Modeling Urban Stormwater Disposal Systems for their Future Management and Design

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B.Sci.(Env.Sci)(Hons)

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ABSTRACT

This thesis investigates aspects of urban stormwater modeling and uses a small urban catchment (NE38) located in the suburb of Nedlands in Perth, Western Australia to do so. The MUSIC (Model for Urban Stormwater Improvement Conceptualisation) model was used to calibrate catchment NE38 using measured stormwater flows and rainfall data from within the catchment. MUSIC is a conceptual model designed to model stormwater flows within urban environments and uses a rainfall-runoff model adapted to generate results at six minute time steps. Various catchment scenarios, including the use of porous asphalt as an alternative road surface, were applied to the calibrated model to identify effective working stormwater disposal systems that differ from the current system.

Calibrating catchment NE38 using the MUSIC model was attempted and this involved matching modeled stormwater flows to stormwater flows measured at the catchment drainage point. This was achieved by measuring runoff contributing areas (roads) together with rainfall data measured from within the catchment and altering the seepage constant parameter for all roadside infiltration sumps. The seepage constant was 509 mm/h. Direct measurement of saturated hydraulic conductivity (K_{sat}) using the constant head permeameter method for roadside infiltration sumps within catchment NE38, enabled comparison of the mean value to the seepage constant. The mean measured value of 520 mm/h was very close to the seepage constant of 509 mm/h and generated stormflows only 1% below measured volumes. Consequently, it was possible to use an uncalibrated MUSIC model to predict flow and contaminant loads, provided the saturated hydraulic conductivity of roadside infiltration sumps and runoff contributing areas (roads) were directly measured.

Furthermore, using input rainfall data sourced from the Perth Airport Meteorological station resulted in a 24% overestimation of runoff, whilst a 10% underestimation occurred as a result of using digital map data without field survey.

Two levels of porous asphalt conversion (35% and 68%) were used as input data together with a modified stormwater disposal system that excludes roadside infiltration sumps and a predicted rainfall dataset for the years 2036 and 2064 in the calibrated model. These results were compared to those generated from the current scenario in 2006, 2036 and 2064, which does not include porous asphalt and uses the existing stormwater disposal system that includes roadside infiltration sumps.

The MUSIC model generated future scenario outcomes for alternative stormwater disposal systems that displayed similar or improved levels of performance with respect to the current system. The following scenarios listed in increasing order of effectiveness outline future stormwater disposal systems that may be considered in future urban design.

1. 35% porous asphalt application with no sumps in 2036
2. 35% porous asphalt application with no sumps in 2064
3. 68% porous asphalt application with no sumps in 2036
4. 68% porous asphalt application with no sumps in 2064

Future scenarios using the current stormwater disposal system (with roadside infiltration sumps) with porous asphalt were also run. These scenarios reduced stormwater runoff and contaminant loading on the catchment drainage point however the inclusion of a roadside infiltration sump system may not appeal to urban designers due to the costs involved with this scenario.

Climate change will affect the design of future stormwater disposal systems and thus, the design of these systems must consider a rainfall reducing future. Based on the findings of this thesis, current stormwater runoff volumes entering catchment drainage points can be reduced together with contaminant loads in urban environments that incorporate porous asphalt with a stormwater disposal design system that is exclusive of roadside infiltration sumps.

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The City of Nedlands was also of extreme help in offering information relating to catchment NE38. Specifically they provided digital information, permission to record flow data and rainfall within catchment NE38 and also provided personnel to assist with the sampling of surface soils from several roadside infiltration sumps located within the catchment.

The Bureau of Meteorology was kind to provide six minute rainfall and evapotranspiration datasets that were used in this thesis for modeling purposes.

The computer support team at the School for Environmental Systems Engineering saved my work on more than one occasion and I thank them for their help and expertise.

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1 Introduction

1.1 Motivation for the study

This thesis focuses on evaluating the potential benefits of adopting source treatment of stormwater in a small urban catchment in Perth, Western Australia. Emphasis is placed on using modeling to assess the potential for porous asphalt to enhance source infiltration in current and future scenarios. An altered stormwater disposal system is also modeled in a future rainfall setting to evaluate whether the changed system can improve stormwater disposal in a future urban environment. In order to perform this evaluation it is necessary to firstly assess the characteristics of the current stormwater system by measurement and modeling of stormwater discharge.

Stormwater disposal systems (SDS) vary across the world and their design is affected by climate, environmental setting and local authority policies. Designed in response to urbanisation, SDS provide a route for stormwater to travel down gradient to the drainage point of a catchment. Through this routing process, stormwater may be passed through several treatment or detention measures such as detention basins, roadside infiltration sumps, grassed swales and sediment traps before finally reaching the catchment outlet. The focus for stormwater management has recently shifted from in-transit and end of pipe treatments to source control measures, which include public education, street sweeping and porous asphalt. Source control, in particular infiltration, represents a management option that decreases runoff peaks and volumes and best imitates a pre-developed environment (Mikkelsen et al., 1996).

SDS of urban catchments in Perth, Western Australia, are driven largely by channeling stormwater generated from roads through detention basins and infiltration sumps, before discharging to infiltration basins and water bodies such as the Swan River and Indian Ocean (Fig. 1.1).

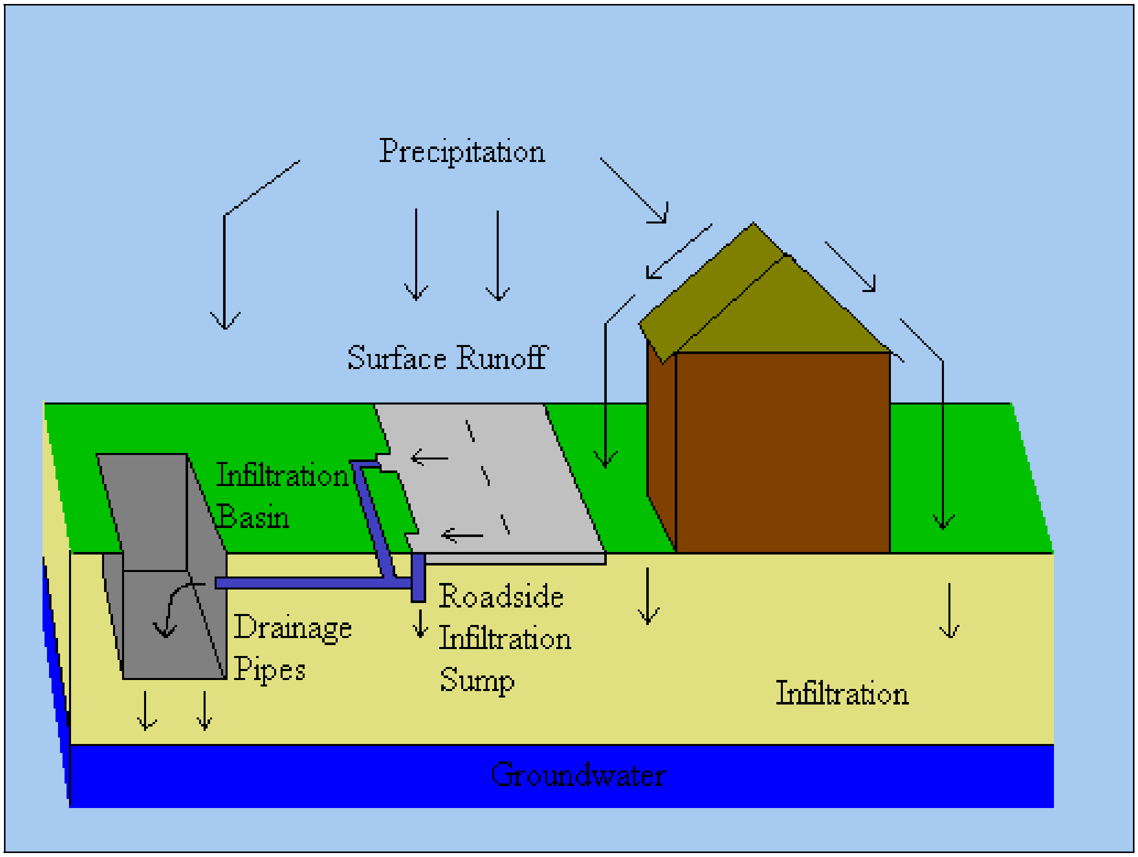

Figure 1.1 Typical urban stormwater system in Perth, Western Australia.

Whilst infiltration practices are incorporated in the current system, they are often utilised at the catchment drainage point, instead of at the point of flow generation. This is especially the case in older established catchments. As a result, high stormflows are directed to infiltration basins and roadside infiltration sumps, placing the pollutant removal capabilities of these treatment devices under load. This can lead to unfiltered recharge, contributing urban contaminants to groundwater. It is therefore desired to adopt measures that will ease the pressure on established end of pipe management options by intercepting and treating stormflows at their source.

Porous asphalt represents such a measure. The majority of urban stormflows are generated from roads, so by targeting road surfaces as source areas for treatment, stormwater flows can be affected. By passing surface water through highly permeable asphalt, stormflows to the SDS can be reduced, thereby limiting flow volumes entering treatment devices. Whilst porous asphalt has been an accessible management option for some time, it has not been as readily adopted in Australia as it has been in Europe. Consequently it is important to model the potential impacts of porous asphalt on a SDS in the Australian setting.

1.2 Sources and management for stormwater contaminants

1.2.1 Introduction

Urbanisation leads to an increase in areas of impervious surfaces such as roads, parking areas, driveways and pavements (Davies and Bavor, 2000), which increase contaminant contributions from anthropogenic sources (Trauth and Xanthopoulos, 1997). Urban coastal catchments are often responsible for the nutrient enrichment of ground and surface waters (Weaver, 1993), highlighting the need to identify and manage the source of contamination. Nutrient contamination of surface water bodies in particular, has serious implications for their eutrophic state. Excessive phosphorous concentration is the most common cause of eutrophication in freshwater lakes and is usually the most important growth limiting nutrient in aquatic environments (Correll, 1998; Vanraaphorst and Vandermolen, 1998). Phosphorous is generally held strongly to Fe and Al hydroxides on bottom sediments (Van Huet, 1990; Correll, 1998), but can also be occluded in calcium carbonates (Vanraaphorst and Vandermolen, 1998). It can result in algal blooms, which occur when conditions in the water column become anoxic, favouring the release of nutrients such as nitrogen and phosphorous (N to P ratio < 30:1); high water temperatures (20-30^{o}C), high pH (8-10), calm water and low light intensity (Balla, 1994). The control of algal blooms is important, particularly in urbanised areas, where aesthetics are highly valued.

In urban environments, stormwater discharge is a major source of nutrients to surface water bodies. Nutrients such as nitrogen and phosphorous can be transported through the atmosphere in dust or aerosols. However their primary mode of transport, particularly in urban areas, is in surface waters (Correll, 1998). Better management of surface water runoff can reduce annual nutrient discharge volumes to receiving waters and assist in improving the health of surface water systems. With increasing recognition that urban catchments are sources of contaminants to major waterways, it is important to identify and manage the sources of contaminants within coastal urban catchments. Source control is the preferred management option for stormwater management and its benefits are discussed in relation to other treatment options below.

1.2.2 The Nature of Urban Contaminants

Common urban contaminants include nutrients, heavy metals and hydrocarbons. Source control technologies that limit contamination include public education of current practices that contribute to contaminant loading such as excess fertilizer application (nutrients) and appropriate car maintenance to minimize oil spills (hydrocarbons). In Perth however, topsoils are predominantly sandy and stormwater is generated almost exclusively from road surfaces and adjacent parking lots and pathways. Therefore it is only necessary to target these paved areas as sources of urban contamination in stormflow.

Davies et al. (2000) reported pollutant concentrations in Perth were not influenced by traffic volumes but rather by factors such as traffic speed and vehicle type. An earlier study in Perth also showed that whilst road surfaces were an important source of particulate bound heavy metals, their contribution of phosphorous (P) and nitrogen (N) were not significant when compared to other sources such as fertilizers (Davies and Pierce, 1999). McComb and Davis (1993) also state that the primary source of nutrients to urban wetlands of the Swan Coastal Plain is from fertilizer applications to domestic gardens, whilst also citing industrial sources and sewerage as the main cause of eutrophication in urban environments.

Although not a primary contributor of nutrients, road surfaces are a significant source of heavy metals and hydrocarbons in the urban setting (Forman and Alexander, 1998). The consequence of heavy metal runoff from road surfaces in Perth is expressed in sediments of the Swan and Canning Rivers, where acid extractable lead concentrations have been reported to be higher than expected due to the presence of particulate lead oxides from road runoff (Gerritse et al., 1998). It is therefore important to model heavy metals and hydrocarbons in the urban setting to improve pollution management. However this thesis focuses on modeling the removal of nutrients and suspended solids which, whilst are not significantly sourced from road surfaces, provide an indication of particulate bound contaminant transport, which is also applicable to heavy metals and hydrocarbons.

1.2.3 Source Control vs End of Pipe Treatment

Source control treatment measures incorporate infiltration-based practices and more closely resemble natural environmental treatment processes when compared to structural, end of pipe treatments. Such measures include grassed swales, filter strips, rainwater tanks, constructed wetlands and porous pavements (Coombes et al., 2002; Lawrence et al., 1996). Infiltration-based practices result in the natural recharge of groundwater, reduced flooding and peak flows, natural purification of stormwater and decentralised treatment costs (Lawrence et al., 1996; Sieker and Klein, 1998). These practices are widely considered to be the most effective treatment of contaminated stormwater.

Treatment of polluted stormflow can occur as water filters through a porous soil medium, where aerobic biological processes can cause mineralization of organic matter and the oxidation of nitrogen compounds (Mottier et al., 2000). In particular, the presence of cyanobacteria species *Nitrosomonas* and *Nitrobacter* in soil can trigger nitrification (Kotlar et al., 1996), which can be followed by denitrification under anoxic conditions

(Table 1.1). The regional application of these natural processes can impact greatly on the quality of stormwater entering waterways.

Table 1.1 The processes of nitrification and denitrification

Nitrification	$NH_4^+ + 1.5O_2 \rightarrow NO_2^- + 2H^+ + H_2O$ (*Nitrosomonas*)
	$NO_2 + 0.5O_2 \rightarrow NO_3^-$ (*Nitrobacter*)
Denitrification	$6NO_3 + C_2H_5OH \rightarrow 2CO_2 + 3H_2O + 6NO_2^-$
	$4NO_2^- + C_2H_5OH \rightarrow 2CO_2 + 2N_2 + H_20 + 4OH^-$

Structural in-transit and end of pipe treatments, which include infiltration basins, detention basins, roadside infiltration sumps, gross pollutant traps, oil and grit separators and sediment and litter traps are often associated with high maintenance costs (Waters and Rivers Commission, 1998). There is also the problem of contaminant loading over time, which can significantly reduce the effectiveness of such treatments. A study into the quality of bed sediments in a 30 year old infiltration basin in France revealed that oxidation of organic carbon stored in the infiltration bed led to almost permanent anoxic conditions that were only interrupted by short oxic periods during rainfall events (Datry et al., 2003). Such conditions favour desorption of phosphorous from stormwater sediment, leading to a more mobile dissolved phosphate in solution.

Contaminant loading also presents a problem with aged structures. Bottom sediments are both a sink and a source of contamination in the aquatic environment (Mudroch and MacKnight, 1994) and the concentrations of pollutants are generally much greater in sediments than in the overlying water column (Baudo et al., 1990). Detention basins, which are designed to accumulate high nutrient loads and remove suspended solids, heavy metals and hydrocarbons from the drainage system (Marsalek and Marsalek, 1997), are also susceptible to contaminant loading. Sediments in a stormwater management pond in an urban Canadian catchment were found to contain elevated levels of heavy metals, with concerns raised over the concentrations of chromium (Cr), copper (Cu) and lead (Pb) (Marsalek and Marsalek, 1997). Under anoxic conditions, particulate bound phosphorous is released into the overlying water column and discharged into receiving waters. The anoxia causes the reduction of ferric ions to ferrous ions and binding to P is consequently weakened, causing phosphate to diffuse into the overlying water column (Correll, 1998). Continued delivery of contaminants to overloaded treatment devices can generate contaminant discharge downstream under anoxic and other unfavourable conditions. It is therefore desirable to limit current loading on these treatment devices to reduce potential contamination loading in receiving waters.

Extensive changes imposed on the urban hydrological cycle have resulted in stormwater quality improvement methods that require initial and ongoing costs to maintain performance. This includes source control methods. It is therefore desired to adopt treatment measures that are best suited to the area of interest with respect to performance, based on local conditions and cost. Ideally, source control treatments are preferred, which leads to the question; what measures are considered suitable for regional scale treatment of stormwater that will both reduce flooding associated with highly impervious areas and treat stormwater?

1.2.4 Limitations to source control treatment

Whilst the trend is to move towards source control-based treatment for stormwater, failure to consider local conditions affecting the efficiency of these treatments can have ramifications for management. Positive and negative aspects of all management options must be investigated to determine the most suitable measure applicable on an event basis. Infiltration-based practices, which are preferred modern day stormwater management options, have limitations. In some cases, point source infiltration can cause groundwater mounding and lead to the long term degradation of surface soil quality (Marsalek and Marsalek, 1997). Infiltration of stormwater through detention and retention basins can increase the risk of groundwater contamination, especially in areas with sandy soils and shallow water tables. This is because rapid movement of water to the saturated zone does not allow sufficient time for contaminants to degrade or sorb onto particulates (Fischer et al., 2003). This scenario is particularly applicable to Perth, where both shallow water tables and sandy soils are prevalent throughout much of the metropolitan area.

Consequently, slow infiltration through green surfaces is preferred, where microbial and chemical processes in the humic root zone have sufficient time to react and protect groundwater from contamination (Mikkelson et al., 1997). Ultimately, slow water percolation and maintenance of oxidation within the soil medium will increase the efficiency of the filtration process.

Infiltration is used worldwide and its success is driven largely by local environmental conditions. Removal efficiencies of total phosphorous (TP) and total kjeldahl nitrogen

(TKN) of 51% and 65% have been reported from an infiltration basin in Sydney, Australia, where water was passed through a filtration media consisting of a 1:6 mixture of zeolite and coarse quartz sand (Birch et al., 2005). In contrast, elevated concentrations of phosphate and dissolved organic carbon were reported in shallow groundwater below an infiltration basin in France, which fluctuated between 2.5 and 3.5 m beneath the bottom of the infiltration basin (Datry et al., 2004). The thickness of the porous media has a significant impact on removal efficiency of contaminants from stormwater. A study on nutrient transport beneath an infiltration basin near Florida, USA, revealed a removal efficiency of 90% within the upper 4.6 m of subsurface (Sumner et al., 1998). Shallow groundwater levels in Perth, combined with highly permeable coarse sands, make infiltration basins prone to poor removal efficiencies of stormwater contaminants. It has been reported in Perth that TP lost from deep grey sands was found to be four times that of duplex soils (sand over clay) and six times that of heavier soils (Ritchie and Weaver, 1993).

However, infiltration-based practices are feasible in shallow, sandy areas previously regarded as unsuitable, provided the surrounding catchment does not generate high stormwater volumes and associated high discharge rates that limit the detention time of water within the filtration zone. Alternatively, if large catchments are divided into several smaller catchments using a series of connected infiltration measures in series, loading on the focal drainage point of the catchment will be reduced. These outcomes are also achieved if broad-scale infiltration is applied over a catchment as opposed to relying on point source infiltration.

The effect of porous asphalt acting as the primary road surface enables stormwater percolation to be spread out over a greater area, allowing significantly lower water volumes filtrating through a given unit of soil and thereby increasing residence times within the soil medium and increasing the opportunity for the natural purification of contaminated stormwater (Field et al., 1982). Porous asphalt reduces the risk of point source contamination of groundwater through poorly filtered recharge, which is more likely to occur at infiltration basins accepting high volumes of stormwater.

1.2 Aims and objectives

This thesis investigates the measurement, prediction and management of stormwater runoff from a small urban catchment. In Perth, it is evident that only minor quantities of TP and total nitrogen (TN) are sourced from roads, however heavy metals and hydrocarbon loads generated from these surfaces are considered to be significant. Currently, TP and TN contaminated stormwater enters infiltration basins and roadside infiltration sumps in dilute form. However potentially higher risk concentrations of heavy metals and hydrocarbons are sourced from road surfaces; and thus source control through diffusive infiltration will increase the capacity for adsorption of all contaminants onto particulate matter and prevent point source contamination of groundwater through roadside sump infiltration.

Data requirements for predicting the measured stormwater response are investigated in the following chapters and several scenarios are explored to determine how stormwater generation processes can be managed. The potential to use an uncalibrated MUSIC model to predict stormwater flow and contaminant loads is investigated by directly measuring the saturated hydraulic conductivity (K_{sat}) of roadside infiltration sumps located within and near catchment NE38 and comparing the data to the seepage constant parameter that is used to calibrate the model.

Stormwater management studies in Perth have hitherto relied on rainfall data from the Perth Airport site and catchment maps from the Department of Land Information (DLI). The accuracy of the Perth Airport data for local stormwater runoff predictions is investigated with reference to more local rainfall data. The adequacy of the DLI maps is also investigated by field mapping of the drainage system.

The model MUSIC (Model for Urban Stormwater Improvement Conceptualisation) is used to explore the influence of these scenarios on predicted stormwater discharge and how these predictions compare to measured discharge. The best input dataset is then used as a basis for modeling potential stormwater and contaminant control using porous asphalt. Whilst road runoff has been identified as a significant source of heavy metals and hydrocarbons in the urban setting, they are not modeled in this thesis. Alternatively, mean annual loadings for total suspended solids (TSS), TP and TN are modeled in MUSIC, using input data sourced from a local Perth catchment.

Finally the potential impact of climate change on stormwater generation and contaminant loadings is assessed using the model with rainfall input generated from predicted climate change (Berti et al., 2004). This input data is modeled with a modified stormwater disposal system that is void of roadside infiltration sumps together with a porous asphalt urban road system to determine whether stormwater improvements can be achieved as a result of these modifications.

2 Background to the MUSIC model

2.1 Model overview

This thesis uses a stormwater model designed specifically for Australian conditions. MUSIC was developed by the MUSIC Development Team at the Cooperative Research Centre for Catchment Hydrology, under the Urban Stormwater Quality Program at Monash University, Victoria, Australia. MUSIC allows users to model stormwater quantity and quality from catchments and is particularly useful for designing urban stormwater treatment systems (Cooperative Research Centre for Catchment Hydrology, 2005).

MUSIC is unique in that it has the ability to model several treatment devices in the one conceptual model. The option of passing stormwater through a treatment train setup on an event or continuous basis gives MUSIC an advantage over other models that focus only on runoff and treatment into one central treatment device and have time-scale limitations.

MUSIC is controlled through a user-friendly graphical user interface and is operated by linking source and receiving nodes. Source nodes are represented by source areas that include urban, agricultural and forested areas, which receive and distribute rainfall from both impervious and pervious surfaces. Receiving nodes include treatment devices with pollutant removal capabilities such as sedimentation basins and gross pollutant traps. A typical model setup is illustrated in Figure 2.1.

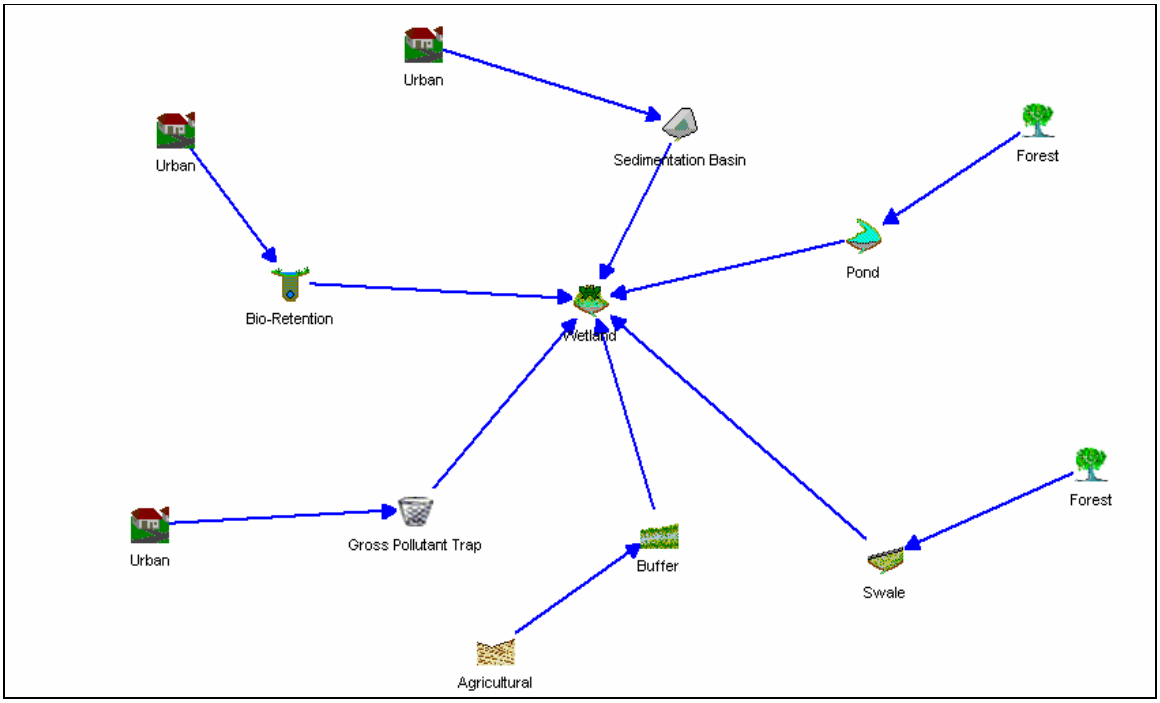

Figure 2.1. Typical setup of an urban stormwater treatment train in MUSIC.

The urban rainfall-runoff model used in MUSIC is based on a model developed by Chiew and McMahon (1997), which generates flows from impervious and pervious surfaces (Fig. 2.2) and has been adapted to generate results at six minute time steps. Flow characteristics and pollutant removal efficiencies of each individual treatment device have been investigated and calibrated by the MUSIC development team in the Australian setting. Equations depicting stormwater flow routing, gross pollutant predictions, bioretention system performance and swale performance are presented and explained in the manual for MUSIC 3.0.1 (Cooperative Research Centre for Catchment Hydrology, 2005).

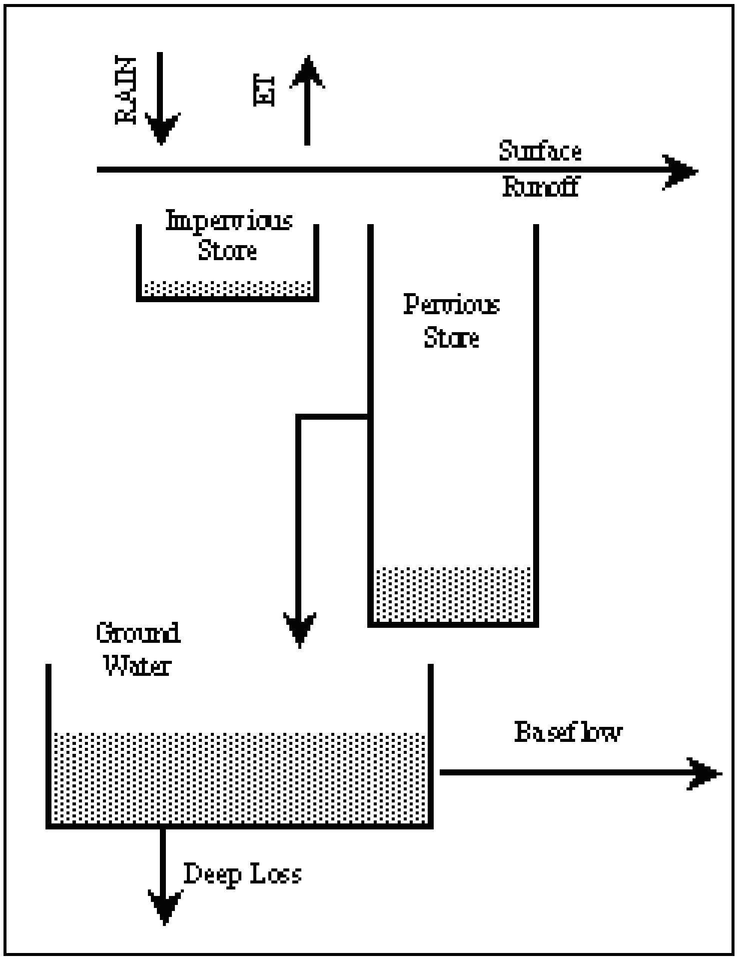

Figure 2.2. Conceptual rainfall-runoff model used in MUSIC (Chiew and McMahon, 1997).

2.1.1 Source Nodes

A source node is separated into adjustable pervious and impervious areas. The properties of both these source areas are adjustable and base and storm flow concentrations of urban contaminants (TSS, TP and TN) can be entered to generate predictions on stormflow volume and contaminant loading. Source nodes range in size from 0.01 – 10000ha.

2.1.2 Treatment Nodes

Treatment node design and function is summarised in Table 2.1.

Table 2.1. Summary of treatment node functions available in MUSIC (Cooperative Research Centre for Catchment Hydrology, 2005).

Treatment	**Type of Treatment**	**Function**
Buffer Strips	Source Control	Sediment removal, pre-treatment for bio-retention
Vegetated Swales	Source Control	Sediment and suspended solid removal
Wetlands	End of Pipe	Suspended solid and soluble contaminant removal
Bioretention Systems	End of Pipe	Particulate and soluble contaminant removal
Infiltration Systems	End of Pipe	Reduce stormwater volume, contain coarse sediment
Ponds	End of Pipe / In Transit	Aesthetics, settle out suspended solids
Rainwater Tanks	Source Control	Re-use of roof runoff
Sedimentation Basin	End of Pipe / In Transit	Compensate flooding, settle out suspended solids
Gross Pollutant Trap	End of Pipe / In Transit	Removal of solids >5mm

2.1.3 Applicability of the model to sandy urban catchments in Perth

MUSIC was designed in Eastern Australia for Eastern Australian soil conditions. MUSIC default values were determined based on calibration of the model to urban catchments in Brisbane and Melbourne. Eastern Australia does not exhibit a shallow groundwater aquifer as Perth does, which can interact with treatment devices such as detention basins in particularly low topographic areas. These marked differences in groundwater characteristics, combined with shallow sandy soils common in Perth, has made the applicability of MUSIC, which was designed originally under different soil / water conditions, challenging (Ewing, 2006). Furthermore, the exposure and use of the model in Western Australia has to date, been limited. Nevertheless, the impervious section of the model remains applicable to catchments worldwide providing they are suitably broken down and adapted to suit the model setup. It was therefore considered that application of the model in the Perth environment was possible, given a focus on impervious areas.

2.1.4 Model Setup

A resolution to overcoming the difficulty of adapting MUSIC to the unique environmental conditions present in Perth by excluding the pervious section of the model is developed in this thesis. Comprising the bulk of the total catchment area, removing pervious areas from the model represents a significant adjustment to the modeling approach. The removal of all pervious surfaces and incorporation of only road surfaces as the impervious section of the model reduced the original catchment contributing area by 95%. Road areas were calculated by analysing digital aerial photographs of the catchment and drainage flow paths were determined by co-analysis of topographic maps and maps of the existing drainage system.

Rainfall input to the model was obtained from an automatic recording rain gauge deployed within the catchment. Later, output from the model using this rainfall input was compared to rainfall input sourced from the Bureau of Meteorology station at Perth airport, which is the conventional source of rainfall data used for Perth.

Model calibration of final flow discharge entering the catchment drainage point is possible by altering the seepage parameter of storm sumps located in series along the road drainage network in order to best match the measured discharge obtained with a flow volume/velocity recorder. The seepage parameter is a constant value applied to all sumps. The sump system is connected to source nodes and other drainage sumps by drainage links, which were not specified lengths and thus had no bearing on volume transfer or time delay of stormwater between connected sumps.

An alternative to undertaking calibration is to measure the K_{sat} of roadside infiltration sumps and set this value as the seepage parameter in the model. This enables the generation of stormflow and contaminant loads using an uncalibrated MUSIC model. Predicted annual loadings for TSS, TP and TN were also generated using MUSIC.

Median TSS, TP and TN values were sourced from a recent road runoff investigation of a local Perth catchment (Davies et al., 2000) and entered into the calibrated model as storm flow concentration parameters (Table 2.2). MUSIC then stochastically generated annual contaminant loads based on the input data using default standard deviations to predict annual pollutant generation (Cooperative Research Centre for Catchment Hydrology, 2005).

Table 2.2. Contaminant input values used in MUSIC

Contaminants	Median (mg/L)	Mean (log mg/L)	Std Dev (log mg/L)
TSS	100	2	0.32
TP	0.5	-0.3	0.25
TN	1.75	0.243	0.19

The particulate removal efficiency of roadside infiltration sumps, which have been modeled as ponds, is governed largely by the velocity of incoming water, as described by Fair and Geyer (1954); and default *k* values enterable in MUSIC, which define the partitioning of water quality constituents that make up TP and TN. Consequently stormwater entering sumps at low velocities will aid the removal efficiency of particulate matter from stormwater. The default *k* values were determined from the water quality of catchments in Melbourne and Sydney. Perth stormwater displays a higher percentage of dissolved phosphorous than other Australian cities (Lund et al., 2000) and as such annual TP loadings predicted by MUSIC using default *k* values may be underestimated.

2.1.5 Model Application

The MUSIC model can be used as a tool for predicting stormwater flows and loadings of TSS, TP and TN under a wide range of environmental conditions. It may be a particularly useful tool for the design and management of existing and planned stormwater management systems and for providing land developers with guidance in meeting pollution generation objectives. In this thesis, the impacts of porous asphalt and climate change on stormwater flow and contaminant loading are assessed. Also identified are the model inputs that influence model performance. This knowledge is important for the setup and application of MUSIC for future catchment modeling scenarios.

3 Modeling stormwater and contaminant flows from a small urban catchment in Perth, Western Australia[*]

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3.1 Abstract

Modeling stormwater and associated contaminant flows in urban watersheds is important for design and management of efficient and safe disposal systems. This study uses measured runoff from a small urban catchment in the suburb of Nedlands, Perth, Western Australia to investigate application of the MUSIC model for stormwater disposal design. We found that without any calibration, the model gave very good predictions of stormwater runoff. To achieve this, we used rainfall data measured within the catchment, carefully defined the impervious contributing area and the location of all roadside infiltration sumps by updating digital maps using field survey. We also correctly identified the seepage parameter for all roadside infiltration sumps by direct measurement of saturated hydraulic conductivity. When the model was run using rainfall datasets from the Perth Airport Meteorological station (conventionally used for stormwater modelling in Perth and located 12 km from the catchment) the runoff was overestimated by 24%. Using only digital maps without field survey led to a 10% underestimation of runoff.

Keywords: Calibration; data validation; infiltration; modeling; MUSIC; parameter; stormwater.

[*] submitted to "Urban Water Journal"

3.2 Introduction

Stormwater runoff in the modern urban setting is dominated by flow from impervious surfaces such as rooftops, roads, pathways and parking lots (Davies & Bavor, 2000). The increase of impervious surfaces changes the hydrological cycle, forcing natural infiltration to be concentrated over much smaller areas, particularly in engineered structures such as infiltration basins, grassed swales and roadside infiltration sumps (Water & Rivers Commission, 1998). The consequence of these changes is far reaching. Urban contaminants including heavy metals, nutrients and petroleum hydrocarbons, are deposited on impervious surfaces, particularly roads (Davies & Pierce, 1999), and are flushed through the stormwater drainage network to stormwater treatment systems. The problem associated with this process is that treatment systems can become loaded over time, compromising their contaminant removal efficiencies (Fischer, Charles & Baehr, 2003). As a result, it is common for untreated contaminants to pass through treatment systems to natural waterways such as rivers, streams and groundwater. The consequences of treatment system overload can include heavy metal and hydrocarbon contamination (Chague-Goff, Rosen & Roseleur, 1999) and eutrophication from nutrient enrichment (Herrman & Klaus, 1997). All forms of contamination pollute the natural ecosystems of receiving waterways, which can affect aquatic life, aesthetics and compromise human recreational use.

Conceptual models of urban stormwater and contaminant transport are potentially useful for assessing the current efficiency of a stormwater treatment system and for predicting stormwater volumes and contaminant loads under changed management scenarios. One such conceptual model is MUSIC (Model for Urban Stormwater Improvement Conceptualisation) and in this study, we investigate the paramaterisation and use of MUSIC to predict storm runoff from a small urban catchment in the suburb of Nedlands, Perth, Western Australia. The catchment is modeled at a fine scale using 6 minute rainfall data and sub-catchment areas as low as 0.01 ha to identify model sensitivity to input data. To commence, we run the model using the best available input data. This comprises rainfall data measured within the catchment using a logging raingauge, updated mapping of the impervious areas and position of roadside infiltration sumps using field survey to amend information available from digital maps and identification of the seepage parameter for all roadside infiltration sumps by direct measurement of saturated hydraulic conductivity. We compare this *a priori* parameterised model to measured runoff data and then examine the errors introduced by using data that would typically be available for stormwater modelling in Perth.

Reliance is often placed on using rainfall datasets obtained from the Perth Airport Meteorological station (12 km from the study catchment) so we examine the error introduced to the model output using the data, rather than the measured catchment rainfall. Finally, we use the original uncorrected digital maps of the drainage network to investigate this source of input error on the model output, by comparison to the original model output using the updated field survey mapping.

3.3 Methods

3.3.1 Catchment Location and Stormwater Network

This study was undertaken in catchment Nedlands 38 (NE38; E386849.8, N6460558.6) as described by JDA (2002), which covers an area of 34.2ha and is located within the Nedlands Council district in the City of Perth, Western Australia (Fig. 3.1 & 3.2) and is included within the Western Regional Organisation of Councils.

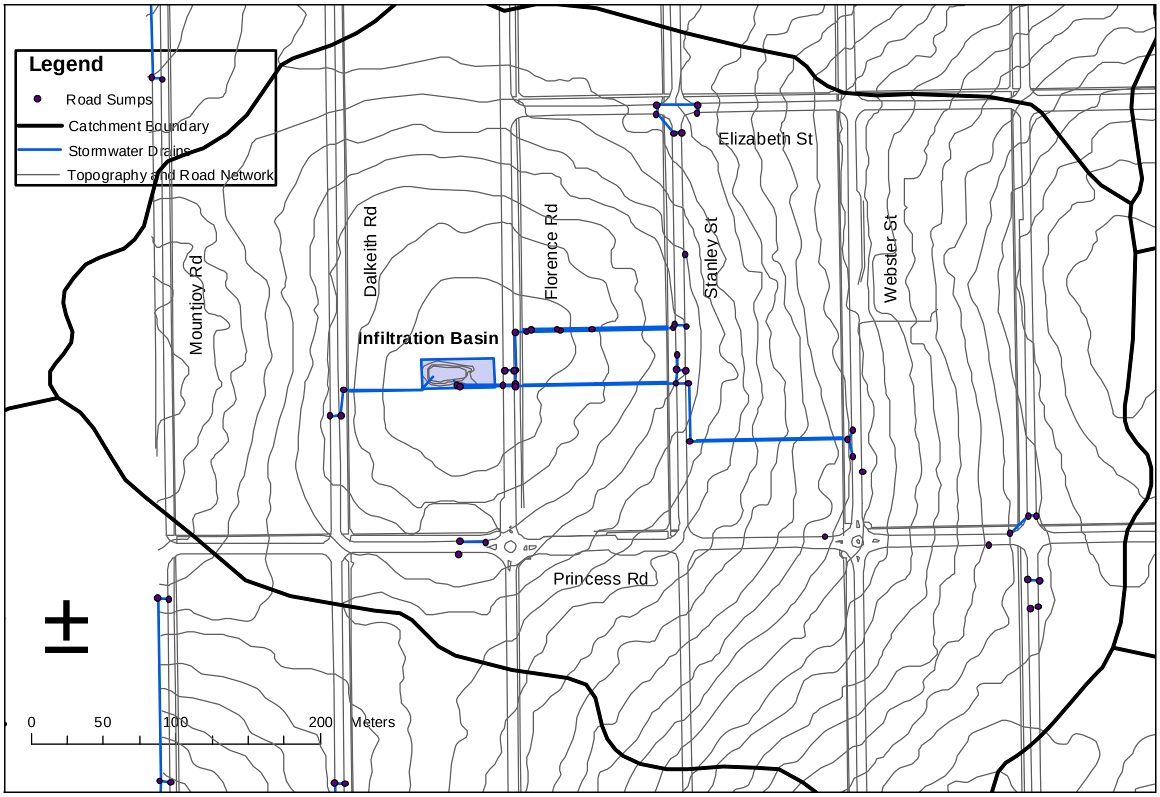

Figure 3.1. Map denoting location and features within NE38

NE38 was selected for the study as it drains to one infiltration basin that receives stormwater discharge from two inlet pipes. Approximately 75% of total stormwater flows are directed through the primary inlet pipe, which has a diameter of 0.61 m. This permits the measurement of high volume urban stormwater flows. MUSIC 2.1 was used to model the scenario of urban stormwater flows within NE38.

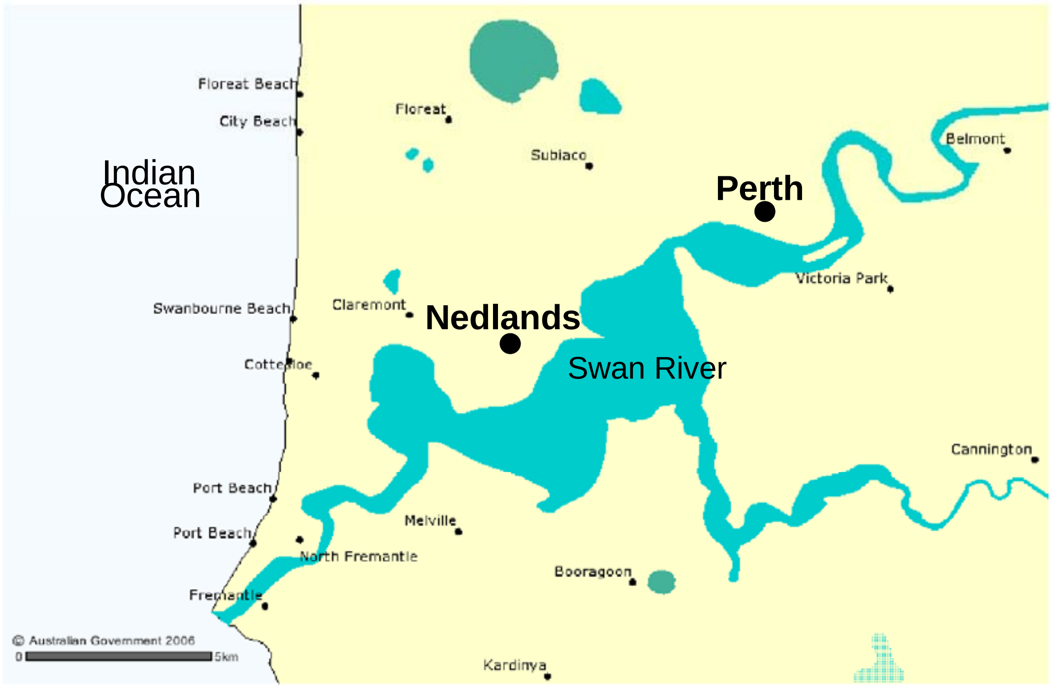

Figure 3.2. Location of Nedlands in relation to Perth and surrounding suburbs (Australian Government, 2006).

3.3.2 Model Description

MUSIC is a conceptual design tool intended as an aid to decision making relating to urban stormwater design (Cooperative Research Centre for Catchment Hydrology, 2003). It has the capability of modeling conceptual designs incorporating stormwater treatment and is useful for assessing performance and predictions on stormwater quantity and quality. This is achieved by creating a treatment train using a series of source nodes and treatment nodes to best represent the particular urban catchment.

3.3.3 Rainfall and Runoff Monitoring

Rainfall input was obtained using 6 minute rainfall data measured on-site using the Davis Tipping Bucket Rain Gauge integrated with Odyssey Data Recorder at a 0.2 mm resolution. Observed flows were measured with a Starflow Ultrasonic Doppler Sensor 6526A, which recorded flow velocities and flow volumes using a 30s scan rate and 1 min logging interval and was mounted at the outlet of the primary inlet pipe using an expanding band clamp. Although the Starflow cannot measure flow data for water depths less than 20 mm, the flow volumes associated with these shallow depths are minor and do not significantly affect the calibration process over the range of typical stormflows (Fig. 3.3).

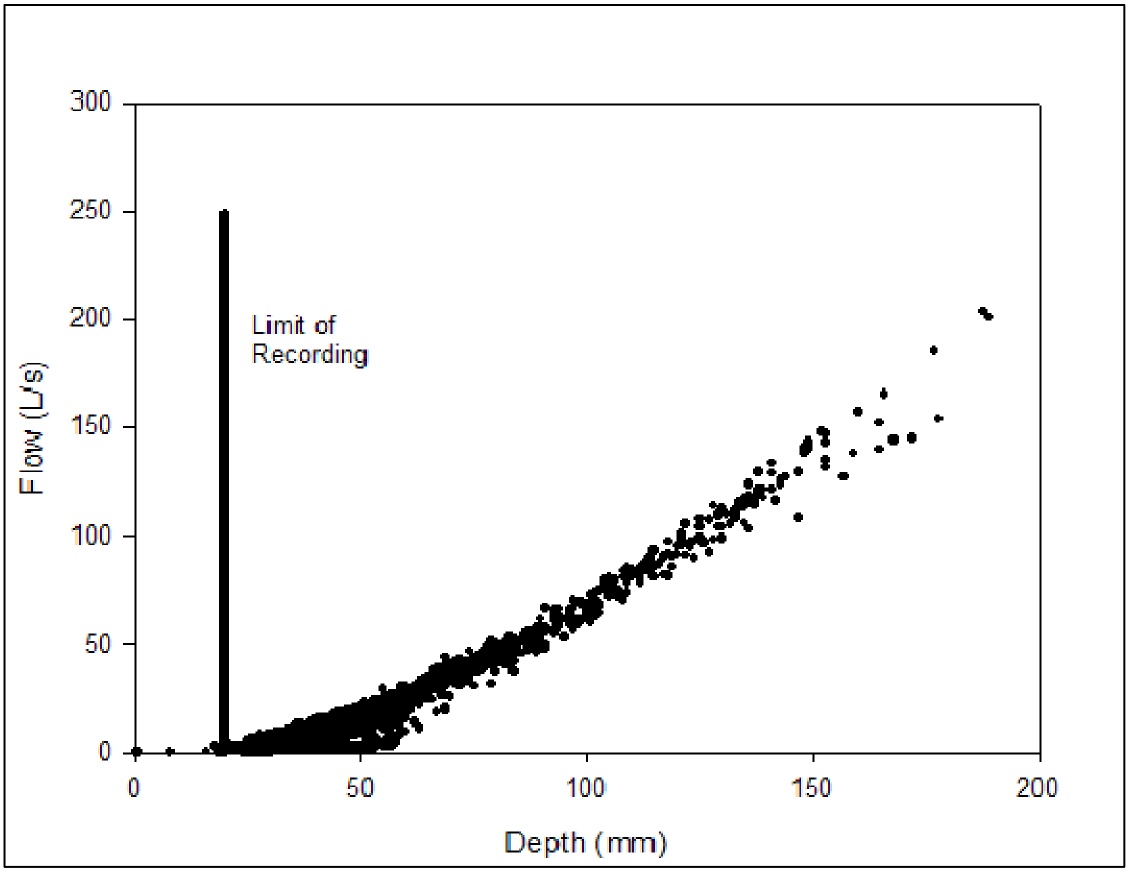

Figure 3.3. All flow data points combined, illustrating limitations of Starflow sensor and the insignificance of flow volumes generated below depths of 20 mm.

Twenty rainfall events were monitored between May 2nd and August 30th 2005. A rainfall event was classified as the total rainfall that fell within a 24 h period. The measured flow data from these events was used for model evaluation and the measured rainfall data was used as model input. Daily evapo-transpiration was taken from the Perth airport over the monitored period. The model was subsequently used with the Perth airport 2004 annual six minute rainfall and daily evapo-transpiration dataset to generate annual stormflow volumes and contaminant loads for that year. All measured rainfall events were plotted against corresponding rainfall events measured at Perth airport (Fig. 3.4). The relationship indicates that in most cases, the rainfall for each event was higher at Perth airport.

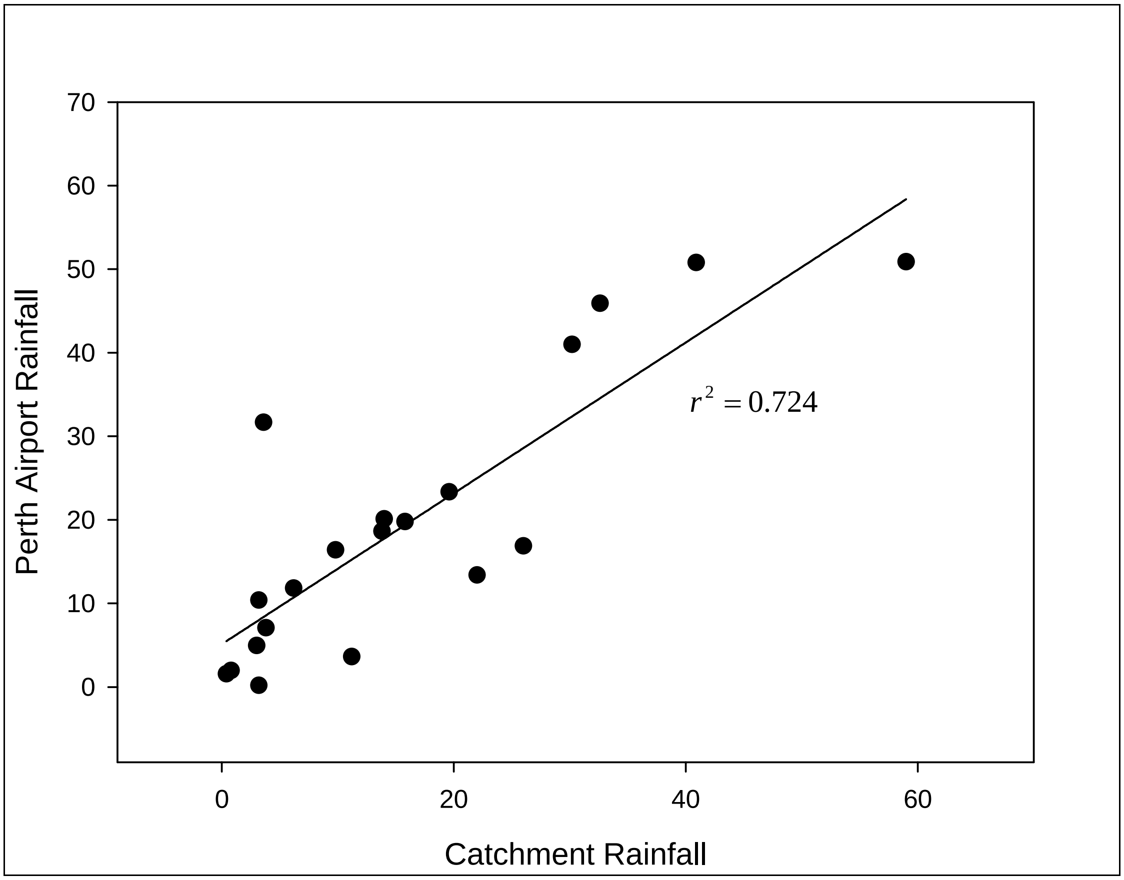

Figure 3.4. Relationship between measured rainfall within the catchment and rainfall from the Perth airport.

MUSIC uses a modified conceptual rainfall-runoff model developed by Chiew & McMahon (1997) to generate urban runoff from impervious and pervious surfaces at six minute time steps (Fig. 3.5). However the pervious section of the model was not utilized when modeling catchment NE38 and thus only impervious modeling was undertaken as stormwater runoff was generated exclusively from impervious surfaces.

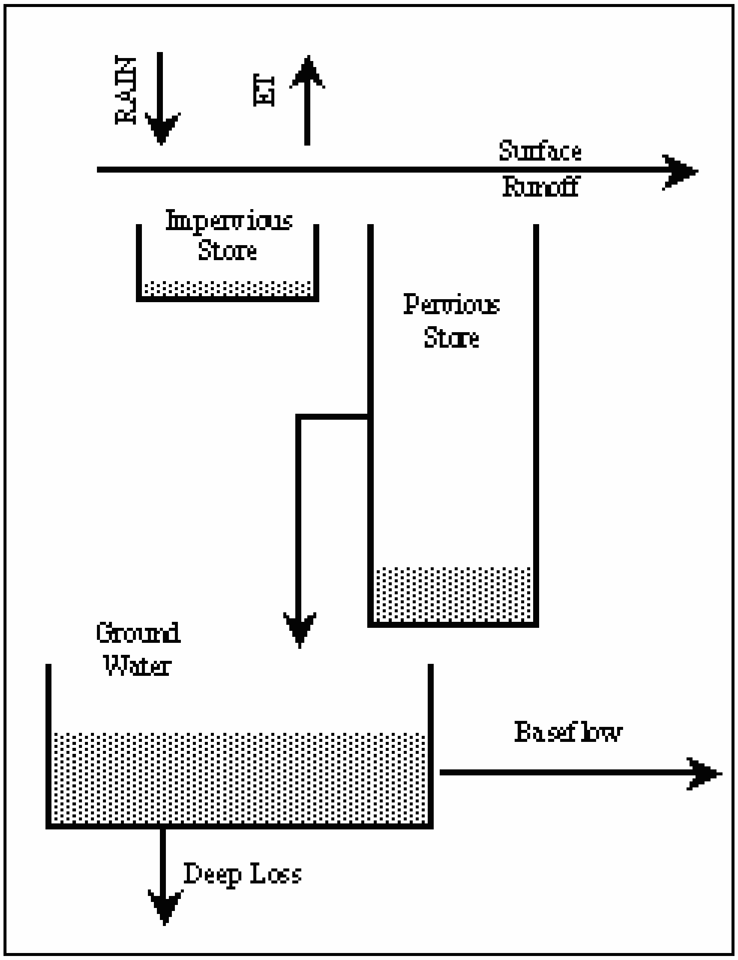

Figure 3.5. Conceptual rainfall-runoff model used in MUSIC

3.3.4 Drainage System Mapping

The catchment drainage system is comprised predominantly of road surfaces with interconnected drainage pipes and roadside infiltration sumps that drain into an infiltration basin that represents the catchment drainage point. Roof surfaces are disconnected from the urban stormwater system. The separation of total catchment area into percentage pervious/impervious areas is undertaken in MUSIC to separate surfaces that infiltrate and generate runoff. Developed initially to suit soil conditions in Eastern Australia, work is still being undertaken to adapt MUSIC to the sandy soil conditions present in Perth.

Consequently, pervious surfaces were not modeled as they do not contribute to stormwater flows in the Perth urban setting (Ewing, 2006). This reduced the model runoff producing area to 1.60ha of the catchment area. At that scale, the exact definition of impervious areas is critical. Thus, the catchment was broken down into several smaller source nodes, or sub-catchments, represented by disconnected segments of the road network, to accurately simulate stormflows within the catchment.

The sub-catchment areas were measured using SkyView, an online digital aerial photography platform developed by the Department of Land Information (DLI), W A. The drainage system and stormwater flow paths were re-organised through analysis of the road network and 1m contour data, which was sourced from the Nedlands council, originally produced by DLI, WA. A rainfall threshold of 2 mm/d was applied to the model to best account for stormwater flow time delays and initial detention of stormwater within impervious areas. This value was selected as it produced modeled hydrographs that best matched the hydrographs generated from measured stormwater volumes.

Based on observations from drainage network maps, it was assumed that roadside infiltration sumps located along the road network were connected by pipes and that inundated sumps overflowed to the next sump down gradient without stormwater loss. Connecting pipes were not assigned specified lengths and thus had no bearing on volume transfer or time delay of stormwater between connected sumps. Sump drainage designs indicate sumps detain half their total storage volume before overflow occurs via the pipe network to the next receiving node. However, several isolated sumps located within the drainage system were disconnected from other sumps. To maintain connectivity to the drainage system, their total storage volume was required to be met before assuming overflow to sumps down gradient (Fig. 3.6).

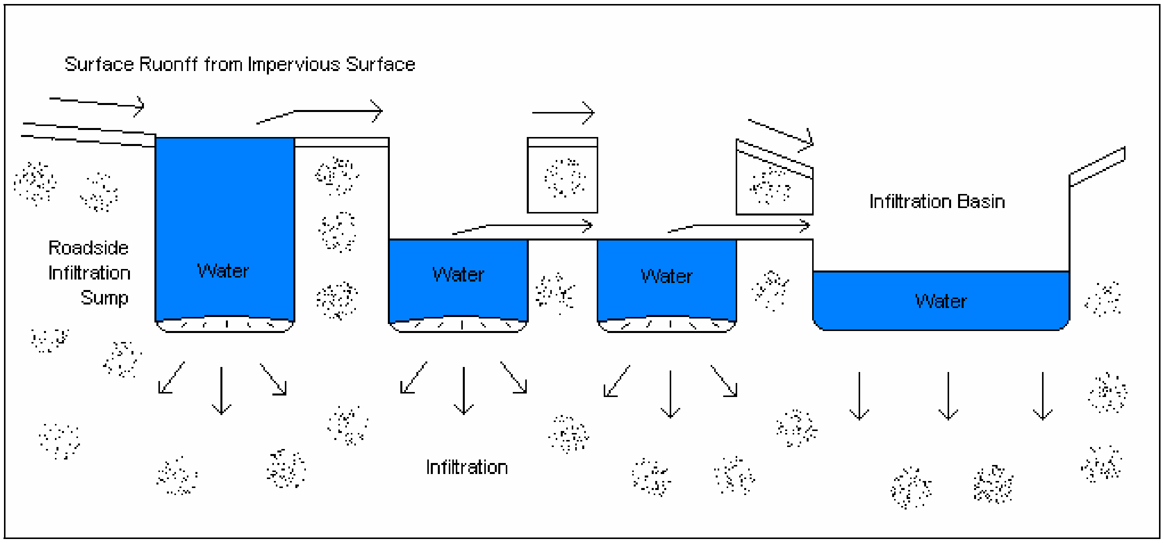

Figure 3.6. Schematic outlining drainage system within NE38.

This overflow is described by a discharge equation (Cooperative Research Centre for Catchment Hydrology, 2003) and is given by:

$$Q = C_w L H^{3/2} \tag{3.1}$$

Where:

Q = Discharge over the weir (m^3/s)

C_w = Weir Coefficient (1.7)

L = Overflow weir width (m)

H = Height of pond above the Extended Detention Depth (m)

3.3.5 Model Setup

The model was set up as a series of source and treatment nodes. Treatment nodes were modeled as ponds (representing roadside infiltration sumps and the infiltration basin). The ponds were selected to model roadside infiltration sumps as they present the option of defining a seepage parameter, which mimics the function of the sump to infiltrate stormwater, thereby removing it from the stormwater system. The storage capacities of receiving nodes were determined from sump designs, whilst pipe outlet parameters were taken from GIS maps of the drainage system acquired from the DLI, W A. Field inspection was undertaken to validate the digital maps of the catchment, in particular the presence of roadside infiltration sumps. The infiltration function of sumps is critical to the modeling process. The field inspection revealed an additional four sumps within the drainage system that were not present on digital maps. It also revealed a series of six sumps connected in series that were not identified on the digital maps and a series of six sumps connected in series that had been removed from the drainage network. Model outputs were generated for total flow, total suspended solids (TSS), total phosphorous (TP) and total nitrogen (TN). Detailed data within NE38 for TSS, TP and TN was not available. Consequently, input values for TSS, TP and TN were taken from median road runoff results produced from a recent investigation in the Perth metropolitan area (Davies, Vukomanovic, Yan & Goh, 2000; Table 3.1). MUSIC then used this input data to stochastically generate mean annual TSS, TP and TN loads.

Table 3.1. Contaminant input values used in MUSIC

Contaminants	**Median (mg/L)**	**Mean (log mg/L)**	**Std Dev (log mg/L)**
TSS	100	2	0.32
TP	0.5	-0.3	0.25
TN	1.75	0.243	0.19

3.3.6 Seepage from Roadside Infiltration Sumps

Soil samples were taken from eight roadside infiltration sumps located within and nearby catchment NE38. Samples were repacked to field density and K_{sat} values were determined by the constant head permeameter method (Bohne, 2005). The mean value was used to define the seepage parameter in MUSIC. These values were also compared to laboratory tested K_{sat} values of Bassendean Sands surface soils samples, which underlie the catchment.

3.4 Results

Over the monitored period, 315 mm of rainfall was recorded, yielding 3 ML of stormflow. For catchment NE38, a strong linear relationship ($R^2 = 0.86$) was found between the magnitude of rainfall events and generated stormflow volumes (Fig. 3.7). This relationship is empirical and specific for the impermeable area and sump characteristics of catchment NE38. The results from MUSIC using the catchment rainfall data, corrected drainage map and an average seepage rate of 520 mm/h for K_{sat} measurements are shown in (Fig. 3.8). This figure illustrates a typical example of matched predicted and measured flow for a typical rainfall event. The recession limbs of predicted flow are not well predicted by the model. This may be due to time delays within the pipe network that the model was unable to predict. Despite this, the fit is remarkably good, given that there has been no calibration.

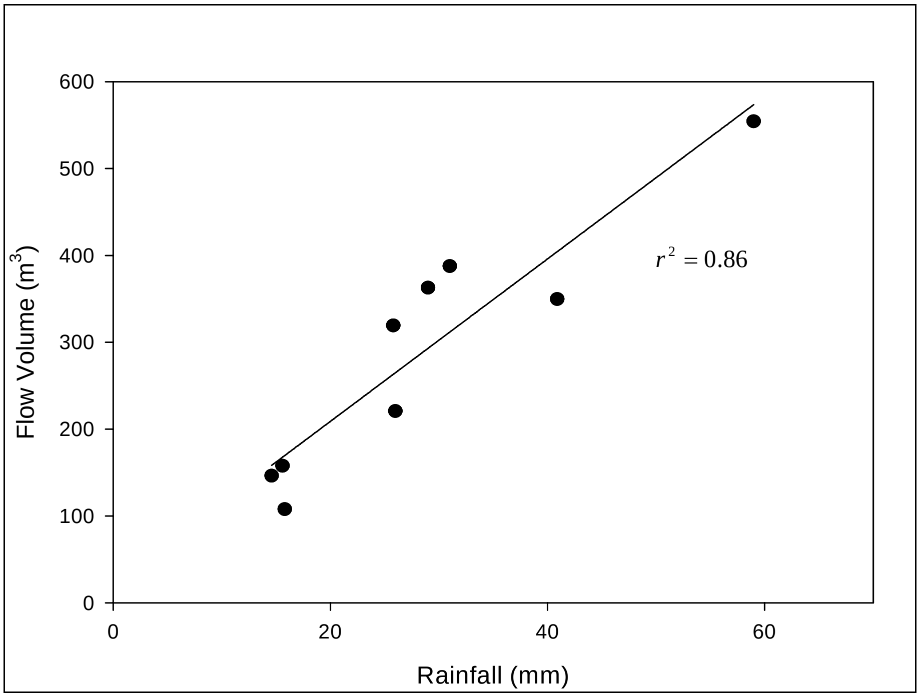

Figure 3.7. Relationship between Rainfall Event magnitude and Stormflow Volume production

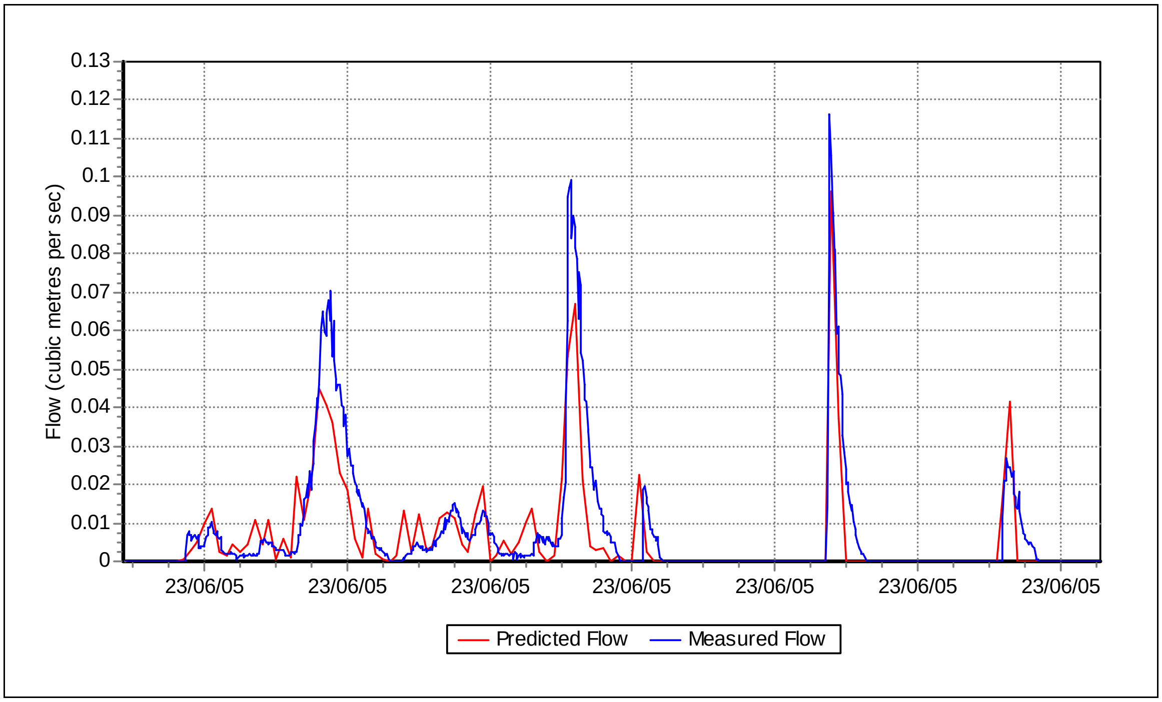

Figure 3.8. Measured vs Predicted flow data hydrograph displaying flow velocities and resolution limitations of Starflow Sensor in NE38.

Due to the limitations of the Starflow sensor, very low flows generated at depths <20mm were not measured (Fig. 3.3). Consequently MUSIC occasionally produced flows peaks <0.01 m^3/s that could not be detected by the Starflow sensor (Fig. 3.8). As a result, there is a slight model overestimation for low flow events. Replacing the catchment rainfall dataset with data from the Perth Airport Meteorological station produced flow volumes 24% greater than observed flow volumes (Fig. 3.9).

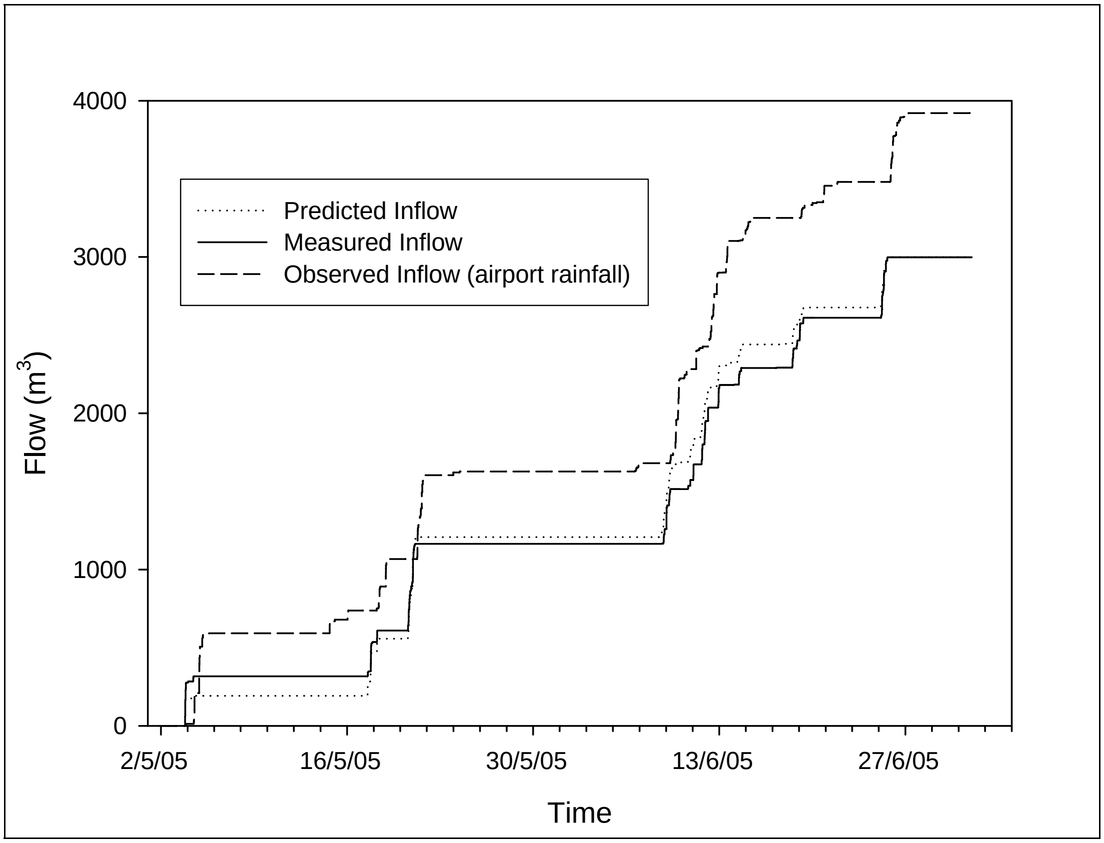

Figure 3.9. Cumulative flows displaying calibration and comparison to airport rainfall dataset

Results from the MUSIC model runs presented in Table (3.2) compare the base scenario (run using measured rainfall data from the catchment, together with the digital map of the drainage system updated and rectified from field observations), with a scenario run using the raw digital map data. The results show that flow volumes decreased by 9.73%, whilst decreases were also evident for mean annual TSS, TP and TN loadings (Table 3.2). The total predicted mean annual stormwater volume using measured rainfall and updated digital map information for NE38 is 5.15 ML, which equates to a stormwater production volume of 3.21 ML/ha.

Table 3.2. Comparison of mean annual production using 2004 six minute rainfall data

Parameters	Scenario Using Corrected Stormwater Drainage System from Field Observations	Scenario Using Original Digital Map Information	% Change
Flow (ML/yr)	5.15	4.67	-9.33
TSS (kg/yr)	606	564	-6.93
TP (kg/yr)	2.88	2.6	-9.72
TN (kg/yr)	10.0	9.25	-7.5

Laboratory tested mean K_{sat} values were also available for 38 Bassendean Sand soils surface samples, which are typical of soils in catchment NE38. The mean K_{sat} value of 760 mm/h from these samples (an increase of 240 mm/h) generated predicted flow volumes 13% below measured volumes.

3.5 Discussion

MUSIC gave a good representation of stormwater discharge once the drainage network was accurately defined and seepage from roadside infiltration sumps had been measured. Validation of digital maps is recognized as an integral part of producing accurate simulations for geographical information systems (GIS) and should be given attention to ensure accurate results in remote sensing studies (Brogaard & Olafsdottir, 1997). The process of field validation revealed several changes to the drainage network, which were not detailed on digital maps of the system. The loss of two roadside infiltration sumps was expected to increase the total flow volume; however a 9.7% increase was unexpected, considering a total of 43 sumps are present within the drainage network system. This increase may be attributed to six sumps that were removed from the drainage network and the change in stormflow paths caused by their removal. They were connected in series and were linked to a single source node at the top of the catchment. Their removal resulted in a source area of 0.12 ha that redirected runoff down-gradient around the pre-existing sumps and placed additional hydraulic load on a separate sump system. This effect, combined with the addition of other sumps, which further disaggregated the catchment, reduced the infiltration potential of the drainage system.

Of significant importance were K_{sat} values measured from roadside infiltration sump surface soils samples. Over the total study period, predicted stormflow using the measured K_{sat} data varied by only 1% compared to measured volume. The 520 mm/h value is lower than the mean value taken from laboratory tested K_{sat} values from Bassendean Sands and this may be attributed to the infilling of surface pore space by fine material derived from stormwater runoff. The implications of these results suggest that within the Perth urban setting, stormwater runoff volumes can be predicted without calibration using the MUSIC model provided K_{sat} values of roadside infiltration sumps are measured and the impervious contributing area is reliably mapped.

In this study there is an intercompensation of errors, with the Perth rainfall dataset giving an overestimate of stormflow, and the original digital map giving an underestimate. It would therefore be quite possible to ‘calibrate’ the model using these input datasets by simply increasing the seepage parameter. The result could lead to flawed design decisions because the capacity of roadside infiltration sumps would be overestimated. We therefore recommend direct measurement of the seepage parameter in MUSIC.

3.6 Conclusions

We have shown that MUSIC can be applied to predict stormwater flows in a catchment with soil conditions vastly different to those it was originally designed for. This adaptability suggests that MUSIC is a useful tool for design and management of stormwater systems in a wide range of urban settings. We demonstrated that when runoff generation is restricted to impervious surfaces and seepage losses occur through well defined roadside infiltration sumps, no model calibration was required, provided the input datasets are of sufficient quality. . It should also be emphasized the pervious component of the model was not evaluated in this study and further investigation is required to fully test its application in the Perth urban setting, whilst re-evaluation of the model approach used in this study should be undertaken for urban settings with additional stormwater connections such as rooftops.

4 A practical approach to the future management of urban stormwater pollution in Perth, Western Australia**

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4.1 Abstract

Urbanisation affects the hydrological cycle by reducing infiltration and increasing surface water flows. Urban contaminants present in stormwater are transported via stormwater disposal systems to treatment devices such as roadside infiltration sumps and infiltration and detention basins. Implementing source control technologies to limit contamination loading on these structures may even eliminate their necessity altogether. The conversion of traditional to porous asphalt can reduce traffic noise and also act as a source control treatment measure for lightly trafficked urban areas, with a potential to reduce storm flows to the stormwater disposal system. This study uses an existing urban stormwater model MUSIC, previously shown to give a good representation of runoff from a small urban catchment in Perth, Western Australia. Here we use the model to investigate the effects of porous asphalt on future stormwater flows within the previously modeled small urban catchment in the suburb of Nedlands, Perth, Western Australia. The study aims to determine whether roadside infiltration sumps are necessary in future stormwater disposal systems that accommodate porous asphalt. To achieve this, we modeled stormwater flows using a predictive rainfall dataset covering the years 2036 – 2064. Results identify three future stormwater disposal scenarios that can function at a similar or improved level of performance when compared to the current stormwater disposal system.

Keywords: Infiltration; porous asphalt; source control; stormwater, sumps.

**submitted to “Journal of Environmental Engineering”

4.2 Introduction

4.2.1 The Modern Urban Environment

Most urban watersheds contain impervious surfaces, a direct result of urbanisation and industrialization, leading to the large-scale construction of roads, pathways and buildings. These alterations to the natural environment cause the reduction of broad-scale infiltration and increase surface runoff, particularly from roads, which are an important source of pollutants in urban environments (Ball et. al. 1998; Drapper et al. 1999). To compensate for the increase in surface water runoff, the installation of large drainage systems are common in urban areas and are designed primarily to capture and dispose of surface waters to limit flooding. These changes considerably alter the way rainfall interacts with groundwater by reducing regional scale infiltration, caused by concentrated urban stormflows, which are commonly directed to point sources such as infiltration sumps and basins (Lawrence et al. 1996).

Impervious surfaces function as a source for urban contaminants, predominantly heavy metals, nutrients and hydrocarbons derived from automotive activity, atmospheric deposition and leaching of contaminants from organic materials (Allison et al. 1998). They also act as pathways for contaminants to end of pipe locations, encouraging the fast tracking of stormwater to hydrologically connected treatment nodes (Appleyard 1993). Modern stormwater drainage systems treat contaminated waters by passing them through treatment nodes such as detention basins, wetlands, swales, pollutant traps, roadside infiltration sumps and infiltration basins (Ellis and Marsalek 1996). Although these structures can be effective in treating contaminated waters, source control of contaminant loading eases pressure on end of pipe treatments and improves the quality of stormwater entering waterways and groundwater (Elliot 1998; Sieker and Klein 1998).

4.2.2 Stormwater System Design and Contamination

Many of Perth's urban watersheds located on the Swan Coastal Plain are underlain by coarse, highly permeable sands with shallow groundwater levels (Whelan and Barrow 1984), overlying the Gnangara Mound; a north-south trending elongated shallow unconfined aquifer (Raper and Sharma 1989; Farrington and Bartle 1989). These features, combined with the effects of urbanisation have led engineers to design stormwater disposal systems that are geared to extract stormwater rapidly into large drains to limit the effects of flooding (Department of Environment 2004).

In much of Perth's developed urban areas, stormwater is characterized as runoff from road and adjacent impervious surfaces only (Ewing 2006) due to the high infiltration capacities of Perths sandy soils, together with government policies that require onsite detention of roof water runoff via soakwells. The current stormwater disposal system is focused on directing runoff into centralized drainage systems that re-route it to wetlands and detention basins to accommodate large water volumes, or infiltration basins, which filtrate stormwater through a porous medium to groundwater (Davies 1992). Problems associated with this approach, particularly with infiltration methods, are the coexistence of infertile soils, displaying high saturated hydraulic conductivity (K_{sat}) values, and shallow groundwater.   This combination can cause stormwater to rapidly recharge groundwater in an unfiltered condition. Groundwater beneath 16 infiltration basins in sandy soils in New Jersey, USA exhibited lower levels of dissolved oxygen and greater detection frequencies of petroleum hydrocarbons, pesticides and herbicides (Fischer et al. 2003). High K_{sat} values are consistent throughout soils of the Swan Coastal Plain. A study of soils in the southern Gnangara Mound on the Swan Coastal Plain revealed K_{sat} values ranged from 0.56 to 2.85 m/d for topsoils and 3.42 to 6.38 m/d in subsoils (Salama et al. 2001).

Stormwater generated from roads is consistently polluted with heavy metals, nutrients and hydrocarbons. Sources of urban contaminants are listed in Table 4.1. Studies on road sediments have revealed roads are a significant source of heavy metals, particularly lead (Pb), zinc (Zn) and copper (Cu) (Birch et al. 1999), but not a significant source of nutrients according to local Perth studies (Davies and Pierce 1999). Given Perth's stormwater system is based on stormflows generated almost exclusively from road surfaces, treating road runoff at its source (i.e. road surface) has the potential to significantly improve the overall quality of storm flows.

Table 4.1. Common road contaminants in the urban environment (Davies et al. 2000; Marcos et al. 2002; Sharma et al. 1995; Van Bohemen and Van De Laak 2003; Young et al. 1996).

Common Urban Contaminants	**Source**
Copper	Tyre and brake/radiator wear
Lead	Fuel combustion, tyre wear
Zinc	Tyre and brake wear
Nitrogen	Fertilisers, atmospheric deposition

Phosphorous	Fertilisers, atmospheric deposition
Hydrocarbons	Fuel combustion, engine leaks

4.2.3 Managing Stormwater Pollution

Recently, the focus for the control and management of stormwater pollution has shifted from end of pipe treatment to source control. Best management practices (BMPs) and stormwater treatment trains (STTs) are preferred stormwater control measures compared to single focus end of pipe treatments, as they incorporate several treatment measures including source management, whilst benefit cost analyses (BCA), which focus on the advantages and disadvantages of public policies, are also employed as an alternative approach (Kalman et al. 2000). Water quality improvements in urban areas have also been achieved through education (Dietz et al. 2004). It is clear that the control of pollution at its source, as opposed to treatment via end of pipe structural solutions can be an influential and cost effective stormwater treatment method (Andoh and Declerck 1997, Seiker and Klein 1998).

Broad-scale management of environmental issues reduces the need for costly end of pipe treatments such as roadside infiltration sumps, gross pollutant traps (GPTs) and wastewater treatment plants. One such method that has been used successfully in European countries such as Denmark and Switzerland is porous asphalt (Raaberg et al. 2001; Poulikakos et al. 2004). Porous asphalts differ to traditional asphalt in that they allow surface water to pass through the asphalt material due to its composition of larger aggregates, which exhibit a significantly high porosity of 20% or greater (Poulikakos et al. 2004). An aggregate spacing of 10mm is typical of porous asphalt, compared to a typical spacing of 2 mm, which is representative to that of traditional asphalt (Fwa et al.

2003). Advantages and disadvantages of using porous asphalt as an alternative road material are listed in Table 4.2.

Table 4.2. Advantages and disadvantages of porous asphalt (Field et al. 1982; Raimbault et al. 1999; Main Roads WA 2004; USEPA 1999)

Advantages	Infiltration and natural water treatment; reduce road spray; similar cost to traditional asphalt; improved skid resistance; recharge aquifers; reduced road noise; cost reduction of road infrastructure (kerbs, drains, sewers)
Disadvantages	Not suited to high traffic volumes; use on low sloping areas <6%; limited life span; limited use over soils with low infiltration capacities; prone to clogging; maintenance required

Road runoff contributes the bulk of Perth's stormwater (Stovold and Smettem *submitted*). The use of a source control pollution measure such as porous asphalt therefore has the potential to greatly reduce stormwater volumes in the drainage system and significantly improve stormwater quality by means of regional scale filtration through a porous medium. The conversion of traditional road asphalt to porous asphalt, which currently comprises approximately 5% of urban catchments in Perth, could shift rainfall / groundwater interactions closer to their pre-developed state. This may in turn reduce the hydraulic pressure placed on roadside infiltration sumps and could even eliminate dependence on these intermediate treatment devices altogether where porous asphalt is present. At a similar cost to traditional asphalt, porous asphalt is a suitable replacement option to traditional asphalt, which currently routes contaminated surface water to the drainage network. The inclusion of porous asphalt may negate the current hydraulic function of roads by reducing total runoff volume, peak discharges, duration of high flows and time to peak runoff (Lawrence et al. 1996; Holman-Dodds et al. 2003). The effect of urbanisation has caused on average a 1 to 2 year flood to become 2 to 4 times larger, which increases strain on the natural geomorphology of streams, thereby increasing erosion and causing the straightening of channels (Rutherford and Ducatel 1994), thus the implementation of porous asphalt will ease pressure on both natural and artificial waterways.

In this paper we use the MUSIC (Model for Urban Stormwater Improvement Conceptualisation) model (Cooperative Research Centre for Catchment Hydrology 2003) to investigate impact scenarios of porous asphalt on stormwater flows in an urban catchment to determine whether the inclusion of roadside infiltration sumps is required in future stormwater disposal systems. We achieve this by combining two scenarios of asphalt conversion using a predicted rainfall dataset for the years 2036 and 2064 with a modified stormwater disposal systems that includes and excludes roadside infiltration sumps and compare these to model runs using a typical 2006 rainfall dataset together with the current stormwater design system.

4.3 Methods

4.3.1Catchment Location

This study refers to catchment Nedlands 38 (NE38; E386849.8, N6460558.6) as described by JDA (2002), which covers an area of 34.2 ha and is located within the

Nedlands Council district in the City of Perth, Western Australia (Fig. 4.1 & 4.2) and is included within the Western Regional Organisation of Councils (WESROC). Measured stormwater outflow from the NE38 catchment has been accurately predicted using the MUSIC 2.1 model (Stovold and Smettem *submitted*). The NE38 catchment was originally modeled using a six minute rainfall dataset. To replicate this modeling approach, we extracted six minute rainfall data from an annual daily timestep rainfall dataset for the years 2006, 2036 and 2064.

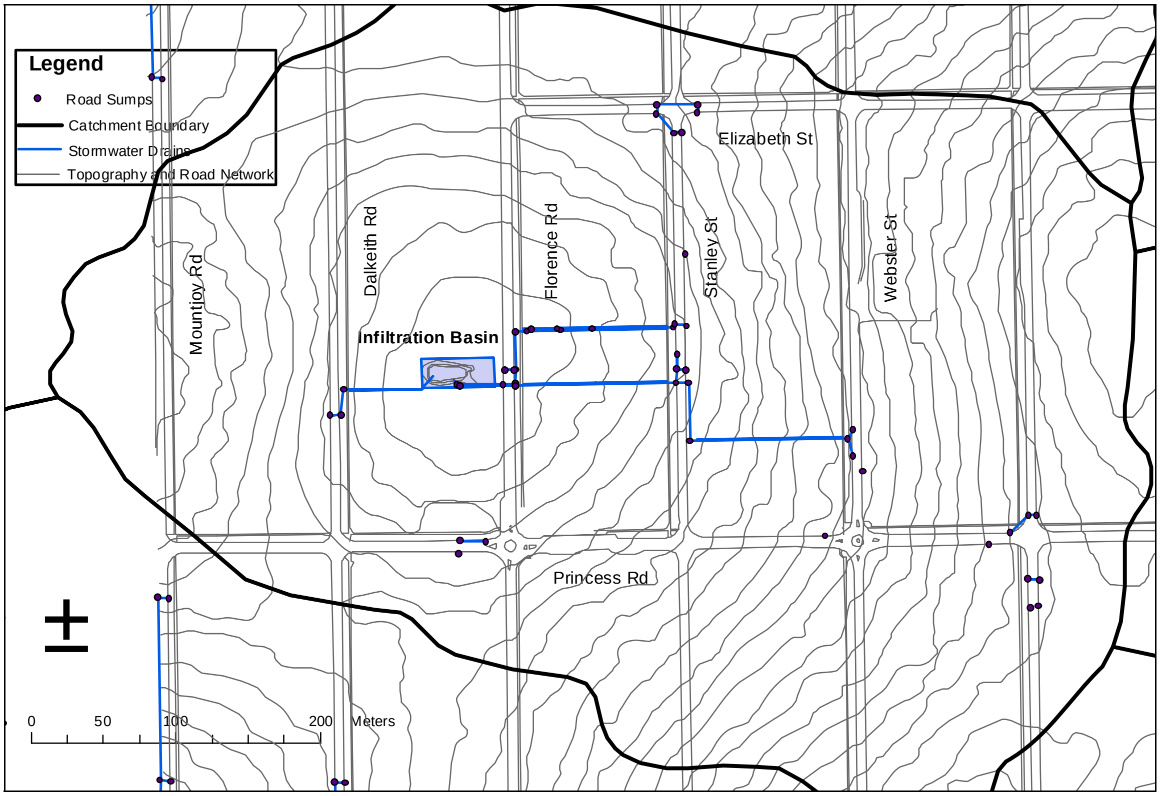

Figure 4.1. Map denoting location and features within NE38

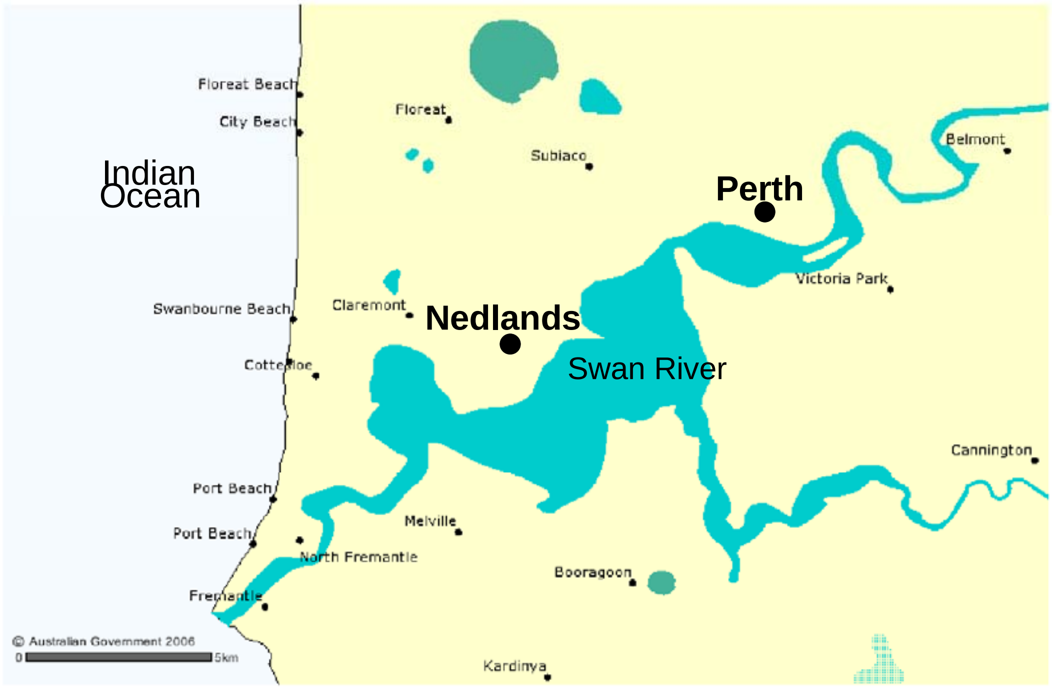

Figure 4.2. Location of Nedlands in relation to Perth and surrounding suburbs (Australian Government 2006).

4.3.2 Predicted Rainfall Series

The predicted rainfall dataset produced for Perth airport was used for future scenario modeling (Berti et al. 2004) and consisted of six simulations of downscaled daily rainfall using CSIRO CCAM atmospheric predictors for the years 2036 – 2064 (SRES A2 run). This time period was selected to provide an indication the effects reduced rainfall may have on future modeling scenarios and as such the rainfall predictions should be used as an indicator only of how rainfall may be in the future. All six simulations were randomly generated from the same atmospheric dataset. Analysis was undertaken on all simulations to generate an average prediction of long term annual rainfall. The predicted rainfall dataset displayed decreasing annual rainfall over the modeled time-scale. A linear trendline indicates the average annual rainfall declines from about 710 mm in 2036 to 580 mm in 2064 (Fig. 4.3). An annual rainfall dataset on a six minute timestep representative of the average predicted rainfall for the years 2006, 2036 and 2064 was selected in order to model catchment NE38 with and without roadside infiltration sumps. The combined average annual rainfall over the predicted rainfall time series is presented in Figure 4.3.

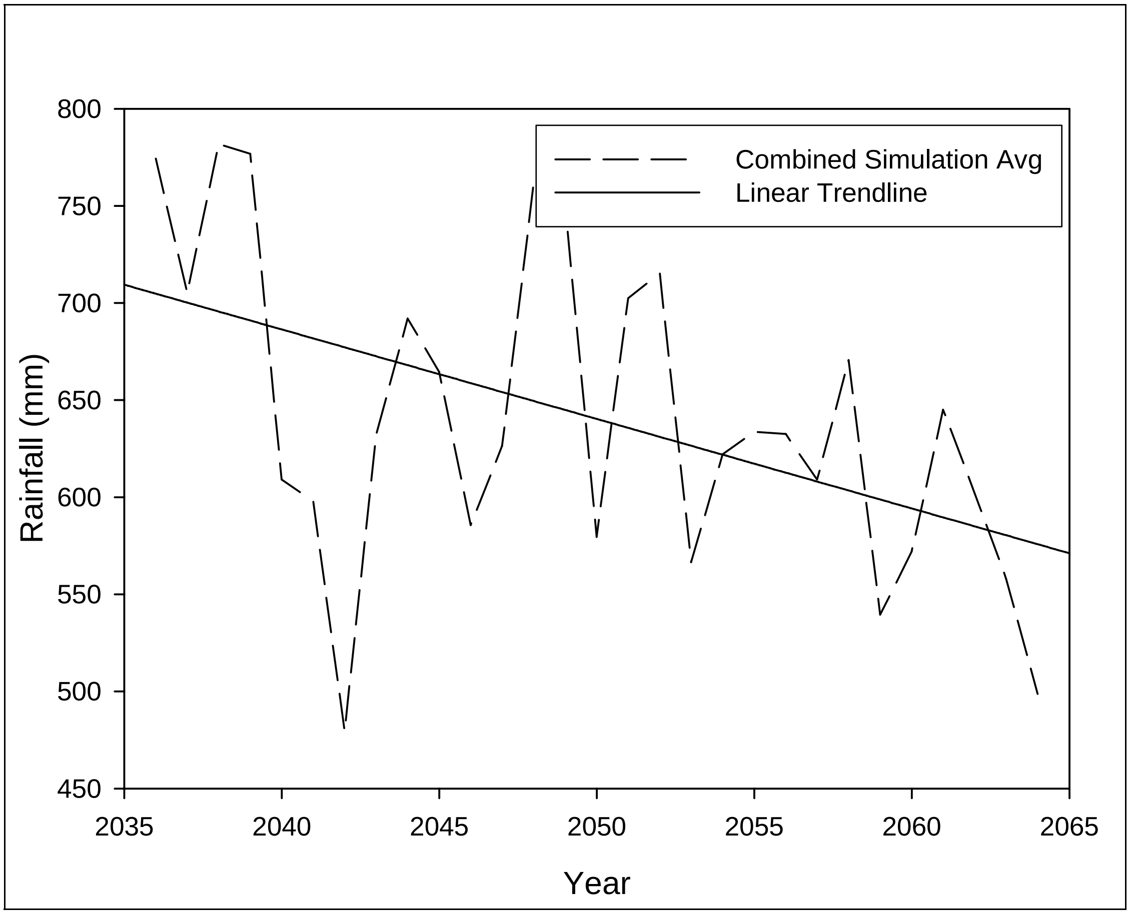

Figure 4.3. Combined simulation average generated from six randomly generated simulations.

4.3.3 Model Setup

MUSIC is a conceptual design tool intended as an aid to decision making relating to urban stormwater design (Cooperative Research Centre for Catchment Hydrology 2003). It has the capability of modeling conceptual designs incorporating stormwater treatment and is useful for assessing performance and predictions on stormwater quantity and quality, which is achieved by creating a treatment train using a series of source nodes and treatment nodes to best represent a catchment.

Porous asphalt displays infiltration rates that exceed precipitation rates for most storms occurring in the NE38 catchment. Hydraulic conductivities of two porous asphalt mixes from Japan and Switzerland were compared using a traditional asphalt mix to represent new asphalt and a packing mix to represent compacted, aged asphalt. These mixes displayed hydraulic conductivities ranging from 198 to 319 m/d and 103 to 190 m/d for the traditional mix and packing mix respectively (Poulikakos et al. 2004). Based on these findings, porous asphalt was modeled as 100% pervious, thus generating no surface runoff.

Two scenarios of porous asphalt application were modeled. In Scenario 1, Mountjoy Rd, Florence Rd and Webster Rd (Fig. 4.1) were assumed to under porous asphalt, equating to 35% of the modeled catchment. Scenario 2 modeled all Scenario 1 roads with the addition of Stanley Rd and Dalkeith Rd (Fig. 4.1), equating to 68% of the modeled catchment. Princess Rd and Elizabeth St are more heavily trafficked than the selected roads and were therefore not identified for porous asphalt conversion. Scenario 1 and 2 were modeled using projected average annual rainfall for 2006, 2036 and 2064 with both a stormwater disposal system that included and excluded roadside infiltration sumps. The 2036 and 2064 results were compared to model outcomes generated using an annual six minute rainfall dataset representative of the 2006 average rainfall amount together with the current stormwater disposal system that includes roadside infiltration sumps. Scenarios were also run to identify future stormflows generated in catchment NE38 under traditional asphalt and a stormwater disposal system that was void of roadside infiltration sumps. All model runs generated mean annual values for total stormwater flow and loadings for total suspended solids (TSS), total phosphorous (TP) and total nitrogen (TN). MUSIC 2.1 was not capable of modeling heavy metals and hydrocarbons and as such they were not modeled.

4.4 Results

Model outcomes were generated to observe reductions on mean annual flow and contaminant loadings affected by two different stormwater disposal systems (with and without roadside infiltration sumps) that were subject to the application of porous asphalt using average annual six minute rainfall for the years 2006, 2036 and 2064. These results are presented in Table 4.3. Results show that projected stormwater disposal systems operating with roadside infiltration sumps have a greater impact on reducing stormflow and contaminant loads than a system void of sumps. However Scenario 1 and 2 results generated from model runs in 2036 and 2064 for a stormwater disposal system void of roadside infiltration sumps demonstrate stormflow and contaminant loadings that are similar to or less than those generated under the current stormwater disposal system (with sumps) for the same projected years (2036 and 2064).

Table 4.3. Comparison of projected stormwater system outcomes using a stormwater system without sumps and the current stormwater system (with sumps) together with road networks consisting of traditional asphalt, 35% porous asphalt (Scenario 1) and 68% porous asphalt (Scenario 2).

		With Roadside Infiltration Sumps			**Without Roadside Infiltration Sumps**		
Year	**Parameters**	**Traditional Asphalt**	**Scenario 1**	**Scenario 2**	**Traditional Asphalt**	**Scenario 1**	**Scenario 2**
2006	**Flow (ML/yr)**	**6.96**	**4.57**	**2.24**	**10**	**7.5**	**5.25**
	TSS (kg/yr)	791	534	248	1520	904	492
	TP (kg/yr)	3.7	2.6	1.2	5.4	4.2	2.4
	TN (kg/yr)	13.3	8.8	4.3	22.2	14.8	10.5
2036	**Flow (ML/yr)**	**6.00**	**3.94**	**1.90**	**8.88**	**6.44**	**4.25**
	TSS (kg/yr)	662	461	202	1390	802	437
	TP (kg/yr)	3.2	2.2	1	5	3.7	2.1
	TN (kg/yr)	11.5	7.7	3.5	19.5	12.6	8.4
2064	**Flow (ML/yr)**	**4.43**	**2.90**	**1.38**	**7.06**	**4.76**	**2.71**
	TSS (kg/yr)	502	356	143	1100	614	338
	TP (kg/yr)	2.4	1.7	0.7	3.9	2.8	1.5
	TN (kg/yr)	8.7	5.6	2.6	15.8	9.3	5.2

The greatest flow and contaminant load reductions were generated under a stormwater disposal system inclusive of roadside infiltration sumps under Scenario 2 in 2036 and

2064, which generate mean annual flow and contaminant loadings significantly lower than results generated under the current unchanged system modeled for the same years.

However results generated under a modified stormwater disposal system void of sumps indicated Scenario 2 in 2036 and 2064 provided good reductions, generating flow and contaminant loadings that were all lower than those generated under the current system, whilst Scenario 1 in 2036 and 2064 generated flow volumes only 7% greater than those generated for the same years under the current system, whilst average contaminant loadings for both years were only 17%, 14% and 8% for TSS, TP and TN respectively when compared to contaminant loadings generated for the same years under the current system.

Results also show that for Scenarios 1 and 2 with roadside infiltration sumps, there is a proportional reduction in both the percentage of stormwater flow and percentage of contaminant loading as the percentage of porous asphalt is increased. Similar reductions, with the exception of TSS, were also evident for all scenarios under a stormwater disposal system that was void of roadside infiltration sumps. TSS removal was noticeably greater under the current stormwater disposal system (with sumps) for mean annual stormflows greater than 5 ML/y (Fig. 4.4). Under a 100% porous asphalt application there is no flow generated under the model assumptions used here.

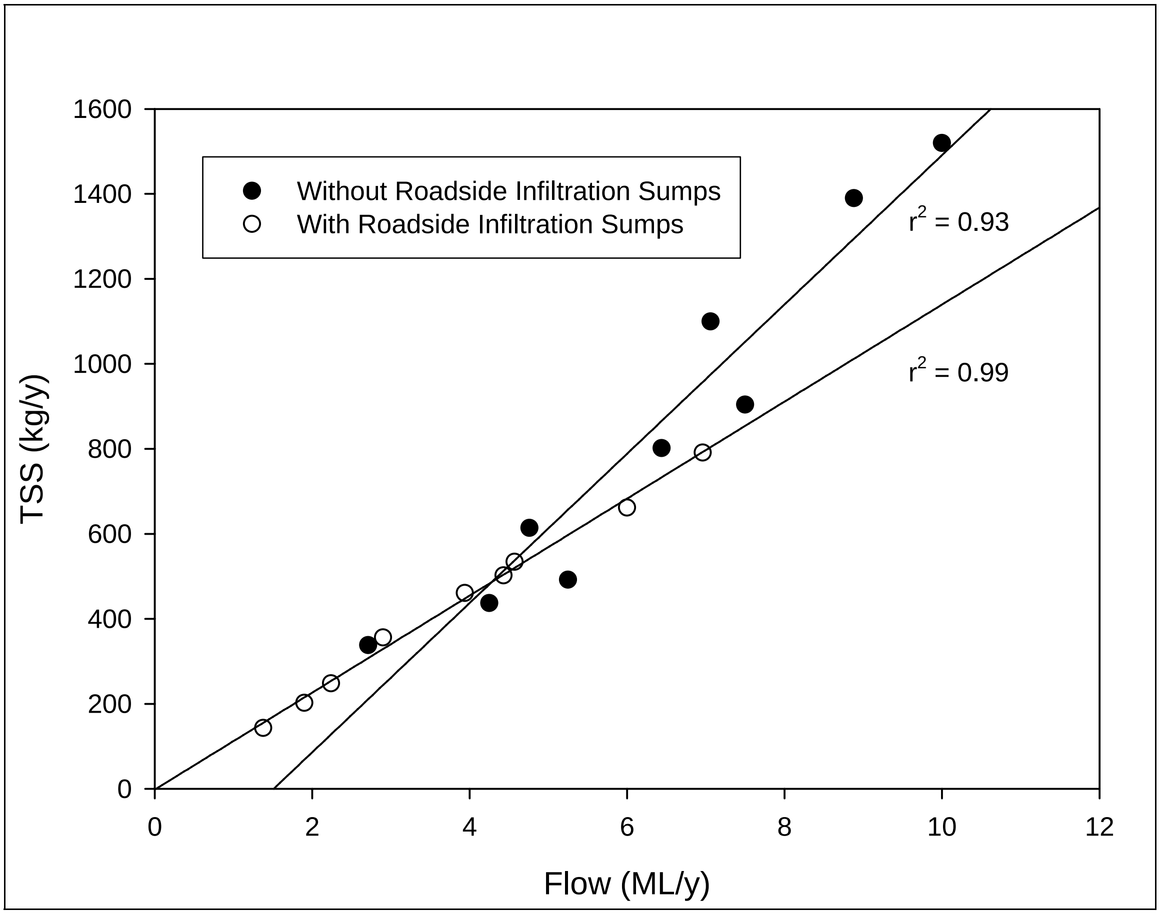

Fig. 4.4. The relation between flow and TSS for stormwater disposal systems with and without roadside infiltration sumps.

4.5 Discussion

The results indicate the potential to use porous asphalt as a source control measure for stormwater pollution in Perth. Porous asphalt could alleviate pressure placed on treatment structures such as roadside infiltration sumps and infiltration basins, which are currently subject to significant hydraulic load. A Spanish study on sandy soils similar to those in Perth revealed ammonium oxidation and chemical oxygen demand (COD) removal reached 98% and 87% respectively in sands 2 m below the soils surface; however these removal rates were only sustainable providing the hydraulic load did not exceed 0.25 m/d (Mottier et al. 2000). Saturate hydraulic conductivities of between 1 and 5 m/d are typical of sandy soils in Perth (Davies et al. 1996), whilst a mean value of 12.5 m/d was measured for roadside infiltration sumps in catchment NE38 (Stovold and Smettem *submitted*), implying the pollutant treatment capabilities of these structures are inhibited. The introduction of porous asphalt would redistribute infiltration, reduce loading on roadside infiltration sumps and infiltration basins and increase the removal efficiency of contaminants from stormwater.

Modeling Scenario 1 and 2 using projected average annual rainfall for 2036 and 2064 without a roadside infiltration sump system demonstrated potential reductions in stormflow and contaminant loads that may result from climate change and a modified stormwater disposal system. Results indicate under the current system with roadside infiltration sumps and traditional asphalt, the mean annual flow in 2006 is 6.96 ML/y. Modeling results suggest this figure can be met and improved on in future scenarios that were modeled without a sump system. Namely, Scenario 1 in 2036 and 2064 generated mean annual flows of 6.44 and 4.76 ML/yr respectively, whilst figures of 4.35 and 2.71 ML/y were generated for Scenario 2 in 2036 and 2064 respectively (Table 4.4). Furthermore, contaminant loads generated for Scenarios 1 and 2 together with the stormwater disposal system void of roadside infiltration sumps were all similar to, or below values generated under the current system.

However the adequacy of both porous asphalt and a stormwater disposal system void of sumps is best measured by comparing future flows and contaminant loads against those generated under the current stormwater disposal system (with sumps) together with a traditional asphalt road network for the modeled year.

Using this comparison, model runs for Scenario 1 with the modified stormwater disposal system void of sumps generated slightly higher flows and contaminant loads when compared to the current system with traditional asphalt in 2036 and 2064. Model runs generated for Scenario 2 with the modified stormwater disposal system void of sumps offered the best results, demonstrating significant reductions in both flow and contaminant loading when compared to the current system in 2036 and 2064.

These results have consequences for future urban development. They effectively remove dependence on roadside infiltration sumps altogether in future stormwater disposal systems that incorporate a porous asphalt road system. The results also show that 100% conversion to porous asphalt is not necessary to completely remove the dependence on sumps. In effect, for a stormwater drainage system in 2036 and 2064, a 68% application of porous asphalt and a stormwater disposal system that is void of sumps will generate mean annual flow volumes that are lower than volumes produced in the current system for those years. Model runs for Scenario 1 with a modified stormwater disposal system display slightly higher results than those generated under the current system in 2036 and 2064, however these values are still similar to, or lower than those generated under the current system in 2006.

Slightly higher contaminant removal efficiencies evident for Scenarios 1 and 2 with the current stormwater drainage system (with sumps) can be attributed to the presence of the roadside infiltration sumps, which function to remove solids from stormwater as described by Fair and Geyer (1954):

$$R = 1 - (1 + (1/n)\ (v_s/n\ Q\ /\ A))^{-n} \tag{4.1}$$

Where:

R = Fraction of initial solids removed

v_s = Settling velocity of particles (m^3/s)

Q/A = Rate of applied flow (m^3/s) divided by the surface area (m^2) of the basin

n = Turbulence and short-circuiting parameter (between 0 and 1)

It is feasible that lower flows generated under Scenarios 1 and 2 with the current stormwater disposal system may cause greater particulate bound contaminant loads to settle in roadside infiltration sumps and thus we recommend that cleaning of these structures is undertaken more regularly to compensate for the increased contaminant loads in future stormwater disposal systems that accommodate roadside infiltration sumps.

It should be noted that Perth has a higher proportion of dissolved phosphorous than Melbourne and Sydney (Lund et al. 2000), where *k* values, which refer to the speciation of water quality constituents, have been determined from Melbourne and Sydney stormwater quality and used as default values for MUSIC (Cooperative Research Centre for Catchment Hydrology 2003). Consequently these default values may at present overestimate TP removal for Perth conditions.

4.6 Conclusions

Four future stormwater disposal systems were identified that could operate at a similar or improved level of performance with respect to the current stormwater disposal system for the given year as a result of removing all stormwater sumps. They are listed in increasing order of effectiveness.

1. 35% porous asphalt application with no sumps in 2036
2. 35% porous asphalt application with no sumps in 2064
3. 68% porous asphalt application with no sumps in 2036
4. 68% porous asphalt application with no sumps in 2064

The removal of roadside infiltration sumps in future stormwater disposal systems will lead to savings in initial infrastructure and setup costs whilst also creating additional urban space, which is highly valued in urban design.

Results have also shown that significant reductions in urban contaminant generation are feasible with the application of porous asphalt under the current stormwater disposal system.

Future work is needed to provide more accurate information on the pollutant removal efficiency of porous asphalt, particularly for the long term performance of established, aged materials.

5 Conclusions

A small urban catchment (NE38) in the suburb of Nedlands, Perth, Western Australia, was used in this study to model stormwater flows. This thesis investigated the process of calibrating NE38 using stormwater discharge measured at the catchment drainage point. The challenges associated with calibration were discussed and problems affecting calibration were identified. Furthermore, the possibility of using an uncalibrated model to predict stormwater flows was also investigated. The thesis then applied catchment scenarios to the existing model to simulate changes to stormwater and contaminant generation as a result of both climate change and the application of porous asphalt as an alternative road system to determine whether road sumps are a necessary component of future stormwater disposal systems.

Chapter one discussed the problems associated with the management of stormwater pollution in the urban environment and identified source control methods, with a focus on infiltration, as the recommended means to improve the management of stormwater pollution. Chapter two introduced the conceptual stormwater model MUSIC, which was used to model stormwater and contaminants in the urban setting and justified its application in Perth.

Chapter three modeled stormwater flows within catchment NE38 and calibrated the MUSIC model by matching predicted to measured stormwater discharge and using updated field data of the drainage system together with rainfall data measured within the catchment. The effectiveness of using an uncalibrated MUSIC model to predict stormwater discharge was also tested. This was undertaken by directly measuring the saturated hydraulic conductivity of surface soil samples taken from road sumps within the catchment. Samples displayed mean K_{sat} values (520 mm/h) which was very similar to the seepage constant (509 mm/h) used for calibration. Using the measured K_{sat} values in place of the seepage constant generated predicted stormflows only 1% lower than measured volumes. These results imply an uncalibrated MUSIC model can be used to predict stormwater flows and contaminant loads within urban catchments provided the saturated hydraulic conductivities of road sumps and the impervious drainage areas are measured. This was the case for Perth, where stormwater is generated almost exclusively from impervious areas, however further testing should be undertaken to measure the applicability of this approach in different urban settings.

Field mapping was also undertaken to validate digital information of the catchment. Using the original digital data underestimated mean annual stormwater flows by 10%. Increases in annual TSS, TP and TN loads also occurred as a result of this process. Further comparison of a remote rainfall dataset taken from the Perth Airport Meteorological centre (the conventional source of rainfall in Perth) to the rainfall dataset measured within the catchment resulted in a 24% overestimation of mean annual stormwater flows. These input datasets could be combined in the model and calibrated by increasing the seepage constant; however this would imply an overestimation of infiltration sump capacity and may lead to flawed design decisions.

Chapter four used the calibrated model of NE38 as a tool to model stormwater quality improvement measures to investigate their impacts on annual stormwater flows and contaminant load generation. Specifically, the potential working system of a future stormwater disposal system that excluded road sumps was investigated. Scenarios of the stormwater drainage system were modeled without road sumps in 2006, 2036 and 2064 to determine whether roadside infiltration sumps are a necessary component of future stormwater disposal systems. Modeling stormwater disposal systems without roadside infiltration sumps together with two levels of porous asphalt application in 2036 and 2064 revealed four future scenarios that could function at a similar or improved level of performance when compared to model runs with the current stormwater disposal system in 2006 and are listed in increasing order of effectiveness.

1. 35% porous asphalt application with no sumps in 2036
2. 35% porous asphalt application with no sumps in 2064
3. 68% porous asphalt application with no sumps in 2036
4. 68% porous asphalt application with no sumps in 2064

These findings assist in the management of stormwater within urban catchments where the application of porous asphalt is in consideration. These results could potentially save local authorities considerable expense in infrastructure for future stormwater disposal systems that incorporate porous asphalt as a road surface and exclude roadside infiltration sumps from the drainage system.

The application of two levels of porous asphalt application (35% and 68%) as an alternative road system were also modeled in 2036 and 2064 to determine their impact on stormwater flows and chemical losses from the current stormwater disposal system inclusive of roadside infiltration sumps. Results showed that for Scenarios 1 and 2 with roadside infiltration sumps, there is a proportional reduction in both the percentage of stormwater flow and percentage of contaminant loading as the percentage of porous asphalt is increased, whilst it was noted the contaminant removal efficiency was slightly better for stormwater disposal systems that included roadside infiltration sumps.

This thesis investigated stormwater modeling in catchment NE38 and concluded that an uncalibrated MUSIC model can be used to predict stormwater flows and contaminant loads in urban catchments provided the saturated hydraulic conductivities of infiltration sumps are directly measured, together with the impervious contributing area, which consists almost exclusively of road surfaces. In addition, it has also been concluded that stormwater flows and contaminant loads can be reduced in future stormwater disposal systems constructed without roadside infiltration sumps provided porous asphalt is incorporated into urban design.

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