COMPLEX, DETERMINISTIC HYDROLOGICAL MODELLING TOWARDS DECISION SUPPORT FOR URBAN CATCHMENT MANAGEMENT

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DECLARATION OF AUTHENTICITY

I, the undersigned, hereby declare that the work contained in this thesis is my own original work, and that I have not previously in its entirety or in part submitted it at any university for a degree.

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ABSTRACT

Historically, urban water resources have too often been managed without recognition that the flow in a river integrates many landscape and biological features. This has often resulted in the elimination of natural processes and their replacement by man-made streamlined structures with the effects of increased urbanisation being primarily addressed from an engineering and economics point of view to the detriment of environmental and social issues.

Catchment Management, as legislated in the Water Act, No. 36 of 1998, is a management approach to address the negative consequences of an urban stormwater design philosophy restricted to flood restriction. It is a systems approach that integrates engineering and scientific skills, socio-economic concerns, and environmental constraints within a new multi-disciplinary decision-making process that recognises the different components of the hydrological and aquatic cycles are linked, and each component is affected by changes in every other component.

In order to make effective management decisions, catchment managers require tools to provide reliable information about the performance of alternative arrangements of stormwater management facilities and to quantify the effects of possible management decisions on the water environment. A deterministic hydrological model is such a tool, which provides the link between the conceptual understanding of the physical catchment characteristics and the empirical quantification of the hydrological, water quality and ecological response.

In order to provide effective computer based decision support, the hydrological model must be part of an integrated software application in which a collection of data manipulation, analysis, modelling and interpretation tools, including GIS, can be efficiently used together to manage a large potion of the overall decision process. This decision support system must have a simple and intuitive user interface able to produce easily interpreted output. It must have powerful graphical presentation capabilities promoting effective communication and be designed to solve ill-structured problems by flexibly combining statistical analysis, models and data.

The Great Lotus River canal, situated on the Cape Flats, Cape Town, has been designed and controlled through extensive canalisation and the construction of detention pond facilities to avoid the flooding of urban areas of the catchment. This approach has resulted in these channels becoming stormwater drains, transporting waste and nutrients in dissolved and particulate forms, and reducing their assimilatory capacity for water quality improvement.

In order to investigate the use of hydrological modelling in decision support for Catchment Management, the semi-distributed, physically based model, SWMM, was applied to the Great Lotus River canal. SWMM consists of a number of independent modules allowing the hydrological and hydraulic simulations of urban catchments and their conveyance networks on an event or continuous basis.

In order to ease the application of the Fortran based SWMM model, the GUI, PCSWMM98, was developed by Computational Hydraulics Inc (CHI). This provides decision support for SWMM through large array of tools for file management, data file creation, output visualisation and interpretation, model calibration and error analysis and storm dynamic analysis thus easing any simulations with SWMM. In addition, PCSWMM was developed with a GIS functionality for graphically creating, editing and/or querying SWMM model entities and attributes, displaying these SWMM layers with background layers and dynamic model results, and exporting data to SWMM input files thus providing an interface between a GIS and SWMM.

In terms of Catchment Management, the above DSS can be used effectively to assist decision-making. This is to address tensions between the fundamental catchment management considerations of physical development, social considerations and maintaining ecological sustainability. It is at the stages of *Assessment* and *Planning* that the model can play the most significant role in providing decision support to the Catchment Management process.

Assessment in the Catchment Management process refers to the collection, storage, modelling and interpretation of catchment information. It is in this quantification, interpretation and assessment of catchment information that a hydrological model contributes to an increase in knowledge in the Catchment Management process. In identifying and quantifying, at a sufficient temporal and spatial scale, the dominant cause and effect relationships in the urban physical environment, a hydrological model is able to highlight the main contributing factors to an issue. This is used in the *Planning* stage of the Catchment Management process and when combining these contributing factors with assessments of the socio-economic and administrative environments, enables the prioritisation of the principal issues requiring attention in a Catchment Management Strategy.

It is possible to link the multiple decision-making requirements of Catchment Management with the abilities of a hydrological model to provide information on these requirements in a conceptual framework. This framework consists of the fundamental catchment considerations of Physical Development, Environmental Management and Social Development and resolves these considerations into the various management issues associated with each consideration as well as its management solution. The management solutions are linked to the model through formulating the solution in terms of the model parameters and perturbing the affected parameters in ways to simulate the management solution. This results in model output and graphical interpretation of the effects of the suggested management solution. A comparison between the simulated effects of each management solution allows the Catchment Management body to identify optimal management solutions for the various management issues.

The present model of the Great Lotus River catchment is sufficient to simulate the overland and subsurface flows from individual parts of the catchment and to route these flows and associated pollutant loadings to the catchment outlet. At its present level of complexity, the finely discretised model subcatchment and conveyance network provides decision support for Catchment Management through the simulation, at a pre-feasibility stage, of various Catchment Management issues and their proposed solutions.

Given more detailed canal and drainage network dimensions and water quality data, it is possible for the model to incorporate hydraulic calculation routines to assess the implications of alternative river rehabilitation techniques and waste management strategies. This would allow greater capability in assessing the role of the various BMPs in ameliorating stormwater impacts and pollutant loading. In addition, a detailed level survey of the stormwater pipe and canal network could result in hydrological modelling being utilised to identify critical areas where stormwater upgrading would be necessary.

In order to facilitate future complex, finely discretised catchment hydrological models, it is imperative that complete and detailed drainage patterns and stormwater network characteristics are available. In addition, to minimise model generation costs and time of model setup, this spatially representative data must be captured in a GIS for rapid inclusion into the model. Furthermore, complete spatially representative precipitation datasets are necessary to ensure that model error is reduced. These two issues of available spatial data and comprehensive precipitation records are crucial for the generated models to function as effective decision support systems for Catchment Management.

SAMEVATTING

Histories is stedelike waterbronne te dikwels bestuur sonder inagneming dat die vloei van die rivier baie landskap- en biologiese kenmerke insluit. Dit het dikwels daartoe gelei dat natuurlike prosesse uitgeskakel is en vervang is deur mensgemaakte, stroombelynde strukture waarvan die effek van toenemende verstedeliking hoofsaaklik aangespreek word vanuit 'n ingenieurs- en ekonomiese oogpunt tot nadeel van omgewings- en sosiale kwessies.

Opvangsgebiedsbestuur, soos bepaal deur die Waterwet, Wet 36 van 1998, is 'n bestuursbenadering om die negatiewe gevolge van 'n stedelike stormwaterontwerpfilosofie wat beperk is tot vloedbeperking aan te spreek. Dit is 'n stelselbenadering wat ingenieurs- en wetenskaplike vaardighede, sosio-ekonomiese probleme en omgewingsbeperkings integreer in 'n nuwe multidissiplinêre besluitnemingsproses wat erkenning daaraan gee dat die verskillende komponente van die hidrologiese en watersiklusse verbind is, en elke komponent beïnvloed word deur veranderings in elke ander komponent.

Om doeltreffende bestuursbesluite te neem, benodig opvangsgebiedsbestuur die hulpmiddels om betroubare inligting oor die prestasie van alternatiewe moontlikhede vir stormwaterbestuurfasiliteite en om die effek van moontlike bestuursbesluite op die wateromgewing te kwantifiseer. 'n Deterministiese hidrologiese model is so 'n hulpmiddel wat die skakel daarstel tussen die konseptuele begrip van die fisiese opvangsgebiedskenmerke en die empiriese kwantifisering van die water-, waterkwaliteit- en ekologiese reaksie.

Om doeltreffende rekenaarbesluitnemingsteun te verskaf, moet die hidrologiese model deel wees van 'n geïntegreerde sagteware-aanwending waarin 'n versameling datamanipulasie-, analise-, modellerings- en interpreteringshulpmiddels, insluitend GIS, doeltreffend saam gebruik kan word om 'n groot deel van die algehele besluitnemingsproses te bestuur. Hierdie besluitnemingsteunstelsel moet 'n eenvoudige en intuïtiewe gebruikersvlak hê wat in staat is om maklik interpreteerbare uitsette te lewer. Dit moet goeie grafiese voorleggingsvermoëns hê wat doeltreffende kommunikasie vergemaklik en ontwerp wees om swak gestruktureerde probleme deur die buigsame samevoeging van statistiese analise, modelle en data op te los.

Die Groot Lotusrivierkanaal op die Kaapse Vlakte, Kaapstad is ontwerp en word beheer deur uitgebreide kanalisasie en die konstruksie van detensiedamfasiliteite om die oorstroming van stedelike opvangsgebiede te vermy. Hierdie benadering het daartoe gelei dat hierdie kanale stormwaterafvoerpype geword het wat afval en nutriënte in opgelosde en partikelvorm vervoer en hulle assimilasievermoë vir die verbetering van waterkwaliteit verminder.

Om die gebruik van hidrologiese modelle in besluitnemingsteun vir Opvangsgebiedsbestuur te ondersoek, is die semi-verspreide, fisiesgebaseerde model, SWMM, op die Groot Lotusrivierkanaal toegepas. SWMM bestaan uit 'n aantal onafhanklike modules wat die hidrologiese en hidroulika simulasies van stedelike opvangsgebiede en hulle vervoernetwerke per geleentheid of deurlopend monitor.

Om die aanwending van die Fortran gebaseerde SWMM model te vergemaklik is die GUI, PCSWMM98 deur Computational Hydraulics Inc (CHI) ontwikkel. Dit verskaf besluitnemingsteun vir SWMM deur 'n groot aantal hulpmiddels vir lêerbestuur, die skep van datalêers, uitsetvisualisering en interpretasie, modelkalibrasie, foutanalise en stormdinamika-analise om enige simulasies met SWMM te vergemaklik. Daarby is PCSWMM ontwikkel met 'n GIS funksionaliteit vir die grafiese daarstelling, redigering en/of navraagfunksie van SWMM model entiteite en kenmerke, wat hierdie SWMM vlakke met agtergrondvlakke en dinamiese modelresultate vertoon en data in SWMM insetlêers plaas en op daardie manier 'n koppelvlak tussen 'n GIS en SWMM verskaf.

Volgens Opvangsgebiedsbestuur kan bogenoemde DSS doeltreffend gebruik word in besluitneming. Dit is om die spanning tussen fundamentele opvangsgebiedsbestuursoorwegings van fisiese ontwikkeling, sosiale oorwegings en ekologiese volhoubaarheid aan te spreek. Dis in die stadiums van *Waardebepaling* en *Beplanning* wat die model die belangrikste rol kan vervul in die verskaffing van besluitnemingsteun vir die Opvangsgebiedsbestuursproses.

Waardebepaling in die Opvangsgebiedbestuursproses verwys na die versameling, berging, modellering en interpretasie van opvangsgebiedsinligting. Deur hierdie kwantifisering, interpretasie en waardebepaling van opvangsgebiedsinligting dra 'n hidrologiese model by tot 'n verhoging in kennis in die Opvangsgebiedsbestuur. Deur die identifisering en kwantifisering, op 'n ruim genoeg tydelike en ruimtelike skaal, van die dominante oorsaak en gevolg verhoudings in die stedelike fisiese omgewing, kan die hidrologiese model die hoof bydraende faktore uitlig. Dit word gebruik in die *Beplanningsfase* van die Opvangsgebiedproses en wanneer hierdie bydraende faktore by die waardebepaling van die sosio-ekonomiese en administratiewe omgewings saamgevoeg word, maak dit moontlik om die belangrike kwessies wat aandag behoort te kry in 'n Opvangsgebiedsbestuurstrategie in volgorde van voorrang te plaas.

Dit is moontlik om die verskeidenheid besluitnemingsvereistes van Opvangsgebiedsbestuur met die vermoëns van 'n hidrologiese model te koppel om inligting oor hierdie vereistes in 'n konseptuele raamwerk te verskaf. Die raamwerk bestaan uit die fundamentele opvangsgebiedsoorwegings van Fisiese Ontwikkeling, Omgewingsbestuur en Sosiale Ontwikkeling en los hierdie oorwegings op in die verskillende bestuursaangeleenthede wat met elke oorweging en die bestuuroplossing geassosieer word. Die bestuursoplossings word aan die model gekoppel deur die formulering van die oplossing volgens die modelparameters en versteuring van die relevante parameters op sekere manier om die bestuursoplossing te simuleer. Dit lei tot modeluitset en grafiese interpretasie van die effek van die voorgestelde bestuursoplossing. 'n Vergelyking tussen die gesimuleerde effek van elke bestuursoplossing laat die Opvangsgebiedsbestuursliggaam toe om die optimale bestuursoplossings vir die verskeie bestuursaangeleenthede te identifiseer.

Die huidige model van die Groot Lotusrivieropvang is genoegsaam om die bo- en ondergrondse vloei vanaf individuele dele van die opvangsgebied te simuleer en om die watervloei en geassosieerde besoedelstofladings na die opvangsgebiedsuitlaatplek te lei. Op sy huidige vlak van kompleksiteit verskaf die fyn gediskretiseerde model subopvangsgebied en vervoernetwerk besluitnemingsteun aan Opvangsgebiedsbestuur deur die simulasie, teen 'n voor-lewensvatbaarheidstudie, van verskeie opvangsgebiedsbestuurkwessies en die voorgestelde oplossings.

Indien meer gedetailleerde kanaal- en dreineringsnetwerkdimensies- en waterkwaliteitdata ingevoer word, is dit moontlik vir die model om hidroulikaberekeningsroetines te inkorporeer om die implikasies van alternatiewe rivierrehabilitasietegnieke en afvalbestuurstrategieë te beoordeel. Dit sou die vermoë verbeter om die waarde van die verskeie BMPs te bepaal om die impak van stormwater en besoedelstoflading te versag. Daarby kan 'n gedetailleerde vlakopname van die stormwaterpyp en –kanaalnetwerk daartoe lei dat hidrologiese modelle gebruik kan word om kritieke areas te identifiseer waar stormwateropgradering nodig is.

Om toekomstige komplekse, gediskretiseerde opvangsgebiedshidrologiese modelle te verbeter, is dit noodsaaklik dat volledige en gedetailleerde dreineringspatrone en stormwaternetwerkkenmerke beskikbaar is. Om die model-ontwikkelingskoste en tyd bestee aan die opstel van 'n model te minimiseer, moet hierdie ruimtelik verteenwoordigende data ingelees word in 'n GIS vir vinnige insluiting in die model. Daarbenewens is volledige, ruimtelik verteenwoordigende presipitasie datastelle nodig om te verseker dat modelfoute verminder word. Hierdie twee kwessies van beskikbare ruimtelike data en omvattende presipitasierekords is van die uiterste belang sodat die gegenereerde modelle as doeltreffende besluitnemingsteun vir Opvangsgebiedsbestuur kan funksioneer.

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CHAPTER 1
INTRODUCTION

1.1 Motivation for this study

It can be viewed that, historically, the management of water resources in an urban catchment has been primarily concerned with engineering and economics without due consideration of the ecology and local community concerns. Increasing urbanisation results in the hardening of catchments through more roads, buildings, parking lots and other impervious surfaces. These surfaces have a profound impact of the hydrology by increasing the magnitude of storm peak and total runoff volume.

In order to account for these increases, a traditional engineering approach was to accept these increases and to design and construct efficient stormwater removal facilities such as concrete pipe and canal conveyance systems. The consequences of this design philosophy, aimed principally at flood management, can frequently be seen in terms of deteriorating stream water quality, degraded stream profiles and habitat and decreased in stream ecological biodiversity.

Changes in the approach to management of catchments and the water resources within these catchment, enshrined in the new National Water Act, No. 36 of 1998, have lead to an acceptance that management must now focus on the holistic needs of the river and its catchment. This is tending towards viewing the river with a multi-objective catchment management strategy with flood hazard reduction thus being seen as only one component.

This is only possible if a systems approach is followed which integrates engineering skills, socio-economic concerns, and environmental constraints within a new multi-disciplinary decision-making process through consideration of the needs and aspirations of the user, stakeholder and environmental communities.

Catchment Management, as legislated in the Water Act, No. 36 of 1998, is such an approach that recognises that the different components of the hydrological and aquatic cycles are linked, and each component is affected by changes in every other component.

Given that management decisions now involve larger areas of interest, multiple spatial and temporal scales, cross many different organisational hierarchies and involve diverse groups of stakeholders, this results in urban water resources being managed with ever-increasing number of competing objectives in mind. In order to balance theses objectives and select optimal management alternatives, watercourse managers and stakeholders must rely on detailed, accurate catchment information and require methods of objectively quantifying responses of various resources to catchment planning scenarios.

This can be achieved through the use of hydrological modelling of the catchment at an appropriate level of complexity in spatial and temporal resolution. Hydrological modelling can be seen to provide the link between a conceptual understanding of the physical catchment and its characteristics, and the empirical quantification of the hydrological, water quality and ecological response. The aim of this research is therefore to investigate the use of hydrological modelling and how it can serve catchment managers and other decision makers in the decision making process.

1.2 Objectives of this research

The above motivations set the context for the research reported in this thesis. As discussed, the thesis focuses on the role a complex, deterministic hydrological model can play as a decision support tool for Catchment Management. This is achieved through applying one such model, the USEPA's SWMM and an associated Graphical User Interface (GUI), PCWMM98, to the multiple landuse urban catchment of the Great Lotus River.

The Great Lotus River catchment, situated on the Cape Flats, Cape Town, was the focus of a recent Water Research Commission study, "Integrated Catchment Management in an Urban Context: The Great and Little Lotus Rivers" (Grobicki *et al*., in press). From a hydrological point of view, the focus of this study was to identify the major sources of pollution in the catchment, both point and non-point sources. This was through a detailed flow gauging study and a water quality sampling programme carried out between July 1997 and October 1998. Much of data used in this research was collected during the course of this WRC study.

The objectives of the research reported here were:

- To unpack the notions of hydrological modelling and decision support systems

- To apply PCSWMM98 to the Great Lotus River catchment in order to obtain a water quantity, and to a lesser extent, water quality, simulation for the monitoring period of the above WRC study
- To assess the role of a hydrological model in providing decision support for Catchment Management through simulating various hypothetical management solutions
- To present a conceptual framework linking the multiple management and decision-making requirements of Catchment Management with the ability of a hydrological model to provide decision support for these requirements
- To assess the applicability of using SWMM and PCSWMM98 to fulfil this role.

1.3 Structure and Layout of this thesis

This thesis begins with the view that management of urban catchments requires the use of multi-disciplinary approaches linking the frequently opposing issues of environment, physical development and social considerations. Chapter 2 describes how this can be achieved through the approach of Catchment Management, which as a philosophy, a process and an implementation strategy, seeks the utilisation, and protection of water resources in an urban catchment. It is recognised that effective management decisions in the Catchment Management approach requires detailed catchment information and methods of objectively quantifying responses of various resources to catchment planning scenarios. This decision support can be facilitated through the use of complex deterministic hydrological modelling

Chapter 3 provides a background to modelling and identifies the range of modelling approaches that can be applied. This is ranging from the empirical through conceptual and deterministic to physically based modelling approaches. The various model attributes are described in addition to a generic framework for a catchment model building exercise. The role of Geographical Information Systems (GIS) and Remote Sensing (RS) in hydrological modelling is addressed together with a description as to what constitutes a decision support system (DSS).

Chapter 4 provides a background to the Great Lotus River catchment and provides a summary of the data collection methodology and results of the flow and quality monitoring period of the WRC study. It is noted that this data is limited to a short period of continuous flow data pertaining to 16 months as well as attention restricted solely to the canal itself. These limitations have implications for the credibility of the generated model of the catchment and are discussed further in Chapter 6.

Before the model of the catchment is described in Chapter 6, an overview of SWMM and PCSWMM98 is provided in Chapter 5. This includes a description of the model structure, its principal assumptions as well as a description of the GUI, PCSMWW98, and the decision support functionality that is added to SWMM through this interface.

Chapter 6 then describes the modelling methodology for generating a complex, deterministic SWMM model of the Great Lotus River catchment. This includes the sources and assumptions of the necessary input data, the SWMM modules used in the generation of this model of the catchment, as well as the results of simulation in terms of water quantity and quality. The limitation associated with the water quality modelling is discussed.

Given the many parameters associated with such a model building exercise, Chapter 6 continues with a sensitivity analysis of the generated model and thereby identifies the significant sensitive parameters for the model calibration. This calibration, undertaken to obtain a better "goodness of fit" between model output and observed flow record, is described together with an error analysis to identify areas of model uncertainty.

The various elements of the thesis are tied together in the final chapter, Chapter 7. In this chapter, the function the hydrological model can serve as decision support in Catchment Management is identified in the Catchment Management process. This is in the key stages of *Assessment* and *Planning* in the Catchment Management process. The issue of varying model complexity is investigated together with an identification of significant Best Management Practices (BMPs) that can be applied in the course of Catchment Management to address the impacts of stormwater.

As output of this thesis, a generic framework is presented linking the multiple management requirements of Catchment Management with the ability of the hydrological model to provide decision support for these requirements. This framework identifies the various management issues within the fundamental catchment considerations of physical development, environment and social considerations and links them to various solution strategies. These strategies are reformulated in terms of input requirements of the hydrological model and culminate in the model output providing information as to the effects of each strategy.

By way of example, a selection of hypothetical Catchment Management alternatives are applied to the hydrological model and the effects observed of these alternatives. Because it provides a predictive quantification of the impacts of possible management actions and/or future development scenarios, the hydrological model thus shows how water managers are able to differentiate between possible management alternatives and to select the optimal alternatives for a particular catchment based on its responses.

The thesis closes with conclusions and recommendations together with an assessment of the appropriateness of applying SWMM in this study. Recommendations for future work are made.

CHAPTER 2

CATCHMENT MANAGEMENT IN AN URBAN CONTEXT

2.1 Conceptual Overview

Historically, urban water resources have too often been managed without recognition that the flow in a river integrates the effects of many landscape and biological features (Jewitt, 1998). This has often resulted in the effects of increased urbanisation being primarily addressed from an engineering and economics point of view to the detriment of, or with neglect of, environmental and social issues.

Of particular concern is the elimination of natural processes in urban streams and their replacement by man-made streamlined structures as the degree of urbanisation increases. Increased urbanisation results in increased hardening of a catchment through, amongst others, more roads, roofs, parking lots and houses. Excess rain is no longer free to flow overland and meander along unlined channels. Instead, precipitation is washed off these hardened surfaces conveying pollution into stormwater drains that replace natural streams. The associated increase in the degree of impermeability of the catchment results in groundwater starvation through less infiltration into the underlying soil and, therefore, more surface runoff as stormwater. In addition, the low hydraulic roughness of these impermeable surfaces results in stormwater flows that peak more rapidly. Increasing urbanisation within a catchment consequently results in greater stormwater runoff volumes in addition to higher peak discharges.

These factors result in increased risk of flooding with associated loss of life, destruction of property and the need for large sums of public money to be spent on alleviating hardship through proper management (Neilson, 1997). In order to address this increased flooding, Neilson (1997) submits that the *goals* for managing this increased stormwater include:

- The protection of life and property from flood hazards
- The improvement of the quality of life of a community
- The preservation of the natural environment

These goals can be translated into o*bjectives* (Corin, 1997):

- To provide a stormwater drainage system for the convenience of the community and the protection of property from damage by the runoff from frequent storms
- To prevent loss of life and reduce damage to property by the runoff from severe storms
- To prevent land and watercourse erosion
- To protect water courses and downstream receiving waters against pollution
- To preserve natural water courses and their ecosystems
- To restore degraded urban watercourses so that both their natural eco-functioning and their amenity value is increased
- To augment the amenity value of urban water courses and their riparian zones for recreational and aesthetic benefits to urban dwellers
- To achieve the fore-going objectives at optimal total cost

As development proceeds, development densities and runoff rates increase and pressure for further intrusion into the flood plain becomes stronger. This rapid urbanisation, coupled with infilling and inappropriate floodplain development, leads to increased runoff as well as increased nutrient and heavy metal concentrations from different point and non-point sources.

The traditional solution was to accept these intrusions and, in addressing the increased runoff, to engineer an 'improved' channel cross section capable of carrying a greater flow in a smaller cross-section (Neilson, 1997). This results in the design and construction of substantial concrete lined canals, culverts and other stormwater facilities to cater for events with a defined risk of exceedance of capacity, to the detriment of water quality and aquatic ecosystems.

Unfortunately, therefore, the above stormwater objectives are frequently not all met with equal consideration. In an urban context, the protection of life and property are often considered more significant than the prevention of erosion and pollution and the protection of watercourses and their ecosystems. The "engineered" channels, designed to convey stormwater as rapidly as possible, flow more strongly during times of floods and the decreased hydraulic roughness promotes the washing away of ecosystems that might have established themselves in such channels. In addition, the impermeable channel linings prevent interactions with the underlying groundwater and diminish any self-purification abilities the channel may possess.

In terms of the research reported here, the conventional design of the Great and Little Lotus Rivers can be seen clearly in light of the above discussion. This system has been extensively designed as a conventional stormwater removal facility. Increased urbanisation of the catchment had resulted in greater surface runoff and the associated flood risk. In order to protect property from flooding the canal was modelled and designed to cater for the 1: 50 year flood (Taylor, 1994). This design included the construction of large concrete lined culverts and dissipation structures for the rapid removal of floodwaters. In order to prevent the structures from becoming excessively large and therefore expensive, detention ponds were constructed along the length of the canal to reduce outflows (Taylor, 1994).

In terms of flood control, this approach is partially successful but frequently inadequate in dealing with other needs that may arise. It can be thought of as a re-active approach looking at the river itself and concentrating mainly on the routing of flood waters without due consideration to the broader aspects of the river, particularly its ecological, recreational and aesthetic needs (Neilson, 1997) as well as water quality. A more pro-active approach is required that focuses on the holistic needs of the river and its surrounds. This is tending towards viewing the river with a multi-objective flood plain management strategy with flood hazard reduction thus being seen as only one component (Neilson, 1997).

This multi-objective approach is required, in addition, to account for the heterogeneity of urban catchment characteristics and constraints. These catchments are characterised by multiple landuse types including agricultural (as in the case of part of the Great Lotus River catchment) and varying urban landuse ranging from open areas through commercial and industrial to highly developed residential areas. Each of these landuse types has their own unique characteristics and responses to storm event conditions.

Coupled with this are the varying catchment constraints identified in the above stormwater design objectives. These constraints include balancing competing user concerns, flooding and water quality issues with maintaining the environment and the aesthetic and amenity value of a particular water resource. It is only with a multi-objective approach to management that includes the above catchment heterogeneity and multiple competing constraints, that sustainability of these diminishing urban water resources can be promoted.

The growing complexity of these urban catchments, coupled with the scale of the problems that need to be addressed, thus requires the development and implementation of new approaches by South African urban water resource managers. It is important to recognise that a water resource includes not only the water but also the structural components (morphology, riparian and instream habitats) and the biotic components of the aquatic ecosystem (DWAF, 1996). This implies that management of the resource must consider ecological principles with management related to water quantity, quality and the physical and structural characteristics of the resource so as to ensure the integrity of the biotic component of the water body (DWAF, 1996).

It is essential that these new approaches incorporate a detailed understanding of the water course, in addition to consideration of the needs and aspirations of the user and stakeholder communities. Technical, economic, social, political, legal and environmental considerations will have to be taken into account in the management process. This is only possible if a systems approach is followed which integrates engineering and scientific skills, socio-economic concerns, and environmental constraints within a new multi-disciplinary decision-making process (DWAF, 1996).

The concept of "Integrated Catchment Management" (ICM) is such an approach. The conceptual basis of ICM relies on the recognition that the different components of the hydrological and aquatic cycles are linked, and each component is affected by changes in every other component. These components, therefore, cannot be managed effectively as isolated units.

ICM can be considered simultaneously as "a philosophy, a process and an implementation strategy to achieve a sustainable balance between utilisation and protection of all *environmental resources* in a catchment and to grow a sustainable society through stakeholder, community and government partnerships in the management process." (Görgens *et al.*, 1998)

Catchment Management (CM) is a subset of the above ICM with a slightly different focus. It is also a philosophy, process and implementation strategy yet seeks a sustainable balance of *water resources* as opposed to *environmental resources*. It thus addresses the mutual dependence of water and land management at the local catchment level to ensure sustainability. This is in contrast to ICM, above, which includes management of land, air, water and ecological resources, in addition to integrated pollution and waste control strategies [1] (Görgens *et al.*, 1998).

In its widest possible sense, ICM recognizes the need to integrate all environmental, economic and social issues within a river basin (or related to a river basin) into an overall management philosophy, process and plan.

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[1] Whilst accepting the integrated nature of the interactions between components, the focus of the research reported herein, is to quantify the effects of land and water management on stream quantity and quality. We shall, therefore, focus on CM in the remaining chapters of this thesis and not ICM, per se.

This is aimed at deriving the optimum selection of sustainable benefits for future generations and the communities in the area of concern, whilst protecting the resources which are used by these communities and minimizing possible adverse social, economic and environmental consequences (DWAF, 1996).

As a system approach, it recognises that a disturbance made at any place in the system will be translated to all other parts of the system. This may be indirect and dampened due to natural resilience, or it may be more direct and increase in significance as it moves through the system.

An integrated approach to catchment management thus entails, amongst others (DWAF, 1996):

- seeing the catchment and associated water as one system and acknowledging the direct and indirect effects that actions in any one part of the system may have on any other parts
- ensuring that actions taken by a management body or agency in one part of the catchment are not taken in isolation from, or in conflict, with the actions of other agencies
- ensuring that actions are taken with due attention to the needs of other stakeholders in the catchment who may be affected, either directly of indirectly by these actions.

If this notion of a catchment as an integrated system is accepted, then management of the water resources of that catchment would entail the planning and execution of actions designed to maintain the system at a particular status (in terms of water quality, quantity etc) within a range of accepted variability and reliability (DWAF, 1996).

Early attempts at water resource management provided an understanding of the many technical, environmental and engineering-related complexities of managing water resources on a catchment scale (DWAF, 1996). They were, however, limited in that they consisted mostly of technical inventories and largely ignored public participation in the development and acceptance of water resources management plans. This resulted in negative public perceptions as to the control of these resources and as a consequence, resulted in later management strategies being more people oriented rather than dominated by the technical or bureaucratic considerations of the past (Görgens *et al.*, 1998).

Given that the impacts of many land-based activities on water resources can be dealt with at an individual stakeholder level, one of the significant principles of ICM is to promote a stakeholder approach recognising the importance of involving individual citizens in a participatory process towards decision-making for the conservation and use of water resources affecting their lives (DWAF, 1996).

This social consideration through public participation and stakeholder involvement, coupled with the ecological considerations, represents a significant paradigm shift for technical water resource managers accustomed to the traditional stormwater management approach discussed earlier. This paradigm shift towards integrated, participatory and cooperative urban water resources management is crucial and is now legislated in South Africa (WISA, 2000).

2.2 National Water Act and Catchment Management

The multi-objective, integrated approach introduced above, has been encompassed within the National Water Act, No 36 of 1998 (DWAF, 1998). In its preamble, the Act recognises the need for integrated management of all aspects of water resources and the delegation of management functions to a regional or catchment level so as to enable stakeholder participation. This in line with the "Earth Summit", the UN Conference on Environment and Development in Rio de Janeiro in 1992. This summit agreed, amongst others, that by the year 2000, all countries should have national action programmes for water management based on catchments and subcatchments and efficient water use programmes (Jewitt, 1998). This implies the integration of water resources planning with land use planning and other development and conservation activities.

ICM thus represents a systems approach to the management of natural resources, in particular water resources, within the bounds of a geographical unit that is based on the catchment area of a single river system. This approach allows clear segmentation of river systems into logical or functional management units (catchments and sub-catchments) that can then be linked together into an overall management plan for an entire river basin (DWAF, 1996).

The purpose of the National Water Act is to ensure that the nation's water resources are protected, managed, developed, conserved, and controlled in ways that account for, amongst others:

- promoting the efficient, sustainable and beneficial use of water in the public interest
- facilitating social and economic development

Although there are many different definitions of sustainability, the common theme to the different definitions is that the development of a resource should be regulated so that the characteristics and integrity of this resource be protected and maintained within agreed limits (Jewitt, 1998). Given the above discussion on traditional, single-minded approaches to management, a sustainable approach would thus require that economic and engineering concerns be considered within the framework of available ecological management options and that the competing issues of societal needs and maintaining the integrity of the environment be balanced.

Five key catchment management themes, each with a strong social focus, are identified by the Act as follows: (WISA, 192000)

- public participation in the establishment of Catchment Management Agencies
- developing and sustaining catchment management structures (statutory, non-statutory and advisory)
- integrating resource and catchment management strategies with social and developmental plans and objectives
- ensuring the involvement of communities in water resource planning and in catchment management
- building institutions and systems for participatory management.

Given this emphasis on stakeholder involvement and in order to bring about the sustainable management of water resources, the Act makes provision for the establishment of suitable institutions termed Catchment Management Agencies (CMAs) for each of 19 different water management areas. These agencies have been mandated to develop and establish a Catchment Management S*trategy* (CMS) for the water resources within its water management area. This strategy, developed through cooperation and agreement from stakeholders and interested persons sets the principles by which a catchment may be managed. It includes the strategies, objectives, guidelines and procedures for the protection, management, development, conservation, and control of water resources within its area. It takes into account the geology, demography, land use, climate, vegetation and waterworks within its water management area and, furthermore, considers the needs and expectations of water users and community stakeholders. The function of a catchment management agency is thus to coordinate the related activities of water users and water management institutions within its water management area with a view towards the sustainable management of these resources.

The Catchment Management Strategy (CMS), as developed by a Catchment Management Agency, is a formal document, at a national level, requiring Ministerial approval. On a local level, the equivalent is the Catchment Management Plan (CMP). The CMP is a comprehensive set of management strategies aimed at addressing the full spectrum of management issues, pertaining to the water cycle, that exist in a catchment (Nicolson, 2000). The CMP is necessary in an urban context, as opposed to a Catchment Management Strategy, in that it is more applicable to the smaller, urban catchments and yet is detailed enough to qualify as comprehensive (Nicolson, 2000). In addition, the scale of local level Catchment Management Planning allows for meaningful interaction with the affected communities both at the input stage of plan formulation as well as at implementation. A CMP, although less formal than a CMS, will nevertheless have to take cognisance of the CMS and the National Water Resources Strategy (NWRS).

The *process* of Catchment Management follows a number of iterative stages leading to the development and implementation of the Catchment Management Plan. The various steps in the Catchment Management process can be conceptualised as follows (Görgens *et al*., 1998):

- *Initiation* – start of management process triggered by various possibilities such significant issues in the water or landuse environment
- *Assessment* – catchment studies undertaken to understand the physical and socio-economic cause-and-effect relationships affecting the water resource in the catchment, and to evaluate the administrative environment in terms of management requirements
- *Planning* – based on understandings derived from the above assessment, and with stakeholder consensus on water and land strategies, social and ecological concerns, funding and stakeholder concerns, a vision for the catchment is generated and promulgated as a Catchment Management *strategy*
- *Implementation* – Programmes of action identified and implemented to address the management strategies specified in the above *strategy*.
- *Administration* – Catchment Management Agency monitors the implementation of the strategies, screens new development proposals and maintains stakeholder involvement in the *strategy*
- *Monitor* – information pertaining to the catchment water use and catchment water health in terms of quality and quantity continuously gathered, processed, interpreted and stored for the monitoring of present strategies and screening of new strategies

- *Review and Audit* – reassess, replan and revise responsibilities, objectives and strategies based on audits to assess the success of the process

Regardless of the mechanisms that initiate the above Catchment Management process and regardless of the state of evolution of the Catchment Management Agency, the process develops through approximately similar stages in an iterative fashion (Görgens *et al.*, 1998). For sustainable management, stakeholder participation and public consultation need to form part of all the steps of this process. The various stages in the process are listed above as introduction. They are revisited in Chapter 7 in the discussion on decision support tools for Catchment Management.

As discussed earlier, historically, aspects of the system where understanding is more qualitative than quantitative, as in ecology, have largely been ignored in the decision making process. Urban water resources management, largely a prescriptive affair in the past, seeking to minimise flood damage, now recognises that management for environmental values, such as ecological biodiversity, and social and cultural values, is necessary (Jewitt, 1998). Management decisions now involve larger areas of interest, multiple spatial and temporal scales, cross many different organisational hierarchies and involve diverse groups of stakeholders. This results in urban water resources being managed with ever-increasing number of objectives in mind. To do this, managers and stakeholders must rely on up-to-date information, modelling and communication and require methods of objectively quantifying responses of various resources to catchment planning scenarios.

Water resource modelling can be used effectively for support of catchment management. Modelling provides the link between the conceptual understanding of the physical catchment characteristics and the empirical quantification of the hydrological, water quality and ecological response (Pegram *et al.*, 1997). It can thus be utilised for the evaluation and prioritisation of water management issues, including water quantity and quality, and the selection and operation of possible management techniques. Because it provides the only method of predictive quantification of the impacts of possible management actions and/or future development scenarios, it allows water managers to differentiate between possible management alternatives and to select the optimal alternatives for a particular catchment based on its responses. By providing such quantifiable responses, models thus aid objectivity in planning exercises whilst ensuring the participation of stakeholders in catchment management.

It follows that sustainable management of water resources implies the adoption, in an iterative manner, of three successive steps: (Jewitt, 1998).

1. Identification of water resources system characteristics pertaining to different problems or systems encountered (biophysical, economic, social and environmental characteristics of the system)
2. Prediction of the behaviour of the water resources system under solution scenarios for the aforementioned problems or issues.
3. Management of the water resources system

Chapter 3 expands upon the notion of modelling in support of catchment management. An overview of the various modelling approaches is provided, together with the application of new technologies, Geographical Information Systems (GIS) and Remote Sensing (RS), in setting up these models. It continues with a discussion on the need for Decision Support Tools (DSTs) and Systems (DSSs) for Catchment Management. These are tools representing the various modelling capabilities that are integrated into computer based information systems to provide decision support to managers and stakeholders.

The application of one particular hydrological model to the Great Lotus River catchment is described in Chapter 5 and 6. Chapter 5 provides a background to the model, SWMM and its GUI, PCSWMM and discusses the model structure and principal assumptions. The application to the Great Lotus River catchment is described in Chapter 6. This modelling exercise is undertaken to investigate the application of this hydrological model as an aid for decision support for Catchment Management in the Lotus River catchment.

The use of a decision support is a key aspect when striving for the goal of Catchment Management. The link between decision support and Catchment Management is discussed in more detail in Chapter 7 where a conceptual framework is presented linking the technical, environmental and social issues of Catchment Management with the abilities of a complex, deterministic hydrological model to quantify and differentiate between these issues.

CHAPTER 3

HYDROLOGICAL MODELLING

Catchment management can be seen on one level to be concerned with addressing critical water resource problems in an integrated manner, based on a thorough understanding of the causes and effects of those problems (Görgens *et al.*, 1998). Current trends in catchment management and the desire of the community for an enhanced aquatic environment require information about the water environment within the catchment (Ball and Powell, 1998). This understanding of catchment resources and their interactions is fundamental to sound decision making and is obtained through a combination of detailed assessment of available information and catchment hydrological modelling (Görgens *et al.*, 1998).

Jewitt (1998), in discussing the role of models as integrative communication tools, submits that models have the ability to bring both knowledge and intuition to the fore and to make them explicit by means of rules or equations. Models structure knowledge whilst also identifying shortfalls in understanding and data availability and thus help to further direct research and monitoring.

Hydrological models can be seen as vehicles to describe the reality of a catchment through either conceptual or mathematical means. The many applications of these models can be categorised into the areas of "understanding" and "prediction" according to the modelling objective (Carstensen *et al.*, 1997). Models applied for "understanding" aim at the increase of knowledge of system behaviour. The objective is to develop a simple yet universal model of the system under consideration that gives an adequate description of reality as it was observed (Reichert, 1994). Models applied for "prediction" aim at providing an accurate and fast image of real systems behaviour under different conditions than those prevailing during model configuration. The model can either aim at forecasting future states of the system (simulation with new inputs) or at predicting system behaviour under hypothetical scenarios (simulation with new parameter values)

An abstract representation of a real system by the ideas on its constituents and functional relationships is called a conceptual model (Carstensen et al., 1997). The characteristics and relationships in the model are conceptualised rather than determined by observations and measurements (Alexander, 1991). If the model is formulated mathematically, however, they are termed mathematical models and can be used to give quantitative answers to questions about a subject's behaviour under given external conditions (Carstensen et al., 1997).

Mathematical models can also be seen as quantitative expressions of a process or phenomenon one is observing, analysing or predicting (Overton and Meadows, 1976). Numerical simulation models, on the other hand, consist of a computer program that has one or more outputs that mimic a chronological sequence of outputs for the system being modelled. Model algorithms are numerical descriptions as opposed to mathematical equations (Alexander, 1991).

In order to avoid the misuse of existing terminology or use of unclear terminology, it is beneficial to initially define the scope and extent of modelling terminology. For this purpose, the exposition by Carstensen, *et al.* (1997) is followed:

A model can be thought of as a machine transforming inputs (**u**) to outputs (**y**) by defined relations, where **u** and **y** are, when discretised, sequences of scalars or vectors. The features of the input-output relations determine the basic structure type of the model, which is either an input/output or a state-space description. The inputs of a model consist of disturbances or fluxes and manipulated variables. The two model structure types are:

- **Input/output models** consists of a set of transfer functions (**g**) that transform the inputs **u** directly to outputs **y**. This type of description (denoted as external) of system behaviour omits the consideration of the mechanism by which inputs are related to outputs. It is this mechanism that is considered in state-space model

- **State-space models** introduce state variables (vector **x**) which act as mediators between the inputs and outputs. These state variables are additional model constituents and the system description is consequently described as internal. It is characterised by the fact that **x** is obtained from present **u** and past(**x** ; **u**) by means of the state-transition equation whilst **y** is generated from **x** by means of the observation equation. The state of the system (described by the model) is defined as the values of the state variables at any instant of time.

Irrespective of the model structure, the mathematical equations that relate inputs to outputs contain three types of constituents: **variables**, **constants** and **parameters**. Variables, inputs and outputs are **variables** in the equations. **Constants** can be defined as those model constituents that never change value throughout all possible applications of the model. **Parameters**, on the other hand, are model constituents whose value varies with the circumstance of its application. This value needs to be defined for each particular application of the model and even possibly modified during specific applications (e.g. during model calibration).

3.1 Model attributes

Whilst model constituents describe the fundamental elements of a model, the characteristics of a model can be addressed by a number of descriptive terms, and are called model attributes. (Carstensen *et al.*, 1997) differentiate between "strong" or "weak" model attributes depending on the stringency of their definition with the more "strong" model attributes being applied, the better the model is characterised. What follows is a listing of the more significant terms: (Carstensen *et al.*, 1997)

3.1.1 *Strong model attributes*

- **Linear** and **non-linear** attributes relate to the structure of the model equations and, unless otherwise stated, refer to linearity in the variables. This affects the solution of the model given that analytical solutions can be obtained. For non-linear models, numerical solutions are necessary.

- **Dynamic** (as opposed to static or steady state) models are those in which the variables evolve over time. Dynamic therefore refers to a time dependency in the model which can be formulated as dynamic input variables and/or state variables. Output is frequently in terms of time series. If model parameters are constant over time, the model is characterised as time-invariant.

- If the model has a space-dependency, it is referred to as a **distributed parameter** as opposed to lumped parameter model. **Lumped** or **aggregated** models refer to model variables or equations being unified in a simplified description.

- Models are frequently termed as **continuous** or **discrete**. In most cases this relates to the model formulation of difference/differential equations with respect to time, i.e. continuous-time or discrete-time models (An event based model, related to specific precipitation events and disregarding all dry-weather processes such as recovery of infiltration loss rates, could therefore be considered a discrete-time model). In addition, discrete-space or continuous-space are two other model attributes describing a space relationship for up to three dimensions in the model formulation. Continuous-time differential equations are either solved analytically or discretised into discrete time difference equations which are solved numerically. Note that most programs apply a discretisation to the continuous-time and continuous-space differential equations, and the discretised equations are solved as algebraic equations.

- If the model contains elements of randomness, the model is termed stochastic. This uncertainty is generated through a combination of:

  (1) uncertainty in input variables
  (2) uncertainty in parameter values
  (3) uncertainty in model structure

  Stochastic models presuppose that the outcome of the modelling exercise to be uncertain and are based on the statistical properties of chronological sequences of recorded data. No attempt is made to mimic the processes in the system being modelled. Since, however, they contain components that describe elements in terms of distribution functions or random variation, statistical approaches can be used for identifying model structure, estimation of model parameters and model validation (Harremoës and Madsen, 1998). These models generate sets of equally likely sequences and are very useful for gaining insight into the probable range of future responses of the system (Alexander, 1991). The output of a stochastic model can be described as a probability density function. Examples include regression models (linear) and transfer models. If uncertainty is neglected the model is **deterministic** and the output is determined uniquely by input and initial conditions.

3.1.2 *Weak model attributes*

- **Mechanistic**, **physical, process** and **white-box** are terms that describe the model's structure being based on physical, chemical and biological laws. These models follow a deterministic approach based on reductionist philosophy and attempt to relate all underlying physical, chemical and biological laws to sets of partial differential equations that govern an engineering application (Harremoës and Madsen, 1998). The relationships within the model must have been determined directly from observations or from theoretical considerations and not from indirect means such as calibration (Alexander, 1991). It assumes that a system or process operates such that the occurrence of a given set of events leads to a uniquely definable outcome (Edwards, 1988). A famous example of a deterministic distributed model is Systeme Hydrologique Europeen (SHE) (Abbot *et al.*, 1986)

- **Phenomenological, black-box, empirical** or **heuristic** are the opposite extreme and are attribute terms describing the model as based on empiricism rather than laws. Empirical (black box) models require a trial and error approach involving calibration against a recorded database in order to optimise model assumptions.

- **Grey-box** is a term describing models with a combination of mechanistic and empirical approaches. Although any deterministic model is based on understanding the physics of the modelled system it, however, includes empirical components (Hughes, 1991). This is due to all models being an approximation of reality and thus subject to simplifying assumptions and errors. This can imply models reflecting *a priori* knowledge as well as black box parts (Holst *et al.*, 1992). They represent a compromise between limitations of available data, sound conceptualisation and model formulation (Hughes, 1991). This approach makes it possible to combine information in terms of physical, chemical and biological knowledge with information embedded in available databases. They frequently use subcatchment distribution systems and the model algorithms are based on a mixture of physically measured and empirically based parameters (Hughes, 1991). These models are also referred to as semi-physical models (Carstensen *et al.*, 1996). Examples include SWMM (Huber and Dickinson, 1992) and WITWAT (Green, 1984)

3.2 Model Configuration

The choice of which model to utilise is related to the desired level of complexity, with the appropriate level of analysis dependent upon: (Yen, 1994)

- Objective and approach taken – continuous (historical) vs. event-based (design) analysis
- Output information needed – design discharge or runoff hydrographs
- Accuracy required
- Available data – drainage network (pipes, catchpits, junctions), catchment (topography, impermeability, soil characteristics), rainfall (spatial and temporal)
- Tools available – computer capability and numerical techniques
- Flow conditions – network, catchment properties, roughness, Froude numbers

For a particular modelling application it is thus necessary to define the desired complexity and information required based on available data.

Figure 3.1, below, summarises a generic framework for a model configuration exercise and is an adapted form derived from (Carstensen *et al.*, 1997). (Note, model configuration, as used in this context, refers to the configuration or setup of a particular model for its various applications and does not refer to the creation of a model through computer software coding.)

This framework is an attempt to provide a methodology for considering all likely modelling situations and therefore appears, perhaps, unnecessarily complex. The numbers in the framework denote a typical sequence that might be followed in the model configuration exercise and the inclusion of all possibilities is for completeness. Once the steps have been completed successfully, the model can be applied for its intended purpose. The individual terms of the framework are defined further below.

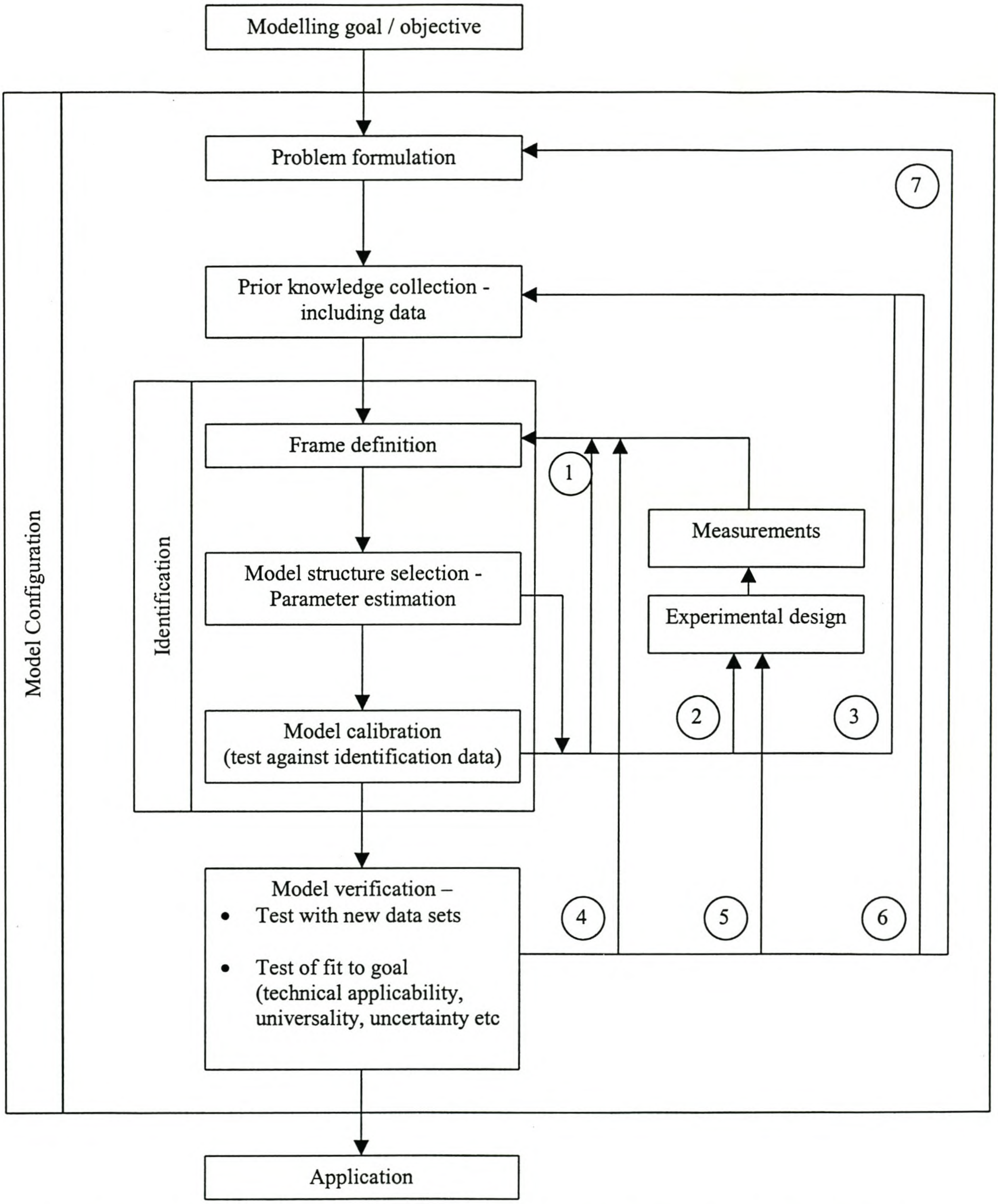

Figure 3.1: Flow chart depicting a model configuration approach (Carstensen *et al.*, 1997)

The various terms in Figure 3.1, above, can be described as:

- **Goal / Problem formulation**

It is critical that clear formulation of the model goal is initially attained. Questions such as desired accuracy of results, degree of uncertainty in the provided answers, time scale of the solution, system boundaries, important variables, environmental conditions etc., need to be addressed in order to select the most appropriate modelling approach.

- **Prior knowledge collection**

This is the collection of available, relevant, *a priori* knowledge from literature, experts and other sources. Experiments, including field studies, may be conducted or data from previous modelling exercises may be accessed and utilised.

- **Frame definition**

Once the above two tasks have been completed, the first iteration of model conceptualisation can occur. Frame definition delineates the conditions under which a model will be used (e.g. temperature), the class of models that are fit for the task (time series, state-space, distributed parameter, stochastic), the variables that are significant for the solution of the formulated problem (inputs, outputs, states), the range of constants that need to be covered, etc.

- **Model structure selection**

Candidate models may then be constructed combining the collected a priori knowledge and creativity and skill of the modeller. Model parameters are estimated through interpretation of the above collected *a priori* knowledge with the aim of providing input values for the initial or boundary conditions of the state variables. The goal is to select a unique model structure according to the principles of goodness-of-fit and parsimony. This implies the best possible configuration with an economy of effort.

- **Model calibration**

Once the parameters have been identified, it remains to investigate whether the identified model violates the assumptions made in the initial frame definition. This can be conducted using goodness-of-fit statistical tests of, say, systematic or unacceptable deviations between model results and measurement. This model calibration process involves optimising the initial model inputs and parameters using one set of data to produce a closer fit between model output and recorded data. It is most effectively undertaken after a sensitivity analysis is completed of the significant model parameters. This allows the ranking in sensitivity of the parameters determining which parameters should be perturbed to obtain the closest fit of simulated to observed data.

- **Model verification**

Whilst calibration is the adjustment of model parameters using one set of data, verification is the testing of this parameter selection by using an independent data set. Model verification is, therefore, the process in which the model is evaluated by comparing its performance with data obtained under different conditions than the ones prevailing at the time of collection for the initial model conceptualisation. It is a process that will test the model to its limits and may reveal inadequacies that are sufficient to conclude that the model is no longer appropriate. This placing of the model in jeopardy as it were is also called validation. Given that a model only describes part of the reality (the one defined in the frame) in a simplified manner, it is obvious that a model can never describe reality completely and therefore there will always be experimental conditions for which the model is not valid.

Beck (1999), in a discussion focussed on state-of-the-art of models, argues that those who construct models are driven largely by the search for the theoretical completeness in the product of their efforts. Given the increase in computational power, and the knowledge of things with potential relevance, why should any factors be left out (Beck, 1999)? Although it can be argued that the introduction of additional variables will not necessarily increase modelling accuracy (see Alexander (1991), the consequence is that present models seem destined to get larger. Coupled with this is the recognised need for high quality comprehensive databases of information for accurate model output. The implication of these two issues appears to be larger, more complex models, utilising large unwieldy datasets.

Another problem in modelling is the difficulty in collecting, manipulating and storing large datasets as well as identifying this data if no such information is available. These can be laborious, time-consuming activities with the accuracy of the generated data being questionable. Two tools addressing these issues and thus having considerable application for runoff modelling are Geographical Information Systems (GIS) and Remote Sensing.

3.3 Technologies to assist in model configuration

3.3.1 *Geographical Information Systems (GIS) for hydrological modelling*

This section, whilst in no way attempting to comprehensively document GIS, its history or present state-of-the-art, recognises the role of GIS and remote sensing in hydrological modelling. A context is thus set with descriptions of desktop case studies of its various applications. A brief overview is given of GIS functioning, with its associated applications for hydrological modelling, followed by studies incorporating a GIS, hydrological model interface and the role this combination can play as a Decision Support Tool. The application of remote sensing in calculating input data for hydrological models is then discussed.

It is necessary to recognise that many of the parameters and input data for the various hydrological models are derived from geographically referenced physiographic information (topography, geology, soils etc). The time consuming task of data capture and manipulating can be most easily carried out using a GIS system (Herald, 1991). Similarly, in a review on contemporary approaches in urban drainage, Marsalek and Sztruhar (1994) state that the collection and processing physiographical data for drainage modeling and presentation results are greatly simplified by GIS

GIS can be defined as a computerised system for the creation, storage, analysis and display of data of either a spatial or non-spatial nature (Fisher and Wijers (1991), Parker, 1988)). It can also be considered as a decision support system involving the integration of spatially referenced data in a problem-solving environment (Cowen, 1988). GIS can be thought of as consisting of two parts; with the first part controlling the graphic or geographic part and the second part handling the database part of the system. They are generally independent of each other (Bailey and Kakebeeke, 1991).

Given that a river basin can be considered as a geographical unit with spatial and non-spatial data pertaining to its various components; the spatial data can be divided into: (Bailey and Kakebeeke, 1991)

- points (single set of coordinates representing, say, a rainfall station or flow gauge)
- lines (set of point coordinates joined by arcs representing rivers or canals, etc)
- polygons (or areas) (several lines describing the outline of an area such as a subcatchment)

All the features of the landscape can be reduced to one of these categories, enabling the GIS to locate features in space. These features are stored in separate layers within the GIS and can be recalled in an infinite combination for analysis and/or output as either tables, maps or digital data for input to the model (Fisher and Wijers, 1991). Note that these features can have non-spatial data attached to each feature providing descriptive information relating to the feature. All spatial data input for storage into the database is via the GIS, and may be used to generate input parameters to the simulation models.

The value of GIS thus stems from its relational database facility, which enables the manipulation of both spatial and temporal information. If properly used, this feature of GIS can provide the hydrological modeller with a powerful tool for determining model input parameters and for the compiling and managing of input data, especially that for distributed physically based models (Herald, 1991). In addition, GIS provides the flexibility to redefine spatial features, to carry out a comparison of graphical features, to query attributes and to automatically calculate areas and lengths of features. These all contribute to making GIS a powerful tool for modelling.

Other advantages include: (Herald, 1991)

- ease of data retrieval
- ability to synthesise large amounts of data for spatial examination
- ability to make scale and projection changes
- ability to discover and display spatial relationships through the application of empirical and statistical models

Of interest to hydrologists are the applications for runoff modelling. Marsalek and Sztruhar (1994) argue that a GIS can be used in conjunction with distributed hydrologic models to compute runoff hydrographs comparing well to those produced by conventional models (Zech *et al*., 1994). In addition, it is used for the following applications (Fisher and Wijers, 1991):

- input of spatial data
- spatial analyses
- spatial representation

Spatial data includes rainfall, evaporation, topography, catchment and sub-catchment boundaries, dams, etc.

Spatial analyses are used for two distinct stages of the modelling process:

Firstly, to prepare data for input into the model such as:

- calculation of subcatchment areas
- determination of overland flow lengths and slopes
- remote sensing to produce landuse data, including % imperviousness, existing dams and irrigation

This results in the minimisation of user subjectivity in parameter selection and a reduction in the costs of analysis due to time savings.

Secondly, spatial analysis is used to analyse the results of model output. Runoff data analysed on a catchment basis can be used to identify areas of variable runoff and sources of inputs to the stream, be it quality or quantity considerations.

Spatial representation of data is in form of maps produced on-screen with non-spatial information attached, or hardcopy printouts at any scale. This permits graphical queries from users and decision-makers and thus benefits any ICM process through the GIS analytical features combined with the ability of rapid continuous interactive updating.

3.1.1.1 Integrating GIS and hydrological models

Of increasing interest to hydrological modellers is the interfacing of GIS and model to produce a Decision Support Tool for effective management. Given the applications of GIS for hydrological modelling, increasing attention has been given to coupling the model and GIS. Hydrological modelling, which makes use of geographically referenced information including catchment physiography and climatic data, can be greatly enhanced when coupled to a GIS. This is due to the associated ease of data access and extraction and increased speed and efficiency of data manipulation (Tarboton, 1991). Conjunctive use of model and GIS can thus provide a tool for water resource management and planning which can be continuously updated as more information about the study area becomes available (Schultz *et al*., 1991).

The coupling of GIS and hydrological model is based on the assumption that these systems may be regarded as similar in that both attempt to organise and present aspects of geographical reality. It has been proposed that both GIS and modelling systems can be described in terms of subsystems (Nyerges, 1992). GIS can be thought of consisting of subsystems for the user interface, data entry, data manipulation and analysis. Modelling software often displays similar subsystems, except for data entry, but with an emphasis on analysis and display. The most common linkage occurs through the data management subsystems.

(Nyerges, 1992) holds that there are four different application coupling environments, termed, *isolated, loose, tight and integrated.* Isolated and loosely coupled interfaces occur through human operators effecting communication between the separate systems through file transfers. Each information system is accessed independently with the operator creating the files for data transfer between systems. This can be shown in Figure 3.2, below.

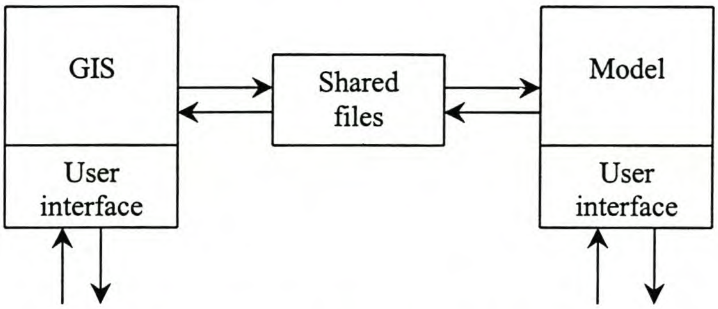

Figure 3.2: Loosely couple system

Tight coupling, whilst also relying on file transfer, has the transfer performed automatically through the software. The operator access the information systems through a common interface, as shown in Figure 3.3, below. This makes them easier to use than the loose coupled interfaces, but require more skill and resources to develop.

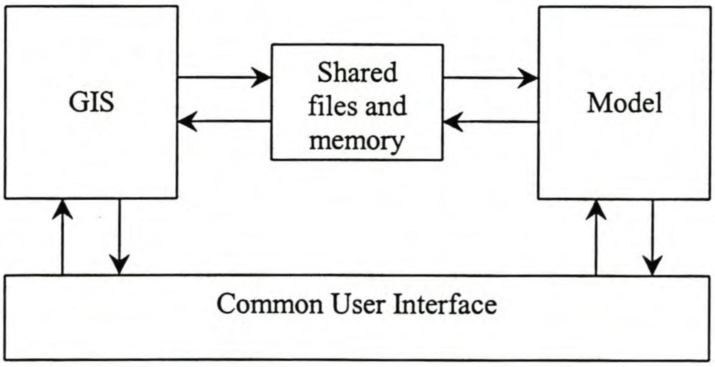

Figure 3.3 Tight coupling

For integrated coupling, the GIS and modelling components have been developed as one software system thus not requiring any file transfer operations. Integration requires the programming intensive production of customized programme interfaces This is shown in Figure 3.4, below. The shortcoming, however, is the major undertaking required to develop and modify such a system. This approach has been followed by Shea *et al.*, (1993) andRoss and Tara (1993)

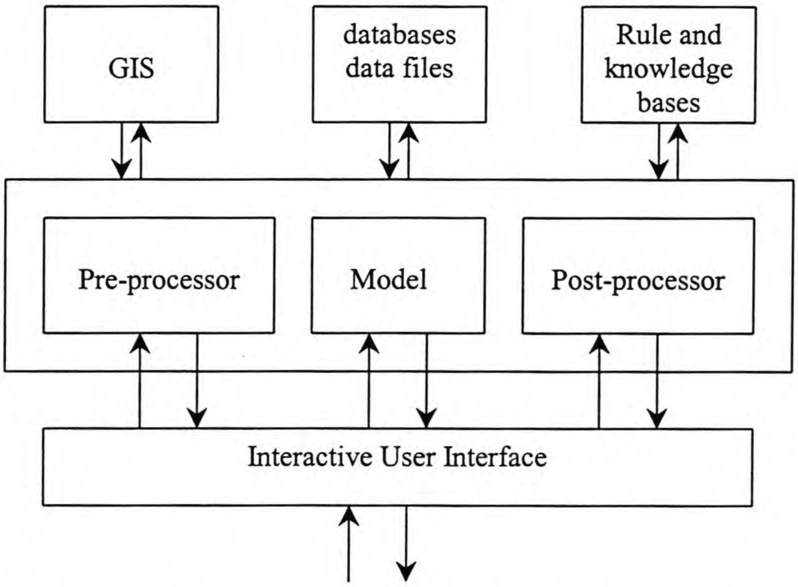

Figure 3.4: Integrated system

A review of the literature indicates that the major application of coupled GIS and hydrological model has been in the pre-processing of data for the model. This principally involves the calculation of the spatial extent of hydrological parameters using standard geometrical overlay techniques (Wolff-Piggott, 1994).

Whilst the advanced state of hydrological modelling has resulted in the use of complex models, it is this complexity that makes them difficult to implement within GIS. The most common coupling has therefore been a loose linkage which relies on operator skill and judgement in generating adequate data quality (Wolff-Piggott, 1994). Here, the spatial database is transferred to the modelling system for analysis with the GIS being limited to pre- and post-processing of the data.

Wolff-Piggott (1994) investigated the coupling of GIS and modelling systems with particular reference to catchment hydrological models. The objectives of this research included:

1. to develop a framework for the coupling of GIS and models
2. to redefine the framework with specific reference to domain of catchment hydrological modelling
3. to demonstrate the application of this framework in a case study by creating a coupling between ARC/INFO GIS and DISA catchment hydrological model.

Due to the tedious configuration of the DISA model, the coupling of the GIS and DISA model focussed on assisting this configuration. As discussed above, this is a loose coupling with the GIS performing as the spatial data capture and management system.

Through internal verification of the model, the data transfer process from the GIS database to the model was shown to be functionally correct. The modelling correctness was shown by the close match between simulations carried out using the original configuration database and the coupled model/GIS derived database. This allowed the conclusion to be made that the use of GIS reduced the time required for data capture because it offers specialised spatial data capture and integration capabilities as well as tools for analysing it (Wolff-Piggott, 1994).

3.1.1.2 Case studies of applications of GIS in hydrological modelling

Numerous studies have been undertaken in modelling hydrological systems with the aid of GIS. Some significant studies are described below.

Meiner (1996) describes an integrated system combining GIS software with a simulation model for non-point source pollution management. The test catchment is divided up into spatial modelling units (areas with unique set of parameters thus modelled as single hydrologically homogenous areas) using a series of map overlays. In this case, the model is imbedded directly within the GIS. The GIS is thus initially invoked, the model is then called for a simulation run (with possible input editing), importing of model output to a GIS compatible database file, establishing a file relation between the model output and geo-referenced attribute file, and displaying and analysing model results. The integration of model with GIS is intended to extend existing GIS software. It can be described as running the model within a GIS subsystem and showed that combining watershed spatial units polygons) with a river network can provide a very useful framework for watershed analyses.

Zech *et al*. (1994) also present an integrated approach to runoff modelling for partly urbanised watersheds. A DTM (a digital representation of the ground levels at each node of a fixed rectangular grid), thus allowing use of GIS techniques, was built for both the undeveloped and urbanised areas of a partly urbanised test catchment. Houses were schematised by increased elevation and the sewer network by fictitious trenches thus allowing a unique model for the whole catchment area. Comparisons between model results with measurements showed excellent results with this DTM GIS approach proving more accurate than other models including SWMM and WALLRUS of the same area. Of significance, because the concept is based on GIS routines, much of the computation is automatic and thus avoids the need for time-consuming labour to be invested in it. It was concluded that the integration of model with GIS allows all possible use of GIS power for urban hydrology and hydraulics. In addition, the authors contend that it also becomes relatively easy to check the consequences of urban planning options.

Funnpheng *et al.* (1994) attempted to develop an operational, integrated information system to support planning and decision making with regard to the use of land resources at subregional level. An integrated information system that includes a GIS with remote sensing image processing capabilities coupled with a relational database and modelling techniques, was found to be a powerful tool for the evaluation of sustainability of land use systems. Such an information system makes it possible to:

- Update the present land cover and land use information using remote sensing data
- Integrate data that are related to different map units
- Predict ecological and economic consequences of the introduction of alternative land-uses in areas with sustainability problems.
- Present the results of the evaluation in a clear and attractive way.

3.1.1.3 Concluding remarks on GIS model interface

GIS can be considered to be a spatial data handling technology providing the model developer with advantages including the efficient storage, retrieval, processing and output of spatial data, usually a tedious time-consuming exercise for the modeller. In addition, it allows the production of new data for model applications through the overlay, buffering and networking capabilities of GIS. The coupling of GIS with hydrological models, results in systems serving as Decision Support Tools for managers and decision makers.

This coupling between GIS and hydrological modelling can be seen to be contributing towards optimising scientific understanding and linkages by helping to bridge the gaps between information and knowledge (Tarboton, 1991). This interfacing enables communication between the two systems for meaningful hydrological simulation and the effective use of the geographical system. It allows the effective use of spatial geographic information and the transformation of this information into representative variables for hydrological simulation.

The key advantages of a GIS-based approach may be summarised as follows:

- More accurate parameter estimations
- More rapid parameter estimations
- Facilitates potential for utilising existing public databases
- Facilitates potential for grid-based distributed hydrologic modelling
- Facilitates an integrated analysis of the various data sets through the spatial overlay capability
- Facilitates a more realistic representation of data
    - Raster backdrops to vector data
    - Thematic representation of data
- Facilitates effective communication medium
- Facilitates wide spread diffusion of information
- Facilitates spatial analysis for planning
    - Simplified spatial analysis tools
    - Complex spatial analysis tools

An aditional technology that seems to offer potential for model configuration is Remote Sensing (RS).

3.3.2 *Applications of Remote Sensing in hydrological modelling*

The evaluation of runoff from urban catchments is complex due to the various transformations imposed by human activities on the catchment and by the diversity of information required for an accurate evaluation. Tools are required which permit basin behaviour to be monitored closely and rapidly, as urbanisation develops, whilst containing resources to manipulate data of different kinds, in different formats and in different quantities (Campana *et al.*, 1995). Increasingly, hydrologists seeking to model the response of urban basins to rainfall are able to exploit the opportunities offered by remote sensing and GIS.

Given increasing computing power, hydrological models are able to be more complex whilst utilising increasing volumes of input data. The development of more complex, physically representative, distributed hydrological models has dramatically increased the demand for spatial data. In addition, data collection agencies are also frequently under budgetary pressure to reduce the size of the conventional ground-based networks. Remote sensing techniques can be considered as innovative means for obtaining data.

Remote sensing can be defined as the observation of a target or process from a distance through the medium of electromagnetic energy (Bailey and Kakebeeke, 1991). This is frequently obtained from aerial photography and, increasingly, from satellite imagery. The advantage of satellite imagery is that the data is digital, with high resolution in time and space, and that areal related information can be produced instead of mere point measurements, which still predominate in hydrology. In addition, areas can be covered where no direct measurements exist. Multispectral satellite imagery can be classified to identify different types of landuse, vegetation, crop types, rivers, dams etc. This is due to the spectral signature of each land cover being unique. Land covers can thus be identified and differentiated from each other by their unique spectral response patterns.

Kite and Pietroniro (1996) assessed the applications of remote sensing in hydrological modelling, especially for physically based models. This is due to these models requiring significant volumes of spatially and temporally varied data with the remote sensing as a possible source of this data at reduced cost. Although the imagery is relatively expensive to purchase, major cost savings can potentially occur during the setting up of complex data intensive models using satellite imagery. Present manual methods for assessing catchment characteristics are frequently inaccurate, laborious and time-consuming. The advantage of satellite technology is that time series imagery of a catchment can be obtained and analysed using a computer system. Given skilled personnel utilising imagery with sufficient resolution, the consequence for hydrological modelling is that input parameters can be generated automatically (thus rapidly) and accurately, with catchment characteristics being deduced in a fraction of the time with good accuracy. In addition, the acquisition of such imagery can be used to maintain a database of landuse change or other catchment characteristic variations either spatial or temporal.

Kite and Pietroniro (1996), in reviewing Salomonson (1983), argue that the use of remote sensing in hydrological models can be divided into three categories or levels of use:

(1) to identify items of interest such as snow covered areas or plumes

(2) to obtain data such as land use, geological features or other hydrological parameters through interpretation and classification of remotely sensed data

(3) to use digital data to estimate hydrological parameters directly through correlation of known hydrometric data with remote sensed data (to derive soil moisture estimates or precipitation data for example)

The authors contend that all three levels of use have been applied successfully with perhaps the second category being particularly well suited to hydrological models. If we accept that an improved understanding of the hydrological cycle is obtained though measurement of time series at a point, time series which vary spatially and data which do not change temporally over the modelling period, remotely sensed data is attractive to hydrological modelling given its combination of wide spatial coverage and frequency of measurements.

Table 3.1, below, provides examples of catchment parameters/variables used in hydrological models and the satellites/sensors that can provide information on each.

Parameter / variable	Satellite / sensor	Resolution
Precipitation	Meteosat	3 km
Evapotranspiration	NOAA	1.1 km
Land cover / land use	Landsat 7 MSS	25 m
Vegetation	NOAA Landsat 7	1.1 km 25 m
Groundwater	Landsat 7	25 m
Water depth	Landsat 7	25 m
Snow cover	NOAA	1.1 km
Snow depth	GOES Nimbus 7	2 km 30 km

Table 3.1: Hydrological variables determined with satellite imagery

None of these satellites are purpose-built for hydrological purposes yet they may yield information for hydrologists. Inspection of the coverage of the satellites in the above Table 3.1, reveals that the resolution varies from coarse (~ km) to fine scale (~ m). This has implications for the desired level of information required by the particular application. Sensors with a resolution on the km scale are adequate for subcontinental or other large-scale investigations. For small scale urbanised subcatchment applications, such as modelling the Lotus River catchment with its varying landuse types, resolution of 25 m or less is necessary. The necessary resolution is discussed further below.

Landuse is a dominant variable in hydrological modelling and its derivation is a common application via any satellites with visible band data (e.g. Landsat or NOAA). Land use classification was one of the earliest products of satellite data and has often been used to provide data for conventional hydrological techniques.

Rango *et al.* (1983) describe the derivation of land use through Landsat MSS (Multi-Spectral Scanner) data as input to flood frequency models for urban planning. Deguchi and Sugio (1994) investigated the applicability of using satellite technology in predicting percentage imperviousness in urbanised areas. Using three different images, LANDSAT-MSS, MOS-MESSR (Multi-Spectral Electronic Self-Scanning Radiometer) and SPOT-HRV (High Resolution Visible) with resolutions of 80 m, 50 m and 20 m respectively, the authors were able to classify the land-use development of the urbanised areas into three categories, "High-Density", "Medium Density" and "Low Density". By comparing the imperviousness of the test area obtained from aerial photographs with that from the above classifications, the authors were able to conclude that percentage imperviousness derived from the satellite imagery agrees well with that obtained from visual interpretation. The estimation error using the satellite imagery is similar to that obtained from visually interpreting the aerial photographs. Satellite imagery can therefore be used to estimate the percentage imperviousness for the simulation of urban runoff.

In another study, Oroda *et al.* (1996) describe the results of a project integrating satellite and ground data in a GIS to model water level changes on three closed lakes in the Central Kenyan Rift Valley. Using LANDSAT TM and MSS imagery, a landuse map was created as input into the model. Using land reference units (again areas with unique set of parameters thus modelled as single hydrologically homogenous areas) created using GIS overlays of soil, topography, landuse and other data, the information was read into a mathematical model and run for 9 years providing change in lake level as the output. With a few notable exceptions, the integrated model simulated monthly changes in lake level with a reasonable degree of accuracy. Land and water use practices can be effectively analysed through the integrated use of remote sensing techniques with GIS and modelling facilities. The project was seen to demonstrate how an integrated approach embracing a relatively simple physical model with GIS and remote sensing techniques could produce a potentially effective Decision Support System (DSS).

The above study indicates how landuse may also be used as a classifier for parameters of a hydrological model. If we assume that each type of land use will have a distinct roughness coefficient and a distinct infiltration rate, then using models where this parameterisation is included implicitly (such as the SCS model which uses runoff curve numbers (CN) based on land type and soil group) the land types can be conveniently derived from remote sensing. (Kite and Pietroniro, 1996) cite a number of researchers, (Blanchard, 1973), (Ragan and Jackson, 1980) and (Harvey and Solomon, 1984) who have all successfully used remotely sensed land use data to estimate runoff curve numbers for further input into the SCS model.

In an effort to derive catchment information for the Lotus River, and to evaluate the efficacy of utilising remotely sensed data for hydrological modelling, satellite imagery purchased during the Lotus River Project (Grobicki *et al.*, 192000)) was used. The classification of this image was carried out in the GIS laboratory of the Department of Botany, University of Western Cape under the guidance of Dr Richard Knight. His assistance is gratefully acknowledged. Three specific modelling needs were identified as being potentially addressed through the use of remote sensing techniques. These were required in order to generate input parameters for the SWMM model and included:

1. **Identification of imperviousness areas of each subcatchment -**

A principal variable in the SWMM model is the percentage impervious area. This is usually determined through inspection of aerial photography. Given that remote sensing techniques have the potential for generating this data automatically and accurately, it thus remained to assess the feasibility for the Lotus River imagery.

2. **Identification of areas of open water in agricultural subcatchments -**

An additional modelling uncertainty was seen to be the role of farm dams in the agricultural subcatchments of the Lotus River. These dams, mostly excavated for irrigation purposes, are located on the channels draining the subcatchments and thus have implications for storing any flood peaks flowing through these channels. In order to adequately model runoff from subcatchments incorporating these farm dams, an estimate of the total volume to be stored was required. Given an average depth of dam, it required a total surface area of water to approximate the total volume. This would result in the modelling of a dummy storage dam with storage area generated through the remote sensing imagery.

3. **Identification of areas of tarmac in urbanised subcatchments -**

A principal variable of any SWMM modelling exercise is the generation of overland flow length for each subcatchment. For a developed urban area, the road/gutter network might be assumed to be the principle conduit for overland flow before routing into the subsurface stormwater network. The calculation of this overland flow length could perhaps be addressed through the use of remote sensing techniques given a unique spectral signature for the road surfaces in the catchment. It was hypothesised that given a remotely sensed total area of road, with an assumed average road width, the total length of road could be determined and hence an approximation of the overland flow length for each subcatchment. It remained to assess whether this could be a systematic means for generating representative subcatchment overland flow lengths (i.e. close to that of reality).

The above needs require a high resolution classified image in order to obtain the necessary accuracy. Given the resolution of the imagery purchased during the Lotus River Project, it was necessary to see if this would be sufficient.

3.3.2.1 Use of remote sensing in the Lotus River catchment

In an attempt to determine the landuse and to gauge the vegetation cover of the Lotus River catchment, a Landsat TM (thematic mapping) image with 7 bands was purchased from Satellite Application Centre (SAC), Mikomtek, CSIR, Pretoria. This image, taken in May 1997, has a resolution of 25 m with the following Table 3.2 indicating the respective bands:

Band	Description	Wavelength (μ m)
1	Blue	450-520
2	Green	520-600
3	Red	630-690
4	Infra Red	760-900
5	Mid Infra Red	1550-1750
6	Thermal	10400-12500
7	Mid Infra Red (longer than 5)	2080-2350

Table 3.2: Landsat multispectral bands and wavelengths

It was questioned whether this 25 m resolution was sufficient for generating data for the small, varied landuse catchment of the Lotus River. In attempting to increase this resolution, a SPOT 2 Panchromatic image, taken in 1998 with a resolution of 10 m, was also purchased from SAC. The two images were fused using an innovative technique currently employed in the Department of Land Surveying at UCT to result in a multispectral image with 6 bands (thermal band 6 was excluded) at a 10 m resolution.

Figure 3.5, below, displayed using IDRISI software (Eastman, 1993), depicts the Landsat Spot-fused image with bands 2, 4 and 5 visible and the subcatchment boundaries of the Lotus River overlain. These boundaries were obtained from hard copy maps generated by Gibb Africa (Pty) Ltd (Taylor, 1994), subsequently modified by Abbot Grobicki (Pty) Ltd (Grobicki *et al.*, in press) and digitised onto MapInfo coverages of Cape Town. These coverages were then exported using MapInfo Interchange File Format to IDRISI vector files and imported into IDRISI.

The image, shown in Figure 3.5, below, and displayed using a false colour composite with 256 colours, provides an indication of the varying landuse distribution prevalent in the Lotus River catchment. Each colour represents areas with a specific reflective index pertaining to a specific landuse type. In order to determine the landuse types and to calculate the extent of each landuse type, the image required classification. This is discussed below.

Figure 3.5: Fused Landsat Spot image depicting bands 2, 4, 5 with Lotus River subcatchment boundaries overlain

The fused image can be classified using two different methods:

- supervised classification - user develops the spectral signature of known categories such as open water, cultivated and the software assigns pixels to the cover type of which its signature is most similar.
- unsupervised classification - the software groups pixels into categories of like signatures with the user identifying what cover types these represent.

An unsupervised classification was initially carried out on the Spot-fused image. With this approach, the dominant spectral response patterns (or classes) in the image are extracted with these classes then being identified through ground truthing. The spectral response patterns are extracted using a *histogram peak selection* technique. This is equivalent to searching for the peaks in a one-dimensional histogram where a peak is a value with a greater frequency than its neighbours on either side. Once the peaks have been identified, all possible values are assigned to the nearest peak. This results in a number of clusters conforming to the various land covers in the image.

The unsupervised classification of the Spot-fused image of the Lotus River revealed that there were eight principal clusters. From a desktop ground-truthing exercise based on an understanding of the different land uses in the catchment, the clusters were identified as:

- deep water
- shallow water / vlei
- urban - high density development
- urban - low density development
- road
- herbaceous (cultivated and grassed)
- trees
- open area

In order to assess the efficiency of the classification, a scatter plot of the above clusters was carried out. This showed that the unsupervised classification resulted in good discrete identification of both the low and high-density development, the open areas and the herbaceous areas. There was, however, poor differentiation between the clusters representing deep water and trees, and between tarmac and shallow water.

In an attempt to improve the above differentiation, a supervised classification was subsequently carried out. This methodology requires the identification of representative examples of each landcover type called *training sites*. Polygons are digitised around each training site with a unique identifier assigned to each cover type. The pixels in the training site are analysed with the creation of spectral signatures for each cover type. Finally, the entire image is classified by considering each pixel and comparing it with each of the known signatures. Decisions about the similarity of signatures are made using a number of different statistical analyses, called *classifiers*.

Using the results of the above unsupervised classification, known areas of deep water and trees, tarmac and shallow water, and open space and lightly developed were identified as training sites. A classifier, the *maximum likelihood* classifier was used to further refine the image. With this classifier, the distribution of reflectance values in a training site is described by a probability density function developed on the basis of Bayesian statistics. This classifier evaluates the probability that a given pixel will belong to a category and classifies the pixel to the category with the highest probability of membership. The supervised classification resulted in significantly better differentiation of the image. This resulted in good identification of the following land covers:

- deep water
- build up (high density development)
- low density development
- herbaceous (cultivated and grassed)
- trees
- open area

Unfortunately the differentiation between tarmac and shallow water remained inaccurate. This is possibly due to the similar reflective indices of these two covers. Figure 3.6, below, depicts the classified image pertaining to the Lotus River catchment.

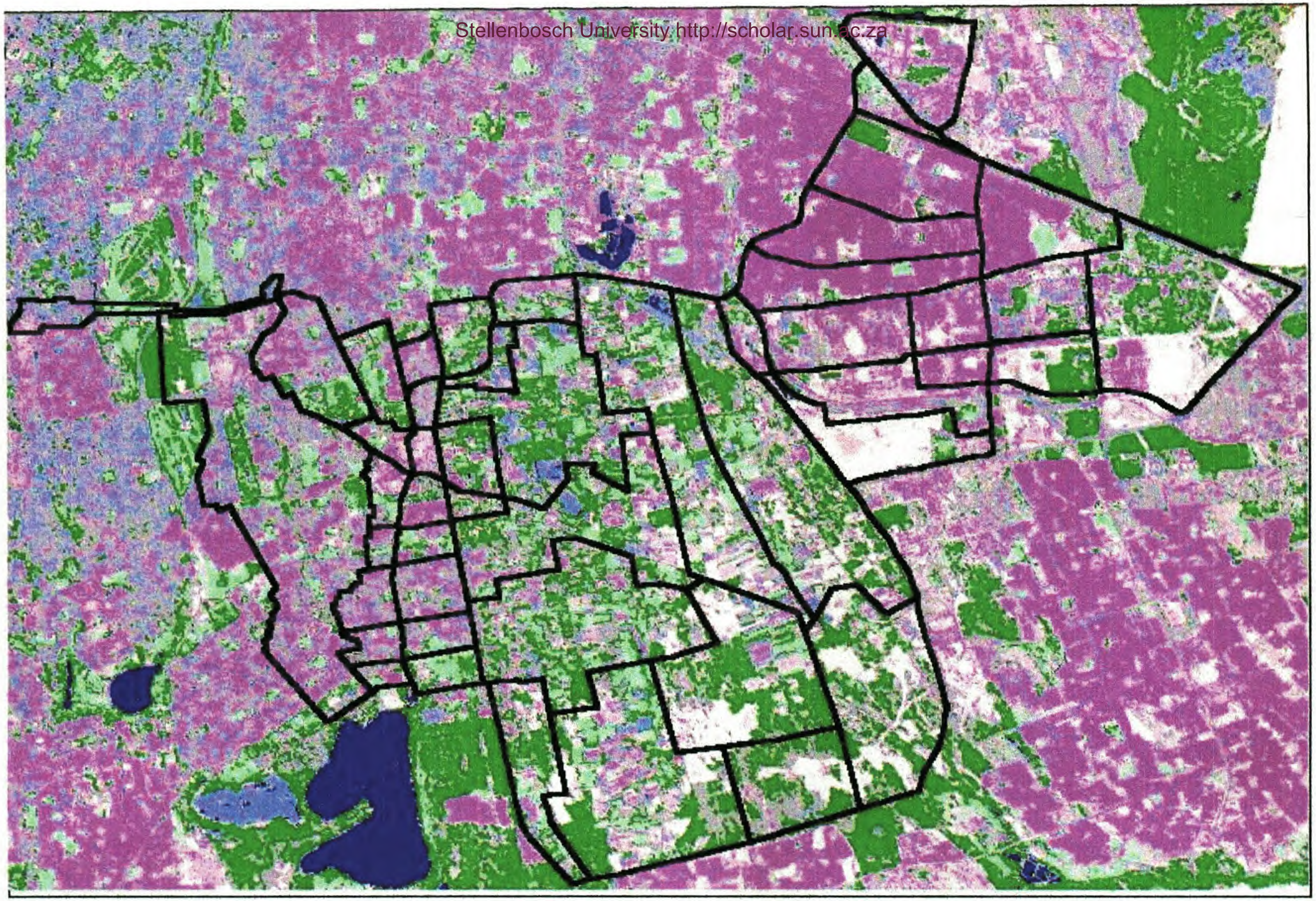

Figure 3.6: Classified image of Lotus River catchment depicting principal landcovers and subcatchment boundaries

The following Table 3.3 depicts the different colours and their respective landcovers as shown in Figure 3.6.

Colour	Landcover
White	Open Areas
Light purple	Light density development
Dark purple	High density development
Light blue	Shallow water / vlei
Dark blue	Deep water
Grey	Tarmac
Light green	Herbaceous
Dark green	Trees

Table 3.3: Colours of respective landuse types in classified satellite image

From this classification, it is possible to generate areas of each land cover in the catchment, as shown in Table 3.4, below.

Landcover	Percentage of catchment
Light developed	12.83
Deep water	0.23
Shallow water	3.92
Built up	16.24
Open space	8.65
Tarmac	29.14
Herbaceous	8.14
Trees	20.84

Table 3.4: Landuse types calculated from Remote Sensed approach

In order to assess the accuracy and feasibility of using remote sensing techniques in generating landcover data, the results of the remote sensing analysis was compared with the landuse allocations as calculated by (Taylor, 1994) and shown in Table 3.5, below.

Land Use	**Percentage of catchment**
Industrial	7
Sports Fields	1
Residential	24
Light Industrial, institutional	16
South African	5
Agricultural	47

Table 3.5: Landuse types of Great Lotus River (Taylor, 1994)

The derivation of landuses in Table 3.5, as discussed by Taylor (1994), occurred through the homogenous allocations of landuse to the various classes without accounting for the variation within that allocation. This differs from the more physically based allocation determined using the Remote Sensing technique. A direct comparison can only occur through the combining of classes into a coarse developed versus undeveloped landuse determination. This comparison is shown in Table 3.6 below.

Land Use	**Percentage of catchment**	
	Taylor (1994)	RS (1996)
Developed	52	58
Undeveloped	48	42

Table 3.6: Comparison of landuse types of Great Lotus River

The comparison in Table 3.6 reveals that the above classified image can be seen to capture the different land covers of the Lotus River catchment with a fair degree of confidence. This was strengthened through further ground truthing and shows that the RS techniques can provide good landuse derivations on a catchment wide basis.

In order to assess the accuracy and feasibility of using remote sensing techniques in generating landcover data on a smaller subcatchment basis, the results of the remote sensing analysis was compared to GIS based landcover determinations described in (Grobicki *et al.*, in press).

Two different techniques were applied in determining the above GIS based landcovers. The first method employed a cadastral-based approach utilising the cadastral database produced by the Cape Town Metropolitan Council (CMC). This approach was followed for a selected sub-catchment and the percentage of each landcover was estimated. In practice, however, the cadastral-based approach was concluded to be too time-consuming to carry out on a catchment-wide basis (Grobicki *et al.*, in press). The second method was based on mapping the various land uses from digital orthophotos at a 1:20 000 scale. This second approach, using aerial photography, was a significantly more rapid method, yet produced comparable results with the first cadastral-based approach basis (Grobicki *et al.*, in press).

Land type	Method 1	Method 2	Remote sensed
Open space	2	3	2.3
Trees	-	10	8.5
Build up	71	64	65.9[1]
Tarmac	10	10	19.7
Water	-	-	3
Herbaceous	-	9	0.6

([1]combines light and heavy density developed areas)

Table 3.7: Comparison of the results of the two land use mapping methodologies with the remote sensed data for a selected sub-catchment.

Comparison of the above results in Table 3.7 reveal that, for the selected subcatchment, an area composed largely of formal and informal residential areas, the remote sensed data compares relatively favourably with the GIS based techniques. This favourable comparison also occurs for other urbanised subcatchments with a relatively homogenous land use distribution.

Assessments for the rest of the catchment, however, suggested that given a subcatchment with heterogeneous landcovers, discrepancies occurred between the results obtained from the RS and GIS techniques. These discrepancies are possibly due to a number of potential reasons. As already stated, difficulties were experienced in differentiating between the various landcovers in the RS approach. This is exacerbated by the resolution of the fused satellite image, which is insufficient to determine small features such as tarred roads and farm houses in cultivated areas. An additional reason for the discrepancies is introduced in the GIS approach of visual digitisation of landuse types from orthophotos. As with the limitation perceived in Taylor's 1994 landuse determination, the visual digitisation results in homogenous allocations of landuse to various classes without accounting for the variation within that allocation. This renders direct comparison between the two approaches akin to "comparing apples and oranges".

It can, therefore, be concluded that, with the available image resolution, the RS technique performed successfully on a catchment scale and in subcatchments with relatively homogenous landuse types. For subcatchments with a more heterogeneous land use distribution, inadequate results were obtained through difficulties in differentiating between features in addition to inconclusive verification of the results using the GIS techniques.

The above conclusions have implications for the use of remote sensing in hydrological modelling. Whilst the results of previous studies have shown that it is possible to obtain an automatic identification of impervious areas by remote sensing techniques from satellite images (Deguchi and Sugio, 1994); (Leiss, 1992); (Frankhauser and Jancarkova, 1993); (Frankhauser, 1998);(Frankhauser, 1994) (Halounova, 1994)) the direct applicability of satellite imagery to hydrological modelling remains debatable (Zech and Escarmelle, 1998).

Hydrological modelling in rural catchments is often based on relatively coarse grid-type models (Holden, 1992)). For such areas, imagery such as fused Landsat images with a resolution of 10 m, may permit the estimation of input parameters with an acceptable accuracy for hydrological modelling. Unfortunately, the greater heterogeneity in landuse variation in urban catchments requires that the imagery used for land use mapping be of a far greater resolution than present commercially available satellite imagery to differentiate between the necessary spatial features and land use variations (Grobicki *et al.*, 192000). Zech & Escarmelle (1998) have shown that while the best ground resolution of satellite imaging systems lies at 10 m (the resolution provided by the panchromatic band SPOT images), a resolution of 5 m is needed for the development of urban hydraulic models. Essentially, the resolution of satellite imagery that is currently available would not appear to be sufficient to meet the demands of fine scale urban hydrological modelling. The results obtained using the Spot-fused image of the Great Lotus River catchment, above, would appear to support this conclusion.

With regards to the needs listed in the beginning of this chapter, namely

- determination of percentage imperviousness of the urbanised subcatchments,
- calculation of areas of open water in the agricultural subcatchments
- calculation of areas of tarmac in urbanised subcatchment

it is thus appears only possible to address the determination of the percentage imperviousness for the homogenous residential landuse subcatchments. This is dealt with in the following section. The resolution of the Spot-fused image, coupled with the difficulties in determining accurate areas of water, prevent the adequate resolution of the other two needs, namely the calculation of areas of water in the agricultural subcatchments as well as the calculation of the areas of tarmac road in the urbanised subcatchments.

3.3.2.2 Concluding remarks on RS applications for hydrological modelling

At present, the use of remotely sensed data in contributing to hydrological modelling, is perceived to be low (Kite and Pietroniro, 1996). This is thought to be due to few universally applicable operational methods being available for deriving the hydrologically significant variables from the remotely sensed data.

It has been shown that remote sensing techniques have the ability, given sufficiently skilled personnel deriving the results, of assisting hydrological modellers in determining primary input data. Numerous studies abound in which the degree of impermeability and other landuse information has been derived accurately and effectively through the use of Remote Sensing. Due to the present resolution of commercially available imagery, however, this would appear to be restricted to a fairly coarse level on mere differentiation between urban/non-urban areas. The use of Remote Sensing techniques, using commercially available satellite imagery, thus seems to be most effective in determining total catchment information or for fairly large homogenous landuse areas.

For small, highly heterogeneous urban landuse areas, another approach would be the use of Remote Sensing techniques other than that of satellite imagery. This includes airborne thematic mapper approaches that utilise images obtained from sensors located in aircraft. This airborne approach has the ability to provide resolution to a couple of metres but with higher costs than conventional satellite derived images. Costs precluded the investigation of this approach in the present research.

Given that the focus of the research reported in this thesis is to investigate the use of hydrologcial modelling as a decision support tool for Catchment Management, it is first necessary to understand what a decision support system entails. This is discussed in section 3.4, below.

3.4 Decision Support for catchment management

This section introduces the notion of Decision Support, and discusses how this support, in terms of tools and systems, can be applied in the cause of catchment management. A distinction is made between decision support tools (DSTs) and decision support systems (DSSs). DSTs include, amongst others, spreadsheets, graphics, time series analysis, GIS, statistical analyses, simulation, "expert systems" capabilities and metadata queries (Jewitt, 1998) while decision support systems (DSS) are integrated combinations of decision support tools.

Wolff-Piggott (1994) holds that a widely accepted model of any decision making process consists of three steps: intelligence, design and choice followed, ultimately, by implementation:

- intelligence - collection and examination of data for issues requiring decisions
- design - conceptualisation and analysis of the various strategies that could be adopted
- choice - selection of a particular course of action to address the issue
- implementation - execution of the above choice

This is tending towards a *systems management approach* (Pegram and Bath, 1995) which focuses on the cost-effectiveness of a number of management strategies rather than individual strategies approach. The steps in this approach can be defined as (Beck, 1997):

- define the problem
- develop the solution seeking model (whether conceptual or mathematical)
- identify the alternative courses of action (management strategies)
- predict the consequences of each alternative
- assess and rank the alternative
- communicate the results of the analysis
- implement the decision

Decision-making for the multiple problems faced in catchment management can be addressed in terms of the above approach, and, significantly, requires an extensive set of capabilities. This translates into the use of a great many tools, data and information formats in the examination of catchment data (be it catchment characteristic data or simulation output data) in addition to the comparison of the host of strategies that can be adopted. The development of a software system in which these tools and data are integrated can provide a powerful decision support tool to researchers and managers alike (Jewitt, 1998).

Reynolds, *et al* (in press) states that "a DSS is a software application that provides an integrated environment in which a collection of tools can be efficiently used together to manage a larger portion of the overall decision process". The key here to useful computer based decision support is *integration*. Maguire (1991) extends this in holding that for DSS, the emphasis is additionally on data manipulation and analysis and, particularly, modelling for the purposes of supporting decision makers such as company managers, politicians and government officials.

A DSS might have any or all of the following essential features: (Wolff-Piggott (1994), Maguire (1991))

- They should be easy to use and understand, simple to operate and produce easily interpreted output.
- They should have intuitive user interfaces and powerful graphical presentation capabilities making them easier to use and promoting effective communication
- They should be designed to solve ill-structured problems by flexibly combining statistical analysis, models and data.
- They should be retrieval orientated and easily modified to operate in a flexible manner to suit the changing needs of the user.
- They should be generic enough in its design to allow transferral with minimum effort to other situations where management decisions are required.

Such DSSs are being developed with the recognition that in any given software system for real-world applications, several sources of information or databases, more than one problem representation or model and a multi-faceted and problem orientated user interface need to be combined in a common framework to provide realistic and useful information (Jewitt, 1998).

Whilst catchment management decision-making historically often revolved around single engineering or economic issues such as drainage or flooding, management decisions must now involve wider areas of interest, including diverse stakeholder groups and organisational hierarchies at multiple spatial and temporal scales. This is moving towards a multiple point of view approach in the management of water resources not excluded to engineering or economics. These multiple views could include issues such as good management against the risks of flooding, the protection of downstream receiving water bodies, the rehabilitation of engineered canal systems, ecosystem based design and design increasing social amenity value. It, in effect, amounts to providing a basis for negotiation and arbitration based on these multiple viewpoints and thus making it possible to escape from monolithic logic (exclusively economic or exclusively technical) (Azzout *et al.*, 1995). This results in water resources being managed with ever-increasing number of competing objectives in mind. To do this, managers and stakeholders must rely on up-to-date information, modelling and communication. The provision of information and systems which provide decision support pertaining to the catchment is a key aspect when striving toward effective catchment management (Jewitt, 1998).

Jewitt (1998) argues that DSS are thus software systems that facilitate such management through integration of three types of information:

- Information on the state of the system (the catchment)
- Modelling (simulation) of the system
- Evaluation of different scenarios/plans.

It would seem evident that the various hydrological models and data management systems can be considered as decision support tools. In order for them to be considered as decision support systems for CM, however, two criteria would need to be fulfilled. These criteria can be seen in terms of *integration* and *information*. Firstly, these tools would need to be integrated into a system as discussed above, and, secondly, the system would need to be related to a catchment through information pertaining to that catchment.

3.4.1 *DSS in terms of Catchment Management (CM)*

Chapter 2 introduced the concept of catchment management in terms of the new National Water Act. This section illustrates the use of DSS in this CM.

As discussed in Chapter 2, the National Water Act created a three tiered statutory structure for integrated water resource management. This structure can be seen as follows:

- National Water Resources Strategy (NWRS)
- Catchment Management (CM) strategies
- Statutory institutions/measures for Catchment Management

Inspection of the above framework reveals that Catchment Management Agencies (CMAs) are an essential component of the Act. Görgens (1999) highlights the issues of modelling within the requirements of CMAs and contends that this framework will largely dictate the nature of technical information needs and, therefore, the potential modelling and other decision support requirements of CMAs. In order to ensure that an appropriate DSS is selected for CM, it has to first be placed in context with the NWRS.

Görgens (1999) states criteria in guiding the selection and use of DSS for linking catchment activities to the NWRS. He considers it necessary that flow information must be homologous and consistent across vertical aggregation of time and spatial scales. This can be satisfied if models and DSS tools share a set of naturalised flow series that is consistent across spatial scales and time resolutions (Görgens, 1999).

It can be addressed, perhaps, through the use of a single installed catchment modelling system, consisting of both quantity and quality modules, able to operate at both fine and coarse time scales. Due to the fact that the many objectives of CM are influenced by choices taken at a number of levels of decision-making, this notion of a single modelling system is tempered by the recognition that different management information need levels should be supported by methods or models of a complexity and with data requirements that are appropriate to that management information need level. Decision support relates specific system goals at different levels of catchment hierarchy (site, catchment, region). It is an iterative process with multiple levels of decision making involved in order to move from broad scale management goals for large regions to the finer details required for specific operational schemes for individual tracts of land or river reaches (Jewitt, 1998). This implies that each inter-related level requires more precision of detail, as the spatial and temporal scales become finer.

In order to address this issue of multiple-level decision making, Görgens (1999) proposes the utilisation of an Integrated Catchment Modelling and Information System (ICMIS) which is comprised of a number of models that adequately cover the range of information needs and that is interfaced with a common database with time series and GIS-related viewing abilities. This would allow any specific management information need level be to supported by methods or models of appropriate complexity or feasible input data requirements (Görgens, 1999).

A centralised information system, such as an ICMIS, provides the possibility of highlighting many of the links between the different decision-making levels and different sub-systems, thereby enabling users to gain a more holistic appreciation of a complex situation. They thus offer multiple representations of the available management options by offering combinations of facilities that allow interactive assessment of the various competing aspects of the problem through different models, data visualisation, multi-criteria evaluations and reports (Jewitt, 1998). These systems can be constructed around three main components:

- State information : representation of the environmental resource's states at any given point in time e.g. historical flows, water demands
- Process information: principles governing the resources behaviour over time (simulation models representing a resource's dynamics)
- Evaluation tools: models for transforming raw data into information relevant for decision making e.g. multi-criteria evaluation models, display tools, report and graphic generators etc

Figure 3.7, below, represents a conceptual model of an environmental DSS.

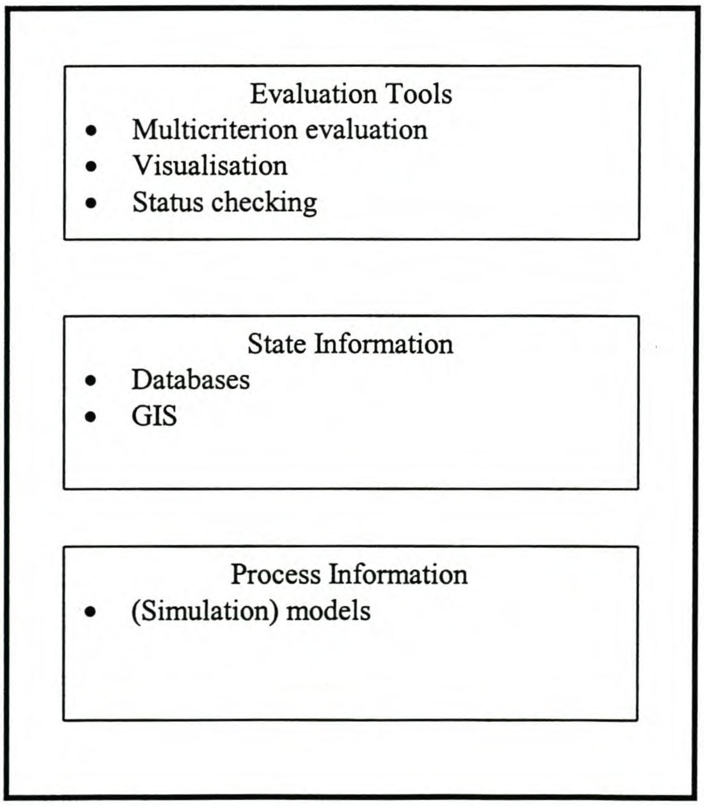

Figure 3.7: An environmental DSS (Jewitt, 1998)

As previously recognised, this information is available in many different forms such as:

- Varying time series (continuous or grab samples, precipitation data)
- Spatial coverages (land use)
- Topographical

and linked to a variety of features such as:

- Point data (monitoring stations, subcatchment exits)
- River reaches
- Spatially distributed form (e.g. land use)

Given that most of the available catchment information is spatially related, it would appear that the most fundamental DSS for CM is a GIS and its relational database. This GIS and related attribute database should thus form a critical underlying part of any DSS.

3.4.1.1 Types of models and DST

In order to address the effective management of catchments, a number of models operating as decision support tools are available. A non-exhaustive summary is provided by Görgens (1999) and includes:

- Overview models - providing a broad summary of water availability/use
- System optimisation models - assessment of reservoir and system yields and operating rules for catchment development and water use
- Demand projection and water use models
- Catchment rainfall-runoff models of coarse resolution for monthly flows, salt loads etc
- Catchment rainfall-runoff models of relatively fine resolution and sensitive to land-use assessment of streamflow reduction and water quality impacts from various landuses
- Hydrodynamic water quality models of river flows and reservoir processes for planning and control of the operation and regulation of river/reservoir systems

The above tools provide water management capabilities from the regional/national NWRS level down to individual catchment and subcatchment level.

3.4.1.2 Concluding remarks on DSS for Catchment Management

Models can be considered useful for generating information about water resource systems at the various levels from subcatchment to national level. Previous modelling approaches often addressed singular management issues with many different models utilised for different conditions. This approach can be considered limited and damaging given the multiple conflicting points of view at different scales.

Models serve as DSS to aid management decision-making so that the various available options can be considered and decisions taken to manage the resource and resolve conflict. As DSS, models provide means for stakeholders and catchment management agencies to assess the possible consequences of their intended actions. The creativity and opportunities for compromise which this process releases is where the real benefit of modelling as a DSS lies.

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Chapter 4 provides a background description of the Great Lotus River catchment. The chapter describes the various reaches of the Great Lotus River main stem. It then focusses on the water quality and quantity sampling methodology and results obtained during the WRC sponsored project on Catchment Management in an urban context (Grobicki *et al.* in press)

Chapter 5 describes one particular deterministic hydrological model, the USEPA sponsored Storm Water Management Model (SWMM). This complex, variable resolution, landuse sensitive, catchment rainfall-runoff model is applied to the Great Lotus River catchment in order to assess the model and its accompanying user interface, PCSWMM98, as a hydrological modelling DSS for Catchment Management.

The application to the Great Lotus River is described in Chapter 6 with the modelling methodology followed, model output and error analysis and a model sensitivity analysis to identify the significant model parameters for calibration. In addition, the limited water quality simulation attempt is described together with the loads generated for Total Phosporus (TP), the significant pollutant in the Great Lotus system. The discussion continues in Chapter 7 where a conceptual framework is presented for the use of hydrological modelling as a decision support tool for catchment management. In addition the efficacy of SWMM, as the model utilised, is discussed.

CHAPTER 4

THE GREAT LOTUS RIVER

The data for this present research was principally collected in a Water Research Commission sponsored project entitled "Integrated Catchment Management in an Urban Context : The Great and Little Lotus Rivers, Cape Town" (Grobicki *et al.*, 192000). This chapter thus serves to give a background to the present research by discussing some of the principal objectives, results and findings derived from the hydrological investigation of the above project.

The Lotus River catchment, situated on the Cape Flats, Cape Town, contains two drainage channels, the Great and Little Lotus Rivers. These channels have been designed and controlled through extensive canalisation, to avoid the flooding of urban areas of the catchment. This approach has resulted in these channels becoming stormwater drains, transporting waste and nutrients in dissolved and particulate forms, and reducing their assimilatory capacity for water quality improvement. The pollutant loads transported by the rivers have placed the receiving water body, Zeekoevlei, under severe ecological stress and it is classified as a hypertrophic system (Harding, 1996b).

The Lotus River Project aimed to establish a blueprint for urban catchment management in South Africa, focusing upon water quality and ecological stability and improvement, as well as on hydraulics and flood control (Grobicki *et al.*, 192000). The objectives included:

(1) to identify major sources of pollution in the catchment, both point and non-point sources;
(2) to carry out a detailed flow gauging study and a water quality sampling programme;
(3) to study the ecology of the river systems, including riverine and benthic invertebrates, and macrophytes;
(4) to develop rehabilitation strategies aimed at improving water quality by instream measures, decanalisation, and the creation of wetlands;
(5) to produce a detailed feasibility study for the upgrading of the Lotus catchment area and Zeekoevlei, with respect to water quality and ecology;
(6) to identify all major stakeholders in the catchment and to develop a working model for community management of the catchment.

The first two objectives entailed a hydrological situation analysis of the catchment due to an observed lack of detailed water quantity and quality data. This was required to identify the hydrological problems in the catchment which become issues for the eventual catchment management plan to address. These objectives resulted in the collection of a detailed database of water quantity and quality data. Given that this forms the backbone of the present research, the methodology, principal results and findings are discussed in this chapter. The remaining objectives, whilst crucial for any integrated approach to management in the catchment, are beyond the scope of this research, and thus ignored.

4.1 Great Lotus River Main Stem Description

The discussion below provides a brief description of the various reaches of the Great Lotus River canal.

4.1.1 Airport Industria to Miller Road

The Lotus River canal starts to the west of the Cape Town International Airport and flows south west through the adjacent Airport Industria area. Detention ponds limit the flow to the N2 to 0.8 cumecs. The river is unlined with large quantities of algae. The canal, after flowing under the N2, flows through the informal settlement area of Barcelona. The canal is earth lined with steep banks resulting in a channel up to 5 metres deep, a base width of approximately 1 m and is approximately 1.6 km long. The lag time (defined for base flow conditions) is of the order of approximately 6 hours. This reach is choked with litter and suffers from a poor visual appearance. The canal servitude is used extensively as a pedestrian access and for livestock grazing. The canal leaves Barcelona and flows into Nyanga/Guguletu. Here it cuts through a waste disposal site upstream of Klipfontein Road before flowing underground through a 900 ∅ pipe to Miller Road.

4.1.2 Miller Road to New Duinefontein Road

For the rest of the reach within Nyanga/Guguletu the canal consists of a 2.88 km long concrete lined trapezoidal channel (depth average = 0.8 m, base width = 1.2 m to 2.04 m) with a small grass lined high flow channel. The photo 4.1, below, is an indication of the Great Lotus River as it flows through Nyanga and Guguletu.

Photo 4.1: Great Lotus River in Nyanga, Guguletu

Stormwater pipework enters the canal at frequent intervals with a number of large stormwater pipes (>1000∅) draining the area, contributing year round flow. The max 50 year flood is calculated to be approximately 21.4 m^3/s (Taylor, 1994)whilst the base flow lag time is approximately 2.4 hours.

The river corridor is well utilised as a pedestrian thoroughfare as well as recreation and the grazing of livestock.

Electrical lighting along selected sections of this reach was upgraded during a recent municipal project attempting to "green" the corridor

Towards the downstream end of this reach, the canal flows past an informal settlement area (Phola Park/Waterfront).

Residents dwelling in shacks in a narrow corridor adjacent to the canal utilise the canal, its servitude and the adjacent open land as a means of sanitation and refuse removal. This can be clearly seen in photo 4.2 below.

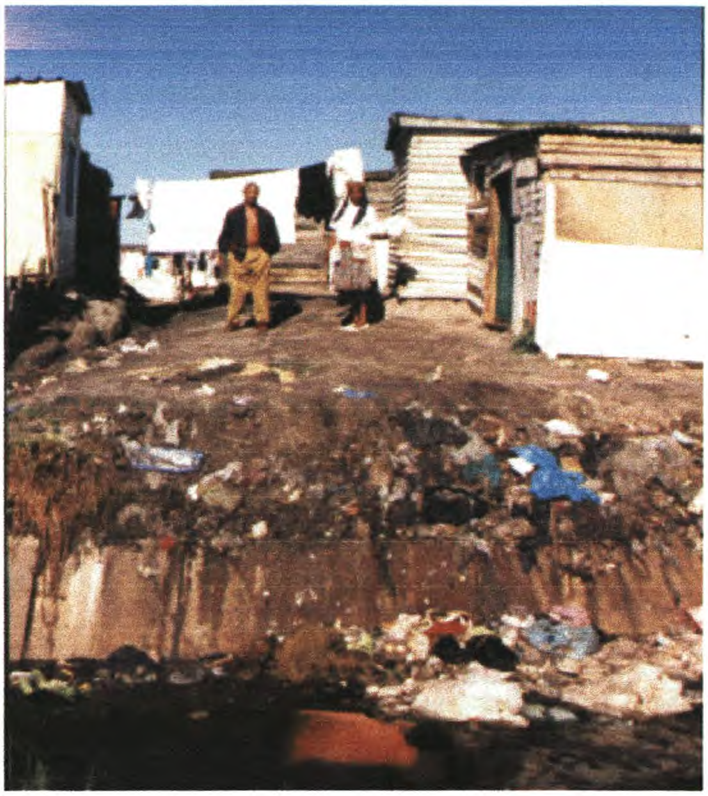


Photo 4.2: Great Lotus River adjacent to informal settlement of Phola Park

Together with sewer overflows into the stormwater network, it results in a poor water quality in the canal with unpleasant odours, evidence of raw sewage and general organic and inorganic litter.

4.1.3 New Duinefontein Road to Vygekraal Road

The canal between New Duinefontein Road and Vygekraal Road was upgraded as a multistage channel approximately 810 m long. It consists of a 3 m wide bottom width concrete lined trapezoidal low-flow channel 0.5 m deep with a wide grassed high flow section (Taylor, 1994). All of the available canal servitude was utilised to create a high flow channel wider than that required to handle the 1: 50 peak flow of 27.8 m^3/s (Taylor, 1994). This is to provide additional flood detention storage. Water quality is poor and gross litter is severe. The baseflow lag is approximately 1.75 hours. A major stormwater pipe draining the light industrial area of Philippi East feeds into the canal in this reach.

A number of detention ponding areas are present in this reach. They collect runoff from the northward draining Weltevreden Agricultural Area. The eastern pond is a natural ponding area and has been retained through the canal upgrading. This pond incorporates the Edith

Stevens Nature Reserve and drains into the canal through a stormwater pipes under Lansdowne Road. This nature reserve is labelled as an *Isoetes* vlei and is characterised by fauna/flora. The western detention pond (Vygekraal Road Detention pond) serves as a flood attenuation facility in addition to collecting flows from the Weltevreden Agricultural Area to the south.

In order to create a natural ponding area the pond was excavated with curvilinear banks. Islands were constructed to provide habitat for aquatic birdlife (Taylor, 1994). Photo 4.3 below shows the detention pond with the constructed islands:

Photo 4.3: Vygekraal Road Detention Pond

The pond attenuates floods due to the limited capacity of the Vygekraal Road culvert. The efficiency of the system was increased by the construction of an entrance weir to the pond.

Flood flows backing up the channel due to the culvert constriction (13.5 m^3/s)are routed over the weir into the pond.

A series of one-way metal gates were built into the weir to prevent silt, polluted low flows and the first-flush flood flows from entering the pond. As the flood flow diminishes the gates permit draining of the pond when the level is below that of the weir crest. Inspection of this entrance weir reveals, however, that the gates have been removed and the entrance is frequently choked with litter and other rubble. Discussions with the Cleansing Department revealed that this is cleaned only on a annual basis prior to the winter rains. It remained choked with litter for the duration of the winter months (*see photo 4.4*), posing a potential flood risk.

Photo 4.4: Entrance Weir to detention pond

4.1.4 Vygekraal Road to Heins Road

Downstream of Vygekraal Road, the canal is an enlarged earthlined channel approximately 6 m wide and 2 m deep catering for the design 1:50 year flood of 13.5 m^3/s. The reach is 950 m long with a base flow lag of approximately 3.75 hours. The channel and the banks are characterised by aquatic and terrestrial vegetation, providing increased ecological habitat, with the river appearing to undergo a visual improvement in water quality. Upstream of Heins Road there is a small offline wetland adjacent to the canal. This is a *Typha* dominated wetland supporting wetland birds and is separated from the canal by an earth berm.

4.1.5 Heins Road to Lansdowne Road

The canal reverts to a concrete lined low trapezoidal channel, 1.02 km long with a 3 m base width and grass lined banks. The design 1:50 year flood flow is 13.5 m^3/s and the base flow lag is approximately 1 hour.

This reach is the most recent of the Lotus River Canal phased upgradings and attempted to incorporate more environmentally friendly design features (Taylor and Duffy, 1996). Instead of the usual straight canal excavation, this reach was excavated with a curvilinear shape to approximate limited river meandering. The concrete lined low flow section was reduced with the remaining section lined with Armoflex® for a total depth of 0.5 m. The high flow section is also overlain with Armoflex® and grassed with a 1 vertical to 3 horizontal slope.

Whilst functioning as an erosion protection mechanism, the Armoflex® provides limited connectivity with the underlying subsoil and allows for vegetative growth through its blocks. This serves to increase habitat diversity with a corresponding increase in biota. The use of curvilinear design and Armoflex®, coupled with local community attempts at increasing amenity value, contribute to reducing the "drain-like" appearance of the canal.

4.1.6 Lansdowne Road to New Ottery Road

This reach is characterised by an enlarged earth lined channel approximately 2.5 km long. The cross section consists of a bottom width between 3 and 6 m with 1vertical to 2 horizontal grassed sloping grass banks. The design 1:50 year flood is 13.5 m^3/s (Taylor, 1994) and the base flow lag is approximately 7 – 8 hours.

This reach flows through an agricultural area, the Philippi Horticultural Area This area is characterised by smallholdings with intensive vegetable cropping. Farms adjacent to the canal abstract water for irrigation purposes.

Photo 4.5, below, is of the Great Lotus River at Springfield Road.

Photo 4.5: Great Lotus River– Unlined canal adjacent to Springfield Road, PHA

Drainage in the adjacent agricultural area results in a diffuse contribution to flow and pollutants in the canal. This diffuse contribution will be shown to be significant in terms of phosphorus loading from the area. The role of the groundwater is significant for this reach and depending on the time of year, either contributes or reduces flow in the canal. During the winter rainfall months, the watertable is high with subsurface flow augmenting flow in the canal. During the drier summer months however, the watertable drops, with a resulting decrease in flow in the canal.

The Springfield Road culvert is characterised by a significant drop off on its downstream side and a concrete stilling basin was constructed to minimise channel and bank side erosion. Below New Strandfontein Road the canal remains an earthlined channel up to 8m wide and flows through a middle income residential area. The canal is characterised by aquatic and terrestrial vegetation. This vegetation increases habitat diversity whilst serving to trap litter where overgrown. There appears to be a visual improvement in water quality when compared to the upstream reaches and the riverine corridor appears utilised for pedestrian access.

4.1.7 New Ottery Road to Ottery Road

4.1.7.1 New Ottery Road to CTM Ottery Canal Confluence

This short reach of 150 m consists of a 11.6 m top width concrete lined trapezoidal low flow channel, 1.2 m deep with base width is 8 m. The design 1:50 year flood flow is 13.6 m^3/s and the base flow lag is approximately 15 minutes. The cross section also includes a wide grass lined high flow channel sloping at 3% towards the lined channel. Flow tends to be shallow and sedimentation occurs. Although the canal is concrete lined this sedimentation permits the establishment of aquatic channel vegetation. The flow pattern becomes braided and the vegetation increases habitat diversity. Flow in the canal is augmented by the Woodlands canal at CTM Ottery Canal Confluence.

4.1.7.2 CTM Ottery Canal Confluence to Ottery Road

This reach whilst remaining a concrete lined trapezoidal canal, is reduced in cross-section and flows for a length of approximately 430 m.. Because of higher shear velocities, this reach is self-scouring. The cross-section consists of a 5 m wide top width channel 1.22 m deep with a base width of 2.21 m. This, together with a grass lined high flow section within the canal servitude, is designed to cater for the design 1:50 year flood of 18.7 m^3/s (Taylor, 1994). The base flow lag is approximately 15 minutes.

The reach flows through a commercial area bounded by Pick 'n Pay and SAB. Historically, natural flood ponding occurred in these low-lying areas and a formal detention pond was thus incorporated into the design of the Pick 'n Pay parking area.

4.1.8 Ottery Road to Klip Road

This reach, characterised by a similar concrete lined trapezoidal cross-section as above, is approximately 1.32 km long with a base flow lag of approximately 1.2 hours. The design 1:50 year flood flow is 19.4 m^3/s (Taylor, 1994). Historically, the reach was characterised by a natural low-lying flood area. This flood area was filled by private developers during a development proposal. To offset this loss in flooded area it was recommended that an additional pond be excavated by the developers.

The resulting detention pond is situated at Sunset Park and, when operating efficiently, attenuates the peak flood in the canal from 19.4 m^3/s to 15.1m^3/s (Taylor, 1994). As the flood level rises it overtops the canal along a length of reduced height and into either side of the detention pond.

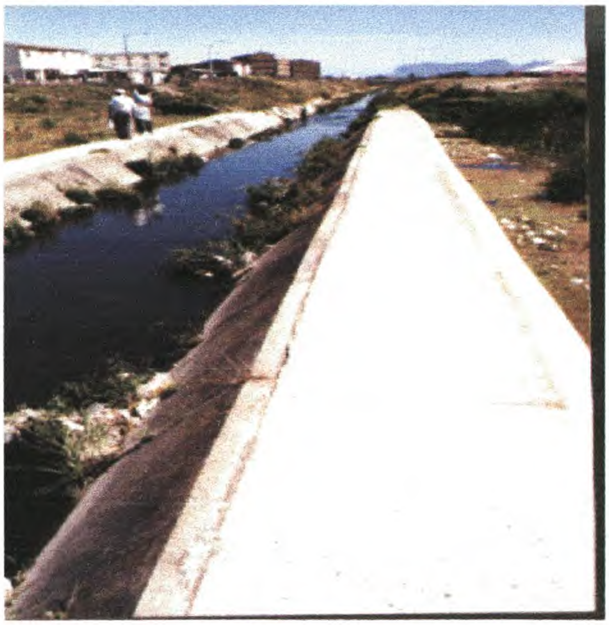


Photo 4.6: Great Lotus River at the Sunset Park Detention Pond, Grassy Park

Photo 4.6, above, shows the overflow wall for this detention pond. Once the floodwaters have passed, the accumulated water in the detention ponds is released back into the canal through outlet stormwater pipes.

4.1.9 Klip Road to Seventh Avenue

As above, this reach consists of a concrete lined trapezoidal section. The reach is 1.1 km, has a design 1:50 year flood flow of 23.9 m^3/s at Seventh Avenue (Taylor, 1994) and a base flow lag of approximately 30 minutes.

Minor flooding outside of the canal servitude is expected for 1: 50 year floods and where the level is above property floor levels, flood levees were constructed. Downstream of Seventh Avenue a drop structure and energy dissipater was constructed. This is the beginning of an unlined section of canal to Zeekoevlei and was constructed to provide sufficient hydraulic gradient and minimise channel erosion.

4.1.10 Seventh Avenue to Fisherman's Walk

This reach, approximately 500 m long, drains into Zeekoevlei and is thus the outlet of the Great Lotus River. It is an enlarged earthlined channel, with a varying base width of 10.4 m to 14 m, excavated with a curvilinear profile. The design 1:50 year flood flow is 28.2 m^3/s. The water level of Zeekoevlei is such that it causes a backwater effect to flood this channel thereby masking the end of the Great Lotus and beginning of Zeekoevlei. For the purposes of flow measurement, to offset the variation in flow regimes for this reach, it was decided to utilise the 7th Avenue culvert as the downstream point of the Great Lotus River.

Upstream of Fisherman's Walk, a litter trap in the form of a fence across the river, serves to collect gross litter and prevent water hyacinth from moving upstream.

During periods of drawdown, this fence is exposed and is cleaned by local authorities.

4.2 Historical Data for the Lotus River Catchment

4.2.1 Historical flow monitoring

Although much engineering work has been done on the Lotus Rivers, actual flow characteristics and chemical loadings in the system have never been quantified. As support to an ICM process, it is therefore deemed important to carry out a thorough flow gauging study and a water and sediment sampling program.

Detailed design flood calculations were performed for the Great Lotus River by HKS / Gibb Africa using synthetic rainfall and storm duration data. Flood peaks were calculated for the 1: 2 and 1 : 50 year rainfall events with these discharges used in the design of the canal upgrades. The above calculations were event simulations with no validation through actual flow measurements.

4.2.2 Historical water quality monitoring

Historically, water quality sampling has been undertaken since 1981 in both of the Great and Little Lotus Rivers as well as in Zeekoevlei. This sampling is done by the Scientific Services Branch of the Cape Metropolitan Council. Sampling in the Great and Little Lotus Rivers is restricted to one site on each river (at 5th Avenue in reach between Klip Road and Seventh Avenue in section 4.2.9 below). Samples are taken monthly and analysed for both physical and chemical parameters. The results are stored on computer, the parameters of which are listed below:

Total Kjeldahl Nitrogen (TKN)
Total persulphate oxidisable nitrogen (TPON)
Dissolved ammonia nitrogen (NO_2)
Dissolved nitrate + nitrite (NH_x)
Total phosphorus (TP)
Dissolved total phosphorus (TP)
Dissolved reactive phosphorus (SRP)
Dissolved reactive silicon (Si)
Chlorophyll a corr for phaeophytin

Water temperature
Dissolved oxygen (DO)
Oxygen saturation
Secchi disk transparency
Electrical conductivity (Ec)
Total suspended solids (TSS)
Total alkalinity
Phaeophytin a
Faecal coliforms

Table 4.1: Water quality parameters measured in Great Lotus River

Limitations of this sampling program are that it only occurs on a monthly basis and does not include any stream discharge observations. The sampling program does, however, provide a database of the long term water quality trends for the Lotus Rivers and Zeekoevlei and thus provide an indication of the variables of concern for the system. The variables of concern are those aspects of water quality in the river, either natural or anthropogenic, which actually or potentially exceed the regional water quality guidelines or users requirements and therefore need to be managed if water quality requirements are to be met. (O'Keeffe *et al.*, 1993)

In order to place the water quality concentrations in context, it is first necessary to detail the water quality guidelines to be followed. Zeekoevlei is used extensively for boating and other aquatic sports and as such the water quality levels for both aquatic ecosystems and recreational usage are assessed. These guidelines, as put forward by DWAF, are to ensure that the quality of water resources remains fit for recognised water uses and the viability of aquatic ecosystems is maintained.(DWAF, 1996d)

The guidelines for aquatic systems are essentially a specification of the water quality required to protect fresh water aquatic ecosystems as well as the qualitative and quantitative criteria for toxic, non-toxic constituents and trophic status for nutrients. (DWAF, 1996d) For the purposes of this appraisal, the Target Water Quality Range (TWQR) is detailed. This is compared to the long term average from 1981 to 1997 as well as the 95 percentile, the concentration value that should not be exceeded for more than 5% of the time.

Parameter	**DWAF TWQR (mg/*l*)**	**Great Lotus (5th Ave) (mg/*l*)**
Ammonia	≤ 0.007	Min = 0.0039 95 percentile = 0.0112 Mean = 0.77 Max = 5.42
Total Nitrogen (Inorganic)	< 0.5 (oligotrophic) 0.5 – 2.5 (mesotrophic) 2.5 – 10 (eutrophic) > 10 (hypertrophic)	Min = 1.25 95 percentile = 1.346 Mean = 6.49 Max = 21.7
Total Phosphorus (Inorganic)	< 0.005 (oligotrophic) 0.005 – 0.025 (mesotrophic) 0.025 – 0.25 (eutrophic) > 0.25 (hypertrophic)	Min = 0.14 95 percentile = 0.2114 Mean = 0.703 Max = 2.31
Total Suspended Solids	< 100	Min = 1 95 percentile = 0.0112 Mean = 32 Max = 400

(Scientific Services, 1981-1997 and (DWAF, 1996d)

Table 4.2: DWAF Water quality guidelines compared to Great Lotus River long term average

The above table 4.2, highlights the variables of concern for the Great Lotus River. The canal can be seen to be nutrient-rich with phosphorus and nitrogen concentrations in the hypertrophic range. Given that the concrete lining of the Great Lotus results in pollutants all effectively being transported to the receiving water body, it is not surprising that Zeekoevlei, itself, is hypertrophic (Harding, 1996b)

The Figure 4.1, below, is an indication of the variation of TP concentration as measured by the Scientific Services department at 5th Avenue. This point is approximately 1 km from the start of Zeekoevlei and thus provides a fairly representative picture of the pollutants transported to Zeekoevlei.

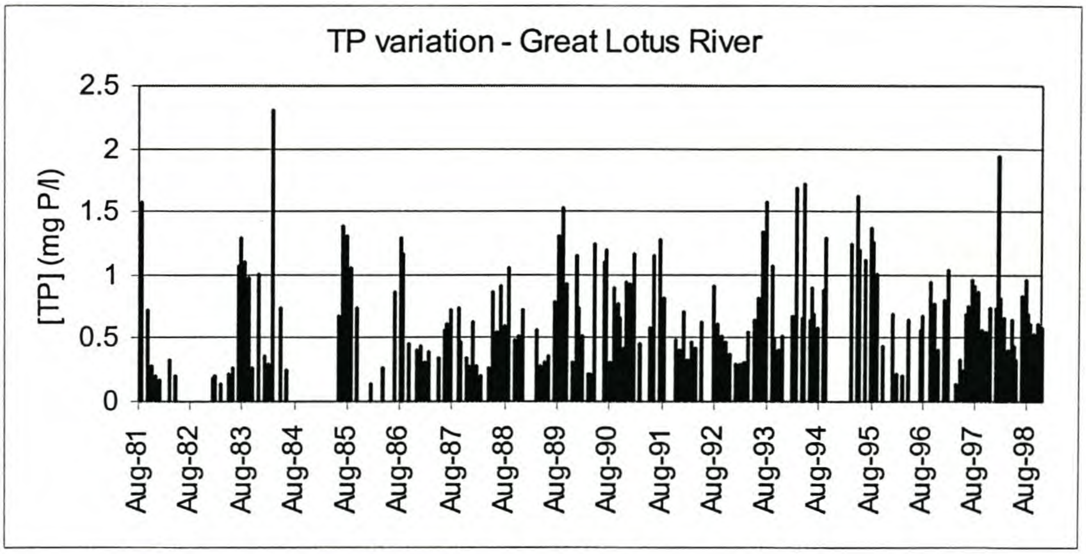
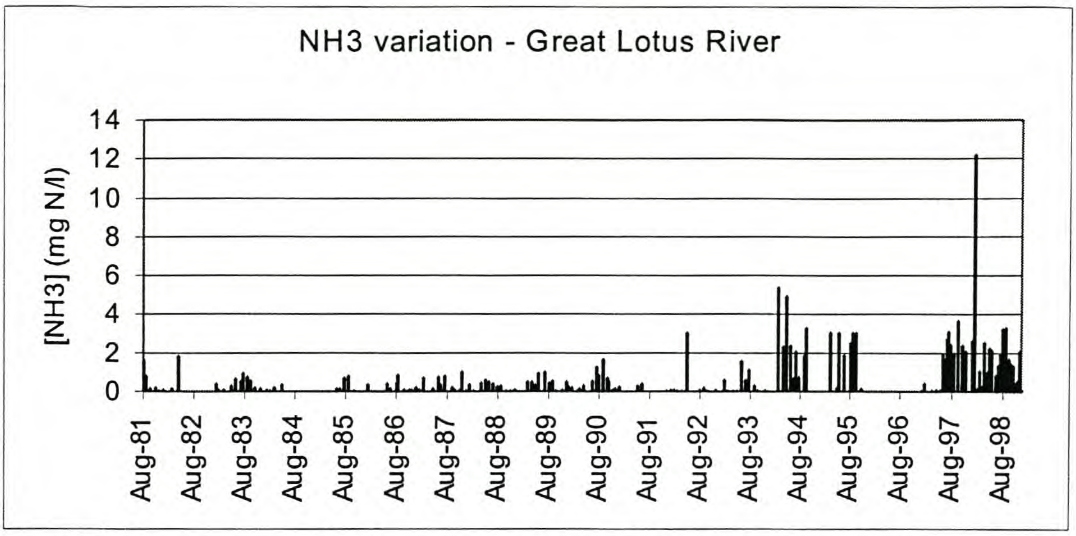


Figure 4.1: Total Phosphorus concentration in the Great Lotus (5th Avenue)

Analysis of the above plot of Scientific Services data for 1981 to 1998, shows that it is difficult to draw any significant conclusions about the variation of TP for the period. Although there appears to be a seasonal variation with higher concentrations during the higher rainfall season, the trend is not consistent for the entire period. Comparison with mean annual rainfall figures for the catchment for 1990 - 1998 (see following section 4.4.1) shows that no significant relationship seems to exist between the rainfall and resultant TP runoff concentrations either. (An assessment of TP sources and relative contributions is made in section 4.6.3.2)

The above uncertainties are possibly due to the extent to which data is missing from the collected database. These omissions create uncertainty in estimating the seasonal trends as well as, in all likelihood, underestimating the peak concentrations.

The plot below, for the same period, is of the variation in ammonia for the Great Lotus River



(TN analysis began January 1996, thus ammonia is selected to show long term annual trends).

Figure 4.2 : Annual variation in Ammonia concentrations – Great Lotus River

Analysis of the above figure 4.2, again shows the large omissions in data. It is impossible to draw any convincing conclusions as to any seasonal variation in concentration. What is apparent, however, is the significant increase that can be noticed from 1994 onwards. This is possibly due to the relatively recent growth in semi formal and informal settlements, with corresponding increases in polluted runoff. (Section 4.6.3.1 below discusses sources of nitrogen in the Great Lotus River catchment)

As discussed the Scientific Services database includes a number of other contaminants. The long term variations of the relevant pollutants are plotted and appear in the attached Appendix.

In addition to the above nutrient pollutants, because the downstream receiving water body, Zeekoevlei, is extensively utilised for aquatic sports including boating and angling, it is necessary to evaluate the water quality guidelines in terms of recreational water usage. These guidelines differentiate between a range of impacts due to water quality changes including health impacts, human safety, aesthetic impacts and economic impacts. Scientific Services have maintained a record of indicator organisms including Faecal coliform bacteria (primary indicator of faecal pollution) and *Escherichia coli* (specific indicator of faecal pollution originating from humans and warm blooded animals)

Organism	TWQR (counts/100ml)		Great Lotus
	Domestic Use[a]	Recreational Use[b]	
Faecal coliform	0	0 – 1000	Mean = 1.78 e 06 Min = 3 e 03 Max = 47 e 06
Escherichia coli	0	0 – 130	Mean = 1.78 e 06 Min = 3 e 03 Max = 47 e 06

(Scientific Services, 1995 – 1998, a - (DWAF, 1996a)b - (DWAF, 1996b)

Table 4.3: Bacteriological counts of the Great Lotus River as compared to DWAF guidelines

Analysis of the above table shows that both indicator organisms are significantly higher than the accepted guideline. The levels correspond to those of raw sewerage and as such constitute a significant health risk for any interaction with the water. Although the values obtained in the Great Lotus for the two indicators are similar, the data is not identical but shows that *E coli* is the major component of the faecal coliform count. Given the urbanised nature of the catchment this is consistent with research that shows *E coli* comprise up to 97% of the coliform bacteria of human faeces. (DWAFb, 1996)

The variables of concern for the Great Lotus River are therefore seen to be:

- Total Nitrogen (TN)
- Total Phosphorus (TP)
- Indicator organisms (Faecal coli, *E coli*)
- Ammonia

In concluding the discussion on the historical water quality database, it is noted that the Scientific Services sampling program does not include any flow measurements. There have thus been no attempts to relate any of the above pollutant concentrations to flow. It will be shown in the following sections that a comprehensive water quality programme requires that flow measurements be undertaken in conjunction with sample analyses. In addition to estimating the relative contributions of each source, relating concentration to flow thus enables actual chemical loadings to be calculated for the system from the supplied data.

Furthermore, in assessing the Scientific Services database, there are frequent gaps in the sampling data or even complete omissions. This is the case for parameters such as total alkalinity and dissolved total phosphorus which were last measured in November and March 1995 respectively (Scientific Services Records 1981-1997). As discussed, the omissions create uncertainty in estimating seasonal trends as well as potentially underestimating peak concentrations. In addition to the need for pollutant loadings, the above sampling omissions justify the development of a detailed project sampling programme for the Great Lotus River.

4.3 Sampling programme methodology

As discussed in the opening paragraph of this chapter, the hydrological objectives of the Lotus River Project included:

- To identify all sources of pollution in the catchment under consideration, both point and non-point sources.
- To carry out detailed flow gauging, including the mapping of surface drainage paths.

In order to address these objectives, a detailed sampling programme was thus undertaken in both the Great and Little Lotus Rivers. Flow measurements were carried out concurrently with the water quality sampling program to determine accurate pollution loadings for the system. This programme was carried out for 14 months (July 1997 - September 1998). Although this period is insufficient to establish historical trends for the river, it identified tributary and non-point pollution sources and provided sufficient data regarding pollutant loads for individual stretches of the river.

4.3.1 Water Quality and Flow data

In order to identify pollutant sources, the sampling program entailed sampling at all significant tributary inflows. The sample points were selected based on a review of the engineering hydrological documentation and site visits. Significant tributary inputs to the Great Lotus River were found to include inflows ranging from stormwater input from urban sub-catchments to agricultural runoff from the Philippi and Weltevreden Horticultural areas. The majority of tributaries to the Lotus River canal are stormwater inputs, dry for significant periods of the year and contributing minimal flows for the remainder. It would be prohibitively expensive and impractical to sample all stormwater inputs. The above selected sample points thus refer to significant tributary inflows relative to the flow in the canal.

4.3.1.1 Discrete sampling

The discrete sampling entailed collecting water samples for chemical analysis as well as recording flow characteristics at each sample point. Samples were taken on a weekly basis for the winter rainfall period of 1997 and then scaled back to a monthly basis for the summer base flow situation (September 1997). The winter period of 1998 was also sampled more frequently, on a fortnightly basis, until the end of the sampling period in September 1998.

Samples for analysis were taken both upstream and downstream of the inflow as well as in the tributary flow itself. Average stream velocities were obtained using a propeller-type velocity meter (OTT model C2 small current meter) with readings taken at 0.6 of the depth of the canal . At each point, three measurements of the velocity and flow depth were taken, and an average flow calculated at each point using the Area-velocity method with knowledge of the canal cross section.

In order to ensure the downstream sampling site provides a reliable estimate of the water quality at that site, it is important that the point be located beyond the minimum distance required for complete mixing to take place. This distance, depending on flow conditions, can be calculated using the equation of (Thomann and Mueller, 1987) to approximate the minimum distance from the influent point to the point of complete mixing:

$$L_m = 8.6 * \frac{U \times B^2}{H} \qquad \text{(4.1)}$$

where L_m = distance to complete mixing (m)

U = average stream velocity (m/s)

B,H = stream width (m), depth (m)

Where tributary flow measurement was impossible due to practical physical constraints, the flow calculation was through consideration of the continuity equation. The mass balance equation is then used to check the accuracy of the data collection.

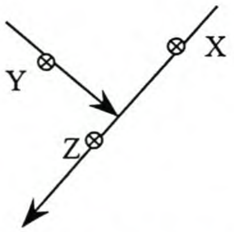


Figure 4.3: Schematic of tributary inflow [Y] joining main flow [XZ]

The continuity and mass balance equations are as follows with Q_x and Q_z measured at X and Z respectively:

$$Q_x + Q_y = Q_z \qquad (4.2)$$

$$C_x \,.\, Q_x + C_y \,.\, Q_y = C_z \,.\, Q_z \qquad (4.3)$$

where Q = discharge at point (m^3/s)

C = pollutant concentration (mg/l)

The table below shows the location of the discrete sampling points as well as the distance of the point from the source. The Great Lotus contributes the majority of flow and pollutant loading to Zeekoevlei and is thus treated in more detail.

Sampling No.	**Distance from source (km)**	**Location - Great Lotus River**
SP 1	0.49	Below N2 culvert
SP 2	2.43	Above NY3A culvert
SP 3	-	In NY 3A stormwater inflow
SP 4	2.46	Below NY 3A culvert
SP 4a	4.34	Downstream of Nyanga/Guguletu
SP 5	4.83	Upstream of Philippi East/Crossroads inflow
SP 6	-	In Philippi East/Crossroads inflow
SP 7	4.88	Below Philippi East/Crossroads inflow
SP 8	5.27	Upstream of Vygekraal Road detention pond
SP 9	-	In Vygekraal Road detention pond
SP 10	5.31	Downstream of Vygekraal Road detention pond
SP10a	7.35	Upstream of Lansdowne Road culvert
SP 11	8.51	Springfield Road culvert – **datalogger**
SP 12	10.00	Above CCC confluence
SP 13	-	In CCC confluence
SP 14	10.04	Downstream of CCC confluence
SP 15	11.77	Above PHA outflow (2) (Klip Road)
SP 16	-	In PHA outflow (2)
SP 17	11.81	Below PHA outflow (2)
SP 18	12.89	Upstream of 7th Avenue culvert

Sampling No.	**Location – Little Lotus River**
SP 19	Upstream of Seventh Avenue culvert
SP 20	Upstream of Klip Road culvert
SP 21	Adjacent to Robin Road

Table 4.4: Sample points of the Great and Little Lotus Rivers

Sample points 4(a) and 10 (a) above, were selected after an initial set of samples were taken. SP 4(a), situated below Guguletu, enables the total contribution of the formal and informal residential areas of Nyanga and Guguletu to the pollution loadings to be calculated. Sanitation and domestic waste collection services are inadequate or non-existent in this area, with severe implications for the water quality in the river channel. SP 10(a) was selected as it is at the start of a 2.5 km stretch of unlined canal, and the data from this point may therefore be used to gauge the assimilatory capacity of this unlined section in reducing pollutant concentrations.

The discrete samples were collected in 500 ml HDPE sample bottles and transported to the Scientific Services Branch of the Cape Metropolitan Council for laboratory analysis. The samples were analysed for the following parameters :

- Total Oxidisable Nitrogen (TN)
- Total Phosphorus (TP)
- Dissolved Reactive Phosphorus (SRP)
- Chemical Oxygen Demand (COD)
- Total Suspended Solids (TSS)
- Total Volatile Solids (TVS)
- Conductivity (EC)

4.3.1.2 Continuous measurement

In addition to the grab samples at the selected sites, flow was monitored continuously in the Lotus River at one point. A continuous data logger was installed in July 1997 on the Great Lotus River at the Springfield Road culvert. The site is isolated from populated areas and was selected to diminish the threat of vandalism. The culvert is box shaped and characterised by a large drop-off into a downstream concrete lined stilling basin. This drop-off ensures that no downstream backwater effects will influence the data measurement.

The datalogger consisted of an automatic sampler (ISCO® 6700) with an interface module for various sensing probes. It contained an Area Velocity Flow module with a probe that continuously measured flow velocity and flow level. The module measured average velocity using ultrasonic sound waves and the Doppler effect (ISCO, 1996). Flow level in the culvert was measured by an internal differential pressure transducer. The difference in pressures exerted by the flow and the atmosphere is recorded as the hydrostatic pressure. Given that pressure is proportional to stream level, the module thus calculated stage from the hydrostatic pressure (ISCO, 1996).

The logger was housed in a secure stainless steel box securely mounted above the culvert. The probes were mounted on a bracket bolted to the concrete base of the canal. Level and flow measurements were taken on a ten minute interval resulting in a continuous database of the flow. The data was stored by the logger and downloaded to a portable notebook computer using Flowlink® software (ISCO, 1995). Analysis of the data was undertaken using Flowlink.

Since installation of the instrument, large fluctuations in the recorded flow velocity were observed. This rendered the Area Velocity method of flow calculation inaccurate. A theoretical stage discharge relationship was thus established for the culvert using Manning's equation (with knowledge of the dimensions and physical characteristics of the culvert) whilst considering stream drawdown effects due to the downstream drop-off. The stage-discharge relationship is as follows, the accuracy of which was verified using the Ott velocity meter and Area-velocity calculation of discharge:

$$Q = 11.418 * h^{1.6306}$$

where Q = flow (cumecs)

h = stage (m)

Flows were thus calculated using level measurements with the probe situated in the middle of the culvert to minimise entrance effects.

The datalogger collected a detailed flow record at ten minute intervals for the period of the sampling programme. By relating rainfall to the continuous flow measurements, rainfall-runoff relationships could thus be investigated together with an analysis of the catchment dynamic response.

4.3.1.3 Storm Event Sampling

In order to obtain an understanding of storm related river water quality processes, the automated sampler was programmed to capture storm events greater than a certain threshold flow. Internationally, research has found that highest pollutant loads are generally transported during flood events with maximum mobilisation around the flood peak (Huber, 1993b), (Chiew and McMahon, 1998b). The automated sampler was thus programmed on a flow volume proportional basis rather than a fixed time interval to ensure maximum samples are taken at the peak. In effect, the greater volume rate transported during the flood peak, results in maximum sample frequency around the peak. As the flow drops off, so does the rate of sample frequency.

In order to program the sampler effectively, it was thus first required to gain some understanding of the flow regime of the Great Lotus River. As discussed, no previous flow measurements had ever been made. Through a comparison of the return period of rain events with the corresponding runoff volume monitored by the datalogger, it possible to determine the storm event most desired to capture, the threshold flow from which to begin sampling as well as the volume interval at which the sampler would take samples.

The monitored discharge from a storm event with a return period of 1 in 6 months was selected initially as a desirable event to capture. The accumulated runoff volume obtained from the datalogger for this event was divided by 24 (the number of bottles in the sampler) to obtain a sample frequency with the threshold flow was set just above the winter base flow condition.

Samples were collected within 2 days of the stormevent and analysed by the Scientific Services Department for non-reactive contaminants: TN, TP, TSS, TVS, pH and EC. This was to offset the possible error through reactive contaminants undergoing transformations whilst stored in the automated sampler and resulting in an inaccurate representation of the actual storm event.

A total of six storm events were captured with only three being of sufficient duration to enable adequate samples to be taken. The results and plots of pollutant variations during an event are shown in the results section.

4.3.2 Heavy metal and Sediment Analysis

The Lotus River catchment includes a variety of landuse types including Industrial, Light Industrial and Agricultural areas. Significant transport corridors are located within the catchment including a national freeway as well as major arterial roads. A number of farms along the length of the river abstract water for irrigation purposes.

Included within the baseline assessment it was thus deemed necessary to assess potential heavy metal concentrations in the Lotus River. These were undertaken quarterly on sediment and water samples and analysed for:

Cadmium (Cd)
Chromium (Cr)
Cobalt (Co)
Copper (Cu)
Iron (Fe)
Zinc (Zn)
Lead (Pb)
Manganese (Mn)
Nickel (Ni)

Samples were collected at five points in the Great Lotus (three sites unlined, two sites concrete lined) on two separate occasions, once towards the end of winter (September 1997) and once in summer (February 1998). The table below shows the location of the sample points that are adjacent to significant transport corridors, below the informal settlement area and in the Philippi Horticultural Area.

Sampling number	**Distance from source (km)**	**Location** **Great Lotus River**
1	0.49	Below N2 culvert
2	4.34	Below Guguletu
3	7.35	Below Lansdowne Road culvert
4	8.51	Above Springfield Road culvert
5	12.89	7th Avenue stilling basin
6	-	Fisherman's Walk (Little Lotus River)

Table 4.5: Sample points for heavy metal analysis

Samples 1, 3 and 4 are located in unlined sections of the canal and sediment cores up to 0.75 m deep were taken. Sample points 2, 5 and 6 are in concrete lined sections that are characterised by significant sediment build up. In an attempt to assess the heavy metal concentrations at these points, the sediment was scooped up into jars. For the water column, samples of 2 litres were collected at each site.

The samples were analysed by the Scientific Services branch of the Cape Metro. The analysed concentrations were compared to the DWAF water quality guidelines for aquatic ecosystems to assess the level of heavy metal pollution within the catchment.

4.3.3 Organic Compounds

Due to the intensive agricultural activities within the Great Lotus catchment, it was deemed necessary to conduct an identification of possible Red List substances and pesticides in the system. Samples were collected on a particular day (18/08/97) and organically screened by the Building Technology Division of the CSIR (Pretoria). Discussions with CSIR revealed that a significant proportion of the Red List substances are unavailable in South Africa and are thus unlikely to be found within the Great Lotus catchment. The organic analysis was thus undertaken for chlorinated and non-chlorinated hydrocarbons and phenolic compounds.

4.3.4 Protozoan parasites

Additional samples were collected and analysed for protozoan parasites principally, *Giardia* and *Cryptosporidium parvum*. These species are recognised as important pathogens causing diarrheal disease in humans and animals. They generally occur in low numbers in water environments however a minimal infectious dose may be as low as a single cyst (*Giardia*) or oocyst(*Cryptosporidium*) (Grabow, 1996)

Collection sites corresponded to two stormwater pipes in Guguletu known to contribute high faecal coliform counts to the Great Lotus River (Scientific Services Data, 1998) as well as Springfield Road in Philippi Horticultural Area and 7th Avenue, considered the downstream point of the Great Lotus River.

Ten litre samples were collected at each point in the Great Lotus River on the 27/08/97 and analysed by the Water, Environmental and Forestry Technology Division of the CSIR.

4.4 Results and discussion

4.4.1 Precipitation in Great Lotus River catchment

A number of organisations are involved in the collection of meteorological data for the catchment. The Cape Town Weather Office, situated at the Cape Town International Airport, thus monitors rainfall for the headwaters of the catchment. In addition to this, there are a number of automatic rainfall gauges in the catchment monitored initially by the Cape Town Municipality (CTM) and now under the jurisdiction of the Catchment Management Department of the Cape Metropolitan Council (CMC).

The CMC gauges are generally of the tipping bucket type and thus facilitate the determination of short interval 5 or 10 minute rainfall periods. This is significant given the dynamic nature of a hardened quick response urbanised catchment. In order to accurately determine rainfall runoff relationships for these catchments it is imperative that short interval rainfall periods are available.

Data from three of these gauges has been collected for the period of discussion. The extent of the catchment which they cover was determined through the use of Theissen polygons and is listed below:

Rain gauge	Catchment Area	% of Total Area
Cape Town Weather Office	28.068	49%
Groenvlei	27.026	48%
Strandfontein	1.666	3%
Mitchell's Plain	-	-

(Morrison, 1998)

Table 4.6: Precipitation gauges in the Lotus River catchment

Analysis of the records showed that a total of three weeks data was missing for the Groenvlei gauge for 1997. The rainfall was estimated for this period based on interpolation of the three other gauges. The figure below depicts the Mean Annual Precipitation (MAP) as measured at the Cape Town Weather Office.

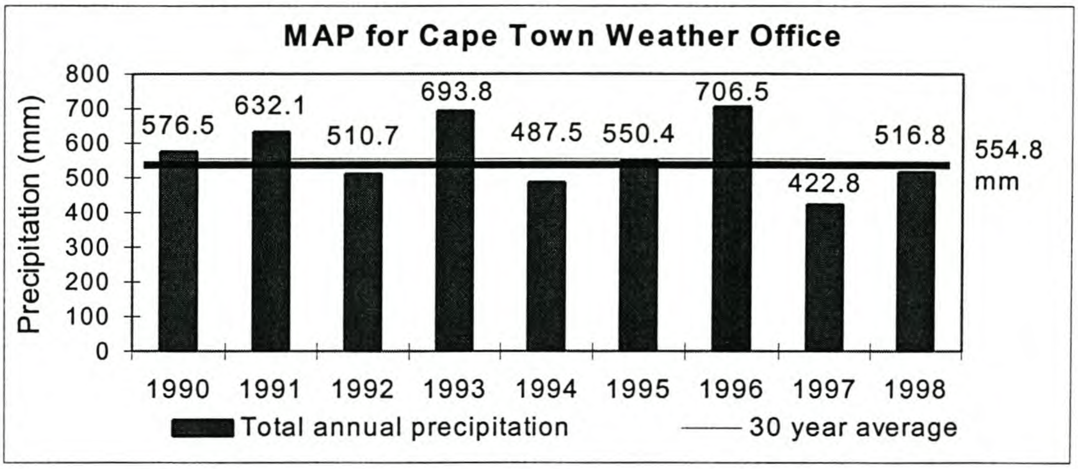


Figure 4.4 : MAP for Cape Town Weather Office

The figure depicts the MAP for the period 1990 to 1998. In addition, the 30 year average of 554.8 mm for the Weather Office is plotted to place the rainfall in context. Analysis of the precipitation records, show that 1997 was characterised by approximately 30% less rainfall than the long term 30 year average. This has implications for the pollutant washoff characteristics of the catchment during the study period. It was thus imperative that the water quality and flow gauging sampling programme be maintained for another season in order to be able to make reliable recommendations based on the collected data. Records for 1998 revealed that the MAR was just under 10% less than the 30 year average and thus is a far more characteristic representation of the annual rainfall as experienced in the catchment.

4.4.2 Flow data

The graph below depicts the variation in flow, plotted on a 10 minute interval, as recorded by the Springfield Road datalogger. The period depicted is for a year of runoff beginning in July 1997, the start of the sampling program. The highlighted blocks indicate the days on which discrete grab samples were taken at the site.

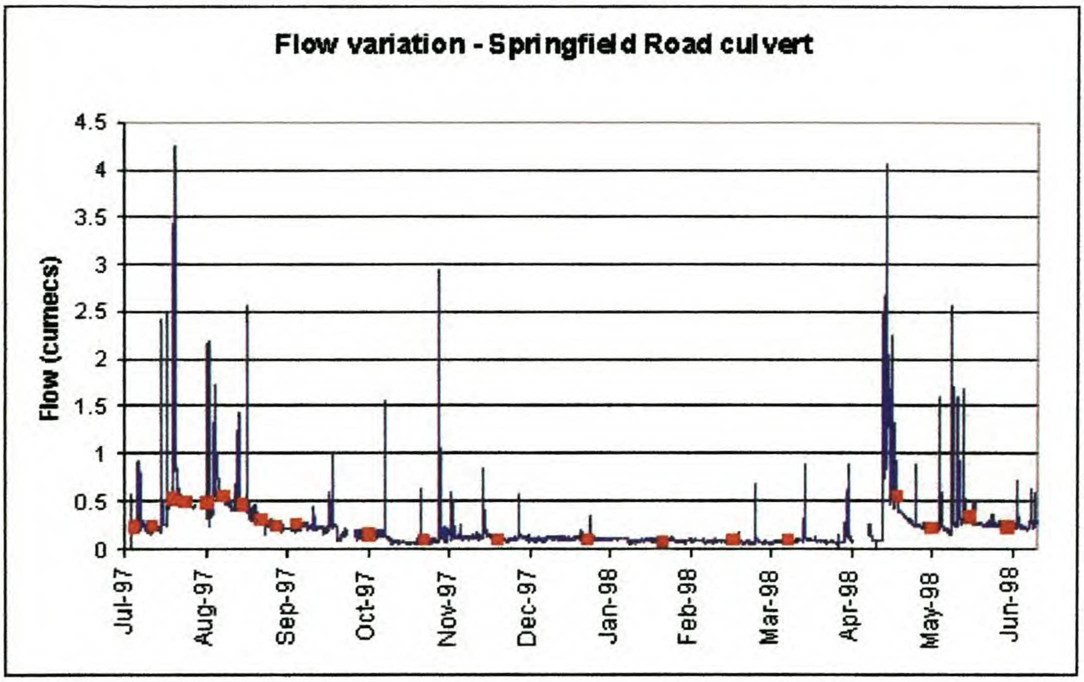


Figure 4.5: Flow variation – Springfield Road, Great Lotus River canal

The winter period ending September 1997 was sampled intensively on a weekly basis. This was then scaled back during the summer base flow conditions to a monthly interval. Although the peak flood flows fell between the discrete sampling days, the sampling program nonetheless managed to obtain a fairly representative picture of the higher winter baseflow situation. Of interest to note are the storm events during October and November of 1997. These events are highly unseasonal and were characterised by high peak flows but low total runoff volume. This will be discussed in more detail in the following section assessing the annual catchment runoff.

As stated previously a principal aim of the sampling program was to identify the major point and non-point contributions to the Great Lotus River. These terms can be defined as follows:

- "point source" - a source that discharges through a conduit at a known location such as from an industry or municipal wastewater treatment plant.
- "non-point source" (or diffuse source) refers to a source from flow distributed over or through the land surface. (Huber, 1993b)

This is echoed by Chiew *et al.*, (1997) who submit that "point sources are those where the polluted water is discharged at a single location – such as a factory or WWTP. Diffuse sources, on the other hand, are those where polluted water is generated from a large area and flow into the drainage system at more than one point."

As previously mentioned, for the purposes of this report, it is assumed that flow from a single location, i.e. a factory or wastewater treatment works is termed a *point source* contribution whilst stormwater collected over a catchment and discharged into a river via a pipe, is a *tributary source* to that river. Tributary sources are therefore strictly outlets for diffuse source contributions with the following land use types being regarded as examples of having non-point source contributions: urban, agricultural, mining and undeveloped (Huber, 1993a).

The Great Lotus River catchment is characterised by few industries and no wastewater treatment plants discharging into the canal. The majority of pollution contributions are therefore from non-point or diffuse sources, i.e. urban residential and agricultural areas, that enter the canal as tributaries. These non-point sources originate principally from rain events and follow the temporal and spatial characteristics of rainfall to a large degree (Huber, 1993a).

In order to assess the relative contributions to the Great Lotus canal, data from the discrete sampling programme is selected and plotted longitudinally. Analysis of the above annual runoff plot indicates that the discrete sampling taken on the 01/09/97 is after a period of sustained rainfall and should thus provide a good indication of the locations of the various tributary sources. As discussed the sample locations were selected at significant stormwater inlets and agricultural channels.

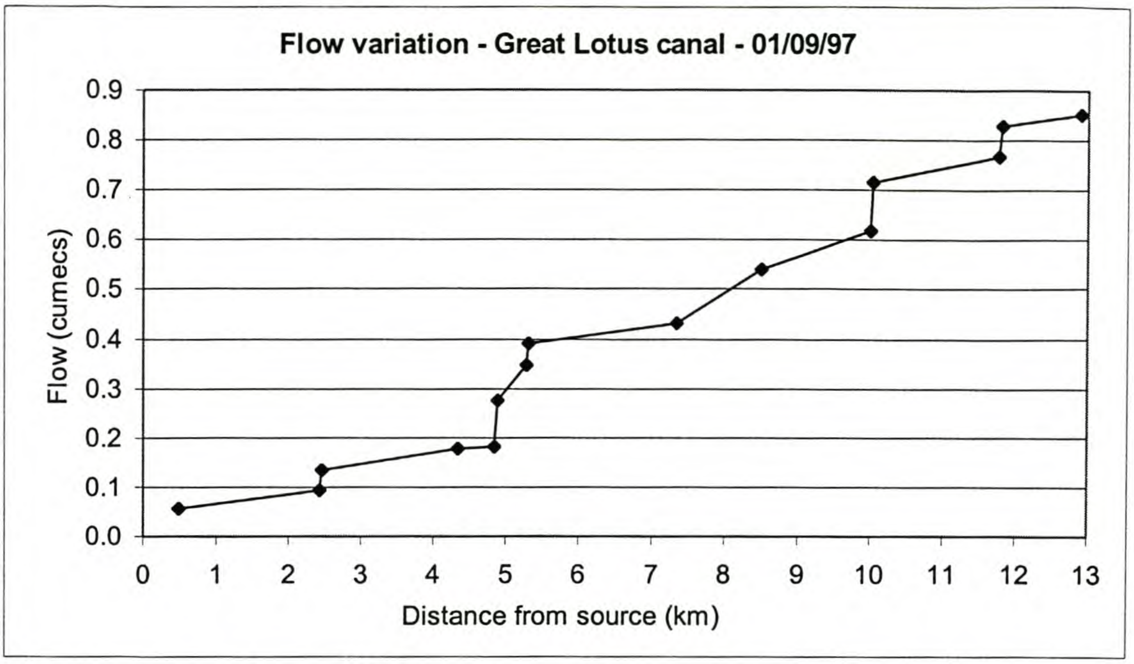


Figure 4.6: Flow variation – 01/09/97 – Great Lotus River

The above flows correspond to a relatively high flow situation. Step changes in flow are due to tributary contributions whilst gradual increases are due to diffuse sources. Significant sources are thus at:

Distance from source	**Contribution**	**% flow contribution**
0.5 – 2.4 km	Diffuse source contributions from Barcelona and upper part of Nyanga/Guguletu	4.77
~ 2.4 km	Tributary source at NY3 stormwater pipeline draining significant portion of Nyanga and Guguletu	5.9
2.4 – 4.3 km	Diffuse source contributions from Nyanga/Guguletu and Phola Park	5.3
	Total contribution of Nyanga, Guguletu, Barcelona	*16*
~ 4.8 km	Tributary source draining Crossroads, Philippi East, Philippi West and Browns Farm	11.8
4.8 – 5.3 km	Diffuse source along Lansdowne Road	8
~ 5.3 km	Vygekraal Detention pond draining PHA subcatchment 140	5.1
~5.3 to 7.3 km	Unlined section along Lansdowne Road permitting groundwater influence	5.15
~7.3 to 10 km	Unlined section through PHA and Turfhall Estate permitting groundwater and subsurface irrigated flow	23.8
~10 km	Tributary source from Lansdowne Wetton Road Corridor	12.2
~10 to 11.8 km	Diffuse source from residential area of Grassy Park	6.66
~11.8 km	Tributary source from subcatchment of PHA	7.7
~11.8 to 12.9 km	Diffuse source from Lotus River residential area	2.9

Table 4.7: Flow contributions to the Great Lotus River

The Cape Flats is characterised by sandy soils and flat topography. The water table exhibits a high seasonality with water level varying between 2 and 5 m below ground level. Depression areas are often inundated with open standing water during the winter months. For the unlined sections of the canal flowing through the Philippi Horticultural Area, this results in the groundwater augmenting flow in the canal during the high water table winter months. This can be seen in the above plot of the longitudinal flow variation with diffuse contributions especially between ~ 7.5 km and 10 km.

Surface runoff to the Great Lotus appears to be mostly from the urbanised catchments. Although the residential settlements of Nyanga and Guguletu exhibit low hydraulic effectiveness (gutters connected to the stormwater system) these areas are characterised by hardened impermeable surfaces and baked calcrete open ground. This results in a high surface runoff component from these areas. The agricultural area of Philippi, on the other hand, is characterised by a drainage network frequently clogged with vegetation and suffering modification through infilling and excavation. Surface runoff is evident only during significant rainfall events coupled with a high water table. The contribution to the Great Lotus is thus frequently in terms of groundwater seepage during high winter water table levels.

The above table shows, for a high flow situation, that the upper township developments of Barcelona, Nyanga, Guguletu, Crossroads and Browns Farm together account for just under 30% of the total flow into Zeekoevlei for this particular day. The Philippi Horticultural Area, on the other hand, through diffuse contributions as well as tributary sources, accounts for just over 40% of the flow. The remainder of flow is thus from the more formalised residential areas of Ottery, Lotus River as well as Lansdowne Wetton.

It is of interest to contrast these conditions with a typical baseflow situation. The figure 4.7 below represents flow measurements taken on the 09/03/98.

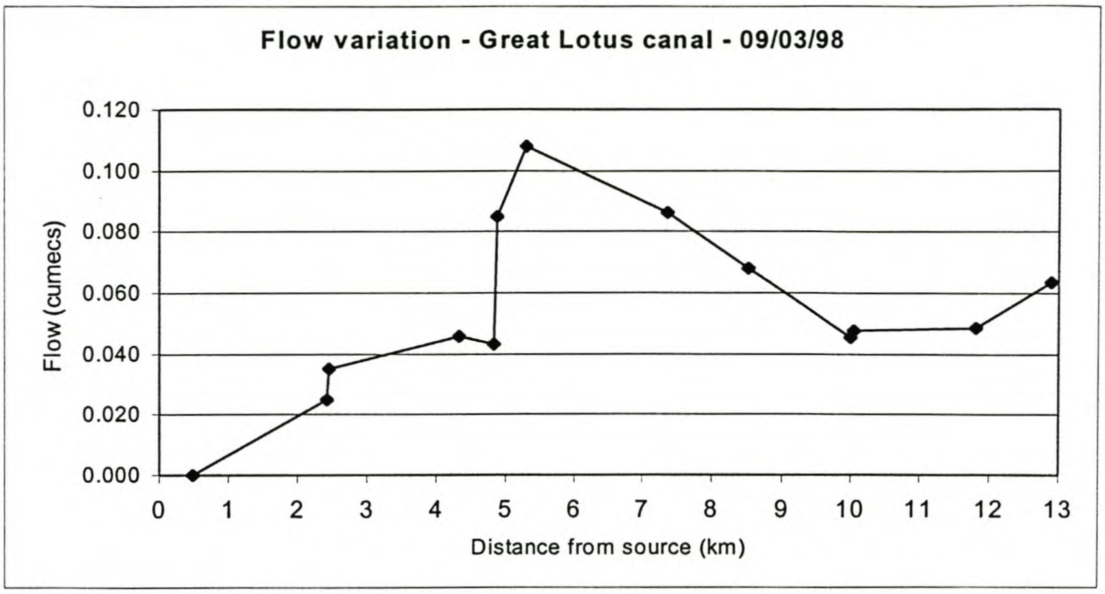


Figure 4.7: Flow variation – 09/03/98 – Great Lotus River

The urbanised sections of the catchment are still contributing to the flow. This is at ~2.4 km (NY3), ~ 4.8 km (Crossroads, Philippi East, Browns Farm). This results in a max flow of 0.108 cumecs (at ~5.3 km) before the start of the unlined sections of the canal. With the low water table characteristic of the summer months, there appears to be a loss of flow into the groundwater where unlined sections of the canal occur. These unlined sections occur between 5.3km and 10 km with an almost 60% loss of flow for this particular day. This interaction of the river with the underlying groundwater is approaching that of a normal river system with implications for the increase and reduction of pollutants in the canal.

4.4.3.1 Storm event monitoring

Figure 4.8, below, depicts hydrographs obtained by the datalogger for two stormevents.

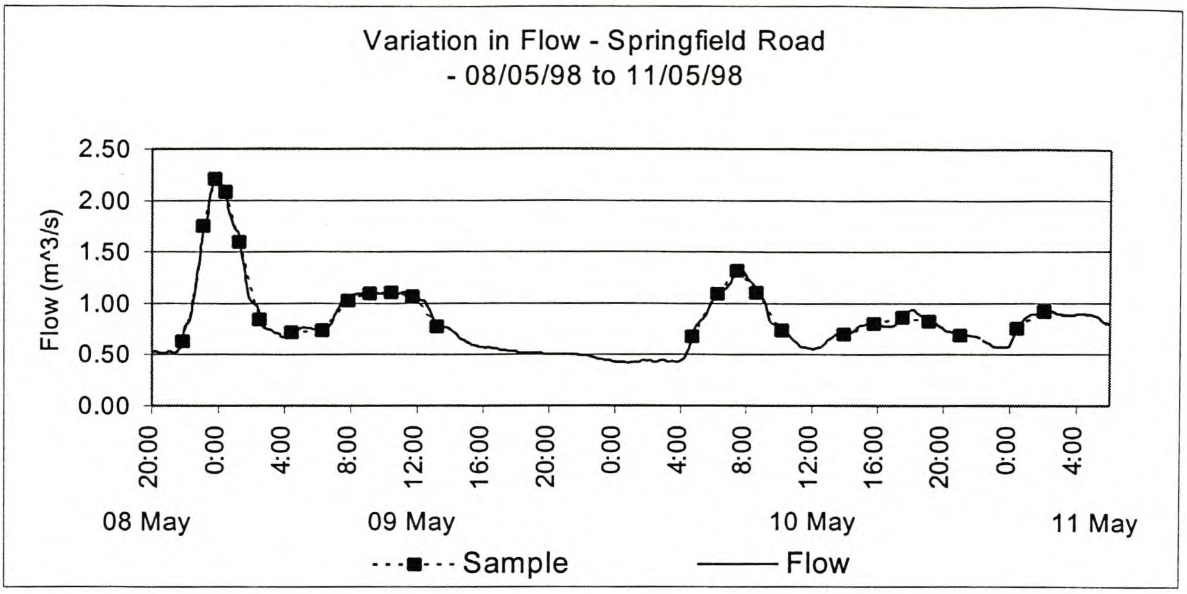


Figure 4.8: Storm event hydrographs – Springfield Road – Great Lotus River

As discussed in the sampling methodology, the sampler was programmed to begin sampling after flow had risen past 0.5 m^3/s with a sample being collected every 8000 m^3. This frequency enabled the above events to be captured fairly successfully. The table below indicates the total runoff of each event.

Event No.	Begin Date	Total Runoff (m^3)
1	08/05/98	56690
2	10/05/98	20836

Table 4.8: Total runoff volume of sampled storms

The samples were analysed by the Scientific Services, the results of which are shown in section 4.6.3.2 below.

The table below compares monthly precipitation (Cape Town Weather Office), monthly evaporation (DWAF) with monthly runoff as recorded by the datalogger at Springfield Road. This is for the period of the flow gauging study from 21 July 1997 to 30 September 1998.

Month	Evaporation (mm/month)	Precipitation (mm/month)	Flow volume (m^3/month)
July 1997	19.9	8	197517
August 1997	44.9	74.8	1420785
September 1997	132.4	6.8	723889
October 1997	183.1	18	423725
November 1997	230.7	45.8	313989
December 1997	247.2	10.4	319167
Total	858.6	163.8	3399072
January 1998	280.6	9.2	267877
February 1998	231.6	0	197017
March 1998	149.3	12	186402
April 1998	91.1	33.8	201692
May 1998	37.7	109.6	1099692
June 1998	36.4	46.2	749714
July 1998	Not Available	99.8	**410133**
August 1998	Not Available	41.6	734984
September 1998	Not Available	28.2	479083
Total		380.4	**4326594**

** - ** - underestimated due to missing flow data

Table 4.9: Monthly comparison of precipitation, flow and evaporation data

4.4.3 Water quality

Analysis of the historical database maintained by the Scientific Services Department of the Cape Metro has shown that the water quality variables of concern are:

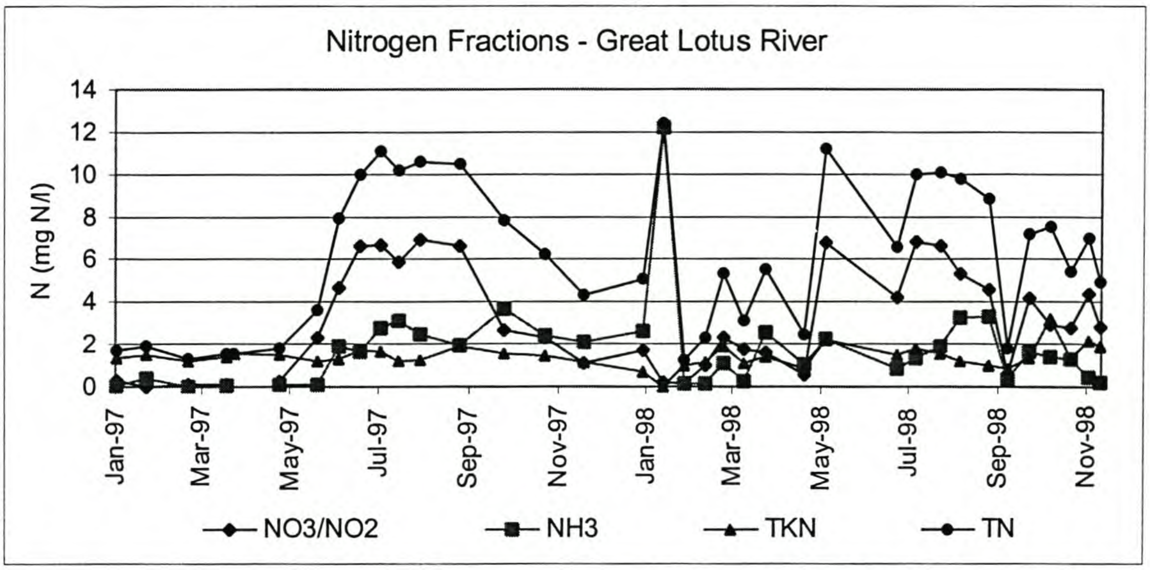
Total Nitrogen (TN)
Total Phosphorus (TP)
Indicator organisms (Faecal coli, *E. coli*)

As discussed sampling of the indicator organisms is undertaken by the Scientific Services on a monthly basis. The results of this sampling are discussed.

In terms of the TN and TP, a detailed sampling program was utilised to determine sources and relative loadings.

4.4.3.1 Total Nitrogen

Total Nitrogen is composed of organic nitrogen, ammonia, nitrite and nitrate but excluding nitrogen gas. Sources of nitrogen in streams include agricultural runoff and industrial activity point sources. Nitrogen is also contained in municipal wastewater discharged into streams as well as in atmospheric deposition. (McCutcheon *et al.*, 1993b). Figure 4.9 below depicts the fractional breakdown of nitrogen for the Great Lotus River at 5th Avenue. This data was obtained from the Scientific Services Department of the CMC.



(Scientific Services, 1998)

Figure 4.9: Fractional composition of Total Nitrogen – Great Lotus River

The above plot, selected for the period January 1997 to December 1998, reveals the varying composition of total nitrogen. It is apparent that a seasonal variation occurs in the concentration of TN with highest concentrations generally occurring during the winter higher rainfall period. This will be discussed in more detail in the following sections. For the winter period, it appears that both the ammonia and nitrate/nitrite concentrations increase with the TKN concentration remaining relatively constant.

Furthermore, the nitrate/nitrite concentration seems to constitute the dominant part of the total TN concentration for the winter period. Because of the high historical levels of Nitrogen, it was required to assess the sources of this pollutant. This will be discussed further in the following sections. Figure 4.10 below provides an indication of the variation in TN flux at the downstream point, 7th Avenue.

It is immediately apparent that the highest TN loading rate (flux) occurs during the winter rainfall months (seen here for 1997/1998). For the period between the end of September 1997 and beginning of April 1998, however, the summer baseflow conditions result in relatively low loads being transported. This seasonal variation is not surprising given that the flux is in terms of flow with seasonal flow variation thus having a dominant effect on the load.

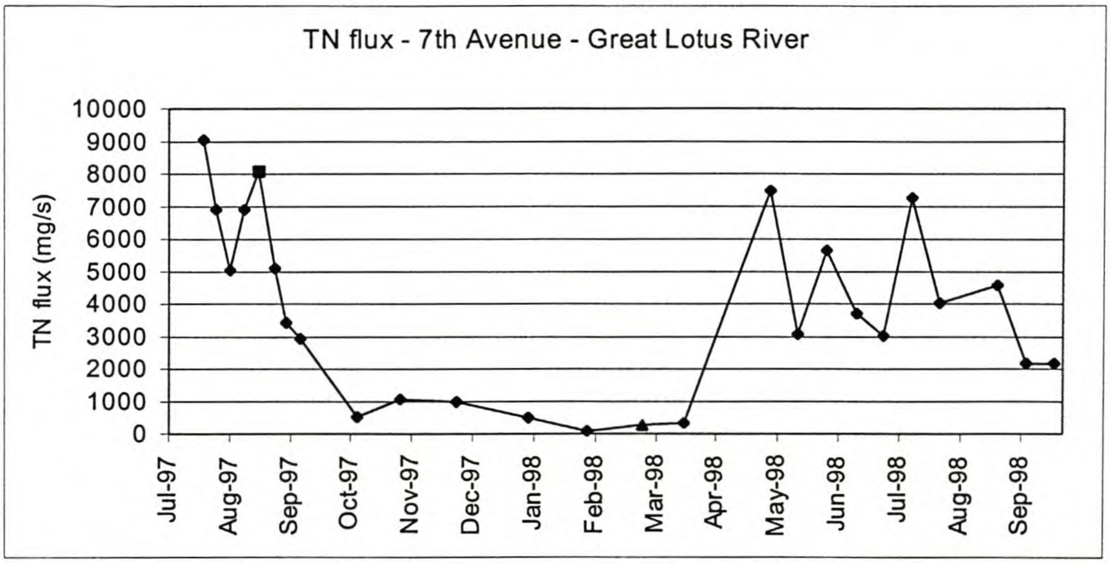


Figure 4.10: Seasonal variation of TN flux – Great Lotus River

It is of interest to assess seasonal effect on TN concentration. Figure 4.11, below, is the variation in TN concentration for 7th Avenue for the same sampling period.

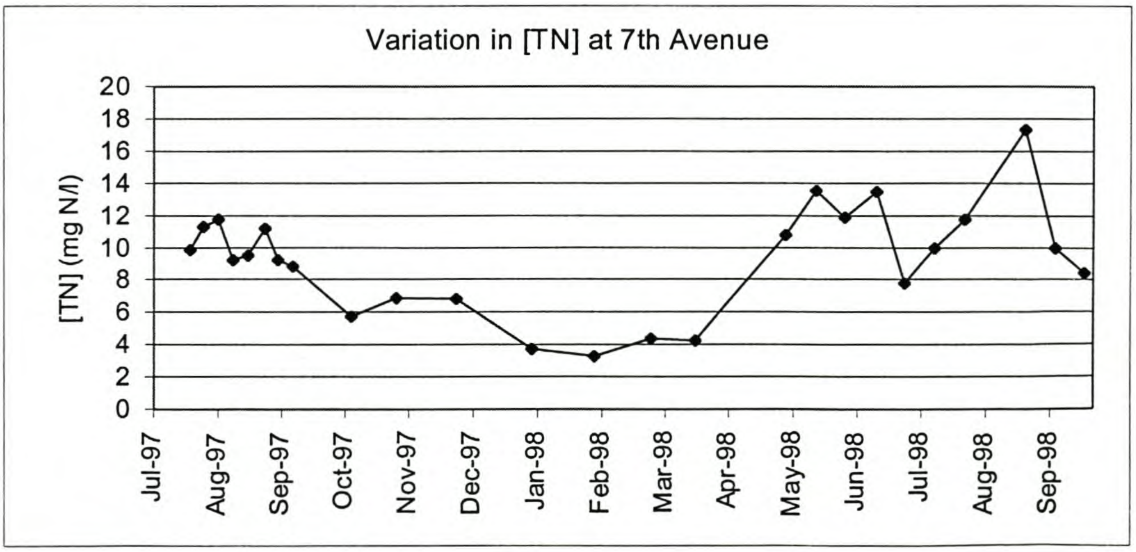


Figure 4.11: Seasonal variation - Total Nitrogen concentration at 7th Avenue

Analysis of Figure 4.11 shows a similar seasonal trend for the concentration data. From the above two plots it can thus be concluded that for TN, both the concentration and loading display a similar seasonal variation with the higher contributions during the winter rainfall season. This is in agreement with the literature ((Chiew and McMahon, 1998a), (Huber, 1993a), (Wright *et al.*, 1993)etc who found that the highest pollutant loads occur with rainfall events.

In order to assess the sources of TN to the Great Lotus River, dates from the sampling program are selected for analysis. To contrast the seasonality of the catchment a high flux situation (01/09/97) and a low flux situation (09/03/98) are selected. These dates also correspond to the dates analysed as high and low flow situations respectively.

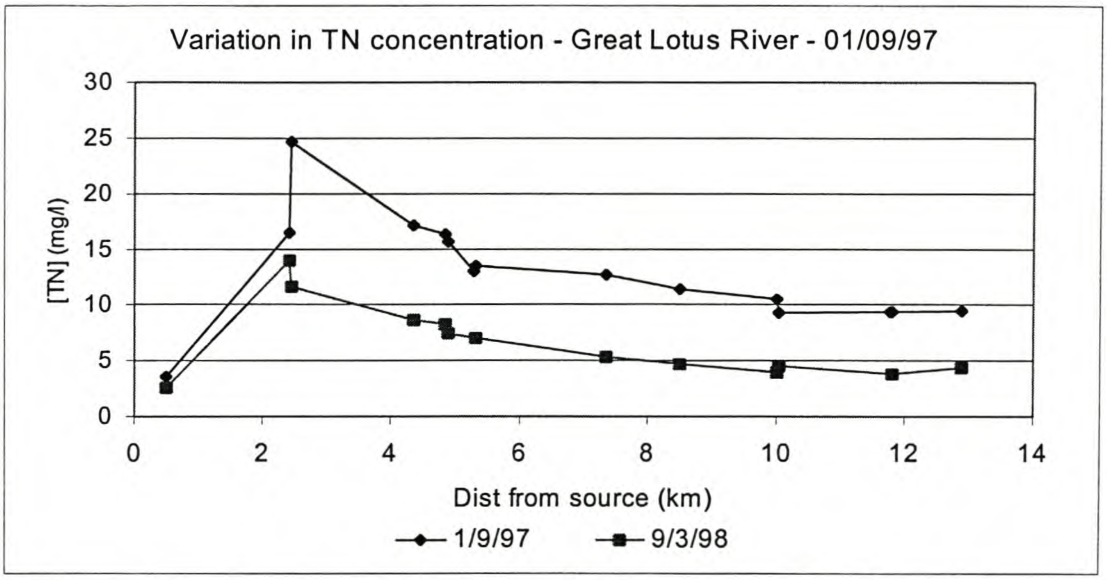


Figure 4.12: Total Nitrogen concentration for selected dates - Great Lotus River

Figure 4.12, above, details the variation in TN concentration along the Great Lotus for both a high load (01/01/97) and low load (09/03/98) situation. Given that the dates refer to a difference in flow regimes, the similarity in the longitudinal variation of TN load for the Great Lotus River is surprising. The concentration profiles are fairly similar with the high flow profile appearing to approximately double the low flow concentration profile.

For both of the selected dates there is a steady increase in the TN concentration leading up to ~2.4 km from the source. This diffuse source contribution can be attributed to the informal settlement of Barcelona as well as the residential areas of Nyanga and Guguletu. At this point, there is a significant jump in concentration corresponding to the tributary source contribution at the stormwater pipe at NY3 draining a large part of Nyanga and Guguletu. From this point onwards the concentration decreases for both the high and low flow situations. This is due to possible dilution and assimilation. Analysing the concentrations alone does not give a clear indication of the relative contributions of each source. It is thus necessary to assess the variation of TN flux depicted in Figure 4.13 below.

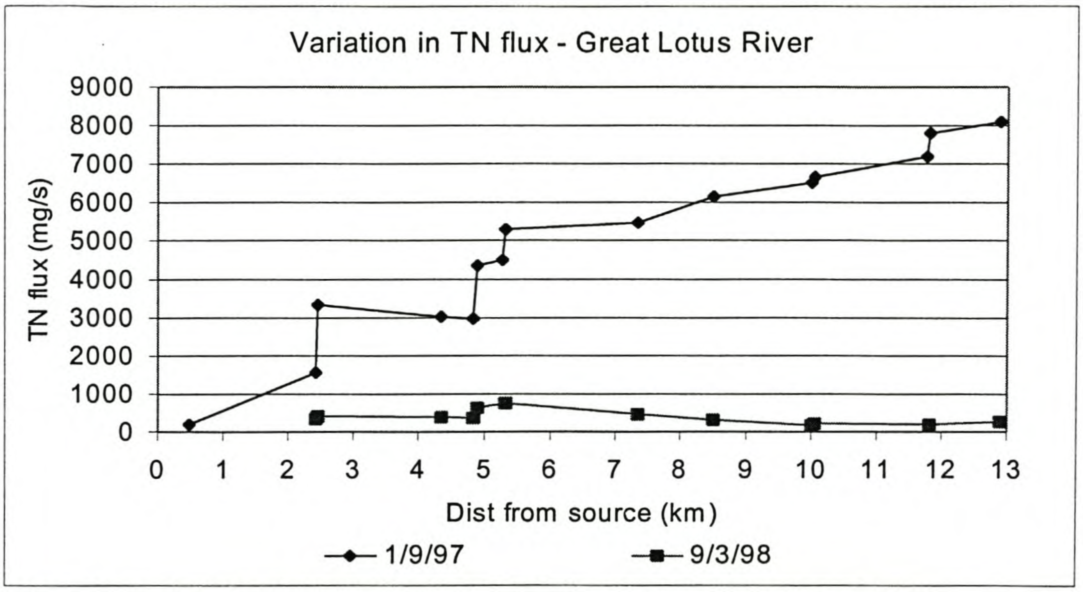


Figure 4.13: Total Nitrogen flux for selected dates - Great Lotus River

Figure 4.13 dramatically highlights the notion of the highest pollutant flux occurring during the high rainfall periods. As discussed the selected high flow date (01/09/97) occurs after a period of sustained rainfall with the accompanying washoff characteristics.

Referring to this high flow situation in Figure 4.13, above, it is possible to identify the dominant contributors to the flux. For this selected date, significant sources are shown in Table 4.10 below:

Distance from source	**Contribution**	**% flux contribution**
0.5 – 2.4 km	Diffuse source contributions from Barcelona and upper part of Nyanga/Guguletu	17.15
~ 2.4 km	Tributary source at NY3 stormwater pipeline draining significant portion of Nyanga and Guguletu	22.5
	Total contribution of Nyanga, Guguletu, Barcelona	*35.8*
~ 4.8 km	Tributary source draining Crossroads, Philippi East, Philippi West and Browns Farm	16.01
~ 5.3 km	Vygekraal Detention pond draining subcatchment of PHA	6.1
~5.3 to 7.3 km	Unlined section along Lansdowne Road permitting groundwater influence	2.32
~7.3 to 10 km	Unlined section through Philippi Horticultural area permitting groundwater and subsurface irrigated flow	8.52
~10 km	Tributary source from Lansdowne Wetton Road Corridor	5.74
~10 to 11.8 km	Diffuse source from residential area of Grassy Park	6.66
~11.8 km	Tributary source from subcatchment of PHA	5.94
~11.8 to 12.9 km	Diffuse source from Lotus River residential area	3.64

Table 4.10: Contributions to TN flux during 01/09/1997

The predominately formal and informal settlements of Barcelona, Nyanga, Guguletu, Crossroads and Browns Farm draining into the Great Lotus canal up to ~ 4.8 km cumulatively contribute just over 51% of the total flux of TN into Zeekoevlei. The two stormwater pipes (NY3, Browns Farm) together contribute 39% of the flux for the selected day. This is possibly due to the inadequate sanitation and cleansing services offered to these areas.

From this point downward, contributions are mainly diffuse sources from the Philippi Horticultural Area (23%) as well as the residential subcatchments of Ottery, Grassy Park and Lotus River. The relative contributions to the flux for these areas are significantly less and it can be concluded that the township settlements are the major source of TN loading to the Great Lotus River. Although only one sampling date was selected for representation, the results are characteristic of other sampling dates with similar flow characteristics.

Consideration of the concentration variation at 7th Avenue, in Figure 4.11, reveals a significant jump in TN concentration for the date 31/08/98. This corresponds to a relatively average TN load and is significant in terms of the potential sources. Figure 4.14 below depicts the variation in TN flux for the Great Lotus River for this date.

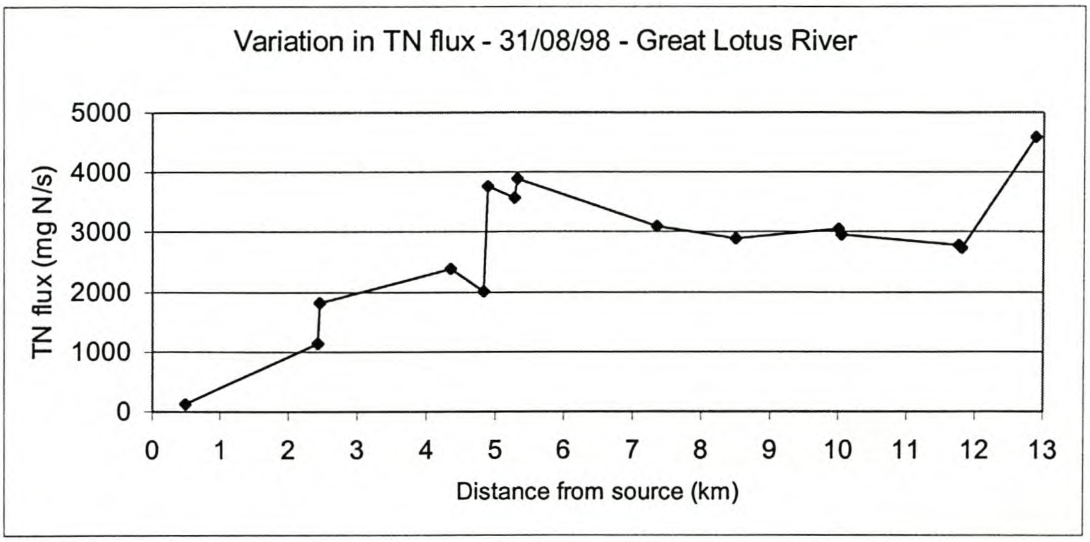


Figure 4.14: Variation in Total Nitrogen flux – 31/08/98 – Great Lotus River

Step increases occur at ~2.4 km (NY3) and 4.8 km (Philippi East) as for the dates discussed above. Of significance for this particular date, however, is the dramatic increase in TN flux between 11.8 and 12.8 km. This reach corresponds to the Lotus River residential area and thus constitutes a diffuse urban source. The increases in TN flux thus all correspond to urbanised sections of the catchment. In contrast to this, the TN flux appears to decrease for the unlined sections of the canal (between 5.3 and 10 km)..

Assessment of the flow variation for this particular day, shown in Figure 4.15 below reveals that increases of flow occur not only at the same tributary points but also from diffuse sources along the unlined sections. This indicates some form of nitrogen assimilation. The above results also seem to support the notion that the principal sources of TN in the Great Lotus River are the urbanised areas of the catchment, composed principally of formal and informal residential areas.

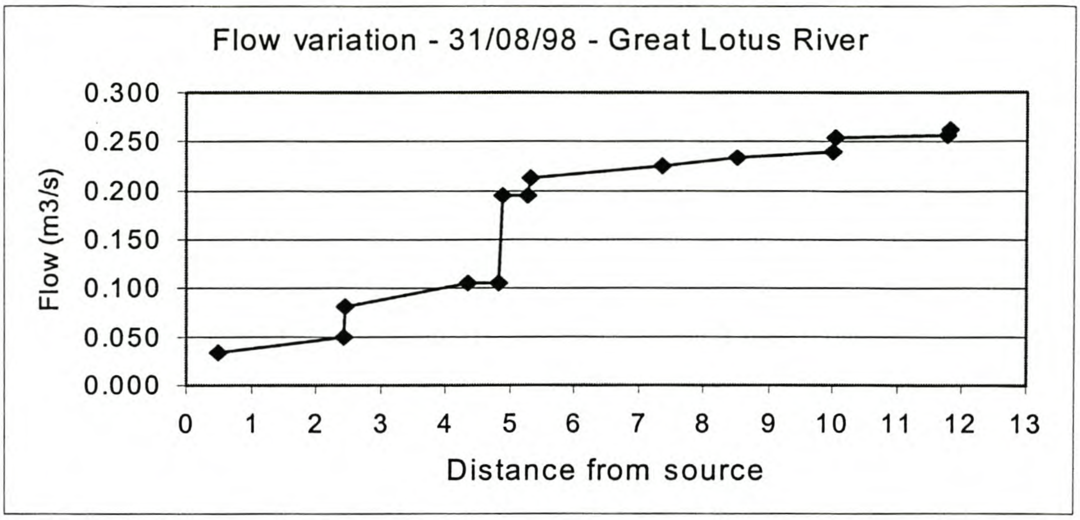


Figure 4.15: Flow variation – 31/08/97 – Great Lotus River

Stormevent monitoring

Figure 4.15 below depicts the effects on Total Nitrogen flux under storm conditions. These events correspond to the events discussed in section 4.6.2.1 above.

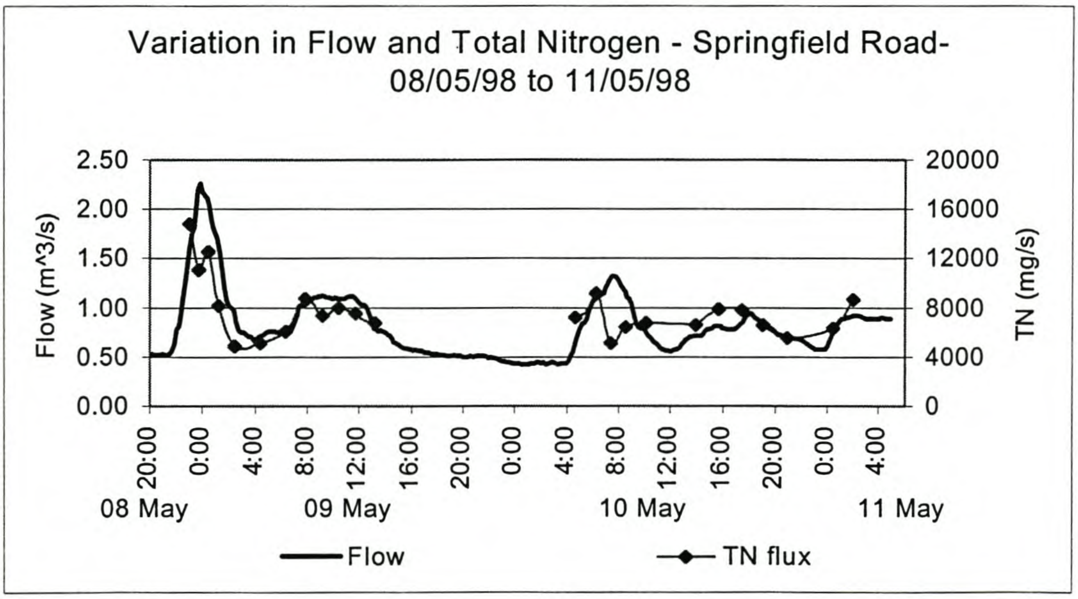


Figure 4.16: Event TN pollutograph – Springfield Road – Great Lotus River

It is of interest to note the effect the peak flow has on TN flux. The rising limb of the hydrograph is characterised by an increase in flux with the peak TN flux leading the peak flow for each event. As the flow reaches its peak, however, there is a corresponding slight drop in flux, followed by an increase in flux as the peak passes.

For the falling limb of the hydrograph, the TN flux decreases. The flux variation shown above conforms to the literature with maximum loading occurring during flood events (Chiew and McMahon, 1998a), (Huber, 1993a).

4.4.3.2 Total Phosphorus

Phosphorus can be divided into dissolved and particulate phosphorus, each with organic and inorganic components. The phosphorus cycle is principally composed of organic P and inorganic P in the form of orthophosphate where orthophosphate is soluble and considered to be the only biologically available form of P (i.e. SRP) (McCutcheon *et al.*, 1993a). Since P strongly associates with solid particles and is a significant part of organic material, sediments influence water column concentrations and are an important component of the phosphorus cycle in streams.

The major sources of phosphorus in streams are natural organic material, organic and inorganic phosphorus in wastewaters and nonpoint sources and phosphorus detergents in wastewaters (McCutcheon *et al.*, 1993a). Agricultural lands are an especially significant diffuse source of phosphorus (Oenema and Roest, 1998b).

Phosphorus can be the limiting nutrient that prevents additional biological productivity from occurring (McCutcheon *et al.*, 1993a). This implies that phosphorus is a limiting nutrient for eutrophication. In this way phosphorus enrichment can cause algal blooms, ecological changes due to changes in the food chain, recreational amenity loss and dissolved oxygen loss (Herricks, 1995).

In terms of the Great Lotus catchment, the downstream water body, Zeekoevlei, is severely hypertrophic with "increased *Microcystis* growth being linked to the increased concentrations of biologically available Phosphorus (SRP) following the winter rains" (Harding, 1996a). Harding continues by stating that "attenuation of external (phosphorus) loading could have a positive effect on the severely impaired trophic state of the lake" (Harding, 1996a). This attenuation brought about through the control of P in sewage, industrial wastewaters and diffuse pollution is therefore critical. Similar findings were reported in research conducted on the Buffalo River where phosphate appears to be the main limiting nutrient in the Buffalo River. It was found to be the variable needing to be managed as the main priority in order to limit eutrophication (O'Keeffe *et al.*, 1993)

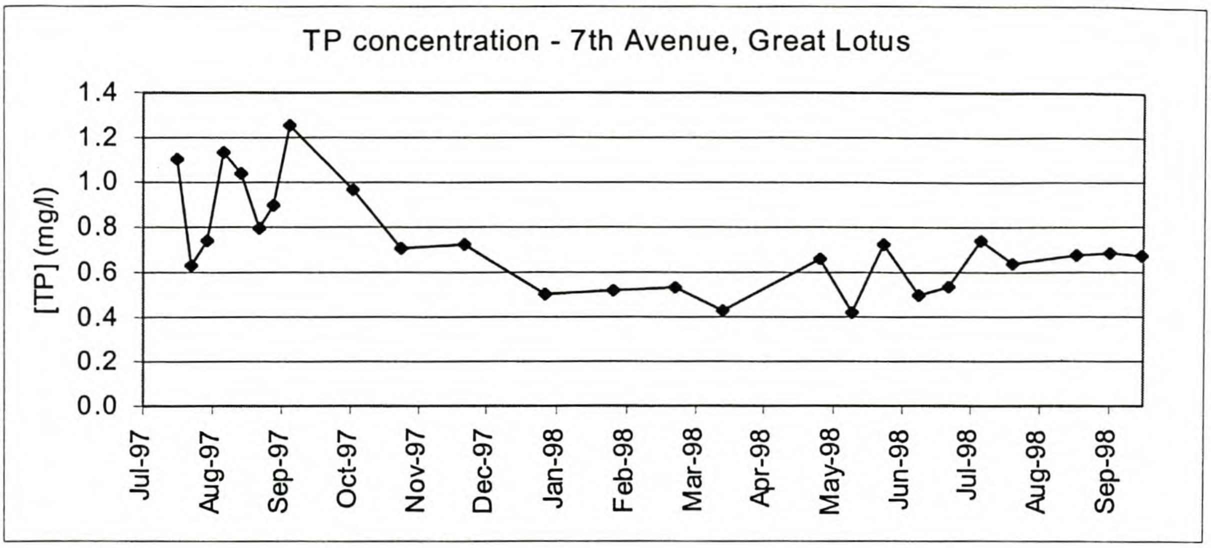


Figure 4.17: Variation in TP concentration at 7th Avenue, Great Lotus River

Figure 4.17 above depicts the variation in Total Phosphorus concentration at the point upstream of Zeekoevlei, 7th Avenue for the duration of the sampling period. This plot shows a marked seasonal variation with higher TP concentrations evident during the higher rainfall months with a corresponding decrease during the summer drier months. This seasonal variation is shown even more strongly when considering the variation in TP flux at the same point for the same interval in Figure 4.18 below.

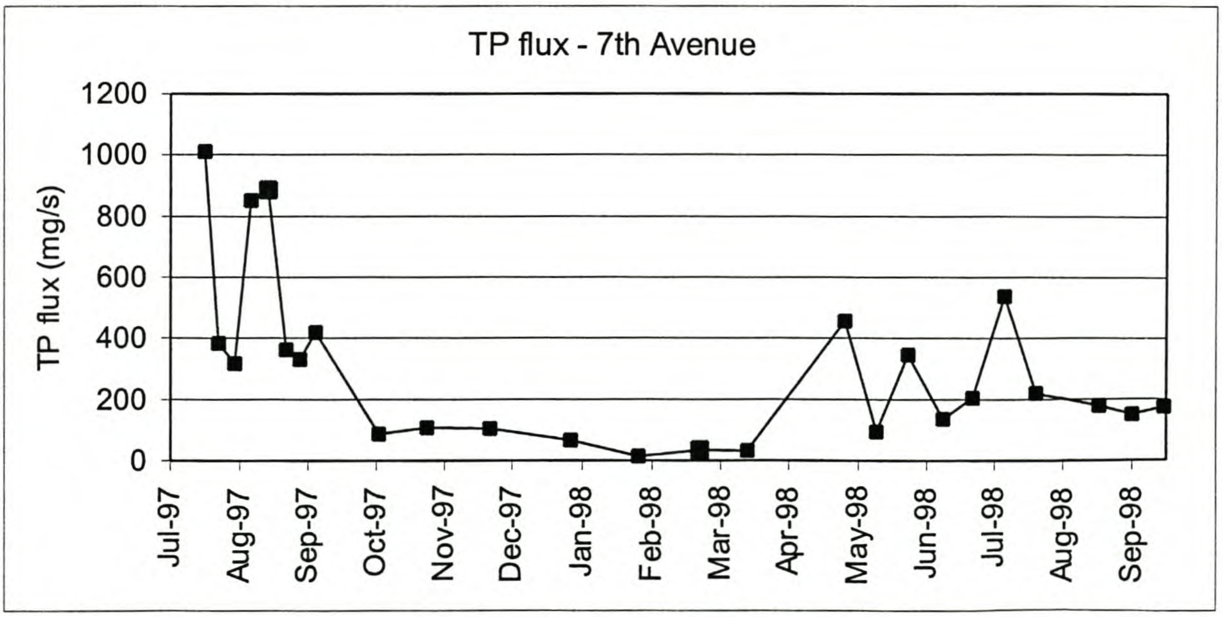


Figure 4.18: Variation in TP flux at 7th Avenue, Great Lotus River

Again the rainfall season is characterised by higher TP fluxes. The drier summer period between October and April displays a baseflow condition resulting in comparably lower fluxes being transported. Of interest to note is the magnitude of both the concentration and flux being relatively less during the rainfall season of 1998 than the similar period of 1997. This maybe accounted by the interval of sampling being greater (fortnightly for winter 1998 as opposed to weekly for winter 1997) during 1998 with the result of more storm events occurring between sample points.

Analysis of the Mean Annual Rainfall as measured by the Cape Town Weather Office reveals that although 1998 received just over 22% more rainfall than 1997 (1997 : 422.8 mm versus 1998 : 516.8 mm) (Cape Town Weather Office Climate Records, 1999*)* the months of June and August were relatively drier during 1998 when compared to the same months for 1997. Storm intensities were low with less washoff during the period.

In order to assess the sources of TP for the Great Lotus River it is necessary to review a longitudinal plot of the variation in TP concentration and flux along the length of the canal. Two dates are selected from the sampling programme, a high flow/flux situation and a low flow/flux situation.

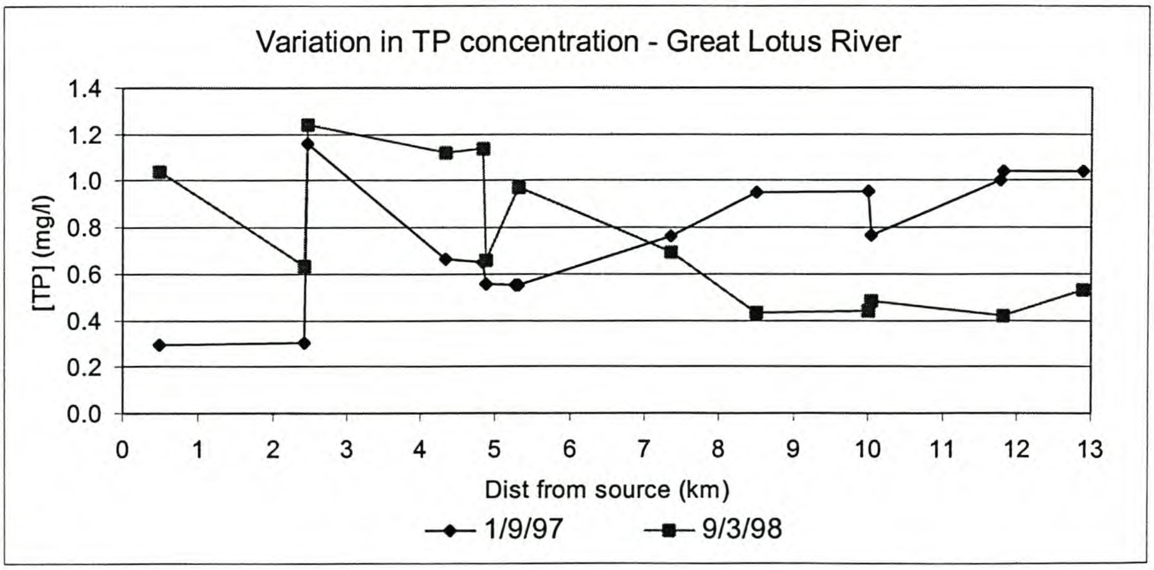


Figure 4.19: Variation in TP concentration for selected dates

A number of conclusions can be drawn from an assessment of Figure 4.19 above. Both the low and high flow situations are characterised by a significant jump in concentration at ~2.43 km. This again refers to the stormwater pipe draining parts of Nyanga and Guguletu and flowing into the canal at NY3. (The relatively high concentration measured at the N2 (~0.5 km) is due to a high organic content at this point due to cleared aquatic vegetation not being removed and choking up the canal.) A decrease in concentration is then evident to the point just below the Nyanga/Guguletu settlements. This is due to diffuse sources contributing flow to the canal with lower concentrations and producing a dilution effect. Further dilution occurs at the sample point at ~4.9 km. This point corresponds to the stormwater pipe draining Crossroad, Philippi and Browns Farm. Although these are residential settlements the stormwater is routed through a number of detention ponds resulting in possible assimilation and a lower concentration of TP.

From this point onwards, the low flow and high flow situations diverge in their characteristics. The high flow situation is seen to have a gradual increase in TP concentration whilst the corresponding low flow situation experiences a decrease in concentration. This reach of the canal coincides with a unlined length of the canal and thus opens up the possibility of interaction of the river with the underlying groundwater. Thus, as previously discussed, the gradual increase/decrease can possibly be attributed to a varying water table contributing nutrient rich agricultural groundwater flow during winter and causing transmission losses during the summer months.

The canal continues to be unlined between ~8.5 km and ~10 km. This corresponds to a more urbanised residential area with traffic corridors crossing the canal. The concentration remains fairly constant for both the low and high flow situation. In order to assess the implications of this, it is required, however to contrast the variation in flux with the above concentration variation. This may detail the extent to which the groundwater plays a role for this reach.

The remainder of the canal flows through formal residential areas with a small tributary source from the Philippi Horticultural Area contributing flow during the winter rainfall season.

In order to compare relatively the various contributions, it is necessary to view the concentrations in terms of flow, i.e. a TP flux variation shown below in Figure 4.20.

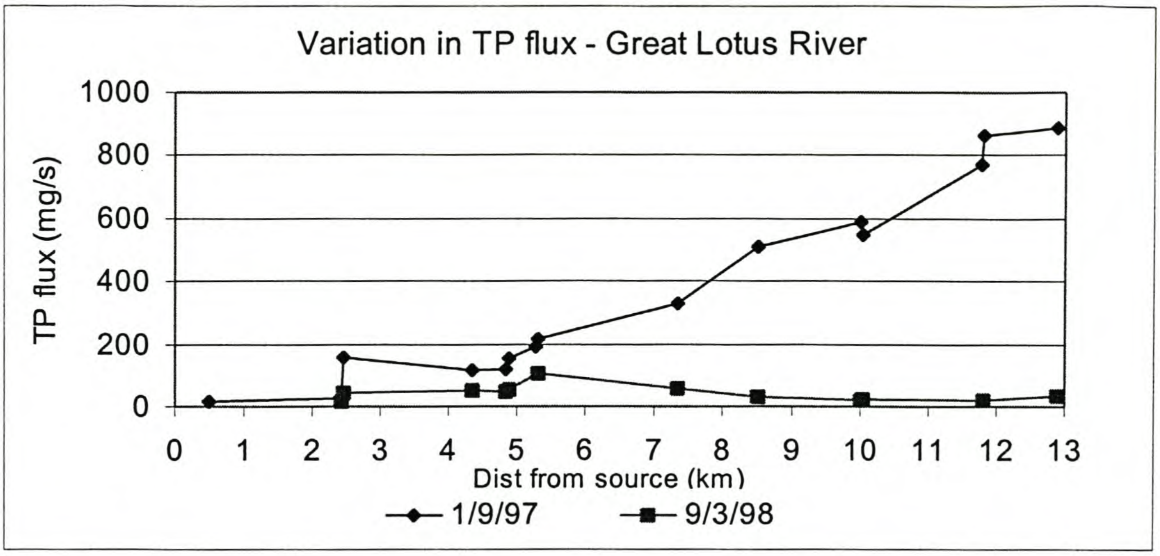


Figure 4.20: Variation in TP flux, Great Lotus River

It is immediately apparent from analysis of the above Figure 4.20 that there is a significant seasonal variation evident for TP fluxes in the catchment. As far as ~5.3 km the contributions to the flux remain fairly small. From this point onward, however, the groundwater begins to play a more significant role. With the high water table characteristic of winter, their appears to be a significant contribution to the flux up to ~10 km. As discussed this is presumably due to nutrient rich agricultural groundwater and, to a lesser extent surface water, augmenting flow in the canal during the unlined sections. For the high flow situation, this accounts for almost 43% of the total TP flux into Zeekoevlei. As in the case of the TN flux plot above, the low flow situation appears to result in a loss of TP from the canal for the corresponding reach of the canal. This is due primarily to the loss of flow to the groundwater as well as possible vegetative assimilation during the longer retention periods of the summer base flow conditions.

Table 4.11 below represents a summary of the significant sources and percentage contributions each source make to the total flux at high flows (01/09/97)

Distance from source	**Contribution**	**% flux contribution**
0.5 – 2.4 km	Diffuse source contributions from Barcelona and upper part of Nyanga/Guguletu	1.39
~ 2.4 km	Tributary source at NY3 stormwater pipeline draining significant portion of Nyanga and Guguletu	7.9
	Total contribution of Nyanga, Guguletu, Barcelona	*11.57*
~ 4.8 km	Tributary source draining Crossroads, Philippi East, Philippi West and Browns Farm	2.88
~ 5.3 km	Vygekraal Detention pond draining subcatchment of PHA	5.48
~5.3 to 7.3 km	Unlined section along Lansdowne Road permitting groundwater influence	13
~7.3 to 10 km	Unlined section through Philippi Horticultural area permitting groundwater and subsurface irrigated flow	21.06
~10 km	Tributary source from Lansdowne Wetton Road Corridor	3.17
~10 to 11.8 km	Diffuse source from residential area of Ottery	25.32
~11.8 km	Tributary source from subcatchment of PHA	10.95
~11.8 to 12.9 km	Diffuse source from Lotus River residential area	2.66

Table 4.11: Contributions to TN flux during 01/09/1997

The above table 4.11 shows, for a high flow situation, that the upper township developments of Barcelona, Nyanga, Guguletu, Crossroads and Browns Farm together account for just under 15% of the total TP flux into Zeekoevlei for this particular day. The Philippi Horticultural Area, on the other hand, through diffuse contributions as well as tributary sources, accounts for just over 50% of the TP flux into Zeekoevlei. The remainder of flux contribution is thus from the more formalised residential areas of Ottery, Lotus River as well as Lansdowne Wetton.

Present literature partitions phosphorus for stormwater and sewage. (McCutcheon *et al.*, 1993a) submit that particulate P accounts for supposedly 95% of the total P in most cases of urban stormwater runoff. This is echoed by Abustan and Ball (1998) by apportioning 85% of TP to inorganic particulate P. Table 4.12 below provides an indication of the principle fractions of phosphorus in both sewage and stormwater:

	Soluble P	Particulate P	
		Organic (%)	Inorganic (%)
Sewage	83	17	0
Stormwater	4.2	11.6	84.2

(Waller and Hart, 1985)

Table 4.12: Total Phosphorus fractions in stormwater and sewage

It is therefore of value to assess the fraction of P that is either soluble or particulate. This can be seen in Figure 4.21 below which compares the soluble fraction to the total P concentration.

Assessment of Figure 4.21 shows that, in fact, the SRP is the major constituent of the TP concentration principally during the winter rainfall months. For the summer base flow conditions it appears that the particulate form of P becomes more significant. (Findings reported by (Gerdes and Kunst, 1998) show that a high content of particulate P causes a low bioavailability, i.e. SRP content) The major proportion of phosphorus transported in surface waters from agricultural soils is generally in particulate form (Oenema and Roest, 1998a) with (Sharpley and Rekolainen, 1997) reporting particulate values between 60 and 90% of the total P load. Because the Lotus River has a high SRP component of the total TP concentration, this seems to suggest that the principal diffuse solutions from the agricultural areas are subsurface influences. In light of the above table, this is augmented by urban stormwater affected by sewer overflows and inadequate sanitation of the upper parts of the catchment.

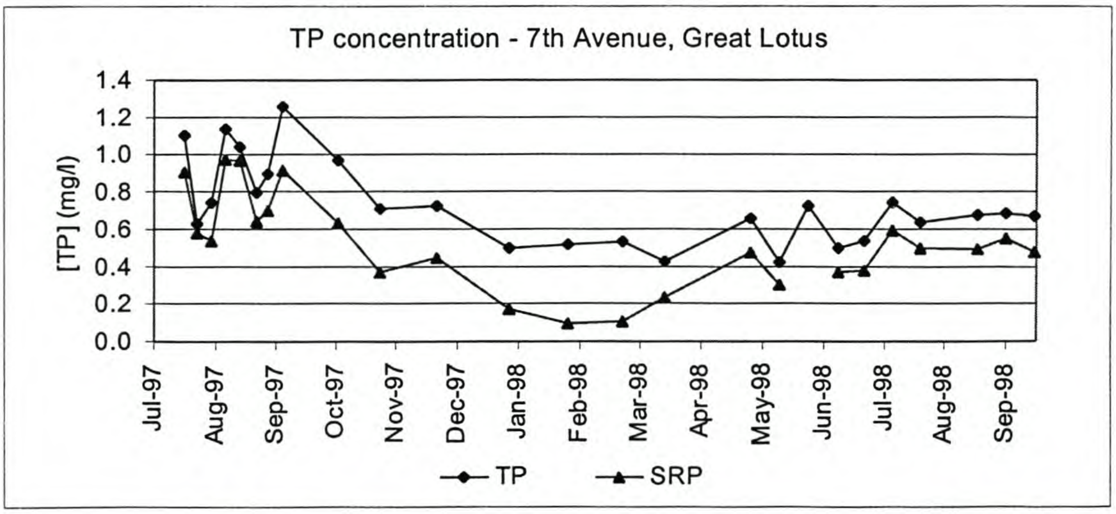


Figure 4.21: Fractional composition of TP – Great Lotus River

For the summer months, however, it appears that the particulate fraction is more dominant. These are periods characterised by low groundwater levels (flow in the canal appearing to be actually lost to the groundwater during these periods). The agricultural influences on the TP flux are thus reduced and the major sources appear to be urban sources including possible sewer overflows and diffuse contributions through inadequate sanitation runoff.

Storm event monitoring

The plot 4.22, below, depicts the variation for TP flux for the sample events discussed in section 4.6.2.1 above.

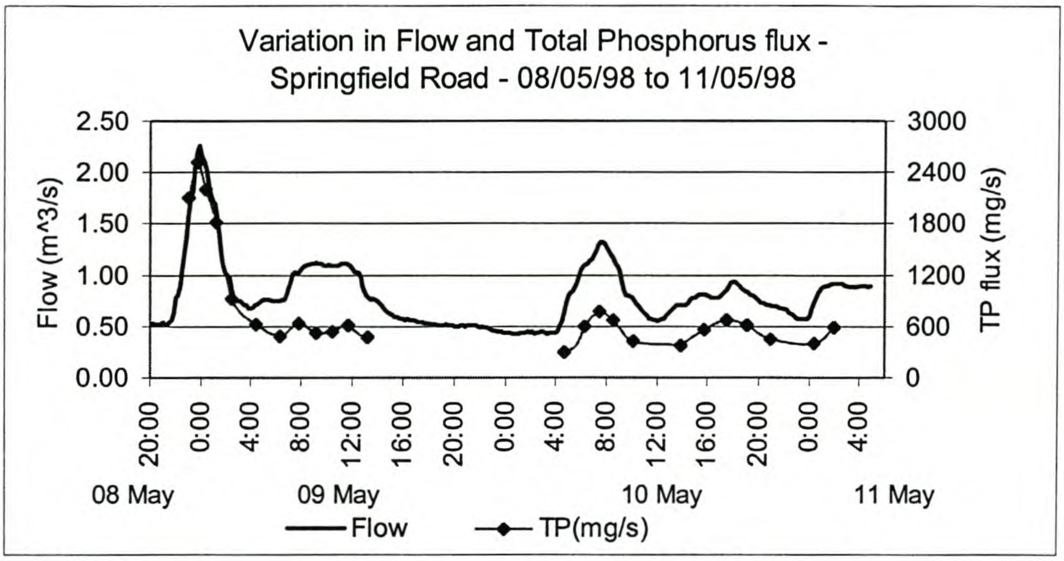


Figure 4.22: Event TP pollutograph – Springfield Road – Great Lotus River

As with the TN storm related variation in section 4.6.3.1 above, the highest TP flux occurs during peak flow. In the case of the TP flux in Figure 4.22 above, the peak TP flux matches the flow hydrograph more closely than for the TN variation with no lag evident between peak flow and peak flux. The rising limb is characterised by an increase in TP flux with the falling limb exhibiting a decrease in TP flux. This again confirms the notion of increased loads being transported during storm events.

4.4.4 Microbial data

Analysis of Scientific Services data reveals that both faecal coliforms and *Escherichia coli* are found in high concentrations in the Great Lotus River. As suggested this is due to a number of reasons including raw sewage effluent overflowing from blocked sewers into the stormwater drains as well as the inadequate or non-existent sanitation characteristic of the

Guguletu and Nyanga residential areas. An additional source appears to be due to the ingress of stormwater into deteriorated sewers. During storm events this results in surcharging of the sewers with overflows occurring at the sewer manholes and thence into the stormwater system.

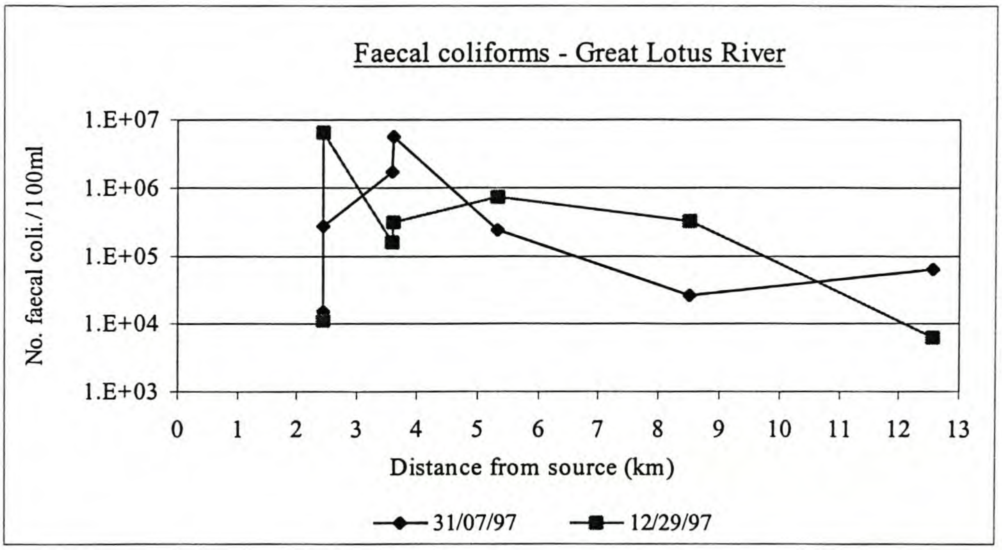


Figure 4.23: Concentration of faecal coliforms in Great Lotus River

Figure 4.23, above, (with y-axis plotted to log-scale) depicts the extremely high faecal coliform counts in the Great Lotus River. These counts originate principally from two stormwater outlets at NY 3 (~2.4km) and NY 3A (~3.6km) in Guguletu. These increases can be seen as step changes at the stormwater inlet due to samples being taken upstream and downstream of the inlet. The gradual increase is due to a diffuse contribution of faecal matter, principally from the informal settlements adjacent to the canal in Guguletu. Further downstream at Springfield Road (~8.5km) and 5th Avenue (~12.5km) dilution and possible bacteriological die off in the unlined reaches of the canal result in decreased counts.

Because of these sources, the Drainage and Sewerage Branch of the Cape Town City Council historically diverted the entire summer base flow to the Strandfontein Treatment Works adjacent to Zeekoevlei. This practice has subsequently ended due to costs of treatment and disagreement between the various substructures as to who should finance the treatment costs. This option is supposedly in the process of being reinvestigated (see section 4.9)

In order to combat the overflowing of effluent into the stormwater system at NY3, an extensive upgrading project was initiated by the Cape Town Municipality. This project entailed the relaying of the entire trunk stormwater line, along NY3, draining into the Lotus in an attempt to repair the overflow points.

Figure 4.24, below, depicts the faecal coliform count following the completion of the project in September 1998 with the y-axis in terms of actual concentrations. This sample taken on the 04/11/98 is contrasted to a sample taken during the similar base flow conditions of 1997.

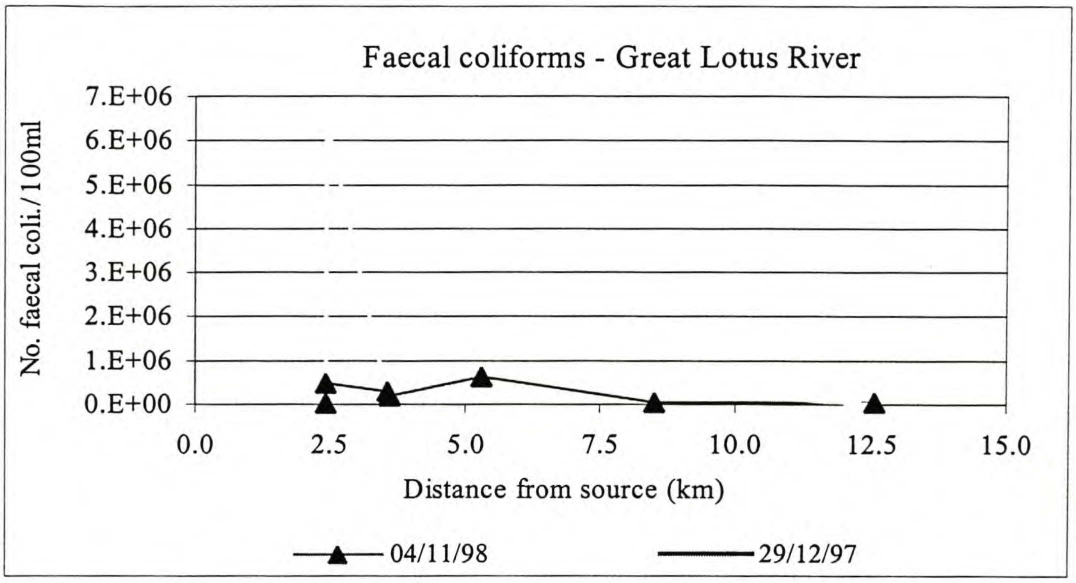


Figure 4.24: Concentration of faecal coliforms in Great Lotus River

Note the concentration at ~2.5 km (the inlet of the upgraded stormwater pipeline) in figure 4.26 is significantly lower for the sample taken post construction (4.8e5 counts/100 ml compared to 6.5e6 counts/100ml). This corresponds to a decrease of just over 90% of the faecal coli count. Thus whilst the faecal coli count is still excessively high, the upgrading of the stormwater pipeline appears to have limited the ingress of sewer effluent into the Lotus canal. In order to assess whether overflows have been completely eradicated, it remains to analyse the counts at this point over a longer period, especially during high flow situations.

4.4.5 Heavy metal analysis

4.4.5.1 Water samples

Interaction of inhabitants within the catchment with water in the Lotus River includes both abstractions for irrigation as well as a potential source of water and disposal system for waste. It is thus necessary to assess the concentrations of selected heavy metals in terms of acceptable levels for agricultural irrigation and domestic usage.

Table 4.13 below provides an indication of the average heavy metal concentration at selected sample points in the Great Lotus River compared to the Target Water Quality Range (TWQR) of the DWAF Water Quality Guidelines for Irrigation and Domestic Use. The uppermost value of the range is quoted below. Note that the irrigation water uses of the above guidelines refer to application to commercial crops and to sustain suitability of irrigated soil whilst domestic water use refers generally to human health as well as aesthetic effects in certain cases.

Constituent (µg/l)	TWQR (µg/l)		N2	Guguletu	Lansd Road	Spring	7th Ave
	Irrigation(1)	Domestic(2)					
Cadmium (Cd)	10	5	1.975	2.075	2.605	2.56	2.46
Chromium (Cr)	100	50	1.135	2.265	1.475	2.18	1.93
Cobalt (Co)	50	-	7.99	39.14	9.645	9.815	8.78
Copper (Cu)	200	1000	4.555	9.56	6.265	4.805	6.38
Iron (Fe)	5000	100	51.89	211.43	86.415	63.645	122.57
Lead (Pb)	200	10	13.49	24.755	22.41	20.43	22.04
Manganese (Mn)	20	50	9.09	26.975	14.7	20.04	24.08
Nickel (Ni)	200	-	10.39	10.7	8.18	9.85	9.7
Zinc (Zn)	1000	3000	24.77	129.11	49.005	110.98	5.28

(1) - (DWAF, 1996c)

(2) - (DWAF, 1996a)

Table 4.13: Suspended heavy metal concentrations - Great Lotus River

From Table 4.13, it can be seen that the concentrations of heavy metals generally fall below the limit concentrations as dictated by DWAF. What it is noticeable, is the relatively higher concentrations of Iron and Lead. These values typically exceed the accepted values for domestic human usage.

Because of the high nutrient and microbiological values of the water, however, the water is unlikely to be used for domestic purposes. In terms of the agricultural usage of the water, therefore, the Iron and Lead contents are well within the accepted guidelines for irrigation.

4.4.5.2 Sediment samples

Table 4.14 below provides an indication of the heavy metal analysis undertaken on the sediment samples. Where sediment cores were taken, an assessment of the historically accumulated solids in the system can be obtained.

Constituent (mg/kg)	N2	Guguletu	Lansd Road	Spring	7th Ave
Cadmium (Cd)	1.3	0.83	0.19	0.21	0.26
Chromium (Cr)	16.17	4.995	2.925	7.53	2.73
Cobalt (Co)	6.24	1.655	0.745	0.565	0.44
Copper (Cu)	13.125	10.705	2.605	1.83	2.52
Iron (Fe)	3851.54	1341.52	594.465	1932.14	1266.63
Lead (Pb)	48.39	77.975	9.275	11.45	8.32
Manganese (Mn)	28.64	22.215	5.92	4.505	6.54
Nickel (Ni)	8.56	4.35	1.25	1.14	0.87
Zinc (Zn)	103.26	155.485	17.79	14.925	21.12

Table 4.14: Sediment heavy metal concentrations – Great Lotus River

Analysis of table 4.14 reveals that heavy metal concentrations in the sediments of the Great Lotus River are also relatively low. As for the above water sample concentrations, the concentrations of iron and lead, whilst exceeding the values for domestic use, are still within the target range for agricultural usage.

An evaluation of water quality parameters for the Great Lotus River system thus reveals that the principle pollutants are in terms of nutrients and microbiological organisms and not heavy metals.

4.4.6 Organic analysis

Figure 4.25, below, depicts the concentrations of the identified organic compounds for a selected day in the Great Lotus River. These compounds are saturated hydrocarbons, more specifically, linear alkanes. They are present in low concentrations. They are insoluble in water or alcohol and are compounds mainly characteristic of fuels and solvents e.g. diesels, motor oils, kerosenes (Neckers and Doyle, 1977)These linear chains are essentially non-toxic and therefore pose more of a fire hazard.

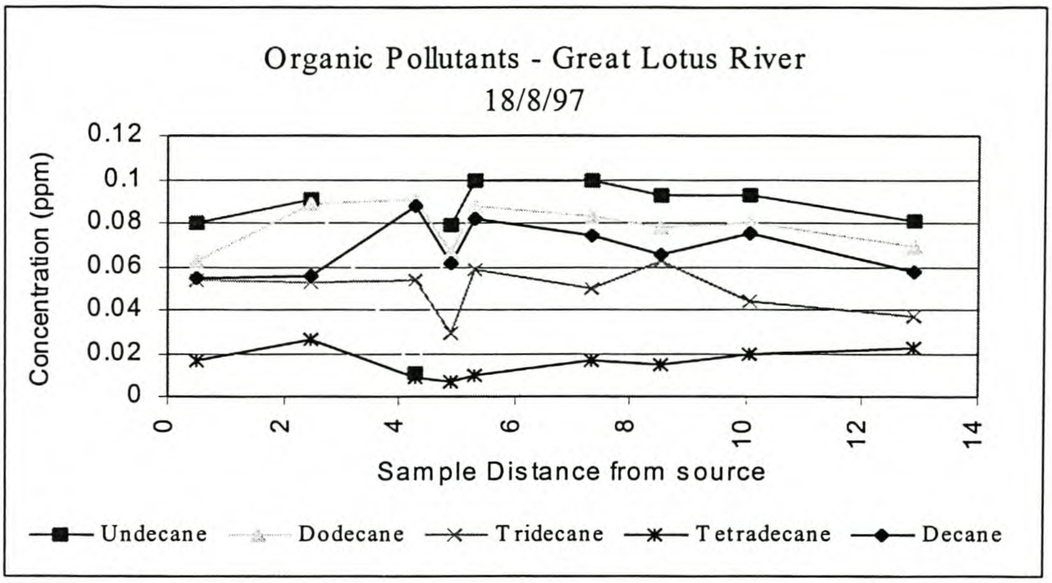


Figure 4.25: Organic concentrations for Great Lotus River

From analysis of figure 4.25, a general increase in concentrations can be noted from the source up to 4 km. This corresponds to the informal settlement areas of Nyanga/Guguletu. Burning of fuels and disposal of oils into the stormwater system are potential sources of these compounds. The decrease in concentrations after this point corresponds to the tributary inflow from Philippi east with low concentration flow diluting the concentrations in the Lotus. The subsequent rise in concentration corresponds to a developed linear commercial area along Lansdowne Road. This area is characterised by high traffic volumes and commercial/industrial activity. Between 7 and 10km, the canal is unlined, flowing through the agricultural area of Philippi with a corresponding decrease in compound concentration.

4.4.7 Protozoan parasites

Table 4.15, below, represents the results of a protozoan analysis undertaken on 27/08/97 for the Great Lotus River.

Location	***Giardia cysts***	***Cryptosporidian* oocysts**
NY3	ND	ND
NY3A	ND	ND
Springfield Road	100	ND
7th Avenue	50	ND

Table 4.15: Protozoan parasites in Great Lotus River

Table 4.15, above, shows that neither *Giardia* nor *Cryptosporidian* were detected in either of the stormwater pipes discharging into the Great Lotus River at NY3 and NY3A. This is in spite of these tributaries being identified as sources of faecal coli. No *Cryptosporidian* oocysts were detected for the remainder of the river. In terms of *Giardia*, however, 100 cysts were found at Springfield Road, and 50 at 7th Avenue. This number is in excess of that required to produce adverse health effects and such constitute a significant health risk for any interaction with the water.

The following table 4.16,summarises the significant water quality data for the sampling period between July 1997 and September 1998.

	1997		
	Springfield Road		
	Min	**Max**	**Mean**
Total Nitrogen (mg N/l)	8.1	12.18	12.18
Total Phosphorus (mg P/l)	0.482	0.997	0.707
Soluble Reactive Phosphorus (mg P/l)	0.282	0.856	0.546
COD (mg O/l)	44.8	74.6	61
TSS (mg/l)	3.4	20.85	9.9
Conductivity (mS/m)	83.7	142.8	107.223
pH	-	-	-
Faecal coliforms (count/100ml)	1.1e4	9.3e6	1.52e6

	1998		
	Springfield Road		
	Min	**Max**	**Mean**
Total Nitrogen (mg N/l)	5.725	11.749	9.289
Total Phosphorus (mg P/l)	0.583	1.257	0.894
Soluble Reactive Phosphorus (mg P/l)	0.372	0.976	0.704
COD (mg O/l)	56.5	79.9	67.5
TSS (mg/l)	4.7	22.85	11.78
Conductivity (mS/m)	76.8	125.3	94.7
pH	-	-	-
Faecal coliforms (count/100ml)	3000	5.2e5	9.98e4

Table 4.16: Summary of water quality results for sampling period

CHAPTER 5

SWMM AND PCSWMMGIS98

In order to assess the use of a hydrological modelling tool in decision support for catchment management, the Storm Water Management Model (SWMM) (Huber and Dickinson, 1992) was applied to the Great Lotus River catchment. SWMM is a semi-distributed, physically based deterministic model with varying levels of complexity. The model, written in Fortran and developed in 1971, has undergone significant upgrading and improvement through decades of input and critical assessment to be capable of simulating urban stormwater runoff on a continuous and event basis (James and James, 1997). Although SWMM was designed principally for urban stormwater runoff problems, the subsurface flow module, incorporating infiltration, evapotranspiration, interflow and percolation, enables pervious rural subcatchments of multi landuse type catchments to be modelled.

The discussion, below, quoting liberally from a number of primary sources including (James and James, 1997), (Huber and Dickinson, 1992), (Roesner and Dickinson, 1992), and (Green and Stephenson, 1986) provides an overview of SWMM and its components.

5.1 SWMM v4 - Overview

SWMM simulates monitored and design storm events on the basis of rainfall (hyetograph) and other meteorological inputs and system (catchment, conveyance, storage/treatment) characterisation to predict outcomes in the form of quantity and quality values. Complex interactions between the meteorological and hydrological processes of an area can be simulated with SWMM being run for an unlimited number of timesteps. This implies a simulation resolution of daily, hourly to even second-based intervals. In this way an overall assessment of urban runoff problems can be performed or critical events from a long period of simulation can be selected for detailed analysis. It permits time series output, i.e., hydrographs and "pollutographs" (concentrations versus time) and daily, monthly, annual and total simulation summaries (for continuous simulation) for review.

If input parameters are correct, the physics of the various processes should be simulated sufficiently well to produce accurate results with minimum calibration. Given inadequate input data coupled with computational algorithms that are simplifications of complex processes, a certain amount of calibration is required to ensure that model behaviour is acceptable. Given sufficient parameters that can be adjusted, a reasonable goodness-of-fit of observed data to simulated output can be obtained.

Primary input into the model is long-term precipitation data. Outputs consist of hydrographs and pollutographs at a specified interval of time steps. The model consists of four simulation components: RUNOFF, TRANSport, Extended TRANSport (EXTRAN) and STORAGE.

An overview of the model structure is shown in Figure 5-1. In simplest terms, the program is constructed in the form of "blocks" as follows with each block being a primary subroutine performing a specific function:

- RUNOFF simulates quantity and quality runoff phenomena for a drainage basin and the routing of flows and contaminants to the major sewer/stormwater lines. It generates surface and subsurface runoff based on arbitrary rainfall (and/or snowmelt) hyetographs, antecedent conditions, land use, and topography and represents each subcatchment as an aggregate of idealised subcatchments and gutters or pipes (James and James, 1997)

- Routing through the sewer/stormwater system is accomplished in the TRANSport block. This includes routing of quantity and quality parameters, estimating dry weather flow, infiltration and storage (Huber and Dickinson, 1992)

- Extended TRANSport (EXTRAN) was developed for complex systems where the assumption of steady flow (as in RUNOFF and TRANSport) cannot be made. It is thus a sophisticated dynamic flow routing module solving the full St Venant equations for gradually varied flow (Roesner and Dickinson, 1992).

- STORAGE simulates the routing of flows and pollutants through storage/treatment plants having detention or non-detention characteristics (Huber and Dickinson, 1992).

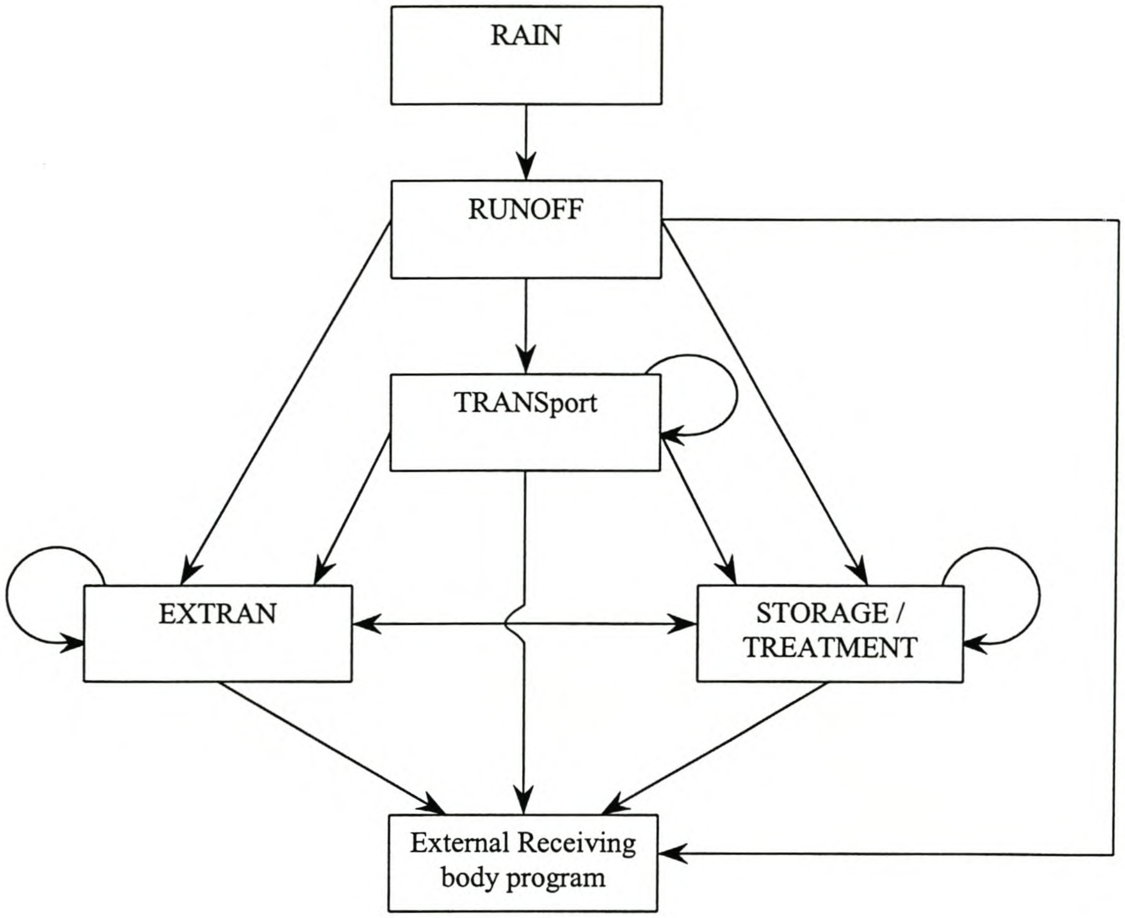


Figure 5.1: Overview of SWMM structure (Huber and Dickinson, 1992)

5.1.1 *RAIN block*

Precipitation is the primary driving force in SWMM. The RAIN module reads in long time series of precipitation records in US available or user-defined formats, performs optional statistical analyses and generates a precipitation interface file for use in the RUNOFF block. The output of RAIN may be voluminous depending on the user selected output options chosen. This includes options to print the entire precipitation file, storm event summaries and statistical summaries of return periods for storm volume, average intensity, duration, and inter-event time. Calculations are made of estimates for the mean, variance, standard deviation, coefficient of variation and coefficient of skewness.

5.1.2 *TEMP block*

The purpose of the TEMP block is to input temperature, evaporation, and wind speed data and make an interface file accessible to the RUNOFF block of SWMM. TEMP reads the input data, translates the temperature, evaporation, and/or wind speed data into the required SWMM format, and prints raw data or summary tables. The program is designed to utilise daily maximum and minimum temperatures, pan evaporation, and daily wind movement, using predefined formats or user-defined time series.

5.1.3 *RUNOFF block*

This block is designed to simulate the rainfall-runoff process on a drainage basin and produce hydrographs and pollutographs at selected locations within the catchment. In order to make use of any of the other computational blocks it is first necessary to run the RUNOFF block as the output from this block forms the basis of input to the other blocks. It can thus be considered the core of SWMM.

Flow generation in SWMM originates with overland runoff. Precipitation is read into RUNOFF either from the RAIN module or input in RUNOFF itself as input hyetographs, with RUNOFF making a step by step accounting of infiltration losses in pervious areas, surface detention, overland flow and channel flow. This leads to the calculation of a number of inlet hydrographs and pollutographs that may be placed on the interfacing file for input into subsequent module.

Input data for this module requires two tasks:

- discretisation of physical drainage system
- estimation of subcatchment coefficients

5.1.3.1 Overland flow

Subcatchments are represented as an aggregate of idealised subcatchments and drainage conduits. A spatially distributed effect is obtained by subdividing the overall catchment into a number of subcatchments, computing the runoff from each subcatchment and then combining each outflow with a routing technique.

Subcatchments are divided into three subareas that simulate impervious areas with or without depression storage and pervious areas. These are areas A1 (impervious areas with depression storage), A3 (impervious areas without depression storage) and A2 (pervious areas) depicted in Figure 5.2 below (for inclusion of snowmelt, a fourth subarea is added to account for presence or absence of snow cover. This case will not be considered for the duration of this thesis)

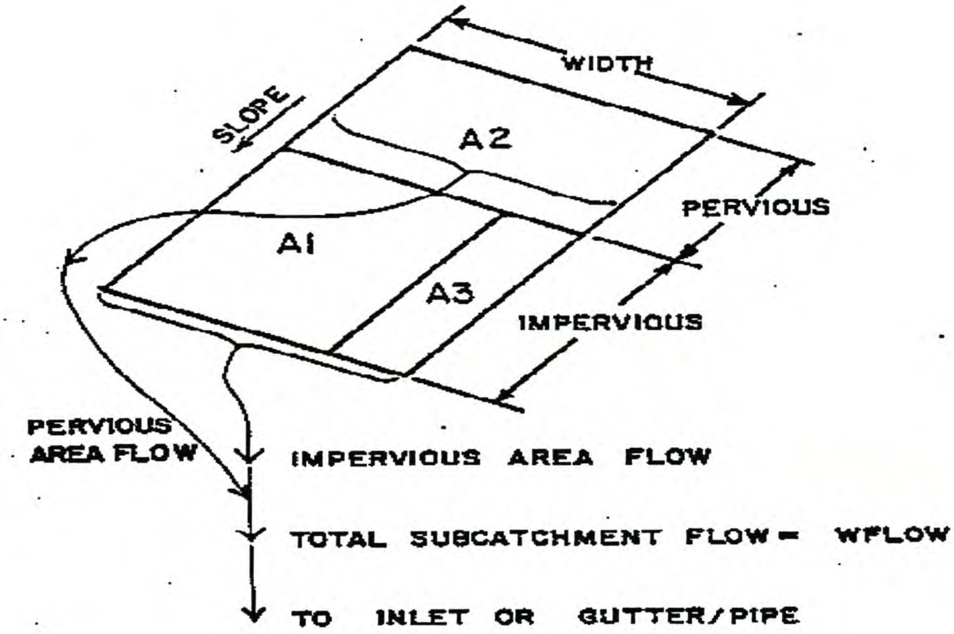


Figure 5.2: Subcatchment schematisation for overland flow

Subcatchments are idealised as rectangular panes on which the overland flow occurs. Flow over each segment flows directly to the subcatchment outlet and doesn't pass over any other segments. Subareas of each subcatchment are approximated as a series of non-linear reservoirs, spatially lumped, with uniform slope, constant roughness, depression storage and infiltration parameters. Computation from these reservoirs is through a simultaneous solution of the continuity equation and Manning's flow equation.

Although the area of a subcatchment can be accurately measured, the shape of this subcatchment is approximated as a sloping rectangular plane in SWMM. Consideration must therefore be given to the flow length and width of this idealised plane. It is possible to begin with the subcatchment length, this being an indication of the actual path taken by the water in flowing down a subcatchment. The width is therefore merely the measured area divided by this length. An increase in the width implies a decrease in flow length and a corresponding decrease in time to equilibrium for the subcatchment. In addition, given that the subcatchment acts as a storage reservoir, the outflow from a narrow subcatchment with long flow length will be more constricted than the case of a wide subcatchment with short overland flow length (rainfall and area equal for both cases)

Subcatchment width can therefore be seen as both a shape parameter as well as a storage parameter; wide catchments resulting in hydrographs that peak sooner than those resulting from long narrow subcatchments

For a subarea, continuity is expressed as

$$\frac{dV}{dt} = I - Q \quad \text{.....(5.1)}$$

where V = vol. in reservoir
I = Inflow rate
Q = Outflow rate
t = time

which can be rewritten as

$$A\frac{dy}{dt} = Ai - Q \quad \text{.....(5.2)}$$

where A = area of subarea
y = depth of water
i = excess rainfall intensity

With the assumption that uniform flow occurs along the length of the subarea (valid for shallow sheet flow conditions), Manning's equation gives:

$$Q = \frac{W}{n}(y - d_p)^{\frac{5}{3}} \times S^{\frac{1}{2}} \quad \text{.....(5.3)}$$

Where Q = Flow (m^3/s)
n = Manning's roughness coefficient
d_p = depth of depression storage (mm)
S = slope of subarea (m/m)
W = subcatchment width (m)
y = depth of water (mm)

Since A = length of subarea multiplied by width (W), substitution of equation (1.3) in (1.1) yields:

$$\frac{dy}{dt} = i - \frac{W}{A \times n}(y - d_p)^{\frac{5}{3}} \times S^{\frac{1}{2}} \quad \text{...(5.4)}$$

This equation (5.4) can be considered as a non-linear differential equation with unknown y and can be solved numerically by a finite difference technique with:

$$\frac{d_2 - d_1}{\Delta t} = i - \frac{W}{A \times n}(\bar{y} - d_p)^{\frac{5}{3}} \times S^{\frac{1}{2}} \quad \text{..................................(5.5)}$$

Replacing $\bar{y}$ with $\frac{y_1 + y_2}{2}$, equation (5.5) can be solved for y_2 using the Newton Raphson iterative technique. The solved value of y_2 is thus substituted back into equation (5.3) to obtain the flow rate off the subarea. This process is repeated for all subareas thereby obtaining hydrographs at each subcatchment outlet for the required time step.

5.1.3.2 Channels and pipes

These hydrographs are routed through the pipe and channel network using similar principles (i.e. of continuity and Manning with numerical finite difference methods), so that, at every time step, a flow rate at each conduit is calculated. This flow rate in each conduit is a combination of routed upstream flow rates and flow rates of the subcatchments contributing directly to the head of the particular subcatchment.

Three cross-sectional shapes are available for channel/pipes: circular, trapezoidal and parabolic. Channel/pipes act as reservoirs with a water surface parallel to the invert, resulting in the distribution of inflows along its length. This leads to flattening of the hydrograph peak when it is routed through a cascade of pipes. Downstream effects are not felt upstream and no backwater effects can be simulated.

In order to save computing power, RUNOFF has three independent time steps:

(1) wet-time step (WET)
(2) transition time step between wet and dry (WETDRY)
(3) dry time step (DRY)

The wet time step is a time step with precipitation occurring on any subcatchment and is normally less than or equal to the inputted rainfall interval. The transition time step has no precipitation input on any subcatchment, but the subcatchment(s) still have water remaining in surface storage. The overland flow routing technique loses water through infiltration, evaporation and surface water outflow during the transitional time step The dry time step has no precipitation input nor water in surface storage (although it can have groundwater flow). This time step is used to regenerate infiltration parameters and to generate groundwater flow The model is considered globally wet, globally transitional or globally dry.

5.1.3.3 Losses

In generating runoff hydrographs from given rainfall inputs, SWMM considers three loss functions:

- evaporation
- depression storage or surface retention
- infiltration

(1) Evaporation

Evaporation data is input as a parameter or as a time series. It is considered as "loss off the top" in that evaporation is subtracted from rainfall depths and/or ponded water prior to calculating infiltration. When considering the rainfall intensity of the above equations, this is therefore rainfall intensity less evaporation.

(2) Depression storage

Depression storage can be considered as the volume that must be filled prior to the occurrence of runoff. Thus, for runoff to occur from a subcatchment, the total depth of water resulting from excess rainfall intensity must exceed the depth available for depression storage. Depression storage is accounted for in both the pervious and impervious areas of each subcatchment.

(3) Infiltration

The final loss function is due to infiltration and can be considered the most significant loss in the model. Infiltration is determined with a choice of either the modified Horton (empirical) or Green-Ampt (physically based) approaches. Losses from infiltration may be optionally routed through a subsurface pathway, first into unsaturated zone storage, then to a saturated zone from which baseflow into an inlet or channel pipe may be generated.

Horton model

Horton's equation is empirical and, in its usual form, is applicable only to events in which the rainfall intensity always exceeds the infiltration capacity. The modified form used in SWMM overcomes this deficiency.

The usual form is:

$$f_p = f_\infty + (f_0 - f_\infty)e^{-k.t} \quad \ldots\ldots\ldots\ldots\ldots\ldots (5.6)$$

where f_p = infiltration capacity into soil at time t
f_∞ = saturated infiltration capacity of soil
f_0 = initial or maximum infiltration capacity of soil
k = decay constant

with actual infiltration being $f(t) = \min\left| f_p(t), i(t) \right|$ .... (5.7)

This says simply that actual infiltration is the lesser of the actual rainfall (i(t)) and infiltration capacity (f_p). Typical values for parameters f_0 and f_p are often greater than typical rainfall intensities. Thus, when Horton's equation is used such that f_p is a function of time only, f_p will decrease even if rainfall intensities are very light. This results in a reduction in infiltration capacity regardless of the actual amount of entry of water into the soil.

To account for the periods when the rainfall rate is less than the prevailing infiltration rate, the integrated form is used in SWMM as follows:

$$F(t_p) = \int_0^{t_p} f_p dt = f_\infty t_p + \frac{(f_0 - f_\infty)}{k}(1 - e^{-kt_p}) \quad \ldots\ldots\ldots\ldots\ldots\ldots (5.8)$$

where $F(t_p)$ = cumulative infiltration at time t_p

This cannot be solved explicitly for t_p, and must therefore be solved iteratively. Given this modification, f_p can therefore be considered as a function of actual water infiltrated and not solely a function of time with the exclusion of other effects.

To summarise, infiltration capacity is computed at any time t as follows:

- Since the program updates the value of F at every time step using equation (1.7), the cumulative infiltration at time t is known and the value of t_p can be computed
- Knowing t_p, the potential infiltration capacity is obtained from equation (1.6)
- This potential infiltration capacity is compared to rainfall intensity at that time step to verify if it can be met or if it should be reset to the lower rainfall intensity.
- Value of F is incremented accordingly and the process is repeated.

For continuous simulation, it is necessary to regenerate infiltration capacity during dry weather. Thus, during dry time steps (no precipitation of surface water) infiltration capacity is recovered according to a hypothetical drying curve given by:

$$f_p = f_0 - (f_0 - f_\infty)e^{-k_d(t-t_w)} \qquad (5.9)$$

where k_d = decay coefficient for the recovery curve

t_w = hypothetical projected time when f_p=f_∞ on the recovery curve

Green-Ampt equation

This equation was originally developed for infiltration with excess water at the surface at all times. Mein and Larson (1973) showed, however, that it could be adapted to a steady rainfall input and proposed a way in which the capillary suction parameter could be determined. This is a two-stage process that first predicts the volume of water that will infiltrate before the surface becomes saturated. From this point the second stage uses the Green-Ampt equation and computes the volume of water infiltrating after surface saturation. Thus for the first stage, until surface saturation has occurred,

where $F < F_s$:

$$f = i \qquad (5.10)$$

and

$$F_s = \frac{S \times IMD}{\frac{i}{K_s} - 1} \quad \text{for } i > K_s \qquad (5.11)$$

whilst for $F \geq F_s$:

$$f = f_p \qquad (5.12)$$

and

$$f_p = K_s(1 + \frac{S \times IMD}{F}) \quad \text{(5.13)}$$

where f = infiltration rate (mm/s)

f_p = infiltration capacity (mm/s)

i = rainfall intensity (mm/s)

F = cumulative infiltration volume, this event (mm)

F_s = cumulative infiltration volume required to cause surface saturation (mm)

S = average capillary suction at the wetting front (mm)

IMD = initial moisture deficit for event (mm/mm)

K_s = saturated hydraulic conductivity of soil (mm/s

Equation (5.11) shows that the volume of rainfall required to saturate the surface depends on the current value of the rainfall intensity. For each time step where $i > K_s$, the value of f_s is calculated and compared with the volume of rainfall already infiltrated for this event. Only if this volume exceeds F_s does the surface saturate. When rainfall occurs at an intensity less than or equal to K_s, all rainfall infiltrates and is used only to update the initial moisture deficit, IMD.

Equation (5.13) shows that the infiltration capacity after surface saturation depends on the infiltrated volume, which depends on the infiltration rates of the previous time step. In order to avoid numerical errors over long time steps, the integrated form of the Green-Ampt equation is used in SWMM with f_p being replaced with dF/dt and integrated to obtain:

$$K_s(t_2 - t_1) = F_2 - C \times \ln(F_2 + C) - F_1 + C \times \ln(F_1 + C) \quad \text{(5.14)}$$

where C = IMD . S

t = time

1,2 = subscripts for start and end of time interval

This equation is solved for F_2, the cumulative infiltration at the end of the time step using a Newton-Raphson iterative technique.

As with the Horton model, a recovery of infiltration capacity is necessary to allow simulation in a continuous mode. This regeneration of the initial moisture deficit (IMD) during dry weather conditions is accomplished with a more empirical process than with the Horton model.

Infiltration is usually dominated by conditions of the uppermost level of the soil. The thickness of this layer is determined by the soil type and the following equation:

$$L = 4\sqrt{K_s} \qquad (5.15)$$

where L = thickness of the layer

K_s = saturated hydraulic conductivity

For periods where there is no infiltration from rainfall or depression storage, a depletion factor DF is applied to the soil moisture where:

$$DF = \frac{L}{300} \qquad (5.16)$$

where L = depth of upper zone

Using a depletion volume DV per time step,

$$FU = FU - DV \quad \text{for} \quad FU \geq 0 \qquad (5.17)$$

$$F = F - DV \quad \text{for} \quad F \geq 0 \qquad (5.18)$$

where FU = cumulative moisture content of upper zone

F = cumulative infiltration volume for event

5.1.3.4 Subsurface flow routing in RUNOFF

Because SWMM was originally designed to simulate sewer overflows in urban catchments, the role of infiltrated water was considered insignificant. Since then, however, SWMM has been utilised in areas ranging from highly urban to relatively undeveloped. It is in these undeveloped areas that primary drainage pathways can be through the surficial groundwater aquifer and the unsaturated zone above it, rather than through overland flow. This results, in this case, in a slow release of water into the receiving surface water and the fate of infiltrated water is highly significant.

In order to incorporate subsurface processes in the simulation of a catchment, and to overcome the historical assumption that infiltrated water is "lost" to the stormwater system, SWMM has now become equipped with a groundwater subroutine.

This subroutine simulates two storage zones, the upper (unsaturated) zone and a lower (saturated) zone with flow from the upper to lower zones determined by a percolation equation with parameters estimated or calibrated depending on existing soil data. This percolation is the only inflow to the lower zone. Losses from the upper zone are solely through upper zone evapotranspiration, whilst for the lower zone include: deep percolation (loss to the system), saturated zone evapotranspiration and groundwater flow.

Individual mass balances account for the physical processes occurring within each zone in order to determine end-of-time step stage, groundwater flow, deep percolation and upper zone moisture. Infiltration is again either through the modified Horton or Green-Ampt equations.

The subroutine has a number of limitations: (James and James, 1997)

- Moisture content of the unsaturated zone is average over the entire zone therefore no moisture profile can be determined. Infiltrated water cannot be modelled as a slug moving from the unsaturated to the saturated zone as could be expected in a real system
- Water cannot move vertically upwards from the saturated zone through diffusion or capillary action
- Non-uniform soil conditions cannot be simulated given the representation of the subsurface storage as two "tanks", a saturated and unsaturated "tank", with infiltrated water assumed spread uniformly over the entire subcatchment area
- Groundwater lateral flow can only augment flow in a drainage channel, reverse flows from the channel back into the groundwater cannot be modelled
- Water quality is not simulated, any constituents entering the groundwater undergo 100% treatment in the soil.

5.1.3.5 Water Quality in RUNOFF

It is accepted that the simulation of runoff water quality is an inexact science with large uncertainties both in the representation of the physical, chemical and biological processes and the acquisition of data and parameters for model algorithms (James and James, 1997). The above uncertainties are addressed in SWMM in two possible ways and are primarily aimed at urbanised areas.

The first approach uses detailed and comprehensive calibration and verification data to calibrate the model algorithms. It assumes that, given adequate data, the algorithms can be sufficiently calibrated to reproduce measured pollutant loads and concentrations. If this data is unavailable, the second approach abandons quality simulation altogether, and either applies a constant pollutant concentration to quantity predictions or utilises some form of statistical method.

The constant concentration approach can be applied either through the use of a rating curve (in which quality loads (mass/time) are generated proportional to flow raised to a power), or by assigning a concentration to the precipitation. The statistical methods are based upon evidence that storm event mean concentrations (EMC) are lognormally distributed (James and James, 1997). These stochastic methods are, unfortunately, dependent upon statistical parameters such as mean, median and variance being available.

For most SWMM applications, the generation of water quality constituents occurs in the RUNOFF module. Several mechanisms are involved in the generation of stormwater quality, with pollutant "buildup" and "washoff" considered the most significant in SWMM. Additional constituent sources are catch basins (treated as reservoirs of constituents) or the precipitation itself adding atmospheric pollution.

Up to ten water quality constituents may be simulated in RUNOFF. These are all user supplied with the appropriate parameters. A maximum of five different landuses can be used to characterise subcatchments although these landuse types are restricted to those found in urban areas. Constituent build up is a function of this landuse, or is considered fixed for each constituent. Street sweeping is also a function of landuse.

The various methods mentioned serve to provide flexibility in the type of constituents modelled, and are discussed in more detail below.

(1) Buildup

It is assumed that the supply of constituents builds up on impervious land surfaces during the dry weather preceding a storm. This can be considered a function of time and factors including traffic flow, dry fallout and street sweeping.

James and James (1997), reporting on data from a number of studies, hold that although build up is mostly linear, it can also be non-linear. The choice of function is dependent on the user with SWMM allowing three functional options for constituent buildup:

1. Power - Linear

$$PSHED = QFACT(3) \times t^{QFACT(2)} \quad \ldots\ldots (5.19)$$

$$PSHED \leq QFACT(1)$$

2. Exponential

$$PSHED = QFACT(1) \times (1 - e^{-QFACT(2) \times t}) \quad \ldots\ldots (5.20)$$

3. Michaelis-Menton

$$PSHED = QFACT(1) \times \frac{t}{QFACT(3) + t} \quad \ldots\ldots (5.21)$$

where PSHED = Constituent quantity (kg)
QFACT(1) = limiting buildup parameter
QFACT(2) = power or exponent
QFACT(3) = coefficient

The linear function is a subset of the power function buildup, with both the exponential and Michaelis-Menton functions having clearly defined upper limits. Numerous studies are mentioned by (James and James, 1997) in order to generate values for the above parameters. This includes tables of summaries of the significant results (Manning *et al.*, 1977) (Ammon, 1979)and examples of the derivation of the build up values for dust and dirt and individual constituents for different urban landuse types. These studies and the data produced are purely empirical and ignore the underlying physics and chemistry of the generation processes. This, however, represents the data that is available and the SWMM modelling techniques are designed to accommodate them (James and James, 1997).

(2) Washoff

Washoff is considered as the process of erosion or solution of constituents from a subcatchment surface into the drainage system during a period of runoff. This washoff may be generated through rainfall energy (as in erosion calculations with particle detachment and motion), or may be a function of bed flow shear stress (as in sediment transport theory with mass flow rate of sediment proportional to flow and bottom shear stress).

James and James (1997) hold that a relationship can be developed to describe the washoff in which the rate of washoff at any time is proportional to the remaining quantity:

$$\frac{dPSHED}{dt} = -k \times PSHED \qquad (5.22)$$

where PSHED$_0$ = initial amount of quantity (kg)
k = coefficient

This can be solved to yield:

$$POFF(t) = PSHED_0(1 - e^{kt}) \qquad (5.23)$$

where POFF(t) = cumulative amount washed off surface at time, t$_0$, (kg)

The coefficient, k, is a function of particle size and runoff rate in that it increases with runoff rate and decreases with particle size. It is evaluated by assuming it is proportional to runoff rate, r:

$$k = RCOEF \times r \qquad (5.24)$$

where RCOEF = washoff coefficient (kg)
r = runoff rate over subcatchment (mm/hr)

Consideration of equations (5.22) and (5.24) reveals that the concentration will always decrease as a function of time, regardless of the time distribution of runoff. This, therefore, doesn't account for the possibility of constituent concentrations being higher during the peak rates of a storm than those preceding. This is addressed in SWMM in making the washoff at each time step proportional to the runoff rate to a power. This is shown in equation (5.25) below:

$$-POFF(t) = \frac{dPSHED}{dt} = -RCOEFX \times r^{WASHPO} \times PSHED \qquad (5.25)$$

where POFF = constituent load washed off at time, t (mg/s)
PSHED = quantity available for washoff (mg)
RCOEFX = washoff coefficient
WASHPO = power
r = runoff rate (mm/hr)

Numerous studies are noted in James and James (1997) illustrating the use of RUNOFF's washoff formulations. This includes urban hydrologic studies including data collection and modelling (Huber *et al.*, 1981), case studies of catchment water quality simulations (Ellis 1978), Alley and Ellis (1979)) and RUNOFF quality calibration studies (Jewell and Adrian (1978), Jewell *et al.* (1978), Jewell and Adrian (1981)).

(3) Rating curve

In addition to the above methods, constituent load rates can be computed using a rating curve method

$$POFF = RCOEF \times WFLOW^{WASHPO} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.26)$$

where POFF = constituent load washed at time, t (mg/s)
RCOEF = coefficient
WFLOW = subcatchment runoff (m^3/s)
WASHPO = exponent

The parameters for equation (5.26) can be derived on a storm event basis by plotting total load versus total flow on a log-log scale. Huber (1980) and James and James (1997) discuss the use of this approach and the range of parameter values that can be expected.

Table 5.1, below, provides an indication of the maximum values for the various RUNOFF parameters for both version 4.31 (the last SWMM version to have official EPA acceptance) and the updated beta version 4.4 presently used.

	4.31	4.4
Number of Subcatchments in the Runoff Block (NW)	250	1000
Number of Channel/Pipes in the Runoff Block (NG)	250	1000
Number of Groundwater Subcatchments in Runoff (NGW)	250	100
Number of Runoff Water Quality Constituents (NRQ)	10	10
Number of Runoff Land Uses per Subcatchment (NLU)	5	10

Table 5.1: Maximum parameter values for SWMM RUNOFF module

5.1.4 *TRANSport block*

Routing through the stormwater network may be accomplished in the TRANSport block. It has extended functionality over RUNOFF in that it can handle more complex channel cross-sections including natural sections. It thus allows for situations where subcatchments drain into a river with routing of flow through the varying cross-sections of the river being undertaken successfully with TRANSport. It routes not only flow quantity but also quality constituents. Hydrographs are input into TRANSport from the preceding RUNOFF module.

Flow routing proceeds downstream through all the elements (conduits, manholes, overflow structures etc) during each time interval until the storm hydrographs are routed through the system. Kinematic theory is used in which disturbances are allowed to propagate in the downstream direction. No backwater effects are modelled and backwater conditions are assumed not to affect upstream computations. (Computations in any of the latter situations is done in the EXTRAN block, section 5.1.4, below) Any surcharging is modelled by storing excess flows at the head of the conduit until the capacity exists to accept the stored volume.

Most of the data inputs are in terms of that needed to describe the conveyance system being modelled (dimensions, slopes, roughness etc). The system is described as a network of conduits (or channels) joined at manholes or another type of structure. When calculating flows in each element, the upstream flows are summed and added to surface runoff, dry weather flow and infiltration entering at that point. This input can only occur at non-conduit elements such as manholes.

It is evident that TRANSport should be used when the effect of in-system storage and attenuation on the outfall hydrograph is significant. This is especially the case for large conduits with appreciable lengths and flatter grades or if detention storage is implemented in the system.

Table 5.2, below, provides an indication of the maximum values for the various TRANSport parameters for both SWMM version 4.31 and the beta SWMM version 4.4.

	4.31	4.4
Number of Elements in the TRANSport Block (NET)	500	300
Number of Storage Junctions in TRANSport (NTSE)	100	100
Number of Input Hydrographs in TRANSport (NTH)	125	80
Number of Tabular Flow Splitters in TRANSport (NTSP)	50	50

Table 5.2: Maximum parameter values for SWMM TRANSport module

5.1.5 *Extended TRANSport block (EXTRAN)*

This block provides for the dynamic routing of inflow hydrographs through an open channel or closed conduit system and computes the time history of flows and hydraulic heads throughout the system. It is intended for application where the assumption of steady flow in computing backwater profiles cannot be made. Using an explicit solution technique the block solves for the full dynamic equations for gradually varied flow (St Venant equations) to step forward in time. The time step is governed by wave celerity in the shorter channels or conduits of the system and is of the order of 5 - 60 seconds, depending on the length of the shortest conduit. This results in computing time being a consideration in the module.

The drainage network is represented by the "link-node" concept with channels (termed as links) separated by nodes (or junctions). This allows a high degree of flexibility in the problems that can be addressed in EXTRAN: parallel pipes, looped systems, diversions such as weirs and orifices, surcharge at manholes and backwater effects within the system.

Input into this block is solely in terms of the elevations, dimensions and characteristics of the drainage network. Because of the computing time consideration, coupled with the need for highly accurate elevation/dimension data, routing through EXTRAN should only be attempted where backwater effects, surcharge and/or diversion facilities affect the flow and hydraulic head calculation. Routing above this point, as a rule of thumb, should be undertaken in RUNOFF and TRANSport.

5.1.5.1 EXTRAN input data - Node (junction) data

The link-node concept reduces the drainage network to a system of nodes (junctions) separated by channels (conduits). The junctions are stipulated at the following points:

- upstream terminal points in the system (where RUNOFF / TRANSport stored hydrographs are routed into EXTRAN)
- downstream outfall and discharge points
- pipe junctions
- junctions where inflow hydrographs are input
- points where pipe size/slope/shape changes significantly
- points where pipe inverts differ significantly (such as at catchpits or manholes)

Each junction is characterised by a ground elevation (the point where the assumption of pressure flow is no longer valid and flooding out of the junction occurs as a loss from the system) and invert elevation.

5.1.5.2 EXTRAN input data – Conduit data

Conduit data required includes shape, size, length, hydraulic roughness, connecting junctions, initial flows and invert distance (referenced to junction invert). The options for conduit shape are standard and include circular, rectangular, horseshoe, egg, basket handle, trapezoidal, parabolic and irregular cross-sections. The option of the irregular shape implies that natural channels may be simulated through the use of surveyed cross-sections.

Table 5.3, below, provides maximum values for the various EXTRAN parameters for both SWMM version 4.31 and the beta SWMM version 4.4.

	4.31	**4.4**
Number of Elements	600	1400
Number of Pumps	100	75
Number of Orifices	100	200
Number of Tide Gates/Free Outfalls	25	200
Number of EXTRAN Weirs	100	60
Number of EXTRAN Printout Locations	50	30
Number of Tide Elements	20	20
Number of Natural Channels	100	200
Number of Storage Junctions	200	300
Number of Time History Data Points	200	500
Number of Data Points for Variable Storage Elements	25	25
Number of Input Hydrographs	250	400
Number of Allowable Channel Connections to Junctions	10	15

Table 5.3: Maximum parameter values for SWMM EXTRAN

Given that RUNOFF, TRANSport and EXTRAN all have conveyance routing abilities, the user may be uncertain as to which module to use. This is very much dependent on the modelling objectives and the available input information. Table A2.1 in Appendix 2 provides a comparison of the routing abilities of the three modules and to enable selection of the appropriate module for a particular modelling exercise.

5.1.6 *Storage/Treatment block (STORAGE)*

The STORAGE block simulates the routing of flows and pollutants through a dry- or wet-weather storage/treatment plant containing up to five units or processes (with detention or non-detention characteristics) for a single-event or continuous simulation. The various units may be linked in a variety of configurations. Sludge handling may also be modelled using one or more units. Additionally, capital cost and operation and maintenance cost may be estimated for each unit.

The STORAGE block will route up to three different pollutants in addition to flow. These pollutants may be input to the block from any external block via the interface file, directly from keyboard input to this block, or a combination of both. Characterisation of the pollutants may be by magnitude (i.e. concentration) or by magnitude and a particle size/specific gravity settling velocity distribution. All input flows and pollutant concentrations are assumed to be instantaneous values whilst the output consists of average values at user-defined time steps, not instantaneous values as in the rest of SWMM.

In addition to the above RUNOFF, TRANSport, EXTRAN and STORAGE simulation blocks, there are a number of service blocks. The RAIN and TEMP blocks have already been discussed in section 5.1.1 and 5.1.2, above. This is due to these blocks providing the input data for the computational blocks. The additional service blocks, STATISTICS and COMBINE are discussed below.

5.1.7 *STATISTICS block*

The STATISTICS block performs simple statistical analyses on time step output from continuous or single-event simulations for both quantity and quality parameters. This analysis is available for one location at a time. The available options include the separation of output into discrete storm events, the ranking of events according to different criteria (e.g., peak or average runoff rate, pollutant load, etc.), the assigning of empirical frequencies and return periods to runoff and pollutant parameters, and the calculation of the first three statistical moments or their derivatives (unbiased estimates for the mean, variance, standard deviation, coefficient of variation and coefficient of skewness printed for each parameter chosen for each constituent chosen). Output from the STATISTICS block can thus be used to identify key events for further study and for other screening and analytical purposes.

5.1.8 *COMBINE block*

This block allows the manipulation of multiple interface files in order to aggregate results of multiple previous runs for input into subsequent blocks. In this manner large, complex drainage systems may be partitioned for simulation in smaller segments. Two principal operations may be followed:

- To collate two different interface files into a single interface file that contains the hydrographs/pollutographs for all nodal locations (and sums flows and loads at common locations). This is to overcome the limitation of each SWMM computational block being able to accept one interface file as input.
- To combine hydrographs and pollutographs at different locations and on different interface files into a single hydrograph/pollutograph time series (i.e., at just one location) on a single interface file.
- The block can also be used to select and/or renumber nodes from a single file or while collating or combining.
- Finally, the COMBINE block may be used to convert an unformatted interface file into a formatted ASCII or text file capable of being read by external programs. Such a file can be input to a spreadsheet program or read by a Basic program, for example, for further analysis.

5.2 PCSWMM 98

Given the difficulties associated with stormwater simulation using the FORTRAN language of SWMM, PCSWMM'98 was developed by Computational Hydraulics Inc (CHI), Canada, as an interface to SWMM version 4. Rewritten for the Windows 95/NT operating systems, PCSWMM was developed as a decision support system for SWMM and provides a powerful, flexible, and intuitive environment for stormwater management modelling. This includes a large array of tools for file management, data file creation, output visualisation and interpretation, model calibration and error analysis and storm dynamic analysis thus easing any simulations with SWMM. In addition, it was written specifically for the web and eases communication with the extensive global user group, debating technical issues and providing solutions to user queries (a database of all question and answer sessions is maintained at http://www.chi.on/swmmqa.html)

5.2.1 *PCSWMM Objects*

PCSWMM represents the various SWMM associated files as objects displayed as icons in the main window. There are 14 different types of objects, such as:

- Rain object
- Temperature object
- Runoff object
- TRANSport object
- EXTRAN object
- Storage object
- Statistics object
- Combine object
- Precipitation data
- Meteorological data
- Observed flow data

Clicking on any of the object icons will result in the display of a menu for various file operations including editing the input file, running SWMM, viewing and plotting the output file and running the Sensitivity Wizard. The properties of each object, including the date and success of last SWMM run, associated files and upstream objects, can also be displayed. The main PCSWMM window, with various objects, is shown in Figure 5.3, below:

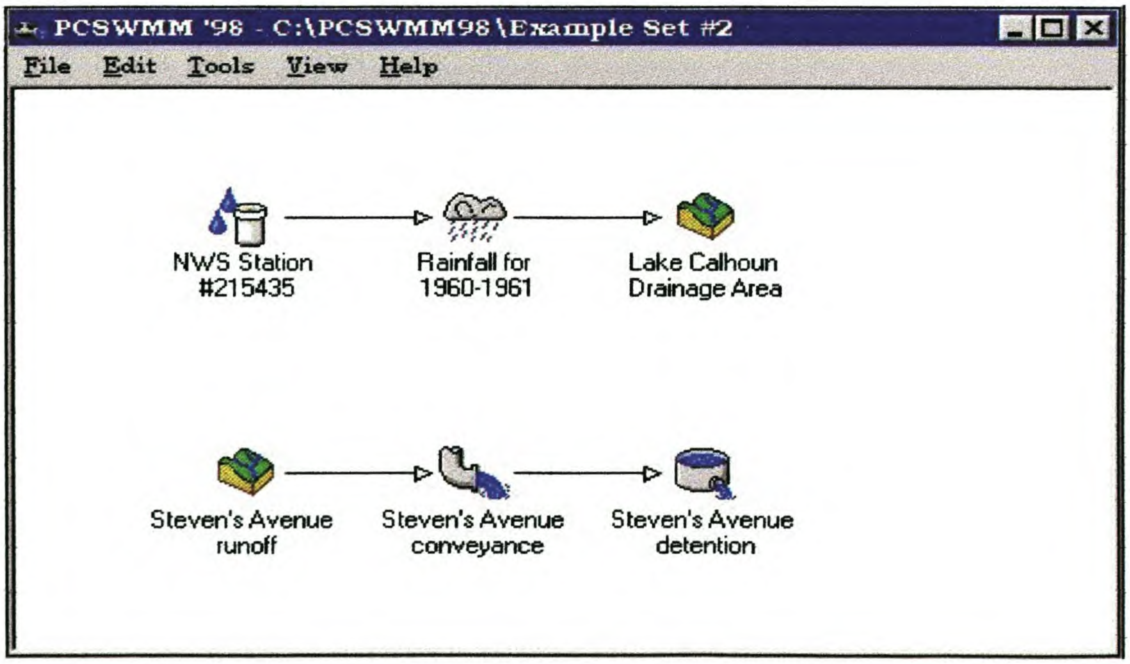


Figure 5.3: PCSWMM Main window with linked objects

The icons in Figure 5.3, above, depict precipitation input data, RAIN and RUNOFF objects in the top line with RUNOFF, TRANSport and STORAGE objects in the bottom line. The arrows between each object represent the linkages between them.

5.2.2 *PCSWMM Files*

Only certain file types are displayed as objects in PCSWMM, however any other file types sharing the same file root as an object can be accessed through that object. These are called associated files and include:

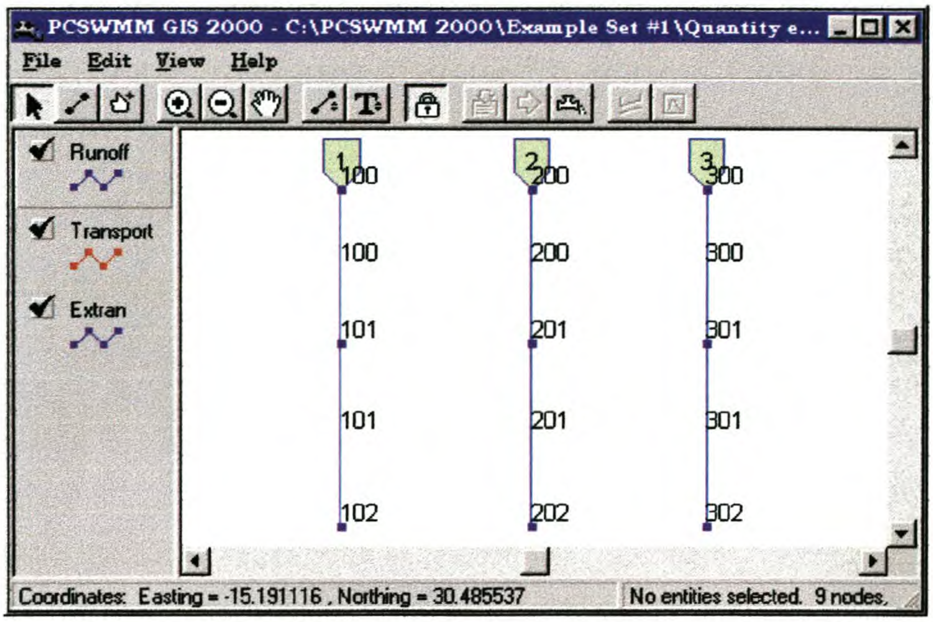
- Input Data File
- Output File
- Interface File
- Precipitation File
- Meteorological File
- GIS Database File
- EXTRAN hot start file
- Observed File
- Sensitivity Analysis File
- Calibration File
- Plot File
- Datalogger File
- Intensity File
- Storm File
- Note (text) File
- URL File
- Scratch File

5.2.3 *PCSWMM GIS*

Given the added functionality coupled with ease of generating input data, PCSWMM98 was extended to include a GIS component. This represents a tight coupling of GIS and hydrological model (as discussed in Chapter 3) relying on automatic file transfer between GIS and model through the software. The operator accesses the information systems through a common interface (as shown in Figure 3.3 of Chapter 3).

PCSWMM GIS fulfils two main roles. It acts firstly as a GIS for graphically creating, editing and/or querying SWMM model entities and attributes, displaying these SWMM layers with background layers and dynamic model results, and exporting data to SWMM input files. Secondly, it acts as an interface between a GIS/IMS and SWMM.

PCSWMM GIS provides a graphical plan view editor for quickly creating, editing and/or querying the physical entities of a SWMM model and their attributes, using any coordinate system. These entities include conduits, nodes and subcatchments which can be graphically created with simple mouse clicks and/or can be imported from existing SWMM files, many database formats, spreadsheets and other file types. Map and image formats can be displayed as backgrounds to these entity layers, including TIFF files, ArcView shape files, AutoCAD DXF and DWG files, MapInfo, and Microstation files, overlaid by the SWMM RUNOFF and EXTRAN model layers. Figure 5.4, below, depicts the plan view editor of PCSWMM GIS. A schematic is shown of three subcatchments draining to three different conveyance systems.

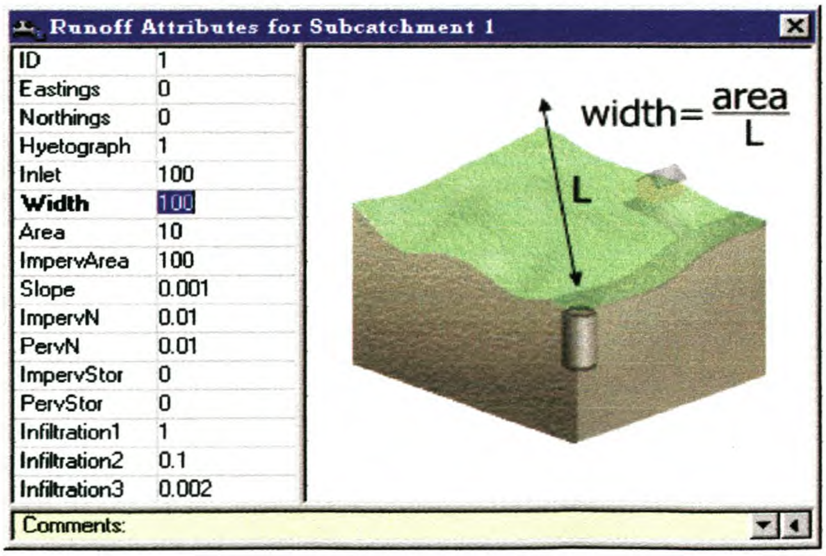


Coordinates: Easting = -15.191116 , Northing = 30.485537

No entities selected. 9 nodes.

Figure 5.4: PCSWMM GIS Editing window

Data for each of the components in the drainage system illustrated in Figure 5.4 can be input or edited merely by clicking on the object in the PCSWMM GIS editing widow. This results in the generation of a data input window as shown in Figure 5.5 below.



ID	1
Eastings	0
Northings	0
Hyetograph	1
Inlet	100
Width	100
Area	10
ImpervArea	100
Slope	0.001
ImpervN	0.01
PervN	0.01
ImpervStor	0
PervStor	0
Infiltration1	1
Infiltration2	0.1
Infiltration3	0.002

Comments:

Figure 5.5: PCSWMM GIS input data window

In addition, PCSWMM GIS also supports linkages to existing GIS and/or Information Management Systems (IMS), databases, spreadsheets and text files, with full SQL query support. Users can import from and export to the Runoff, TRANSport and EXTRAN modules of SWMM. Exporting to XPSWMM's XPX file format is also supported. SWMM model results can be dynamically displayed as a layer and links are provided to other PCSWMM tools.

PCSWMM GIS can be used to automate data input such as subcatchment areas, slopes and conduit lengths into the appropriate SWMM module. Node, conduit, and subcatchment data are transferred automatically from the underlying GIS database (ODBC) into an intermediate database for processing into a useful model. This data is then exported to a SWMM input file (Runoff, TRANSport or EXTRAN). PCSWMM GIS can calculate subcatchment area and conduit lengths from the map display.

Attributes supported by PCSWMM GIS are:

<u>Node Attributes</u>:

- ID,
- easting
- northing
- ground elev (EXTRAN only)
- invert elev (EXTRAN only)
- inflow
- initial depth (EXTRAN only)
- up to 4 pollutant concentrations in inflow (TRANSport only)

<u>Conduit Attributes</u>:

- ID
- upstream node
- downstream node
- type,
- length,
- roughness,
- measurements for cross-sectional shape
- invert elev. at each end (EXTRAN only),
- side slopes (if applicable),
- initial flow (EXTRAN only),
- initial depth (Runoff only)

Subcatchment Attributes:

- ID
- inlet node
- width
- area
- impervious area
- slope
- roughness of impervious area
- roughness of pervious area
- storage in impervious area
- storage in pervious area
- 3 infiltration parameters (Horton's or Green-Ampt equation)

5.2.4 *PCSWMM add-ons*

In addition to the above GIS component, PCSWMM has a number of add-ons to assist in the creation, operation and interpretation of SWMM modelling exercises. The suite of add-ons includes a large array of tools for file management, data file creation, output visualisation and interpretation, model calibration and error analysis and storm dynamic analysis. A brief description of the significant tools is given below. (James and James, 1998)

5.2.4.1 RainPak

RainPak is a precipitation analysis program that can be used for identifying storm systems and storm cells, discretising the various precipitation time series to a fixed, uniform time-step, appending SWMM4 input data files with the discretised precipitation time series and saving the discretised precipitation time-series to a single file for use by the RainPak Velocity module. A number of default rainfall input formats typical of North American raingauges are provided or alternatively a user-defined format can be created for inputting raw precipitation data into the program. RainPak consists of four modules: Import, Velocity, Collate and Direction.

RainPak Velocity provides both visual and computational methods for determining storm cell kinematics. RainPak Collate facilitates the collation of various combinations of storm cell analysis results into a single comma-delimited file for import into spreadsheets and/or the RainPak Direction module. RainPak Direction creates rosette plots of relative frequencies of storm cell directions.

5.2.4.2 Sensitivity Wizard

Sensitivity Wizard provides an analysis of parameter sensitivity for various input functions and objective functions in the SWMM Runoff module. It incorporates a step-by-step interface to simplify the complicated and time-consuming process of manual sensitivity testing. Any number of parameters and input functions can be analysed and re-analysed given any model changes are made. Sensitivity Wizard presents the results in customisable graph formats and displays ranked mean or non-linear sensitivity gradients as well as numeric tables that can all be exported in various forms. Chapter 6 further discusses the use of this tool in assessing the sensitivity of parameters used in the Great Lotus River model.

5.2.4.3 Graph

Graph enables the plotting of hydrographs, pollutographs, depth and velocity graphs from one or more SWMM output files, interface files and plot files as well as user defined observed flow data. Multiple time series can be displayed simultaneously from multiple file sources and exported in various forms.

5.2.4.4 Dynamic Hydraulic Grade Line (HGL)

The Dynamic Hydraulic Grade Line (HGL) tool displays the profile of any selection of channels or conduits from a SWMM EXTRAN model. The hydraulic grade line can be superimposed on this profile for any time within the simulation period, or dynamically played back for the period of simulation.

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The following chapter, Chapter 6, provides a description of the modelling approach utilised in the simulation of the Great Lotus River. It describes the methodology in setting up the SWMM model, the modules used, the collection of input data and the initial assumptions for the various model parameters. It describes the attempt at simulating TP, one of the significant catchment pollutants and the shortcomings of this attempt. Plots of the model output are shown and compared to the observed data file. This is followed by a sensitivity analysis to isolate and rank the most sensitive model parameters for use in the model calibration. The methodology applied in the sensitivity analysis is described. The success of this model calibration is shown together with the associated error analysis and the uncertainty in the input data. Significant statistical parameters are produced evaluating the closeness of fit of the simulated model to the observed data file. Given the short duration of the observed data, the entire data series is used for calibration. No attempt is made to verify the model using any external data sets given that none exist. This calibrated model is then tested in Chapter 7 as the DSS for catchment management together with an analysis of the advantages and disadvantages of SWMM as the DSS.

CHAPTER 6

SWMM MODELLING OF GREAT LOTUS RIVER

As discussed in Chapter 4, the Great Lotus River catchment is composed of multiple landuse types, with urban and agricultural areas prevalent. It thus provides a good case study for the application of the SWMM model to a complex catchment for the testing of its efficacy as a DSS for Catchment Management. (This capability as a DSS for CM is discussed further in Chapter 7). The primary objective of applying SWMM to the Great Lotus River is to simulate streamflow continuously for the 16-month period of monitoring. The secondary objective is to simulate the load variation in Total Phosphorus for the same period.

It should be noted that the focus of this modelling exercise was not to configure a detailed runoff model of the entire Great Lotus River catchment draining to Zeekoevlei, the downstream receiving water body. Rather, the focus was on assessing the use of hydrological modelling as DSS for CM and on the appropriateness of SWMM for this role. The Great Lotus River and catchment is therefore modelled to the point where the continuous flow monitoring station was installed to allow for calibration and verification of the model. This station is situated in the Philippi Horticultural Area, at the Springfield Road culvert, covering approximately 2/3 of the length of the Great Lotus River. The section of river length and subcatchments modelled provide a good representation of the catchment, with the majority of flow and pollutant loading upstream of this point (see Chapter 3 for an overview of the water quantity and quality data collected for the Great Lotus River catchment). The area thus modelled is from the headwaters adjacent to the Cape Town International Airport through Nyanga, Guguletu, Crossroads, Philippi East and a part of the Philippi Horticultural Area.

The section below describes the methodology in configuring the SWMM model for the simulated part of the Great Lotus River catchment. It describes the modelling approach utilised, as well as the assumptions in setting up the input data files.

6.1 SWMM Modelling Methodology

Before any attempt is made to describe the input data, an overview of the modelling approach is provided. As noted in Chapter 5.1, PCSWMM enables management of multiple object types and thus allows the independent creation of the different modules for the meteorological, overland flow generation, and hydraulic routing aspects of the SWMM model.

Precipitation datasets collected from the various sources at variable timesteps were read into and analysed by RAINPAK, which generated precipitation intensity files for inclusion into the RAIN module.

These RAIN modules were then linked to the RUNOFF object. This object generated the overland and subsurface flow at a 15 minute time step, based on the precipitation hyetographs from the previous RAIN object, evapotranspiration data, antecedent surface and subsurface conditions, land use and topography (see section 6.1.2 below). In addition, the RUNOFF object simulated the primary stormwater network draining each subcatchment. This resulted in the storing of a number of outlet hydrographs for the various subcatchments.

These hydrographs were then routed in TRANSport, which simulated the major trunk stormwater network draining the Crossroads and Philippi East subcatchments, as well as the Great Lotus River canal itself (see section 6.1.3). The choice of TRANSport over RUNOFF for this routing is necessary as TRANSport allows more detailed hydraulic analysis, the input of external hydrographs (including baseflow and groundwater flow) and the simulation of varying cross-sections. This is crucial in the modelling of the multi-stage Great Lotus canal with its trapezoidal low flow sections and grass lined high flow sections, as well as the enlarged natural cross sections through the agricultural areas leading to the end point of the simulation. (A more detailed discussion as to the advantage of using TRANSport over RUNOFF is included in Chapter 5.1 and Table A2.1 in Appendix 2). The output from the TRANSport object is thus a hydrograph and pollutograph at Springfield Road for comparison with the flow record captured at this point.

A sensitivity analysis is then carried out on the RUNOFF object to identify the principal parameters for model optimisation and calibration, whilst recognising the various error sources.

6.1.1 *Meteorological information*

6.1.1.1 Rainfall

A number of organisations are involved in the collection of meteorological data for the Great Lotus River catchment. The Cape Town Weather Office (CTWO), situated at the Cape Town International Airport, monitors rainfall for the upper parts of the catchment, including the urban areas of Nyanga, Guguletu and Philippi East, the focus of the present modelling exercise. In addition to this, there are a number of automatic rainfall gauges (Groenvlei, Mitchell's Plain, Strandfontein) in the area and maintained by the Catchment Management Department of the present Cape Metropolitan Council (CMC).

These gauges are generally of the tipping bucket type and thus facilitate the determination of short interval (5 or 10-minute) rainfall periods. This is significant given the dynamic nature of quick responses from urbanised catchment zones. In order to determine accurate rainfall-runoff relationships for these catchments, it is imperative that short interval rainfall periods are available.

Analysis of the CMC rainfall records showed, unfortunately, that data is missing for the Groenvlei gauge for significant periods during both 1997 and 1998. Given that this gauge can be seen as representative of almost half of the entire catchment and is situated adjacent to the flow monitoring station, it was deemed necessary to obtain an interpolated rainfall record for this gauge. Using RAINPAK, a uniform 10-minute rainfall record was generated for each gauge. Numerical rainfall patching techniques were then applied to the missing Groenvlei record and rainfall data filled in according to the inverse distance squared method, as well as the normalised ratio of average yearly values for the other complete gauges (situated at the CTWO and the Mitchell's Plain and Strandfontein Wastewater Treatment Works). (The approach using the normalised ratio technique would have been more accurate if mean monthly values were used instead of mean annual values, but these were unavailable for the Groenvlei gauge (De Boer, 2000).

In order to assess the accuracy of these patching techniques, a patching exercise was carried out for periods of the Groenvlei dataset that were complete. This patched record was then compared against the observed rain data with the error between them calculated as the percentage difference between patched and actual value for each time step. The resultant errors, at the 10 minute interval, showed significant variation whilst the error in daily mean patched versus daily mean observed was found to be greater than 25% when comparing the patched versus actual rainfall records.

Although the Groenvlei gauge has a higher long term mean annual rainfall than the CTWO station, the complete data set of the CTWO station was used as primary precipitation input into the SWMM model for the period of flow monitoring from July 1997 to October 1998 at a 15-minute resolution. This was enforced by the error in the attempted numerical patching exercise at Groenvlei, coupled with the lack of any other available rainfall data for the catchment. This underestimation of the annual precipitation of the catchment will have adverse effects on the accuracy of the SWMM model simulation.

6.1.1.2 Evaporation

Evaporation is the other crucial metrological input into SWMM for the present modelling exercise. This information was obtained from the DWAF monitoring station at the Strandfontein Wastewater Treatment Works. Originally recorded as S-pan values, the evaporation records are converted to "open water free surface" before being supplied to the public (Diedericks, 2000). Daily open water evaporation data for the period of the simulation was thus obtained directly from the DWAF. Given the lack of significant height or temperature variation across the catchment, the evaporation records for this gauge were considered representative of the catchment and read into the RUNOFF block of SWMM for the period of flow monitoring from July 1997 to October 1998.

6.1.2 *SWMM RUNOFF input data*

6.1.2.1 Discretisation of drainage network

As discussed in section 5.1.3, the modelling of any urban catchment area requires the discretisation of the existing drainage network.

The urbanised parts of the catchment in the present modelling exercise consist of the formal and informal settlement areas of Nyanga, Guguletu, Crossroads and Philippi East. These areas have been historically ignored in terms of the provision of water services, including both sewerage and stormwater facilities. This has resulted in a lack of existing services that are capable of providing adequate sanitation. The problem is further exacerbated in that the stormwater network have been improperly documented with no detailed stormwater layout drawings for significant parts of these areas (Grobicki *et al.*, in press).

Analysis of a report detailing an investigation and technical review of the stormwater infrastructure in the Crossroads, Nyanga, Guguletu and Langa areas shows that there is a wide disparity in the detail of available information (Dachs and Orrie, 1997). Although the report compilers collected as many drawings as could be located, the drawings range in detail from very old drawings with no useful information to those of recently completed projects with full detail and in CAD format. These collated records have all been referenced and indicated on a GIS Master plan (Dachs and Orrie, 1997). Examination of this Master plan shows that the area has not been comprehensively covered, rather that individual organisations have completed drawings only for their particular area of interest. As noted before, this has resulted in a wide variation in the information available from these drawings. Furthermore, it also suggests that areas that have not received recent attention are undocumented and there are thus large gaps in the area for which no drawings exist (Dachs and Orrie, 1997).

The lack of detailed comprehensive stormwater data will have a limiting effect on any modelling attempt of the Great Lotus River catchment. If no further data can be identified, it would result in inadequate routing of the collected overland flow with an accompanying deterioration in modelling reliability.

Given that no centralised database of the stormwater infrastructure was available at the time of writing, it was necessary to approach all consultants that had undertaken stormwater work in the area. This resulted in the collection of a large number of hardcopy stormwater drawings. From these available drawings, the drainage network for each area was defined in terms of the dimension, length and slope of each pipe as well as the existing pipe connectivity leading to the outflow point into the Great Lotus River canal. This information was prepared for input into SWMM and the data files are listed in the Appendix 4. A total of 470 conduits were modelled.

Figure 6.1, below, provides an indication of the collated stormwater network. This is merely a schematic of the network (depicted in blue) but when coupled with elevation contours provides a means of determining which overland flow areas drain to which stormwater pipes.

Figure 6.1: Residential area depicting subsurface stormwater network

In addition to the formal and informal residential areas of the upper catchment, two agricultural subcatchments in the Philippi Horticultural Area (PHA) contribute flow to the canal along Lansdowne Road. These subcatchments are characterised by intensive vegetable cropping and fallow fields for live stock grazing. The subcatchments are largely pervious, with excavated drainage channels collecting excess overland flow and groundwater subsurface lateral flow. A number of small, excavated farm dams are present along the length of these drainage channels. Although it is recognised that they are expected to provide flow attenuation in the drainage channel, no attempt is made to model the size or volume of these dams. It is assumed the dams will be full during the wet winter rainfall period with associated shallow water table depths when the drainage channels will be contributing any surface or subsurface flow from the predominantly pervious subcatchments. Any lag influences from these dams are accounted for through increased Manning's roughness coefficient "n" values.

The drainage channels were approximated as trapezoidal cross sections with appropriate Manning’s roughness values (0.2) to simulate the generally vegetation overgrown nature of these channels and the role of the above dams. The channels were routed into two separate detention ponds before flowing into the Great Lotus River canal.

Table 6.1, below, depicts the principal SWMM RUNOFF routing parameters.

Routing parameter description	SWMM code	Parameter value
Channel width (diameter)	GWIDTH	Varying
Channel length	GLEN	Varying
Channel slope	G3	Varying
Channel roughness	G6	0.018 – concrete
		0.2 – natural, veg lined

Table 6.1: RUNOFF routing parameters

6.1.2.2 Subcatchment discretisation and overland flow derivation.

As discussed in Chapter 5, SWMM models the hydrological response of a catchment by routing overland flow off the pervious and impervious surfaces (with and without depression storage) of a catchment to a stormwater conduit. The catchment is conceptually represented by a network of subcatchments, channels and pipes with the hydraulic properties of each element characterised by parameters such as slope, size and roughness. In order to account for the spatially varying nature of the catchment, it is required to discretise the catchment into smaller, homogenous subcatchments with plausibly uniform landuse, topography and roughness conditions. A mathematical representation of the physical drainage system is thus obtained through consideration of topographic data as well as the layout of the subsurface stormwater drainage network.

The subcatchment boundaries were identified from topographical drainage maps (obtained from City of Cape Town 1993 spot height data) together with knowledge of the layout of the stormwater network. Figure 6.2, below, shows an excerpt from the detailed subcatchment discretisation that was undertaken for the urbanised areas of the modelled Great Lotus River catchment. The red lines represent the subcatchment boundary whilst the red arrows indicate the overland flow direction based on contour elevations. The black lines represent the length of the subcatchment. The high degree of discretisation was undertaken in order to examine the issues of desirable complexity and scale of discretisation discussed further in Chapter 7. These 211 subcatchments ranged in size from 0.1 ha to 24 ha in the urban areas depending upon the available information and the detail of the stormwater network. The agricultural subcatchments varied in size between 74 ha and 310 ha.

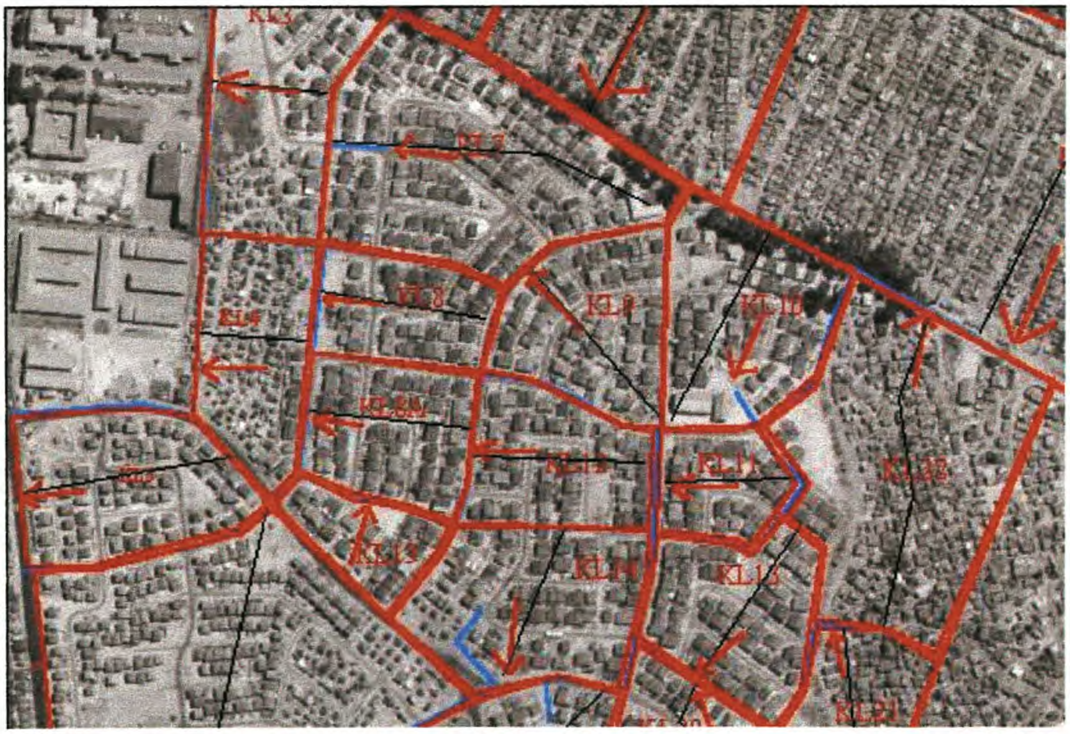

Figure 6.2: Residential area depicting subcatchment boundaries

Subcatchment areas were measured directly off 1996 black and white digital aerial photography at a 0.75m resolution supplied by AOC Pty (Ltd), Cape Town and courtesy of the Cape Metropolitan Council (CMC). This digital aerial photography is linked to spot height data for the area and thus allowed the derivation of subcatchment slopes from the elevation contours. Subcatchment drainage lengths were determined as the length of the flow path from the most remote part of the subcatchment to the subcatchment outlet on the digital aerial photographs. Where detailed stormwater information was available, the smaller subcatchment areas resulted in flow lengths ranging from 34 - 504 m with an average length of 160 m in urban residential areas. Urban subcatchments with less available stormwater data were larger with flow lengths varying between 300 - 2500 m with an average of 1200 m. The agricultural subcatchments had flow lengths ranging from 600 - 4400 m with average length of 1600 m. These flow lengths allowed an initial estimation of the parameter, WIDTH, through dividing each subcatchment area by its estimated overland flow length. WIDTH is a principal calibration parameter and will be discussed in more detail in section 6 below.

The Remote Sensing techniques, described in Chapter 3, provided a measure of the imperviousness of the homogenous urbanised areas. The degree of imperviousness required by SWMM, however, is the "effective" impervious area - the area that is hydraulically connected to the stormwater system (A roof gutter leading to a channel to a road catchpit would be considered hydraulically connected). The percentage imperviousness of the catchment was thus estimated from consultants' estimates from single-event model studies of the area (Taylor (1994), Duffy (1999)) in conjunction with the digital aerial photography. This proved to be a laborious task with questionable accuracy due to the wide variability in perceived hydraulic connections in the formal and informal residential areas. Given that percentage imperviousness is a significant parameter requiring calibration (Thomann and Adams (1998), James and James (1997)), it was decided to assume average percentage impervious values for each landuse and to optimise the parameter assumption during the calibration process. This resulted in an assumed percentage impervious of 50% for the residential areas and 1% in the agricultural areas.

The pervious and impervious depression storage depths were estimated from the literature of other similar RUNOFF models (Ayuso and Heineman (1998), James and Kuch (1998b), Thoman and Adams (1998), Huber and Dickinson (1992), Warwick and Tadepalli (1991)) together with various consultants' estimates. The Manning's roughness coefficients for pervious and impervious areas were estimated in the same way and are representative of the values utilised in other similar RUNOFF models of typical pavement and grasses areas.

Groundwater lateral flow was simulated for the pervious agricultural subcatchments of the Philippi Horticultural Area. As discussed in Chapter 5, SWMM has a simple groundwater flow routing allowing infiltration through a saturated and unsaturated soil horizon and calculating lateral interflow of groundwater as a recharge into agricultural drainage channels.

Infiltration parameters for the groundwater simulation as well as infiltration in the pervious areas of the urbanised subcatchments were derived from collected soil data published in a number of reports (Tredoux (1984), Edwards (1989), Stehr and van Huyssteen (1998), Taylor (1994) and Duffy (1999)). The soils of the area are sandy and generally highly leached with high infiltration rates. The high water table characteristic of the winter rainfall season results in groundwater baseflow augmenting flow in the canal. Although the groundwater routine can handle inflows into a drainage channel from the groundwater, it is not sophisticated enough to allow re-infiltration from the channel to the groundwater.

Table 6.2, below, indicates the parameters used in RUNOFF to represent the catchment as well as the estimate of each parameter.

Parameter description in terms of catchments	SWMM code	Parameter value
%impervious with zero detention	PCTZER	25
width (m)	WIDTH	Varying
area (ha)	WAREA	Varying
% imperviousness	%IMPER	Varying
slope (m/m)	WSLOPE	Varying
impervious Manning's "n"	IMPERN	0.02
pervious Manning's "n"	PERN	0.2
impervious storage depth (mm)	IDS	5
pervious storage depth (mm)	PDS	13
Max infiltration rate (mm/hr)	WLMAX	83
minimum infiltration rate (mm/hr)	WLMIN	15
Decay rate	DECAY	0.00056

Table 6.2: Catchment overland flow parameters

After inputting the characteristics of each subcatchment and its associated drainage inlet, the simulation was undertaken for the entire 16-month rainfall runoff record. In order to save on computing time, multiple time steps were used as follows:

- Wet time step = 15 min
- Transitional time step = 30 min
- Dry time step = 24 hours

As discussed in section 5.1.3.2, the wet time step is a time step with precipitation occurring on any subcatchment The transition time step has no precipitation input on any subcatchment, but the subcatchment(s) still have water remaining in surface storage. The overland flow routing technique loses water through infiltration, evaporation and surface water outflow during the transitional time step The dry time step has no precipitation input nor water in surface storage (although it can have groundwater flow however). This time step is used to regenerate infiltration parameters and to generate groundwater flow. The model is considered globally wet, globally transitional or globally dry i.e. for the entire catchment simultaneously.

Outlet hydrographs were stored at all the tributary inflows into the Great Lotus River canal. The routing of these hydrographs occurs in the TRANSport module detailed below.

6.1.3 *SWMM TRANSport input data*

As discussed in Chapter 5, routing through the stormwater network may be accomplished in TRANSport. For the purposes of the model of the Great Lotus River catchment, TRANSport is used to route flow in the trunk stormwater pipe draining the Crossroads, Philippi East and Brown's Farm residential areas as well as flow in the Great Lotus River canal itself. Although RUNOFF functioned well in routing overland flow through the short, small diameter minor drainage network draining each of the subcatchments, it is weak in accounting for the time displacement of hydrograph peaks. Thus, the large cross-sectional area, long channel lengths of the Great Lotus River and trunk stormwater pipeline draining Philippi East, are more effectively modelled in TRANSport with its kinematic wave approach. The limitation of this, however, is that disturbances are only propagated in the downstream direction and hence no backwater effects can be modelled in TRANSport.

The individual components of the conveyance system modelled in TRANSport are classified as different "elements" with these elements including channels, manholes, overflow structures or any other component of a physical system. Each element has associated parameters dictating the physical characteristics of that element. This includes the dimensions, slope, roughness and connectivity. Input hydrographs are inserted into the module at "manhole" elements.

The trunk stormwater pipeline draining from Philippi East was discretised into circular pipe elements separated by manholes. These manholes are situated where the pipeline undergoes a change of grade and associated change in discharge capacity. They are, in addition, at sites of tributary inflows from the minor drainage network.

An additional modelling requirement was the inclusion of a number of detention ponds on the trunk stormwater line. These detention ponds are large open areas situated above the subsurface stormwater pipeline. A structure in each detention pond, serving as both inlet and outlet, allows pipe surcharges to flow up and out of the pipeline for storage until the flood peak has passed and the pipeline is able to re-incorporate the stored water in the detention pond. For the period of simulation, however, the recorded storms were not extreme enough to bring these ponds into consideration and the trunk pipeline did not surcharge.

The Great Lotus River canal is discretised in a similar fashion to the above trunk stormwater pipeline through conduits separated by manholes. In this case, the manholes are not physical representations, but fulfil the same role as above. The principal difference lies in the detailing of the cross-section of the canal.

As discussed in Chapter 3, the Great Lotus River canal was extensively engineered to convey storm volumes of the 1 in 50 year flood and was constructed with a multi-stage cross-section. This entailed a concrete lined, trapezoidal low flow section and an accompanying grass lined high flow section. This is modelled in SWMM using an irregular cross-sectional element inherited directly from HEC-2. This allows the cross-section to be described through a number of station and elevation pairs. Stations are input in increasing order progressing from left to right across the section, and oriented looking downstream. It, in addition, allows the input of three different Manning's roughness coefficients for the left and right overbank and the channel itself.

Output hydrographs can be plotted at any location. In order to calibrate the model, it was desired to obtain hydrographs at the Springfield Road culvert. TRANSport was run with 96 stormwater and 2 storage elements at a 15-minute time step for the duration of the flow monitoring record. The results of this output are shown in section, below.

6.1.4 *Water quality*

As discussed in section 5.1.2.4, RUNOFF is the origin of water quality constituents for most SWMM simulations. It was shown that up to 10 water quality constituents can be modelled in RUNOFF through a choice between two possible modelling approaches:

1. physically - based approach using constituent buildup and washoff formulations
2. rating curve approach assuming loads are proportional to flow raised to a power.

The physically - based approach holds that the most significant mechanisms for generating stormwater quality are buildup and washoff. During the dry weather prior to a storm, constituents accumulate on the land surface. This can be a function of time and factors such as wind, traffic flow, atmospheric fallout, land surface activities, erosion and street sweeping (James and James, 1997). With the advent of a storm, this constituent accumulation is then washed off into the subsurface drainage network. Added to this can be constituents accumulated in catchpits, which are also flushed out during storms.

Whilst this physically-based approach includes the above buildup factors in empirical equations, it is unrealistic to assume that they can be used to accurately determine the amount of constituent on a surface prior to a storm. It is, in addition, doubtful that these empirical equations can truly represent the complex hydrodynamic, chemical and biological interactions that occur as the constituents are washed off the land surface.(James and James, 1997)

In order to account for the above difficulties, it is therefore necessary to collect comprehensive calibration and verification data. This data can then be used to calibrate the model equations to reproduce measured concentrations and loads.

With regards to the Great Lotus River catchment, the goal of the flow gauging and water quality monitoring programme, discussed in Chapter 4, was to identify the major point and non-point sources of pollution to the Great Lotus River (Grobicki *et al.*, in press). With the focus being a situation assessment of the canal itself, no constituent accumulation data was collected for the catchment. This renders the above physically based water quality simulation approach impractical for the Great Lotus River catchment.

In addition, the water quality programme in the Great Lotus River catchment identified the two significant parameters, Total Nitrogen (TN) and Total Phosphorus (TP), as being principally generated though poor sanitation and interactions between the sewer and stormwater systems in the upper residential communities of Nyanga and Guguletu (for TN) and the nutrient rich groundwater contributions from the Philippi Horticultural Area (for TP). Neither of these two constituents therefore appears to be derived from buildup and washoff mechanisms further resulting in the above physically based approach being unfeasible.

The second approach listed above, uses a "rating curve" to determine constituent loads. It abandons the notion of detailed water quality simulation and because it relates actual constituent loads to observed flow data, it can be justified physically (James and James, 1997) and is easier to calibrate using existing data.

The rating curve equation 5.26 of Chapter 5.1.2.4, is given below.

$$POFF = RCOEF \times WFLOW^{WASHPO} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.26)$$

where POFF = constituent load washed off (mg/s)

RCOEF = coefficient, WASHPO = exponent

WFLOW = subcatchment runoff (m^3/s)

The parameters, RCOEF and WASHPO, are used on a time step basis in equation 5.26, above, and are determined on a storm event basis by plotting the total constituent load versus total flow on a log-log scale (Huber (1980), James and James (1997)).

This rating curve approach is feasible for the Great Lotus River catchment given the sampling of a number of first flush winter storms on a flow basis through an automated sampler during April and May of 1998. This allows the comparison of total constituent load with total flow. Instantaneous load (mg/s) and flow (m^3/s) pairs for every sampling timestep of each storm were obtained. These load and flow pairs were combined into one large sample for all the sampled storms in order to derive a single pair of "power" and "coefficient" for substitution in WASHPO and RCOEF in equation 5.26, above. Figure 6.3, below, shows the plot on a log-log scale of the total load (TP) versus total flow (m^3/s) at the Springfield Road culvert sampler for the combined sample storms of 1998.

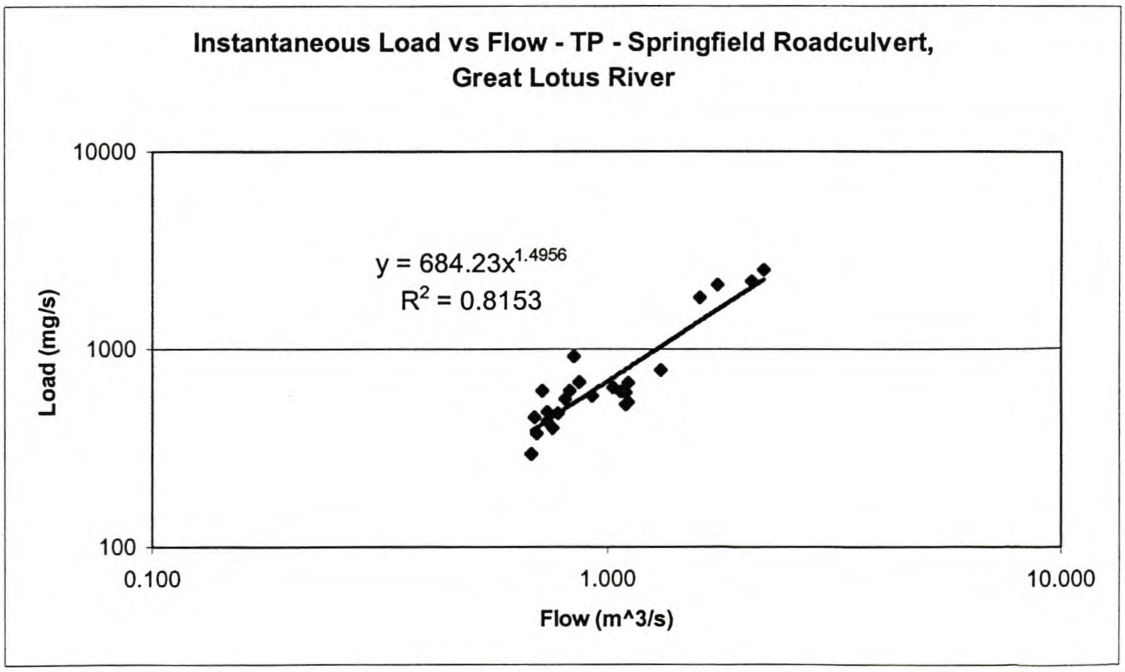

Figure 6.3: Total TP Load vs. Flow – Springfield Road – combined storms

Figure 6.3 shows that the load and flow pairs plot as a straight line on a log-log scale. Applying a power regression yields the following equation:

$$y = 684.23 \times x^{1.4956} \quad \text{(6.1)}$$

where y = TP load (mg/s)
x = Flow (m^3/s)
for n = 36 "pairs"

with a correlation coefficient of $R^2 = 0.8153$. Of significance is the value of the power in equation 6.1. A power equal to 1 would result in a constant concentration of TP. The value of the power being greater than 1, however, implies that the concentration of TP tends to increase with increasing flow for the sampled storms. The values of the constants in equation 6.1 allow the generation of the parameters in equation 5.26, above, with substitution into the rating curve in RUNOFF.

6.2 SWMM Model Results

6.2.1 *Water Quantity*

6.2.1.1 RUNOFF

The total simulated period was 469 days or 11256 hours. At this fine discretisation, RUNOFF simulated 478 conduits and 210 subcatchments. Given the variable length time steps used by SWMM, this resulted in a total number of time steps of 24086 and took 28 minutes on a Pentium I 266 MHz system with 64MB of RAM.

In order to assess the numerical stability of the model, it incorporates a number of continuity error checks. These errors and the magnitude of the error for the modelled Great Lotus River are shown below:

(1) The continuity check for surface water is calculated as follows:

$$\text{Error} = \frac{(\text{Precipitation} + \text{Infiltration} - \text{Evaporation} - \text{Surface Runoff} - \text{Water in Surface Storage})}{\text{Precipitation}}$$

$$= -0.13\%$$

(2) The continuity check for channels and pipes is as follows:

$$\text{Error} = \frac{(\text{Final storage}+\text{Outflow}+\text{Evaporation}-\text{Surface Runoff}-\text{Groundwater inflow}-\text{Initial Storage})}{\text{Final storage}+\text{Outflow}+\text{Evaporation}}$$

$$= 1.601\ \%$$

(3) The continuity check for subsurface water is as follows:

$$\text{Error} = \frac{(\text{Infiltration}+\text{Initial storage}-\text{Final storage}-\text{Subsurface ET}-\text{Groundwater flow}-\text{Deep percolation})}{\text{Infiltration} + \text{Initial storage}}$$

$$= 0.012\ \%$$

These continuity checks, based on mass balances, show that the RUNOFF model is stable. The hydrographs and pollutographs stored in RUNOFF are routed into TRANSport and depicted below.

6.2.1.2 TRANSport

The routing of the trunk stormwater network and the Great Lotus River canal was undertaken in TRANSport. 96 stormwater and 2 storage elements were modelled. Given the total simulated period of 469 days or 11256 hours at a constant 15-minute time step, the simulation took 14 minutes to run on a Pentium I 266 MHz system with 64MB of RAM.

The continuity error is calculated as follows:

$$\text{Error} = \frac{\text{Initial Volume} + \text{Inflows}}{\text{Remaining Volume} + \text{Outflow}}$$

$$= -1.682\ \%$$

The resultant simulated hydrograph is plotted at Springfield Road against the observed flow record at that point. This is shown in Figure 6.4 below. This plot shows the fit of the model-simulated data with the observed flow record. Table 6.3, below, provides a comparison of the objective functions, peak flow and total runoff volume for 1997 and 1998.

Objective Function:	Observed	Simulated	% difference
	1997		
Maximum Flow m^3/s	4.24	6.293	48.4%
Event Mean Flow (m^3/s)	0.245	0.2462	1%
Total Flow (m^3)	3455000	3535000	2.4%
	1998		
Maximum Flow m^3/s	4.035	6.495	61%
Event Mean Flow (m^3/s)	0.1994	0.2335	17%
Total Flow (m^3)	4849000	5849000	20%

Table 6.3: Comparison between simulated flow and observed flow

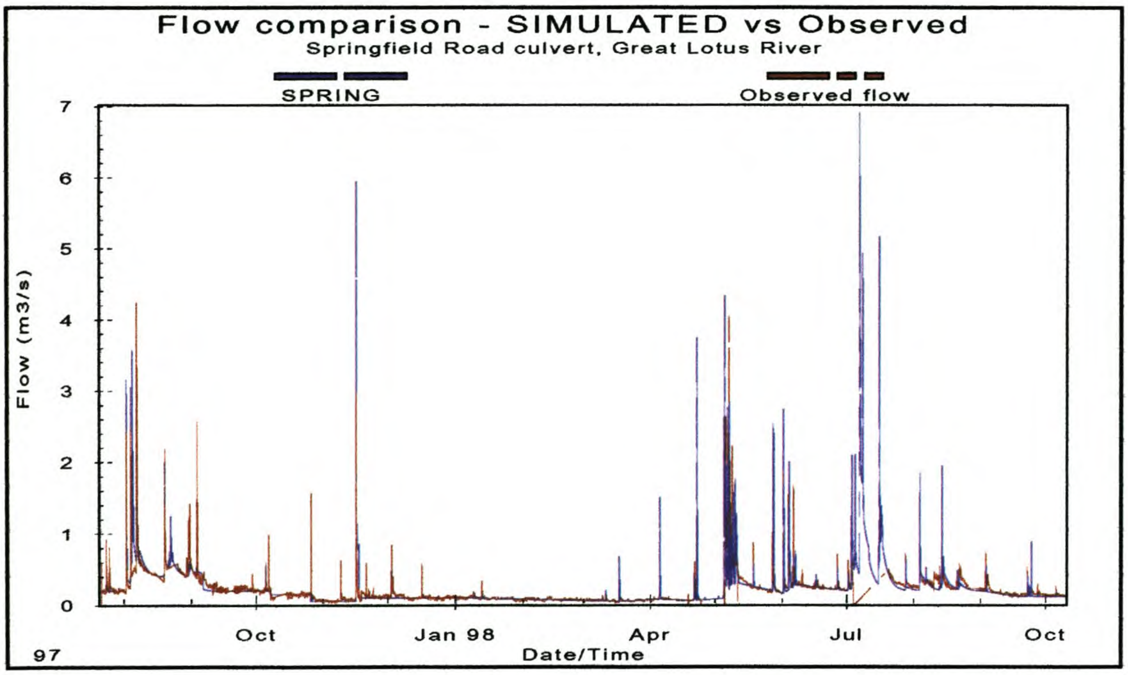

Figure 6.4: Model Simulated hydrograph versus Observed data for period of simulation at Springfield Road

In order to comment of the overall fit between observed and simulated flow, it is necessary to plot the above simulation over a shorter time period. Figure 6.5, below provides an indication of the fit of observed against simulated flows for a shorter period during the winter rainfall period of 1997.

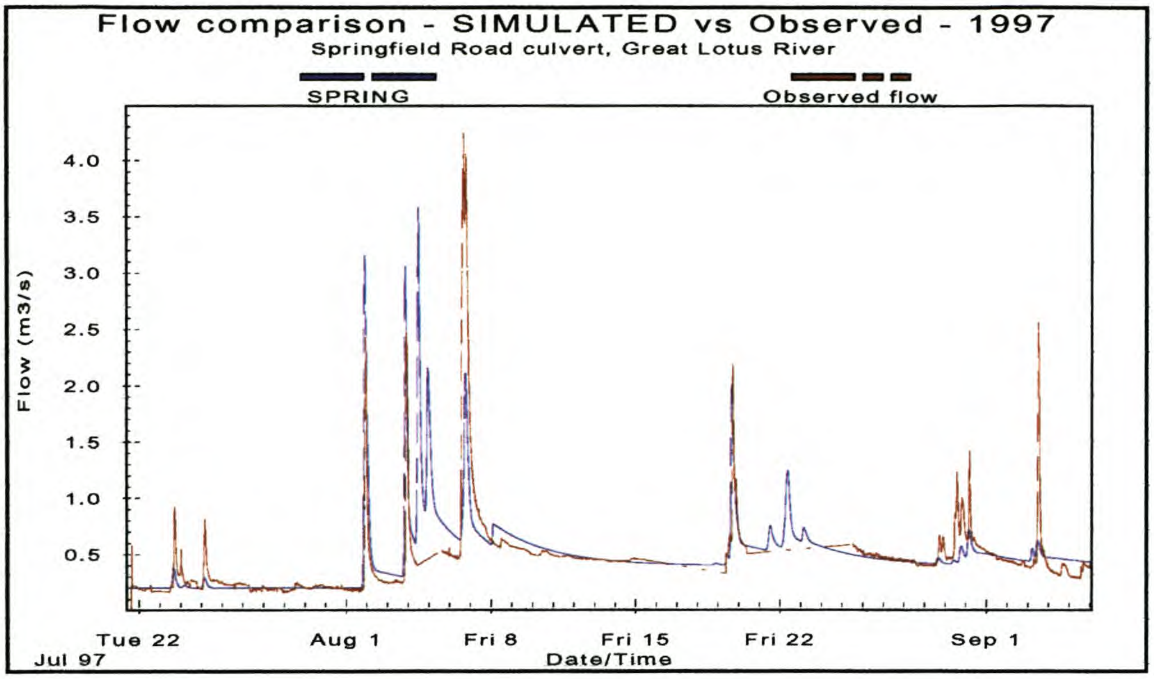

Figure 6.5: Comparison of simulated vs. observed for part of 1997 simulation

Analysis of the comparison in Figure 6.5 reveals that parts of the observed records are characterised by missing data. These correspond to broken straight lines in Figure 6.5 and were caused by datalogger malfunctions and gross litter disrupting the ability of the flow sensor to record flow depths. For the rest of the period where observed data is available, the comparison between observed and simulated shows variation in the degree of fit. Although the simulated response appears to capture the lag of the catchment, the fit between peak flows varies with the simulation, at times, underestimating the observed peak and at other times, overestimating the peak. Similar variability is exhibited in the simulation of 1998.

This variability can be the result of a number of possible errors in both the input parameters for the simulation as well as in the observed flow record itself. This is discussed in section 6.4.3. The variability weakens the objective function of peak flow for the entire period shown in Table 6.3, above. An additional objective function is thus utilised to include the fit of the rest of the significant peaks in the simulation. This objective function is an average peak flow for all events producing a flow of greater than 1.5 m^3/s. Given the gaps in the observed flow record, this average peak flow objective function is based on only those events captured in the flow record. The results of this new objective function are displayed in Table 6.4, below. Five storms were analysed during 1997 and six during 1998.

Objective Function: **Average peak flow > 1.5 m^3/s**	**Observed**	**Simulated**	**% difference**
		1997	
Average Peak Flow (m^3/s)	2.838	3.25	14.68%
		1998	
Average Peak Flow (m^3/s)	2.153	2.603	20.9%

Table 6.4: Comparison between simulated flow and observed flow for new objective function - Average Peak Flow > 1.5 m^3/s.

The objective function depicted in Table 6.4 shows that the average simulated peak is greater than the average observed peak for both 1997 and 1998. Whilst this result agrees with the objective function of peak flow shown in Table 6.3, it is a far stronger objective function in that it allows all major flood peaks (defined as greater than 1.5 m^3/s in the case of the Great Lotus River) to have a say. This allows a fit between all the major peaks and not just one peak, which may or may not have been poorly estimated. The objective function in Table 6.4 will thus tend to diminish the effects of one badly estimated peak affecting the overall estimate of fit between simulated flow and observed flow.

6.2.2 *Water Quality*

The rating curve approach described in section 6.1.4, above, enabled the variation in TP to be determined for the period of simulation from July 1997 to October 1998. The results are plotted in Figure 6.6 below.

The units in the Figure 6.6 are represented as mg/l x m^3/s which resolves to g/s for the above plot. The periods of straight-line loads refer to baseflow conditions with a near constant TP concentration from the rating curve.

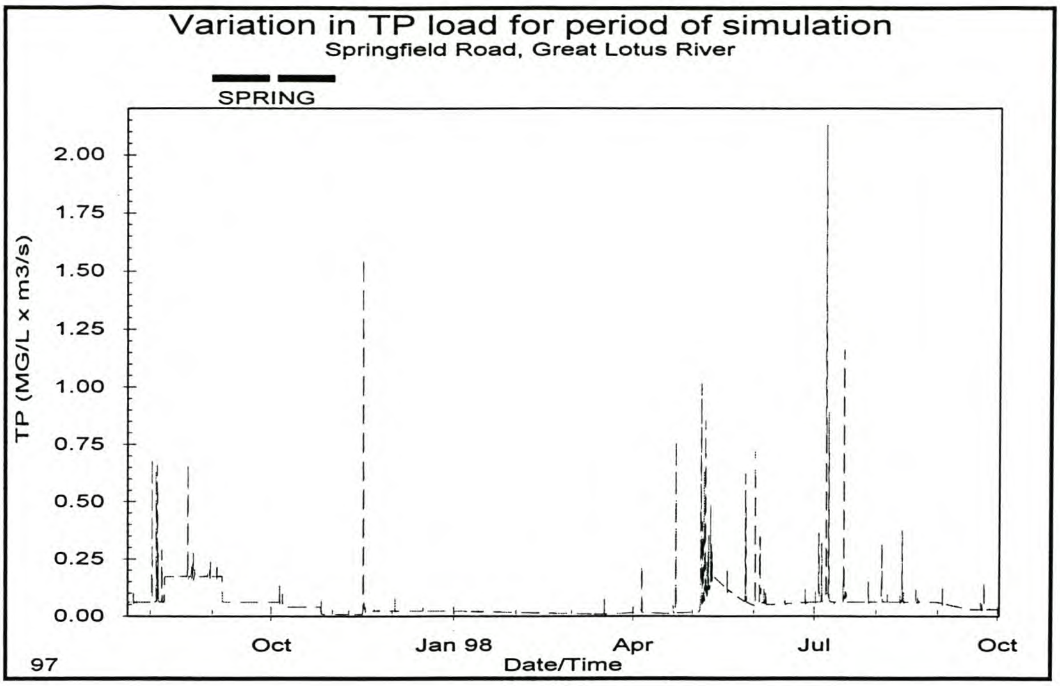

Figure 6.6: TP load – Springfield Road, Great Lotus River

The pollutograph in Figure 6.6, above, provides an indication of the total simulated load for the period of simulation. It allows the patching of missing sampling data and provides a complete record of load variation, something a grab sampling program with its instantaneous load determination is unable to achieve. This can be used for Catchment Management purposes to generate the total annual pollutant loading to the downstream receiving water body. Given the relationship between flow and TP load, the above simulated pollutograph shows how seasonally dependent the load contribution is. The majority of the TP load to the downstream receiving body, Zeekoevlei, occurs during the winter high flow period with significantly less total contributions during the summer base flow conditions.

Given this dependence of load upon flow, the implication for Catchment Management is that any reduction in catchment runoff will have a corresponding decrease in TP load. This can be achieved through various Best Management Practices (BMPs) such as those related to washoff reduction and increased infiltration. The use of such BMP devices to decrease peak flow and total runoff volume is discussed in section 7.4. This illustrates how hydrological modelling can be used in assessing the implications of different management decisions on water quality and quantity.

6.3 SWMM Model Sensitivity Analysis

If we consider Figure 3.1 of Chapter 3, the flow chart depicting a generic model building exercise, the stage of initial parameter estimation is complete and an initial model simulation has been undertaken. The results of this are shown in Figure 6.4 above. The next stage is the calibration of the significant parameters of the model to obtain the "best-fit" between the simulated output and the observed flow record.

An effective calibration of these parameters requires insight into which parameters are most significant and under which conditions does each parameter dominate. This insight is obtained through a sensitivity analysis of the model parameters. This sensitivity analysis essentially consists of repeatedly running the model under different meteorological conditions whilst independently varying the model coefficients or parameters, the amount varied being representative of the uncertainty in the parameter being analysed. The resulting normalised change in simulated response is divided by the normalised parameter variation thus allowing a ranking of the resulting sensitivity gradients from highest to lowest (James, 1994)

Sensitivity analysis thus allows the user to assess the stochastic nature of the hydrological processes in the model, and provides a method for both parameter optimisation and error analysis. At the outset, it is noted that each parameter is associated with a process, which is active only under certain conditions, or states of the model. To estimate the best value of a parameter, the only states that need to be examined are the states or events when the related processes are active. These causative events need to be established, and selected from the short, good, continuous record, to be used for calibration; the specific, observed events are then used to calibrate the related, specific, active processes and parameters.

Before continuing, the following terms are crucial in understanding the process of sensitivity analysis:

- The *input function* (IF) is a driving input hydro-meteorological time series, such as rainfall that acts to drive the model. For the sensitivity analysis it can be a hyetograph of any duration, intensity and shape. Normally, parameter sensitivity varies in some relation to the input function characteristics.

- The *response function* (RF) is the time series output (hydrograph, pollutograph, etc.) of the model. A variety of objective functions can be derived from the response function.

- The *objective function* (OF) is a statistic or a representative number that is the desired output or primary objective of a model simulation run (i.e. the answer to the question the model was set up to address). An almost limitless number of objective functions can be derived from a response function

- The *evaluation function* (EF) seeks a comparison between computed and observed objective functions chosen to evaluate the performance of the model. It is a measure of agreement between simulated and observed values.

Attempting a manual sensitivity analysis on a complex model with multiple parameter uncertainty can be a complicated and lengthy process. Fortunately, as discussed in section 5.2.4 of Chapter 5, the developers of PCSWMM98 provide an add-on sensitivity analysis tool, Sensitivity Wizard '98 (James and James, 1998a). This program provides an analysis of parameter sensitivity for various input functions and objective functions in the SWMM RUNOFF module. Dimensionless sensitivity gradients (DSG) are then presented as a family of plots, one plot for each parameter and thus ranks the parameters that are both most sensitive and have the greatest uncertainty. The outputted sensitivity gradients can be used to estimate the propagated error and to optimise the input parameters against observed objective functions.

The methodology employed in the sensitivity analysis is as follows: Given that the RUNOFF module contains the empirical parameters with uncertainty, a RUNOFF file is selected on which the sensitivity analysis is to be performed (The other principal modules, TRANSport and EXTRAN are mere routing modules with limited uncertainty and no overland flow generation capabilities). Parameters are then selected for analysis where appropriate (obviously, one cannot run a sensitivity analysis on, say, subsurface flow generation, if the runoff file selected is concerned only with surface flow with no subsurface flow being generated). The uncertainty of each parameter is entered followed by the meteorological input functions, the choice of which is listed in Table 6.5, below. Finally the location of the response function and duration of simulation is selected.

For the sensitivity analysis, artificial rainfall time series are used with constant intensities. The intensities and durations are chosen so that they relate in a fuzzy way to the scale of the model problem. They are similar to simple design storms with Table 6.5, below, indicating the various intensities and durations utilised in the Sensitivity Wizard program:

Intensity	Duration Short	 Medium	 Long
High	75 mm/hr for 20 min	25 mm/hr for 1 hr	5 mm/hr for 10 hrs
Medium	10 mm/hr for 20 min	7.5 mm/hr for 1 hr	2.5 mm/hr for 10 hrs
Low	2.5 mm/hr for 20 min	2.5 mm/hr for 1 hr	2.5 mm/hr for 10 hrs

Table 6.5: Storm durations and intensities used in sensitivity analysis

For these given meteorological conditions, it can be expected that the different parameters will have different behaviours under each condition. Tables A-2 through A-4 of Appendix 1 provide a description of each RUNOFF parameter and the conditions in which each parameter is expected to be dominant.

In summary, however, the processes likely to dominate in various situations can be considered as follows (James, 1994): For a light rain intensity it can be expected that overland flow over impervious surfaces will be the dominant process. No overland flow is expected from pervious areas since the infiltration rate is not exceeded in the simulations. As the rainfall intensity increases to a medium intensity, soil infiltration will become more significant. As the rainfall intensity becomes high, overland flow will be expected off the pervious areas as the infiltration capacity is exceeded.

The discussion below details the results from the sensitivity analysis of the significant RUNOFF parameters of the model of the Great Lotus River catchment. Two objective functions were tested, peak flow and total runoff. Although this objective function was found to be weak in assessing the fit between observed and simulated flows for the entire period of simulation, the sensitivity is event - based and the objective functions of peak flow and total runoff volume are adequate to assess the sensitivity of the various parameters.

6.3.1 *Width*

WIDTH is used to assign an average or effective width of overland flow. It is a measure of overland flow width for both the pervious and impervious areas. Longer widths imply shorter response times and are representative of highly drained areas. Smaller subcatchment widths mean longer overland flow lengths and longer response times and are representative of open areas without well-defined surface and engineered drainage systems. With respect to peak flow, the width parameter was most sensitive for the short duration low intensity storm and decreasing in sensitivity as the intensities increased. For these short duration storms, overland flow is derived entirely of overland flow from impervious areas without any depression storage. Increasing the width parameter resulted in an increase in both peak flow and flow volume, as expected. WIDTH was also quite sensitive in the case of the medium duration medium intensity storm. This is due to a new source of contributing overland flow such as a pervious area with depression storage. The parameter was completely insensitive to long duration storms. For the other objective function of total flow volume, however, the width parameter was sensitive for all storm conditions and most sensitive for the long duration storms. Maximum sensitivity was displayed for long duration storms with high rainfall intensity. This is due to pervious area overland flow becoming a significant part of the total flow.

6.3.2 *Area*

WAREA provides a measure of the total area of each subcatchment that is hydraulically connected and displayed sensitivity for all storm types. This is expected, as increasing the area should result in a proportional increase in runoff independent of which storm is being considered. The WAREA parameter is generally not considered to be suitable as a calibration parameter, given the accuracy of GIS and survey techniques in determining these areas.

6.3.3 *Percent imperviousness*

The WW3 or %IMPER parameter assigns the subcatchment area not subject to infiltration losses. For rainfall amounts greater than the impervious area depression storage, all rainfall is converted to overland flow. The percentage impervious area parameter strongly mimicked the sensitivity behaviour exhibited by the above area parameter. The parameter was most significant for the long duration storms with low to medium rainfall intensities. Increasing the parameter results in a corresponding increase in both peak and total flows. This parameter was the most significant of all the calibration parameters tested. This corresponds with other findings that continuous simulation results are excessively dependent on this parameter (Thoman and Adams, 1998). This implies that the parameter must be carefully quantified during use in continuous simulations. Impervious areas must be accurately measured, including separating areas that are directly connected to those which discharge on to pervious areas.

6.3.4 *Slope*

WSLOPE is the SWMM parameter for assigning an average slope to both the pervious and impervious parts of the idealised subcatchment. Increasing the parameter resulted in an increase in peak flow and total runoff volume as would be intuitively expected, given that increasing the slope would result in faster runoff responses. With peak flow as the objective function, the parameter was sensitive to all short and medium duration storms and insensitive to long duration storms. It was most sensitive for short duration low intensity storms and decreased in sensitivity as the storm duration increased. By comparison, with total runoff volume as objective function, WSLOPE was found to be sensitive to all durations and intensities with most sensitivity for the long duration storms from low to high intensity.

6.3.5 *Impervious area Manning's "n"*

The parameter IMPERN is used to assign the Manning's roughness value "n" to the impervious area of the subcatchment. The value used for all subcatchments in the simulation was 0.02. The domain for the sensitivity of the parameter is when overland flow from the impervious area is dominant. The parameter should become less sensitive as overland flow from the pervious areas become more dominant in the total flow generated. The parameter is sensitive to all storm events if any of the impervious areas have zero depression storage. IMPERN was found to be most sensitive for the short duration low intensity storms. Unlike the parameters discussed above, increasing the roughness coefficient produced a decrease in peak flow and total runoff volume. This follows what is intuitively expected, given that the increased roughness impedes the overland flow. As the intensities increased for the short duration storms, the sensitivity of IMPERN decreased. With total runoff as the objective function, the parameter increased in significance and was most sensitive for the medium and long duration storms with highest intensities.

6.3.6 *Pervious area Manning's "n"*

The parameter PERVN is used to assign the Manning's roughness value "n" to the pervious area of the subcatchment. The value used for all subcatchments in the simulation was 0.2. Although it is expected that PERVN should be most sensitive in the case of the high intensity storms with flow from the pervious areas representing a large proportional of the total overland runoff, the parameter was found, in fact, to be insensitive for all storms for both the peak flow and total runoff objective functions.

6.3.7 *Impervious depression storage*

IMDEP assigns the depth of depression storage to the impervious area of the subcatchment. An average value of 5 mm was used during the simulation. No runoff is generated from the impervious areas until the depression storage is filled through excess rainfall depths. For peak flow, the parameter was found to be most sensitive for medium duration storms with low intensity. It was entirely insensitive to long duration storms with high intensities. This is expected given that runoff from the pervious areas should play a more significant role for these events. As the depression storage was increased, the peak flow and total runoff volume decreased. With total runoff as objective function, the parameter was most sensitive for the long duration high intensity storm.

6.3.8 *Pervious depression storage*

PERDEP is used to assign depression storage to the pervious areas of the subcatchment. The rainfall rate must exceed the infiltration rate for a period of time long enough to build up a depth greater than PERDEP before any surface runoff is to occur. The average value used in the simulation was 13 mm. The parameter showed similar sensitivity to IMDEP above with maximum sensitivity displayed for peak flow during the medium duration, low intensity storm. For the total runoff; again the maximum sensitivity was displayed for the long duration high intensity storm.

6.3.9 *Infiltration parameters*

The modified Horton equation was used to generate infiltration in the pervious areas of the subcatchments. WLMAX assigns the initial (maximum) infiltration rate with a value of 83 mm/hr used during the simulation for the leached sandy soils of the Great Lotus River catchment. WLMIN assigns the asymptotic or minimum infiltration rate that occurs upon soil saturation with a value of 15mm/hr used during the simulation. DECAY is the parameter that describes the exponential rate of infiltration rate decrease from WLMAX to WLMIN (the decay rate used was 0.00056 s^{-1}). Unexpectedly these parameters were found to be relatively insensitive. The minimum infiltration rate was found to be slightly sensitive during the high intensity rainfall storms of short and medium duration.

Intensity	**Duration**					
	Short		**Medium**		**Long**	
	peak flow	**total runoff**	**peak flow**	**total runoff**	**peak flow**	**total runoff**
Low	IMPERVN WIDTH WSLOPE	IMPERVN WIDTH %IMPER	IMPDEP PERDEP IMPERVN	IMPDEP PERDEP %IMPER	%IMPER	%IMPER IMPDEP WIDTH
Medium	IMPERV WIDTH IMPDEP	IMPDEP %IMPER WIDTH	%IMPER WIDTH IMPERVN	%IMPER IMPDEP WIDTH	%IMPER	%IMPER IMPDEP PERDEP
High	%IMPER WIDTH IMPERVN	%IMPER IMPDEP WIDTH	%IMPERVIOUS WIDTH IMPERVN	%IMPER IMPDEP IMPERVN	%IMPER	%IMPER IMPDEP WIDTH

Table 6.6: Parameter sensitivity for Great Lotus River model

Table 6.6, above, depicts the ranked peak flow and total runoff volume parameter sensitivity in decreasing order of sensitivity for all storm events for the finely discretised modelled areas of the Great Lotus River catchment.

Inspection of Table 6.6 reveals that the sensitive parameters were found to be mostly associated with the impervious aspects of the model as well as the subcatchment width. These parameters:

- percentage imperviousness
- impervious Manning's roughness coefficient
- impervious depression storage depth
- subcatchment width

are focussed on in the next stage of the model building exercise (Figure 3.1 of Chapter 3), which is the model calibration of these parameters.

6.4 SWMM Model Calibration and Error Identification

As discussed in Chapter 3, and shown in Figure 3.1, the model calibration process involves optimising the initial model inputs and parameters using one set of data to produce an improved fit between model output and recorded data. The calibration of a large, complex SWMM model can be an arduous task, given the multiplicity of parameters describing the active processes. A methodology is therefore required to allow modellers to systematically calibrate parameters by isolating dominant processes and to thus generate a reliable continuous model. This methodology can be described as follows (James, 1994):

1. Perform a sensitivity analysis of all significant parameters using suitable objective and evaluation functions for the series of synthetic storm events selected for the analysis.
2. Rank the results of the sensitivity analysis in order to determine which parameters are most sensitive and in which states they dominate.
3. Select comparable measured rainfall-runoff sets from the existing time series database.
4. Calibrate the parameters in the following order, starting with the most sensitive parameter in each group
    (1) Impervious parameters (IMPERVN, %IMPER, IMPDEP)
    (2) Routing parameters (WIDTH, SLOPE)
    (3) Pervious parameters (infiltration parameters, PERVN, PERDEP)
    (4) Recovery of infiltration
5. Verify all objective functions if other events are available and validate the continuous time series, using the new optimised parameter set.

A systematic calibration of the model is thus undertaken for groups of parameters using unique events in the time series that isolate the dominance of the processes, the parameters being adjusted in order from most sensitive to least sensitive. This is, therefore, not seeking to calibrate all the model processes simultaneously as a continuous simulation. Given the parameter inter-dependence and significantly long model execution times, this is considered unfeasible. The calibration is undertaken for short, causative events for the most sensitive parameters dominant in such an event.

James (1994) suggests that parameters can be categorised under 4 groups for optimising:

1. parameters that can be measured with total certainty –
    catchment areas, pipe diameters, conduit geometries, slopes, lengths, elevations.
2. parameters that can be readily field or laboratory measured –
    percent imperviousness, Manning's roughness coefficient "n" for pipes, etc
3. parameters that cannot be easily measured in the field or laboratory –
    ground slopes, infiltration rates, rainfall, pollutant buildup and washoff, etc.
4. parameters that cannot be measured with any certainty –
    catchment widths, recovery of infiltration capacities.

Given that the four most sensitive parameters of the Great Lotus River (from Table 6.6) are

- percentage imperviousness
- impervious Manning's roughness coefficient
- impervious depression storage depth
- subcatchment width

then, provided that three of the four parameters have been measured accurately in the field, the model output should exhibit a reasonable "closeness-of-fit" to the observed data and not require significant calibration.

It is unlikely, however, that this is the case given the error and uncertainty in determining these parameter values from the available data sources. A limited calibration attempt is therefore carried out sufficient to detail the methodology to be employed and to gain agreement between the observed and simulated data for the objective functions of peak flow, total runoff and average peak flow over 1.5 m^3/s and the significant statistical parameters of mean, std deviation, variance and covariance. This is followed by a discussion on the possible sources of error in the model.

6.4.1 *Selection of rainfall events for calibration*

A synoptic analysis of the individual rainfall events for the simulated period is provided in Appendix 2. This analysis reveals that the simulated period was not characterised by any major storm events. Table 6.7, below, provides a summary of the storm events measured at the Cape Town Weather Office (CTWO).

	Number	Total	Minimum	Maximum	Average	Coef-Var
Duration (hr)	60.	1358.00	1.000	157.000	22.633	1.179
Intensity	60.	-	0.019	2.559	0.484	0.973
Volume (mm)	60.	529.48	0.152	83.165	8.825	1.448
Interevent time	59.	11052.50	38.000	1352.500	187.331	1.090

Table 6.7: Storm event summary for period of simulation – CTWO station

The observed storms are generally low intensity of a medium to long duration. This is not unexpected given the nature of the Cape Peninsula rainfall patterns with precipitation generated principally through sustained anti-cyclonic frontal systems producing relatively long duration storms of low intensity rainfall. It does, however, have implications for the calibration of the model. It implies that the model parameters can only be calibrated against flows produced by the low intensity, medium to long duration storms.

Four such events have been selected for the calibration exercise. They are shown in table 6.7, below:

Date	Storm No.	Start hour	Duration (hr)	Volume (mm)	Ave Intensity (mm/hr)	Max Intensity (mm/hr)
15/11/97	1	23	41.	31.61	0.77	44.80
01/06/98	2	8	9.	13.39	1.49	25.40
10/09/98	3	2	1.	0.40	0.40	1.60
12/01/98	4	23	3.	1.80	0.60	4.00

Table 6.8: Rain events selected for calibration of model parameters

Each parameter is tested for the rain event in which it is expected to dominate. The relationship between storm event and parameter to be calibrated is shown in Table 6.9, below.

Date	Storm	Storm type	Calibration Parameter
15/11/97	1	Low intensity, long duration	% imperviousness
01/06/98	2	Low intensity, medium duration	impervious depression
10/09/98	3	Low intensity, medium duration	impervious roughness
12/01/98	4	Low intensity, medium duration	width

Table 6.9: Selected rain events and calibration parameter

The simulated response to the event is compared to the observed record and the parameter adjusted appropriately depending upon the closeness of fit with the observed event. This exercise was carried out for each of the sensitive parameters to obtain the amount by which that parameter should be perturbed in order to match the observed record for that storm in which it is dominant. Once the values have been established for each parameter, the entire continuous simulation is rerun with the newly adjusted parameter values. The output from this simulation run is compared to the complete observed record and the objective functions recalculated to assess the improvement in fit between simulation record and observed record.

Table 6.10, below, provides a comparison between the observed flow record and the simulated flow for the peak flow and total runoff objective functions shown previously as Table 6.3. This is for the uncalibrated model and is based on the initial parameter estimates.

Objective Function:	**Observed**	**Simulated**	**% difference**
	1997		
Maximum Flow m^3/s	4.24	6.293	48.4%
Event Mean Flow (m^3/s)	0.245	0.2462	1%
Total Flow (m^3)	3455000	3535000	2.4%
	1998		
Maximum Flow m^3/s	4.035	6.495	61%
Event Mean Flow (m^3/s)	0.1994	0.2335	17%
Total Flow (m^3)	4849000	5849000	20%

Table 6.10: Comparison between uncalibrated simulated and observed flow

Given that an observed flow record is only available at the outlet of the simulated area, the calibration was undertaken through global perturbations of the sensitive parameters. Table 6.11 reveals the percentage change of each parameter for all the simulated subcatchments.

Calibration Parameter	**Change**
% imperviousness	0.65 x initial value
impervious depression (mm)	0.85 x initial value
impervious roughness	0.75 x initial value
width (m)	2 x initial value

Table 6.11: Effective change in parameter value for calibration

Table 6.12, below, shows the comparison between the simulated and observed flows after calibration.

Objective Function:	**Observed**	**Simulated**	**% difference**
	1997		
Maximum Flow m^3/s	4.24	4.828	13.86
Event Mean Flow ($^{m3/s}$/s)	0.245	0.2361	-3.6
Total Flow (m^3)	3455000	3350000	-3.04
	1998		
Maximum Flow m^3/s	4.035	5.453	35.14
Event Mean Flow ($^{m3/s}$/s)	0.1994	0.2112	5.92
Total Flow (m^3)	4849000	5165000	6.5

Table 6.12: Comparison between calibrated simulated flow and observed flow

Table 6.12 shows that calibration of the sensitive parameters produced a significant decrease in both the peak flow and total runoff volumes for the model to more closely fit the observed flow record. The calibration was moderately successful for the flow period of 1998 with a reduction in the difference between peak observed and peak simulated flow.

Given the periods of missing flow data as well as possible errors in observations of the above peak flows, however, the peak flow and total runoff volume can be seen to be fairly weak objective functions. In order to allow for major flood peaks (defined as greater than 1.5 m^3/s in the case of the Great Lotus River) to have a say, the objective function of the mean of the flow peaks greater than 1.5% is applied to assess the fit between observed flows and simulated flows. This allows a fit between all the major peaks and not just one peak, which may or may not have been poorly estimated. This objective function of the mean of the flow peaks greater than 1.5% is shown in Table 6.13 below and contrasted against the uncalibrated values.

Objective Function: **Average peak flow > 1.5 m^3/s**	**Observed**	**Simulated**	**% difference**
		1997	
Average Peak Flow - Uncalibrated (m^3/s)	2.838	3.25	14.68%
Average Peak Flow - Calibrated (m^3/s)	2.838	2.774	-2.24%
		1998	
Average Peak Flow - Uncalibrated (m^3/s)	2.153	2.603	20.9%
Average Peak Flow - Calibrated (m^3/s)	2.153	2.151	-0.07%

Table 6.13: Comparison between simulated flow and observed flow for new objective function - Average Peak Flow > 1.5 m^3/s.

This stronger objective function reveals that the calibration produced a reasonable fit of simulated to observed flows. A comparison for a period during 1997 is shown in Figure 6.7 to depict this fit.

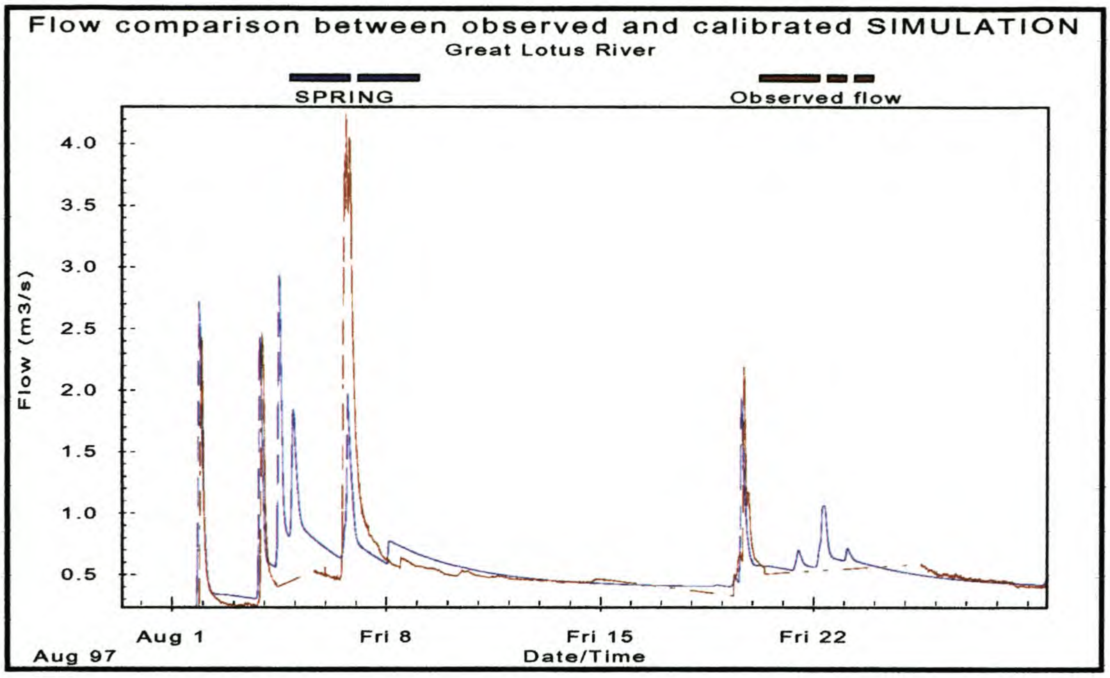

Figure 6.7: Comparison between observed flow and calibrated simulation flow

Whilst these comparisons might lead to the interpretation of the calibration exercise being successful, it is recognised that significant uncertainty still exists with the input parameters. Analysis of the observed flow record reveals that there are many gaps in the flow data due to malfunctions in the monitoring equipment and gross litter that may have changed the characteristics of the Springfield Road culvert. This results in a balancing out of the underestimated peak flow during several large volume storms with simulated flow being generated during periods of no record. In addition, the low flow period of the dry summer months is characterised by daily irrigation abstraction along the length of the canal through the Philippi Horticultural Area. No attempt is made to model this varying abstraction, yet it has an influence on the base flow recorded during this period. Given the potential errors, it thus remains to assess the modelling error and uncertainty.

6.4.2 *SWMM Model Error Analysis*

James (1994) identifies a number of sources of error associated with modelling, which can be related to the Great Lotus River catchment as follows:

(1) **Uncertainty due to natural variability or unobserved input disturbances** – Given the relatively depressed low flow characteristic of the Great Lotus River catchment, random anthropogenic disturbances can have a marked influence on the quality and quantity of flow

in the canal, independent of any meteorological conditions. The abstraction of flow for irrigation discussed above is one such uncertainty.

(2) **Measurement and sampling errors of observed input and output** – this observation error is associated with field instrumentation and is composed of two components, one random and the other systematic. Two significant sources of this error are the collection of rainfall data and streamflow data. Poor estimates of precipitation data occur when the raingauge network does not capture the spatial variability of rainfall or the raingauges are improperly maintained. Fine resolution deterministic modelling requires complete and comprehensive rainfall data at a short time interval. The CTWO rainfall data provided the only complete rainfall record for the catchment for the simulation period. This record was used as primary input whilst recognising that rainfall intensities and volumes might be underestimated for the catchment due to its lower MAR than other gauges in the catchment. Poor estimates of streamflow data can occur through improperly installed and maintained automatic streamflow gauges. The significant levels of gross litter transported by the Great Lotus River caused problems with the stream flow recorder and resulted in frequent gaps and false readings in the data. An accurate and complete streamflow record is imperative in order to properly calibrate and verify the generated model.

(3) **Data input error** – this error recognises the fallibility of the model user in entering the required data. This "human" error can result in unrealistic model output and requires rigorous checking and rechecking to avoid.

(4) **Start up error** – This error is due to the incorrect assumptions of initial values of model storages and state variables. This error was introduced in, amongst others, the assumptions of the initial level of the groundwater and the soil saturation as well as the infiltration rates for the pervious areas.

(5) **Propagated or parameter error** – This error is associated with the initial assumptions for the model parameters. Whilst certain of the parameter values are obtained from physically–based and measurable qualities such as roughness and conduit length, many of the parameters were approximated based on existing literature of similar studies. These were thus arbitrarily chosen and applied to all the subcatchments and conveyances in the catchment. Examples include estimations of the pervious and impervious depression storage, infiltration and decay rates. Many of these parameters are difficult to quantify and hence operations such as the sensitivity analysis and calibration are needed to reduce the uncertainty in the values of the significant parameters.

(6) **Structural error related to disaggregation** – This error is associated with the number and resolution of the processes in the simulation. The ignoring of the groundwater interaction in the urban areas of the catchment is one such possible error. Although infiltration is modelled in these areas, it discounts the possibility of a high winter water table in the pervious parts of the urban area and the associated increase in overland flow from these pervious areas. Ignoring the role of constituent buildup and washoff in the water quality simulation and restricting it solely to a rating curve approach based on storm Event Mean Concentrations is an additional example of this type of error.

(7) **Structural error related to discretisation** – This is recognised to be one of the principal errors in the formulation of the model of the Great Lotus River catchment. It refers to the selected spatial resolution and lumping of the subcatchment and conveyance input data. This is partly due to the model assumption of uniform conditions for each subcatchment, an inadequate representation of the inherent heterogeneity of multiple landuse subcatchments, but is also due to inadequate information for the subcatchments and the subsurface drainage network. It has been shown that parts of the catchment are without detailed stormwater information. This data is either unavailable or inadequate in its description of the physical characteristics of the respective stormwater pipes. For accurate, complex, fine resolution modelling of water quality and quantity, it is imperative that GIS coverages at a high scale be compiled of this data and continuously updated as changes occur within the system.

(8) **Model structure and numerical error** – this is an error associated with poor formulations of one or more of the component process relations and program code. Whilst this error is independent of the present model building exercise, it will nonetheless affect the accuracy of the model output when contrasted with the real, physical system. Such formulation errors include the assumption of uniform subcatchment characteristics identified in (6) above. The assumption in RUNOFF and TRANSport of routing through a "cascade" of elements, each discharging into the next element with no interaction or possible backwater effects, is another such formulation error that will not necessarily represent the real world situation. These formulations attempt to simplify the highly varying, often random nature of the modelled system into pragmatic mathematical expressions with adjustable empirical components to mimic the real behaviour of a system. The numerical error is introduced in the solving of complex non-linear mathematical expressions through numerical approximations and convergence iterations.

(9) **Parameter optimisation error** – this error is possible in the parameter calibration and optimisation stage of model development. Adjustment of a parameter may result in a closer

prediction to one or a group of observations, but also result in a poorer estimate of other observations. This is because SWMM parameters display different sensitivity for various precipitation and meteorological inputs. This sensitivity may vary for storms of different intensities or duration. This error can be introduced in erroneously identifying the parameter spaces in which a parameter is dominant. The resultant calibration of the parameter in that particular space will produce a poorer fit of simulated to observed records under different conditions.

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The above list provides a non-exhaustive summary of the errors associated with the modelling of complex hydrological processes. It is recognised that these errors, amongst others, can possibly account for some of the lack of fit between the simulated flow and the observed flow record for the Great Lotus River. It is, however, suggested that the calibrated simulation of the Great Lotus River and catchment provides a sufficient basis to explore the role of hydrological modelling as a DSS for Catchment Management. This is described in Chapter 7 together with an assessment of SWMM as the hydrological model to drive this process.

CHAPTER 7

HYDROLOGICAL MODELLING AS DECISION SUPPORT FOR CATCHMENT MANAGEMENT

This chapter explores the role a hydrological model can play in decision support for Catchment Management. The various steps in the Catchment Management process are highlighted and the points identified at which a hydrological model can contribute to this process. It is suggested that the three principal facets of Catchment Management pertaining to an urban context and its limited urban water resources can be identified as physical and economic development, environment management and social development and the need to balance these competing issues. The chapter then proposes a conceptual framework linking the multiple management and decision-making requirements of Catchment Management with the ability of a complex, deterministic water quality model to provide decision support for these requirements. A limited set of case studies for the Great Lotus River catchment is provided to illustrate the efficacy of using SWMM and its PCSWMM98 shell as a DSS for Catchment Management.

Before this is attempted, a reminder of the stages in Catchment Management decision-making is provided. This is concerned with the process leading to the creation of a Catchment Management Strategy. No attempt is made to formulate a Catchment Management Strategy for the Lotus River catchment; rather, it is to show how a hydrological model with decision support capabilities can provide input into the information needs of such a strategy.

7.1 Modelling within the Catchment Management Process

As suggested in Chapter 2, an integrated or systems approach is required for Catchment Management for the assessment of the diverse, interacting components of catchment processes and the linkage of possible management actions to impacts on the water resource and the overall state of the catchment. Effective catchment management should address all components of the water resource and all elements of the hydrological cycle that may relate to each issue.

It is recognised that water quality and quantity are interdependent and must be managed in an integrated manner, which is consistent with the broader environmental management approaches (Görgens *et al.*, 1998). This integrated approach must therefore include consideration of water quantity, quality and the aquatic environment (abiotic and biotic), as well as all the processes occurring during the hydrological cycle, including rainfall (pollutant generation), surface runoff (pollutant discharge), streamflow (pollutant transport) groundwater yield, aquatic ecological functioning and water use (Görgens *et al.*, 1998).

However, more often than not, there are tensions between the interests of the three fundamental considerations for sustainable urban catchment management – physical development constraints, social and community requirements and maintaining environmental integrity of the urban watercourse. Catchment management facilitates the resolution of some of these potential water management conflicts. In order to do this, three further requirements for sustainable water use must be considered: (WISA, 2000c)

- Firstly, local water users and stakeholders must be involved in decision-making, otherwise they will not support the decisions;
- Secondly, effective representative institutions must be established to facilitate this decision-making and implement the results;
- Finally, the decision-making process must be supported by appropriate information, based on relevant decision-support technologies.

This can be translated into three essential processes in catchment management that will lead to the successful development and implementation of a catchment management strategy: (WISA, 2000a)

- The technical *analysis* process (specialist and engineering assessment of the status of the catchment in regard to for example water quantity, quality, current and future use, etc.).
- The institutional process (establishing committees and structures, either statutory or non-statutory).
- The public participation process (to stimulate contributions that will enrich both the technical assessment process and institutional process).

It is in the technical analysis process of the above list that hydrological models, with their associated decision support capabilities, can provide detailed input into the Catchment Management process.

As discussed in Chapter 3, this decision support relates specific system goals at different levels of catchment hierarchy (site, catchment, region). It is an iterative process with multiple levels of decision making involved, in order to move from broad scale management goals for large regions to the finer details required for specific operational schemes for individual tracts of land or river reaches (Jewitt, 1998). This implies that each inter-related level requires more precision of detail, as the spatial and temporal scales become finer.

The decision support systems are able to provide multiple representations of the available management options by offering combinations of facilities that allow interactive assessment of the various competing aspects of the problem through different models, data visualisation, multi-criteria evaluations and reports (Jewitt, 1998). They thus provide the possibility of highlighting many of the links between the different catchment elements at different decision-making levels and different sub-systems, thereby enabling users to gain a more holistic appreciation of a complex situation.

In order to assess this role, it is first necessary to review the stages that are followed in a Catchment Management process, as initially introduced in Chapter 2:

- *Initiation* – beginning of Catchment Management process
- *Assessment* – understanding the physical and socio-economic cause-and-effect relationships governing the key water-related problems in the catchment
- *Planning* – developing a Catchment Management Strategy/Plan through understanding of the key issues of the catchment and with stakeholder consensus.
- *Implementation* – identifying and implementing a Programmes of Actions to address the Catchment Management Strategy/Plan.
- *Administration* - monitoring the implementation of management strategies, screening new development proposals and maintaining stakeholder support for the Strategy/Plan.
- *Monitoring* - information continuously gathered, processed, stored and interpreted on water use and catchment water health in terms of quantity and quality indicators.
- *Review and Auditing* – reassess, replan and revise responsibilities, objectives and strategies, to assess the success of the catchment management process.

It is at the stages of *Assessment*, *Planning* and *Review and Auditing* that the model can play the most significant role in providing decision support to the Catchment Management process. The two stages of *Assessment* and *Planning* are discussed further below.

7.1.1 *Hydrological models at* Assessment *stage of CM process*

It can be viewed that planning and decision-making for Catchment Management requires an understanding of the interrelations between the administrative, socio-economic and physical environments associated with the catchment (Görgens *et al.*, 1998).

This is obtained through an assessment of the cause-and-effect relationships and processes in the catchment that are issues for Catchment Management consideration. In an urban context, these causal factors generally imply anthropogenic activities which result in flooding (e.g. urban areas), water quality deterioration (e.g. dense settlements or effluent discharge) and/or destruction of the aquatic environment (e.g. in-stream activities) (Görgens *et al.*, 1998).

Catchment Assessment consists of two phases or processes. The first process is in the collection of data and information, together with the collation and storage of that information. This is crucial for the other process, which includes the quantification, interpretation and assessment of the different catchment elements and interrelations. It is in this quantification, interpretation and assessment that a hydrological model will contribute to an increase in knowledge in the Catchment Management process[2].

Because urban drainage systems are complex incorporating multiple landuses and conveyances and given that long term water quality and environmental impacts are difficult to predict, it is suggested that large-scale deterministic hydrological water quality models are necessary to manage the almost infinite number of calculations required to deal with such complexity (James and Kuch, 1998b).

In addition, accurate, deterministic water quality models are able to produce simulations at a high temporal resolution in order to accurately determine water quantity and quality values, something which manual methods are unable to do. (These issues of spatial and temporal resolution are crucial in determining model complexity and are discussed further in section 7.2, below. This is given that a cost-effective assessment should only address those issues that are critical to understanding the key problems in the catchment at an appropriate scale and resolution. (Görgens *et al.*, 1998).)

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[2] It is recognised that the hydrological model is restricted to providing an understanding of the physical environment. An understanding of the administrative and socio-economic environments would need to be obtained through other means.

Hydrological catchment models that allow water balance calculations and water quality and quantity impact assessments for all major natural components of the catchment, together with the major human impacts on the hydrological cycle, should thus be considered as a necessary part of the assessment stage of the Catchment Management process.

Attention is focused on complex water quality models given that they are able to (James and Kuch, 1998b):

- characterise surface runoff, concentration and load ranges
- determine effects, magnitudes, locations, and combinations of quantity and quality control options
- provide input to a receiving water quality analysis
- perform frequency analyses on quality parameters
- provide input to cost-benefit analyses of Best Management Practices (BMPs) and control options

In addition to the above quantification, interpretation and assessment roles, the hydrological modelling system would provide effective decision support to Catchment Management, if it was able to incorporate the catchment spatial and temporal data in such a way that the information required for effective decision making could be easily accessed and displayed. As discussed in Chapter 3, Geographic Information Systems (GIS) provide such functionality and should thus provide the basis for spatially referenced data. This would allow for the processing and ongoing capture of updated monitoring data and, if linked to the hydrological model, allow the assessment of any change for the Catchment Management Strategy.

The next stage at which a hydrological model can provide input into the Catchment Management process is the *Planning* stage:

7.1.2 *Hydrological modelling at Planning stage of CM process*

Catchment management can be seen to be about implementing management actions throughout the catchment, to address one or more critical issues in an integrated manner, based on a thorough understanding of the causes and effects of those issues (Görgens *et al.*, 1998). This requires, however, that decisions be made about what the management priorities are and how they should be managed.

The stakeholders (through the catchment management structure) should use information about the contribution and manageability of these factors to prioritise them in terms of management of that issue in the catchment. In identifying and quantifying, at a sufficient temporal and spatial scale, the dominant cause and effect relationships in the urban physical environment, the hydrological model is able to highlight the main contributing factors to an issue. Examples may include pollution sources contributing to a water quality problem, increased urbanisation resulting in increased catchment runoff or instream construction activity causing aquatic habitat destruction.

This enables Catchment Management agencies, when combining these contributing factors with assessments of the socio-economic and administrative environments, to be able to prioritise the principal issues requiring attention in a Catchment Management Strategy. Given that a Catchment Management Strategy may be progressively established, this implies that management issues may be prioritised and addressed in a phased manner. The Strategy should thus reflect variability in management priorities for different parts of a water management area (WISA, 2000b).

In conjunction with this prioritisation, it is crucial that the priority management issues are associated with quantifiable and measurable indicators. It is against these measurable objectives that the success of catchment management may be evaluated. Within a quantitative physical environment, the hydrological model is able to compare the results of the outcomes of various management alternatives. This allows selection of the optimal management alternatives for the Catchment Management Strategy. Based on the catchment responses, the model provides a measure of the success of applying those management alternatives.

The success of catchment management in addressing the key catchment issues will ultimately depend upon changes in behaviour, activities or development within the catchment. It is thus critical that the management objectives are selected as a result of a negotiated process between all relevant stakeholders and that they are agreed by consensus (or at least a majority) of the stakeholders.

A decision support system consisting of a GIS-linked catchment model and computerised database may provide a useful tool to foster consensus. This is through analysis of stakeholder concerns and the visual interpretation of the outcomes of such analyses.

7.2 Balancing Environmental, Physical development and Social needs in urban Catchment Management

The above discussion highlighted the areas and means in which a hydrological model can fit into the process of Catchment Management.

The model can provide consideration to the resolution of tensions between the interests of the three fundamental considerations for sustainable urban catchment management

- Physical development and economic constraints,
- Social and community requirements and
- maintaining Environmental integrity of the urban watercourse.

These three fundamental catchment considerations have been categorised into three groups in an urban context together with the appropriate management responses (Nicolson, 2000):

CATEGORY A - The **Physical/Mechanical** aspect. The dynamics of this system are understood in terms of the laws of physics, hydrology, hydraulics and statistics. The system is characterised the erosion, transportation and deposition cycle, fuelled by rainfall and driven by gravity.

The challenge to catchment managers is to manage for **SAFETY** and **convenience**. This is based on the reality that urbanised society living in increasing densities close to the river system are prone to the risk of flooding and the associated potential physical threat to life and property. Management for Category A is achieved by ensuring that the flow capacities of the drainage system are greater than the expected flows (floods). This is the traditional and continuing responsibility of drainage engineers and provides rich opportunity for drainage engineering solutions.

CATEGORY B - The **Chemical/Biological** aspect. The dynamics of this system are understood in terms of the laws of chemistry, biology and zoology. The system is characterised primarily by the life cycles of the biota of the river and its buffer zone, fuelled by nutrients and driven by living forms (birth, growth, propagation, death and decay)

The challenge to catchment managers is to manage for **HEALTH** and **bio-diversity**. Rivers are seen to be the life giving arteries supplying both substance (water resource, nourishment etc.) and habitat (in-stream and riparian). Management for Category B is achieved by ensuring that water quality is maintained at levels high enough to support living systems rather than threaten them. All water resource directed measures, pollution control, ecological reserve determinations, wetland and estuary dynamics studies etc are directed towards this end.

CATEGORY C - The **Social/Cultural** aspect. The dynamics of this system are understood through an acceptance and understanding of the social, psychological and spiritual needs of communities that live in the catchment. The system is characterised by human values, needs and responses to the river, estuary and wetland and fuelled by aesthetic, amenity and educational value as well as economic opportunity.

The challenge to catchment managers is to manage for **ENHANCEMENT** of amenity and **EDUCATIONAL** opportunity. Once the issues of safety and health have been addressed, it remains to assess the socially uplifting opportunity provided by rivers. Management for Category C is achieved by ensuring that maximum interaction (use and responsibility) between community and the drainage elements of the system is enabled and encouraged. Educational programmes and material must be developed to heighten awareness towards improving the amenity value of the catchment and its drainage networks.

In Table 7.1, below, a conceptual framework is proposed that links the multiple management requirements of Catchment Management with the ability of the hydrological model to provide decision support for these requirements. For each ***management issue*** identified, one or more ***strategies*** are to be developed and designed to effectively address the issue. If an issue presents as a problem the strategy represents the solution. Furthermore a strategy must be understood to be an action plan i.e. it is an activity (Nicolson, 2000).

The framework identifies the various management issues within the above fundamental catchment considerations and links them to various solution strategies. These strategies are reformulated in terms of input requirements of the hydrological model and culminate in the model output providing information as to the effects of each strategy.

Given that the strategy (or set of strategies) designed to address the management ***issue*** will be deemed to be a failure if it does not attain the ***objective***, the model provides insight into the possible success or failure of the particular management objective, through quantifying the effects of the proposed solution strategy.

Strategic Objective	Management issue to be addressed	Management solution	Simulation approach	Model output
Physical development	Protection against Flooding	Identification of network shortcomings	Hydraulic simulation of conveyance network and of solutions	Hydrograph at location of surcharge
		Implementation of BMPs • Increased infiltration • Decreased impervious	Hydraulic simulation • Decreased %impervious • Increased depression storage	Hydrograph detailing effects on peak flow and total runoff volumes
	Infrastructure maintenance	Identify crucial areas of network under capacity	Hydraulic simulation of conveyance network and of structural and detention solutions	Output showing pipe surcharges or high ratio of simulated to full flow
	Flood plain development	Identification of potential flooded areas and developmental control	Hydraulic simulation for alternative scenarios of flood plain development	Simulated flood levels identifying flood lines for limiting development
Environment Management	Habitat improvement and maintenance	River rehabilitation • Softening concrete lined canals • Improved habitat • Buffer zones	Hydraulic simulation of conveyance • Increased channel roughness • Enlarged cross-section • Increased bank floodplain roughness	Peak flow, flow depth and backwater affects to determine change in discharge capacity
	Improving water quality through decrease in source contribution	Diffuse agricultural BMP to reduce load • Detention ponding • Buffer strips • Soil testing and education	Hydrological simulation • Increased channel storage • Buildup and washoff formulation Test alternative solutions	Effects on flow and corresponding load Effects on pollutant buildup and concentrations
		Urban source reduction • Waste management • Sewer infrastructure upgrades	Hydrological and hydraulic simulation • Buildup and washoff formulation • Decreased sewer infiltration	Effects on flow and corresponding pollutant load
Social Development	Amenity value	• Improve aesthetic river rehabilitation and conserved riparian zones • Improved water quality through decrease in source contribution	Hydrological and hydraulic simulation • Decreased channel storage • Increased bank and floodplain roughness • Buildup and washoff formulation • Decreased sewer infiltration	Peak flow, flow depth and backwater affects to determine change in discharge capacity Effects on pollutant buildup and concentrations
	Economic value and Job creation	• Tourism promotion by pedestrian bridges and walkways and fostering of riparian vegetation • Reusing existing detention facilities for cultivation	Hydraulic simulation • Increased roughness • Decreased storage capacity	Effects on flood storage and flood levels

Table 7.1 : Conceptual framework linking Catchment Management issues and solutions with model DSS capability

The framework in Table 7.1 suggests an approach of how the hydrological model can be utilised in addressing Catchment Management issues. The depicted list of management issues and solutions is by no means exhaustive, and merely illustrates the types of management issues that can be assessed with their associated solutions, simulation approach and model output. Before further case studies of this application are investigated, a discussion on desired model discretisation or complexity for differing model objectives is presented. This is followed by an assessment of the various Best Management Practices (BMPs) on reducing catchment runoff and pollutant loading and the ability of continuous simulations to generate long-term annual runoffs and loads as well as infill periods of missing data.

Limited case studies are then presented to show how a complex hydrological model can aid Catchment Management decision-making through assessment of the effects of a selection of Catchment Management decision options. The case studies considered attempt to tackle the integrated nature of Catchment Management and the problem of conflicting management needs and suggest how objective differentiation between these issues can be determined by considering the associated impacts of each management option on the hydrological cycle. Issues include

- flood protection
- amenity value
- aesthetic
- environmental
- job creation
- water quality

This is working within the ambit of Catchment Management's need to decide between management options based on the most positive or least negative impacts on the water quality and quantity of the river.

7.2 Model Complexity in Hydrological Modelling

Chapters 5 and 6 have shown how SWMM can be used to simulate the different elements involved in the stormwater and sewer systems of a multiple landuse catchment. The cost of running and setting up such a SWMM simulation is related to the degree of complexity of the model, which in turn is determined by the level of discretisation utilised for a particular catchment.

The issue of modelling complexity needs to be seen in the light of two particular concerns. Increasing model complexity through finer process disaggregation to improve the accuracy and reliability of the output and secondly, increasing model complexity through spatial discretisation to address the specific design and modelling objectives.

These are thus two types of user-controlled model complexity (James, 1994):

1. complexity caused by process disaggregation – activating an unnecessarily large number of processes, parameters and variables at an unnecessarily fine time resolution
2. complexity caused by spatial discretisation – an unnecessarily large number of subcatchments, channels and pipes, amongst others, to be modelled.

Given the cost of collecting, monitoring, analysing and abstracting data for a large number of parameters and variables, it is necessary to reduce both the process disaggregation and spatial discretisation to the minimum needed for a sound design. Although it is desirable to include as many relevant processes at as fine a spatial scale as possible to hopefully improve the accuracy and reliability of the model, it is recognised that a finer disaggregation will not necessary produce a more accurate model.

In a discussion on scale in a physically based modelling philosophy, Alexander (1991) notes that often when numerical simulation fails to provide an adequate result, the introduction of additional variables or the use of finer time or space scales is thought to reduce the levels of uncertainty and improve model accuracy. He argues that unfortunately, however, the introduction of additional variables also introduces accompanying errors in measurement and representativeness. These errors can dramatically reduce the accuracy of prediction (curse of dimensionality) because of the limited data generally available (curse of small samples) In addition, the use of finer time scales is counter-productive because of the random noise often generated (Alexander, 1991).

For any model there is a theoretical limit to the accuracy of the predictions associated with an optimum number of variables (dimensions) and optimum time and space resolution (scale). In fact, the greater the variability of the process, the fewer the number of variables and the coarser the time and space scales required to ensure maximum accuracy (Alexander, 1991).

Given that the inclusion of additional state variables and model sub-routines is concerned with model source code and its reformulation, we will ignore this issue from now on. We are far more concerned with the second point, namely the issue of model complexity as a function of catchment discretisation. This is a far more common model user concern than the former, which is a model developer concern.

The smallest number of parameters, discretised subcatchments and modelled processes required for a model, depends on the design objectives and available catchment information. These objectives are established through discussions between client (or in this case, catchment management agency), engineering committee and modellers and produce questions such as:

- What are the effects on flooding levels of removing concrete canal linings and replacing them with vegetation lined sections?
- What is the cheapest and smallest stormwater sewer or conveyance necessary to convey flows from a particular development at a particular risk of failure?
- What is the smallest and cheapest culvert at a particular site at a particular risk of failure?
- What size of detention storage is necessary at a particular site so that there will be no net increase in flood levels at a particular risk of failure downstream?
- What are the effects on detention storage if it is planted with vegetation for pollutant removal? What will the retention time be? What will the increase in flood level in the pond be?

When design questions are formulated in this way, it is much easier to relate the design objectives and evaluation criteria and to provide quantitative solutions. (James, 1994)

The optimal level of complexity for a particular model is thus directly related to the model objectives and will vary depending on the project at hand. If flow quantity and quality information is required to, say, describe the conditions of each of the conduits of a particular conveyance system, then it is necessary to employ a fine discretisation to define the subcatchments that are tributary to each of the conduits modelled. On the other hand, if the objective is merely to simulate the outflow from the entire catchment to produce annual stream flow or pollutant loadings, it is desirable to use a coarser discretisation, thereby reducing the time and effort required for simulation.

Zaghloul (1981) investigated the accepted level of discretisation used for flow simulation over an urban area and illustrated the effect of reducing the number of subcatchments on the accuracy of runoff simulation. He provided a methodology in aggregating the subcatchments and conveyance system to reduce the complexity of the model whilst retaining a similar hydraulic response. He contended that using weighted average properties of detailed subcatchments, and the summation of individual hydraulic widths will provide an aggregated equivalent catchment. Provided this is undertaken correctly, the surface runoff hydrographs generated from both the detailed subcatchments and the aggregated equivalent catchment are quite similar (Zaghloul, 1981). In terms of overall catchment response, conduit routing from small areas proves to be insignificant.

In light of the above, SWMM simulation using coarse discretisation will result in a reduction of the costs of setting up and computer runtime. Zaghloul (1981)cautions, however, that flow simulation using coarse discretisation should be used as a planning tool for overall catchment response rather than for design purposes. A detailed, finely discretised simulation is necessary for design and for consideration of subunits within the catchment (Zaghloul, 1981).

As a case study in the Great Lotus River catchment, a coarse discretisation was employed to model the same area based on an event model (Duffy, 1999). This discretisation is compared to the fine discretised model generated in this research, in Table 7.2 below:

	Coarse discretised	**Fine discretised**
No of subcatchments in RUNOFF	41	209
No of conduits in RUNOFF	40	478
No of conduits in TRANSport	47	96
Run time RUNOFF	4.03 min	28.43 min
Run time TRANSport	1.82 min	13.83 min

Table 7.2: Comparison of coarse and fine discretised models

The coarse discretised model employed a spatial lumping of subcatchment characteristics and included hydraulically ineffective areas. It employed a coarse resolution for the drainage network with the range of pipe sizes from 0.6 to 2.5m with an average pipe diameter of 1.2m. This is in contrast to the fine discretised model that considered the smallest homogeneous subcatchments draining to a stormwater network ranging from 0.3 to 1.8m pipes with average diameter of 0.6m.

Figure 7.1, below, provides a comparison of the outflow of the coarsely discretised model with the outflow from the calibrated finely discretised model.

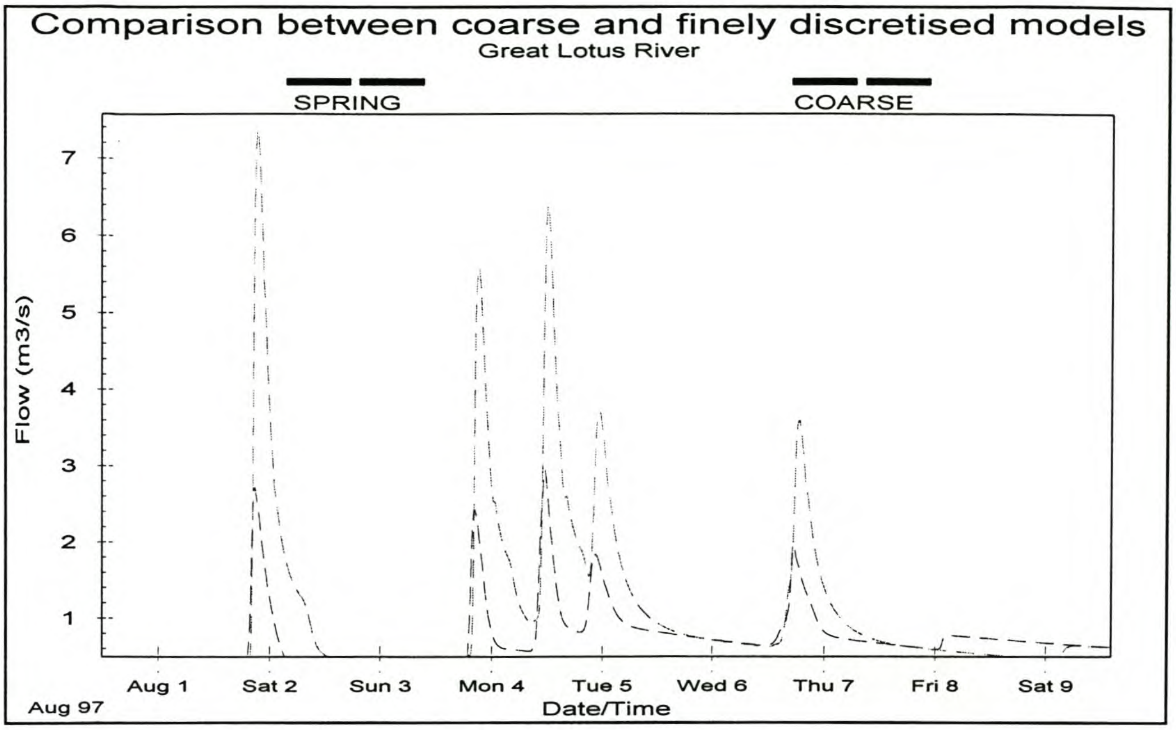

Figure 7.1: Comparison of coarse and finely discretised models

The hydrographs depicted in Figure 7.1 reveal that the coarsely discretised model produced significantly greater peak flows and total storm runoff volume than the calibrated finely discretised model. In addition, the coarse peaks lagged the finely discretised peaks and showed a longer time of recession.

Given the existing flow record it was possible to calibrate the coarse model (restricted to perturbing the %imperviousness and subcatchment width parameters)to produce a comparable total runoff to the fine discretised model at a significantly faster runtime and less setup time. The peak flow was overestimated, however, due to the inclusion of hydraulically ineffective areas as effective.

In order to obtain a closer fit between the two models of different spatial complexity, the coarse discretised model was calibrated using the %impervious and width parameters, shown in Chapter 6 to be the most significant parameters for calibration.

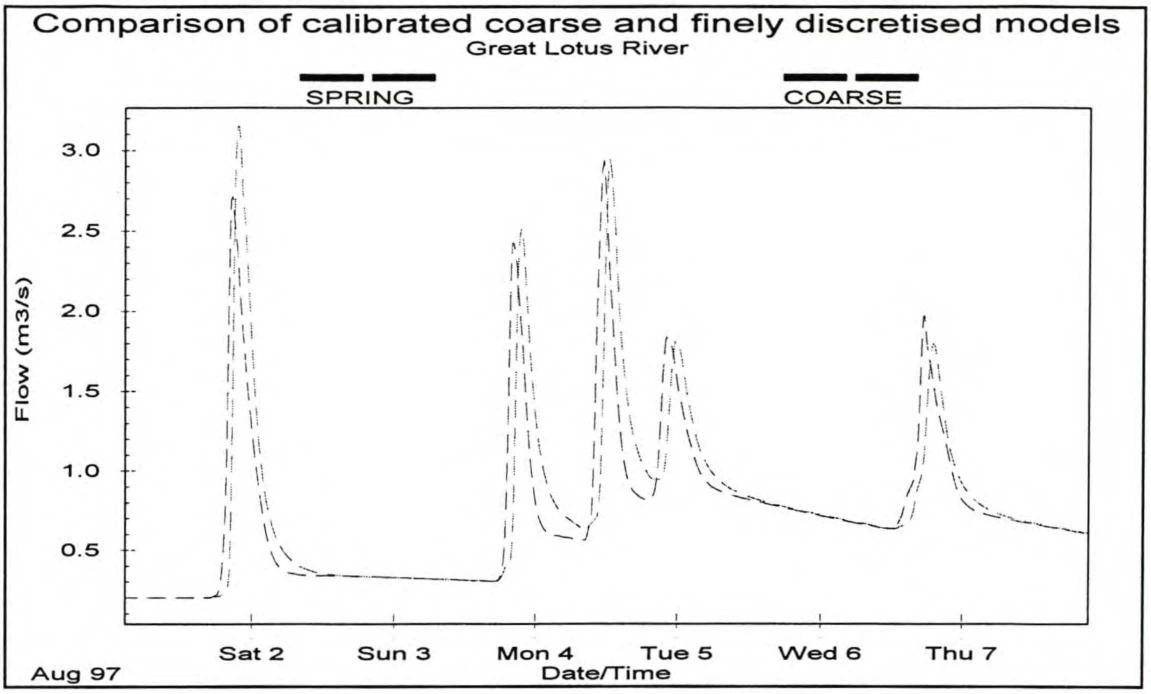

Figure 7.2: Comparison between calibrated coarse and finely discretised models

Figure 7.2 shows that, given adequate calibration, a good fit can be obtained between the coarse and finely discretised models. In order to achieve this fit, both the %impervious parameters and the hydraulic widths were significantly reduced. Table 7.3 shows the required parameter adjustments in order to obtain the fit illustrated in Figure 7.2.

Calibration Parameter	Change
% imperviousness	0.3 x initial value
width (m)	0.6 x initial value

Table 7.3: Parameter adjustment for calibration of coarse model

The adjustments shown in Table 7.3, to calibrate the coarsely discretised model, are in sharp contrast to those required for the finely discretised model. The percentage imperviousness for the coarse model is approximately half that of the equivalent percentage imperviousness of the finely discretised model. It would appear that a coarse lumping of subcatchment areas would tend to overestimate the directly connected impervious areas. In order to obtain a fit with simulated output from a finely discretised model, this requires a greater adjustment in the value assumed for the directly connected impervious areas.

In addition, whereas the finely discretised model required an increase in the hydraulic width to decrease the hydraulic response times of the subcatchment, the coarsely discretised model required that the hydraulic width of the catchment be decreased to delay and attenuate the peak hydrograph. This is necessary to induce more surface storage to compensate for the exclusion of the conduit storage in the coarsely discretised model.

The implications for model users would seem to be that, provided an observed record is available to calibrate the simulation, a coarsely discretised model has the ability to simulate catchments with limited input information and to generate overall catchment response more rapidly and with reduced model setup costs than a fine discretised model. The catchment width should be decreased to allow for increased surface storage and the %imperviousness should be significantly reduced to overcome the error of over assuming the extent of directly connected impervious areas.

Provided they are calibrated against an existing flow record, coarsely discretised models are able to produce sufficiently accurate results to allow the identification of overall catchment response through annual flow hydrographs and pollutant loadings.

Many of the concerns of Catchment Management are at a finer resolution than overall catchment response, however. In order to accommodate multiple stakeholder concerns, not all identified at the time of model configuration, it is necessary to produce the most finely resolved model possible, given time and budgetary constraints. This has the additional advantage that as the model complexity increases through finer discretisation, model uncertainty due to spatial aggregation or lumping is decreased (James *et al.*, 1998a).

Is there a limit, however, to the size and complexity of large, complex, finely discretised models? Given the increased power and lower cost of computing, larger and larger systems models are possible. The limitations for modelling larger systems lies with the ability of the modeller to review and assimilate the many pieces of data that make up the model (Crawford *et al.*, 1995). Through difficulties in reviewing the voluminous output from large complex models, its easier to fall into the trap of accepting the model output without scepticism and enjoy the relief of a completed run with stable model results particularly with many trials and aborted runs. In addition, relying on a review of model output through continuity errors, period averages and summaries, is frequently inadequate in identifying model problem areas (Crawford *et al.*, 1995). This can lead to model users overlooking crucial model situations, which lead to misunderstandings of the hydraulic system.

In large, complex system models, the modeller must be cognisant of the many possible interactions between system components and be able to track these interactions to ensure model reasonableness. Larger and more complex models require database management and the application of visual representation techniques. Management of data, model runs, and output processing must be performed under an integrated information management system that includes mapping, system maintenance databases and model management (Crawford *et al.*, 1995). The ultimate question in any model development and in the determination of size and complexity should be: what is the intended model use and can this be achieved without modelling to the finest detail?

In terms of defining optimal complexity for various levels of discretisation, it can be concluded that the optimum or simplest level of discretisation should be dictated by the design problem objectives. The effort must start with a clear statement of the design problems to be addressed in the modelling exercise, and end with the meticulous interpretation of model output, uncertainty and relationship to the design questions (James *et al.*, 1998a). The smallest feasible number of processes must be selected, based on these design objectives, whilst rendering the others inactive. This is followed by selection of the coarsest feasible subspace discretisation (subcatchments and conveyances) at the biggest time step possible to capture the dynamic nature of the simulated area. It is thus recommended to test the simplest models first that achieve the desired modelling objectives, proceeding to more complex until the required accuracy of the computed response function is achieved. Using the least number of processes, discretised spaces and the biggest time step will result in the smallest number of uncertain parameters to be estimated to deliver the optimal level of complexity and model reliability (James, 1994).

7.3 Application of Stormwater Best Management Practices

As discussed in Chapter 2, the major preoccupation with urban stormwater management has, until recently, been primarily with the protection of urban developments against flooding. This is through the rapid removal of precipitation from these developments as drained runoff and the disposing of this runoff into streams and other receiving water bodies of water.

Simultaneously, this runoff transfers pollutants from their points of discharge to those same receiving waters with little possibility of natural assimilation. An associated third effect is on ground water storage with increased impermeable paved surfaces depriving aquifers of (former) infiltration inflows and the loss of base-flow maintenance in the case of rivers and streams dependent on underground and spring waters.

Stormwater management of post-urbanised developments thus resulted in the carrying of exaggerated peak flows to natural bodies of water and together with compromised base flows, has inevitable impacts on established hydrologic equilibria as well as the stream hydraulic and morphological regimes (Blackmore, 1998).

Inevitably, the need for flood and pollutant reduction has led to an emphasis on a stormwater management approach that focuses on keeping pollutants out of the receiving bodies of water, by upstream control – attenuation and treatment measures close to where run-off is generated. Best Management Practice – BMP – is a term describing approaches and engineering devices for the better handling of, inter alia., urban stormwater. "Best Management (i.e. Stormwater Management) Practice" (BMP) thus has widespread acceptance as embracing:

> *"any and all measures that can reduce the quantity of flow and pollutants delivered by stormwater runoff to a receiving water body. This includes both source controls and 'end of pipe' treatments, the emphasis being on practice"* (Blackmore, 1998)

Urbonas (1994), in assessing BMPs, catalogues the essential objectives of BMPs – as measures for the improvement of stormwater quality – thus:

- Prevention – minimisation of pollution of the urban landscape
- Source controls – interception of pollution from runoff (which would embrace physical trapping BMP measures)
- Source disposal and treatment – attenuation of runoff at or near its source
- Follow-up treatment – downstream interception of runoff using structural BMPs to provide follow-up treatment.

The BMP objective can be targeted from two directions:

- ***Non-Structural*** measures are exclusively concerned with prevention. Success means fewer pollutants from urban sources being discharged onto the landscape, and hence less total load being transported. These BMPs include a variety of institutional and educational practices focussing on land development, public education to modify behaviour contributing to pollutant deposition, as well as the detection of illicit wastewater connection and the enforcement of ordinances designed to prevent the deposition of pollutants on the urban landscape (Urbonas, 1994)

- ***Structural*** measures act as a backup to the above "good housekeeping measures" and act as attenuation or treatment facilities before transportation to watercourses as ultimate environmental receptors.

A non-exhaustive summary of the various types of BMPs is as follows:

7.3.1 *Non-structural Best Management Practices*

As noted above, this category of BMP include a variety of institutional and educational practices aimed at creating a climate of enlightened awareness and of law enforcement and are measures that can be seen to comprise a least-cost strategy for minimising damage at the source – the individual (Blackmore, 1998). Below is a list of measures as identified by Urbonas (1994):

- Adoption and implementation of building and site development codes to encourage or require the installation of structural BMPs
- Adoption and implementation of site disturbance control programs
- Encouraging the *minimisation of directly connected impervious areas* in new developments (aimed at reducing the volume of runoff to the stormwater system through on site storage and percolation), the use of landscaped areas, grassed buffers and roadside swales instead of curb, gutter and storm sewer
- Public education on proper use and disposal of household chemicals, paints, solvents, motor oils, pesticides, herbicides, fertilisers etc
- Street sweeping and leaf pickup
- Detection and elimination of illicit discharges of wastewater lines to separate storm sewers
- Enforcement of operation and maintenance requirements of privately owned stormwater management facilities, including structural BMPs and non-structural programs on site

Similar measures include:

- more environmentally sensitised approaches to urban development and its control
- campaigns to promote public awareness in the media, focussing on, for example, environmentally sound approaches to disposal of household chemical wastes

- encouraging growth of *stakeholder* involvement in the condition of the street, the neighbourhood, the town centre, the open spaces
- introducing environmental positivism into the school system so that early mind-sets are created in children
- identifying and penalising offenders against environmental legislation.

7.3.2 *Structural Best Management Practices*

Whilst the above *Non-structural* BMPs generally are mostly aimed to *encourage, educate* and *enforce* the use of various devices, it is the devices themselves that are referred to as *Structural* BMPs. Structural BMPs comprise, not exclusively, the following (Blackmore, 1998):

- Run-off minimisation design approaches – non-traditional layouts of urban streets, buildings and parking lots, for example, that are relevant in new development or redevelopment contexts. This refers to the concept of *minimised directly connected impervious area* introduced above and is concerned with the slowing down of the disposal of runoff.

- Infiltration enhancement approaches - percolation trenches and infiltration basins, with due consideration to the type of urban land use generating the run-off. These include (Urbonas, 1994)
    - Grass swales and buffer strips – lowering overland runoff velocity thus promoting pollutant removal through sedimentation and tending toward a linear detention effect
    - Porous pavement – self-draining pavements, constructed from porous asphalt or concrete paving block.
    - Percolation trenches – rock filled percolation trenches temporarily storing stormwater and permitting percolation into the ground (serve small impervious areas typically two hectares or less)

- Filter basins – sand filters in conjunction with upstream detention/settlement structures

- Water Quality Inlets - Underground masonry tanks, compartmented for enhanced solid and oil separation, and serving relatively small catchments.

- Source trapping devices
    - Side entry pit trap (SEPT) – baskets fitted below entrance to drains from road edge gutters
    - Litter control device (LCD) – baskets positioned below point of entry to an inlet pipe
    - Continuous deflection separation (CDS) – a device installed in stormwater channels, diverting solid pollutants into a separation and containment chamber where they are kept in continuous motion during flow and prevented thereby from blocking the screened outlet
    - Gross pollutant trap (GPT) – comprising a large concrete-lined wet basin upstream of a weir protected by a trash rack. Decreased flow velocities encourage sedimentation in the basin with the trash rack at the downstream end retaining gross material. Major and minor GPTs have been developed to cater for small, 2 – 50ha and large 50 – 500ha catchments

- Floating debris trap (FDT) – effectively a litter boom, multi-cell and partially submerged, which "collects" floating objects in contact with it, i.e. the highly buoyant and less polluting of the gross pollutant load

- Extended detention basins (dry) the dry type comprising globally the most common type of detention facility. If the basin is to function as a water quality enhancing BMP, with sedimentation as the main treatment process, they require storage and drainage over an extended period of time. Thus the term extended detention basin. (Urbonas (1994) suggests a 1-year run-off volume of 40 hours, as the BMP yardstick).

- Retention ponds – a *wet* system with permanent pool and a surcharge detention volume above this pool. In addition to having the flood attenuating properties of the above detention ponds, retention ponds offer significant additional benefits in terms of water quality. Not withstanding sedimentation processes, retention ponds, through approaching natural wetlands, encourage the development of chemical and bio-chemical activity, together with assimilation through established aquatic and bank side vegetation.

- Wetlands – providing a filtering, settling, stabilising, oxygenating, and nutrient uptake environment. Wetlands provide both flood protection/prevention measures and environmental enhancement. They have the capacity to attenuate major storm flood flows, and by a combination of physical and chemical processes they are able to intercept a major fraction of influent pollutants given sufficient retention time.

Whilst the above list captures the extent of BMP available, the promise, from a catchment management point of view, lies with the selection of systems offering multiple uses. In essence, selection of the optimal BMP to offer advantages to a host of multiple competing concerns:

- detention basins incorporated into amenity open space designed to attenuate infrequent major flood peaks whilst providing more purposeful leisure or utilitarian uses, soccer fields or parking lots for example.
- features such as wetlands, with a degree of bio-diversity, which encourage the development of recreational and educational attractions.

It is in the quantitative assessment of the above multiple BMP measures in ameliorating stormwater impacts that a complex, fine resolution hydrological model can provide effective decision support for Catchment Management.

The following section shows how the calibrated hydrological model of the Great Lotus River catchment can provide information on the effects of applying a selection of the BMPs listed above. At the outset, this assessment will be mostly in terms of analysing the effects of structural BMPs. In addition, it will focus on an assessment of those BMPs that offer advantages to different concerns.

It is recognised that proper decision-making would need to be based on a continuous model founded on a longer rainfall time series. This is to allow for greater events given that most of the above case studies will have some effect on the flood peak. This present approach is merely to suggest possible management decisions that could be considered and the role that a hydrological model could play in quantifying the effects.

Issues addressed within a Catchment Management context include the application of:

(1) retention ponds

(2) detention ponds

(3) infiltration

(4) decreasing directly connected impervious areas (KL2 in Crossroads)

(5) qualitative discussion on how waste management practices can affect loads

The principal parameters utilised in interpreting the results of application of the above measures are:

- %imperviousness
- Manning's roughness coefficient "n" for pervious and impervious surfaces
- Depression storage

7.4 Selected case studies of the application of catchment management proposals

7.4.1 *Use of detention ponding to reduce peak flow*

A large portion of the Nyanga area is drained by a series of stormwater pipes leading into the Great Lotus River canal along Terminus Road. A hypothetical Catchment Management objective could be to change the layout of the existing stormwater line leading along Terminus Road, Nyanga. A specific question could be: What are the effects on streamflow if a detention pond is incorporated within an open piece of land at a point approximately 250m upstream of the inlet into the canal. It is desired for the detention pond to be online resulting in simple pipe inlet and outlet structures. It is anticipated that the pond can utilise the existing area of 35 x 140m and the dimensions and characteristics of the pond are shown in Table 7.4 , below.

Detention pond characteristics	
Dimensions	140 * 35 m
Slope	0.0001
Depth	1.5 m
Manning's roughness coefficient "n"	0.25
Starting depth	0.1 m

Table 7.4: Dimensions of detention pond, Terminus Road, Nyanga

Figure 7.3, below, provides an indication of the outflow into the Great Lotus River canal based on flow from the detention pond compared to the present stormwater layout. The blue line represents the present situation whilst the lesser green line represents the hydrograph due to the potential detention pond.

As can be seen in Figure 7.3, construction of a detention pond with characteristics as in Table 7.4 and pipe inlet and outlets, produces a significant decrease in peak flow (48% for the largest storm shown in Figure 7.3) in addition to a lag in the time to peak and slower recessions.

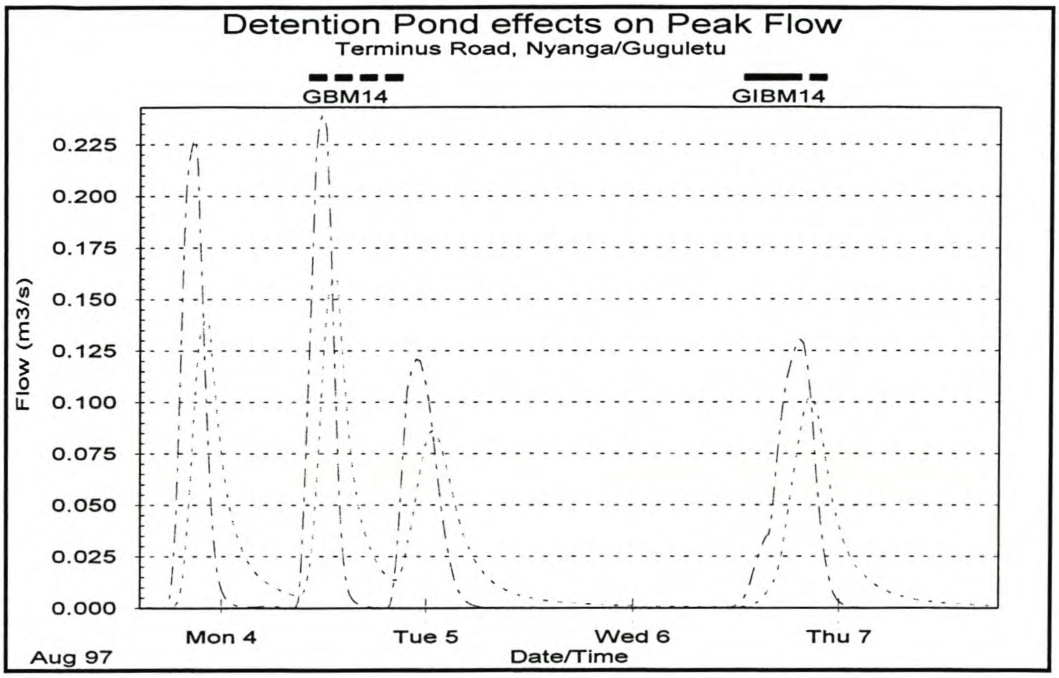

Figure 7.3: Effects of detention pond on peak flow, Nyanga

This will have implications for the size of downstream pipes between the detention pond and the inlet to the Great Lotus River canal. By reducing this peak, the instantaneous maximum pollutant load is also decreased to the Great Lotus River canal. In addition, increased flow due to increased urbanisation upstream of the detention pond can be catered for by the detention pond and upgrading of the downstream pipes can be delayed.

From an overall catchment response point of view, the effects are less noticeable at the Springfield Road culvert. The peak flow is reduced by 10% for the period of simulation. However, whilst this is a simplistic example of the effects of inclusion of a detention pond structure, a fine resolution hydrological model of the catchment allows a feasibility investigation of multiple sites and varying dimensions without requiring the creation of a new model at each site.

7.4.2 *Decreasing the directly connected impervious area in Crossroads*

As discussed in Chapter 6, the degree of imperviousness is perhaps the single most significant parameter in the generation of overland flow from urbanised subcatchments. This imperviousness is a measure of the connectivity of the surface impervious areas to the subsurface drainage network.

Minimising the directly connected impervious areas is an effective means to reduce peak flow rate of runoff, its volume as well as the load of pollutants it carries. Urbonas (1994) contends that storms with less than 13 to 25 mm of rainfall can be virtually eliminated. This has positive implications for the Great Lotus River catchment with its average low intensity storm conditions coupled with the good infiltration rates of the sandy soils.

Minimising the directly connected impervious areas is best achieved in developing and redeveloping areas through a non-traditional layout of streets, parking lots and buildings to slow the flow of runoff. Runoff previously collected from impervious surfaces and rapidly removed to stormwater drains is now initially channelled over pervious surfaces to maximise possible infiltration. Provision is made for the construction of grass swales and buffer strips and infiltration trenches (Urbonas, 1994). This can be quite simply achieved through the redirecting of downpipes from impervious roof collection over pervious surfaces, such as gardens and lawns, to allow for the increased depression storage to decrease runoff velocity, promote infiltration and decrease surface runoff to the stormwater system.

In conjunction with this is the establishment of a variety of infiltration measures such as permeable pavements, infiltration trenches and sand filter basins with their corresponding runoff attenuation and pollutant removal abilities.

No attempt is made to model the abilities of any of these structural BMPs. What is shown, however, is the possible decrease in runoff flow rate and volume that can be achieved if the directly connected impervious area is reduced. This is undertaken for the Crossroads residential area of the Great Lotus River catchment.

This part of the Great Lotus River catchment has a hydraulically effective area of 132.15 ha. Figure 7.4, depicts a set of hydrographs for the outlet of the Crossroads residential area for selected storms. The %imperviousness was decreased 33% from 15% to 10%. The higher flow represents the response to the present level of directly connected area whilst the lesser peaks correspond to a decrease in the directly connected impervious area. The figure shows the significant decrease in peak flow for a number of storms in 1997 that was achieved in decreasing the directly connected impervious areas. The overall results for the simulation during 1997 are shown in Table 7.5.

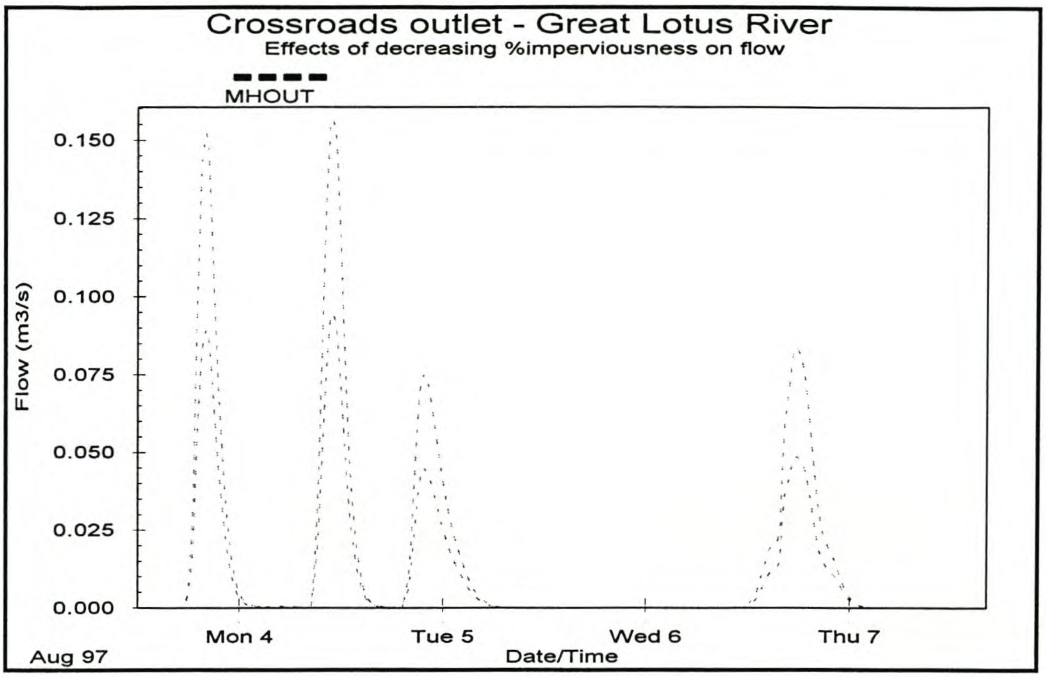

Figure 7.4: Effects of decreasing directly connected impervious areas

Table 7.5 reveals that a 33% decrease in the directly connected impervious area of Crossroads results in a corresponding decrease of 41% in peak flow and 39% in total runoff volume. Given the relationship between pollutant load and flow this will have similar results for a decrease in pollutant loading. Any stormwater management decisions must therefore include a detailed and concerted effort at minimising the directly connected impervious areas in order to address the issue of increased flow through urbanisation.

	Peak Flow (m^3/s)	Total Runoff (m^3)
Present imperviousness = 15%	0.4567	20450
Decreased imperviousness = 10%	0.2703	12450
Percentage change	41% decrease	39% decrease

Table 7.5: Comparison of peak and total flow changes from decreasing directly connected impervious areas

7.4.3 *The re-design of a stormwater detention facility to create job opportunities*

This example deals with the issue of job creation within the context of stormwater attenuation. An initiative has been suggested to cultivate coloured cultivars of Arum lilies for export. The suggestion is that local communities would plant, maintain and harvest the lilies, thereby generating wealth for low-income communities. Ideal site conditions are large open patches of land, inundated periodically, yet well drained. It is required to assess the feasibility of re-utilising existing detention facilities for this purpose and it is, thus, necessary to determine the effects on flooding.

An ideal site is the Detention Pond 03, situated in the Philippi East low-income residential community. It has an area of 30 300m^2, and at present is designed with an inlet/outlet structure that causes downstream pipe surcharges to flow up and out of the inlet structure into the pond for temporary storage. After the flood peak has passed, the stored water is fed back into the subsurface stormwater pipe network through grid openings in the above inlet/outlet structure. For the study period of 1997 – 1998, the pond did not come into use and instead lay overgrown, polluted through litter with low amenity value.

The above strategy can be investigated at the pre-feasibility stage through use of the hydrological model of the area. The pond would require redesign with the removal of the inlet/outlet structure and replacement with pipe inlet and outlets at the upstream and downstream sides of the pond. This allows for a low flow continuously through the pond for irrigation as well as the occasional flooding during winter storms. Provided that adequate drainage is ensured, this flooding should not compromise the cultivated arum lilies.

For the pre-feasibility investigation, the pond is simulated as a trapezoidal lined channel at a shallow incline slightly less than the original detention pond. The dimensions of the cultivated area cover the entire area of the existing detention facility. The intensive cropping would result in flow retardation due to increased roughness and is simulated using a Manning's roughness coefficient "n" of 0.3. The effects of the re-design of the pond can be seen in Figure 7.5.

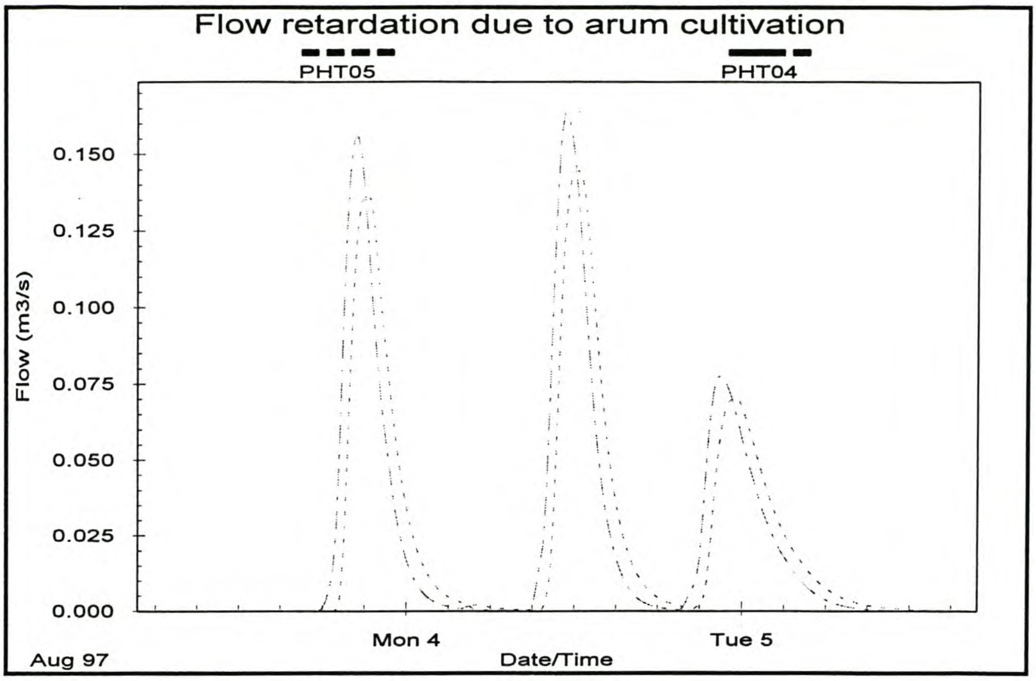

Figure 7.5: Flow retardation due to redesign of existing detention pond

The upstream flow, PHT04, in Figure 7.5 has been slightly retarded by redirection through the cultivated detention pond. The peak has been decreased (for the entire period of simulation the peak was reduced by 12% to 0.414 m^3/s) whilst the flow volume has remained essentially the same. From an overall catchment point of view, the change of flow regime would not significantly affect the flow at the most downstream point.

A more detailed investigation would need to be undertaken, using EXTRAN, to more closely simulate the hydraulic characteristics of the pond at a smaller time step. Pending this more detailed hydraulic analysis, the proposal to redesign an existing detention by bringing it online and cultivating with arum lilies appears promising and potentially offers an increase in amenity value as well as job creation.

The present hydrological model serves effectively as a tool assisting in the selection of appropriate sites and assessment of the suitability of the design proposal at a pre-feasibility stage.

7.4.4 *Effects of landuse change on runoff*

A significant question to be resolved by Catchment Management in an urban context, is the issue of changing land use on the peak flow and accompanying pollutant loading. This is due to the pressure on available land for development for residential and commercial areas. It remains to assess the potential implications of such a landuse change.

As discussed in Chapter 3, the Great Lotus River catchment is partly composed of rural areas in the Philippi Horticultural Area (PHA). Given increased squatting in the area, it is desired to assess the implications of developing a part of the PHA currently zoned as agricultural for housing.

This area, adjacent to Vanguard Drive, is composed of two subcatchments with a total area of approximately 380 ha, slightly over 20% of the total simulated area. At present it is almost entirely pervious, with an estimated 1% directly connected impervious area. It is characterised by groundwater influences during the winter rainfall period with drainage through limited overland flow and lateral subsurface groundwater flow. As a worst-case scenario, the development is expected to be conventional with significant impervious areas removing the interaction with the groundwater and significant directly connected impervious areas draining to concrete subsurface drains leading directly to the Great Lotus River canal. It is required to assess the potential increases in flow due to such a high-density residential development.

The development is simulated with no groundwater subsurface flow into the drainage network. The directly connected impervious area is increased to 15% to accommodate the increase in surface hardening due to the buildings, roads and parking areas. The pervious Manning's roughness coefficient "n" is decreased to 0.2 to approximate the maintained gardens and lawns of the residential development as opposed to the cultivated and bush/scrub areas of the historical undeveloped area. The associated implications for the peak flow and runoff volume draining this area are shown in Figure 7.6 below with a small part of the entire simulated period displayed for comparison. The blue line represents the developed condition, whilst the pink line is the present rural condition.

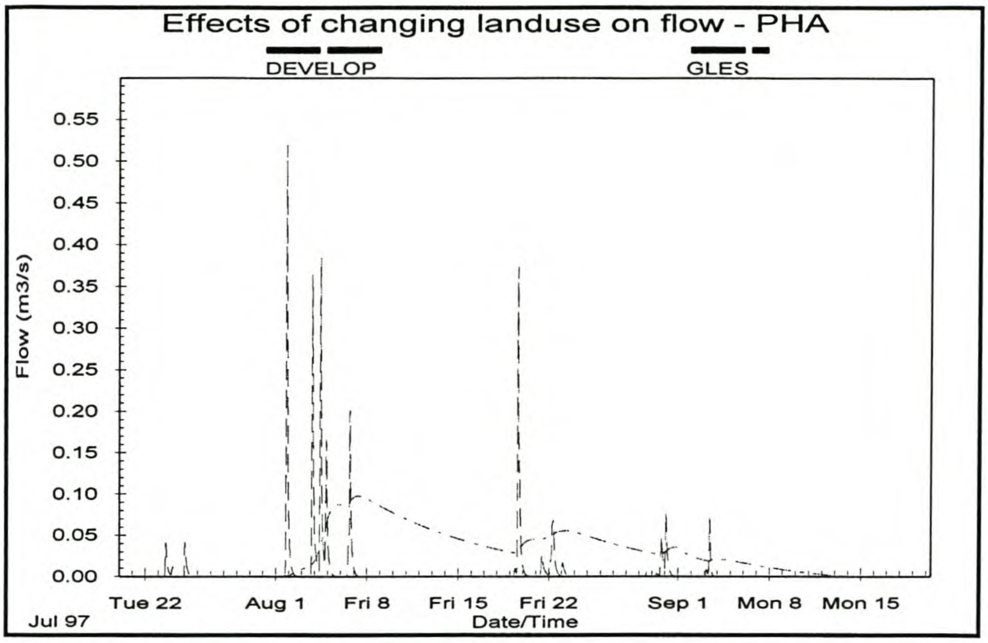

Figure 7.6: Effects of landuse change in PHA on flow

It is interesting to note the multiple effects of the landuse change. As expected, the peak flow is significantly increased in the post development scenario. Although Figure 7.6 only displays a part of the simulation period, the flow peak for the entire period simulated (1997) increased from 0.098 m^3/s for the undeveloped rural situation to 1.414 m^3/s for the developed scenario, an increase of over 1300%!

Corresponding to this increase in peak flow, however, was a decrease in the total runoff volume due to the effects of the groundwater subsurface flow being removed. The total runoff volume for the period simulated, decreased by 65% from 141700 m^3 to 48750m^3. This flow is due entirely to rain event induced overland flow being channelled into the stormwater network for eventual disposal into the Great Lotus River canal.

Whilst the above shows the localised effects of such a development, it also has implications for the entire catchment. The effects on flow at the downstream point are shown in Table 7.6, below, for the simulated period in 1997.

	Peak Flow (m^3/s)	Total Runoff (m^3)
Present agricultural landuse	3.084	3499000
Future developed landuse	4.421	3407000
Percentage change	43 % increase	3 % decrease

Table 7.6: Overall catchment response to landuse change in PHA

The change in flow at the Springfield Road culvert is fairly significant due to the possible development scenario discussed above in the Philippi Horticultural Area. Development of this area, approximately 20% of the entire simulated catchment, resulted in the simulated peak at Springfield Road being increased by 43% due to the increased overland flow and reduced infiltration. The loss of baseflow in the developed area produced a relatively small overall decrease in runoff volume for the simulated catchment of 3% given the contributions from the rest of the agricultural area.

The hydrological model of the Great Lotus River catchment can thus provide an initial assessment of the changes in flow and pollutant loading due to changes in landuse. This allows catchment managers to determine the effects of such management decisions. The case study presented is of the pressures of increasing development to cater for social needs such as housing. It is not restricted to this, however. Given the emphasis on integrated stormwater management, the above scenario could be contrasted against additional scenarios incorporating BMPs to reduce the degree of imperviousness of the catchment and increase infiltration to minimise the increases in peak flow. A hydrological model of a sufficiently fine temporal and spatial resolution has the capability to assess the implications of each of the above scenarios and to enable catchment managers to select optimal alternatives based on the catchment responses of each scenario.

7.4.5 *Effects of changes of waste management strategies on pollutant loadings*

Although the present hydrological model of the Great Lotus River catchment includes a limited water quality simulation, it is based entirely on observed data to obtain a rating curve linking flow and pollutant load.

Given sufficient input data, SWMM can provide a simulation of pollutant buildup and washoff from a particular urban subcatchment. This simulation can therefore be utilised to assess the implications of various waste management proposals proposed in a Catchment Management context. This section describes how such proposals could be examined given the inadequacy of the above rating curve approach.

As discussed in Chapter 5, SWMM contains empirical equations used to generate pollutant buildup and washoff. The buildup formulations are a function of landuse with up to five user-supplied landuses possible. The pollutant buildup can be a function of this landuse dependent on the type of buildup equation specified in SWMM. For a given pollutant the buildup is computed as either a fraction of dust and dirt with the function dependent on landuse type, or individually for each pollutant with the function constant for each subcatchment landuse. The buildup is dependent on some form of street sweeping or flushing and the efficiency of that cleansing.

Washoff is formulated in terms of erosion or solution of pollutant from a subcatchment surface during runoff. Although sediment transport theory can be applied to generate the degree of erosion of pollutant, this is often impractical given lack of existing data (James and James, 1997). What is often therefore used is an exponential relationship between the load washed off, the amount of pollutant available for washoff as well as the runoff rate responsible for the washoff.

Given sufficient sampled stormwater data from a particular subcatchment, it is possible to calibrate the above empirical equations to generate good closeness of fit between observed and simulated data. Waste management strategies, such as increased street sweeping or flushing, can be evaluated by varying the parameters related to the beginning and end of annual street cleaning programmes, the cleaning interval and the estimated efficiency of cleaning. This is not attempted within the context of the present research, but highlights the possibility of a calibrated hydrological model in assessing the effectiveness of these and other waste management strategies on pollutant loading.

7.4.6 *Effects of river rehabilitation strategies*

As discussed in Chapter 2, the conventional approach to addressing increased urbanisation has been to construct concrete lined subsurface stormwater and surface canal systems for the rapid removal of the increased flow. This is in order to minimise the risk of flooding. This is the case with the Great Lotus River, which was designed in 1994 with a trapezoidal concrete lined low flow section. This design, whilst successfully minimising the risk of flooding, has negative implications for the water quality of the canal, as well as its ecological biodiversity. In addition, the poor aesthetical appearance reduces the amenity value of this facility with negative associations from local communities.

As part of a Catchment Management initiative, it may be necessary to investigate the possibilities of river rehabilitation to overcome the above inadequacies. This can be through the provision of increased riparian vegetation zones along the channel servitude to decrease pollutant laden overland flow. More significant, however, are the effects of total or partial removal of the concrete lining on peak flow and pollutant loading and its replacement with earth-lined or ecologically friendly erosion protection measures such as gabions or Armoflex.

This removal can have positive implications for water quality and ecological biodiversity through increased interaction between stream flow and the subsurface soil and groundwater. It allows potential nutrient assimilation through the interflow between stream and subsurface soil as well as the establishment of aquatic vegetation with its own nutrient removal processes. The improved water quality and reduction of stream velocity through increased channel roughness allows the increased establishment of aquatic biota.

The potential negative consequences, however, are increased risk of flooding due to decreased channel discharge capacity, as well as the increased maintenance costs associated with increased channel vegetation.

A fine-resolution, deterministic hydrological model incorporating hydraulic calculation routines, has the capability of assessing the implications of the above Catchment Management proposals for river rehabilitation. Unfortunately, the lack of available catchment information pertaining to the invert and ground elevations of the drainage network and canal itself, preclude the establishment of an EXTRAN model of the Great Lotus River canal. This module, as described in Chapter 5, is a complex data intensive hydraulic program and, if configured into part of the hydrological model of the Great Lotus River, would be able to simulate the implications of increased channel roughness on flow depth, as well as assess the backwater effects induced by the decreased discharge capacity.

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The RUNOFF and TRANSport modules utilised in the present hydrological model of the Great Lotus River catchment are sufficient in order to simulate the overland and subsurface flows from individual parts of the catchment and to route these flows and associated pollutant loadings to the catchment outlet. The present finely discretised model subcatchment and conveyance network provides decision support for Catchment Management through the simulation, at a pre-feasibility stage, of Catchment Management issues including the use of detention facilities to decrease flow and loading for a particular subcatchment as well as the effects of varying landuse and imperviousness on flow and pollutant loading.

Given additional data on water quality it is possible for the model to provide assessment of waster management strategies by simulating the resultant pollutant loads of the different strategies. Given more detailed canal and drainage network dimensions, inverts and ground elevations, it is possible for the model to incorporate hydraulic calculation routines to assess the implications of alternative river rehabilitation techniques. This would, in addition, produce a greater capability to assess the role of the various BMPs identified above in addressing the amelioration of stormwater impacts and pollutant loading In addition, a detailed level survey of the stormwater pipe and canal network could result in hydrological modelling being utilised to identify critical areas where stormwater upgrading would be necessary.

It is imperative that detailed drainage patterns and stormwater network characteristics as well as comprehensive, spatially representative precipitation datasets are available to facilitate the generation of complex, finely discretised catchment hydrological models. This is in order for these models to function as effective decision support systems for Catchment Management. This needs to be emphasised at the local authority level, stressing the necessity for such information, and if lacking, that funding should be made available for the rapid acquisition of this information. It is only with a detailed knowledge of the catchment and its drainage network (with its capacity and response to flood events), that Catchment Management organisations and local authorities will be able to, confidently and holistically, develop and implement any management, upgrading and maintenance programmes.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The aim of the research reported in this thesis was to investigate, in an urban context, the use of hydrological modelling as a decision support system for Catchment Management. This thesis has described how a shifting paradigm in the management of urban catchments towards an integrated approach called Catchment Management, has resulted in the need for detailed catchment information and required objective decision-making tools to select optimal management alternatives. This can be effectively provided by complex, deterministic hydrological modelling.

8.1 Conclusions

In the course of this study, the following conclusions were reached:

8.1.1 *Contextual conclusions*

- Catchment Management, as legislated in the Water Act, No. 36 of 1998, is an approach that can integrate engineering skills, socio-economic concerns, and environmental constraints within a multi-disciplinary decision-making process.

- In order to provide effective management solutions, Catchment Management requires tools to provide reliable information about the performance of alternative arrangements of stormwater management facilities and to quantify the effects of possible management decisions on the water environment. A deterministic hydrological model is such a tool, which can provide detailed, reliable, long-term information of a catchment at the necessary temporal and spatial resolutions.

- The model building exercise consists of a number of steps. These steps include formulation of the model objectives, the collection of available catchment information, defining model parameters and input values through interpretation of the above collected *a priori* knowledge, simulation runs, model calibration based on analysis of the sensitive input parameters and model verification, which tests the above parameter selection against an independent data set.

- The hydrological model must be ideally part of an integrated software application in which a collection of data manipulation, analysis, modelling and interpretation tools can be used together to provide effective computer based decision support,

- A decision support system must have a simple and intuitive user interface able to produce easily interpreted output. It must have powerful graphical presentation capabilities promoting effective communication and be retrieval orientated and easily modified to operate in a flexible manner to suit the changing needs of the user.

- Effective Catchment Management decision support systems must incorporate Geographical Information Systems (GIS) as a spatial data handling technology providing the efficient storage, retrieval, processing and output of spatial data. This allows the effective use of spatial geographic information and the transformation of this information into representative variables for hydrological simulation.

- Remote Sensing (RS) is an approach that given skilled personnel utilising imagery with sufficient resolution, can automatically and accurately generate input parameters for use in hydrological modelling. For the present research, however, the available image resolution resulted in the RS technique performing successfully on a catchment scale and in subcatchments with relatively homogenous landuse types. Using commercially available satellite imagery thus seems to be most effective in determining total catchment information or for fairly large homogenous landuse areas.

8.1.2 *The Lotus River catchment*

- The extensive canalisation of the Great Lotus River has effectively provided the drainage and flood control needed to service the urban development, yet, has contributed to this channel becoming a stormwater drain, transporting waste and nutrients in dissolved and particulate forms to Zeekoevlei, and reducing its assimilatory capacity for water quality improvement.

- Surface runoff to the Great Lotus appears to be mostly from the urbanised catchments. Surface runoff from the Philippi Horticultural Area is evident only during significant rainfall events coupled with a high water table. The significant contribution to the Great Lotus from the agricultural areas appears to be through groundwater seepage during high winter water table levels.

- Pollutant constituents of concern in the Great Lotus River canal are Total Nitrogen (TN), Total Phosphorus (TP), Indicator organisms (Faecal coli, *E coli*) and Ammonia. The canal is e nutrient-rich with phosphorus and nitrogen concentrations in the hypertrophic range.

- The majority of pollution contributions are from non-point or diffuse sources, principally the urban residential and agricultural areas, which enter the canal as tributaries.

8.1.3 *Model configuration*

In configuring a SWMM model of the Great Lotus River catchment, the following conclusions were drawn :

- Given sufficient detailed input data of the catchment and its conveyance network, SWMM is able to generate hydrographs and pollutographs at various points of the Great Lotus River at varying temporal resolution.

- On its own, SWMM is challenging to work with given the strict input requirements of its Fortran code. PCSWMM, as a GUI, significantly simplifies the model configuration through providing more flexible input editing windows and add-on programs.

- PCSWMM eases SWMM model runs through the automatic defining of input, interface, scratch and output file name and locations as well as permitting model runs with multiple modules.

- A major difficulty of using SWMM is interpreting the poor error messages that are generated. This makes model debugging a time consuming and, often, undirected exercise.

- SWMM has poor output printing routines which are only included in the output file and are difficult to analyse. PCSWMM provides powerful output plotting functionality facilitating better interpretation of the simulated output.

- The effectiveness of SWMM as a DSS for Catchment Management is significantly improved by the added functionality of PCSWMM. The improved output plotting routine, sensitivity analysis tools and allowable exporting to external file formats for added analysis, permit more effective interpretation and communication of model output for stakeholders and other users.

8.1.4 *Decision Support for Catchment Management*

- Modelling complexity in Catchment Management is a function of process and spatial disaggregation. The optimal level of complexity for a particular model is directly related to the model objectives and will vary depending on the project at hand.

- The need for flood peak and pollutant reduction is addressed through Best Management Practice (BMP) approaches and engineering devices for the better handling of urban stormwater. Non-structural BMPs are focussed on *encourage, educate* and *enforce* the use of Structural BMP devices including runoff minimisation designs, infiltration enhancement through minimising directly connected impervious areas, source trapping devices, detention and retention ponds and wetlands.

- In terms of Catchment Management, the DSS represented by SWMM and PCSWMM can be effectively used to assist decision-making. This is to address tensions between the fundamental catchment management considerations of Physical Development, Social considerations and maintaining Ecological sustainability. It is at the stages of *Assessment* and *Planning* that the model can play the most significant role in providing decision support to the Catchment Management process.

- *Assessment* in the Catchment Management process refers to the collection, storage, modelling and interpretation of catchment information. It is in this quantification, interpretation and assessment of catchment information that a hydrological model contributes to an increase in knowledge in the Catchment Management process.

- In identifying and quantifying, at a sufficient temporal and spatial scale, the dominant cause and effect relationships in the urban physical environment, a hydrological model is able to highlight the main contributing factors to an issue. This can be used in the *Planning* stage of the Catchment Management process to enable the prioritisation of the principal issues requiring attention in a Catchment Management Strategy.

- It is possible to link the multiple decision-making requirements of Catchment Management with the abilities of a hydrological model to provide information on these requirements in a conceptual framework. This is through the resolution of Catchment Management issues into potential solutions that are reformulated in terms of the model parameters. The resulting model output created through perturbing the appropriate model parameters allows a juxtaposition of alternatives and allows the Catchment Management body to identify optimal management solutions for the various management issues.

- The present model of the Great Lotus River catchment is sufficient to simulate the overland and subsurface flows from individual parts of the catchment and to route these flows and associated pollutant loadings to the catchment outlet. At its present level of complexity, the finely discretised model subcatchment and conveyance network provides decision support for Catchment Management through the simulation, at a pre-feasibility stage, of various Catchment Management issues and their proposed solutions.

- Given more detailed canal and drainage network dimensions and water quality data, it is possible for the model to incorporate hydraulic calculation routines to assess the implications of alternative river rehabilitation techniques and waste management strategies. This would allow greater capability in assessing the role of the various BMPs in ameliorating stormwater impacts and pollutant loading. In addition, a detailed level survey of the stormwater pipe and canal network could result in hydrological modelling being utilised to identify critical areas where stormwater upgrading would be necessary.

- In order to facilitate the development of future complex, finely discretised catchment hydrological models, it is necessary that complete and detailed drainage patterns and stormwater network characteristics are available. In addition, to minimise model configuration costs and time of model setup, this spatially representative data must be captured in a GIS for rapid inclusion into the model. Furthermore, complete spatially representative precipitation datasets are necessary to ensure that model error is reduced. The two issues of available spatial data and comprehensive precipitation records are crucial for the configured models to function as effective decision support systems for Catchment Management.

8.2 Recommendations for Further Work

The following recommendations are made for further work:

- The model of the Great Lotus River is, at present, based on available information, which has been shown to be lacking in detail for parts of the catchment. Given the process of updating stormwater records currently being undertaken by local councils, the updated information must be incorporated into model. This would allow a more complex routing analysis of the conveyance network facilitating more detailed Catchment Management alternatives and their proposed solutions to be assessed.

- The model is based upon a short existing data set of precipitation, runoff records. The consequences are that verification of the model is not undertaken. A longer time series of flow data, coupled with the corresponding precipitation records spatially represented across the catchment, needs to be collected to allow for the verification of the updated model.

- The model is at present, a simulation of only part of the entire Great Lotus River catchment. In order to allow for management recommendations to be made for Zeekoevlei, the downstream receiving water body, it is necessary to simulate the remaining parts of the catchment. Given that this area contains more of the agricultural parts of the Philippi Horticultural area, it is further recommended that more attention be devoted to simulating the agricultural subcatchments than the present lumped approach. This includes identifying the hydraulically connected areas of these agricultural subcatchments as well as considering the role of excavated farm dams in attenuating flows in more detail.

- The water quality simulation in the present research is based on limited available data and restricted to a rating curve method using records from a small selection of sampled storms. This approach should be extended to include additional storms through out the rainfall season to assess the variation of TP loading during the period of significant pollutant loading. Alternatively, attention could be focused on the more physically based approach to attempt to assess the buildup and washoff formulations necessary to simulate water quality in a more spatially representative way.

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APPENDIX A:

TABLE A-1.
SUMMARY OF EPA STORM WATER MANAGEMENT MODEL (SWMM) CHARACTERISTICS (HUBER AND ROESNER, 1992)

Applicable Land Drainage Area

(1) Urban.
(2) General non-urban.

Time Properties

(1) Single-event or continuous simulation; both modes have an unlimited number of time steps.
(2) Precipitation: input at arbitrary time intervals for single-event simulation (typically 1-15 min) and continuous simulation (typically 1-hr); for snowmelt daily max-min temperatures required for continuous, temperatures at arbitrary intervals for single-event.
(3) Output at time step intervals (or multiples); daily, monthly, annual, and total summaries for continuous simulation.
(4) Time step arbitrary for single-event (typically 5 minutes) and continuous (typically one hour); variable time step available in RUNOFF block; time step for Extended Transport block (EXTRAN) routing depends on stability criteria, may be as small as a few seconds.

Space Properties

(1) Small to large multiple catchments.
(2) Surface: lumped simulation of surface flow with allowance for up to 200 subcatchments and 10 input hyetographs, up to 200 channel/pipes may be simulated by non-linear reservoir routing.
(3) Channel/pipes: one-dimensional network, up to 200 conduit/non-conduit elements for TRANSPORT block, up to 200 conduits in EXTRAN block, up to 30 in-line storage units in TRANSPORT block. Values easily changed using Fortran Parameter statement.
(4) Catchment area may be disaggregated and modelled sequentially for simulation of areas too large for existing SWMM dimensions.
(5) Storage/treatment simulated separately, receiving input form upstream routing.
(6) Output from surface, channel/pipe, or storage/treatment simulation may serve as new input for further simulation by same or different blocks.

Physical Processes

(1) Flow derived from precipitation and/or snowmelt; snow accumulation and melt simulated using temperature-index methods developed by National Weather Service; snow redistribution (e.g., plowing, removal) may be simulated.
(2) Overland flow by non-linear reservoir using Manning's equation and lumped continuity, depression storage, integrated Horton or Green-Ampt infiltration (with optional subsurface routing), recovery of depression storage via evaporation between storms during continuous simulation, also exponential recovery of infiltration capacity.
(3) Subsurface routing only of flows through unsaturated and saturated zones simulated using lumped storage; subsurface outflow by power equation; simulation of ET and water table fluctuation.
(4) Channel/pipes:
(a) non-linear reservoir formulation for channel/pipes in RUNOFF block, includes translation and attenuation effects,

(b) modified kinematic wave formulation in original TRANSPORT block assumes cascade of conduits, cannot simulate backwater over more than one conduit length, surcharging handled by storing water at surcharged junction pending available flow capacity;
(c) Extended Transport (EXTRAN) block solves complete St. Venant equations including effects of backwater, flow reversal, surcharging, looped connections, pressure flow,
(d) infiltration and dry-weather flow may enter conduit of either transport simulation.
(5) Storage routing using modified Puls method assuming horizontal water surface, outlets include pumps, weirs, orifices.
(6) Surface quality on basis of linear or non-linear build-up of dust/dirt or other constituents during dry-weather and associated pollutant fractions, power-exponential washoff with decay parameter a power function of low rate only (rating curve); erosion by Universal Soil Loss Equation.
(7) Dry-weather flow quantity and quality on basis of diurnal and daily variation, population density and other demographic parameters, build-up of suspended solids in conduits by dry weather deposition using Shield's criterion.
(7) Quality routing by advection and mixing in conduits and by plug flow or complete mixing in storage units, scour and deposition of suspended solids in conduits (original TRANSPORT block) using Shield's criterion.
(8) Storage/treatment device simulated as series-parallel network of units, each with optional storage routing.
(9) Treatment simulation:
(a) use of arbitrary user-supplied removal equations (e.g., removal as exponential function of residence time);
(b) use of sedimentation theory coupled with particle size-specific gravity distribution for constituents.

Chemical Processes

(1) Ten arbitrary conservative constituents in RUNOFF block, rainfall quality included, choice of concentration
(2) units are arbitrary; erosion "sediment" is optional.
(3) Four constituents may be routed through the original transport module (with optional first order decay), three through the STORAGE module and none through EXTRAN (quantity only).

Biological Processes

(1) Coliform simulation may be included.
(2) Biological treatment may be simulated.

Mathematical Properties

(1) Physically based model.
(2) Surface quantity: iterative solution of coupled continuity and Manning equations, Green-Ampt or integrated form of Horton infiltration (infiltration rate proportional to cumulative infiltration, not time).
(3) Surface channel/pipe routing: non-linear reservoir assuming water surface parallel to invert.
(4) Channel/pipes:
(a) original TRANSPORT: implicit finite difference solution to modified kinematic wave equation;
(b) EXTRAN transport: explicit finite difference solution of complete St. Venant equations, stability may
(5) require short time step.

(6) Storage/detention: modified Puls method requires table look-up for calculation of outflow.
(7) Surface quality, quality routing and treatment: algebraic equations, no iterations required once flows and conduit volumes are known.

Input Data Requirements

(1) Historical or synthetic precipitation record; uses National Weather Service precipitation tapes for continuous simulation.
(2) Monthly or daily evaporation rates.
(3) For snowmelt: daily max-min (continuous) or time-step (single event) temperatures, monthly wind speeds, melt coefficients and base melt temperatures, snow distribution fractions and areal depletion curves (continuous only), other melt parameters.
(4) Surface quantity: area, imperviousness, slope, width, depression storage and Manning's roughness for pervious and impervious areas; Horton or Green-Ampt infiltration parameters.
(5) Subsurface quantity: porosity, field capacity, wilting point, hydraulic conductivity, initial water table elevation, ET parameters; coefficients for groundwater outflow as function of stage and tail water elevation.
(6) Channel/pipe quantity: linkages, shape, slope, length, Manning's roughness; EXTRAN transport also requires invert and ground elevation, storage volumes at manholes and other structures; geometric and hydraulic parameters for weirs, pumps, orifices, storage, etc.; infiltration rate into conduits.
(7) Storage/sedimentation quantity: stage-area-volume-outflow relationship, hydraulic characteristics of outflows.
(8) Surface quality (note: several parameters are optional, depending upon methods used): land use; total curb length; catchpit volume and initial pollutant concentrations; street sweeping interval, efficiency and availability factor; dry days prior to initial precipitation; dust/dirt and/or pollutant fraction parameters for each land use, or pollutant rating curve coefficients; initial pollutant surface loading; exponential and power washoff coefficients; concentrations in precipitation; erosion parameters for Universal Soil Loss Equation, if simulated.
(9) Dry-weather flow constant or on basis of diurnal and daily quantity/quality variations, population density, other demographic parameters.
(10)Optional particle size distribution, Shields parameter and decay coefficients for channel/pipe quality routing and scour/deposition routine.
(11)STORAGE: parameters defining pollutant removal equations; parameters for individual treatment options, e.g., particle size distribution, maximum flow rates, size of unit, outflow characteristics; optional dry-weather flow data when using continuous simulation.
(12)Storage/treatment costs: parameters for capital and operation and maintenance costs as function of flows, volumes and operating time.
(13)Data requirements for individual blocks much less than for run of whole model; large reduction in data requirements possible by aggregating (lumping) of subcatchments and channel/pipes, especially useful for continuous simulation.

Output and Output Format

(1) Input data summary including precipitation.
(2) Hydrographs and pollutographs (concentrations and loads versus time) at any point in system on time step or longer basis; no stages or velocities printed.
(3) EXTRAN transport also outputs elevation of hydraulic grade line.
(4) Surcharge volumes and required flow capacity; original transport model will resize conduits to pass required flow (optional).
(5) Stage, discharge and soil moisture content for subsurface routing in RUNOFF block.

(6) Removal quantities in Storage/treatment units, generated sludge quantities.
(7) Summaries of volumes and pollutant loads for simulation period, continuity check, initial and final pounds of solids in conduit elements.
(8) Daily (optional), monthly, annual and total summaries for continuous simulation, plus ranking of 50 highest time-step precipitation runoff and pollutant values.
(9) Line printer plots of hyetographs, hydrographs, and pollutographs.
(10)Costs of simulated Storage/treatment options.
(11)Statistical analysis of continuous (or single event) output for event separation, frequency analysis, moments and identification of critical events.

Linkages to Other Models

(1) Linkage provided to EPA WASP and DYNHYD receiving water quality models.
(2) Individual blocks and the total SWMM model have been linked to the HEC STORM model, the QUAL-II model, simplified receiving water models, and others.
(3) Individual blocks (e.g., RUNOFF block) have been altered by various groups.

Model Accuracy

(1) Quantity simulation may be made quite accurate with relatively little calibration.
(2) Quality simulation requires more extensive calibration using measured pollutant concentrations; quality results will almost certainly be very inaccurate without local measurements.
(3) EXTRAN transport accurately simulates backwater, flow reversal, surcharging, pressure flow; original transport routines may be used at less cost if these conditions not present.

Sensitivity to input parameters depend upon schematisation, however, surface quality predictions are most sensitive to pollutant loading rates.

TABLE A2:
EXPECTED PARAMETER SPACES FOR MAXIMUM PARAMETER SENSITIVITY – SUBCATCHMENT PARAMETERS

Parameter description in terms of catchments	SWMM code	SWMM line	Parameter space for max sensitivity	
			Duration	Intensity
%imp with zero detention	PCTZER	B4:1	Long	Low
width	WW(1)	H1:4	Short to Medium	Low to High
Area	WAREA	H1:5	Short to Long	Low to High
% imperviousness	WW(3)	H1:6	Long	Low
Slope	WSLOPE	H1:7	Short to Long	Low to High
Impervious Manning's "n"	WW(5)	H1:8	Long	Low
Pervious Manning's "n"	WW(6)	H1:9	Short	Medium
Impervious storage depth	WSTORE1	H1:10	Long	Low
Pervious storage depth	WSTORE2	H1:11	Short	Medium
Max infiltration rate	WLMAX	H1:12	Short	Medium
Minimum infiltration rate	WLMIN	H1:13	Short	Medium
Average capillary suction	SUCT	H1:12	Short	Medium
Sat. hydraulic conductivity	HYDCON	H1:13	Short	Medium

TABLE A3:
EXPECTED PARAMETER SPACES FOR MAXIMUM PARAMETER SENSITIVITY – CONVEYANCE ROUTING PARAMETERS

Routing parameter description	SWMM code	SWMM line	Parameter space for max sensitivity	
			Duration	Intensity
Channel width (diameter)	GWIDTH	G1:4	Short to Long	Medium to High
Channel length	GLEN	G1:5	Short to Long	Medium to High
Channel slope	G3	G1:6	Short to Long	Medium to High
Channel roughness	G6	G1:9	Short to Long	Medium to High
Channel starting depth	GDEPTH	G1:11	Short to Long	Medium to High

TABLE A4:
EXPECTED PARAMETER SPACES FOR MAXIMUM PARAMETER SENSITIVITY – GROUNDWATER PARAMETERS

Description in terms of GW	SWMM code	SWMM line	Parameter space for max sensitivity	
			Duration	Intensity
Groundwater flow coefficient	A1	H3:1	Long	Low
Groundwater flow exponent	B1	H3:2	Long	Low
Coefficient for channel water influence	A2	H3:3	Long	Low
Exponent for channel water influence	B2	H3:4	Long	Low
Coefficient for the cross product between groundwater flow and channel water	A3	H3:5	Long	Low
Porosity	POR	H3:6	Long	Low
Wilting point	WP	H3:7	Long	Low
Field capacity	FC	H3:8	Long	Low
Saturated hydraulic conductivity	HKSAT	H3:9	Long	Low
Initial upper zone moisture	TH1	H3:10	Long	Low
Hydraulic conductivity vs. moisture content curve-fitting parameter	HCO	H4:1	Long	Low
Average slope of tension versus soil moisture curve	PCO	H4:2	Long	Low

APPENDIX B:

TABLE B1:
FLOW ROUTING CHARACTERISTICS OF RUNOFF, TRANSPORT AND EXTRAN MODULES (JAMES & JAMES, 1997)

	RUNOFF	TRANSport	EXTRAN
Flow Routing method	Non-linear reservoir, cascade of conduits	Kinematic wave, cascade of conduits	Complete equations, interactive conduit network
Computational expense for identical networks	Low	Moderate	High
Attenuation of hydrograph peak	Yes	Yes	Yes
Time displacement of hydrograph peaks	Weak	Yes	Yes
In-conduit storage	Yes	Yes	Yes
Backwater of downstream control effects	No	No	Yes
Flow reversal	No	No	No
Surcharge	Weak	Weak	Yes
Pressure flow	No	No	Yes
Branching tree network	Yes	Yes	Yes
Looped connections	No	No	No
No. opf preprogrammed conduit shapes	3	16	8
Alternative hydraulic elements	No	Yes	Yes
Dry weather and base flow	No	Yes	Yes
Pollutograph routing	Yes	Yes	Yes
Solids scour/deposition	No	Yes	No
Input hydrographs	No	Yes	Yes

APPENDIX C:

TABLE C1:
STORM CHARACTERISTICS OF LOTUS RIVER CATCHMENT DURING SAMPLING PERIOD JULY 1997 TO OCTOBER 1998

Storm No	Date	Start Hour	Dur-ation hours	Volume millim	Ave Inten mm/hr	Max Inten mm/hr	Inter-event hours	Hours Missing Data	Hours Meter Stuck
--	----	----	-----	------	-----	-----	-----	----	-----
1	7/ 2/97	0	3.	2.99	1.00	5.75	Undef	0	0
2	7/16/97	19	2.	0.40	0.20	1.40	352.	0	0
3	7/19/97	14	17.	0.36	0.02	0.82	65.	0	0
4	7/23/97	7	47.	7.59	0.16	8.24	72.	0	0
5	8/ 1/97	16	5.	12.80	2.56	18.79	178.	0	0
6	8/ 3/97	16	30.	23.31	0.78	18.40	43.	0	0
7	8/ 6/97	10	7.	6.59	0.94	12.32	36.	0	0
8	8/ 8/97	8	2.	0.19	0.10	0.66	39.	0	0
9	8/10/97	6	5.	0.38	0.08	0.80	44.	0	0
10	8/12/97	5	8.	0.15	0.02	0.08	42.	0	0
11	8/18/97	16	27.	11.51	0.43	20.30	147.	0	0
12	8/21/97	6	48.	8.61	0.18	3.43	35.	0	0
13	8/27/97	10	3.	0.20	0.07	0.48	100.	0	0
14	8/29/97	10	44.	8.28	0.19	4.80	45.	0	0
15	9/ 3/97	2	8.	5.38	0.67	8.85	68.	0	0
16	9/ 6/97	8	2.	0.40	0.20	1.15	70.	0	0
17	10/ 5/97	0	53.	8.86	0.17	11.60	686.	0	0
18	10/11/97	2	1.	0.20	0.20	0.80	93.	0	0
19	10/26/97	5	4.	6.59	1.65	16.50	362.	0	0
20	11/ 9/97	1	4.	3.60	0.90	8.13	328.	0	0
21	11/15/97	23	41.	31.61	0.77	44.80	162.	0	0
22	11/20/97	18	41.	6.26	0.15	4.25	74.	0	0
23	11/23/97	8	21.	2.76	0.13	4.01	21.	0	0
24	12/ 2/97	8	23.	5.96	0.26	20.00	195.	0	0
25	12/16/97	9	39.	3.67	0.09	6.38	314.	0	0
26	1/ 8/98	23	20.	6.32	0.32	3.85	527.	0	0
27	1/12/98	23	3.	1.80	0.60	4.00	76.	0	0
28	3/ 9/98	9	48.	4.34	0.09	7.21	1327.	0	0
29	3/17/98	3	9.	7.16	0.80	16.80	138.	0	0
30	4/ 4/98	22	9.	9.77	1.09	15.20	442.	0	0
31	4/ 7/98	16	3.	0.79	0.26	2.52	57.	0	0
32	4/21/98	2	38.	21.24	0.56	20.00	319.	0	0
33	4/25/98	22	1.	1.00	1.00	4.00	78.	0	0
34	5/ 2/98	3	15.	1.18	0.08	2.55	148.	0	0
35	5/ 4/98	17	157.	83.16	0.53	34.40	47.	0	0
36	5/18/98	11	17.	4.71	0.28	8.00	173.	0	0
37	5/27/98	11	14.	17.77	1.27	27.30	199.	0	0
38	6/ 1/98	8	9.	13.39	1.49	25.40	103.	0	0
39	6/ 3/98	17	17.	13.73	0.81	10.64	48.	0	0
40	6/ 5/98	22	30.	6.10	0.20	4.97	36.	0	0
41	6/ 9/98	23	5.	0.39	0.08	0.64	67.	0	0
42	6/15/98	22	13.	4.97	0.38	2.79	138.	0	0
43	6/19/98	0	3.	0.59	0.20	0.86	61.	0	0
44	6/26/98	8	14.	4.96	0.35	11.20	173.	0	0
45	7/ 1/98	8	11.	3.95	0.36	8.82	106.	0	0
46	7/ 2/98	18	19.	11.75	0.62	14.44	23.	0	0
47	7/ 4/98	9	19.	6.33	0.33	14.46	20.	0	0
48	7/ 6/98	15	43.	41.97	0.98	74.40	35.	0	0
49	7/ 9/98	11	1.	0.20	0.20	0.80	25.	0	0
50	7/15/98	12	42.	27.89	0.66	27.20	144.	0	0
51	7/28/98	2	28.	5.96	0.21	15.42	260.	0	0
52	8/ 3/98	16	10.	11.19	1.12	25.20	130.	0	0

```
   53  8/ 6/98   16     13.    3.39    0.26   8.00     62.     0        0
   54  8/12/98   21     53.   16.17    0.31  14.39    136.     0        0
   55  8/20/98   22     44.    9.72    0.22  12.51    140.     0        0
   56  9/ 3/98    3     30.    7.29    0.24  11.46    273.     0        0
   57  9/10/98    2      1.    0.40    0.40   1.60    137.     0        0
   58  9/20/98   13    112.   16.11    0.14  12.65    250.     0        0
   59  9/27/98    3     18.    2.90    0.16   2.40     46.     0        0
   60 10/ 5/98   12      4.    2.19    0.55   4.92    183.     0        0
   61 10/11/98    5     43.    7.16    0.17  11.43    133.     0        0
 Total                       377.97                            0        0

      **************************************
      *         Precipitation Summary      *
      **************************************

      Rainfall summary for station         CTWO
      Total missing hours                     0  hours
      Total hours of meter malfunction        0  hours
      Total rainfall                     536.63  millimeters
      Total number of years                   2  years


Rainfall Statistics by Storm (for period of record)
        Number      Total   Minimum    Maximum    Average    Coef-Var
        ------      -----   -------    -------    -------    --------
Duration      60.    1358.00      1.000   157.000     22.633      1.179
Intensity     60.      29.05      0.019     2.559      0.484      0.973
Volume        60.     529.48      0.152    83.165      8.825      1.448
Delta         59.   11052.50     38.000  1352.500    187.331      1.090


     Rainfall Statistics by Year  (for period of record)
         Number      Total   Minimum    Maximum    Average    Coef-Var
         ------      -----   -------    -------    -------    --------

1997

Duration      25.     485.00      1.000    53.000     19.400      0.936
Intensity     25.      11.91      0.019     2.559      0.476      1.249
Volume        25.     158.66      0.152    31.613      6.346      1.180
Delta         24.    4035.00     43.500   713.500    168.125      0.935
Months         5.     158.66      9.260    64.603     31.732      1.050


1998

Duration      35.     873.00      1.000   157.000     24.943      1.261
Intensity     35.      17.15      0.078     1.488      0.490      0.750
Volume        35.     370.82      0.200    83.165     10.595      1.451
Delta         35.    7017.50     38.000  1352.500    200.500      1.159
Months         9.     370.82      6.143   119.045     41.202      1.381
```

APPENDIX D:
SWMM DATA FILES

TABLE D1 : RAIN DATA FILE

```
*     Call the Rain Block to generate Precipitation file
$RAIN
A1   ' Lotus'
A1   ' STATION 10001'
B0   0       0       1
*   IFORM       ISTA  IDECID      IYBEG  IYEND   IYEAR  ISUM      MIT
NPTS   IFILE       A   NOSTAT
B1    3         10001   1         970701  981013  1        1         1
0       0       0       1111
B2    15.0    1        0         '(i8,5i8,f11.4)' 1.0     1         2
3       4       5       6       7
$ENDPROGRAM
```

TABLE D2 : RUNOFF DATA FILE

```
$NOQUOTE
$ANUM
*============================================================================
$RUNOFF
*============================================================================
A1   'RUNOFF  -  Great Lotus   River   Catchment'
A1   ''
*============================================================================
*   METRIC ISNOW   NRGAG   INFILM  KWALTY  IVAP    NHR     NMN     NDAY    MONTH   IYRSTR
B1   1       0       1       0       1       3       0       0       01      07      97
*============================================================================
*       B2          Line    :
*============================================================================
*       IPRN(1)     IPRN(2) IPRN(3) IRPNGW
B2   0       1       2       10000
*============================================================================
*       WET         WET/DRY DRY     LUNIT   LONG
B3   900     1800    86400   4       981012
*============================================================================
*       ROPT
D1   1
*============================================================================
*       EVAPORATION DATA    for     Cape    Flats   TreatmenWorks   (Jan        1997to      Dec         1997)
F1   97      24
F2   266.4   224.5   161.4   95.7    54.7    38.9    54.5    44.9    132.4   164     207.5   222.2
F2   252.4   208     134.5   94.4    28.1    22.3    39.1    78.6    117.3   156     178.7   218.1
*============================================================================
*       NAMEG       NGTO    NPG     GWIDTH  GLEN    G3      GS1     GS2     G6      DFULL   GDEPTH
*
*       Airport     Industria
G1   'AI1'   'GIBM3' 2       2.1     120     0.005   0       0       0.018   0       0
G1   'AI2'   'GIBM3' 2       2.5     1330    0.0033  0       0       0.018   0       0
*
*       Nyanga   pipework
G1   'FEN0'  'FEN1'  2       0.375   69      0.004   0       0       0.018   0       0
```

```
G1   'FEN1'   'FEN2'   2       0.525   261     0.001   0      0      0.018   0      0
G1   '3RD3'   'FEN2'   2       0.375   58      0.003   0      0      0.018   0      0
G1   'FEN2'   'FEN3'   2       0.6     242     0.001   0      0      0.018   0      0
G1   'FEN3'   'TERM10' 2        0.75    306     0.001   0      0      0.018   0      0
G1   'TERM10' 'TERM11' 2         1.05    45      0.003   0      0      0.018   0      0
G1   'ZWS2'   'ZWS3'   2       0.6     75      0.0021  0      0      0.018   0      0
G1   'ZWS3'   'ZWS3A'  2       0.6     20      0.0021  0      0      0.018   0      0
G1   '3RD1'   '3RD2'   2       0.45    143     0.002   0      0      0.018   0      0
G1   'ZWS4'   '3RD2'   2       0.45    220     0.002   0      0      0.018   0      0
G1   '3RD2'   '3RD2A'  2       0.825   35      0.0057  0      0      0.018   0      0
G1   'EMS0'   'EMS1'   2       0.45    203     0.0024  0      0      0.018   0      0
G1   'EMS1'   'EMS2'   2       0.525   217     0.004   0      0      0.018   0      0
G1   'EMS2'   'EMS3'   2       1.2     179     0.0013  0      0      0.018   0      0
G1   '4TH1'   'EMS3'   2       0.45    184     0.006   0      0      0.018   0      0
G1   'EMS3'   'EMS4'   2       1.338   50      0.001   0      0      0.018   0      0
G1   'EMS4'   'BKS1'   2       0.9     4       0.1429  0      0      0.018   0      0
G1   'TERM8'  'TERM9'  2       1.05    38      0.001   0      0      0.018   0      0
G1   'TERM9'  'TERM10' 2        1.05    125     0.002   0      0      0.018   0      0
G1   'GTD1'   'GTD2'   2       0.375   149     0.0028  0      0      0.018   0      0
G1   'GTD2'   'GTD3'   2       0.525   149     0.0023  0      0      0.018   0      0
G1   'GTD3'   'GTD4'   2       0.675   153     0.001   0      0      0.018   0      0
G1   'NTL1'   'NTL2'   2       0.3     70      0.0051  0      0      0.018   0      0
G1   'NTL2'   'NTL3'   2       0.375   70      0.0051  0      0      0.018   0      0
G1   'NTL3'   'NTL4'   2       0.45    65      0.0039  0      0      0.018   0      0
G1   'NTL4'   'NTL5'   2       0.525   70      0.0046  0      0      0.018   0      0
G1   'NTL5'   'GTD4'   2       0.675   255     0.0022  0      0      0.018   0      0
G1   'GTD4'   'TERM7'  2       1.05    236     0.001   0      0      0.018   0      0
G1   'SAK1'   'TERM1'  2       0.3     245     0.005   0      0      0.018   0      0
G1   'TERM1'  'TERM2'  2       0.825   68      0.0032  0      0      0.018   0      0
G1   'TERM2'  'TERM3'  2       0.825   68      0.0029  0      0      0.018   0      0
G1   'TERM3'  'TERM4'  2       0.825   67      0.004   0      0      0.018   0      0
G1   'ZWN1'   'TERM4'  2       1.05    22      0.0011  0      0      0.018   0      0
G1   'ZWN2'   'ZWN1'   2       0.9     24      0.002   0      0      0.018   0      0
G1   'ZWN3'   'ZWN2'   2       0.9     64      0.0024  0      0      0.018   0      0
G1   'ZWN4'   'ZWN3'   2       0.825   43      0.0025  0      0      0.018   0      0
G1   'ZWN5'   'ZWN4'   2       0.825   50      0.0025  0      0      0.018   0      0
```

```
G1   'ZWN6'   'ZWN5'   2       0.825   37      0.0025  0       0       0.018   0       0
G1   'TERM4'  'TERM4A' 2        1.2     25      0.0036  0       0       0.018   0       0
G1   'TERM5'  'TERM6'  2       1.2     75      0.0016  0       0       0.018   0       0
G1   'TERM6'  'TERM7'  2       1.05    117     0.0052  0       0       0.018   0       0
G1   'TERM7'  'TERM8'  2       1.2     145     0.0039  0       0       0.018   0       0
G1   'NY1'    'NY2'    2       0.375   169     0.007   0       0       0.018   0       0
G1   'NY2'    'NY3'    2       0.525   228     0.01    0       0       0.018   0       0
G1   'NY3'    'NY4'    2       0.675   153     0.002   0       0       0.018   0       0
G1   'MBW1'   'NY4'    2       0.375   50      0.02    0       0       0.018   0       0
G1   'NY4'    'NY5'    2       0.75    150     0.002   0       0       0.018   0       0
G1   'JKL1'   'JKL2'   2       0.45    216     0.0049  0       0       0.018   0       0
G1   'JKL2'   'JKL3'   2       0.525   38      0.011   0       0       0.018   0       0
G1   'JKL3'   'JKL4'   2       0.62    217     0.006   0       0       0.018   0       0
G1   'NY5'    'NY6'    2       0.75    120     0.002   0       0       0.018   0       0
G1   'JKL4'   'NY6'    2       0.675   236     0.014   0       0       0.018   0       0
G1   'NY6'    'TERM14' 2       1.05    112     0.002   0       0       0.018   0       0
G1   'TERM11' 'TERM12' 2       1.2     250     0.005   0       0       0.018   0       0
G1   'TERM12' 'TERM13' 2       1.2     240     0.005   0       0       0.018   0       0
G1   'TERM13' 'TERM13A' 2      1.2     8       0.013   0       0       0.018   0       0
G1   'TERM14' 'TERM15' 2       1.2     282     0.0016  0       0       0.018   0       0
G1   'ZWS3A'  '3RD2'   2       0.825   206     0.0021  0       0       0.018   0       0
G1   'ZWN7'   'ZWN6'   2       0.75    16      0.0025  0       0       0.018   0       0
G1   'ZWN8'   'ZWN7'   2       0.75    32      0.0025  0       0       0.018   0       0
G1   'ZWN9'   'ZWN8'   2       0.675   54      0.0024  0       0       0.018   0       0
G1   'ZWN10'  'ZWN9'   2       0.6     55      0.0057  0       0       0.018   0       0
G1   'ZWN11'  'ZWN10'  2       0.6     55      0.0037  0       0       0.018   0       0
G1   'ZWN13'  'TERM4'  2       0.6     160     0.0018  0       0       0.018   0       0
G1   '2ND1'   'ZWS3'   2       0.3     130     0.0033  0       0       0.018   0       0
G1   'XRD2'   'TERM0'  2       0.45    52      0.0044  0       0       0.018   0       0
G1   'XRD1'   'TERM0'  2       0.45    13      0.01    0       0       0.018   0       0
G1   'TERM0'  'TERM1'  2       0.525   175     0.0043  0       0       0.018   0       0
G1   'TERM4A' 'TERM5'  2       1.2     25      0.0016  0       0       0.018   0       0
G1   'BKS1'   'BKS2'   2       1.05    95      0.0022  0       0       0.018   0       0
G1   'BKS2'   'BKS3'   2       1.05    33      0.0024  0       0       0.018   0       0
G1   'BKS3'   'BKS4'   2       1.05    85      0.0012  0       0       0.018   0       0
G1   'BKS4'   'TERM8'  2       1.05    44      0.001   0       0       0.018   0       0
```

```
G1   'MAH1'  'XRD1'  2       0.45    200     0.0036  0       0       0.018   0       0
*G1  'EMS4A' 'TERM8'   2     1.05    257     0.0021  0       0       0.018   0       0
G1   '3RD2A' '3RD2B' 2       1.05    182     0.0015  0       0       0.018   0       0
G1   '3RD2B' 'EMS2'  2       1.05    200     0.0029  0       0       0.018   0       0
G1   'TERM13A' 'TERM14' 2    1.2     235     0.01    0       0       0.018   0       0
G1   'TERM15' 'TERM16' 2     1.2     9       0.0077  0       0       0.018   0       0
G1   'TERM16' 'GIBM14' 2     1.2     36      0.0067  0       0       0.018   0       0
*G1  'OVTRM14' '5011'  2     0.9     20      0.0225  0       0       0.018   0       0
G1   '4TH2'  '4TH1'  2       0.45    147     0.004   0       0       0.018   0       0
G1   '3RD'   '3RD1'  2       0.45    44      0.005   0       0       0.018   0       0
*       Nyanga continued
G1   'NK1'   'NC1'   2       0.375   188     0.0075  0       0       0.018   0       0
G1   'NC1'   'NK2'   2       0.375   97      0.0054  0       0       0.018   0       0
G1   'NK2'   'ZWL1'  2       0.45    201     0.0095  0       0       0.018   0       0
G1   'ZWL1'  'ZWL2'  2       0.6     57      0.027   0       0       0.018   0       0
G1   'ZWL2'  'ZWL3'  2       0.6     49      0.0167  0       0       0.018   0       0
G1   'ZWL3'  'NY8'   2       0.6     49      0.04    0       0       0.018   0       0
G1   'NY8'   'OUT2A' 2       0.9     25      0.0133  0       0       0.018   0       0
G1   'NY7'   'NY8'   2       0.9     192     0.005   0       0       0.018   0       0
G1   'NON1'  'LOY1'  2       0.3     208     0.0112  0       0       0.018   0       0
G1   'LOY1'  'LOY2'  2       0.45    107     0.0217  0       0       0.018   0       0
G1   'LOY2'  'NY9'   2       0.45    62      0.02    0       0       0.018   0       0
G1   'DAV1'  'DAV2'  2       0.375   237     0.007   0       0       0.018   0       0
G1   'DAV2'  'NY9'   2       0.45    294     0.001   0       0       0.018   0       0
G1   'NY9'   'OUT2A' 2       0.75    135     0.0056  0       0       0.018   0       0
G1   'OUT2A' 'OUT2B' 2       1.05    80      0.0034  0       0       0.018   0       0
G1   'OUT2B' 'OUT2D' 2       1.01    80      0.0024  0       0       0.018   0       0
G1   'OUT2C' 'OUT2B' 2       0.45    42      0.005   0       0       0.018   0       0
G1   'OUT2D' 'GIBM19' 2      1.05    337     0.002   0       0       0.018   0       0
*       Nyanga(1153)
G1   'KNF1'  'KNF2'  2       0.375   48      0.02    0       0       0.018   0       0
G1   'KNF2'  'KNF3'  2       0.525   56      0.0127  0       0       0.018   0       0
G1   'TOM1'  'TOM2'  2       0.375   155     0.0041  0       0       0.018   0       0
G1   'TOM2'  'TOM3'  2       0.45    87      0.012   0       0       0.018   0       0
G1   'TOM3'  'TOM4'  2       0.375   95      0.0058  0       0       0.018   0       0
G1   'TOM4'  'KNF3'  2       0.525   86      0.0064  0       0       0.018   0       0
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G1   'KNF3'   'KNF4'   2      0.675  147    0.0054 0     0     0.018  0     0
G1   'KNF4'   'NY10'   2      0.825  198    0.0053 0     0     0.018  0     0
G1   'MCP1'   'NON2'   2      0.375  154    0.0123 0     0     0.018  0     0
G1   'NON2'   'NON3'   2      0.45   36     0.0061 0     0     0.018  0     0
G1   'NON3'   'NON4'   2      0.525  62     0.0029 0     0     0.018  0     0
G1   'NON4'   'KNF4'   2      0.6    114    0.006  0     0     0.018  0     0
G1   'NDA1'   'NTLK1'  2      0.45   56     0.0078 0     0     0.018  0     0
G1   'NTLK1'  'NTLK2'  2      0.45   67     0.0043 0     0     0.018  0     0
G1   'NTLK2'  'MND2'   2      0.525  54     0.0048 0     0     0.018  0     0
G1   'MND1'   'MND2'   2      0.375  68     0.0099 0     0     0.018  0     0
G1   'MND2'   'NY10'   2      0.6    67     0.0091 0     0     0.018  0     0
G1   'NY10'   'NSA'    2      0.9    102    0.0101 0     0     0.018  0     0
G1   'NSA'    'NSB'    2      0.9    140    0.0041 0     0     0.018  0     0
G1   'NSB'    'NSC'    2      0.9    164    0.005  0     0     0.018  0     0
G1   'NSC'    'NSD'    2      0.9    101    0.0071 0     0     0.018  0     0
G1   'NSD'    'NSE'    1      1.8    300    0.0012 0     0     0.018  0.6   0
G1   'NSE'    'GIBM22' 1      1.8    250    0.0024 0     0     0.018  0.6   0
G1   'NY531'  'NY532'  2      0.4    245    0.0025 0     0     0.018  0     0
G1   'NY532'  'NY533'  2      0.45   27     0.003  0     0     0.018  0     0
G1   'NY533'  'NY534'  2      0.6    65     0.003  0     0     0.018  0     0
G1   'NY534'  'GIBM22' 2      0.7    72     0.003  0     0     0.018  0     0
G1   'NY11A'  'GIBM22' 2      0.45   200    0.005  0     0     0.018  0     0
*      Nyanga/G        -1154
G1   'NY3A'   'NY3B'   2      0.45   240    0.005  0     0     0.018  0     0
G1   'NY3B'   'NY3C'   2      0.425  145    0.005  0     0     0.018  0     0
G1   'NY3C'   'NY3E'   2      0.55   37     0.005  0     0     0.018  0     0
G1   'NY3D'   'NY3E'   2      0.45   100    0.005  0     0     0.018  0     0
G1   'NY3E'   'NY3F'   2      0.6    94     0.005  0     0     0.018  0     0
G1   'NY3F'   'NY33'   2      0.75   134    0.005  0     0     0.018  0     0
G1   'NY31'   'NY32'   2      0.55   220    0.005  0     0     0.018  0     0
G1   'NY32'   'NY33'   2      0.8    180    0.005  0     0     0.018  0     0
G1   'PHO0'   'NY33'   2      0.45   167    0.0018 0     0     0.018  0     0
G1   'NY33'   'GIBM24' 2      1      400    0.005  0     0     0.018  0     0
G1   'PHO1'   'PHO4'   2      0.35   106    0.0028 0     0     0.018  0     0
G1   'PHO2'   'PHO3'   2      0.45   140    0.003  0     0     0.018  0     0
G1   'PHO3'   'PHO4'   2      0.45   280    0.0029 0     0     0.018  0     0
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G1   'PHO4'  'GIBM24' 2      0.45    67      0.0018  0       0       0.018   0       0
G1   'MIL1'  'MIL2'  2       0.6     630     0.0022  0       0       0.018   0       0
G1   'MIL2'  'MIL3'  2       0.6     33      0.0022  0       0       0.018   0       0
G1   'MIL3'  'MIL4'  1       0.84    324     0.0022  0       0       0.018   0.5     0
G1   'MIL4'  'GIBM7' 2       0.525   943     0.0048  0       0       0.018   0       0
*============================================================================
*       Cross Roads stormwater network
G1   'KPN0'  'KPN1'  2       0.3     100     0.004   0       0       0.018   0       0
G1   'KPN1'  'KPN2'  2       0.375   117.27  0.004   0       0       0.018   0       0
G1   'KPN2'  'CPA1'  2       0.45    104.1   0.004   0       0       0.018   0       0
G1   'KPN2A' 'CPA1'  2       0.45    15      0.02326 0       0       0.018   0       0
G1   'CPA1'  'CPA2'  2       0.45    86      0.00244 0       0       0.018   0       0
G1   'CPA2'  'CPA3'  2       0.45    192.7   0.00244 0       0       0.018   0       0
G1   'CPA3'  'CPA4'  2       0.45    133     0.002857 0      0       0.018   0       0
G1   'CPA4'  'TRY1'  2       0.45    105.85  0.002857 0      0       0.018   0       0
G1   'CRD8'  'CRD61' 2       0.375   42.26   0.008333 0      0       0.018   0       0
G1   'CRD61' 'CRD63' 2       0.45    88.61   0.00565 0       0       0.018   0       0
G1   'CRD62' 'CRD63' 2       0.375   31.5    0.018182 0      0       0.018   0       0
G1   'CRD63' 'CRD42' 2       0.525   81      0.001887 0      0       0.018   0       0
G1   'CRB50' 'CRB51' 2       0.375   22.71   0.005682 0      0       0.018   0       0
G1   'CRB51' 'CRB52' 2       0.375   17.36   0.004   0       0       0.018   0       0
G1   'CRB52' 'CRD40' 2       0.375   45      0.01282 0       0       0.018   0       0
G1   'CRD40' 'CRD41' 2       0.45    90.34   0.006024 0      0       0.018   0       0
G1   'CRD41' 'CRD42' 2       0.45    36.16   0.005714 0      0       0.018   0       0
G1   'CRD42' 'CRJ1'  2       0.6     88.21   0.002   0       0       0.018   0       0
G1   'CRD10' 'CRD11' 2       0.3     28.01   0.004   0       0       0.018   0       0
G1   'CRD11' 'CRD12' 2       0.375   73.1    0.004   0       0       0.018   0       0
G1   'CRD12' 'CRJ1'  2       0.45    50.1    0.01    0       0       0.018   0       0
G1   'CRJ1'  'TRY2'  2       0.6     19      0.00222 0       0       0.018   0       0
G1   'KLP0'  'KLP1'  2       0.3     34      0.003971 0      0       0.018   0       0
G1   'KLP1'  'KLP2'  2       0.45    44      3.86E-03 0      0       0.018   0       0
G1   'KLP2'  'KLP3'  2       0.375   6.5     5.23E-03 0      0       0.018   0       0
G1   'KLP2A' 'KLP3'  2       0.375   10      0.005   0       0       0.018   0       0
G1   'KLP3'  'KLP4'  2       0.375   70.17   0.004   0       0       0.018   0       0
G1   'KLP4'  'KLP5'  2       0.45    51.3    0.00426 0       0       0.018   0       0
G1   'KLP5'  'KLP6'  2       0.45    46.5    0.005   0       0       0.018   0       0
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G1   'KLP6'   'KLP7'   2        0.45    46.5    0.005    0        0        0.018   0        0
G1   'KLP6A'  'KLP7'   2        0.3     32.4    0.00145  0        0        0.018   0        0
G1   'KLP7'   'KLP8'   2        0.525   56.06   0.00602  0        0        0.018   0        0
G1   'KLP8'   'KLP9'   2        0.6     39.1    0.00263  0        0        0.018   0        0
G1   'KLP9A'  'KLP9'   2        0.3     33.22   0.01     0        0        0.018   0        0
G1   'KLP9'   'KLP11'  2        0.675   109.04  0.00235  0        0        0.018   0        0
G1   'KLP10'  'KLP11'  2        0.375   78.5    0.00893  0        0        0.018   0        0
G1   'KLP11'  'KLP12'  2        0.675   27.65   0.004    0        0        0.018   0        0
G1   'KLP12'  'KLP17'  2        0.675   49.5    0.004    0        0        0.018   0        0
G1   'KLP13'  'KLP14'  2        0.375   70.82   0.00833  0        0        0.018   0        0
G1   'KLP14'  'KLP15'  2        0.375   44.61   0.004    0        0        0.018   0        0
G1   'KLP15'  'KLP16'  2        0.45    90      0.004    0        0        0.018   0        0
G1   'KLP16'  'KLP17'  2        0.45    34.2    0.00725  0        0        0.018   0        0
G1   'KLP17'  'KLP18'  2        0.675   44      0.004    0        0        0.018   0        0
G1   'KLP18'  'KLP18B' 2        0.675   70.65   0.00333  0        0        0.018   0        0
G1   'KLP18A' 'KLP18B' 2        0.675   32.09   0.00503  0        0        0.018   0        0
G1   'KLP18B' 'CRC1'   2        0.675   30.32   0.00333  0        0        0.018   0        0
G1   'KLP19'  'CRC1'   2        0.375   69.47   0.00893  0        0        0.018   0        0
G1   'CRC1'   'CRC2'   2        0.675   94.21   0.0044   0        0        0.018   0        0
G1   'CRC2'   'CRC3'   2        0.675   62.81   0.00391  0        0        0.018   0        0
G1   'CRC3'   'CRC4'   2        0.675   76.98   0.00412  0        0        0.018   0        0
G1   'CRC4'   'CRC5'   2        0.75    94.48   0.00284  0        0        0.018   0        0
G1   'A1'     'A5'     2        0.375   76.74   0.004    0        0        0.018   0        0
G1   'A2'     'A3'     2        0.3     66.24   0.004    0        0        0.018   0        0
G1   'A3'     'A4'     2        0.375   22.43   0.00303  0        0        0.018   0        0
G1   'A4'     'A5'     2        0.45    39.2    0.00244  0        0        0.018   0        0
G1   'A5'     'A6'     2        0.45    81.41   0.00244  0        0        0.018   0        0
G1   'A5A'    'A6'     2        0.45    82.53   0.00485  0        0        0.018   0        0
G1   'A6A'    'A7'     2        0.3     35.44   0.004    0        0        0.018   0        0
G1   'A6'     'A7'     2        0.45    42.56   0.00714  0        0        0.018   0        0
G1   'CRC5'   'CRC6'   2        0.75    66.16   0.00293  0        0        0.018   0        0
G1   'CRC6'   'CRC7'   2        0.75    23.91   0.00264  0        0        0.018   0        0
G1   'CRC7'   'CRC8'   2        0.75    30.18   0.002857 0        0        0.018   0        0
G1   'CRC8'   'CRC9'   2        0.825   16.25   0.00271  0        0        0.018   0        0
G1   'CRC9'   'TRY3'   2        0.825   56.39   0.002695 0        0        0.018   0        0
G1   'A7'     'A8'     2        0.45    151.28  0.004717 0        0        0.018   0        0
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G1    'A8'     'N1'     2        0.45     20.9     0.006452 0       0         0.018    0        0
G1    'N1'     'NOUT'   2        1.2      351.59   0.001238 0       0         0.018    0        0
G1    'NOUT'   'MHOUT'  2        1.2      9        0.001222 0       0         0.018    0        0
G1    'CR4H1'  'CR4H2'  2        0.375    48.5     0.01794  0       0         0.018    0        0
G1    'CR4H2'  'CR4H3'  2        0.45     41.5     0.00542  0       0         0.018    0        0
G1    'CR4H3'  'CR4H4'  2        0.525    93       0.005419 0       0         0.018    0        0
G1    'CR4H4'  'CR4H5'  2        0.525    36.75    0.005388 0       0         0.018    0        0
G1    'CR4L'   'CR4H5'  2        0.375    95       0.022379 0       0         0.018    0        0
G1    'CR4H5'  'CR4H6'  2        0.6      85       0.005459 0       0         0.018    0        0
G1    'CR4H6'  'CR4H7'  2        0.675    127      0.006551 0       0         0.018    0        0
G1    'CR4H7'  'CR4H8'  2        1.05     82.5     8.24E-04 0       0         0.018    0        0
G1    'CR4J'   'CR4H7'  2        0.45     125      0.02763  0       0         0.018    0        0
G1    'HW2'    'SW1312' 2        0.6      11.76    0.01     0       0         0.018    0        0
G1    'SW1312' 'SW1210' 2        0.9      37.35    0.001    0       0         0.018    0        0
G1    'SW1210' 'SW109'  2        0.9      151.3    0.001    0       0         0.018    0        0
G1    'SW109'  'SW98'   2        1.05     79.1     0.001    0       0         0.018    0        0
G1    'SW98'   'SW86'   2        1.05     83.12    0.001    0       0         0.018    0        0
G1    'SW86'   'CR4H7'  2        1.05     86.02    0.001    0       0         0.018    0        0
G1    'CR4H8'  'CR4H9'  2        1.05     210      0.0008   0       0         0.018    0        0
G1    'CR4H9'  'CR4H10' 2        1.05     93.8     0.001236 0       0         0.018    0        0
G1    'CR4H10' 'CRDE3'  2        1.05     64.82    0.0008   0       0         0.018    0        0
G1    'CRDE3'  'CRDE2'  2        1.05     80.2     0.0008   0       0         0.018    0        0
G1    'CRDE2'  'CRDE1'  2       1.05     84.88    0.001236 0        0         0.018    0        0
G1    'CRDE1'  'N1'     2       1.2      11.43    0.001236 0        0         0.018    0        0
G1    'TRY1'   'TRY2'   2        0.9      116      0.00124  0       0         0.018    0        0
G1    'TRY2'   'TRY3'   2        0.9      488      0.00124  0       0         0.018    0        0
G1    'TRY3'   'NOUT'   2        0.9      258      0.00124  0       0         0.018    0        0
*=============================================================================
*=============================================================================
*       Philippi East Stormwater conduits
*
*=============================================================================
*       Philippi Vil1conduits
G1    'BFAM1'  'BFAM2'  2        0.75     18       0.037    0       0         0.018    0        0
G1    'BFAM2'  'BFAM3'  2        0.75     87       0.0043   0       0         0.018    0        0
G1    'BFAM3'  'BFAM4'  2        0.75     48       0.0085   0       0         0.018    0        0
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G1    'BFAM4'  'BFAM5'  2         0.75     45        0.0059  0        0        0.018   0        0
G1    'BFAM5'  'BFAM6'  2         0.75     30        0.0058  0        0        0.018   0        0
G1    'BFAM6'  'BFAM7'  2         0.75     68        0.057   0        0        0.018   0        0
G1    'BFAM7'  'BFAM8'  2         0.75     158       0.0058  0        0        0.018   0        0
G1    'BFAM8'  'BFAM9'  2         0.75     142       0.0029  0        0        0.018   0        0
G1    'BFDT1'  'BFAM9'  2         0.75     17        0.017   0        0        0.018   0        0
G1    'BFAM9'  'BFAM10' 2         0.75     32        0.003   0        0        0.018   0        0
G1    'BFAM10' 'BF142'  2         0.75     109       0.0029  0        0        0.018   0        0
G1    'BFBR1'  'BFAM8'  2         0.75     34        0.0013  0        0        0.018   0        0
G1    'BFBR2'  'BFBR1'  2         0.75     85        0.0027  0        0        0.018   0        0
G1    'BFBR3'  'BFBR2'  2         0.75     25        0.0056  0        0        0.018   0        0
G1    'BFBR4'  'BFBR2'  2         0.75     105       0.0027  0        0        0.018   0        0
G1    'BFB30'  'BFB18'  2         0.75     150       0.0091  0        0        0.018   0        0
G1    'BFB18'  'BFBR4'  2         0.75     57        0.0023  0        0        0.018   0        0
G1    'BFB19'  'BFB18'  2         0.75     74        0.0031  0        0        0.018   0        0
G1    'BFB20'  'BFB19'  2         0.75     48        0.01    0        0        0.018   0        0
G1    'BFB20A' 'BFB20'  2         0.75     145       0.0059  0        0        0.018   0        0
G1    'BFBR5'  'BFBR4'  2         0.75     128       0.0074  0        0        0.018   0        0
G1    'BFBR6'  'BFBR5'  2         0.75     75        0.0074  0        0        0.018   0        0
G1    'BFBR7'  'BFBR6'  2         0.75     102       0.0041  0        0        0.018   0        0
G1    'BFBR8'  'BFBR7'  2         0.75     79        0.0059  0        0        0.018   0        0
G1    'PH164'  'PH163'  2         0.3      85        0.0041  0        0        0.018   0        0
G1    'PH163'  'PH162'  2         0.3      70        0.0053  0        0        0.018   0        0
G1    'PH162'  'BF142'  2         0.3      41        0.0433  0        0        0.018   0        0
G1    'PH169'  'PH168'  2         0.3      90        0.0044  0        0        0.018   0        0
G1    'PH168'  'PH167'  2         0.3      50        0.0063  0        0        0.018   0        0
G1    'PH167'  'PH166'  2         0.3      43        0.0053  0        0        0.018   0        0
G1    'PH166'  'PH165'  2         0.3      79        0.013   0        0        0.018   0        0
G1    'PH165'  'BF142'  2         0.3      24        0.062   0        0        0.018   0        0
G1    'BF142'  'BF137'  2         1.2      140       0.0029  0        0        0.018   0        0
G1    'BF137'  'BF136'  2         1.2      9         0.086   0        0        0.018   0        0
G1    'BF136'  'MH87'   2         1.2      46        0.041   0        0        0.018   0        0
G1    'BF134'  'BF133'  2         0.3      90        0.0132  0        0        0.018   0        0
G1    'BF133'  'BF132'  2         0.3      90        0.0132  0        0        0.018   0        0
G1    'BF132'  'BF131'  2         0.3      35        0.041   0        0        0.018   0        0
G1    'BF135'  'BF131'  2         1.05     24        0.0025  0        0        0.018   0        0
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G1   'BF131' 'PH466A' 2      1.05     26       0.0025  0       0       0.018   0       0
G1   'BF130' 'PH466A' 2      0.3      154      0.0076  0       0       0.018   0       0
G1   'PH108' 'PH109' 2       0.3      64       0.0084  0       0       0.018   0       0
G1   'PH109' 'PH111' 2       0.3      66       0.0078  0       0       0.018   0       0
G1   'PH104' 'BF130' 2       0.375    99       0.0054  0       0       0.018   0       0
G1   'PH111' 'PH11A' 2       0.375    14       0.0061  0       0       0.018   0       0
G1   'PH11A' 'PH4A6' 2       0.9      460      0.0066  0       0       0.018   0       0
G1   'PH107' 'PH104' 2       0.3      98       0.0065  0       0       0.018   0       0
G1   'BF136' 'MH87'  2       1.2      46       0.041   0       0       0.018   0       0
G1   'PH106' 'PH111' 2       0.3      69       0.0053  0       0       0.018   0       0
G1   'PH387' 'PH385' 2       0.375    43       0.005   0       0       0.018   0       0
G1   'PH385' 'PH384' 2       0.375    94       0.005   0       0       0.018   0       0
G1   'PH384' 'PH380' 2       0.375    133      0.0196  0       0       0.018   0       0
G1   'PH380' 'PH377' 2       0.75     134      0.0016  0       0       0.018   0       0
G1   'PH377' 'BF136' 2       0.75     22       0.0036  0       0       0.018   0       0
*============================================================================
*       PhilippiVill       2
G1   'BFB21' 'BFB22' 2       0.3      22       0.0071  0       0       0.018   0       0
G1   'BFB22' 'BFB23' 2       0.3      42       0.0048  0       0       0.018   0       0
G1   'BFB23' 'BFB24' 2       0.3      69       0.0071  0       0       0.018   0       0
G1   'BFB24' 'BFB25' 2       0.375    81       0.004   0       0       0.018   0       0
G1   'BFB25' 'BFB26' 2       0.45     67       0.0048  0       0       0.018   0       0
G1   'BFB26' 'BFB11' 2       0.6      81       0.0025  0       0       0.018   0       0
G1   'BFDT2' 'BFB11' 2       0.45     17       0.077   0       0       0.018   0       0
G1   'BFB11' 'BFB12' 2       0.6      56       0.0025  0       0       0.018   0       0
G1   'BFB12' 'PH2B74' 2      0.6      85       0.0031  0       0       0.018   0       0
G1   'BFB381' 'BFB25' 2      0.3      43       0.025   0       0       0.018   0       0
G1   'BFB382' 'BFB26' 2      0.3      46       0.0037  0       0       0.018   0       0
G1   'PH2B74' 'PH2B73' 2     0.6      51.5     0.0017  0       0       0.018   0       0
G1   'PH2B75' 'PH2B73' 2     0.675    28       0.0017  0       0       0.018   0       0
G1   'PH2B73' 'PH2B71' 2     0.675    99       0.0017  0       0       0.018   0       0
G1   'PH2B47' 'PH2B48' 2     0.3      19       0.0056  0       0       0.018   0       0
G1   'PH2B48' 'PH2B49' 2     0.3      31       0.0334  0       0       0.018   0       0
G1   'PH2B49' 'PH2B50' 2     0.3      7        0.0055  0       0       0.018   0       0
G1   'PH2B50' 'PH2B70C' 2    0.3      23       0.0313  0       0       0.018   0       0
G1   'PH2B70C' 'PH2B70A' 2   0.525    31       0.025   0       0       0.018   0       0
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G1   'PH2B70A' 'DP11CHA' 2   0.9     24      0.025   0       0       0.018   0       0
*=============================================================================
*
*       PhilippiVill3conduits
G1   'BFC41' 'BFC42' 2       0.3     84      0.0048  0       0       0.018   0       0
G1   'BFC17' 'BFC42' 2       0.3     19      0.0177  0       0       0.018   0       0
G1   'BFC42' 'BFC43' 2       0.375   40      0.0053  0       0       0.018   0       0
G1   'BFC43' 'BFC44' 2       0.45    77      0.005   0       0       0.018   0       0
G1   'BFC44' 'BFC45' 2       0.45    158     0.004   0       0       0.018   0       0
G1   'BFC45' 'BFC46' 2       0.45    88      0.01    0       0       0.018   0       0
G1   'BFC30' 'BFC47' 2       0.3     121     0.0124  0       0       0.018   0       0
G1   'BFC31' 'BFC48' 2       0.3     39      0.0084  0       0       0.018   0       0
G1   'BFC32' 'BFC45' 2       0.375   62      0.0053  0       0       0.018   0       0
G1   'BFC46' 'BFC47' 2       0.6     84.5    0.00345 0       0       0.018   0       0
G1   'BFC47' 'BFC48' 2       0.6     87      0.00426 0       0       0.018   0       0
G1   'BFC50' 'BFC51' 2       0.3     112     0.0044  0       0       0.018   0       0
G1   'BFC51' 'BFC52' 2       0.3     54      0.0044  0       0       0.018   0       0
G1   'BFC101' 'BFC52' 2      0.3     67      0.0089  0       0       0.018   0       0
G1   'BFC52' 'BFC53' 2       0.375   73.5    0.0044  0       0       0.018   0       0
G1   'BFC53' 'BFC48' 2       0.375   45      0.021   0       0       0.018   0       0
G1   'BFC48' 'PH380' 2       0.675   155     0.00351 0       0       0.018   0       0
G1   'BFC310' 'BFC311' 2     0.3     40      0.0163  0       0       0.018   0       0
G1   'BFC311' 'BFC27' 2      0.3     29      0.0328  0       0       0.018   0       0
G1   'BFC33' 'BFC34' 2       0.3     55      0.0133  0       0       0.018   0       0
G1   'BFC34' 'BFC26' 2       0.3     49      0.0061  0       0       0.018   0       0
G1   'BFC26' 'BFC27' 2       0.3     35      0.005   0       0       0.018   0       0
G1   'BFC27' 'BFC28' 2       0.375   66      0.0049  0       0       0.018   0       0
G1   'BFC28' 'BFC29' 2       0.375   20      0.0287  0       0       0.018   0       0
G1   'BFC29' 'MH18'  2       0.375   2       0.0475  0       0       0.018   0       0
G1   'BFC35' 'BFC36' 2       0.3     89      0.005   0       0       0.018   0       0
G1   'BFC36' 'BFC37' 2       0.3     34      0.0047  0       0       0.018   0       0
G1   'BFC37' 'BFC38' 2       0.3     32      0.0154  0       0       0.018   0       0
G1   'BFC9'  'BFC37' 2       0.3     27      0.0166  0       0       0.018   0       0
G1   'BFC38' 'MH02'  2       0.3     7       0.1175  0       0       0.018   0       0
G1   'BFC200' 'BFC201' 2     0.3     67.5    0.008   0       0       0.018   0       0
G1   'BFC41A' 'BFC201' 2     0.3     32      0.00478 0       0       0.018   0       0
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G1   'BFC201' 'BFC311' 2     0.3     36      0.04    0       0       0.018   0       0
G1   'BFC202' 'BFC38' 2      0.3     20      0.024   0       0       0.018   0       0
G1   'BFC20A' 'BFC21' 2      0.3     48      0.0127  0       0       0.018   0       0
G1   'BFC20B' 'BFC21' 2      0.3     41      0.004   0       0       0.018   0       0
G1   'BFC20C' 'BFC21' 2      0.3     10      0.0227  0       0       0.018   0       0
G1   'BFC21' 'BFC22' 2       0.3     91      0.065   0       0       0.018   0       0
G1   'BFC22' 'BFC23' 2       0.3     42      0.0143  0       0       0.018   0       0
G1   'BFC23' 'BFC25' 2       0.3     55      0.0263  0       0       0.018   0       0
G1   'BFC24' 'BFC25' 2       0.3     36      0.043   0       0       0.018   0       0
G1   'BFC25' 'DP11CHA' 2     0.375   25      0.04    0       0       0.018   0       0
*=============================================================================
*
*       Philippi    Village        4conduits
G1   'PH464' 'PH384' 2       0.3     121     0.007   0       0       0.018   0       0
G1   'PH445' 'PH444' 2       0.3     17      0.021   0       0       0.018   0       0
G1   'PH444' 'PH443' 2       0.3     35      0.006   0       0       0.018   0       0
G1   'PH443' 'PH442' 2       0.3     31.5    0.0057  0       0       0.018   0       0
G1   'PH442A' 'PH442' 2      0.3     200     0.023   0       0       0.018   0       0
G1   'PH442' 'PH440' 2       0.3     90      0.011   0       0       0.018   0       0
G1   'PH440' 'PH439' 2       0.3     26      0.0154  0       0       0.018   0       0
G1   'PH439' 'PH437' 2       0.3     10.5    0.0057  0       0       0.018   0       0
G1   'PH438' 'PH437' 2       0.3     13.5    0.0323  0       0       0.018   0       0
G1   'PH437' 'PH436' 2       0.3     27.5    0.0055  0       0       0.018   0       0
G1   'PH436' 'PH435' 2       0.3     30.5    0.016   0       0       0.018   0       0
G1   'PH435' 'PH433' 2       0.3     10      0.0235  0       0       0.018   0       0
G1   'PH434' 'PH433' 2       0.3     11.5    0.012   0       0       0.018   0       0
G1   'PH433' 'PH432' 2       0.375   40      0.0133  0       0       0.018   0       0
G1   'PH432' 'PH431' 2       0.375   62.5    0.021   0       0       0.018   0       0
G1   'PH431' 'PH426' 2       0.375   43      0.0313  0       0       0.018   0       0
G1   'PH430' 'PH429' 2       0.3     32.5    0.0067  0       0       0.018   0       0
G1   'PH429' 'PH428' 2       0.3     67      0.057   0       0       0.018   0       0
G1   'PH428' 'PH427' 2       0.3     53      0.0123  0       0       0.018   0       0
G1   'PH427' 'PH426' 2       0.3     27      0.0046  0       0       0.018   0       0
G1   'PH426' 'MH25'  2       0.375   5       0.333   0       0       0.018   0       0
G1   'PH424' 'PH423' 2       0.3     26      0.0162  0       0       0.018   0       0
G1   'PH423' 'MH22'  2       0.3     5.5     0.0047  0       0       0.018   0       0
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G1   'PH452' 'PH451' 2       0.3     48      0.016   0       0       0.018   0       0
G1   'PH451' 'PH450' 2       0.3     50      0.0081  0       0       0.018   0       0
G1   'PH450' 'PH449' 2       0.3     22.5    0.011   0       0       0.018   0       0
G1   'PH449' 'MH87'  2       0.375   107     0.0036  0       0       0.018   0       0
G1   'MH87'  'MH88'  2       1.2     15      0.004   0       0       0.018   0       0
G1   'MH88'  'DP03CHA' 2     1.2     196     0.004   0       0       0.018   0       0
G1   'PH413' 'PH412' 2       0.3     28      0.028   0       0       0.018   0       0
G1   'PH412' 'PH411' 2       0.3     42      0.034   0       0       0.018   0       0
G1   'PH414A' 'PH411' 2      0.3     36      0.025   0       0       0.018   0       0
G1   'PH411' 'PH409' 2       0.3     40      0.0127  0       0       0.018   0       0
G1   'PH409' 'PH408' 2       0.3     77.5    0.0055  0       0       0.018   0       0
G1   'PH408' 'PH407' 2       0.3     17      0.0426  0       0       0.018   0       0
G1   'PH407A' 'PH407' 2      0.3     36.5    0.06    0       0       0.018   0       0
G1   'PH407' 'PH406' 2       0.3     53      0.01    0       0       0.018   0       0
G1   'PH406' 'PH405' 2       0.3     22.5    0.0625  0       0       0.018   0       0
G1   'PH405' 'PH404' 2       0.3     67      0.017   0       0       0.018   0       0
G1   'PH410' 'PH414' 2       0.3     10      0.016   0       0       0.018   0       0
G1   'PH414' 'PH405' 2       0.3     16.5    0.07    0       0       0.018   0       0
G1   'PH404' 'PH402' 2       0.3     41      0.03    0       0       0.018   0       0
G1   'PH402' 'MH17'  2       0.375   26      0.004   0       0       0.018   0       0
G1   'PH417' 'PH416' 2       0.3     25      0.0188  0       0       0.018   0       0
G1   'PH416' 'PH415' 2       0.3     50      0.042   0       0       0.018   0       0
G1   'PH415' 'PH402' 2       0.3     12.5    0.0052  0       0       0.018   0       0
G1   'PH466A' 'PH466' 2      1.05    82      0.0011  0       0       0.018   0       0
G1   'PH466' 'PH467' 2       1.05    89      0.0011  0       0       0.018   0       0
G1   'PH467' 'MH68'  2       1.05    16      0.0011  0       0       0.018   0       0
G1   'PH421A' 'PH421' 2      0.3     31.5    0.01    0       0       0.018   0       0
G1   'PH421' 'PH420' 2       0.3     37.5    0.012   0       0       0.018   0       0
G1   'PH420' 'MH19'  2       0.3     6       0.0055  0       0       0.018   0       0
G1   'PH458' 'PH457' 2       0.3     38      0.03    0       0       0.018   0       0
G1   'PH457' 'PH456' 2       0.3     15.5    0.065   0       0       0.018   0       0
G1   'PH456' 'PH453' 2       0.3     80      0.005   0       0       0.018   0       0
G1   'PH462' 'PH460' 2       0.3     65      0.0096  0       0       0.018   0       0
G1   'PH460' 'PH453' 2       0.3     32      0.042   0       0       0.018   0       0
G1   'PH453' 'PH409' 2       0.3     51      0.0077  0       0       0.018   0       0
G1   'PH4A32' 'PH4A31' 2     0.3     37      0.011   0       0       0.018   0       0
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G1   'PH4A33' 'PH4A31' 2    0.3    11    0.024   0    0    0.018  0    0
G1   'PH4A31' 'PH4A30' 2    0.3    41    0.012   0    0    0.018  0    0
G1   'PH4A34' 'PH4A30' 2    0.3    9     0.016   0    0    0.018  0    0
G1   'PH4A30' 'PH4A29' 2    0.375  63    0.014   0    0    0.018  0    0
G1   'PH4A29' 'PH4A28' 2    0.375  59    0.014   0    0    0.018  0    0
G1   'PH4A28' 'PH4A27' 2    0.375  37    0.0125  0    0    0.018  0    0
G1   'PH4A35' 'PH4A27' 2    0.3    69    0.027   0    0    0.018  0    0
G1   'PH4A27' 'PH4A26' 2    0.45   44    0.015   0    0    0.018  0    0
G1   'PH4A26' 'PH4A25' 2    0.525  28    0.0088  0    0    0.018  0    0
G1   'PH4A25' 'MH24'  2     0.525  15    0.004   0    0    0.018  0    0
G1   'PH4A42' 'PH4A41' 2    0.3    40    0.01    0    0    0.018  0    0
G1   'PH4A41' 'PH4A40' 2    0.3    74    0.0083  0    0    0.018  0    0
G1   'PH4A40' 'PH4A36' 2    0.375  53    0.005   0    0    0.018  0    0
G1   'PH4A36' 'DP01'  2     0.45   35    0.0071  0    0    0.018  0    0
G1   'PH4A44' 'PH4A40' 2    0.3    55    0.015   0    0    0.018  0    0
G1   'PH4A50' 'PH4A49' 2    0.3    78    0.0072  0    0    0.018  0    0
G1   'PH4A49' 'PH4A48' 2    0.3    58    0.0074  0    0    0.018  0    0
G1   'PH4A48' 'PH4A47' 2    0.3    65    0.0071  0    0    0.018  0    0
G1   'PH4A47' 'PH4A46' 2    0.3    61    0.0061  0    0    0.018  0    0
G1   'PH4A46' 'PH4A45' 2    0.3    43.8  0.006   0    0    0.018  0    0
G1   'PH4A45' 'DP01'  2     0.3    28    0.01    0    0    0.018  0    0
G1   'PH4A39' 'PH4A38' 2    0.3    68    0.024   0    0    0.018  0    0
G1   'PH4A38' 'PH4A37' 2    0.3    25    0.0133  0    0    0.018  0    0
G1   'PH4A37' 'PH4A36' 2    0.3    60    0.0053  0    0    0.018  0    0
G1   'PH4A4' 'PH4A3' 2      0.3    94    0.016   0    0    0.018  0    0
G1   'PH4A5' 'PH4A3' 2      0.3    7     0.03    0    0    0.018  0    0
G1   'PH4A3' 'PH4A2' 2      0.375  104   0.006   0    0    0.018  0    0
G1   'PH4A2' 'MH01'  2      0.45   15    0.01    0    0    0.018  0    0
G1   'PH4A9' 'PH4A8' 2      0.375  62    0.016   0    0    0.018  0    0
G1   'PH4A8' 'PH4A7' 2      0.375  97    0.0172  0    0    0.018  0    0
G1   'PH4A7' 'MH01'  2      0.45   6.5   0.013   0    0    0.018  0    0
G1   'PH4A15' 'PH4A12' 2    0.375  50    0.0088  0    0    0.018  0    0
G1   'PH4A14' 'PH4A13' 2    0.3    47    0.015   0    0    0.018  0    0
G1   'PH4A13' 'PH4A12' 2    0.3    7.5   0.025   0    0    0.018  0    0
G1   'PH4A12' 'MH11'  2     0.375  4     0.00001 0    0    0.018  0    0
G1   'PH4A18' 'PH4A17' 2    0.375  66.5  0.0093  0    0    0.018  0    0
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G1   'PH4A17' 'MH16'  2      0.375   4       0.013   0       0       0.018   0       0
G1   'PH4A6' 'PH4A23' 2      1.05    86      0.005   0       0       0.018   0       0
G1   'PH4A23' 'PH4A22' 2     1.05    88      0.0044  0       0       0.018   0       0
G1   'PH4A22' 'PH4A21' 2     1.05    15      0.0028  0       0       0.018   0       0
G1   'PH4A21' 'PH4A20' 2     1.05    42      0.0022  0       0       0.018   0       0
G1   'PH4A20' 'MH24'  2      1.05    26      0.002   0       0       0.018   0       0
G1   'RL406' 'RL405' 2       0.45    213     0.0025  0       0       0.018   0       0
G1   'RL405' 'RL404' 2       0.6     400     0.0025  0       0       0.018   0       0
G1   'RL404' 'RL403' 2       0.75    200     0.0025  0       0       0.018   0       0
G1   'RL403' 'RL402' 2       0.75    150     0.008   0       0       0.018   0       0
G1   'RL402' 'RL401' 2       1.8     407     0.008   0       0       0.018   0       0
G1   'RL401' 'MH24'  2       1.8     43      0.008   0       0       0.018   0       0
G1   'PH465' 'PH385' 2       0.3     18      0.012   0       0       0.018   0       0
*
*       Philippi    Agricultareas
*
G1   '35D'   '35B'   2       0.9     210     0.0011  0       0       0.018   0       0
G1   '35B'   '35A'   2       1.2     520     0.0008  0       0       0.018   0       0
G1   '35A'   'ESDP'  2       1.5     550     0.005   0       0       0.018   0       0
G1   'ESDP'  '35'    1       550     600     0.0017  0.5     0.5     0.25    0.75    0
G1   '35'    'GLES'  2       0.65    30      0.0033  0       0       0.018   0       0
G1   '40A'   '40B'   1       1.5     1500    0.0015  0.6     0.6     0.2     2       0
G1   '40B'   '40C'   1       1.5     980     0.00182 0.6     0.6     0.2     2       0
G1   '40C'   'VYDP'  1       1.5     1490    0.0013  0.6     0.6     0.2     2       0
G1   '1035D' '35B'   3       0       0       0       0       0       0       0       0
G1   '1035C' '35A'   3       0       0       0       0       0       0       0       0
G1   '1040A' '40B'   3       0       0       0       0       0       0       0       0
G1   '1040B' '40C'   3       0       0       0       0       0       0       0       0
G1   '1040C' 'VYDP'  3       0       0       0       0       0       0       0       0
G1   'PHIGW' 'GLGW'  3       0       0       0       0       0       0       0       0
*
*==========================================================================
*       Enter       Subcatchon      line    H1.     Repeat  for     each    subcatchment
*       (Maximumof  NW      differensubcatchments).
*==========================================================================
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*       SURFACE     WATER   DATA
*       SURFACE WATER   DATA
*   JK       NAMEW   NGTO    WIDTH   AREA    %IMP     SLP     IMPN    PERVN   IDS      PDS      WLMAX    WLMIN    DECAY
* CALIBRATION 1
H1   1       -1      0        2       0       0.65    0       0.75    0        0.85    0        0        0        0
*       PhilippiAgricultural
H1   1       '135D'  '35D'    450     74.8    5       0.0053  0.02    0.3      5       13       83       15       0.00056
H2   '135D'  '1035D' 1        1       0       30      1.8     1.8     -1
H3   0.1     1       0        0       0       0.15    0.03    0.08    15       0.08
*H3          0.1      1        0       0       0        0.46    0.15     0.3      15     0.08
*       HCO      PCO      CET      DP       DET
*H4           10       15     0.35  2.00E-02       3
H4   10      5       0.25     2.00E-02 1
*
H1   1       '135C'  '35A'    700     310     5       0.002   0.02    0.3      5       13       83       15       0.00056
H2   '135C'  '1035C' 1        1       0       30      1.8     1.8     -1
H3   0.1     1       0        0       0       0.15    0.03    0.08    15       0.08
*H3          0.1      1        0       0       0        0.46    0.15     0.3      15     0.08
*       HCO      PCO      CET      DP       DET
*H4           10       15     0.35  2.00E-02       3
H4   10      5       0.25     2.00E-02 1
*
H1   1       '140A'  '40A'    2040    142     5       0.0025  0.02    0.3      5       13       83       15       0.00056
H2   '140A'  '1040A' 1        1       0       30      1.8     1.8     -1
H3   0.1     1       0        0       0       0.15    0.03    0.08    15       0.08
*H3          0.1      1        0       0       0        0.46    0.15     0.3      15     0.08
*       HCO      PCO      CET      DP       DET
*H4           10       15     0.35 2.00E-02       3
H4   10      5       0.25     2.00E-02 1
*
H1   1       '140B'  '40B'    1450    85      5       0.007   0.02    0.3      5       13       83       15       0.00056
H2   '140B'  '1040B' 1        1       0       30      1.8     1.8     -1
H3   0.1     1       0        0       0       0.15    0.03    0.08    15       0.08
*H3          0.1      1        0       0       0        0.46    0.15     0.3      15     0.08
*       HCO      PCO      CET      DP       DET
*H4           10       15     0.35  2.00E-02       3
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H4   10      5       0.25    2.00E-02 1
*
H1   1       '140C'  '40C'   1900    150     5       0.0018  0.02    0.3     5       13      83      15      0.00056
H2   '140C'  '1040C' 1       1       0       30      1.8     1.8     -1
H3   0.1     1       0       0       0       0.15    0.03    0.08    15      0.08
*H3          0.1       1       0       0       0         0.46    0.15     0.3      15    0.08
*       HCO     PCO     CET     DP      DET
*H4           10      15    0.35 2.00E-02       3
H4   10      5       0.25    2.00E-02 1
*
H1   1       'PHA'   'PHISW' 1300    200     5       0.003   0.02    0.3     5       13      83      15      0.00056
H2   'PHA'   'PHIGW' 1       0       0       30      1.8     1.8     -1
*       A1      B1      A2      B2      A3      POR          WP      FC      HKSAT   TH1
H3   0.1     1       0       0       0       0.15    0.03    0.08    15      0.08
*       HCO     PCO     CET     DP      DET
H4   10      5       0.25    2.00E-02 1
*
*       Airport Industria
*
H1   1       'AI101' 'AI1'   1200    105     60      0.0106  0.02    0.2     5       13      83      15      0.00056
H1   1       'AI102' 'AI2'   270     8       60      0.0019  0.02    0.2     5       13      83      15      0.00056
H1   1       'AI103' 'GIBM3' 885     124     60      0.004   0.02    0.2     5       13      83      15      0.00056
*
*       N2      adjacent
*
H1   1       'N104'  'GIBM4' 150     38      57      0.0028  0.02    0.2     5       13      83      15      0.00056
*
*       Guguletuand     Nyanga
*
H1   1       'G105'  'GIBM5' 180     8       57      0.0021  0.02    0.2     5       13      83      15      0.00056
H1   1       'G106'  'GIBM6' 150     25      57      0.0041  0.02    0.2     5       13      83      15      0.00056
H1   1       'G107'  'MIL1'  200     23      57      0.0024  0.02    0.2     5       13      83      15      0.00056
H1   1       'G108'  'GIBM8' 275     33      10      0.006   0.02    0.2     5       13      83      15      0.00056
H1   1       'G129'  'GIBM29' 270    32      60      0.0057  0.02    0.2     5       13      83      15      0.00056
H1   1       'NG1'   'FEN0'  209     5.23    50      0.004   0.02    0.2     5       13      83      15      0.00056
H1   1       'NG2'   'EMS0'  342     1.711   50      0.0204  0.02    0.2     5       13      83      15      0.00056
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H1   1      'NG3'    'FEN1'   210    5.47    50     0.002    0.02   0.2   5    13    83    15    0.00056
H1   1      'NG4'    'EMS0'   284    5.97    50     0.032    0.02   0.2   5    13    83    15    0.00056
H1   1      'NG5'    '2ND1'   202    3.23    50     0.0012   0.02   0.2   5    13    83    15    0.00056
H1   1      'NG6'    'ZWS2'   148    4.74    50     0.005    0.02   0.2   5    13    83    15    0.00056
H1   1      'NG7A'   '3RD2'   149    2.68    50     0.016    0.02   0.2   5    13    83    15    0.00056
H1   1      'NG7B'   '3RD2A'  126    2.26    50     0.016    0.02   0.2   5    13    83    15    0.00056
H1   1      'NG7C'   '3RD2B'  158    2.84    50     0.016    0.02   0.2   5    13    83    15    0.00056
H1   1      'NG8'    'ZWS2'   135    1.49    50     0.0012   0.02   0.2   5    13    83    15    0.00056
H1   1      'NG9'    '3RD1'   256    4.6     50     0.0034   0.02   0.2   5    13    83    15    0.00056
H1   1      'NG10'   '3RD1'   153    0.92    50     0.0027   0.02   0.2   5    13    83    15    0.00056
H1   1      'NG11'   'FEN1'   333    1.8     50     0.008    0.02   0.2   5    13    83    15    0.00056
H1   1      'NG12'   'FEN2'   265    5.04    50     0.0052   0.02   0.2   5    13    83    15    0.00056
H1   1      'NG13'   'EMS2'   207    7.85    50     0.0053   0.02   0.2   5    13    83    15    0.00056
H1   1      'NG14'   '3RD1'   387    7.35    50     0.0027   0.02   0.2   5    13    83    15    0.00056
H1   1      'NG15'   'DAV1'   305    1.68    50     0.012    0.02   0.2   5    13    83    15    0.00056
H1   1      'NG18A'  '4TH2'   207    4.56    50     0.0017   0.02   0.2   5    13    83    15    0.00056
H1   1      'NG18B'  '4TH1'   190    3.42    50     0.0039   0.02   0.2   5    13    83    15    0.00056
H1   1      'NG19'   'ZWS4'   304    4.26    50     0.0032   0.02   0.2   5    13    83    15    0.00056
H1   1      'NG20'   'MAH1'   173    2.77    50     0.0042   0.02   0.2   5    13    83    15    0.00056
H1   1      'NG21A'  'TERM0'  73     0.58    50     0.0096   0.02   0.2   5    13    83    15    0.00056
H1   1      'NG21B'  'TERM0'  164    0.82    50     0.0026   0.02   0.2   5    13    83    15    0.00056
H1   1      'NG22'   'TERM1'  838    11.73   50     0.0004   0.02   0.2   5    13    83    15    0.00056
H1   1      'NG23'   'TERM3'  1073   15.02   50     0.0004   0.02   0.2   5    13    83    15    0.00056
H1   1      'NG24A'  'TERM5'  1159   11.59   50     0.0021   0.02   0.2   5    13    83    15    0.00056
H1   1      'NG24B'  'TERM5'  195    0.975   50     0.0111   0.02   0.2   5    13    83    15    0.00056
H1   1      'NG25'   'TERM7'  251    2.76    50     0.0049   0.02   0.2   5    13    83    15    0.00056
H1   1      'NG26A'  'SAK1'   212    2.54    50     0.0031   0.02   0.2   5    13    83    15    0.00056
H1   1      'NG26B'  'TERM0'  194    3.68    50     0.0023   0.02   0.2   5    13    83    15    0.00056
H1   1      'NG27'   'ZWN4'   391    7.04    50     0.0056   0.02   0.2   5    13    83    15    0.00056
H1   1      'NG28'   'ZWN3'   131    2.48    50     0.0053   0.02   0.2   5    13    83    15    0.00056
H1   1      'NG29'   'NTL2'   125    3.63    50     0.0031   0.02   0.2   5    13    83    15    0.00056
H1   1      'NG30'   'NTL3'   62     1.8     50     0.007    0.02   0.2   5    13    83    15    0.00056
H1   1      'NG31'   'NTL2'   61     1.78    50     0.0023   0.02   0.2   5    13    83    15    0.00056
H1   1      'NG32'   'NTL4'   59     1.7     50     0.0001   0.02   0.2   5    13    83    15    0.00056
H1   1      'NG33A'  'NTL5'   293    4.1     50     0.0064   0.02   0.2   5    13    83    15    0.00056
H1   1      'NG33B'  'TERM5'  217    6.52    50     0.0017   0.02   0.2   5    13    83    15    0.00056
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H1	1	'NG34'	'GTD2'	315	11.01	50	0.0024	0.02	0.2	5	13	83	15	0.00056
H1	1	'NG35'	'GTD3'	113	0.9	50	0.005	0.02	0.2	5	13	83	15	0.00056
H1	1	'NG34A'	'TOM1'	191	2.68	50	0.0135	0.02	0.2	5	13	83	15	0.00056
H1	1	'NG35A'	'TOM4'	162	3.4	50	0.0055	0.02	0.2	5	13	83	15	0.00056
H1	1	'NG36'	'KNF1'	147	4.12	50	0.0041	0.02	0.2	5	13	83	15	0.00056
H1	1	'NG37'	'KNF1'	177	4.08	50	0.0063	0.02	0.2	5	13	83	15	0.00056
H1	1	'NG38'	'MCP1'	419	5.03	50	0.0092	0.02	0.2	5	13	83	15	0.00056
H1	1	'NG39'	'NON2'	156	0.78	50	0.0014	0.02	0.2	5	13	83	15	0.00056
H1	1	'NG40'	'NON3'	156	0.78	50	0.0174	0.02	0.2	5	13	83	15	0.00056
H1	1	'NG41'	'KNF3'	189	1.89	50	0.0117	0.02	0.2	5	13	83	15	0.00056
H1	1	'NG42'	'KNF4'	283	10.74	50	0.0026	0.02	0.2	5	13	83	15	0.00056
H1	1	'NG43'	'NDA1'	223	3.34	50	0.012	0.02	0.2	5	13	83	15	0.00056
H1	1	'NG44'	'MND1'	172	1.72	50	0.01	0.02	0.2	5	13	83	15	0.00056
H1	1	'NG45'	'NY10'	179	1.79	50	0.0002	0.02	0.2	5	13	83	15	0.00056
H1	1	'NG43A'	'LOY1'	142	3.98	50	0.0098	0.02	0.2	5	13	83	15	0.00056
H1	1	'NG44A'	'NK1'	141	3.11	50	0.0051	0.02	0.2	5	13	83	15	0.00056
H1	1	'NG46'	'NK2'	131	2.61	50	0.0054	0.02	0.2	5	13	83	15	0.00056
H1	1	'NG47'	'DAV2'	151	2.41	50	0.019	0.02	0.2	5	13	83	15	0.00056
H1	1	'NG47A'	'DAV2'	55	1.42	50	0.012	0.02	0.2	5	13	83	15	0.00056
H1	1	'NG48'	'ZWL1'	203	3.45	50	0.012	0.02	0.2	5	13	83	15	0.00056
H1	1	'NG49'	'NY7'	145	2.9	50	0.0086	0.02	0.2	5	13	83	15	0.00056
H1	1	'NG50'	'NY9'	172	2.58	50	0.0014	0.02	0.2	5	13	83	15	0.00056
H1	1	'NG51'	'KNF3'	141	0.99	50	0.022	0.02	0.2	5	13	83	15	0.00056
H1	1	'NG53A'	'NY2'	135	1.08	50	0.0363	0.02	0.2	5	13	83	15	0.00056
H1	1	'NG53B'	'NY2'	150	0.9	50	0.032	0.02	0.2	5	13	83	15	0.00056
H1	1	'NG53C'	'NY1'	127	0.89	50	0.02	0.02	0.2	5	13	83	15	0.00056
H1	1	'NG53D'	'NY2'	131	1.83	50	0.05	0.02	0.2	5	13	83	15	0.00056
H1	1	'NG53E'	'NY1'	217	1.3	50	0.031	0.02	0.2	5	13	83	15	0.00056
H1	1	'NG54'	'NY2'	65	1.43	50	0.032	0.02	0.2	5	13	83	15	0.00056
H1	1	'NG55'	'NY2'	252	4.29	50	0.018	0.02	0.2	5	13	83	15	0.00056
H1	1	'NG56'	'NY3'	137	5.46	50	0.014	0.02	0.2	5	13	83	15	0.00056
H1	1	'NG57'	'NY4'	148	2.96	50	0.0065	0.02	0.2	5	13	83	15	0.00056
H1	1	'NG58'	'JKL1'	126	2.01	50	0.043	0.02	0.2	5	13	83	15	0.00056
H1	1	'NG58A'	'GTD1'	348	2.78	50	0.038	0.02	0.2	5	13	83	15	0.00056
H1	1	'NG59'	'JKL1'	154	2.31	50	0.022	0.02	0.2	5	13	83	15	0.00056
H1	1	'NG59A'	'GTD3'	294	3.23	50	0.0077	0.02	0.2	5	13	83	15	0.00056

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H1   1      'NG60'  'JKL1'  185     2.77    50      0.017   0.02    0.2     5       13      83      15      0.00056
H1   1      'NG61A' 'JKL1'  295     6.48    50      0.0033  0.02    0.2     5       13      83      15      0.00056
H1   1      'NG62'  'NY5'   129     2.7     50      0.0088  0.02    0.2     5       13      83      15      0.00056
H1   1      'NG63'  'TERM12' 115    1.84    50      0.0068  0.02    0.2     5       13      83      15      0.00056
H1   1      'NG64'  'NY6'   120     3.37    50      0.012   0.02    0.2     5       13      83      15      0.00056
H1   1      'NG66'  'TERM12' 98     2.45    50      0.0138  0.02    0.2     5       13      83      15      0.00056
*============================================================================
*       Cross Road Subcatch details
H1    1         'KL1'    'KPN0'   215.6822 4.35678 50      9.21E-03 0.02      0.2       5         13        83        15
0.00056 0       0
H1    1         'KL2'    'KPN2'   179.1429 3.135    50      1.81E-02 0.02      0.2       5         13        83        15
0.00056 0       0
H1    1         'KL3'    'CPA2'   258.1222 2.3231   50      1.68E-02 0.02      0.2       5         13        83        15
0.00056 0       0
H1    1         'KL4'    'CPA3'   175.8519 1.4244   50      9.88E-03 0.02      0.2       5         13        83        15
0.00056 0       0
H1    1         'KL5'    'TRY1'   108.7721 1.7186   50      9.94E-03 0.02      0.2       5         13        83        15
0.00056 0       0
H1    1         'KL6'    'TRY2'   170.8746 9.22723 50      2.65E-03 0.02      0.2       5         13        83        15
0.00056 0       0
H1    1         'KL7'    'CRD8'   130.2136 3.25534 50       0.01564 0.02      0.2       5         13        83        15
0.00056 0       0
H1    1         'KL8'    'CRD63'  81.38906 1.04178 50      2.99E-02 0.02      0.2       5         13        83        15
0.00056 0       0
H1    1         'KL8A'   'CRD42'  102.5645 1.2718   50      1.67E-02 0.02      0.2       5         13        83        15
0.00056 0       0
H1    1         'KL9'    'CRD40'  96.38312 1.4843   50      1.95E-03 0.02      0.2       5         13        83        15
0.00056 0       0
H1    1         'KL10'   'KLP6A'  115.7736 1.8408   50      3.52E-03 0.02      0.2       5         13        83        15
0.00056 0       0
H1    1         'KL11'   'KLP10'  73.57    0.7357   50       0.01     0.02      0.2       5         13        83        15
0.00056 0       0
H1    1         'KL12'   'CRD10'  101.6908 1.32198 50      1.29E-02 0.02      0.2       5         13        83        15
0.00056 0       0
H1    1         'KL13'   'CRD11'  108.8    1.4036   50       0.0151  0.02      0.2       5         13        83        15
0.00056 0       0
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H1    1        'KL14'   'KLP19'  155.5167  1.8662   50      0.0025   0.02     0.2     5       13      83      15
0.00056 0      0
H1    1        'KL15'   'CR4H8'  278.3913  5.7627   50      0.014203 0.02     0.2     5       13      83      15
0.00056 0      0
H1    1        'KL16'   'CRDE2'  149.6267  2.2444   50      9.33E-03 0.02     0.2     5       13      83      15
0.00056 0      0
H1    1        'KL17'   'A5A'     96.54105 1.83428  50      2.37E-02 0.02     0.2     5       13      83      15
0.00056 0      0
H1    1        'KL18'   'A6A'    170.1838  6.2968   50      5.41E-03 0.02     0.2     5       13      83      15
0.00056 0      0
H1    1        'KL19'   'A2'      67.23529 1.143    50      0.022    0.02     0.2     5       13      83      15
0.00056 0      0
H1    1        'KL20'   'KLP15'   63.54245 1.3471   50      0.56E-02 0.02     0.2     5       13      83      15
0.00056 0      0
H1    1        'KL21'   'KLP13'   64.55502 1.3492   50      2.97E-03 0.02     0.2     5       13      83      15
0.00056 0      0
H1    1        'KL22'   'KLP3'   145.8208  3.4997   50      0.006125 0.02     0.2     5       13      83      15
0.00056 0      0
H1    1        'KL23'   'KLP1'   529.5417  12.709   50      4.17E-03 0.02     0.2     5       13      83      15
0.00056 0      0
H1    1        'KL24'   'CR4H1'  282.6087  10.4     50      0.012    0.02     0.2     5       13      83      15
0.00056 0      0
H1    1        'KL24A'  'SW1312' 261.1533  7.8346   50      0.0061   0.02     0.2     5       13      83      15
0.00056 0      0
H1    1        'KL25'   'SW98'   281.3175  14.1784  50      3.31E-03 0.02     0.2     5       13      83      15
0.00056 0      0
H1    1        'KL27'   'SW109'  217.2647  2.2161   50      6.27E-03 0.02     0.2     5       13      83      15
0.00056 0      0
H1    1        'KL28'   'CR4H4'  208.6565  2.7334   50      7.63E-03 0.02     0.2     5       13      83      15
0.00056 0      0
H1    1        'KL29'   'CR4H3'  260.625  5.2125    50      0.00315  0.02     0.2     5       13      83      15
0.00056 0      0
H1    1        'KL30'   'CR4J'   141.6797  2.1677   50      6.54E-03 0.02     0.2     5       13      83      15
0.00056 0      0
H1    1        'KL31'   'CR4H7'  126.9397  1.4725   50      4.31E-03 0.02     0.2     5       13      83      15
0.00056 0      0
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H1    1         'KL32'   'CR4J'   128.328  3.2082   50          0.00736  0.02      0.2       5         13         83         15
0.00056 0       0
H1    1         'KL33'   'CRC5'   101.7589  2.2794   50       1.34E-02  0.02      0.2       5         13         83         15
0.00056 0       0
H1    1         'KL34'   'N1'      107.1772  1.6934   50       1.16E-02  0.02      0.2       5         13         83         15
0.00056 0       0
H1    1         'KL35'   'NOUT'   178.1387  6.1636   50       1.23E-02  0.02      0.2       5         13         83         15
0.00056 0       0
*============================================================================
*============================================================================
*       PhilippiEast    Subcatchdetails
*============================================================================
*       JK       NAMEW    NGTO     WIDTH    AREA     %IMP          SLP      IMPN     PERV     IDS      PDS      WLMAX    WLMIN
DECAY
*H1   1       -1       0        0        0        0.6      0        0        0        0        0        0        0        0
H1   1       'PH01'  'BFBR8' 183       5.064    50       0.0153  0.02     0.2      5        13       83       15       0.00056
H1   1       'PH02'  'BFB21' 207       5.289    50       0.0039  0.02     0.2      5        13       83       15       0.00056
H1   1       'PH03'  'BFBR7' 54        0.418    50       0.0115  0.02     0.2      5        13       83       15       0.00056
H1   1       'PH04'  'BFB23' 125       0.962    50       0.0094  0.02     0.2      5        13       83       15       0.00056
H1   1       'PH05'  'BFB11' 277       5.533    50       0.0068  0.02     0.2      5        13       83       15       0.00056
H1   1       'PH06'  'BFB26' 232       1.718    50       0.0112  0.02     0.2      5        13       83       15       0.00056
H1   1       'PH07'  'BFB24' 107       1.267    50       0.0136  0.02     0.2      5        13       83       15       0.00056
H1   1       'PH08'  'BFB381' 87       1.871    50       0.013   0.02     0.2      5        13       83       15       0.00056
H1   1       'PH09'  'BFB26' 86        1.583    50       0.0115  0.02     0.2      5        13       83       15       0.00056
H1   1       'PH10'  'BFB30' 59        0.415    50       0.013   0.02     0.2      5        13       83       15       0.00056
H1   1       'PH11'  'BFB30' 68        0.852    50       0.008   0.02     0.2      5        13       83       15       0.00056
H1   1       'PH12'  'BFB18' 46        0.355    50       0.0101  0.02     0.2      5        13       83       15       0.00056
H1   1       'PH13'  'BFB19' 75        0.919    50       0.009   0.02     0.2      5        13       83       15       0.00056
H1   1       'PH14'  'BFB20' 49        0.467    50       0.0135  0.02     0.2      5        13       83       15       0.00056
H1   1       'PH15'  'BFB19' 51        0.576    50       0.0181  0.02     0.2      5        13       83       15       0.00056
H1   1       'PH16'  'PH169' 103       0.619    50       0.0147  0.02     0.2      5        13       83       15       0.00056
H1   1       'PH17'  'BFB20A' 71       0.678    50       0.0115  0.02     0.2      5        13       83       15       0.00056
H1   1       'PH18'  'BFB12' 63        1.072    50       0.0136  0.02     0.2      5        13       83       15       0.00056
H1   1       'PH19'  'BFB11' 52        0.53     50       0.0164  0.02     0.2      5        13       83       15       0.00056
H1   1       'PH20'  'BFB12' 79        1.339    50       0.007   0.02     0.2      5        13       83       15       0.00056
H1   1       'PH21'  'PH2B49' 57       0.841    50       0.0054  0.02     0.2      5        13       83       15       0.00056
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H1   1        'PH22'   'PHM01' 74      1.285   50       0.0104  0.02    0.2     5      13     83     15       0.00056
H1   1        'PH23'   'BFC22' 74      0.481   50       0.0286  0.02    0.2     5      13     83     15       0.00056
H1   1        'PH24'   'BFC23' 52      1.017   50       0.0166  0.02    0.2     5      13     83     15       0.00056
H1   1        'PH25'   'PH2B73' 122    1.113   50       0.0011  0.02    0.2     5      13     83     15       0.00056
H1   1        'PH26'   'BFC310' 98     0.644   50       0.0108  0.02    0.2     5      13     83     15       0.00056
H1   1        'PH27'   'BFC310' 93     0.485   50       0.0025  0.02    0.2     5      13     83     15       0.00056
H1   1        'PH28'   'BFC28' 119     1.072   50       0.0218  0.02    0.2     5      13     83     15       0.00056
H1   1        'PH29'   'BFC35' 121     1.469   50       0.013   0.02    0.2     5      13     83     15       0.00056
H1   1        'PH30'   'BFC36' 69      1.15    50       0.0266  0.02    0.2     5      13     83     15       0.00056
H1   1        'PH31'   'BF142' 85      1.303   50       0.024   0.02    0.2     5      13     83     15       0.00056
H1   1        'PH32'   'PH380' 57      0.694   50       0.0335  0.02    0.2     5      13     83     15       0.00056
H1   1        'PH33'   'BFC48' 48      0.667   50       0.0203  0.02    0.2     5      13     83     15       0.00056
H1   1        'PH34'   'BFC24' 136     3.678   50       0.0124  0.02    0.2     5      13     83     15       0.00056
H1   1        'PH35'   'BFC44' 222     1.468   50       0.0206  0.02    0.2     5      13     83     15       0.00056
H1   1        'PH36'   'BFC43' 148     2.848   50       0.0043  0.02    0.2     5      13     83     15       0.00056
H1   1        'PH37'   'BFC50' 97      1.943   50       0.0117  0.02    0.2     5      13     83     15       0.00056
H1   1        'PH38'   'BFC47' 90      1.291   50       0.0069  0.02    0.2     5      13     83     15       0.00056
H1   1        'PH39'   'BFC48' 107     1.885   50       0.0053  0.02    0.2     5      13     83     15       0.00056
H1   1        'PH40'   'PH106' 317     24.19   50       0.008   0.02    0.2     5      13     83     15       0.00056
H1   1        'PH41'   'PH107' 163     5.638   50       0.0115  0.02    0.2     5      13     83     15       0.00056
H1   1        'PH42'   'PH107' 147     2.936   50       0.0166  0.02    0.2     5      13     83     15       0.00056
H1   1        'PH43'   'PH104' 159     4.538   50       0.0191  0.02    0.2     5      13     83     15       0.00056
H1   1        'PH44'   'PH104' 133     3.798   50       0.0164  0.02    0.2     5      13     83     15       0.00056
H1   1        'PH45'   'PH4A6' 183     1.153   50       0.0254  0.02    0.2     5      13     83     15       0.00056
H1   1        'PH46'   'PH4A5' 100     1.719   50       0.0538  0.02    0.2     5      13     83     15       0.00056
H1   1        'PH47'   'BF130' 63      0.98    50       0.0457  0.02    0.2     5      13     83     15       0.00056
H1   1        'PH48'   'PH466A' 75     0.998   50       0.021   0.02    0.2     5      13     83     15       0.00056
H1   1        'PH49'   'PH402' 194     1.801   50       0.0304  0.02    0.2     5      13     83     15       0.00056
H1   1        'PH50'   'PH4A36' 210    0.903   50       0.0886  0.02    0.2     5      13     83     15       0.00056
H1   1        'PH51'   'PH4A42' 110    1.2     50       0.0113  0.02    0.2     5      13     83     15       0.00056
H1   1        'PH52'   'PH4A27' 133    2.989   50       0.0238  0.02    0.2     5      13     83     15       0.00056
H1   1        'PH53'   'PH405' 197     2.189   50       0.0378  0.02    0.2     5      13     83     15       0.00056
H1   1        'PH54'   'PH416' 45      0.207   50       0.0148  0.02    0.2     5      13     83     15       0.00056
H1   1        'PH55'   'PH402' 20      0.072   50       0.0117  0.02    0.2     5      13     83     15       0.00056
H1   1        'PH56'   'PH404' 45      0.178   50       0.012   0.02    0.2     5      13     83     15       0.00056
H1   1        'PH57'   'PH417' 40      0.141   50       0.0017  0.02    0.2     5      13     83     15       0.00056
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H1   1      'PH58'  'PH417' 79     1.499   50     0.0207  0.02   0.2    5     13    83    15    0.00056
H1   1      'PH59'  'PH431' 76     0.736   50     0.0213  0.02   0.2    5     13    83    15    0.00056
H1   1      'PH60'  'PH450' 79     0.397   50     0.0202  0.02   0.2    5     13    83    15    0.00056
H1   1      'PH61'  'PH452' 1669   1.502   50     0.0356  0.02   0.2    5     13    83    15    0.00056
H1   1      'PH62'  'PH464' 219    3.809   50     0.0053  0.02   0.2    5     13    83    15    0.00056
H1   1      'PH63'  'PH436' 134    1.244   50     0.0153  0.02   0.2    5     13    83    15    0.00056
H1   1      'PH64'  'PH433' 87     0.723   50     0.0252  0.02   0.2    5     13    83    15    0.00056
H1   1      'PH65'  'PH442A' 68    0.48    50     0.0031  0.02   0.2    5     13    83    15    0.00056
H1   1      'PH66'  'PH444' 43     0.148   50     0.0124  0.02   0.2    5     13    83    15    0.00056
H1   1      'PH67'  'PH442' 85     0.119   50     0.0321  0.02   0.2    5     13    83    15    0.00056
H1   1      'PH68'  'PH409' 105    2.251   50     0.0035  0.02   0.2    5     13    83    15    0.00056
H1   1      'PH69'  'PH406' 101    2.661   50     0.017   0.02   0.2    5     13    83    15    0.00056
H1   1      'PH70'  'PH414A' 129   0.916   50     0.0172  0.02   0.2    5     13    83    15    0.00056
H1   1      'PH71'  'PH458' 170    3.978   50     0.0174  0.02   0.2    5     13    83    15    0.00056
H1   1      'PH72'  'PH4A30' 108   2.373   50     0.0258  0.02   0.2    5     13    83    15    0.00056
H1   1      'PH73'  'PH4A31' 84    0.945   50     0.0065  0.02   0.2    5     13    83    15    0.00056
H1   1      'PH74'  'PH4A41' 57    0.615   50     0.036   0.02   0.2    5     13    83    15    0.00056
H1   1      'PH75'  'PH4A36' 82    0.634   50     0.0421  0.02   0.2    5     13    83    15    0.00056
H1   1      'PH76'  'PH4A49' 61    0.25    50     0.0151  0.02   0.2    5     13    83    15    0.00056
H1   1      'PH77'  'PH4A50' 89    0.34    50     0.0384  0.02   0.2    5     13    83    15    0.00056
H1   1      'PH78'  'PH4A47' 60    0.52    50     0.0462  0.02   0.2    5     13    83    15    0.00056
*===========================================================================
JJ   0
*       NQS          JLAND   IROS    IROSAD  DRYDAY  CBVOL   DRYBSN  RAINIT  REFFDD  KLNBGN  KLNEND
J1   1       1        0       0       4       16      1       0       0.4     0       0
*       LNAME        METHOD  JACGUT  DDLIM   DDPOW   DDFACT  CLFREQ  AVSWP   DSLCL
J2   'family' 0       2       0       0       0       0       0       0
*    PNAME   PUNIT    NDIM    KALC    KWASH   KACGUT  LINKUP  QFACT1  QFACT2  QFACT3  QFACT4  QFACT5  WASHPO  RCOEF
CBFACT  CONCRN  REFF
J3   'TP'    'MG/L'   0       4       1       0       0       0       0       0       0       0       1.4956  684.230
0       0       0
*       KTO          KFROM   F1
*       NQS          JLAND   IROS    IROSAD  DRYDAY  CBVOL   DRYBSN  RAINIT  REFFDD  KLNBGN  KLNEND
*       NAMEW        KL      BASINS  GQLEN
L1   '135D'  1        500     50      /
L1   '135C'  1        500     50      /
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L1   '140A'  1        500     50      /
L1   '140B'  1        500     50      /
L1   '140C'  1        500     50      /
L1   'PHA'   1        500     50      /
L1   'AI101' 1        500     50      /
L1   'AI102' 1        500     50      /
L1   'AI103' 1        500     50      /
L1   'N104'  1        500     50      /
L1   'G105'  1        500     50      /
L1   'G106'  1        500     50      /
L1   'G107'  1        500     50      /
L1   'G108'  1        500     50      /
L1   'G129'  1        500     50      /
L1   'NG1'   1        500     50      /
L1   'NG2'   1        500     50      /
L1   'NG3'   1        500     50      /
L1   'NG4'   1        500     50      /
L1   'NG5'   1        500     50      /
L1   'NG6'   1        500     50      /
L1   'NG7A'  1        500     50      /
L1   'NG7B'  1        500     50      /
L1   'NG7C'  1        500     50      /
L1   'NG8'   1        500     50      /
L1   'NG9'   1        500     50      /
L1   'NG10'  1        500     50      /
L1   'NG11'  1        500     50      /
L1   'NG12'  1        500     50      /
L1   'NG13'  1        500     50      /
L1   'NG14'  1        500     50      /
L1   'NG15'  1        500     50      /
L1   'NG18A' 1        500     50      /
L1   'NG18B' 1        500     50      /
L1   'NG19'  1        500     50      /
L1   'NG20'  1        500     50      /
L1   'NG21A' 1        500     50      /
L1   'NG21B' 1        500     50      /
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L1    'NG22'  1       500      50      /
L1    'NG23'  1       500      50      /
L1    'NG24A' 1       500      50      /
L1    'NG24B' 1       500      50      /
L1    'NG25'  1       500      50      /
L1    'NG26A' 1       500      50      /
L1    'NG26B' 1       500      50      /
L1    'NG27'  1       500      50      /
L1    'NG28'  1       500      50      /
L1    'NG29'  1       500      50      /
L1    'NG30'  1       500      50      /
L1    'NG31'  1       500      50      /
L1    'NG32'  1       500      50      /
L1    'NG33A' 1       500      50      /
L1    'NG33B' 1       500      50      /
L1    'NG34'  1       500      50      /
L1    'NG35'  1       500      50      /
L1    'NG34A' 1       500      50      /
L1    'NG35A' 1       500      50      /
L1    'NG36'  1       500      50      /
L1    'NG37'  1       500      50      /
L1    'NG38'  1       500      50      /
L1    'NG39'  1       500      50      /
L1    'NG40'  1       500      50      /
L1    'NG41'  1       500      50      /
L1    'NG42'  1       500      50      /
L1    'NG43'  1       500      50      /
L1    'NG44'  1       500      50      /
L1    'NG45'  1       500      50      /
L1    'NG43A' 1       500      50      /
L1    'NG44A' 1       500      50      /
L1    'NG46'  1       500      50      /
L1    'NG47'  1       500      50      /
L1    'NG47A' 1       500      50      /
L1    'NG48'  1       500      50      /
L1    'NG49'  1       500      50      /
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L1   'NG50'  1        500     50        /
L1   'NG51'  1        500     50        /
L1   'NG53A' 1        500     50        /
L1   'NG53B' 1        500     50        /
L1   'NG53C' 1        500     50        /
L1   'NG53D' 1        500     50        /
L1   'NG53E' 1        500     50        /
L1   'NG54'  1        500     50        /
L1   'NG55'  1        500     50        /
L1   'NG56'  1        500     50        /
L1   'NG57'  1        500     50        /
L1   'NG58'  1        500     50        /
L1   'NG58A' 1        500     50        /
L1   'NG59'  1        500     50        /
L1   'NG59A' 1        500     50        /
L1   'NG60'  1        500     50        /
L1   'NG61A' 1        500     50        /
L1   'NG62'  1        500     50        /
L1   'NG63'  1        500     50        /
L1   'NG64'  1        500     50        /
L1   'NG66'  1        500     50        /
L1   'KL1'   1        500     50        /
L1   'KL2'   1        500     50        /
L1   'KL3'   1        500     50        /
L1   'KL4'   1        500     50        /
L1   'KL5'   1        500     50        /
L1   'KL6'   1        500     50        /
L1   'KL7'   1        500     50        /
L1   'KL8'   1        500     50        /
L1   'KL8A'  1        500     50        /
L1   'KL9'   1        500     50        /
L1   'KL10'  1        500     50        /
L1   'KL11'  1        500     50        /
L1   'KL12'  1        500     50        /
L1   'KL13'  1        500     50        /
L1   'KL14'  1        500     50        /
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L1    'KL15'  1        500     50       /
L1    'KL16'  1        500     50       /
L1    'KL17'  1        500     50       /
L1    'KL18'  1        500     50       /
L1    'KL19'  1        500     50       /
L1    'KL20'  1        500     50       /
L1    'KL21'  1        500     50       /
L1    'KL22'  1        500     50       /
L1    'KL23'  1        500     50       /
L1    'KL24'  1        500     50       /
L1    'KL24A' 1        500     50       /
L1    'KL25'  1        500     50       /
L1    'KL27'  1        500     50       /
L1    'KL28'  1        500     50       /
L1    'KL29'  1        500     50       /
L1    'KL30'  1        500     50       /
L1    'KL31'  1        500     50       /
L1    'KL32'  1        500     50       /
L1    'KL33'  1        500     50       /
L1    'KL34'  1        500     50       /
L1    'KL35'  1        500     50       /
L1    'PH01'  1        500     50       /
L1    'PH02'  1        500     50       /
L1    'PH03'  1        500     50       /
L1    'PH04'  1        500     50       /
L1    'PH05'  1        500     50       /
L1    'PH06'  1        500     50       /
L1    'PH07'  1        500     50       /
L1    'PH08'  1        500     50       /
L1    'PH09'  1        500     50       /
L1    'PH10'  1        500     50       /
L1    'PH11'  1        500     50       /
L1    'PH12'  1        500     50       /
L1    'PH13'  1        500     50       /
L1    'PH14'  1        500     50       /
L1    'PH15'  1        500     50       /
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L1    'PH16'  1       500     50       /
L1    'PH17'  1       500     50       /
L1    'PH18'  1       500     50       /
L1    'PH19'  1       500     50       /
L1    'PH20'  1       500     50       /
L1    'PH21'  1       500     50       /
L1    'PH22'  1       500     50       /
L1    'PH23'  1       500     50       /
L1    'PH24'  1       500     50       /
L1    'PH25'  1       500     50       /
L1    'PH26'  1       500     50       /
L1    'PH27'  1       500     50       /
L1    'PH28'  1       500     50       /
L1    'PH29'  1       500     50       /
L1    'PH30'  1       500     50       /
L1    'PH31'  1       500     50       /
L1    'PH32'  1       500     50       /
L1    'PH33'  1       500     50       /
L1    'PH34'  1       500     50       /
L1    'PH35'  1       500     50       /
L1    'PH36'  1       500     50       /
L1    'PH37'  1       500     50       /
L1    'PH38'  1       500     50       /
L1    'PH39'  1       500     50       /
L1    'PH40'  1       500     50       /
L1    'PH41'  1       500     50       /
L1    'PH42'  1       500     50       /
L1    'PH43'  1       500     50       /
L1    'PH44'  1       500     50       /
L1    'PH45'  1       500     50       /
L1    'PH46'  1       500     50       /
L1    'PH47'  1       500     50       /
L1    'PH48'  1       500     50       /
L1    'PH49'  1       500     50       /
L1    'PH50'  1       500     50       /
L1    'PH51'  1       500     50       /
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L1   'PH52'  1       500     50      /
L1   'PH53'  1       500     50      /
L1   'PH54'  1       500     50      /
L1   'PH55'  1       500     50      /
L1   'PH56'  1       500     50      /
L1   'PH57'  1       500     50      /
L1   'PH58'  1       500     50      /
L1   'PH59'  1       500     50      /
L1   'PH60'  1       500     50      /
L1   'PH61'  1       500     50      /
L1   'PH62'  1       500     50      /
L1   'PH63'  1       500     50      /
L1   'PH64'  1       500     50      /
L1   'PH65'  1       500     50      /
L1   'PH66'  1       500     50      /
L1   'PH67'  1       500     50      /
L1   'PH68'  1       500     50      /
L1   'PH69'  1       500     50      /
L1   'PH70'  1       500     50      /
L1   'PH71'  1       500     50      /
L1   'PH72'  1       500     50      /
L1   'PH73'  1       500     50      /
L1   'PH74'  1       500     50      /
L1   'PH75'  1       500     50      /
L1   'PH76'  1       500     50      /
L1   'PH77'  1       500     50      /
L1   'PH78'  1       500     50      /
*=====================================================================
*    NPRNT     INTERV
M1   6       6
*    NDET STARTP(1) STOPPR(1)
M2   1       0       0
*     IPRNT(1)...IPRNT(NRPNT)
M3   'MHOUT' 'TERM8' 'GIBM7' 'GIBM14' 'GIBM19' 'GIBM22'
*========================================================================
$ENDPROGRAM
```

TABLE D3:
TRANSPORT DATA FILE

```
$ANUM
$TRANSPORT
*============================================================================
A1  'Complete catchment transport'
A1  'INCLUDES DETENTION PONDS'
*============================================================================
*   ISLOPE  ITRAP IFLIP INFLEW
B0       1     1      0     0
*============================================================================
*   NDT  NINPUT NNYN NNPE NOUTS NPRINT NPOLL NITER IDATEZ METRIC INTPRT
B1  45024   2     1     1     3    1      0     4     970701  1      6
*============================================================================
*   DT   EPSIL  DWDAYS  TZERO  GNU      TRIBA
B2 900.0  0.00001  0.0    0.0  0.00001    1913
*============================================================================
*  NCNTRL  NINFIL  NFILTH  NDESN
B3   0      0       0       0
*============================================================================
*   NKLASS KPRINT
C1    0      0
*============================================================================
*        NOE       N(1) N(2)   N(3) TYPE DIST   GEOM1 SLOPE ROUGH GEOM2 BARREL      GEOM3 KGEOM
E1    'SHF' ''     ''    ''   19    0       0   0     0     0     0     0     ''
E1    'MH18'      ''     ''    ''   19    0     0     0     0     0     0     0     ''
E1    'MH02'      ''     ''    ''   19    0     0     0     0     0     0     0     ''
E1    'MH25'      ''     ''    ''   19    0     0     0     0     0     0     0     ''
E1    'MH22'      ''     ''    ''   19    0     0     0     0     0     0     0     ''
E1    'MH17'      ''     ''    ''   19    0     0     0     0     0     0     0     ''
E1    'MH68'      ''     ''    ''   19    0     0     0     0     0     0     0     ''
E1    'MH19'      ''     ''    ''   19    0     0     0     0     0     0     0     ''
E1    'MH24'      ''     ''    ''   19    0     0     0     0     0     0     0     ''
E1    'MH01'      ''     ''    ''   19    0     0     0     0     0     0     0     ''
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E1    'MH11'       ''     ''    ''    19    0     0     0     0     0     0     0     ''
E1    'MH16'       ''     ''    ''    19    0     0     0     0     0     0     0     ''
*E1   'MH88'       ''     ''    ''    19    0     0     0     0     0     0     0     ''
*E1   'DP03'       ''     ''    ''    19    0     0     0     0     0     0     0     ''
E1    'DP01'       ''     ''    ''    19    0     0     0     0     0     0     0     ''
E1    'PHM01'      ''     ''    ''    19    0     0     0     0     0     0     0     ''
E1    'SHF01'      'SHF'    ''     ''   1   45    1.5   0.0018      0.018 0     1     0     ''
E1    'SHF02'      'SHF01'      ''    ''     1    150   0.9   0.001 0.018 0     1     0      ''
E1    'SHF03'      'SHF02'      ''    ''     1    137   0.9   0.001 0.018 0     1     0      ''
E1    'SHF04'      'SHF03'      ''    ''     1    195   0.9   0.001 0.018 0     1     0      ''
E1    'SHF05'      'SHF04'      ''    ''     1    214   0.9   0.001 0.018 0     1     0      ''
E1    'SHF06'      'SHF05'      ''   ''    1      178   1.05  0.0011      0.018 0     1     0      ''
E1    'SHF07'      'SHF06'      ''   ''    1      258   1.05  0.0011      0.018 0     1     0      ''
E1    'SHF08'      'SHF07'      ''   ''    1      17.3  1.35  0.0011      0.018 0     1     0      ''
E1    'MHOUT'      ''          ''     ''    19    0     0     0           0     0     0     0     ''
E1    'EIS01'      'MHOUT'      ''   ''    1      40    1.35  0.00125     0.018 0     1     0      ''
E1    'EIS02'      'EIS01'      ''   ''    1      86    1.35  0.00204     0.018 0     1     0      ''
E1    'EIS03'      'EIS02'      ''   ''    1      260   1.35  0.0018      0.018 0     1     0      ''
E1    'EIS04'      'EIS03'      ''   ''    1      196   1.35  0.0012      0.018 0     1     0      ''
E1    'EIS05'      'EIS04'      ''   ''    1      227   1.35  0.0012      0.018 0     1     0      ''
E1    'EIS06'      'EIS05'      ''   ''    1      224   1.35  0.0012      0.018 0     1     0      ''
E1    'PHT01'      'EIS06' 'SHF08' 'PHM01' 1      110   1.35  0.00374     0.018 0     1     0      ''
E1    'DP11CHA'    'PHT01'   ''   '' 2    2.7   2.1   0.001       0.018 2.5   1     0      ''
E1    'DP11OUT'    'DP11CHA' ''       ''   21    0     2.2   0           0     0     0     0      'PHT02'
E1    'DP11'       'DP11OUT' '' ''   22    0      0     0           0     0     0     0      ''
E1    'PHT02'      'DP11OUT'   'DP11' ''   1      330   1.35  0.00374     0.018 0     1     0      ''
E1    'PHT03'      'PHT02'     'MH18' ''   1      180   1.35  0.00374     0.018 0     1     0      ''
E1    'PHT04'      'PHT03'     'MH02' ''   1      364   1.35  0.0028      0.018 0     1     0      ''
*E1   'DP03'       'PHT04'     'MH88' ''       22  0    0     0           0     0     0     0      ''

E1    'DP03CHA'   'PHT04'     ''  '' 2    3      1.525 0.001       0.018 4.8   1     0      ''
E1    'DP03OUT'    'DP03CHA'   ''     ''   21    0     2.4   0           0     0     0     0      'PHT05'
E1    'DP03'       'DP03OUT'   ''     ''   22    0     0     0           0     0     0     0     ''
E1    'PHT05'      'DP03OUT'   'DP03' ''   1      96    1.35  0.00338     0.018 0     1     0      ''
*E1   'PHT05'      'PHT04'      ''    ''   1      96    1.35  0.00338     0.018 0     1     0      ''
E1    'PHT06'      'PHT05'     'MH25' ''   1      112   1.35  0.00338     0.018 0     1     0      ''
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E1    'PHT07'     'PHT06'     'MH22' ''   1     122   1.35  0.00338     0.018 0     1     0      ''
E1    'PHT08'     'PHT07'     'MH68' ''   1     57    1.35  0.00338     0.018 0     1     0      ''
E1    'PHT09'     'PHT08'     'MH19' ''   1     91    1.35  0.00338     0.018 0     1     0      ''
E1    'PHT10'     'PHT09'     'MH18' ''   1     90    1.35  0.00338     0.018 0     1     0      ''
E1    'PHT11'     'PHT10'     'MH16' ''   1     88.5  1.35  0.00338     0.018 0     1     0      ''
E1    'PHT12'     'PHT11'     'MH11' ''   1     44    1.35  0.00338     0.018 0     1     0      ''
E1    'PHT13'     'PHT12'     'MH01' ''   1     116   1.35  0.00338     0.018 0     1     0      ''
E1    'PHT14'     'PHT13'     'MH24' ''   1     21    1.35  0.00338     0.018 0     1     0      ''
*E1   'DP01'      'PHT14'     ''    ''    22   0 0    0           0     0     0     0    ''

*E1   'PHT15'     'DP01'       ''   ''    1     207   1.8   0.00238     0.018 0     1     0      ''
E1    'PHT15'     'PHT14'      ''   ''    1     207   1.8   0.00238     0.018 0     1     0      ''
E1    'PHT16'     'PHT15'      ''   ''    1     207   1.8   0.00238     0.018 0     1     0      ''
E1    'PHT17'     'PHT16'      ''   ''    1     207   1.8   0.00238     0.018 0     1     0      ''
E1    'PHT18'     'PHT17'      ''   ''    1     207   1.8   0.00238     0.018 0     1     0      ''
E1    'PHT19'     'PHT18'      ''   ''    1     207   1.8   0.00238     0.018 0     1     0      ''
E1    'PHT20'     'PHT19'      ''   ''    1     207   1.8   0.00238     0.018 0     1     0      ''
E1    'PHT21'     'PHT20'      ''   ''    1     207   1.8   0.00238     0.018 0     1     0      ''
E1    'PHT22'     'PHT21'      ''   ''    1     207   1.8   0.00238     0.018 0     1     0      ''
E1    'PHT23'     'PHT22'      ''   ''    1     207   1.8   0.00238     0.018 0     1     0      ''
E1    'PHLANSD'   'PHT23'      ''   ''    19    0     0     0           0     0     0     0     ''
*
*     NOE N(1)    N(2)  N(3) NTYPE DIST GEOM1 SLOPE ROUGH GEOM2 BARREL GEOM3  KGEOM
*
*    Manholes for inflow hydrographs
*
E1    'GIBM3' ''  ''    ''    19    0     0     0     0     0     0     0     ''
E1    'GIBM4' ''  ''    ''    19    0     0     0     0     0     0     0     ''
E1    'GIBM5' ''  ''    ''    19    0     0     0     0     0     0     0     ''
E1    'GIBM6' ''  ''    ''    19    0     0     0     0     0     0     0     ''
E1    'GIBM7' ''  ''    ''    19    0     0     0     0     0     0     0     ''
E1    'GIBM8' ''  ''    ''    19    0     0     0     0     0     0     0     ''
E1    'GIBM14' '' ''    ''    19    0     0     0     0     0     0     0     ''
E1    'GIBM19' '' ''    ''    19    0     0     0     0     0     0     0     ''
E1    'GIBM22' '' ''    ''    19    0     0     0     0     0     0     0     ''
E1    'GIBM24' '' ''    ''    19    0     0     0     0     0     0     0     ''
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E1    'GIBM29' '' ''    ''    19    0     0     0     0     0     0     0     ''
E1    'GIBM36' '' ''    ''    19    0     0     0     0     0     0     0     ''
E1    'GLES' ''   ''    ''    19    0     0     0     0     0     0     0     ''
E1    'VYDP' ''   ''    ''    19    0     0     0     0     0     0     0     ''
E1    'GLGW' ''   ''    ''    19    0     0     0     0     0     0     0     ''
E1    'PHISW' ''  ''    ''    19    0     0     0     0     0     0     0     ''
E1    'GIBB3' 'GIBM3' ''  ''  13    100   0.6   .002  0.04  2.4   1     2     ''
E1    'GIBB4' 'GIBB3' 'GIBM4' '' 16  0    0     .0029 0     0     50    0     ''
E1    'GIBB5' 'GIBB4' 'GIBM5' '' 16  0    0     .0029 0     0     51    0     ''
E1    'GIBB6' 'GIBB5' 'GIBM6' '' 1  163   1.2   .0049 .012  0     1     0     ''
E1    'GIBB7' 'GIBB6' 'GIBM7' '' 1  167   1.2   .0049 .012  0     1     0     ''
E1    'GIBB8' 'GIBB7' 'GIBM8' '' 16  0    0     .0051 0     0     150   0     0
E1    'GIBB8A' 'GIBB8'  ''    '' 16  0    0     .0043 0     0     175   0     0
E1    'GIBB14' 'GIBB8A' 'GIBM14' '' 16    0     0     .0015 0     0     200   0     0
E1    'GIBB19' 'GIBB14' 'GIBM19' '' 16    0     0     .0043 0     0     210   0     0
E1    'GIBB22' 'GIBB19' 'GIBM22' '' 16    0     0     .001  0     0     220   0     0
E1    'GIBB24' 'GIBB22' 'GIBM24' '' 16    0     0     .0089 0     0     230   0     0
E1    'GIBB29' 'GIBB24' 'GIBM29' '' 16    0     0     .0018 0     0     250   0     0
*
*
E1    'GIBB34' 'GIBB29' ''    ''    13    217   0.5   .013  0.018 3     1     0.5   ''
*
*
E1    'GIBB36' 'GIBB34' 'PHLANSD' 'GLES'  13    560   .5    .013  0.018 3     1     0.5   ''
E1    'GIBB41A' 'GIBB36' 'VYDP'     ''    13    40    .5    .013  0.018 3     1     0.5   ''
E1    'VYCULV'  'GIBB41A' ''  ''    2     12    1.4   .013  0.018 3.04  1     0     ''
E1    'GLLR'  'VYCULV'  ''    ''    13    950   2     .003  0.032 3     1     2     ''
E1    'HEIN'  'GLLR'    ''    ''    13    1050  0.5   .003  0.018 3     1     0.5   ''
E1    'GLPHI1' 'HEIN'   ''    ''    13    570   3     .003  0.032 2     1     1     ''
E1    'GLPHI2' 'GLPHI1' 'PHISW' 'GLGW'    13    570   3     .003  0.032 2     1     1     ''
E1    'SPRING'  'GLPHI2'      ''    ''    2     14    1.5   .00143 0.018      5     1     0     ''
*
*   HEC Station elevation pairs for natural cross-sections
*
*E2  XNL    XNR   XNCH
E2    .1     .1    .035
```

```
*E3   SECNO NUMST STCHL STCHR XLOBL XLOBR LEN  PXSECR PSXECE
E3    50    9     28.5  31.5  0     0     488   0      0
*E4   EL1   STA1  EL2   STA2  EL3   STA3  EL4   STA4  EL5   STA5
E4    0     0     -4.33 15    -5.2  21.5  -5.75 28.5  -6.73 30
E4    -5.75 31.5  -5.46 36.5  -5.36 42.5  -5.36 60
E3    51    9     28.5  31.5  0     0     360   0      0
*E4   EL1   STA1  EL2   STA2  EL3   STA3  EL4   STA4  EL5   STA5
E4    0     0     -4.33 15    -5.2  21.5  -5.75 28.5  -6.73 30
E4    -5.75 31.5  -5.46 36.5  -5.36 42.5  -5.36 60
*E2  XNL    XNR   XNCH
E2    0.03  .03   .02
*E3   SECNO NUMST STCHL STCHR XLOBL XLOBR LEN  PXSECR PSXECE
E3    150   10    6.23  9.69  0     0     365   0      0
*E4   EL1   STA1  EL2   STA2  EL3   STA3  EL4   STA4  EL5   STA5
E4    0     0     0     4.17  -.8   4.97  -.67  6.23  -1.58 7.31
E4    -1.58 8.5   -.71  9.69  -.67  10.88 .26   11.6  .38   17.45
*
*E3   SECNO NUMST STCHL STCHR XLOBL XLOBR LEN  PXSECR PSXECE
E3    175   10    6.23  9.69  0     0     388   0      0
*E4   EL1   STA1  EL2   STA2  EL3   STA3  EL4   STA4  EL5   STA5
E4    0     0     .26   4.17  -1.08 4.97  -.86  6.23  -1.84 7.31
E4    -1.8  8.5   -.87  9.69  -.92  10.88 .2    11.6  -.14  17.45
*
*E3   SECNO NUMST STCHL STCHR XLOBL XLOBR LEN  PXSECR PSXECE
E3    200   10    5.12  8.9   0     0     620   0      0
*E4   EL1   STA1  EL2   STA2  EL3   STA3  EL4   STA4  EL5   STA5
E4    0     0     .55   2.82  -.91  4.06  -.82  5.12  -1.63 5.96
E4    -1.62 8     -.79  8.9   -.77  9.76  .13   11.04 -.06  16.04
*
*E3   SECNO NUMST STCHL STCHR XLOBL XLOBR LEN  PXSECR PSXECE
E3    210   10    5.12  8.9   0     0     72    0      0
*E4   EL1   STA1  EL2   STA2  EL3   STA3  EL4   STA4  EL5   STA5
E4    0     0     .55   2.82  -.91  4.06  -.82  5.12  -1.63 5.96
E4    -1.62 8     -.79  8.9   -.77  9.76  .13   11.04 -.06  16.04
*
*E3   SECNO NUMST STCHL STCHR XLOBL XLOBR LEN  PXSECR PSXECE
```

```
E3    220   10    5.12  8.9   0     0     65    0     0
*E4   EL1   STA1  EL2   STA2  EL3   STA3  EL4   STA4  EL5   STA5
E4    0     0     .55   2.82  -.91  4.06  -.82  5.12  -1.63 5.96
E4    -1.62 8     -.79  8.9   -.77  9.76  .13   11.04 -.06  16.04
*
*E3   SECNO NUMST STCHL STCHR XLOBL XLOBR LEN    PXSECR PSXECE
E3    230   10    5.12  8.9   0     0     77     0      0
*E4   EL1   STA1  EL2   STA2  EL3   STA3  EL4   STA4  EL5   STA5
E4    0     0     .55   2.82  -.91  4.06  -.82  5.12  -1.63 5.96
E4    -1.62 8     -.79  8.9   -.77  9.76  .13   11.04 -.06  16.04
*
*E3   SECNO NUMST STCHL STCHR XLOBL XLOBR LEN    PXSECR PSXECE
E3    250   8     1.55  5.15  0     0     135    0      0
*E4   EL1   STA1  EL2   STA2  EL3   STA3  EL4   STA4  EL5   STA5
E4    1.8   0     1     0.8   1     1.55  0     2.55  0     4.15
E4    1     5.15  1     5.9   1.8   6.7
*============================================================================
*   Detention pond 11
*     LOUT(IS)
G1    0
*    TSDEP  TSAREA   TSTORE   TSQOU
G2    0     3032        0     1.5
G2    0.5   3265        0     1.5
G2    1.1   3505        0     1.5
G2    1.5   4755        0     1.5
G2    2     5025        0     1.5
*============================================================================
*    STORL  PTCO(1)  PTCO(2)  PTCO(3)  PTCO(4)
* G5    50.0    0.0      0.0
G5    0     0
*============================================================================
*   Detention pond 03
*     LOUT(IS)
G1    0
*    TSDEP  TSAREA   TSTORE   TSQOU
G2    0     0           0     1.5
```

```
G2    0.715 3200        0     1.5
G2    1.43  17000       0     1.5
*===========================================================================
*    STORL  PTCO(1)  PTCO(2)  PTCO(3)  PTCO(4)
* G5    50.0    0.0      0.0
G5    0     0
*===========================================================================
*   Detention pond 01
*     LOUT(IS)
*G1    0
*    TSDEP  TSAREA   TSTORE   TSQOU
*G2   0     3032        0     3
*G2   0.5   3265        0     3
*G2   1.1   3505        0     3
*G2   1.5   4755        0     3
*G2   2     5025        0     3
*===========================================================================
*    STORL  PTCO(1)  PTCO(2)  PTCO(3)  PTCO(4)
* G5    50.0    0.0      0.0
*G5   0     0
*===========================================================================
*    JN(1)   .....  JN(NOUTS)
H1   'SPRING' 'PHISW'  'GLGW'
*===========================================================================
*  Inlets for input of varying baseflow conditions
I1  'GIBM3'     'SHF'
*===========================================================================
*    NYN(1)    .....  NYN(NNYN)
J1   'SPRING'
*===========================================================================
*    NPE(1)    .....  NPE(NNPE)
J2   'SPRING'
*===========================================================================
R1   0       0.1
R1   912     0.1
R1   912     0.1
```

```
R1   8101    0.1
R1   8101    0.1
R1   8219    0.138
R1   8219    0.138
R1   8755    0.07
R1   8755    0.07
R1   9556    0.07
R1   9556    0.07
R1   10224   0.07
R1   10224   0.07
R1   10661   0.06
R1   10661   0.06
R1   11256   0.06
R1   11256   0.06
*==============================================================================
*               End your input data set with a $ENDPROGRAM.
$ENDPROGRAM
```