% very fine sand	X	X
	% silt	X	X
	% sand	X	X
	% Clay		
	Permeability class	X	X
3.	**Topographic**	X	X
	Slope Angle	X	X
	Slope length across contours	X	X
4.	**Erosion control practices**		
	Water control measures	-	-
5.	**Vegetation**		
	Type of plant cover	X	X
	% Canopy/tree cover	X	X
	Cover Roughness	X	X
	Fall height	X	X
	Root mass	X	X
6.	Management practices		
	Land use type	X	X
	%Surface area disturbed	X	X
	%external residual added to the surface	X	X
	Depth of incorporation	X	X
	Initial roughness	X	X
	Final roughness	X	X
	%Surface residual after practices	X	X
	%Remaining surface residue	X	X
	Ridge Height	X	X
7.	Erosion and run-off	-	-
8.	Location		
	Field size	-	-
	Area of catchment	-	-
	Elevation	-	-

3.3.2 Model suitability for urban conditions

Both models have been applied to model catchments which include aspects of urban development but have not been fully adopted to deal within a full urban application. Most models developed have agricultural applications and origins of development, as seen from chapter 2. Most of these models are not suited for application in urban areas (Moojong e*t al*, 2008).

The US EPA (2004) suggested a model for the estimation of yield from urban drainage areas and was applied by Moojong *et al* (2008) to determine the relation between sedimentation in sewers (combined sewers) and inundation. Sediment loadings is determined per source from each sub-catchment and is divided into four categories, namely; litter, roadway sanding for snow/ice, street dust and dirt and soil erosion. The model uses different equations per source and uses the revised Universal Soil Loss Equation (RUSLE) to estimate soil erosion.

Sub-catchments or basins are divided into attached and detached land parcels per land use type and linked to the system. The primary focus of the model is however combined sewers which do not apply to South Africa. A different approach is therefore required and adaptations of the USLE and SLEMSA are required. These adaptations will be disused in chapter 6.

3.3.3 Calibration of the erosion models

Calibration of soil loss modelling is difficult due to the complexity of the processes and often limitations in short and long term measurements from catchments. In a study such as this, focussing on urban erosion, the availability of data and an appropriate model is also a limitation.

As will be discussed in chapter 4, sub-surface profiling of the Boksburg Lake was done to quantify (to a high degree of accuracy) the sedimentation layer thickness and volume in the lake. This was done to estimate the requirements for another cleaning operation similar to one completed in the 1990s. With the year of the clearing operations known, the average specific density of the sediment material, and the erosion period since then, the soil loss model can be calibrated.

Chapter 5 deals with the modelling of soil loss over the almost two decade period using known volumes and development trends as discussed in section 4.7. There are however not enough data to calibrate the phosphorus model and the model therefore relies on previous studies.

3.4 Phosphorus model selection

The phosphorus models discussed in section 2.3.2 primarily deal with eutrophication processes and phosphorus balancing within reservoirs. Few models have been developed to deal with urban environments and where they do; they are primarily developed for combined sewer systems.

This study focus on adsorbed phosphorus as it is the aim of this study to indicate the decrease in phosphate loadings associated with sediment reduction.

The main goal of this section of the study was to develop a simple method for estimating loadings that would be useful to water quality managers considering their fiscal and time constraints. This component of the study was influenced by the practical factors that influence the use of such a model in the real world. The following criteria were set to guide the method development.

- Because of financial and resources constraints the method had to be developed from available data. This proved to be much harder than anticipated because water and sediment quality data are simply not available. Where possible sources were found, the data were not released due to possible copyright infringements.
- The method should require little time to use.
- The method should be applicable to surrounding lakes and study areas.
- Only non-point loadings apply.

Because of the lack of data pertaining to the specific study area, the reliability of the method and model will remain low until it can be evaluated to the fullest extent possible to enable the user of the method to realistically judge the value of the estimate. The aim however was only to indicate that a reduction in sediment loadings will amount to a reduction in phosphorus loadings.

For this study a simplified approach was followed. This will be discussed in chapter 5.

4 STUDY AREA: BOKSBURG LAKE

4.1 Background and locality of the study area

Boksburg Lake was built in 1888 by Montague White (Boksburg Historical Association, 2006), mining commissioner of the Boksburg Goldfields on request from President Kruger. The lake could rather have been considered a swamp with a few mud islands in it according to White (Boksburg Historical Association, 2006). It was not until it was filled after a sudden rainstorm in 1891 that its real value as a recreational attraction was realized (Boksburg Historical Association, 2006 and Boksburg Historical Association, 2009).

Boksburg Lake is a shallow urban lake situated within the city centre of Boksburg, falling within the Ekurhuleni Metropolitan Municipality (EMM) (Figure 9). Several industries, Boksburg Central Business District, and residential housing are all situated within the small catchment of the lake.

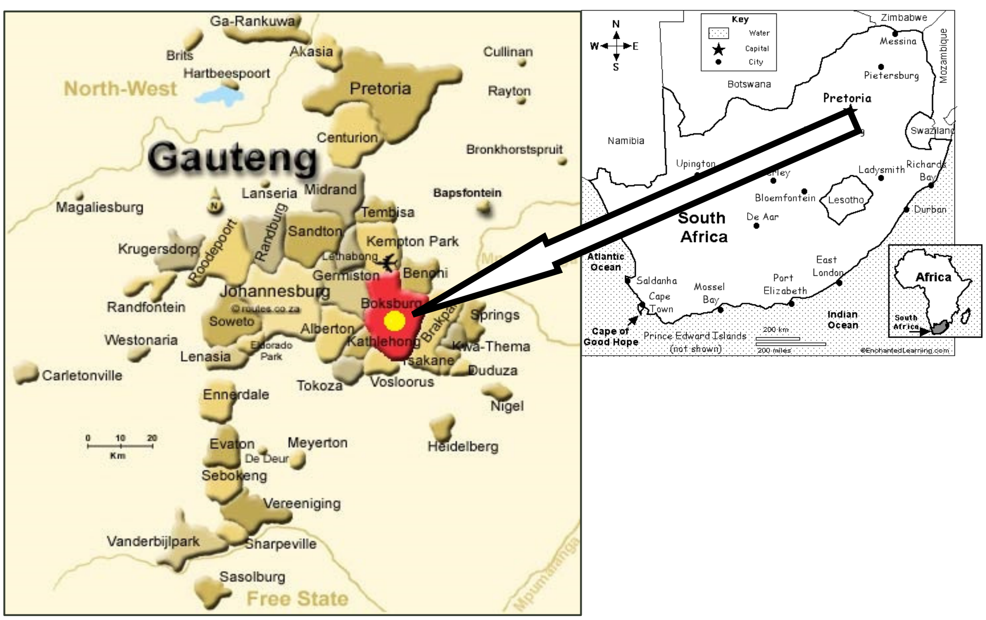

Figure 9 Locality Map of Boksburg Lake (from http://www.routes.co.za/gp/boksburg/)

4.2 Physical attributes of Boksburg Lake

The physical attributes were ascertained through physical measurement of various parameters, using a Geographical Positioning System, ground surveys and various types of graphical software (South Africa. Aurecon, 2011). The lake has the following parameters:

Table 9 Boksburg Lake physical attributes

Parameter	Unit	Measured Value	Comments/ Notes
Location		Near Boksburg CBD	
Coordinates	DMS	26°13'15"S, 28°14'51"E	South Africa.Aurecon (2010)
Maximum Lake width (N-S)	m	314.00	South Africa. Aurecon (2010)
Maximum Length (E-W)	m	893.00	South Africa. Aurecon (2010)
Mean Water Depth	m	1.39	South Africa. Aurecon (2010)
Maximum Water Depth	m	3.50	South Africa. Aurecon (2010)
Maximum Sediment at Depth	m	5.05	South Africa. Aurecon (2010)
Minimum Sediment thickness	m	0.50	South Africa. Aurecon (2010)
Maximum Sediment thickness	m	2.00	South Africa. Aurecon (2010)
Average thickness of sediment layer	m	0.65	South Africa. Aurecon (2010)
Estimated Sediment Volume	m^3	164,200.00 (2009) 155,484.00 (2010)	Sub-surface profile of 2010. South Africa. Aurecon (2010). See Figure 10
Circumference	m	2,190.00	Calculated using AutoCAD from 2010 topographical survey

			(South Africa. Aurecon (2010))
Lake inflow (average)	m^3/hr	3,300.00	Estimated from baseline water depth. South Africa. Aurecon (2010)
Area of water surface	m^2	152,000.00	Calculated using AutoCAD from 2010 topographical survey. South Africa. Aurecon (2010)
Mean retention time	days	5.61	South Africa. Ndumo (2008)
Lake total displacement volume	m^3	444,280.00	Sub-surface profile of 2010. See section 4.12. South Africa. Aurecon (2010)
Source water		Storm water Sewage water Effluent spills	Observed flows
Catchment main land use (Current)		45% residential 34% industrial 15% commercial 1 % Schools/education 5% open spaces	Based on 2009/2010 Land use data
Impoundment use		Recreation Storm water control	
Climate		Summer rainfall Highveld Zone	See Section 4.11 Temperature

The lake forms part of the Upper Vaal catchment.

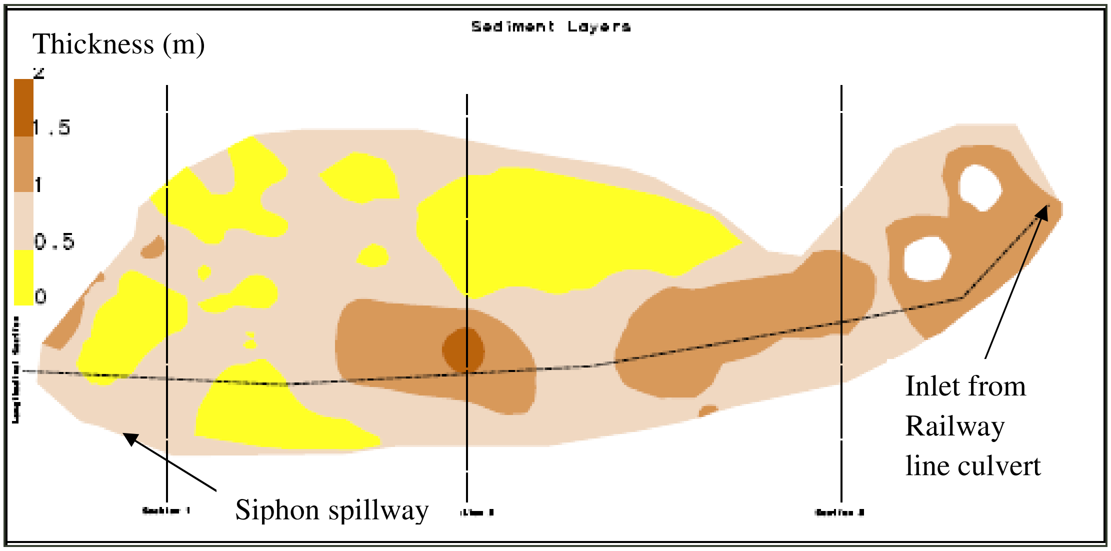

Figure 10 Boksburg Lake Sedimentation Layers (South Africa. Aurecon, 2011)

4.3 Catchment characteristics

Impervious surfaces are surfaces such as pavements (roads, sidewalks, driveways, and parking areas), and compacted soils or rock. Pavement areas are covered areas covered by impenetrable materials such as asphalt, concrete, brick, and stone.

The Boksburg catchment is 29.43 km^2 in size with an average percentage imperviousness of 36% with a predominantly commercial and industrial land-use with some residential and open spaces but mainly in the upper reaches of the catchment. The southern and south eastern portions of the catchment are business districts and residential dwellings. The catchment includes the land-uses as listed in Table 10.

The land use distribution as presented in Table 10 was calculated using ArcGIS with land use features as provided from the Ekurhuleni Metropolitan Municipality (dataset of 2012). Figure 47, Appendix C, refer to agricultural holdings where on site it was found to represent small holdings (the town planning categories make no provision for sub-categorizing). These are areas where no agricultural practices take place anymore and few to none livestock are kept, mostly in the form of horses and petting zoos for children parties.

Table 10 Land-use distribution within the catchment

Suburb	Land use category							
	Industrial	Commercial	Redidential	Open Spaces	Schools	Small holdings	Mining	CBD
Anderboldt	X							
Boksburg East Ext 2	X				X			
Eyerspark		X	X					
The stewards			X	X				
Everleigh		X	X			X		
Jensen Park		X	X			X		
Dunmadelay		X	X					
Morganridge			X					
Jansmutsville			X			X		
Boksburg West			X					
Ravenswood			X			X		
Boksburg North		X	X		X			
Musswelldale	X							
Cason		X	X		X		X	
Satmar	X	X						
Plantation			X		X		X	
Westwood			X			X		
Bardene			X					
Dunnswart	X							
CBD								X

The land use distribution (using only the predominant uses such as Industrial, Commercial, Residential and Open spaces were used) as presented in Figure 11 and Figure 47 was calculated using ArcGIS and the Boksburg land use of 2010 as provided by the local municipality. Land use distribution presented in Figure 47, Appendix C.

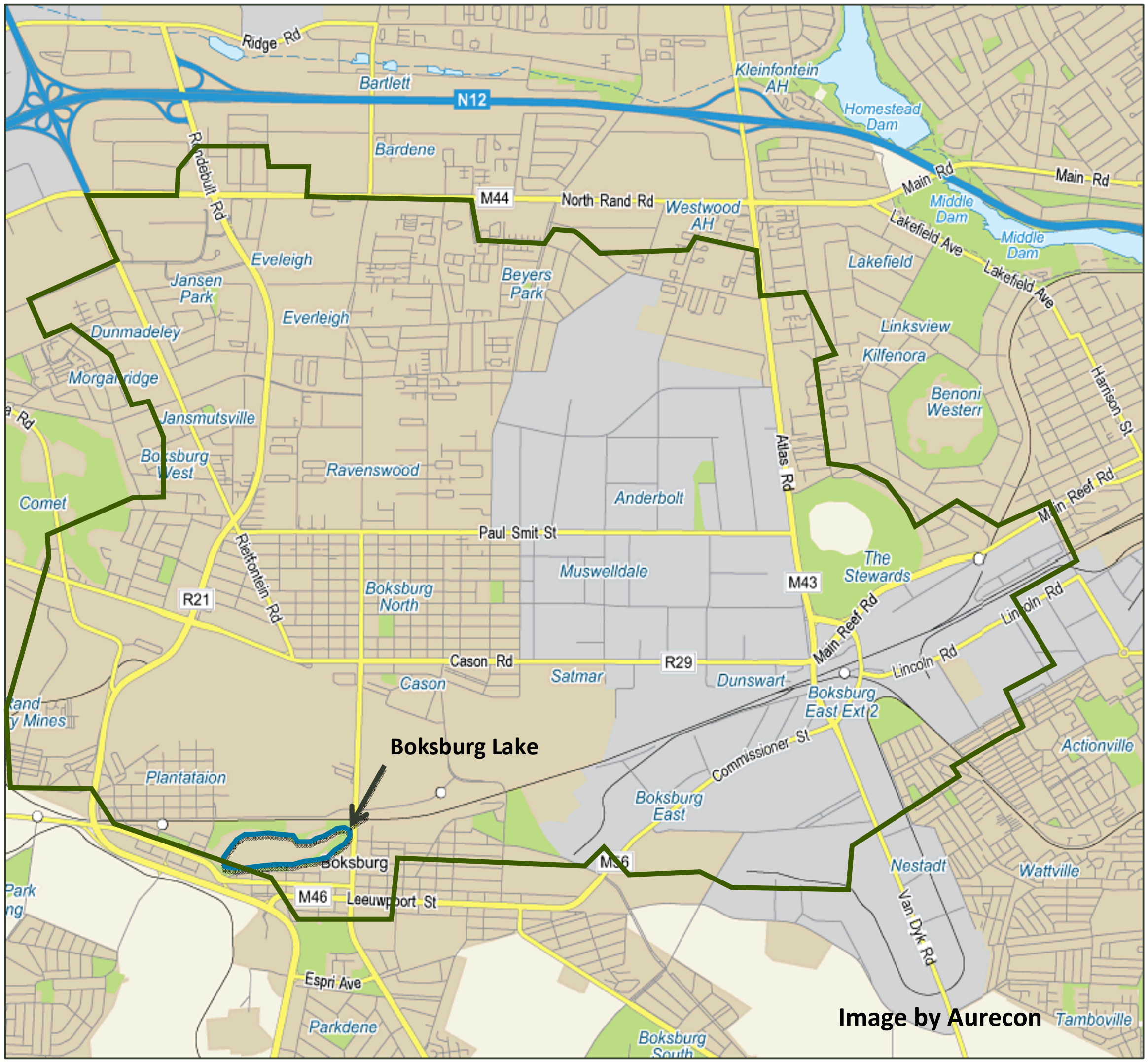

Figure 11 Suburbs within the Boksburg lake catchment (Catchment outline indicated in green and lake indicated)

4.4 Water Quality

A number of scientific studies have been carried out on the lake, funded by various private and government organisations. On a local government level, the Ekurhuleni Metropolitan Municipality has been responsible for conducting many of these. The most significant work carried out on the lake by private organisations include, the Boksburg Lake Wetland project funded by Unilever and managed by the Institute of Water Research (IWR) at Rhodes University. The project has been running since 2005 and has been looking at the environmental water quality of the lake (South Africa. Ndumo, 2008).

Only data from two water quality tests were made available from the Ekurhuleni Metropolitan Municipality. These tests were conducted in consecutive years. Testing in October 2010 was done by Waterlab (Pty) Ltd to determine which environmental factors may have been responsible for fish mortalities in the lake (South Africa. Ndumo, 2008).

The water samples submitted were analysed for a number of parameters related to sewage and organic pollution, including Dissolved Oxygen, Ammonia-N, and particularly Chemical Oxygen Demand. The sediment samples submitted were subjected to two liquid extractions, being (i) Water extracted to determine the amount of Amonia-N and Orthophosphate-P available in the sediments, and (ii) Acid extract (Aqua Regia) in order to determine the amount of potentially toxic metals which may be leached from the sediments under unfavourable environmental conditions, particularly when conditions are strongly reduced in the lake sediments (South Africa. Ndumo, 2008).

The 2010 tests found that water quality from the lake shows a number of parameters which are of particular concern, and are indicative of severe organic pollution in the lake. These include dissolved oxygen (2.7 mg/l), Ammonia (1 mg/l), total Phosphate (0.864 mg/l) which include phosphorus in the sediment, suspended solids (77 mg/l) and chemical oxygen demand (228 mg/l). In particular, the SS and COD clearly indicate organic pollution of the lake. For comparative purposes, the discharge limits for treated sewage are 25 mg/l SS and 75 mg/l COD (South Africa. Ndumo, 2008).

Results obtained from a water extract of the sediment (grab samples) showed an extremely high concentration of Ammonia-N (21 mg/l), which could have possible negative impact on aquatic organisms when released into the water column, or when aquatic organisms are exposed to it close to the lake sediment (South Africa. Ndumo, 2008).

Metal extractions showed high concentrations of Aluminium, Chromium, Copper, Iron, Lead, Titanium, and Zinc (South Africa. Ndumo, 2008).

Sampling in April 2009, conducted with the purpose of establishing the lake contamination profile had the following primary focus:

- Determine physical characteristics of the lake. It must be noted that the study by Aurecon in 2011 utilized better methods to determine the characteristics, as was reported in section 4.2.
- Map and quantify the lake sludge/sediment.
- Develop a profile of the sediment or sediment chemical profiling.
- Determine the tropic status of the lake.

The testing concluded that concentrations of certain heavy metals within the sediments have reached extremely high levels (similar to previous years testing), and these specifically include Manganese, Nickel, Lead, and Zinc. These seemed to be associated mostly with the thick layer of organic detritus found within the west and central reaches of the lake (South Africa. Ndumo, 2008).

The study found that the trophic status of the lake is poor (using methods proposed by the Department of Water Affairs) as it contains high nutrient loads which have resulted in the proliferation of algae and bacteria within the water body. This together with the dissolved oxygen levels and temperature profile, turbidity and water clarity makes it ecologically unsuitable for the survival of most aquatic organisms and unsuitable for recreational use. Positive aspects of the lacustrine water quality are the low salinity levels, hardness and pH (South Africa. Ndumo, 2008).

4.5 Topography

The catchment has an average slope of 1.85%, ranging from a mild 2.2% to a flat 0.4% in the lower reaches.

4.6 Geology and soil type

Based on the 1:250 000 geological maps for East Rand Sheet 2628 (Geological Survey, 1986) as presented in Appendix B, the site area is predominantly underlain by the metamorphosed sedimentary rocks of the Witwatersrand Super Group. In the area of interest, these rocks comprise ferruginous shale, quartzite and banded ironstones of the Hospital Hill Formation, West Rand Group; overlain by quartzites, conglomerates and sandy shales of the Turffontein Formation, Central Rand Group; and quartzites and conglomerates of the Johannesburg Formation, Central Rand Group. Sandstones, shale and coal beds of the Vryheid Formation, Ecca Group, Karoo Supergroup complete the sedimentary sequence in the area. The sequence is intruded by the Jurassic-aged dolerite dykes and sills. The 1:250 000 land type map of the East Rand Sheet 2628 (Soil and Irrigation Research Institute, 1985), shows that the soils in the area are generally classified as plinthic catena. Fey (2010) describes these soils as sequences consisting of red soils on well drained crests, grading via yellow soils on mid slopes to grey soils in poorly drained bottomlands. Approximately three quarters of the area are covered by red soils of low to moderate fertility (Ba36 and Ba1). In the rest of the area, classified as Bb3, the red soils are not as widespread.

The soil profile of the study area may range from large rock pinnacles to either soft or clayey silts of low permeability and which are often volumetrically unstable. Soils in the upper reaches of the catchment are predominantly sandy loams and those of the lower reaches predominantly clayey loams. The above is an indication that the soils are derived from weathered sandstone.

4.7 Soil Erosion processes and erosion within study area

The different types of water erosion are discussed in section 2.5. Within the catchment the various erosion types were observed.

1. Sheet erosion: although not easily observed over a short period, sheet erosion is observed on most undeveloped open stands and areas under development. This is particularly clear from sediment depositions on the street surfaces.
2. Rill sand inter-rill erosion: On stands with longer overland lengths, rill erosion is observed. This is especially the case on the derelict tailings storage site where gully formation is also observed.
3. Gully erosion: Gully formation was observed on the derelict tailings storage site (See Figure 53).

4. Channel bank erosion: Channel bank erosion due to stream movement was not observed along the main channel to the Boksburg Lake as the banks are concrete lined. Some rill erosion was observed on the bank slopes which must not be confused with either gully and bank erosion.

4.8 Possible Sources of phosphorus within the catchment

General sources of phosphorus were discussed in Section 2.3.3. The following possible sources were identified in the study area:

1. Sewerage: multiple sites were identified with clear evidence of sewer manhole overflow. This is specifically the case adjacent the main outfall channel, parallel to Railway Street, where manholes were found to be open. The same is true for manholes parallel to Trichardt Street. The extent and duration of sewer contamination could not be verified or quantified. It is assumed that exposure is limited and for relatively short durations.
2. Lawns. Approximately 50% of the catchment comprises residential and open stands. Although an old town, the use of fertilizers and lawn treatments are still evident (visual observation only – on multiple occasions have the author observed the use of fertilizer during on site investigations).
3. Vehicle emissions.

4.9 Land-use change from 1995 to 2013

A rapid rate of development was experienced in Boksburg over the last few decades (South Africa. Ekurhuleni Metropolitan Municipality, 2010). The rapid rate of development (where development is defined as the change in land-use from one type to the other or densification took place with no change in land-use type) invariably puts pressure on the local environment. Figures 12 and 13, below illustrate the rate of change.

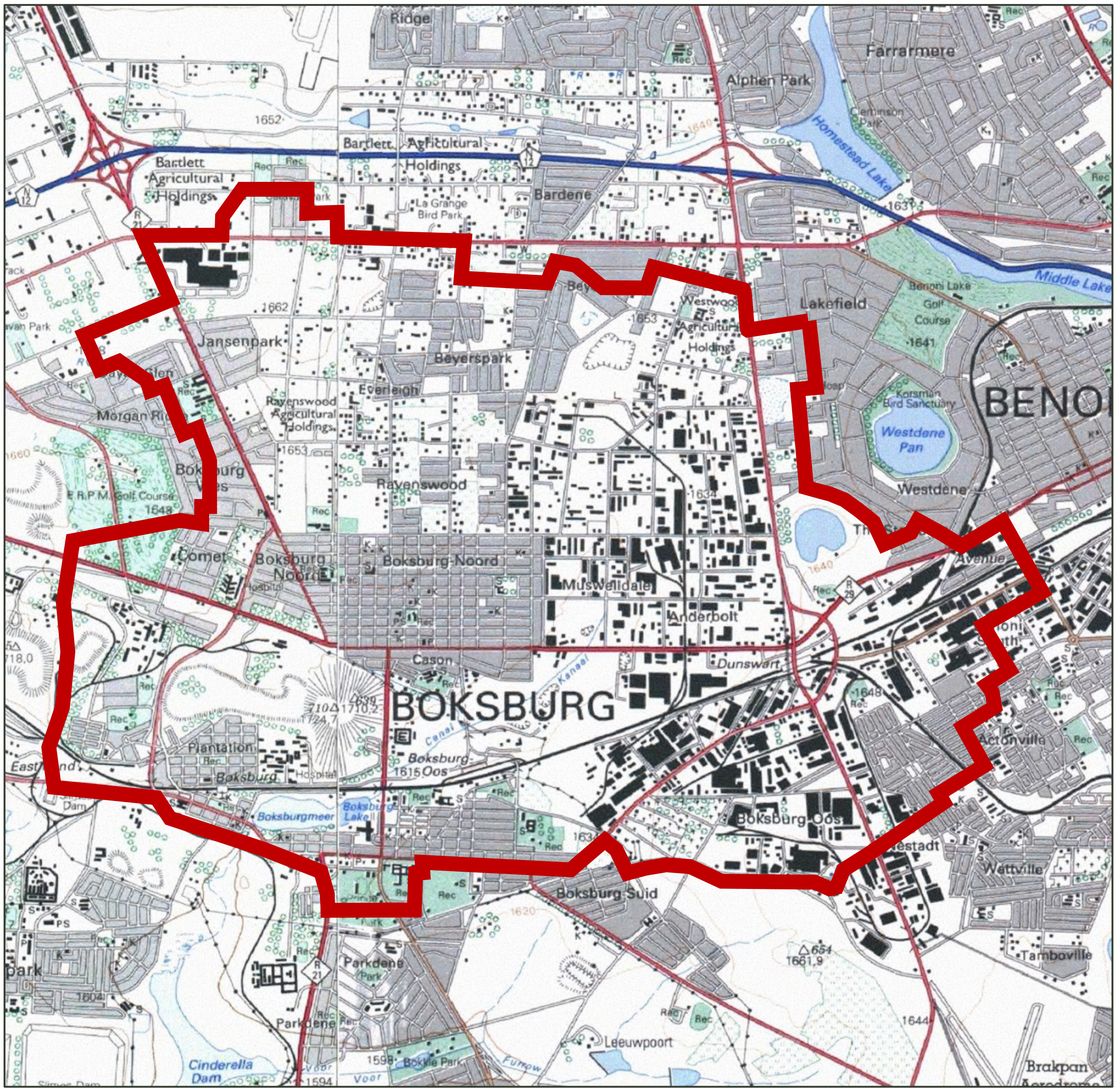

Figure 12 1: 50 000 Topographical Map (2628AA Johannesburg & 2628AB Benoni, 1994)

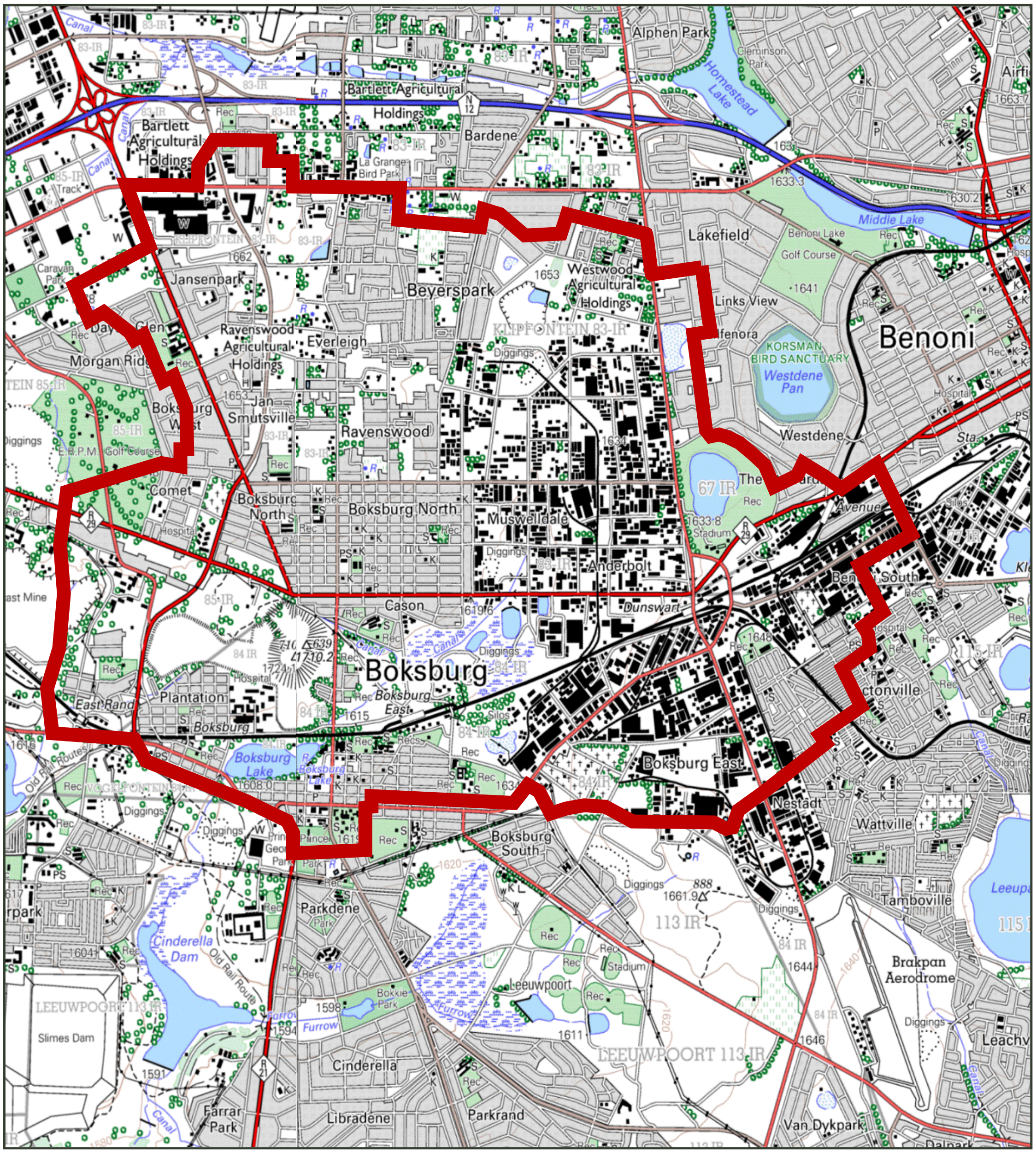

Figure 13 1: 50 000 Topographical Map (2628AA Johannesburg & 2628AB Benoni, 2002)

Since the early 1990s, Boksburg’s land use has changed extensively from agricultural to residential which in its turn is giving way to commercial developments. This is evident when comparing the 1: 50 000 maps of the catchment in for 1994 and 2002 (Figure 12 and Figure 13). The industrial areas of Anderbolt and Mussweldale showed increased development as did Jansenpark, Ravenwood, and Beyers Park. These areas changed from mostly agricultural to high density residential developments. Boksburg North's land use is in the process of changing from residential to commercial. The areas of change, as identified by the comparison of the 1: 50 000 maps (Figure 12 and Figure 13) and Google Earth Images for the period 2003 to 2012, are indicated in the GIS map illustrated by Figure 45 in Appendix C. Data was available for years 1995, 2002, 2005, 2006, 2008, 2010, and 2013 as presented in Figure 14 below. Intermediate years were interpolated assuming linear growth between datasets.

The rate of development is illustrated in the following graph. It is expected that the soil loss annual yield will follow a similar trend as the effect of development (urban sprawl) is much greater than the effect of rural use (Laker 2012).

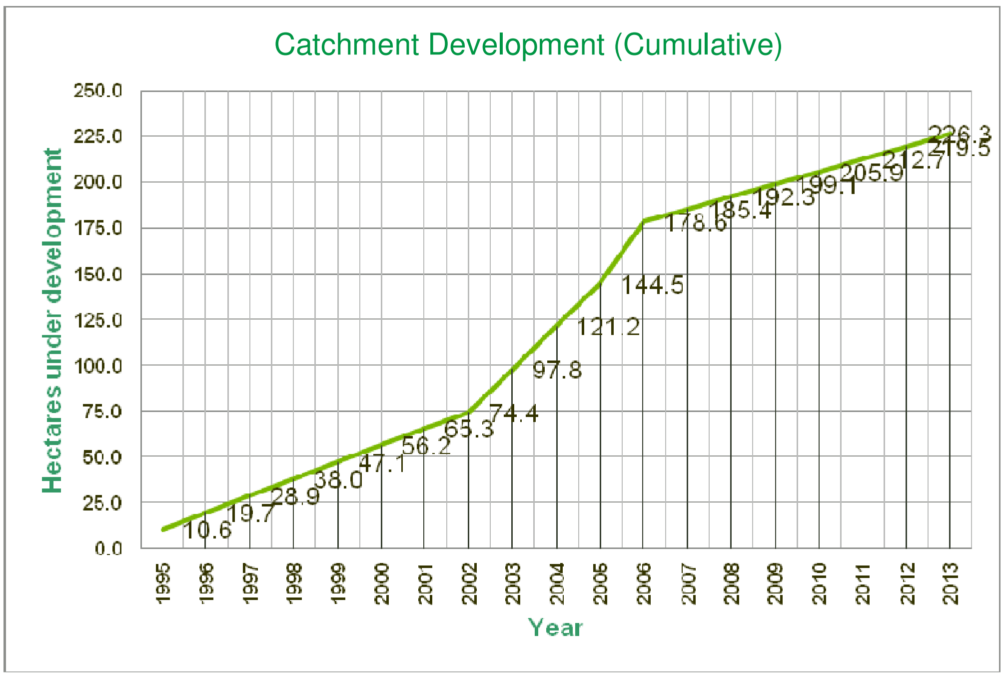

Figure 14 Development graph

The above reflect an average annual increase of 19.4%.The comparison and development graph is only based on visible developments that took place in this period and does not give a true representation of densification. There is still a significant amount of vacant land open for development. This represents an opportunity for substantial urban infill and densification and hence put pressure on existing engineering and social infrastructure.

The overall density of residential development in the area is indicated as being low (South Africa. Ekurhuleni Metropolitan Municipality, 2010) as derived from the five year spatial development framework (SDF) as shown in Figure 47. Many agricultural areas, as per the development framework, are in fact under development ranging from commercial to high density residential developments (townhouse complexes).

The Ekurhuleni Metropolitan Municipality admits that, contrary to the SDF, there are a large number of land use developments, specifically on the agricultural holdings and some major routes. Furthermore, considerable informal trade takes place along North Rand road (Deminey, 2012).

Soil loss models will be compiled for each year to illustrate the influence land-use changes have on the quantity of lost soil produced.

4.10 Rainfall

The area falls within the summer rainfall region of Southern Africa (Figure 16, below) with an average annual rainfall of 675 mm as obtained from Technical Report TR102 by Adamson from the Department of Environmental Affairs of 1983, with station number 476433 BOKSBURG (MUNICIPAL) at latitude 26° 13’ and longitude 28° 15’. Figure 15 gives the average monthly rainfall for Boksburg as obtained from the South African Weather Bureau and Table 11 the rainfall depths derived from 74 years of data.

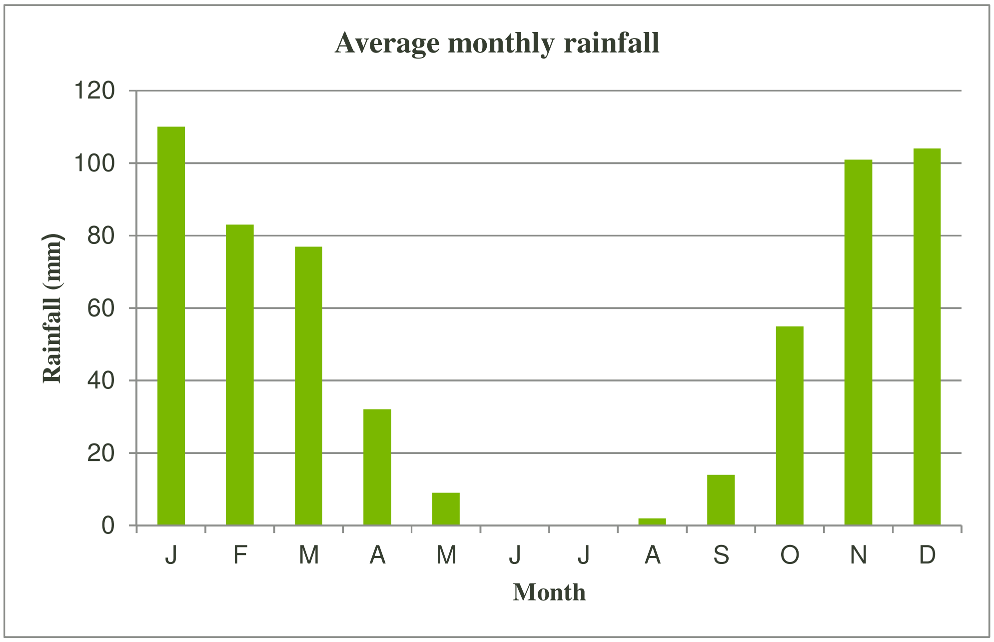

Figure 15 Average monthly rainfall for the Boksburg Lake catchment

Table 11 24-Hr rainfall depths for Boksburg (Adamson, 1983)

Duration	2	5	10	20	50
1 Day (mm)	54	76	92	110	137

Daily rainfall information for the period 1886-August 2000 was obtained from an earlier dataset received from the South African Weather Bureau (SAWB) and archived by Africon Engineering. This dataset only covers the period 1996 to 2000 of the modelling period of 1996 to 2012. A revised dataset for station number 476433 was obtained from the South African Weather Bureau (SAWB) but is limited to January 2005 only. This dataset has errors for the years 1999 and 2005 as is illustrated in Table 12 with erroneous data for the two overlapping years as indicated. Hourly rainfall data are required for the calculation of rainfall erosivity which could not be provided by the SAWB. Additional data (hourly) for the period of January 1995 to April 2013 was sourced from the SAWB for the OR

Tambo International Airport, located approximately 7.8 km (station to centroid of catchment) from Boksburg.

A combined dataset was compiled for the study area as represented in Table 12.

Table 12 Daily Rain Averages (mm)

Year	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	MAP
1995	51.1	24.4	220.3	47.1	2	0	0	18.8	11.7	58	199.1	207	840
1996	170.7	233.9	77.3	71.5	18.9	0	0	8	1.2	127.1	77.5	146.7	933
1997	86.8	66	349.9	27.4	100	10.5	7.5	0	50.8	28	126.2	71.4	925
1998	130.1	94.6	25.4	0	0	0	0	0	17.7	167.8	231.6		667
1999	74	46.5	**0**	**0**	0	0	0	0	0	**0**	**0**	**0**	**121**
1999*	74	46.5	70.6	39.3	0	0	0	0	0	16.6	62.9	189.7	500
2000	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	35	81	**0**	89.2	**205**
2000*	132.6	259.4	201.3	27.7	38.7	4.3	-	-	-	-	-	-	-
2000**	149.8	255.8	158.6	33.2	23.8	1.8	0	4.6	40	115.4	106.8	162.6	1052
2001	117.8	106	**1**	36.5	11.5	0	0	10	12.1	108.5	21.5	81.6	507
2001**	71	100	50.2	29.2	51.5	5.4	1.2	13.6	116	180.6	148	79.8	847
2002	0	0	39.5	16	42	9.5	0	0	24	57	19.5	153.7	361
2002**	124.4	119.2	93.6	22.6	51	30.6	0	25.4	4.6	5	0.5	156.4	633
2003	93	21	30.2	0	0	12	0	10	13.2	83.5	-	-	**263**
2003**	131.6	104.4	95.8	3.6	0	20	0	8.4	9	70	45.4	29.4	518
2004	-	-	68.5	26	0	3.5	12.5	0	0	50.5	57	63.9	**282**
2004**	171	206.6	114.8	48.8	0	3.8	13	0.2	0	14.6	49.6	206.2	829
2005	206.8	-	-	-	-	-	-	-	-	-	-	-	**207**
2005**	154.8	73.2	102	88.6	1.6	0	0	0	0	0	100	72.6	593
2006**	176.6	150.6	74.6	34.2	2	0	0	31.4	0.8	6.8	23.4	22.6	523
2007**	14.6	2.6	9.4	9.4	0	34.6	0	1.2	31.6	108.8	59.8	75.6	348
2008**	211	60.4	140.8	19.8	37.6	16.4	0	0	0	65	99	99.6	750
2009**	147.4	153.6	135.6	1	31.8	16.2	0	11.2	19	85.6	135.6	169	906
2010**	222.2	115.6	91.8	100.6	41.4	0.2	0	0	0	29.4	104.2	204.8	910
2011**	172	63.8	133.8	54.6	7.4	21.8	0	6.2	2.8	82.2	79.8	182.4	807
2012**	152	92	51	15.6	4.4	2.8	0	0.2	95.8	71	69.4	136.2	690
2013**	106	31.2	38.6	118.2									

*Older data set (1886 - Aug 2000)

**OR Tambo International Airport Weather station

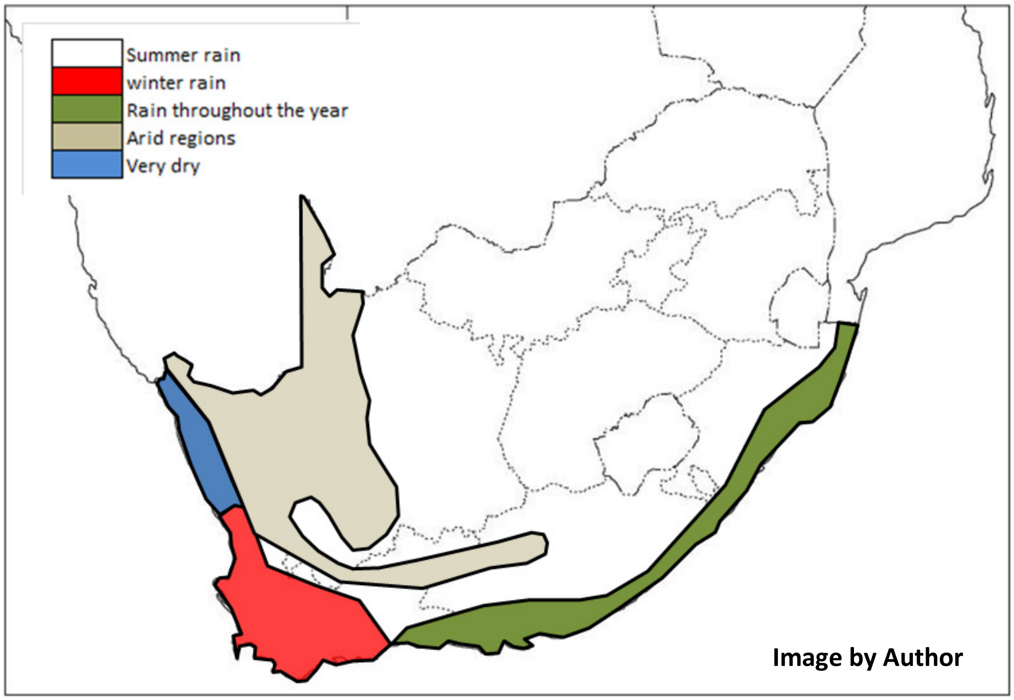

Figure 16 South African Rainfall Regions (sourced from http://cnx.org/)

4.11 Temperature

Monthly average temperature data were obtained from the South African Weather Bureau. The monthly distribution of the average daily (midday) maximum temperatures are indicated in the Figure 17. The average midday temperatures for the catchment range from 17° in June to 26° in January. Boksburg is the coldest during July with a minimum average of 0.2° during the night. The average midday high and night-time lows temperatures are indicated in Figure 17.

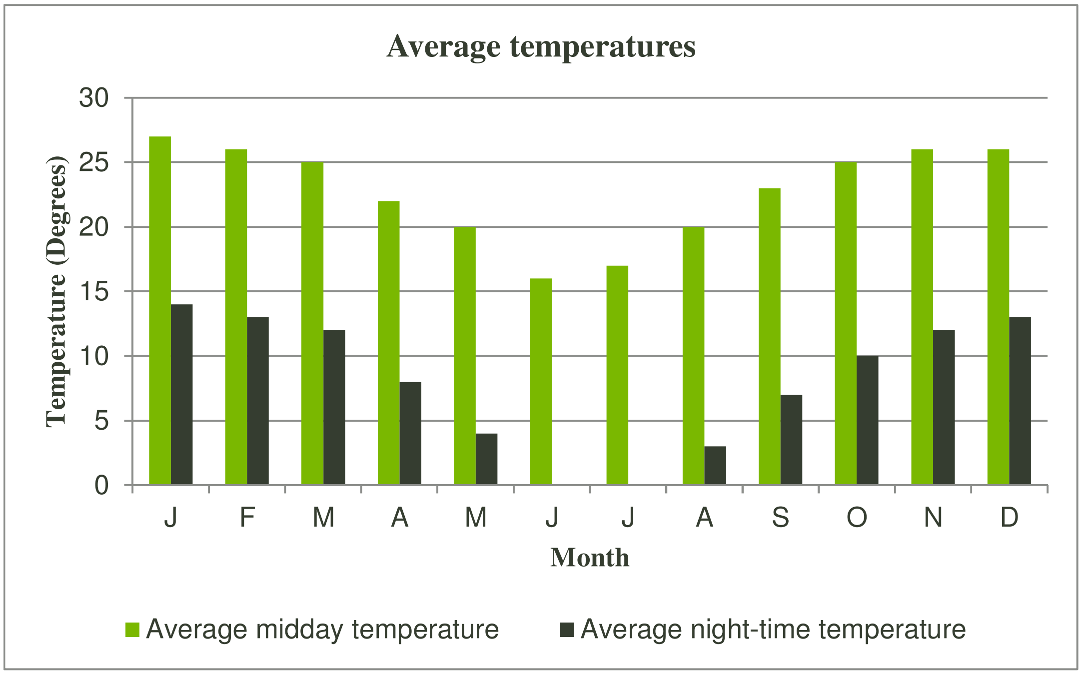

Figure 17 Average midday high and night-time low temperatures for the Boksburg Lake catchment

4.12 Bathymetry

A bathymetric survey was done in September 2011 by Aurecon South Africa as part of a project to determine the measures to reduce sedimentation of the lake, to reduce visible litter and to create additional attenuation in or around the lake to reduce flooding of the Trichardt Street Bridge. The survey was performed by Underwater Surveys (Pty) Ltd.

Bathymetric data was acquired on the survey vessel using a Reson NS 110 SBES. The sonar was mounted on an ‘over side-mount’. The sonar equipment was interfaced to the navigation computer for data control. Calibration for speed of sound was carried out within the operation area by taking velocity readings prior to survey activity, using a Reson SVP-15 sound velocity profiler.

A Survey grid of 20 m-25 m were used. Survey Lines were surveyed perpendicular to the contours. Very shallow areas and the inlet stream were surveyed using conventional survey methods. The full supply level (FSL) was surveyed using Conventional Survey methods. Basin Capacity was calculated to the FSL.

4.12.1 Sub-bottom profiling

The basic principle of seismic sub-bottom surveying is the recording and interpretation of a reflected signal from a geological interface. An acoustic source generates a compressional acoustic signal, which is directed towards the waterbed of Boksburg Lake. The incident signal is either totally reflected or partially reflected and transmitted through the sub-seabed. The acoustic signature of the reflected signal depends on the nature of the initial signal and the acoustic impedance of the transmitting medium. The acoustic impedance is a function of the physical characteristics of the sediment and any change in the physical nature of the sediment will influence the acoustic transmission and reflection of the signal (South Africa. Aurecon, 2011).

Reflected signals are received by pressure sensitive hydrophones connected to the recording/ processing system. Various processes may be used to clean and enhance the signal including band pass filters, gain control, time varied gain and swell filtering. The cleaned signal is then passed to a digital processor, capable of converting the signal amplitude levels and displays them as levels of grey (South Africa. Aurecon, 2011). When displayed in the above manner the reflected sound from the sub-bottom layers produces a continuous image of the interfaces between the layers. The different signal signatures generated by various types of geological strata and interfaces can give an indication of the type of material and thickness of individual layers.

The sub-bottom survey was done in September 2011 by Aurecon South Africa as part of a project to determine the sedimentation layer thickness of the lake. This was done to determine the remaining life of the lake before completely silted and to determine approaches to remove the sedimentation layer (South Africa. Aurecon, 2011).

The profiling was performed by Underwater Surveys (Pty) Ltd.

4.12.2 Capacity and volume calculation

Model Maker (Digital Terrain Modelling program) was used to calculate the Capacity and amount of Silt in the basin. Two Digital Terrain Models (DTM) were processed and interpolated from the Bathymetry and the Sub-Bottom survey results. The Bathymetry DTM was used as the base-dataset and the following calculations were done from it:

- Water Capacity in the basin calculated to the FSL.
- Amount of silt in the basin was calculated by combining the Bathymetry and the Sub-bottom DTM's and a Standards Cut & Fill calculation were done between the two DTM's.

The capacity calculations were performed by Underwater Surveys (Pty) Ltd and reported upon by Aurecon. The lake volume is summarised in the following table (Table 13 and Figure 18).

Table 13 Boksburg Lake volume

Contour value (m)	Area (m^2)	Volume (m^3)	Remarks
1603.00	12.84	1.16	
1603.50	6721.70	3362.00	
1604.00	39102.06	22913.03	
1604.50	69617.32	57721.69	
1605.00	100644.63	108044.01	
1605.50	126691.39	171389.70	
1606.00	150796.53	246787.97	
1606.50	168763.88	331169.91	
1607.00	176192.78	419266.30	
1607.14	178669.98	444280.09	Full Supply Level

Current volume at full supply level (FSL): 444 280 m^3

Prescribed Height at FSL: 1607.14 m.a.m.s.l

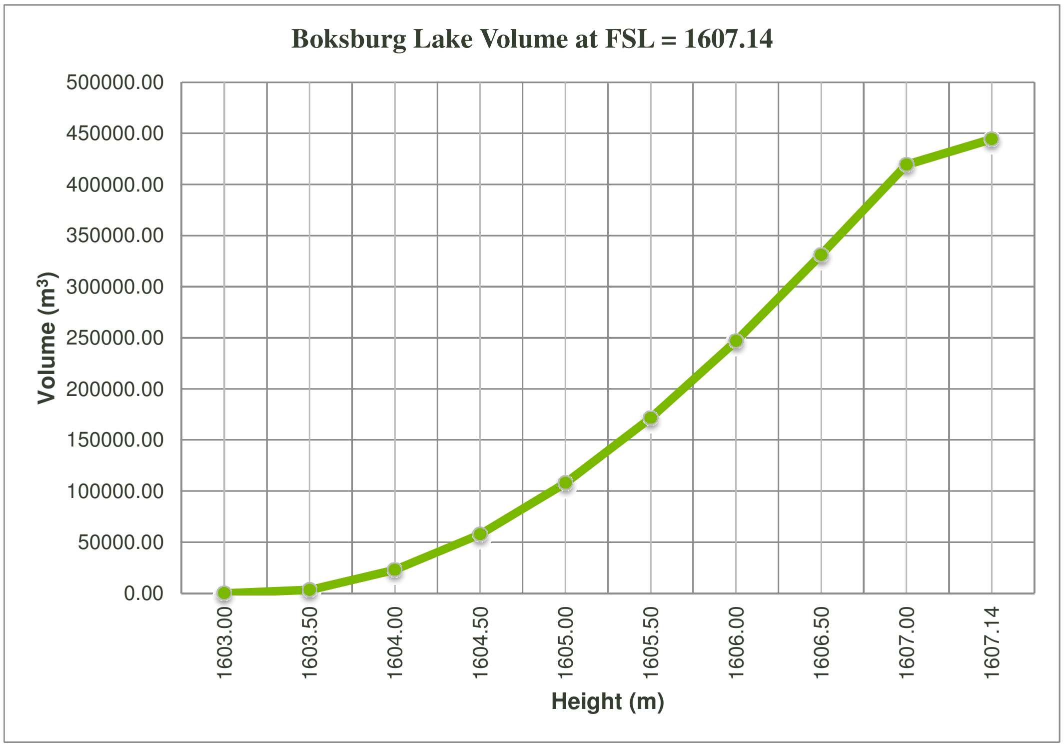

Figure 18 Boksburg Lake Stage - Volume at FSL of 1607.14

The lake was cleaned in 1995 of all sediment to the levels (to rock level) indicated in the survey. The wall was removed and the lake left to dry whilst drainage was diverted by means of diversion channels. The original floor of the lake showed up on the records as a rugged surface (rock), obliterated with rock boulders and gravel, manifesting itself by numerous hyperbolic point source reflectors. Overlying this surface was a layer of acoustically transparent muddy sediment. The thickness of the overlying unconsolidated sediment was measured along the individual survey lines and contoured at 0.5 metre contour intervals.

The mud layer was found to be relatively thin, varying in thickness between 0 and 1.7 metres with an average of 0.65 metres. The maximum thickness occurred in the centre of the lake towards the southern bank. The upper surface of the mud layer presented a strong interface and no indication of a gradual increase in density within the water column was observed on the records.

The sediment volumes are summarised in Table 14.

Table 14 Sediment Volume per depth increment

Depth (m)		Sediment (m^3)
From	To	
0.00	0.25	39006
0.25	0.50	38915
0.50	1.00	58311
1.00	2.00	19253
2.00	3.00	0
Total silt Volume		**155485**

At the time of the survey in 2010/2011, the lake was 35% silted. This yields an average siltation rate of 10 042 m^3 (minimum of 9 718 m^3 and maximum of 10 366 m^3) or 19 375 tons annually considering a linear increase from 1996 (using the average low). For the simulations of section 6.6 (Table 24), full calendar years (full 365 day cycles) were considered yielding a total of 170 731 m^3.

It is however expected that the curve will follow the same trend as that of Figure 14 (development curve).

Based on this linear trend, the lake has a remaining life expectance of another 26 years (2041) if a near 100% trapping efficiency is assumed. Sampling of the sediment material conducted by Geostrada laboratories in 2011 indicated densities ranging between 1 898 and 2 116kg/m^3. Using 2 000 kg/m^3, the estimated tonnage of silt material for the period amounts to 310.97 x 10^6 kg or 310 970 tons.

4.13 Hydrology

In 2011 detailed stormwater infrastructure asset register (as-built data) was compiled for the entire Ekurhuleni Metropolitan Municipality catchment as illustrated below and Boksburg catchment number N1d (South Africa. Aurecon, 2011) identified in Figure 19. This entailed several months of on-site data collection. A hydrological model using PCSWMM Version 5.0.18 was superimposed over the as-built information. Input data and simulation results are included in Appendix D. The catchment parameters adopted for the model was verified through site observations and discussions and review of other consultant reports.

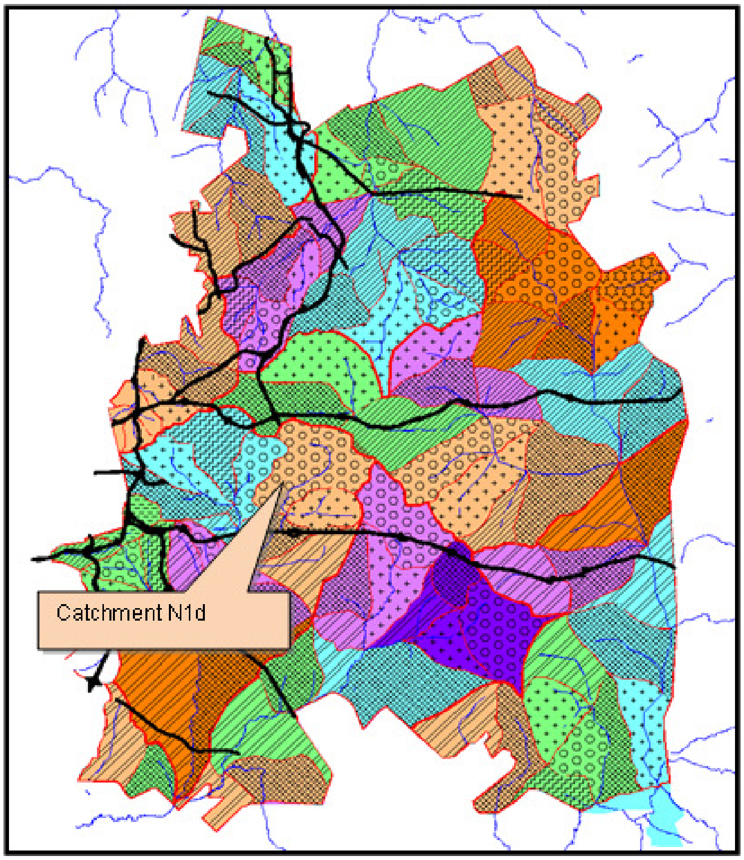

Figure 19 Ekurhuleni Catchment boundaries (South Africa. Aurecon, 2011)

PCSWMM is a dynamic rainfall runoff simulation model used for single event or long-term (continuous) simulation of runoff quality and quantity from urban areas. The runoff component of SWMM operates on a collection of sub-catchment areas that receive precipitation and generate runoff and pollutant loads. The Universal Soil Loss equation (USLE) has been adapted for use in PCSWMM. It is used in PCSWMM to predict the average soil loss for a given storm, recurrence or period.

The catchment was sub divided in 529 sub-catchments with an average catchment size of 5.6 hectares.

The influencing parameters include:

1. Percentage Imperviousness: Imperviousness of the catchment area
2. Infiltration rate: infiltration in permeable soils
3. Slope: Average slope of the catchment

4. Overland flow length
5. Depression storage

4.13.1 Percentage Imperviousness

Percentage imperviousness refers to the percentage of the catchment with no infiltration. It is a parameter that can be measured to a high degree of accuracy using aerial photos, land-use maps and satellite imagery. Another method of estimating imperviousness area given measured data is to plot the runoff (in mm) vs. rainfall (mm) for small storms. For the purpose of this study representative sites were selected and the values extrapolated to similar areas using aerial photos and imagery from Google Earth version 6.1.0.5001. Alternatively, regression formulations have been developed. These typically relate percentage imperviousness to population density. A representative value can be calculated using the following;

$$Imp = 23.71\ PD_d \quad (4.1)$$

Where,

Imp = imperviousness (%)

PD_d = population density in developed portions of the urbanised area (persons per hectare)

PD_d excludes agricultural holdings within a developed area. This excludes the use of this relationship for the purposes of this study as a large portion of the catchment is still classified as agricultural.

The following imperviousness values were found to apply for the ranges of land-use within the study area.

Table 15 Imperviousness ranges

LAND USE	IMPERVIOUSNESS	INFILTRATION		POND STORAGE	
		INITIAL	FINAL	PERVIOUS	IMPERVIOUS
	%	mm/h	mm/h	mm	mm
Residential					
Residential 15 u/ha	30	30	5	3	1
Low density 25 u/ha	35	30	5	3	1
Medium density 40 u/ha	40	30	5	3	1
High density 60 u/ha	45	30	5	3	1
School	25	30	5	3	1
Office	45	30	5	3	1
Retail	45	30	5	3	1
Malls	60-80	30	5	3	1
Light Industrial	40 – 50	30	5	3	1
Heavy Industrial	60	30	5	3	1
CBD	50	30	5	3	1
Open space/Parks	1 – 5	30	5	5	3
Agricultural	5	30	5	5	3
Grasslands	3	30	5	5	3
Forestry	2	30	5	3	1
Rocky Terrain	1	30	5	3	1

4.13.2 Infiltration

Horton's integrated equation was used for the infiltration model. Horton's model is empirical and perhaps the best known of infiltration equations. No tests were performed to ascertain the actual soils. The infiltration values used by Aurecon ranged from an initial infiltration rate of 40 mm/hr to a final infiltration rate of 10 mm/hr.

4.13.3 Slope

The sub-catchment slope reflects the average along the pathway of overland flow to inlet locations. The slope is simply the elevation difference divided by the length of flow.

4.13.4 Depression storage

Depression storage is a volume that must be filled prior to the occurrence of runoff on both pervious and impervious areas. It represents a loss or initial abstraction caused by surface ponding, surface wetting, interception and evaporation.

The depression storage volume is calculated from an estimated storage depth multiplied by the surface area. Typical values in urban areas range from 1 mm, in paved surfaces, to 3 mm for rougher surfaces.

4.13.5 Defining sub-catchments

Sub-catchments are divided using topography, cadastral and land use. Sub-catchments are linked to the drainage network as a “downstream” link in the PCSWMM model.

4.13.6 Integration of hydrological model with the phosphorus model

Phosphorus concentrations values are listed in Table 22 in section 5.7 were phosphorus values are related to imperviousness values used for the hydrological model (which on its turn was related to the land uses). These values were multiplied by the annual runoff from each catchment in order to estimate a phosphorus loading for the entire catchment. Losses were accounted for and include infiltration, ponding and depression storage losses.

The model was applied for the project period. The results of the study are discussed in chapter 6.

5 MODELLING METHODOLOGY

5.1 Introduction

This chapter will focus on the requirements for compiling an urban erosion/soil loss model by applying the Universal Soil Loss Equation and Soil Loss Estimation Model methodologies. The equations for calculating the factors have been presented in the following sections with the subsequent results presented in Chapter 6. The datasets the information is based in is limiting and in some instances lacking, assumptions have therefore been made.

Slope factors were derived from available digital terrain information. Different characteristics of the soil influence the risk of erosion of the soil (erodibility). Soil types were analysed using limited sample data obtained from previous studies of consulting firms; these were used to determine the soil erodibility. Rainfall kinetic energy was calculated using available rainfall information as described in a preceding section.

The approaches to the calculation of the factors, using the dataset described above, differ. The difference in these approaches is defined in the equations used.

5.2 Effective contributing area

With the delineation of sub-catchments two distinct areas are identified, namely impervious and pervious areas (areas without and with infiltration). Impervious areas are considered as covered with an impermeable layer (e.g. concrete or asphalt) with no soil loss contribution. They must not be confused with bare soil areas where soil loss does occur.

Within catchments not all eroded material is transported to the outfall, as deposition and storage occurs along the slopes, behind buildings and other obstructions. This is the basic principle behind sediment deliver ratios discussed in section 6.2. Within urban catchments, artificial barriers are also encountered in the form of fences and gardens where deposition occurs due to ponding and low flow velocities. These areas are can be considered as being cut off from the soil loss contributing catchment.

Actual contributing catchment percentages were calculated based on aerial photography and on-site inspections and related to the land-usage for ease in the model. Land-usage was earlier related to imperviousness values as part of the hydrological model. The results are presented in Table 16.The values were rounded.

Table 16 Actual catchment contribution factor related to imperviousness

Imperviousness (%)	ECC* (fraction)
60	0.1
50	0.2
45	0.3
40	0.4
35	0.7
30	0.8
25	0.85
5	0.95

*ECC = Effective contributing catchment.

5.3 Delineation of sub catchments

To estimate the sediment loadings from the urban areas, it is necessary to divide the study area into sub-catchments. The study area was divided into 529 catchments as per the hydrological model discussed earlier. It was found that smaller catchment delineation and factor allocation (imperviousness, depression storages, infiltration rates etc.) works more efficiently than larger catchments especially with the estimation of imperviousness values. Estimating values for larger catchments with a wide range of land-use changes become cumbersome.

The sub-catchments are divided and may include several land use classes namely: high-density residential, low density residential, schools, community facilities, industrial areas (high and low), parks, roads, and mining. Land-use is not the only determining factor in catchment delineation, which is primarily dependent on topography and cadastral layout. Sediment loads are estimated for each sub-catchment for the period 1995 to 2013.

Land use changes over all 529 sub-catchments were evaluated for the period 1995 to 2013 (refer to section 4.9 and discussed in chapter 6).

5.4 Soil Loss Estimation Model for Southern Africa (SLEMSA)

Soil Loss Estimation for Southern Africa was initially developed for Zimbabwean conditions in the late 70s by Elwell (1978) to predict long term average annual soil losses by sheet and rill erosion from small scale farming areas. It has since been applied to various other regions (Bobe, 2004).

The model is neither meant for estimation of sediment yields to river and dams nor soil depositions in depressions but is rather a model for soil removal and for the differentiating areas of high and low erosion potential (Smithen and Schulze, 1982). Smithen and Schulze (1982) found that SLEMSA over predicts soil loss due to its sensitivity to rainfall kinetic energy and topography.

The major erosion control variables that have been identified in the SLEMSA model include: Rainfall kinetic energy (E), percent effective vegetation cover (i), soil erodibility index (F), percent slope steepness (S) and slope length (L). These variables were combined into three factors namely, Soil loss factor (K), Cover factor (C), and a topographic factor (X) (Bobe, 2004).

SLEMSA utilises the following equation:

$$Z = K\,X\,C \qquad (5.1)$$

Where:

Z = Predicted annual soil loss from the land (tons/ha/yr)

K = Soil-erodibility factor (tons/ha)

X = Slope length and steepness factor

C = Crop management factor

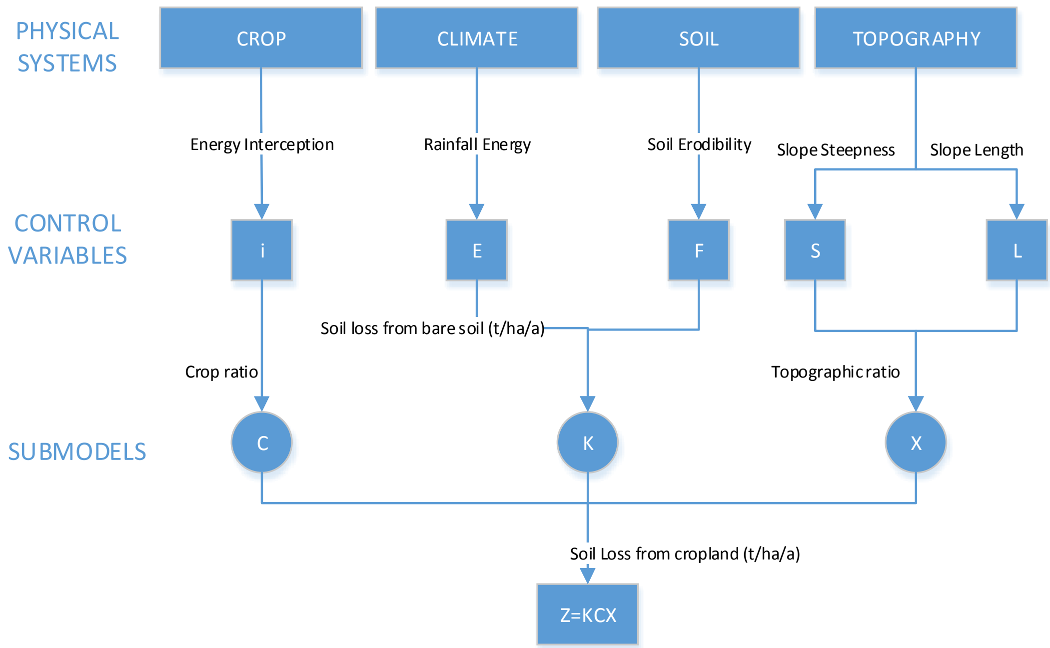

Figure 20 Structure of SLEMSA (Elwell, 1981)

The values of K, X and C are determined from the following equations:

5.4.1 Soil erodibility (K)

Soil erodibility is based on the soil texture classes and other relevant soil surface and subsurface conditions that directly or indirectly affect the soil inherent sensitivity to erosion including percent clay content. It is calculated using the following equation:

$$K = \exp\left[(0.4681+0.7663F)\ \mathrm{Ln}\ E + 2.884 - 8.1209\ F\right] \qquad (5.2)$$

Where

F = Soil erodibility (corresponds to the K value of USLE);

E = annual rainfall energy (see section 5.4.2)

5.4.2 Rainfall kinetic energy (E)

Estimation of rainfall kinetic energy (E) is based on annual rainfall data. The rainfall kinetic energy has been expressed in terms of rainfall intensity equations developed by Elwell and Stocking (1981) in equation 5.3.

$$E = (29.82 - 127.51/I) \quad (5.3)$$

Where

E = Rainfall kinetic energy ($J/m^2/mm$)

I = Rainfall Intensity (mm/hr)

The rainfall kinetic energy factor (E) above was determined according to the values suggested in Figure 21 which is a reclassification of the mean annual precipitation to the values of Elwell and Stocking (1981). The soil erodibility (F) was determined in the same manner as the K factor for the USLE.

Rainfall intensity is to be calculated using equation 5.12.

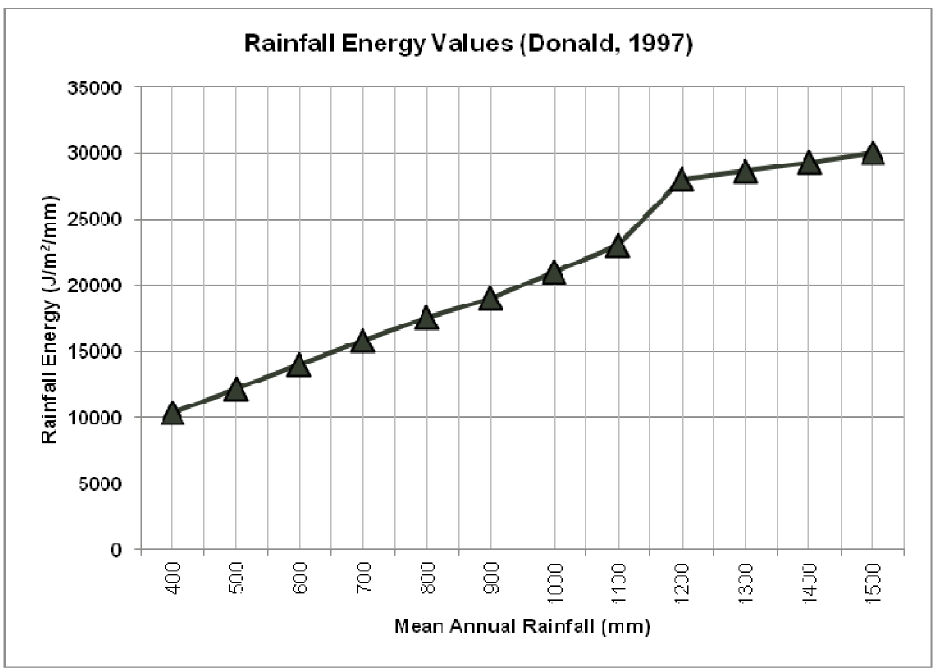

Figure 21 Annual rainfall energy values (Donald, 1997)

5.4.3 Slope length and steepness factor (X)

The slope length factor consists of two factors: the slope gradient factor and the slope length factor. The topographical relationships are given by:

$$X = (L)^{1/2} (0.76 + 0.53 S + 0.076 S^2)/25.65 \quad (5.4)$$

Where

X = topographic ratio

L = Slope length (m)

S = Slope steepness (%)

5.4.4 Crop management factor (C)

The crop management factor is based on a Zimbabwean model developed initially for grassland conditions by Elwell and Stocking in 1981. For sparsely grassed areas (where it can be expected that less than 50% of the rainfall energy will be intercepted by the crop cover) the crop factor can be calculated using equation 5.5.

$$C = e^{-0.06\, i} \quad (5.5)$$

Where:

i = percentage rainfall energy intercepted by the crop

For dense pastures and mulches (comparable to dense kikuyu grass covers) when i > 50 percent, it is

$$C = (2.3 - 0.01i)/30 \quad (5.6)$$

The cover management factor is calculated from the value of soil loss from standard bare soil conditions and that of a cropped field depends on the percentage of the rainfall energy intercepted by the crop (i) (Elwell and Stocking 1981). The cover information was obtained from visual observation of the site and by estimation. The cover factor used in soil loss models are normally based on dominant crops/covering for the areas and are not readily used for urban conditions where gardens and grassed areas are considered.

5.5 Universal Soil Loss Equation (USLE)

USLE is an erosion model designed for the prediction of the long term average soil losses in runoff. It is the most widely known and used empirical soil loss model all over the world. It was modified in the 1980s to the Revised Universal Soil Loss Equation (RUSLE), an improved version of the USLE with corrections to previous limitations.

Due to inadequate availability of input data for the study sites to comply with the input requirements of the RUSLE, the USLE was used. It evaluates four major factors affecting erosion namely climate erosivity (R), soil erodibility (K), topography (LS) and land use and management (CP) (Bobe, 2004).

Like SLEMSA, it does not estimate deposition, sediment yield at specific locations and ephemeral gully erosion, and does not represent fundamental erosion processes and interactions (Renard *et al*, 1997).

The USLE has the following formula;

$$A = R\ K\ (LS)\ C\ P \qquad (5.7)$$

Where,

A = the mean annual soil loss from the land (in tons/ha/yr)

R = Rainfall Erosivity factor (10^7J/ha x mm/hr)

K = Soil-erodibility factor (tons/ha)

LS = Slope Length and Slope Gradient factor (dimensionless)

C = Crop management factor

P = Erosion-control practice factor

The mean annual rainfall used in the USLE model is the same as those used for SLEMSA (section 5.4).

5.5.1 Rainfall erosivity (R)

Rainfall erosivity (R) is calculated from the kinetic energy of rainfall. The following equation is used:

$$R = EI_{30} \qquad (5.8)$$

Where,

R = rainfall erosivity factor in metric units (MJ mm/m^2/h)

E = Rainfall kinetic energy (J/m^2)

I_{30} = 30 minute rainfall intensity (mm/hr)

Rainfall kinetic energy and intensity data are not always available. In recent studies the erosivity factor (R) has been related to the mean annual rainfall (P) (Bobe, 2004). To calculate EI_{30} continuous rainfall intensity data are needed. Although rainfall data are available (see section 4.10) continuous data are not available.

It is generally given by a regression equation:

$$R = -8.12 + 0.562\,P \qquad (5.9)$$

Where,

Pm = Mean annual rainfall (mm)

In study by Rosewell and Yu (1996) a strong correlation between the rainfall erosivity factor and the 2-year ARI, 6-hr storm event have been identified. According to this the R-factor can be obtained from the following equation.

$$R = 164.74(1.1177)^{S} S^{0.6444} \qquad (5.10)$$

Using measurements of drop size and terminal velocity Wischmeier and Smith (1978) derived a relationship between rainfall intensity and kinetic energy. The proposed relationship is a logarithmic equation of the form:

$$E = 11.87 + 8.73 Log_{10} R \qquad (5.11)$$

Where,

R is the rainfall intensity in mm/h. The rainfall kinetic energy has been expressed in terms of rainfall intensity equations developed by Elwell and Stocking (1981) in equation 5.3.

Op Ten Noort (1983) analysed the rainfall data abstracted from South African Weather Bureau publications, which was also presented as a co-axial plot in the

Hydrological Research Unit Report 2/78 (Midgley and Pitman, 1978), and by means of regression analysis derived the following relationship for the calculation of the average rainfall intensity. This relationship was applied for the calculation of I_{30} for inland conditions.

$$I = ((7.5+0.034\ MAP)\ R_c^{0.3})/(0.24+t_d)^{0.89} \quad (5.12)$$

Where,

I = average rainfall intensity (mm/hr)

MAP = mean annual precipitation (mm)

R_c = recurrence interval (years)

t_d = storm duration (hours)

5.5.2 Soil erodibility (K)

The Soil erodibility factor (K) depend on the main properties of soil namely soil texture, organic matter content, soil structure and permeability. Wischmeier and Smith (1978) compiled nomographs from which the K values could be read (Figure 22 Nomograph for computing K factor values (After: Wischmeier and Smith, 1978)Figure 22). In cases where the silt fractions did not exceed 70% the following equation was used to estimate K;

$$K = 0.01317[0.00021(12\text{-}OM\%)M^{1.14} + 3.25(Ss\text{-}2)+2.5(Ps\text{-}3)] \quad (5.13)$$

Where,

OM% = percentage of organic matter

Ss = Structure code (Table 18)

Ps = Permeability code (Table 17)

M = product of the primary particle size fraction, [SS%(SS%+Sa%)] (5.14)

SS% = percent silt plus very fine sand (0.002-0.1 mm size fraction)

Sa = percent sand (0.1 – 2 mm size fraction)

Table 17 Permeability information for the major soil classes (Renard, et.al. 1997)

Texture class	Permeability class	Saturated Hydraulic conductivity mm/hr	Permeability rating
Clay, Silty Clay	6	<1	Very slow
Silty clay loam, Sandy clay	5	1-2	Slow
Sandy clay loam, Clay loam	4	2-5	Slow to moderate
Loam, Silty loam, silt	3	5-20	Moderate
Loamy sand, Sandy loam	2	20-60	Moderate to rapid
Sand	1	>60	Rapid

Table 18 Soil structure codes for use in estimation of K value in USLE (Wischmeier and Smith, 1978)

Structure codes	Description
1	Very fine granular
2	Fine granular
3	Medium to course granular
4	Blocky, Platy or massive

Information regarding the above factors was limited with only one test site at the outfall to the Boksburg Lake where an attenuation dam was to be constructed. The Department of Agriculture Technical Services, DATS (Wischmeier and Smith, 1978) have rated soil forms and series according to their erodibility for the approximation of K factor values (Table 19).

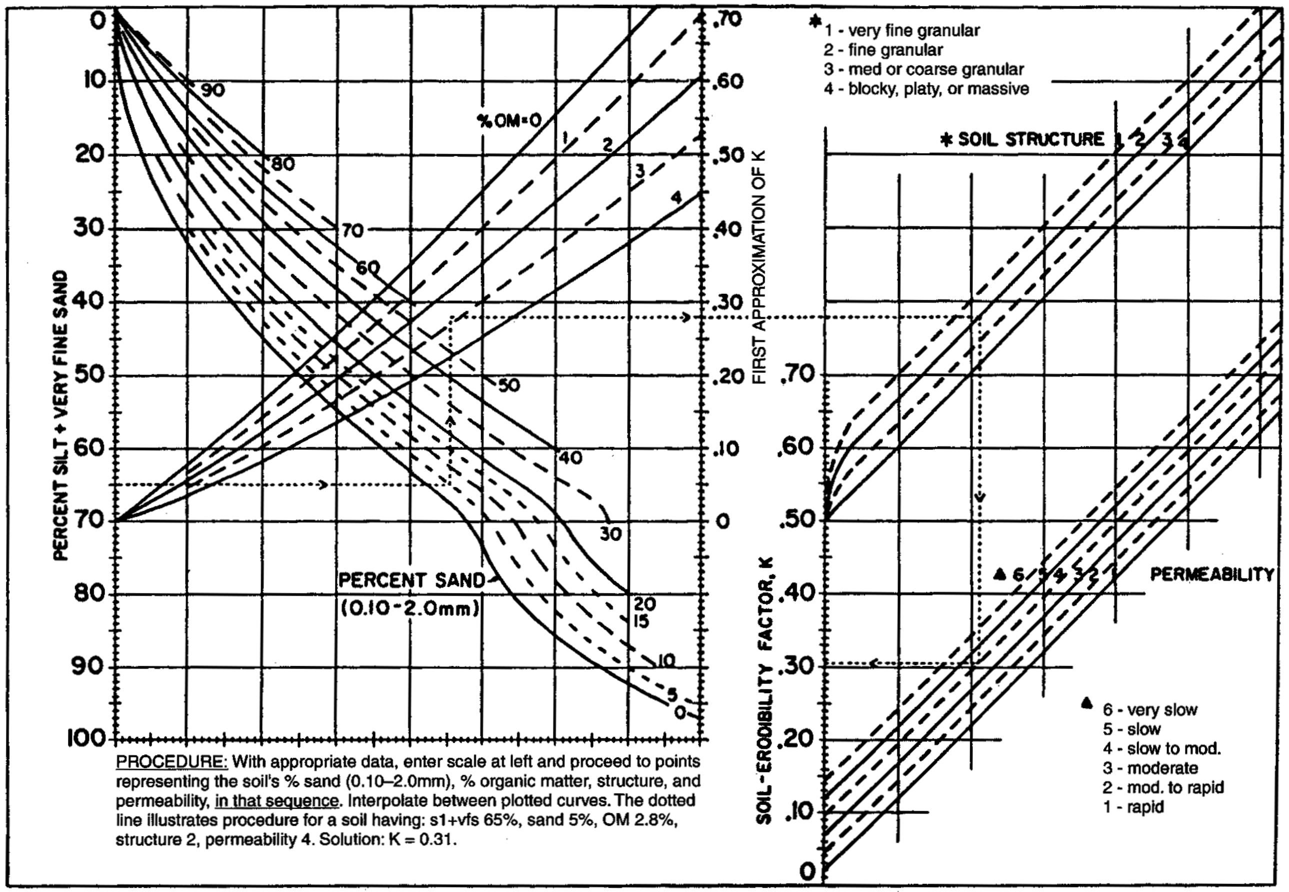

Figure 22 Nomograph for computing K factor values (After: Wischmeier and Smith, 1978)

Table 19 Erodibility factors for soil erodibility classes (Crosby *et al*, 1983)

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

5.5.3 Topographical factor (LS)

The factor is estimated from the slope length and slope gradient for each sub-catchment. This value will differ from user to user as it involves considerable judgement.

$$LS = (l/22.13)^n(0.065+0.045S+0.0065S^2) \quad (5.15)$$

Where,

l = slope length (m)

n = an exponent related to slope gradients (n = 0.5 if S>= 5%; n = 0.4 if 3%<=S<5%;n = 0.3 if 1%<=S<3%, n = 0.2 if S< 1%)

S = Slope gradient (%)

For the purpose of this study, equation 5.4 was used.

5.5.4 Cover Management Factor (C)

The cover management factor can be defined as the ratio of soil loss from land under specified crop or mulch conditions to the corresponding loss from continuously tilled, bare soil. This factor must not be confused with the runoff coefficient used in hydrological calculations of the rational method. C-factors for urban environments were extracted from studies by Bobe, and Breetzke in 2004, specifically the case when considering urban developments. C-values provided by Leh et al in 2011 are listed in Table 20.

Table 20 C-factors for urban areas (Leh et al, 2011)

Description	Urban C-factor
Urban low intensity	0.042-0.25
Urban High Intensity developments	0.003 (impervious areas)
Barren land	0.5
Water	0

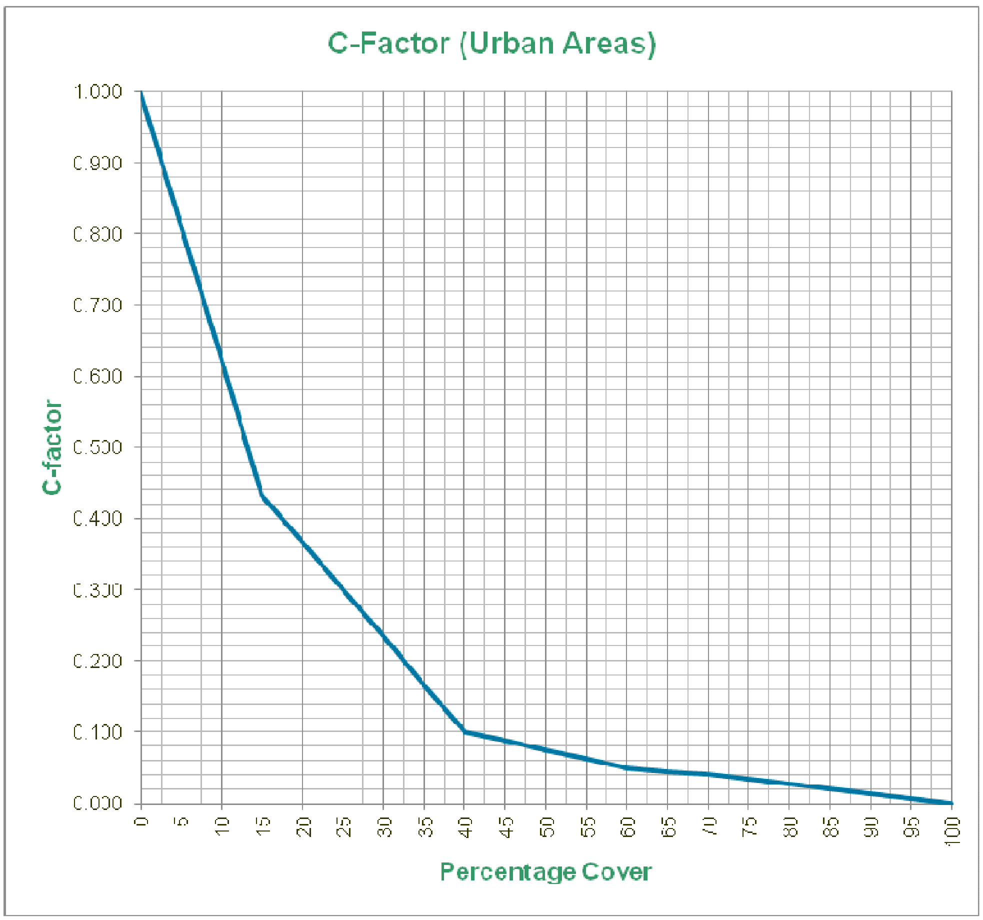

Figure 23 Urban C-Factor

5.5.5 Support Practice Factor (P)

The support practice factor (P) or Erosion control practice is the ratio of soil loss with a nominated surface condition ploughed up and down the slope. It is reduced by practices employed to reduce the amount of runoff and reduction in velocity. With construction and sites under development, it reflects the typical roughening and smoothing of soil surfaces by artificial means. Typical values for urban developments are presented in Table 21 as provided by the Sunshine Coast Council in Queensland, Australia in 2014.

Table 21 P-factors for urban developments (Sunshine Coast Council, 2014)

Surface condition	P-Factor
Compacted and smooth	1.3
Track-walked along the contour	1.2
Urban environs	1.0
Track-walked up and down the slope	0.9
Punched straw	0.9
Loose to 0.3 m depth	0.8

5.6 Sediment Delivery Ratio (SDR)

Within catchments not all eroded material is transported to the outfall, as deposition and storage occurs along the slopes. To account for this reduction in yield, a proportion representing the amount of eroded soil reaching the outfall is used. It is known as the sediment delivery ratio (SDR) or index.

Delivery ratios try to account for catchment characteristics but there is no precise procedure to estimate the SDR (Kim, 2006). Several models/approaches have been developed to estimate the SDR and sediment yield. These include:

1. Sediment loss – sediment yield approach

The expression for computing sediment delivery ratio can be written as follow (Ouyang, 1997):

$$SDR = SY/E \quad (5.16)$$

Where,

SY = the sediment yield

E = the gross erosion per unit area above a measuring point

Other equations relating deposits in reservoirs to drainage area size and mean annual runoff include the following as reported by Ouyang (1997).

$$S = 1280\, Q^{0.46}(1.43-0.26 \log A) \quad (5.17)$$

This equation applies for runoff less than 50 mm.

Or

$$S = 1958e^{-0.055}Q\ (1.43-0.26\log A) \quad (5.18)$$

Equation 5.18 applies for all other areas.

Where,

S = sediment yield

Q = runoff

A = Area

2. Drainage area and SDR

The United States Department of Agriculture established a relationship for SDR which try to account for the sediment source, texture, proximity to streams, channel density, basin are, slope, length, land use cover, and rainfall factors (Kim, 2006). The larger the area, the lower the sediment delivery ratio because large areas have more chances to trap soil particles. The following equations are proposed.

$$SDR = 0.51(259*A)^{-0.11} \quad \text{(USDA SCS)} \quad (5.19)$$

$$SDR = 0.42(259*A)^{-0.125} \quad \text{(by Vanoni in 1975 reproduced by Kim)} \quad (5.20)$$

$$SDR = 0.31(259*A)^{-0.3} \quad \text{(by Boyce in 1975 reproduced by Kim)} \quad (5.21)$$

Vanoni’s equation is considered more generalized but the USDA is more widely used (Kim, 2006).

Where,

A = catchment area in hectares

Williams (1977) suggested a better correlation with relief-length ratio, and runoff curve numbers. Their respective equations are:

$$Log(SDR) = 2.94259+0.82362\log(R_r/L) \quad (5.22)$$

Where,

R_r = relief of watershed, defined as the difference in elevation between the maximum elevation of the watershed divide and the watershed outlet

L = maximum length of a watershed, measured approximately parallel to mainstream drainage

3. Rainfall runoff

A SDR model used in the Soil and Water Assessment Tool (SWAT) takes runoff into account. The following equation applies:

$$SDR = (q_p/R_{ep})/(0.782845+0.217155\ Q/\ R))^{0.56} \qquad (5.23)$$

Where,

q_p = the peak runoff rate in mm/hr

R_{ep} = the peak rainfall excess rate in mm/hr

4. Slope, gradient, and relief-length ratio

Williams (1977) found a correlation with drainage area, relief-length ratio, and runoff curve number. The model is expressed as follow:

$$SDR = 1.366x10^{-11}\ A^{-0.0998}\ ZL^{0.3629}\ CN^{5.444} \qquad (5.24)$$

Where,

ZL = relief-length ratio in m/km

CN = long term average SCS curve number

5. Particle size

SDR is also affected by the sediment texture where the texture of the eroded materials is associated with the sources of erosion (Walling, 1983). The following sediment delivery ratio is based on the proportions of clay in the sediment and in the soil.

$$SDR\,(\%) = C_{soil}\,(\%)\,/\,C_{sed}\,(\%) \qquad (5.25)$$

Where,

C_{soil} = the percentage content of clay in the soil

Csed = the percentage content of clay in the sediment

The sediment delivery ratio is affected by many varying characteristics. Several of the methods have been discussed in this section. Ouyang (1997) compared these methods and found that SDRs range from 17.1% to 21.6%. He also found that there is less variation in values for larger catchments than smaller ones.

The adjustment of these equations to account for losses in urban and developed areas is not clearly stated and it is expected that the SDR calculated will be too low.

SDR were calculated for each sub-catchment from source to sink. Once reaching the drainage network it was assumed that all sediment will be transported to the lake. Assessing in-stream sediment transport is complex, and even more so for urban systems, and was therefore not considered for this study.

5.7 Phosphate modelling

The ability to assess nutrient (in this case only phosphate) from diffuse sources and those resulting from land use changes is essential for municipal managers to focus resources in the mitigation of strong environmental pressures.

From section 2.3.3 the following sources of phosphorus entering the system has been identified:

- Fertilisers in gardening applications. These include garden waste and pet waste.
- Atmospheric deposition (was excluded from the study as to little data is available in this regard).
- Vehicle emissions. In order to estimate the emission rates, traffic volumes and data from a traffic model is required. This information is limited and where available, very fragmented.

- Rain.
- Domestic Sewerage (this could also not be quantified and only an annual percentage was allowed for). During site investigations, several main sewerage outfall lines have been found to be open, blocked and overflowing into the stormwater system. A distinct odour is present in the stormwater channel at the crossing of Railway Road and Trichardt Street.

Two approaches to the estimation of phosphorus exports from urban areas are predominantly used, namely looking at concentration values measured in mg/l and secondly, estimates of loading or yield measured as mg/m^2.

Because of the lack of information on phosphorus loadings in urban areas in South Africa as well as the lack of actual sampling results, assumptions were made and comparisons drawn between results from various similar studies.

The following range of total phosphate was extracted from a study by Baginska (2010) on the impact of urbanization on the nutrient loads in New South Wales, Australia.

Table 22 Total Phosphorus Concentrations per selected land-use types

Description	TP (mg/l)
Agricultural/cropped/tilled	1.3
Open stands	0.1
Parks and recreational	0.25
Urban Low density	0.3
Urban Medium Density	0.5
Urban High Density	0.6
Commercial/Industrial	0.7

The concentrations listed in Table 22 above were related to imperviousness values used for the hydrological model (which on its turn was related to the land uses). These values were multiplied by the annual runoff from each catchment in order to estimate a phosphorus loading for the entire catchment. Losses were accounted for and include infiltration, ponding and depression storage losses. The model was applied for the project period. The results of the study are discussed in chapter 6.

6 MODELLING OUTCOME AND RESULTS

6.1 Introduction

Two modelling methodologies were selected in chapter 3, namely the Soil Loss Estimation model for South Africa (SLEMSA) and the Universal Soil Loss Equation (USLE), and the outline of a basic phosphorus model. The modelling requirements were discussed in chapter 5 for each method.

This section will deal with the model results and the alignment of the models to the input requirements of the hydrological model (specifically the imperviousness value). A relationship between the hydrological, soil loss and phosphorus models is attempted in an effort to illustrate that a change in land use (encapsulated in the imperviousness value) affects both soil loss and phosphorus loadings.

6.2 Sediment Delivery Ratio (SDR)

Various delivery ratio methodologies have been discussed in section 5.6, each with its specific characteristics, variables, and limitations. For the purpose of this study the drainage area ratio formulae (Equations 5.19, 5.20, and 5.21) was used. SDR values range from 18.6% to 29.6% with an average value of 23.5%, a median of 23.7% and standard deviation of 1.54%. These values were also applied to the SLEMSA model (Figure 24).

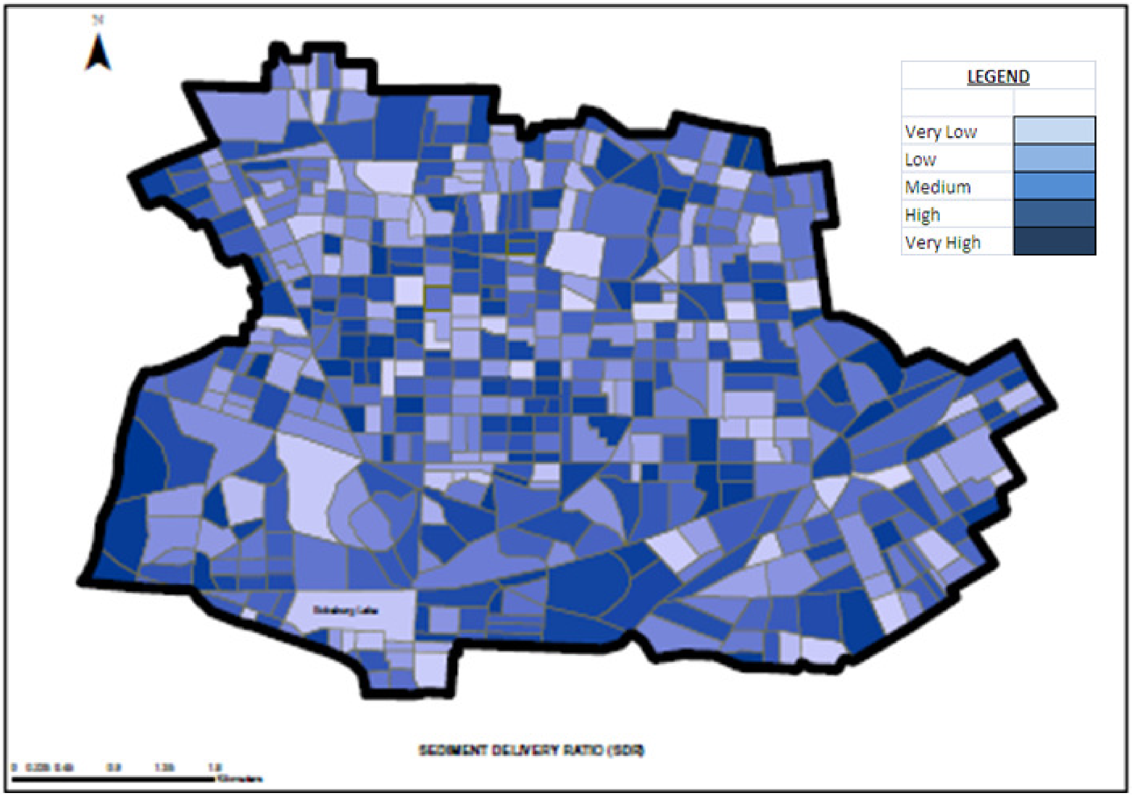

Figure 24 Sediment Delivery Ratio (SDR – Equation 5.19))

6.3 USLE factors

6.3.1 Rainfall erosivity

Distinct erosive rainfall events are defined as a storm when total rainfall exceeds 12.5 mm, maximum 5-minute intensity exceeds 25 mm/h and the event is isolated by at least a rain-free period (Elwell and Stocking, 1976; Nel and Sumner, 2007).

Of the storm events for the period January 1995 to April 2013, 221 storms events qualify with a total of 3 394 mm of erosive rainfall. This is 24.9% of the total rainfall of 13 632 mm over this period. These values are derived from the rainfall data for the OR Tambo rain gauge. Only hourly data were available.

The rainfall erosivity has been calculated to be 2323 (MJ.mm /ha.hr). The value differs by factor 10 from equations 5.8 to 5.10 to account for unit differences. The resulting value is in range when compared to interpolation method discussed by Msadala in 2010 and represented in Figure 6Figure 2. The erosivity values estimated from Figure 6 range from 2 000 to 6 000 MJ .mm/ha.hr. Because of the small catchment of the Boksburg Lake this value was applied to all the study area sub-catchments.

6.3.2 Soil erodibility

The soil erodibility is calculated using equation 5.13 and amounts to 0.046 MJ/ha.mm/hr and compares well to the estimate of 0.050 MJ/ha.mm/hr derived from Figure 7. A value of 0.050 MJ/ha.mm/hr was used for the soil loss calculation. This is based on an organic matter content of less than 1%, average sand percentage less than 40%, and an average silt loading (< 2 mm particle size) of 7%.

6.3.3 Topographical/Slope factor

The overland flow lengths and slope values used in the hydrological model as compiled in PCSWMM was used as inputs to equation 5.4 (Figure 25).

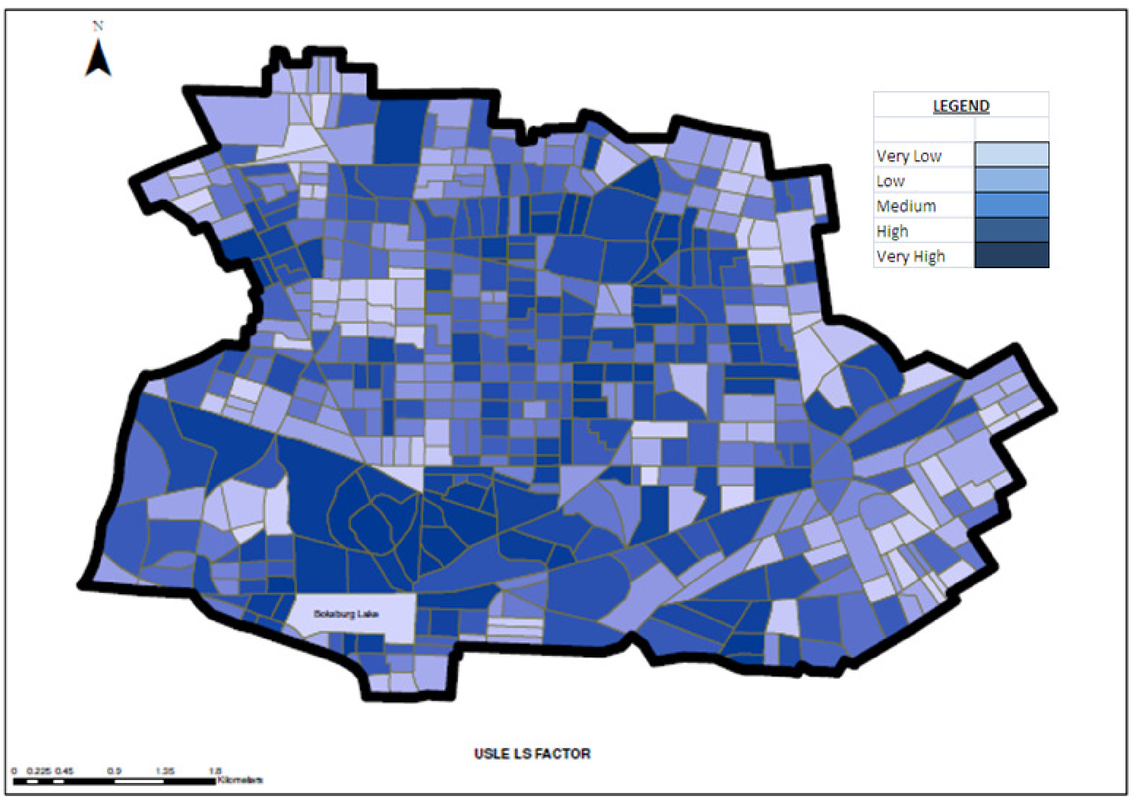

Figure 25 Topographical/Slope factor

6.3.4 Cover management factor

Urban areas are excluded from the modelling application in studies by Bobe (Bobe, 2004) and Breetzke (2004). C-factors were either omitted or values of 1 used in these studies and applied to SLEMSA, USLE and RUSLE. For both these studies, the urban areas are relatively small compared to the total study area and would not have had a large influence on the results. For the purpose of this study, which only addresses urban catchments, the impervious areas were subtracted from the sub-catchment size. The remainder comprises gardens with lawns, shrubs and trees. The cover factors were calculated for these pervious areas and values were derived from Figure 23 (Final cover management map in Figure 26).

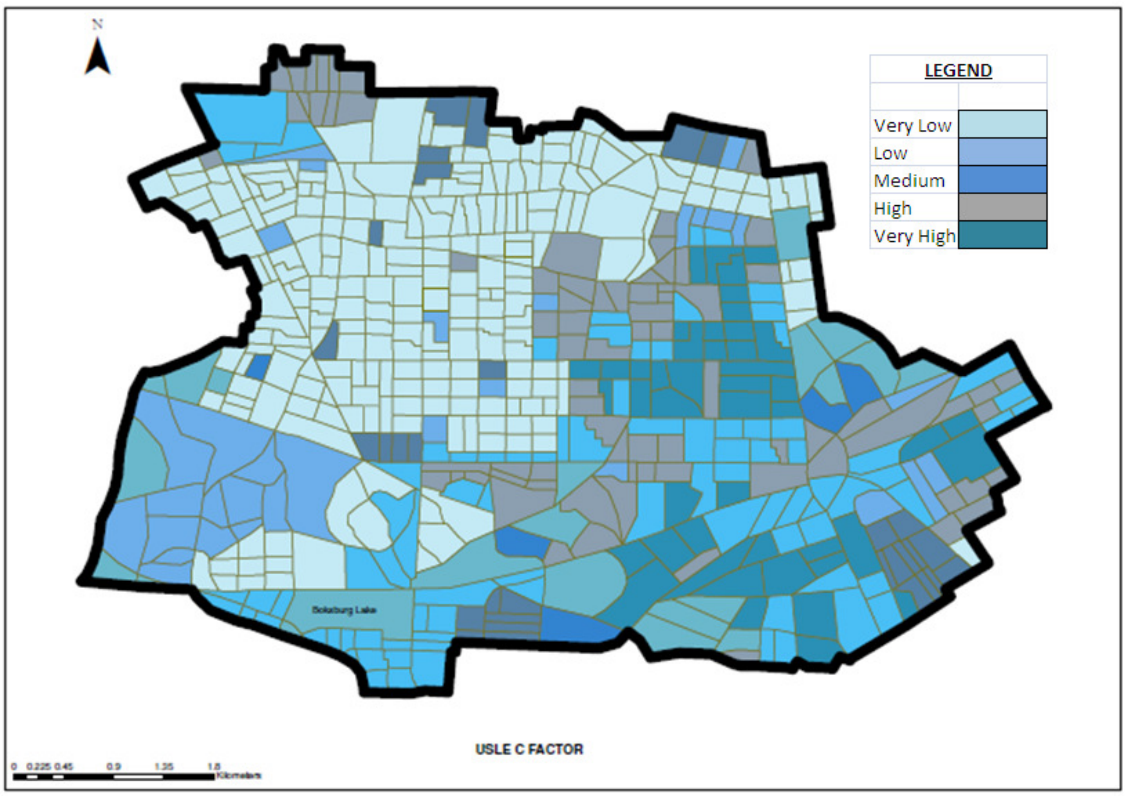

Figure 26 Cover management factor (C)

Although a mine dump is situated in the study area it was found to be in various stages of rehabilitation at the time of the study. Only portions of the mine catchment had bare soil and therefore an average value was assumed. For earlier years of the model, values relating to bare soil conditions were accepted.

6.3.5 Support Practice factor

The Support Practice factor has been determined as per Table 21 in section 5.5.5.

6.4 SLEMSA factors

6.4.1 Soil erodibility

The soil erodibility was calculated using equation 5.2. The rainfall kinetic energy factor (E was determined according to the values suggested in Figure 21 which is a reclassification of the mean annual precipitation to the values of Elwell and Stocking (1978). Soil erodibility was calculated as per equation 5.13.

6.4.2 Topographical factors

The topographical factor (X) was calculated using equation 5.4. The slope steepness and length components were determined from the input parameters of PCSWMM (see section 4.13).

6.4.3 Crop management factors

Vegetation cover and specifically ground covers are important to urban environments and can be managed to reduce erosion (Breetzke, 2004). Crop management factors dealing with crop coverage in urban areas are limited. Typical interception values were calculated per land-use type based on typical tree, shrub, and grass coverage. This relationship is presented in Figure 27.

Only the c-factors for imperviousness values from 5% to 60% were calculated. For sub-catchments with imperviousness values greater than 60%, the highest value listed was applied. As with the cover management factor of the USLE, crop management factors were limited to describe urban conditions and similarly to cover values cover management values were calculated for pervious areas.

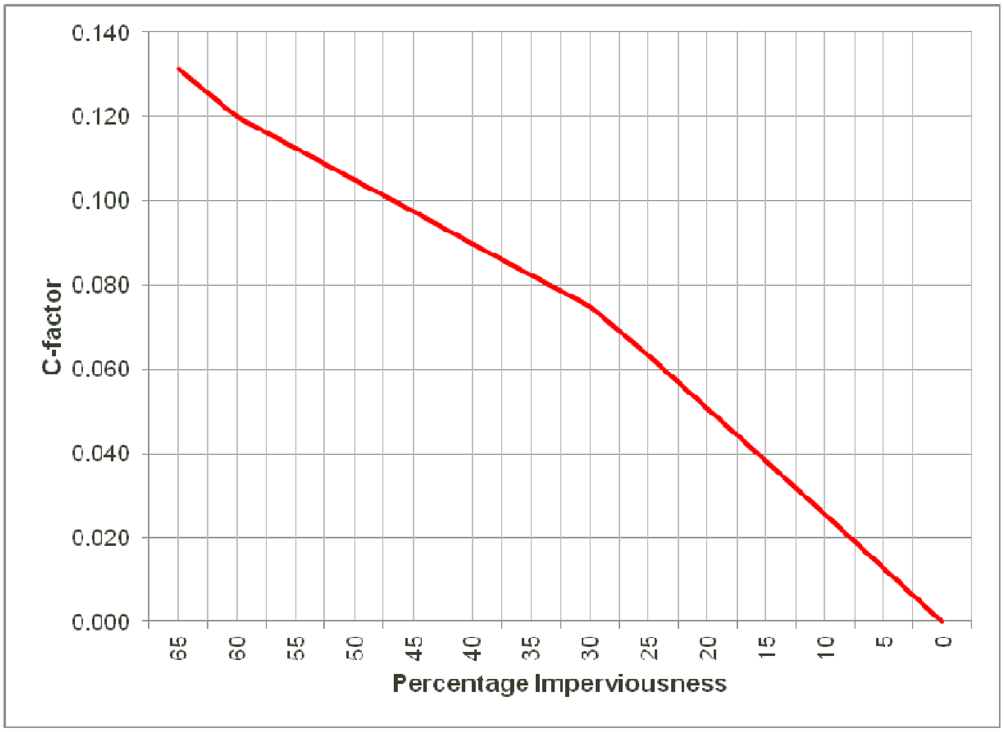

Figure 27 Relation of Cover factor to imperviousness

6.5 Soil Loss Model calibration and results

A model was compiled for calibration purposes using the catchments and factors as discussed in the preceding sections. The 2010/2011 land-use and cover information was used. 2011 was selected because it coincided with the year the sub-surface survey was done to determine the silt volumes in the Boksburg Lake (section 4.12.1). Figure 28 below summarises the sub-catchment size distribution for the model area which gives an indication on the spread of catchment sizes.

As illustrated in Figure 28 an almost equal distribution of catchment sizes is found with 39% smaller or equal to 5 hectares, 31% between 5 and 10 hectares, and the remaining 30% greater than 10 hectares but smaller than 20 hectares. This is indicative of urban models.

The soil loss distribution as per catchment size for the USLE and SLEMSA models are presented in Figure 29 and Figure 30. The distribution is comparable to the catchment distribution of Figure 28. The fact that the distributions of Figure 29 and Figure 30 are similar is an indication that the models are comparable.

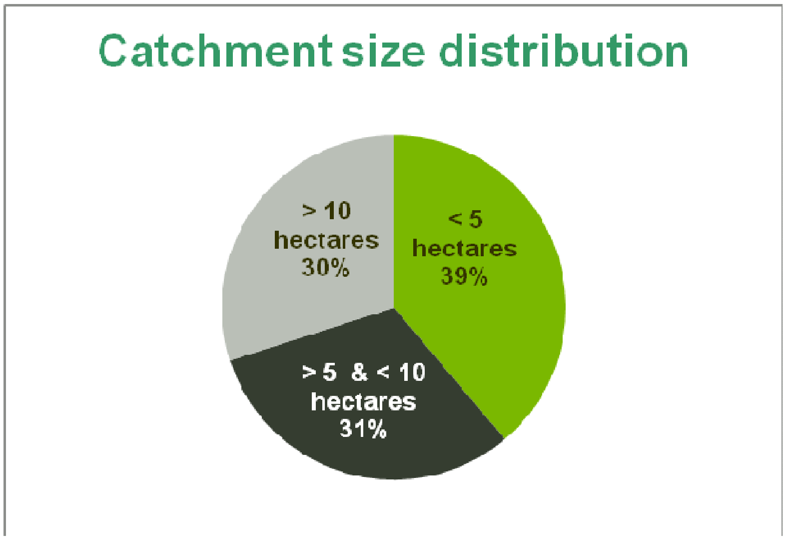

Figure 28 Catchment size distribution in the model

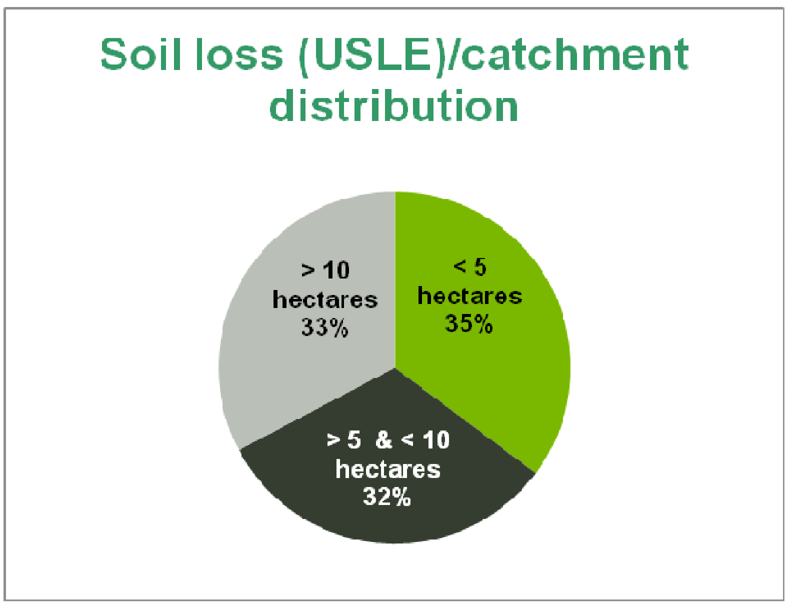

Figure 29 Soil loss (USLE) per catchment size distribution

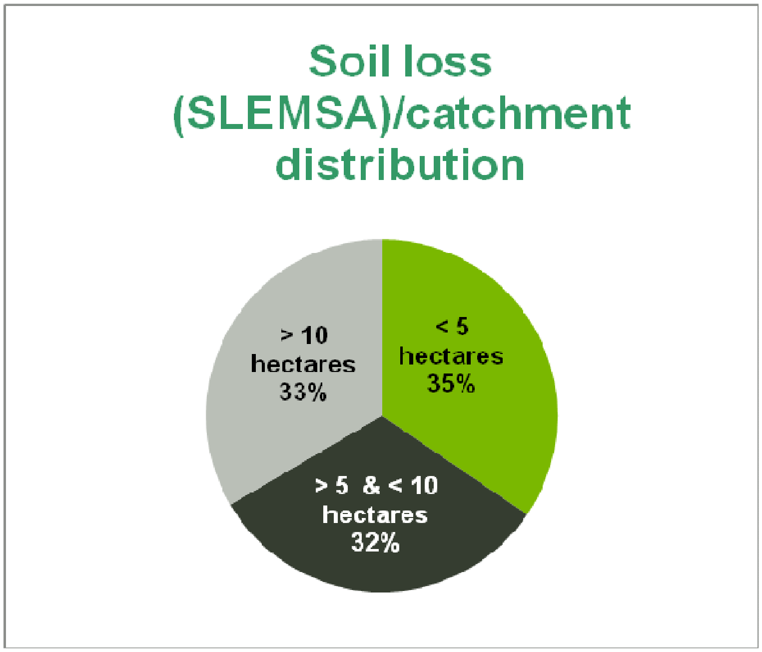

Figure 30 Soil loss (SLEMSA) per catchment size distribution

6.5.1 Use of single models as indication of soil loss (Baseline model)

Four model scenarios were compared using the parameters and factors discussed. The scenarios were applied using both SLEMSA and USLE. The scenarios are:

1. Basic model: only applying the factors required for the model construction. No delivery ratios or adjustment factors have been applied.
2. Sediment Delivery Ratio: Applying Sediment delivery ratios to the basic model. Three ratios were compared (Drainage area ratios of section 5.6)
3. Effective Contribution Catchment: applying the effective contributing ratio of catchment, as was discussed in section 5.2, contributing to the soil loss
4. 50% Delivery ratio: Constant factor of 0.5 applied to all catchments

The volume of soil lost for the year 2010/2011 was calculated. The obtained volume was cumulatively added from the simulation start of 1995/1996 assuming a linear increase until the end of 2011. The total volumes were compared to that of section 4.12.2 (Table 13). The above was done to obtain an indication as to which model methodology will compare the best. The results of the simulations are presented in Table 23.

Table 23 Indicative model comparison

Model	Volume Calculation (m^3)	Over or under estimate	Annual estimate (m^3)
Measured volume	155,485	0%	10,366
USLE (BASIC)	266,835	71.61%	17,789
USLE (SDR USDA)	201,765	29.76%	13,451
USLE (ECC)	133,065	-14.42%	8,871
SLEMSA (BASIC)	310,350	99.60%	20,690
SLEMSA (SDR USDA)	233,955	50.46%	15,597
SLEMSA (ECC)	160,875	3.46%	10,725
USLE (50%SDR)	133,425	-14.19%	8,895
SLEMSA (50%SDR)	155,175	-0.20%	10,345
USLE (SDR Vanoni)	175,410	12.81%	11,694
SLEMSA (SDR Vanoni)	203,310	30.75%	13,554
USLE (SDR Boyce)	245,565	57.93%	16,371
SLEMSA (SDR Boyce)	283,560	82.37%	18,904

Both basic models yielded soil loss estimates higher than the sediment volume of 155 485 m^3.The USLE estimate is 71.6% higher and SLEMSA 99,6%. Three sediment delivery ratios were applied namely the USDA SCS (equation 5.19), Vanoni equation (equation 5.20), and Boyce equation (equation 5.21) discussed in section 5.6. The USDA SCS method decreased the basic USLE and SLEMSA models within 29.76% and 50.46%, respectively. The results from the Vanoni equation decreased the model yields to within 12.81% and 30.75, respectively. Compared to the USDA SCS and Vanoni equations the Boyce equation only managed to decrease the yield to within 57.93% and 82.37% within the measured results for the USLE and SLEMSA models respectively. The Vanoni equation provides the best results.

Additional to the application of the sediment delivery ratios, the Effective Contributing Catchment (ECC) was also applied and yielded results -14.42% and 3.46% within the measured results, USLE and SLEMSA respectively. This is also within acceptable limits. As a last measurement an average sediment delivery ratio of 50% was applied. These yielded results within -14.19% and -0.2% for the USLE and SLEMSA models respectively. The application of a 50% ratio is an unverified method and can only be used as a quick measure.

Results from five of the models yielded results within 15%, or 85% confidence, of the measured results. Four of these models are however not generally accepted methods and can only be used as indication. The USLE method utilizing the Vanoni SDR equation is the preferred method and will be applied in subsequent modelling with the USLE ECC for comparison only. The results of the model comparison are further illustrated in the graph below (Eighty five percentile line indicated in grey).

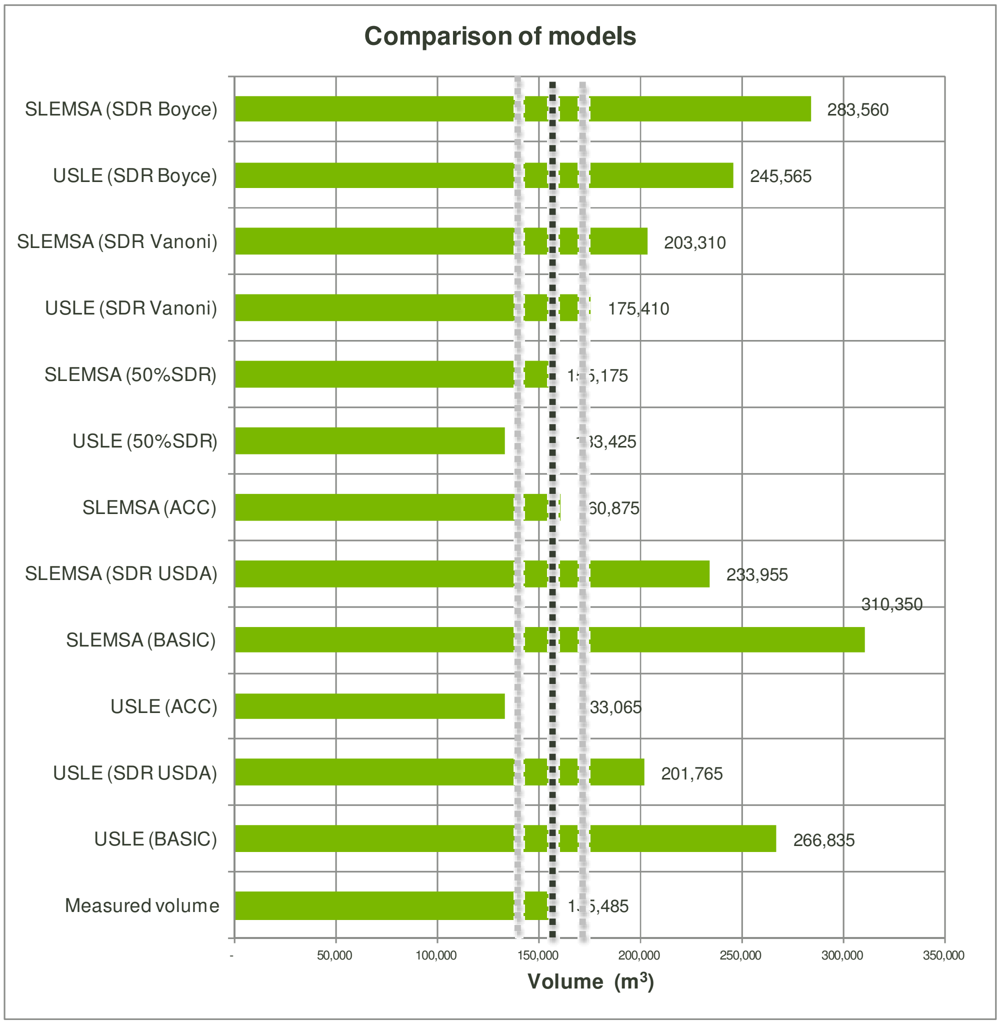

Figure 31 Basic Comparison of models

6.5.2 Considering development and land use changes within the catchment

To verify if the annual soil loss yield correspond to the development trend represented in Figure 14 erosion models were compiled for the years 1995, 2002, 2005, 2006, 2010, and 2011, each considering land use changes within each timeframe. The results of the simulations are summarised in Table 24 and Figure 32. Also indicated in Figure 32 is an upper and lower confidence level within 10% of the measured results. Without development 154 309 m^3 soil would have entered the lake over the simulation period. With an annual increase in development of 19.4% (section 4.7) a total of 176 222 m^3 is expected.

Table 24 Comparison of models considering land use changes and development within each catchment

	USLE				Average	Volume
Model	1995	2002	2006	2011	volume	1995 to 2011
BASIC	**10366**	**10366**	**10366**	**10366**	**10,366**	**176,222**
Basic USLE	13714	14596	16193	17,789	15,375	261,367
ECC USLE	7158	7165	8337	8,871	7,775	132,169
SDR USDA USLE	10432	11075	12263	13,451	11,657	198,177
Vanoni USLE	**9077**	**9633**	**10664**	**11,694**	**10,139**	**172,357**
Boyce USLE	12828	13563	14967	16,371	14,257	242,373
50% SDR USLE	6857	7298	8097	8,895	7,687	130,686
Basic SLEMSA	14995	15095	17892.5	20,690	16,799	285,589
ECC SLEMSA	**9443**	**9450**	**10296**	**10,725**	**9,897**	**168,254**
SDR USDA SLEMSA	11484	11543	13570	15,597	12,781	217,279
Vanoni SLEMSA	**10001**	**10050**	**11802**	**13,554**	**11,121**	**189,050**
Boyce SLEMSA	14270	14313	16608.5	18,904	15,721	267,252
50% SDR SLEMSA	7497	7548	8946.5	10,345	8,400	142,796

Three models compared favourable. The USLE model applying the Vanoni equation is within 2.19% with 172 357 m^3. The SLEMSA Vanoni model yielded results within 7.28% with 189 050 m^3 whilst the SLEMSA ECC came within 4.52% with 168 254 m^3.

The USLE Vanoni model (see Figure 33) again yielded the best results when compared to the indicative model in the subsequent section. Contrary to the previous single model approach, the SLEMSA Vanoni model also yielded comparable results. From this can be concluded that the use of the Vanoni equation can be used with both SLEMSA and USLE when applied to urban areas. Also clear is that the same trend is followed as the development curve in Figure 14.

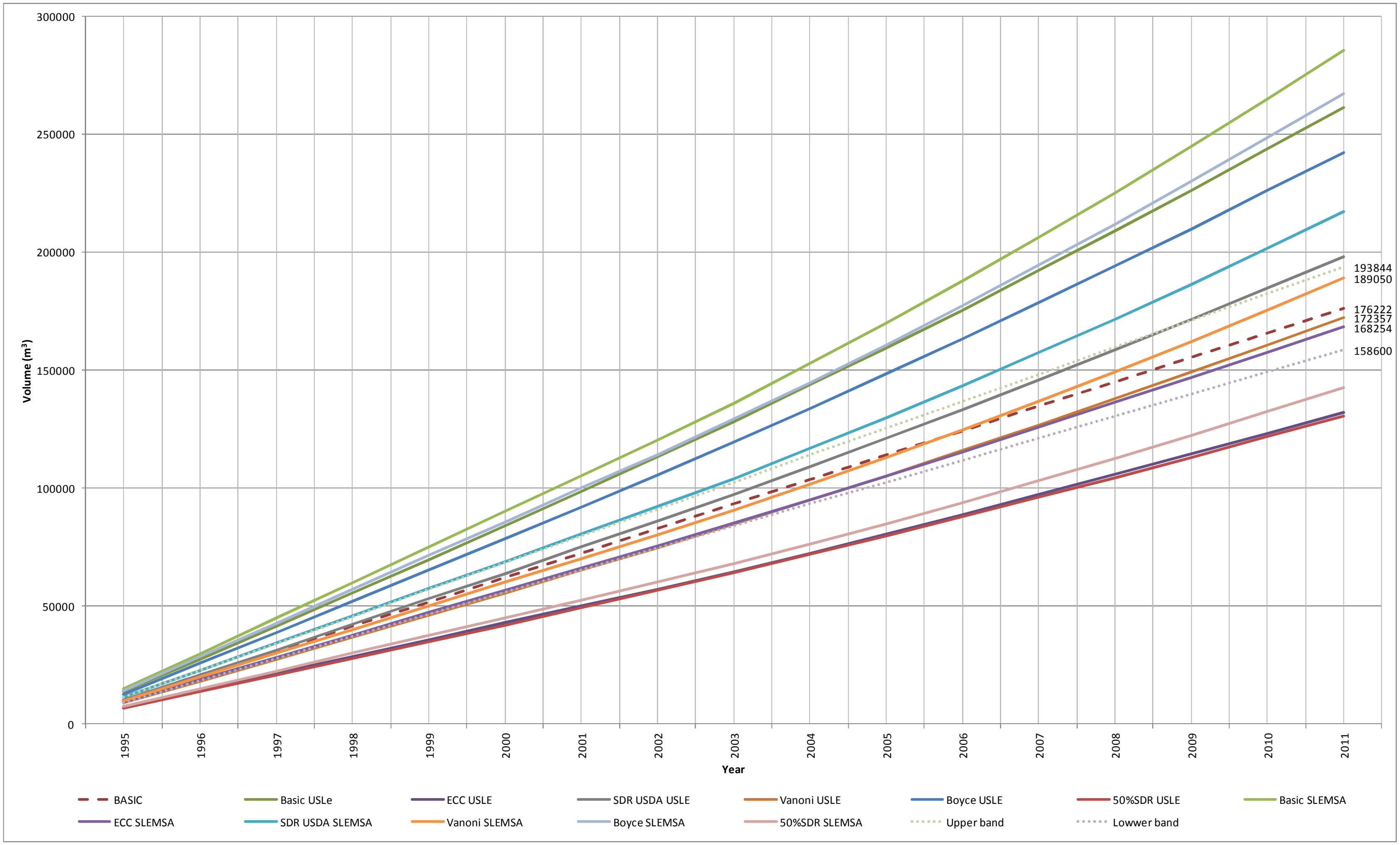

Figure 32 Comparison of models

The effective contribution catchment ratio also produced comparable results. This is an indication that the effective contributing ratios defined in Table 16 can be refined.

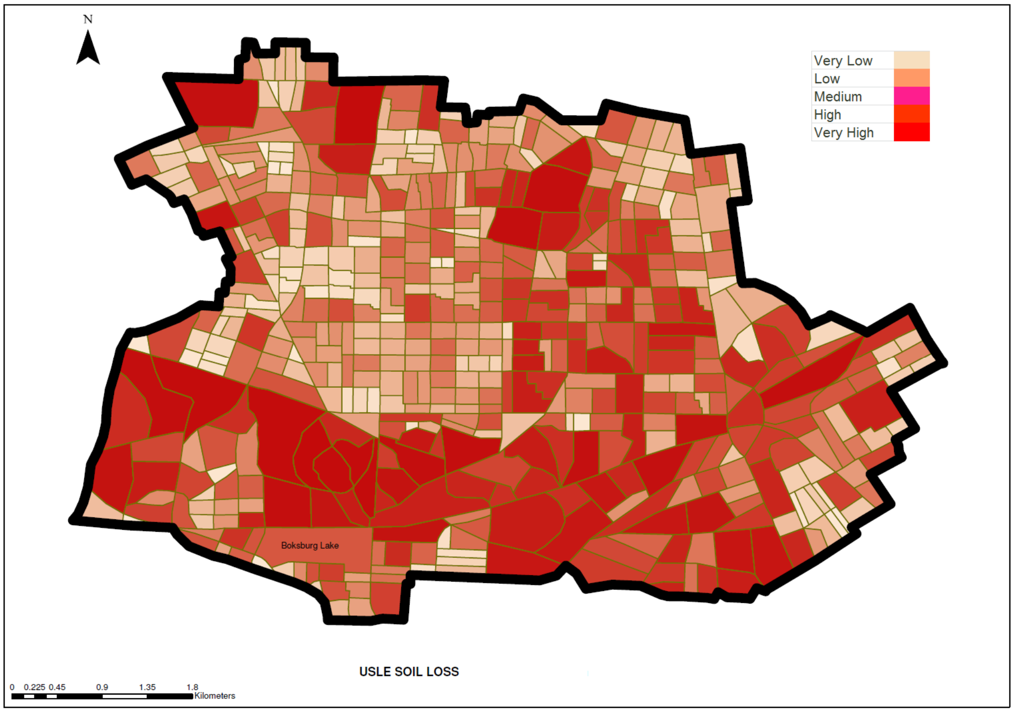

Figure 33 Total Soil Loss

6.5.3 Sensitivity Analysis

The relative impact of each of the preceding factors in modelling soil loss for as particular area is critical. Conducting a sensitivity analysis of the model input parameters assists in the data collection process, and in determining the experimental needs as well as providing further insights into the physical processes involved (Bonda *et al*, 1999).

A sensitivity analysis was performed for the area. The analysis entailed investigating the effects of increasing and decreasing the factors by an arbitrary percentage. While one parameter is analysed, values for all other parameters are held constant. The obtained sensitivity index value represents a relative normalised change in output to a normalised change in input. This makes allowance for a valid mean of comparing sensitivities. The Sensitivity Index (SI) is given by the following equation:

$$SI = [(O2-O1)/O12]/[(I2-I1)/I12] \quad (6.1)$$

Where I1 and I2 are the least and greatest input values, I12 the average input. O1 and O2 are the associated outputs with O12 the average. Values greater than zero indicate a high rate of sensitivity to changes.

The following is evident:

- Both methods are sensitive to crop/cover management practices (SI values of 1.4 and 0.88, respectively)
- Both methods are sensitive to changes in soil erodibility
- Both methods are less sensitive to topographical changes (SI values of 1.32 and 0.89, respectively)
- USLE is less sensitive to erosivity. Indicated a weak influence

Of the above, changes in erodibility had the biggest influence. In an instance a 20% increase in erodibility resulted in a 25% decrease in soil loss.

6.5.4 Comparison of results between SLEMSA and USLE

The difference between the estimated losses using the two methods is large for most catchments although still comparable and highly correlated (Figure 34).

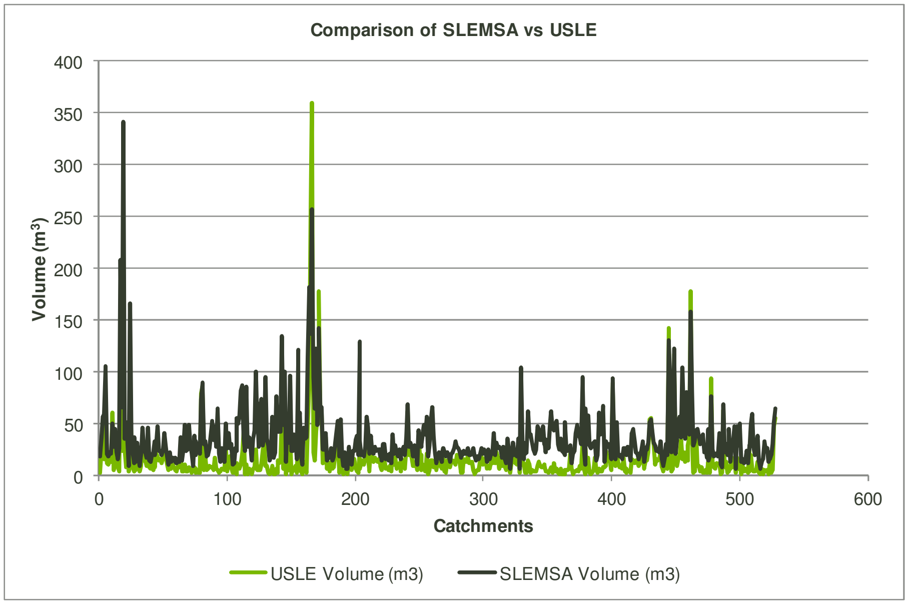

Figure 34 Comparison of SLEMSA versus USLE

It can be concluded that depending on the ease of determining the input variables and the level of accuracy required either of the two methods, and utilizing the Vanoni SDR equation, can be used to assess the level of soil erosion within urban environments. Also evident from the investigation was that further investigation and refinement of the ECC factors can yield highly comparable results. The models do give a clear indication that differences in soil loss volumes are experienced as a result of changing catchment conditions.

6.6 Phosphorus model results

The total catchment size is 29.43 km^2 with a mean annual precipitation of 675 mm (Section 4.8). Considering infiltration and depression storage losses the total expected annual runoff volume from the catchment is approximately 8.23 Mm^3. On average the dam could be filled 21 times per annum or every 17 days. This implies an almost continuous spilling. Approximately 43.6% of the phosphorus ending in the lake is adsorbed to the sediment with a loss of 56.4% spilling into the downstream system.

A report in 2008 for the Ekurhuleni Metropolitan Municipality (South Africa. Ndumo, 2008) indicates an average concentration of phosphorus in the dam water at that time to be 0.7 mg/l. This yields a total phosphorus load of 5 761 kg phosphorus per year. This is however only an indication of the total possible loading but correlates to the annual values as calculated using the methodology described below (Figure 35).

Considering a 43.6% of the total loading of 5 761 kg is adsorbed to sediment, a loading of 2 512 kg is yielded. This is comparable to a loading of 2 089 kg obtained from readings by Ndumo in 2008 of 103 mg/kg of the sediment. This equates to an adsorption ratio of approximately 36%.

The phosphorus concentrations of Table 22 were applied to each sub catchment. This was applied for the simulation years from 1996 to 2011. The following was observed.

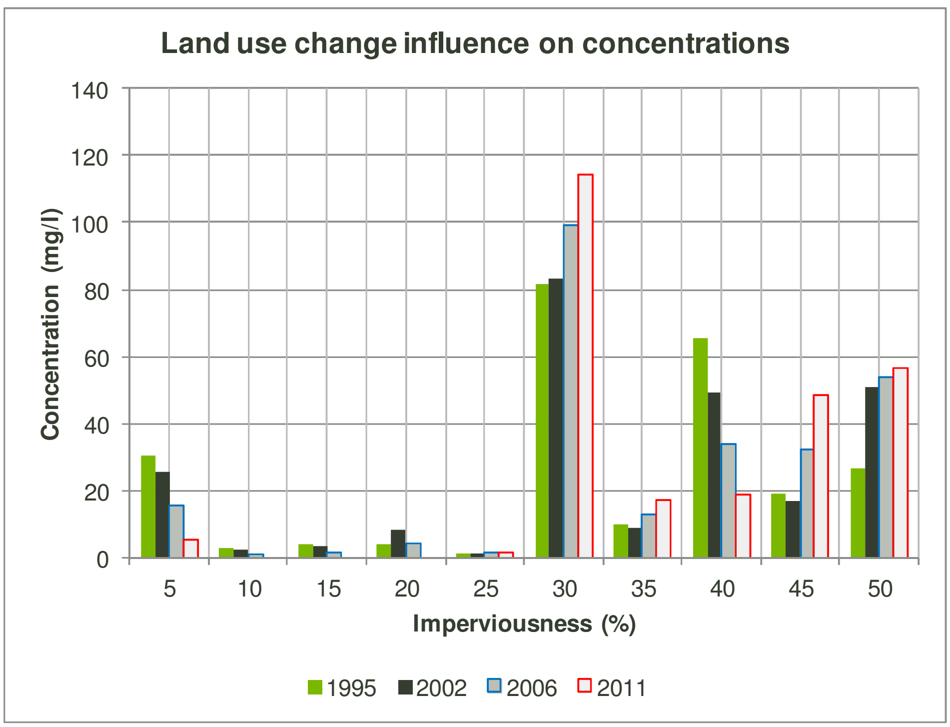

Figure 35 Land use change influence on phosphate concentrations

The increase in phosphate concentrations for residential type developments (imperviousness values of 25 to 35%) is clear from 2002 onwards. The opposite is true for higher density residential developments and light commercial stands (imperviousness values of 40%). Two possible reasons appear to be the cause; the first is the increase in density (development) on existing stands to higher density townhouses, and secondly the encroachment of higher residential developments on stands earlier utilized for commercial purposes. This brings about an increase in concentrations for imperviousness values greater than 40%. The graph clearly indicates that there was a change in land use from low residential (including urban agriculture) to medium and high density developments. This is especially the case adjacent primary access routes in Boksburg.

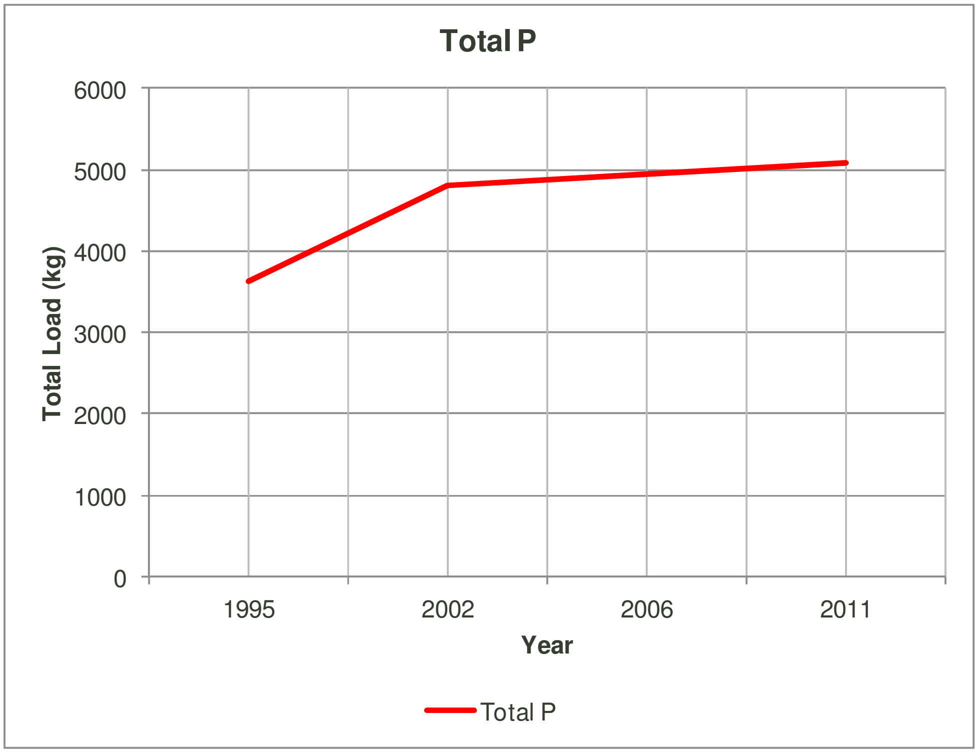

Figure 36 Total phosphate loadings for the simulation period (annual values)

Figure 36 illustrates that the phosphate loadings followed the same trend observed with the soil loss models (Figure 32 and Figure 14). The steep increase from 1995 to 2002 is a result of the observed increase in residential developments in the area. From 2006 a stabilisation is observed which might be as a result of the global financial crisis when expenditure in urban developments and housing declined (Johannesburg Property, 2012). A decline of up to 19% was experienced in Gauteng property prices (Johannesburg Property, 2012).

What can be concluded from the simulation is that an increased or constant rate of development results in an increase soil loss volume as well as phosphate loadings.

By managing the soil loss brought about by developments in a catchment, the phosphate loadings can be reduced. The reduction measures are discussed in the subsequent chapter.

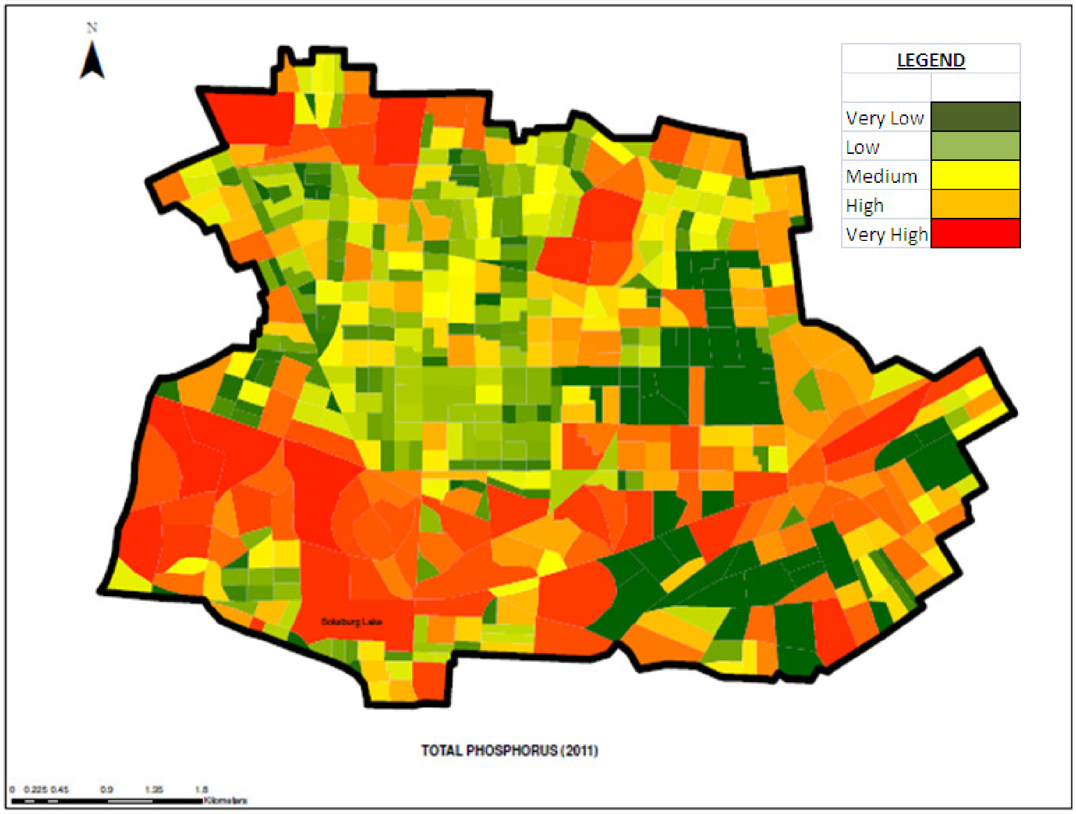

Figure 37 Total phosphorus

From Figure 37, above, it is clear that the higher concentration loadings originate from catchments under development and higher activity regions (orange colour range). Where little land use changes occurred the loadings appear to be lower (green colour range).

The simulation results of the phosphorus loading, although not within a 10% accuracy, relates to the observed loadings of 2008. By observing a similar trend as the sediment loadings, as a result of the development, it can thus be concluded that the phosphorus loadings relate to the soil loss models which was related to changes in the catchments as a result of changes in land usage (imperviousness as indicator).

CHAPTER 7: MANAGEMENT PRACTICES TO REDUCE LOADINGS

A relationship between soil erosion , concentrations/loadings of phosphorus in urban stormwater systems and the influence land use changes has on these loadings have been established in the preceding chapters. This will assist local managers to focus limited manpower and funding to important contributors.

Multiple methods to reduce soil loss and erosion rates in urban areas have been investigated and form part of local authority guidelines. This is especially the case for Australian authorities. Some of these measures will be discussed in the following section.

At a minimum, any erosion prevention plan must:

- Identify actual and potential sources. This has been done in the previous chapters.
- Establish practices and controls to prevent or effectively reduce pollution. This chapter will elaborate more on these.
- Describe how the selected practices and controls are appropriate. This will be elaborated upon in this chapter.
- Discuss the relation between practices and controls such that an integrated catchment-wide approach is followed
- Discuss the maintenance program. For the selected prevention/control measures

7.1 Reducing soil loss

Erosion control is more cost effective than sediment capturing (Sunshine Coast Council, 2014). This is especially the case for fine grained soils (Sunshine Coast Council, 2014). It is within these finer grained particles that the largest amount of phosphates is adsorbed.

Some of the reduction measures listed includes the following:

- Sediment Retention basins

- Lined tanks
- Filter fences
- Grass filter strips and hay bales (on-site practices for developments)
- Street sweeping

Most of the measures listed above stem from Water Sensitive Urban Design Practices (WSUDS) which aims at integrating water practices in an effort to minimize the impact of development. Unfortunately not all apply to the Boksburg area due to the historic high density of development, which has limited space, and municipal practices.

The following general recommendations can be considered in relation to the control of sediment:

- The structures (whether being a sump or basin) should be designed to minimise land/soil disturbances
- Keep sediment as close to its source as possible
- As a "rule of thumb", lower risk sites do not warrant construction of sediment basins. Where annual soil loss from an area average is less than 150 m^3 or approximately 200 tons, the construction of a basin is not feasible and can be considered unnecessary (Sunshine Coast Council, 2014).
- Ensure that adequate time is allowed for settlement (this has an inherently relation to space) of the designated particle sizes
- Ensure allowance is made for adequate capacity
- Disposal of collected sediment should not result in "secondary" loadings
- Design of the structure should ensure that runoff is not diverted from the intended flow path when structures become filled with sediment

7.1.1 Sedimentation Retention Basins (SRB)

Sedimentation basins are designed to provide sedimentation, filtration, and a measure of detention of stormwater. These facilities are designed and operated as follows:

- Runoff enters the basin; velocity of flow slows to allow suspended solids to settle.
- Discharge from the facility normally occurs through a rock gabion wall or low velocity under –flow piping into a secondary filtration basin.
- Additional sediment is removed, together with floating debris/litter and other contaminants, through filter media composed of sand or geo-fabrics
- Excessive runoff is allowed to bypass the facility and may be routed to a secondary basin. Consecutive basins are therefore recommended.
- Overflows or spillways must be provided to convey discharges in excess of the design capacity to exit the facility (e.g. 1:50-year storm runoff).

The placement of adequate sedimentation retention basins within the catchment is limited due to space requirements brought about by the historic developments and limitations in the enforcement of bulk infrastructure contribution from the Ekurhuleni Metropolitan Municipality. It would be ideal to retain runoff at the source but the practicality of having multiple basins is not always achievable.

Ekurhuleni Metropolitan Municipality (EMM) does require, as part of their bulk contribution policy, of new developments to retain runoff before discharging into the existing EMM stormwater system. This is not the case with high density residential developments and is mostly applicable to commercial developments. Mostly, these structures are aimed at reducing flood peaks and are not directly aimed at water quality practices.

Sediment retention basins are facilities aimed at reducing, by intercepting, sediment laden runoff, and thereby protecting downstream waterways from pollution. The retention is achieved by settlement of suspended sediments from stormwater flow and interception of bed load material.

The selection of a sediment retention basin as mitigation measure is dependent on many factors other than location alone. These include (Austin-Bergstrom, 2002):

- Design storm criteria. Basins should be designed to be stable in the peak flows from multiple annual recurrence intervals (ARI).
- Sediment type and particle size.

- Volume requirements
- Turbidity requirements (50 mg/l TSS - 75 NTU)
- Width to length ratio

The effective design and operation of a retention facility, from a water quality perspective, depends on nature of the soil material transported. The basin needs to take into account the settling behaviour of different soil particles. Three classifications are readily used;

- Type 1: soils that contain significant fine material (< 0.0075mm). These are considered clay material and settlement does not occur unless aided through the application of a flocculent. These soils are more dispersive.
- Type 2: coarse grained soils with less than 30% finer than 0.02 mm. because of the large amount of fine grained material (type 1) also present, these materials are considered turbid.
- Type 3: 30% or more is less than 0.02 mm and considered fine grained. These particles settle, but require more time. These materials might not respond well to flocculent treatment.

The capacity of a retention structure is dependent on the sum of two components namely; a settling zone, and sediment storage zone. Water stored in the settling zone allowing settlement. This zone is designed to capture most sediment in a nominated design rainfall event and/or specific discharge water quality.

The sediment storage zone is where deposited sediment is stored until the basin is cleaned (e.g. every three months).

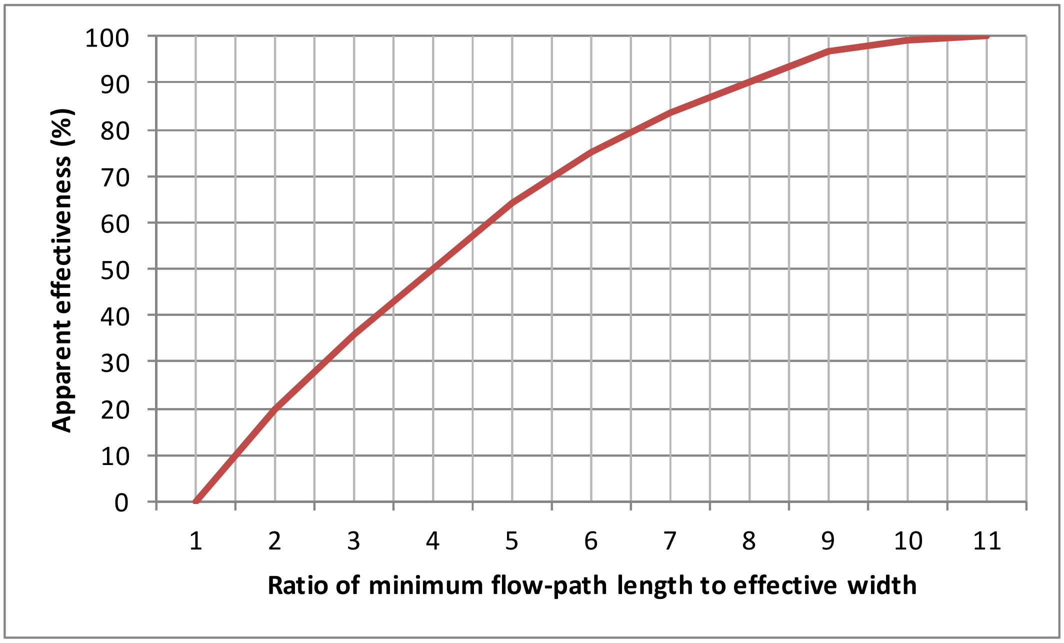

Figure 38 Apparent effectiveness of sediment retention basin (Sunshine Coast, 2014)

The effectiveness of sedimentation retention dams is dependent on the ratio of the minimum flow-path length to the effective width as illustrated in Figure 38 above from the sedimentation and erosion manual of the Sunshine Coast Council of 2014.

Six possible locations for SBR's have been identified as illustrated in Figure 39. The location of the basins was done by considering two main parameters; the contributing catchment size, and available space. This was an iterative process whereby the combined effectiveness of each simulation was compared.

The combined effectiveness of the six basins has a reduction of 92% when an effectiveness of 80% is assumed for each basin and an equal loss distribution. Obtaining an equal loss distribution is however not possible due to the available positions for the basins. A combined effectiveness of 86% is obtained using the proposed positioning. A value as high as 91.73% was obtained but required the expropriation of properties.

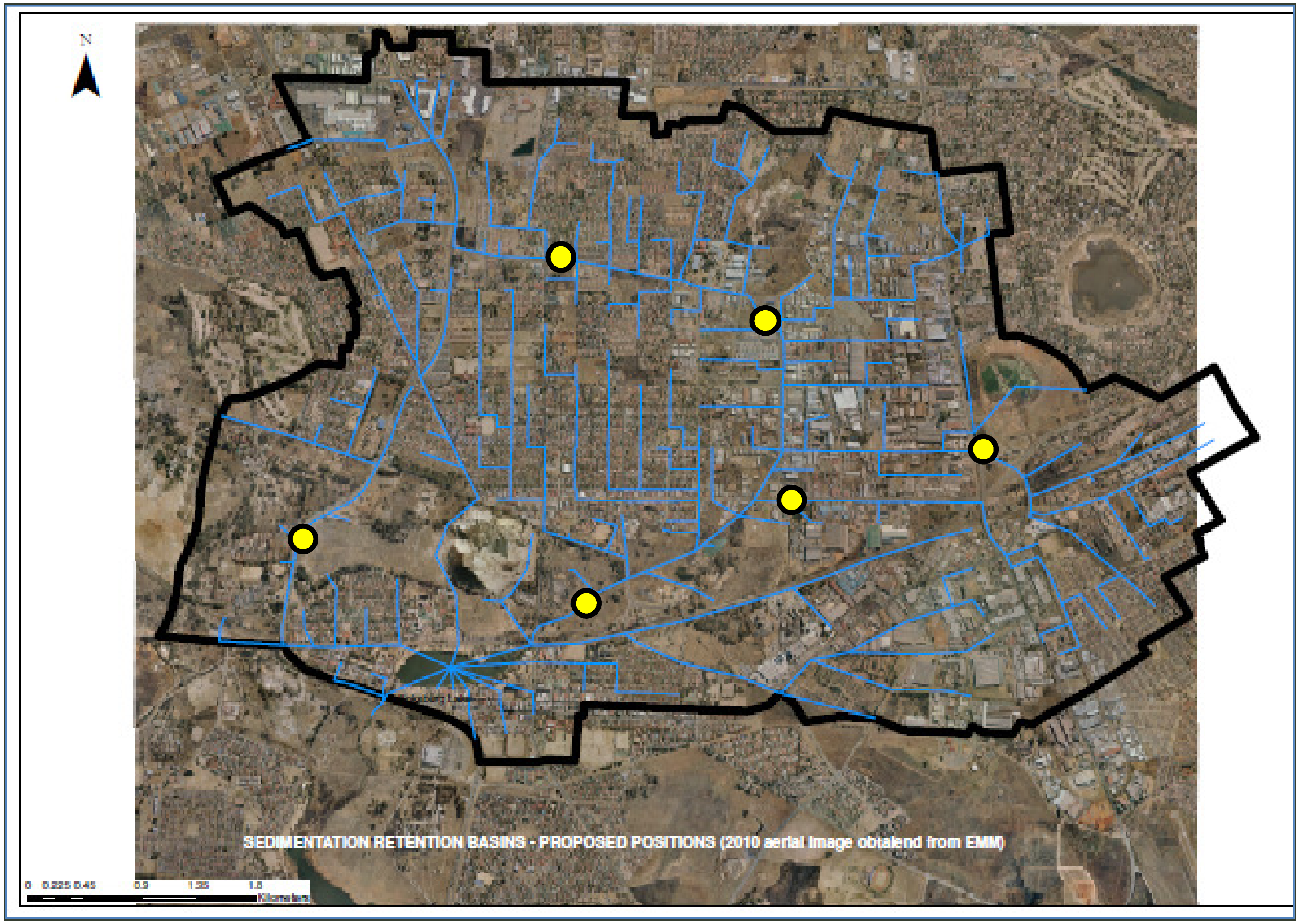

Figure 39 Proposed sedimentation retention dam positions

7.1.2 Street sweeping as reduction measure

It has been indicated in this study that nutrients are transported as sediment bound contaminants and that the concentrations of these contaminants vary with sediment particle size, with high concentrations attached to the finer particles (Walker and Wong, 1999). It was found that 60-80% phosphorus concentrations in urban drainage systems can be associated to these finer particles. By reducing the sediment on impervious surface such as streets, the phosphorus loads in the total system can be reduced.

Most particles found in street surfaces are in the fraction of sand and gravel with approximately 6% in the silt and clay soil size (Walker and Wong, 1999). The clay and silt sizes were found to contain over half the phosphorus and 25% of other pollutants as indicated in the table below.

Table 25 Percentage of street pollutants in various particles ranges (Walker and Wong, 1999)

	Particle Size (µm)					
Pollutant	**< 43**	**43-104**	**104-246**	**246-840**	**840-2000**	**>2000**
Total solids	5.9	9.7	27.8	24.6	7.6	24.4
Phosphorus	56.2	29.6	6.4	6.9	0.9	0
Toxic Metals	27.8	0	23.5	14.9	17.5	16.3

With relation to street sweeping effectiveness, the associated pollutants with these finer and mid-range soil fractions, would suggest that street sweeping needs to remove these particles in order to provide effective control. It has however been found that street sweeping is more effective for materials larger than 300 µm as illustrated in Figure 40, below.

For removal efficiencies greater than 50% particles smaller than 125 µm conventional street sweeping equipment are not suggested and new technologies are required.

Of importance with street sweeping activities is the timing sweeping. Research has shown that the time of day during which sweeping occurs affect the amount of gross pollutants entering the system (Walker and Wong, 2014). Also of importance is the recurrence of sweeping.

Figure 40 Street sweeping efficiency as fraction of particle size (Walker, et.al., 1999)

The particle distribution of the street dirt is unknown. If an average particle size of 500 µm is assumed, a street sweeping efficiency of 47% can be accepted.

If sweeping would have occurred regularly over the entire catchment, the annual soil loss volume of 11 121 m^3 would reduce to 5 894 m^3 per annum but generally street sweeping frequency is determined according to land use and the application is not as general as indicated above. The above assumption is based on the use of mechanised vacuum sweepers with sweeping frequencies of six week.

The introduction of street sweeping can be easily analysed by managers as indicated above and the cost determined. The use of mechanised sweeping in the Boksburg Lake catchment is very limited and only localised broom sweeping was observed.

7.2 Establishment of a management tool

Geographical information systems are readily used and freely available to assist in the representation and scenario analysis in all aspects of engineering. A management tool dealing with the quantification and management of soil loss, through the incorporation of efficiencies of the reduction measures discussed above, is foreseen.

7.2.1 Model integration

An integrated planning process has the potential to identify a prioritized critical path to achieve water quality objectives. It is not the aim to create a complex computational uncertainty model but rather an integrated management model which will eventually integrate the existing hydrological, litter management, proposed soil loss model with phosphorus input values.

The need for integrated management models is high within the municipal environment. These models need to provide high level yet comprehensive and reliable results to municipal managers that will enable them to make informed decisions in the day-to-day management of infrastructure. For this reason an integrated approach was followed in the formulation of the model philosophy.

The hydrological model with its key parameters (catchment size, percentage imperviousness, slope and overland flow length) forms the basis to the integration of the models. Currently the hydrological model input results provided the basis to the litter management system developed for the lake area. The same principles will be applied. This was be elaborated upon in Chapter 6.

Although not a primary aim of the project due consideration was given to a method of easily compiling the model and providing input data in a simple manner with clearly defined values.

Figure 41 below illustrates the data and product flow from the various model components of the Boksburg Lake.

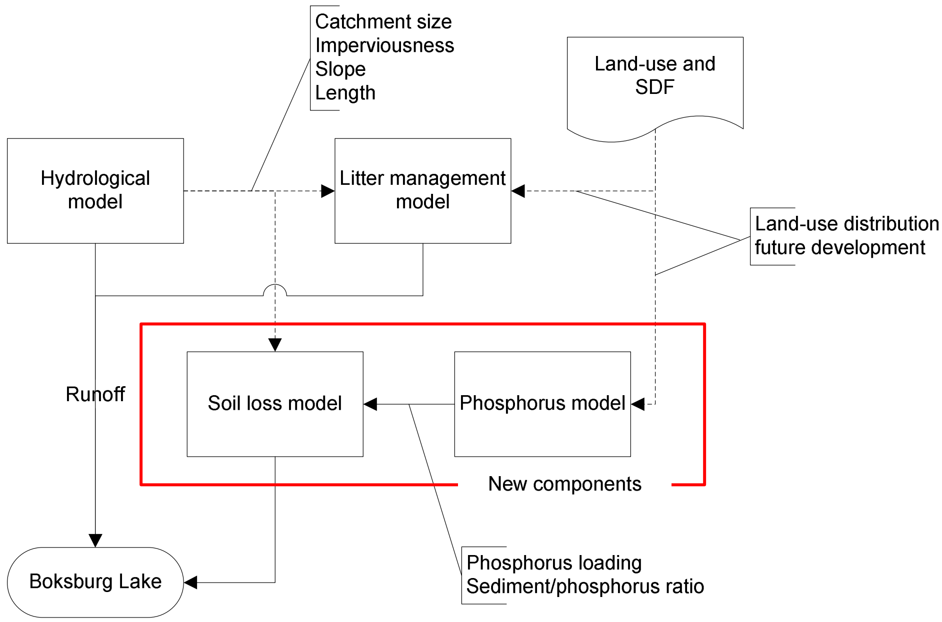

Figure 41 Simplified data flow and component integration for the Boksburg Lake master plan

CHAPTER 8: CONCLUSION

8.1 Introduction

Two models, the Universal Soil Loss Equation (USLE) and the Soil Loss Estimator of Southern Africa (SLEMSA) were used to simulate soil loss for the Boksburg Lake catchment. The simulations were aimed at investigating if current available models can be utilised to investigate the impact land-use changes (i.e. changes in imperviousness due to development within the catchment) will have on soil loss concentrations to the Boksburg Lake.

8.2 Concluding remarks

The following conclusions can be drawn from the study:

1. The models presented in the report are desktop based due to the limitations/lack in datasets and past studies of this kind. It is however recommended to validate on-site data to verify the approaches and methods used. The models presented can however be used to create management tools to assist municipal managers in making informed decision in the absence of data.
2. Many soil loss models are currently in use throughout the world as can be surmised from the literature review in chapter 2. Not all are suitable for urban conditions and are primarily utilised for agricultural studies. Many of these models are empirically based with little spatial distribution and used for long term estimation. Few physically based models are in use with regards to urban modelling and even less can be generalised to other regions of the world other than the study area.
3. Models, aimed at estimating phosphorus concentrations, are few in use. Most are aimed at eutrophication mass balancing for large reservoirs and do not consider localised urban lakes. Even less of these models can be generalised to a wider project area.
4. The quantification of sewer discharge into the system, and hence phosphorus loading could not be verified through the study and it is doubted that realistically it could. It is recommended that an in depth study be conducted to

verify this. It was assumed that although exposure, it was for relatively short durations and will be “washed out” the impoundment.

5. The use of soil loss models is dependent on good and available datasets. This includes information on the rainfall, topography, cover management practices and the soil characteristics. This proved to be a limiting factor in the selection of the models. A model utilizing daily rainfall data, although very favourable from an academic perspective, would have little interest to municipal managers having to deal with limited funding, personnel and resources as the level of complexity is considered too high for the level answer. SLEMSA and USLE were selected as they are easy to understand and apply, have simple parameters and have been used throughout Africa and Southern Africa.

6. The use of the models is also dependent on the use and application of calibrated information. Substantial studies must be conducted to verify the application of these models in urban conditions. The catchment size may have been too large with too varying catchment conditions and the model is therefore very indicative. It still indicates that such models can be used.

7. Direct application of the models (baseline) yielded losses 71.6% and 99.6% higher than the measured sediment volume of 155 485 m^3 which accumulated over the period from 1995/96 to 2011. Sediment Delivery Rations using drainage area approaches were applied to the baseline and multi-year models. Application of the Vanoni SDR equation yielded results within 12.8% and 30.8% for USLE and SLEMSA, respectively. These were not considered to be accurate enough as values fell outside the 15% confidence level.

8. Application of Effective contribution and 50% SDR factors yielded results within 3.46% and -0.2% for SLEMSA and results within -14.42% and -14.19% for USLE when applied to the baseline models. Although the SLEMSA results are found to be within the confidence level, both factors are not generally accepted approaches to SDR calculations.

9. The comparison of results between the two models (baseline and multi-year) indicates that differences in concentrations are high although a correlation can be drawn between the models. SLEMSA results were on average higher than USLE.

10. Multiple scenarios were run applying different Sediment Delivery Ratios for both a base model and annual models. The baseline models, using a linear decrease from 2011 to 1995/6, yielded comparable results to the multi-year model.

11. SLEMSA and USLE showed different degrees of sensitivity to their input variables. Both methods are sensitive to crop/cover management practices (SI values of 1.4 and 0.88, respectively), soil erodibility, and topographical changes (SI values of 1.32 and 0.89, respectively). USLE is less sensitive to erosivity. Of the above, changes in erodibility had the biggest influence. In an instance a 20% increase resulted in a 25% decrease.

12. The study area, 29.43 km^2 in size, yielded a total runoff volume of 8.23 Mm^3. On average the dam would be filled 21 times per annum or every 17 days. Applying an observed total phosphorus concentration of 0.864 mg/l to each catchment's runoff, a total load of 8 187 kg should be expected.

13. It is however not clear from the phosphorus analysis, due to the lack of available information, what the division is between ortho-and adsorbed phosphates. This can only be verified through further monitoring and sampling.

14. It was observed that a correlation exist between changes in land-use, soil loss and total phosphorus loading.

15. Two reduction measures were investigated and included in the management tool. With a street sweeping efficiency of 47%, the totals soil loss can be reduced from 11 121 m^3 to 5 894 m^3 and the total phosphorus concentration from 8 187 kg to 4 339 kg per annum. Six sites have been identified for sedimentation retention basins. The combined efficiencies of the basins result in an estimated reduction of 86% of the annual losses.

16. It can be concluded that both SLEMSA and USLE, applying the Vanoni SDR equation, can be applied to urban catchments with high levels of accuracy. USLE is however preferred for this study and was used for the development of a management tool.

8.3 Generalisation of the model

The model can be expanded to the broader regions of the Ekurhuleni metropolitan municipality as the catchment characteristics, rainfall patterns and land use changes are very similar. This will substantiate the model and calibration method due to the use of empirical models which must be used with caution outside the environments for which it was developed. It is also the impression of the author that very similar problems are experienced in surrounding lakes following discussions with Ekurhuleni Metropolitan Municipality officials.

8.4 Limitations and shortcomings of the study

The study has limitation with regards to existing data set. More soil analysis is required on both the soil characterization of the area and analysis of the sediment in the Boksburg Lake. Future studies should focus in obtaining more up to date and relevant data. The models used are also empirical and should be used under caution. Even though adopted for Southern African conditions the use in urban environments are not fully investigated and additional studies are required to substantiate the generalisation of the results to surrounding areas.

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Appendix A: Proximity of Weather stations

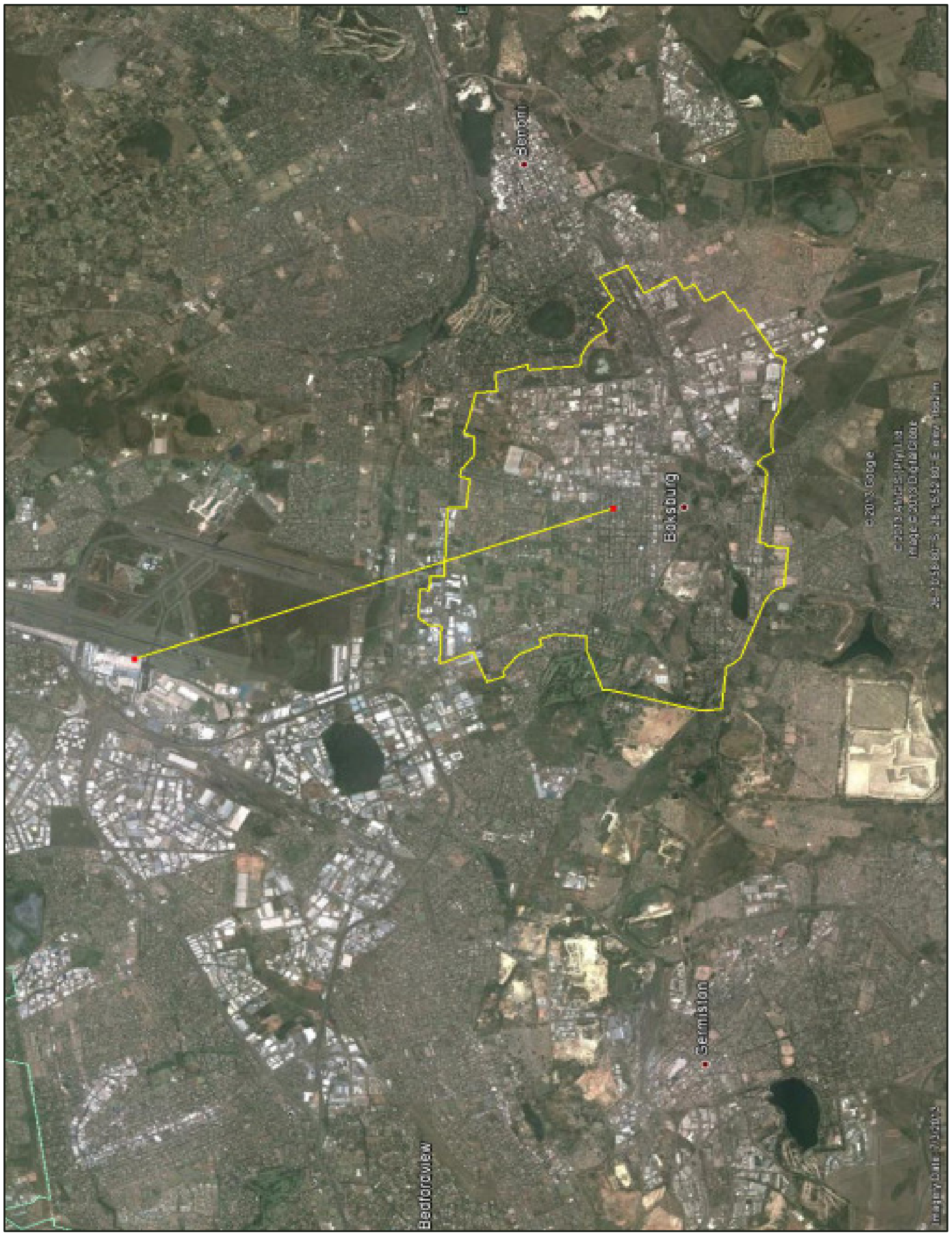

Figure 42. Proximity of catchment to OR Tambo International Airport (< 10 km)

Appendix B: Geological and Soil Maps

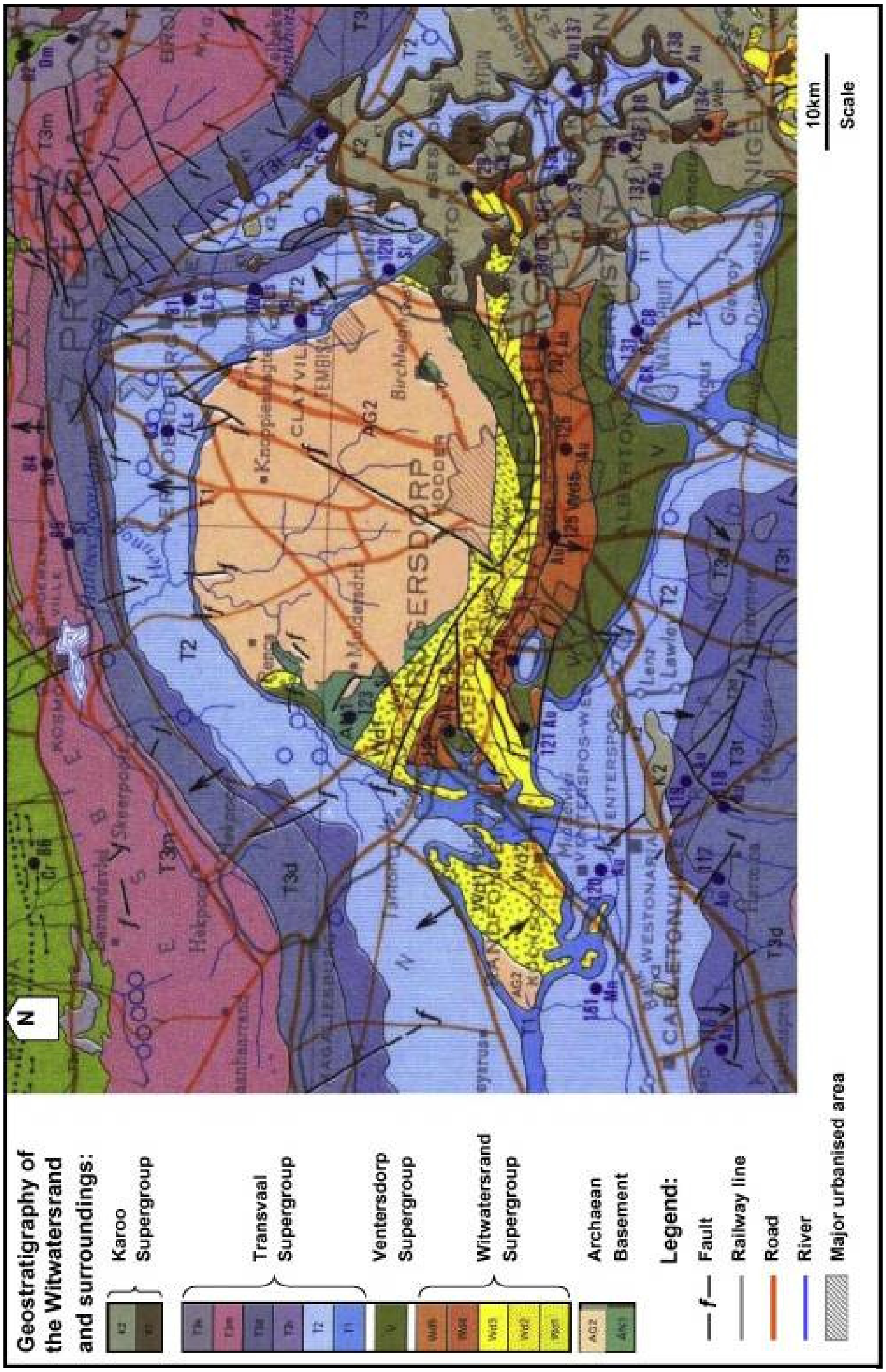

Figure 43 1: 250 000 Geological Map (EAST RAND)

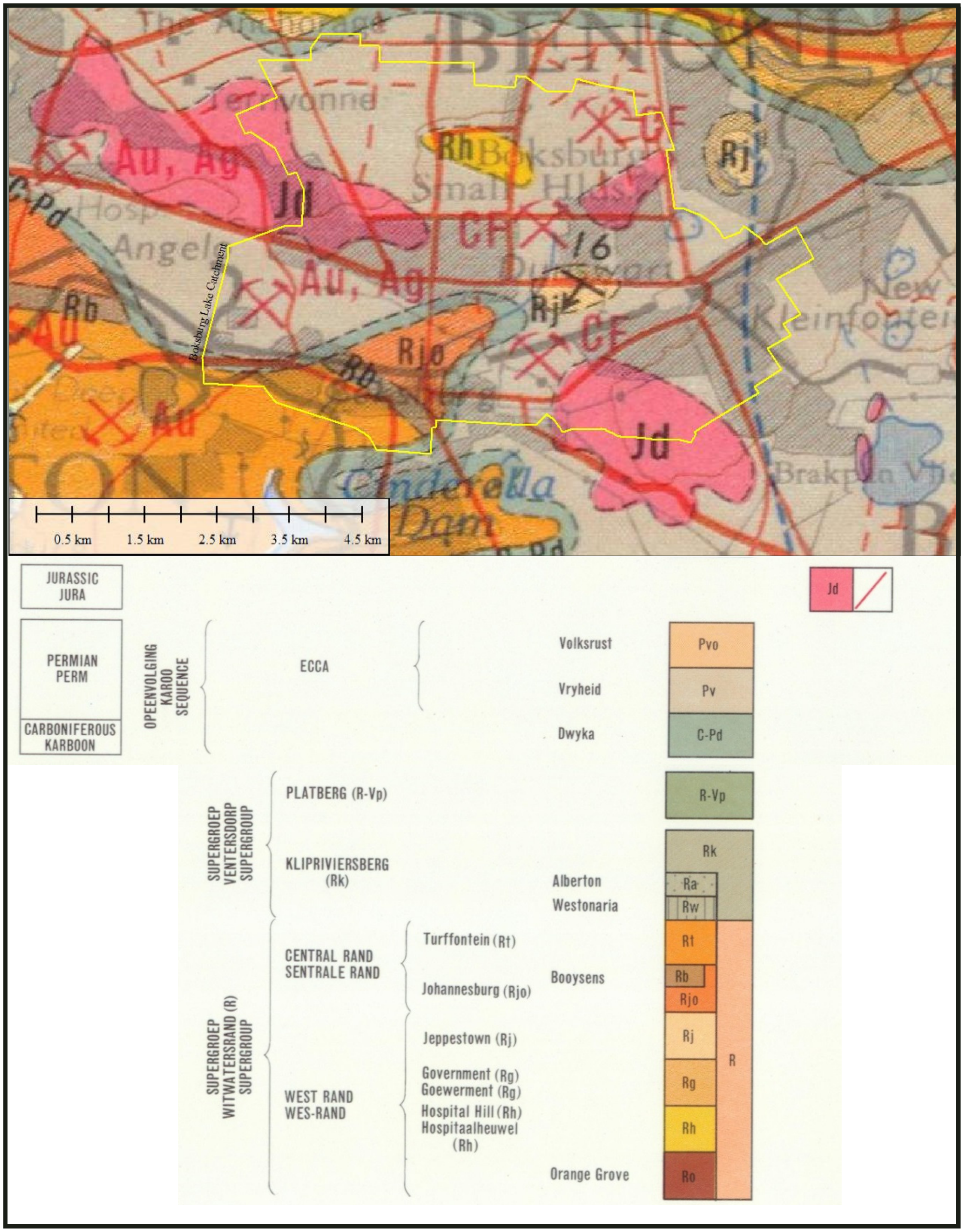

Figure 44 Geological Map of the site area in the Boksburg Lake catchment (Geological Survey, 1986)

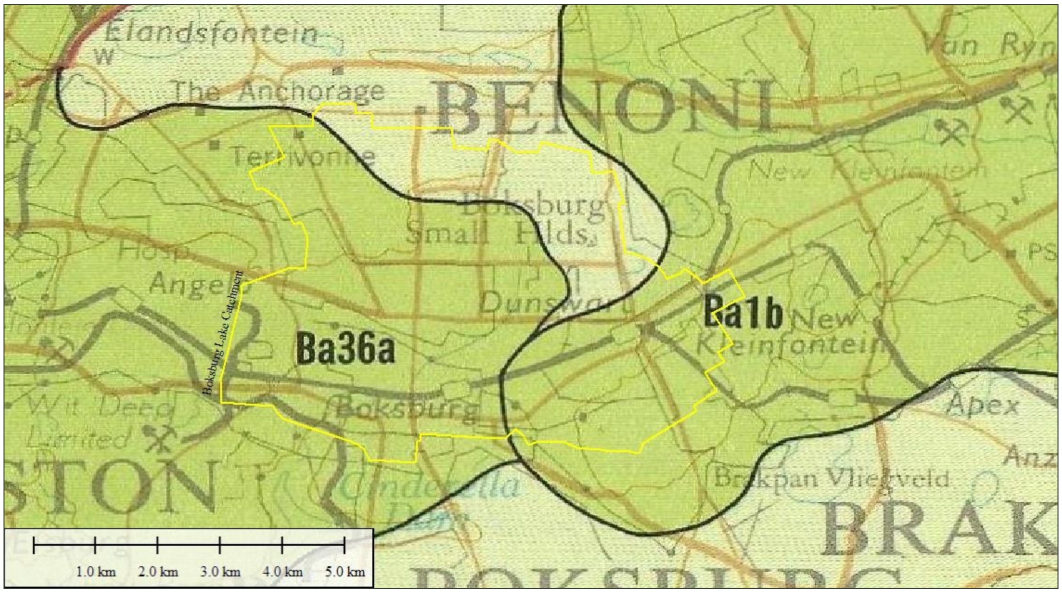

Figure 45 Land Type Map of the site area in the Boksburg Lake catchment (Soil and Irrigation Research Institute, 1985).

Appendix C: Land-use Changes (2003 – 2012)

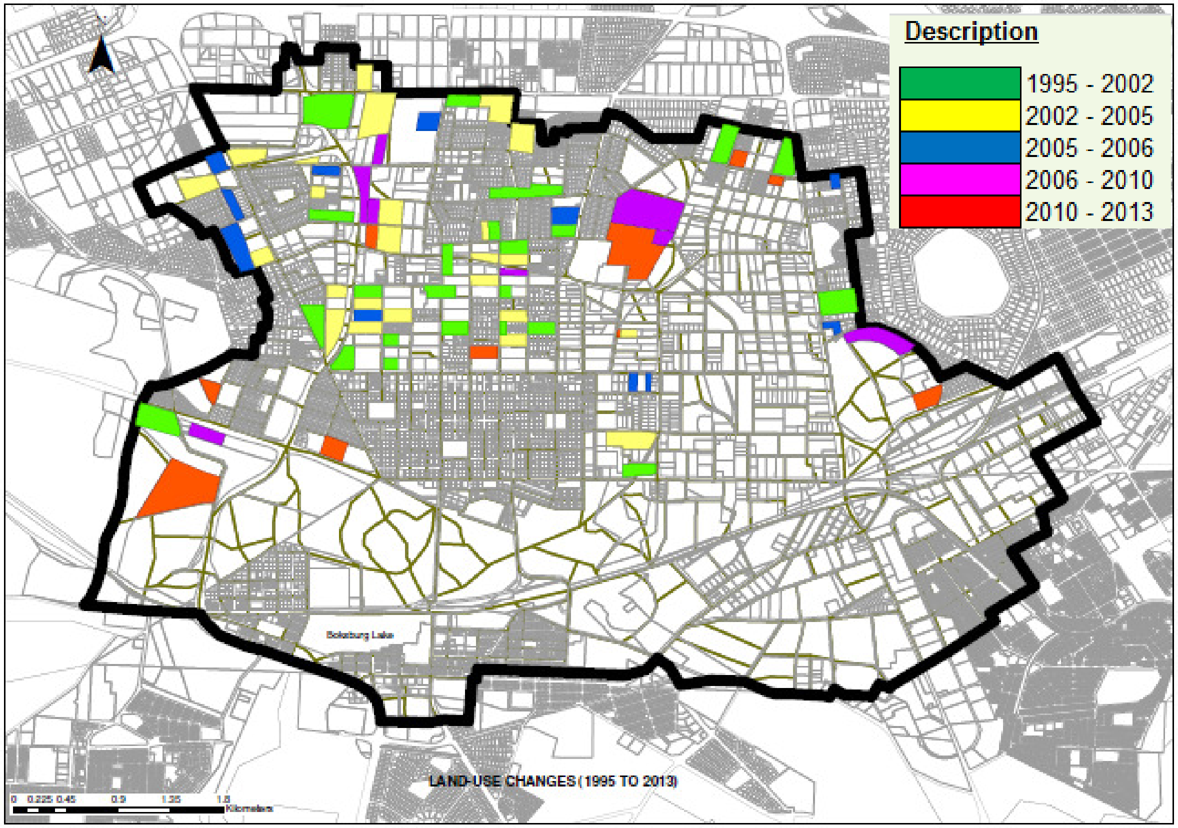

Figure 46 to Developments from 1996 to 2013

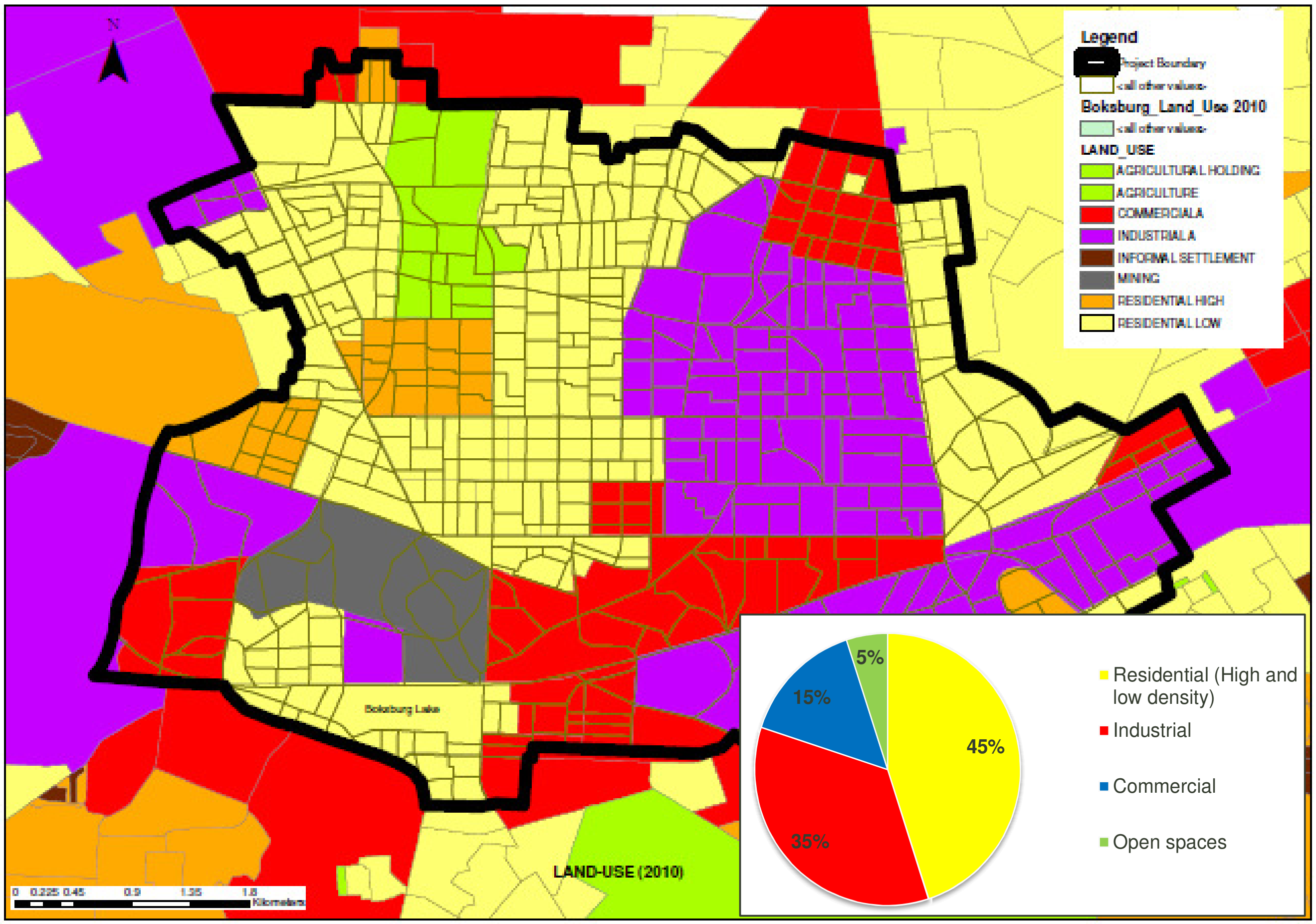

Figure 47 Land use as per 5-year spatial development plan of 2010

Appendix D: PCSWMM Model, Input data and results

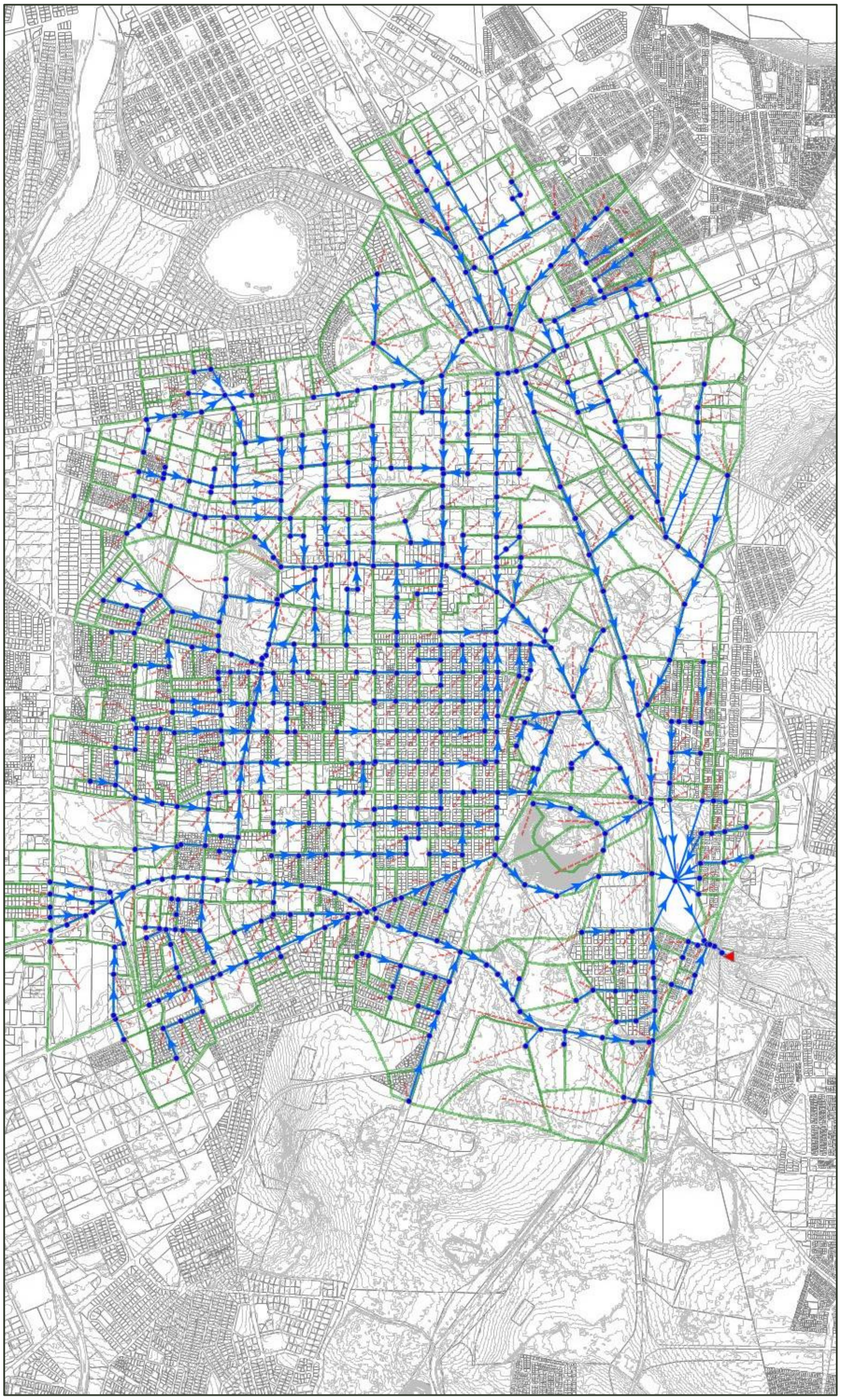

Figure 48 PCSWMM model (hydrological model – section 4.13)

Appendix E: Summary of model evaluation

Evaluation Criteria		Prediction Method										
		USLE	SLEMSA	CORINE	RUSLE	MUSLE	ACRU	CREAMS	EUROSEM	LISEM	Erosion2D/3D	WEPP
Erosion Prediction	Soil Loss	X	X	X	X			X			X	X
	Sediment Yield					X	X	X	X	X	X	X
Type of model	Empirical soil loss	X	X	X								
	Conceptual soil loss				X							
	Empirical sediment runoff					X	X					
	Physical/process							X	X	X	X	X
Prediction purpose	Soil loss	X	X	X	X						X*	X
	Single event								X	X	X	
	Daily sediment yield					X	X				X*	X
	Annual sediment yield					X	X				X*	X
	Non-point source pollution							X			X*	X
Applicable area	Plot-field sized areas	X	X		X		X				X	X
	Basin sized catchments					X						
	Field/small sized catchments			X			X	X	X		X	X
Type of erosion simulated	Inter-Rill	X	X	X	X	X		X	X	X	X*	X
	Rill	X	X	X	X	X		X	X	X	X*	X
	Gully							X			X*	X
	Streambank							X				
Type of erosion process simulated	Detachment	X	X	X	X	X	X	X			X*	X
	Transport by rainfall impact	X	X	X	X						X*	X
	Transport:Overland flow	X	X	X	X	X	X	X			X*	X
	Transport: Runoff					X	X	X	X	X		
	Transport: Stream flow						X			X	X*	X
Factors	R - Rainfall erosivity	X		X	X		X	X			X*	X
	K - soil erodibility	X	X	X	X	X	X				X*	X
	Ki - inter rill soil erodibility							X				
	Kr - rill soil erodibility							X			X*	X
	LS - Slope factors/topography	X	X	X	X	X	X	X			X*	X
	C - Cover	X	X	X	X	X	X	X			X*	X
	P - Management practices	X	X	X	X	X	X	X			X*	X
	PSER - potential erosion risk			X								
	PACT - Actual erosion risk			X								
	Q - discharge					X	X	X			X*	X
	Qp - discharge per meter					X	X	X			X*	X
Applied in SA	Regular/often	X			X		X					
	limited		X					X				
	Not applied/Never			X		X			X	X	X	X
Complexity	Easy	X	X	X	X							
	Complex					X	X	X	X	X	X	X

X* - based on similar model (WEPP)

Figure 49 Assessment of soil erosion models

Appendix F: Photos

Figure 50 Litter on Boksburg Lake

Figure 51 Litter and Silt at inlet to Boksburg Lake directly downstream from the Railway Culvert discharging into the lake

Figure 52 Concentration of runoff through mining site boundary wall. Looking North West from Trichardt Street

Figure 53 Runoff from mining site. Looking south towards Boksburg lake. Trichardt Street running to the left of the image

Figure 54 Sedimentation in the Boksburg channel directly upstream from the Boksburg Lake (Trichardt Street Bridge in background)