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Review of Storm Water Models

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ABSTRACT

This report is part of the CSIRO’s Urban Water Project and it is intended to provide a review of the methods used by models for simulating storm water quantity and quality in an urban environment. This has been achieved by examining a number of storm water models in current use. These models represent a wide range of capabilities and spatial and temporal resolution. The important features of these models have been described in this report. Specific topics covered are: Identifying important urban water quality parameters. The classification of modelling approaches. Modelling approaches used to estimate water quantity and quality. These include statistical, empirical, hydraulic and hydrological models. Water resources management and planning tools, that are included in some urban storm water models, such as economic analysis, optimisation and risk analysis are also discussed.

Features of twelve storm water models have been summarised. These models have been chosen because they demonstrate how components that are important in managing urban storm water have been incorporated in a modelling framework. These models have been categorised in terms of their functionality, accessibility, water quantity and quality components included in the model and their temporal and spatial scale.

This report is useful to planners, managers and modellers. It will provide planners and managers with an overview of modelling approaches that have been used to simulate storm water quantity and quality. In particular, this review provides managers with an appreciation of the limitations and assumptions made in various modelling approaches. This review will also benefit modellers by providing a comprehensive summary of approaches and capabilities of a number of storm water models in current use. This review has also been used to identify potential urban storm water research opportunities.

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A	area
B	width of the channel
C	concentration of substance or runoff coefficient
C_{BOD}	concentration of biochemical oxygen demand
C_{DO}	concentration of dissolved oxygen
c	Chezy coefficient
D	diffusion coefficient
$\mathbf{F}(\mathbf{U})$	flux vector
g	acceleration due to gravity
I	rainfall intensity or inflow
i	rainfall intensity
K	conveyance, $K = \eta / (AR^{2/3})$ or storage or reaction coefficient
k_B	pollutant buildup coefficient
k_w	pollutant removal coefficient
O	outflow
P	wetted perimeter
$P_B(t)$	mass of pollutant buildup
$P_w(t)$	mass of pollutant washoff
Q	flow
q	lateral inflow
R	hydraulic radius
R_{i,m_i}	return function
r	runoff flow rate
$\mathbf{S}$	vector of source variables
S	source or sink of contaminant or storage
S_{ij}	sensitivity coefficient, $S_{ij} = \Delta Y_j x_j / (Y_j \Delta x_j)$
S_0	bed slope
S_f	friction slope
t	time
$\mathbf{U}$	vector of conservative variables
u	velocity
V	Kleitz-Sneddon law, $V = dQ / dA$ or volume
X	independent variable or explanatory variable
x	distance
Y	dependent variable or model response
y	water depth
Z	objective function
$\alpha = K(I - X) + \Delta t / 2$	
Δx	computational distance step
Δt	computational time step
η	the Manning resistance coefficient
μ	mean
σ	standard deviation

Operators

$d(.)$	ordinary derivative
$\Pi(.)$	product of terms
$\partial(.)$	partial derivative
$\int(.)$	integration
$\lvert . \rvert$	absolute value
$\exp(.)$	exponentiation
$\sum(.)$	summation
$\mathrm{E}[.]$	expectation

1. INTRODUCTION

It is estimated that by the year 2000 half of the world's population will be living in urban areas. In many countries, the land occupied by the urban population is often less than 5% of the total area. This concentration of human activities intensifies local competition for all types of resources, with water amongst the most vital. Water is essential for human existence and human settlement and it is employed extensively in urban areas for the disposal of wastes. Water can also have a negative impact on human activity. This includes flooding, drainage, erosion and sedimentation. These problems are exacerbated in urban catchments by altering natural watercourses and increasing impervious areas. Urban run-off is typically highly polluted with pathogenic and organic substances that are a public health threat.

The development of water resources requires the conception, planning, design, construction, and operation of facilities to control and utilise water for a variety of purposes. Flood mitigation is an example of the control of water so that it will not cause excessive damage to property or loss of life and inconvenience to the public. Water supply is an example of the utilisation of water for beneficial purposes. Pollution threatens the utility of water for municipal and irrigation uses and seriously despoils the aesthetic value of natural watercourses.

Water resource managers are faced not only with the control and management of runoff quantity but with the maintenance of water quality as well. This is complicated by the unequal distribution of water and its availability at any place varying with time. The interest in urban storm water quality has also increased with the introduction of legislation, which regulates storm water quality. Computer models of urban storm water flow and quality have been extremely useful in establishing whether various management strategies produce water quality that conforms to the legislation.

In this review, features of a number of well-known and not so well-known storm water models are summarised. In addition, a number of watershed models capable of simulating urban storm water are also described. This is not a comprehensive list of urban storm water models in current use. There are literally hundreds of models that have been developed by academic institutions, regulatory authorities, government departments and engineering consultants. This review illustrates the diversity of approaches and parameters that are considered in urban storm water models. In other reviews, the emphasis is on modelling quality. Due to the importance of flow as the dominant mechanism for transporting pollutants, this review describes flow routing in more detail.

In the following chapter, storm water issues confronting urban catchments are described. Chapter 3 describes the modelling approaches that have been used to model both storm water quantity and quality in and urban environment. Useful management tools that have been incorporated in storm water models are described in Chapter 4. These include optimisation, uncertainty analysis and economic analysis. Twelve storm water models are described in this review. They represent a wide range of capabilities with spatial and temporal resolution. These models have been chosen because they demonstrate how various features described in the previous chapters have been incorporated in a model. Eight urban storm water models have been reviewed in Chapter 5. These models have been categorised in terms of their functionality, accessibility, water quality and quantity components included in the model and their temporal and spatial scale. A number of other available storm water models are listed in Chapter 6. Four non-urban models, which are capable of simulating urban storm water quantity and quality, are described in Chapter 7. A number of conclusions resulting from this review of storm water models are listed in Chapter 8. Potential urban storm water research opportunities have been identified and are described in Chapter 9.

2. URBAN HYDROLOGY

Rain falling over a watershed will fall on either an impervious or a pervious area. On a pervious area, some rainfall may infiltrate the sub-surface and the remainder is surface runoff. Surface runoff and perhaps infiltration will eventually flow into a watercourse or a receiving water body. This is not the case for an impervious area, where nearly all the rainfall becomes runoff. An urban area is by definition an area of concentrated human activity, which is characterised by extensive impervious areas and man made watercourses. The result is an increase in runoff volume and flow that can result in flooding, watercourse and habitat destruction.

Pollutants are also transported through the urban watershed. Rainfall precipitates atmospheric pollutants. The impact of rainfall will dislodge particles on the surface of the ground. Many pollutants adhere to these particles and are conveyed along with soluble pollutants by the runoff. The momentum associated with the runoff dislodges other contaminant-laden particles. These are transported to a watercourse by the flowing water and progress through the urban watershed. Pollutants generated on and discharged from land surfaces as the result of the action of precipitation on and the subsequent movement of water over the land surface, are commonly referred to as *non-point* pollutants or *dispersed* pollutants. Pollutants resulting from the application of water to the land by human activity augment these pollutants. Depending on the type of activity on the land, the volume of runoff and the amount and types of pollutants carried with it will vary. The intensity and duration of precipitation and the time since the last precipitation event also affect the quantity and transport of pollutants generated. Failures in the urban infrastructure (sewer infiltration, leachate from landfills, direct connection of sanitary sewers to storm water drains) represent another source of pollutant. The diversity in the source and type of pollutants encountered on an urban catchment makes managing storm water very complicated.

When pollutants discharged into receiving water bodies exceed the assimilation capacity of these bodies, a myriad of problems can result. Types of biological effects that these water quality problems may cause include; infection of organisms by bacteria and viruses, death from chronic toxicity exposure and alteration to natural habitat cycles and breeding. Pollution and water quality degradation can also interfere with the range of legitimate water uses, as shown in Table 2.1. A similar table can be found in US Environmental Protection Agency (1979). Some types of water uses are more adversely affected by water quality than others. Many of these problems can be considered as natural phenomena, which have been exacerbated by man’s activities. The variety of pollutants that can be expected from various non-point sources in an urban environment are indicated in Table 2.2. Typical concentrations of some of these pollutants are given in Table 2.3. Pollution from human activity produces waste water and storm water quality that can be detrimental to human health and to aquatic organisms. Therefore, urban storm water can cause both quality and quantity problems in receiving waters.

Table 2.1 Limits of Water Uses Due to Water Quality Degradation
(adapted from Chapman 1992 and Dinius 1987)

	Use						
Pollutant	**Drinking Water**	**Aquatic Wildlife, Fisheries**	**Recreation**	**Irrigation**	**Industrial Use**	**Power Generation**	**Transport**
Pathogens	xx	0	xx	x	xx[1]		
Suspended Solids	xx	xx	xx	x	x	x[2]	xx[3]
Organic Matter	xx	x	xx	+	xx[4]	x[5]	
Algae	x[5,6]	x[7]	xx	+	xx[4]	x[5]	x[8]
Nitrate	xx	x		+	xx[1]		
Salts[9]	xx	xx		xx	xx[10]		
Trace Elements	xx	xx	x	x	x		
Organic pollutants	xx	xx	x	x	?		
Temperature	x	xx	x	x	x		
Acidification	x	xx	x	?	x	x	

xx Marked impairment causing major treatment or excluding the desired use
x Minor impairment
0 No impairment
+ Degraded water quality may be beneficial for this specific use
? Effects not yet fully realised

1 food industries
2 abrasion
3 sediment settling in channels
4 electronic industries
5 filter clogging
6 odour, taste
7 in fish ponds higher algae biomass can be accepted
8 development of water Hyacinth (*Eichhomia crassipes*)
9 also includes boron, fluoride etc.
10 Ca, Fe, Mn in textile industries etc.

Table 2.2 Sources of Non-point Urban Runoff Pollutants
(adapted from Whipple *et al*. 1983)

	Source						
		Vehicles					
Pollutant	**Soil Erosion**	**Wear**	**Exhaust**	**Industrial Wastes**	**Fossil Fuels**	**Lawn and Garden Chemicals**	**Animal Wastes**
Suspended solids	M	M			M		
Organic material	M	M	m				M
Nutrients							
Nitrogen	m		M	m		M	M
Phosphorus	M		m			M	M
Petroleum substances		M	M	M			
Micro-organisms							M
Heavy Metals							
Iron	M						
Manganese	M						
Zinc	m	M		m		M	
Lead			M	M			
Copper		M		M			
Chromium		M		M			
Nickel		m		M			
Mercury				M			
Cadmium		m		M			
Sulfur			m		M	M	M
Acids							
Nitric		M			M		
Sulfuric		M			M		
Pesticides						M	

M major source m minor source

Table 2.3 Typical concentrations of pollutants (adapted from Train 1979, Moore and Ramamoorthy 1984, Ellis 1986, Tchobanoglous *et al*. 1987, Chapman 1992, Huber 1992a, Sewards and Williams 1995, Duncan 1995)

Waste Water Type	**Pollutant**											
	BOD mg/l	**SS mg/l**	**Total P mg/l**	**Total N mg/l**	**Lead mg/l**	**Mercury mg/l**	**Iron m/l**	**Zinc mg/l**	**Copper mg/l**	**Chromium mg/l**	**Cadmium mg/l**	**Total Coliforms MPN/100ml**
Urban Storm Water	10 – 250	3 – 11,000	0.2 – 1.7	3-10	0.3 – 3.1	?	?	0.5	0.1	0.02	0.003	$10^3 – 10^8$
Untreated Sewage	100-500	100-500	5-15	20-85	0.05	0.002	4.8	0.46	0.3	0.34	0.016	10^7 - 10^9
Drinking Water*	?	?	5	10	0.015	0.001	0.3	5	1.3	0.05	0.005	<1
Fisheries and Aquatic Life*	3-6	25	?	0.01	?	0.00005	1.0	?	0.03	0.1	0.05	?

*upper limit on water quality ? unknown

3. MODELLING APPROACHES

Computer models have been used to simulate the behaviour of aquatic systems since the mid 1960's (for example, the Stanford Watershed Model , Crawford and Linsley 1966). Models capable of simulating storm water quality and quantity appeared in the earlier 1970' s and were developed primarily by US government agencies, such as the US Environment Protection Agency. Since then, a number of urban watershed models have been developed. These models include very simple conceptual models to complex hydraulic models.

In a computer model, mathematical relationships that represent the behaviour of a system are solved using a computer. If any of the variables in the model are regarded as random variables having a probability distribution, then the model is a *stochastic* model. Otherwise, the model is *deterministic* (Clark 1973). In a deterministic model, all the variables are known with certainty, therefore the model will always produce identical results for the same input parameters. This may not be the case for a stochastic model, where one or more variables are selected at random from a distribution. A stochastic model therefore, will always produce a different model response. A deterministic model could be considered as a stochastic model with the random variables replaced by their mean values. An advantage of a stochastic model is that the uncertainty in a variable, defined by its distribution, is interwoven into the model. Unfortunately, to solve the stochastic equations the random variables are restricted to certain probability distributions and for large problems the solution of stochastic equations are not practical (Li and McLaughlin 1991). *Reliability* techniques (Thoft-Christensen and Baker 1982) are available for estimating the uncertainties in a deterministic model response due to random inputs.

Both stochastic and deterministic models may be further classified into either; *conceptual* or *empirical* depending on whether the model is based on physical laws or not. The distinction is not entirely clear, as demonstrated by Clark (1973) using Darcy's law and Newton's law of motion. Both are physical laws, therefore any model based on these laws should be considered as a conceptual model. However, these laws were established from observations and by definition are empirical laws. Should models based on these laws be considered as empirical?

Distributed and *lumped* models are also used to classify models. These describe how the model treats spatial variability. A lumped model takes no account of the spatial distribution of the input, whereas distributed models include spatial variability. Most urban runoff models are deterministic-distributed models (Nix 1994).

Catchment models can be further classified as either *event* or *continuous process* driven. Event models are short-term models used for simulating a few or individual storm events. Continuous models simulate of a catchment's overall water balance over a long period of time, involving monthly or seasonal predictions, and form the basis of a *planning model* for water resources. Planning models are usually used to estimate the costs associated with different infrastructure configurations over the life of the infrastructure. Event driven models are suitable for the *design* of storm water infrastructure and as *operational* models. Models that are required to control, operate or allocate water resources in real time are known as operational models. Flood forecasting models, models used to control weirs and locks in an irrigation channel and models used to establish what level water is extracted from a reservoir to meet certain water quality requirements are examples of operational models. Design models refer to models that can be used to model in detail the flow through the storm water infrastructure.

There will be circumstances where a model can be used for planning, operations and design. The essential difference in the modelling approaches is the amount of data required, the information that can be obtained from the model, the sophistication of the analysis performed and the simulation period. For example, a planning model may involve an optimisation component. Due to the computational effort required in such a model, detailed hydraulic analysis of the infrastructure is not generally performed. In addition, if infrastructure life cycle costs are modelled, then the simulation period is of the order of years. Hydraulic modelling at this scale is prohibitive. Urban storm water models have been adapted for use as operational tools. However, they are more commonly used as either planning or design tools.

The basic components of an urban storm water model are; (*i*) precipitation, (*ii*) rainfall-runoff modelling (generation of surface and sub-surface runoff from precipitation excess, the washoff and buildup of pollutants from impervious surfaces) and (*iii*) transport modelling (routing of flows and pollutants through the storm water infrastructure, such as open channels, pipe networks and storages). The links between these processes are illustrated in Figure 1. In general, the spatial and temporal distribution of precipitation is the only component that is supplied externally to a storm water model. It is either recorded or generated and supplied as input data to the model.

The dependence of water quality on water quantity should be emphasised for at least two reasons. Firstly, in most water quality models, pollutant concentrations and loads cannot be estimated without having estimated the flows. It is for this reason that most water quality models include a hydrologic or hydraulic component. The hydrologic or hydraulic components simulate the movement of water through the urban catchment to various degrees of complexity. Secondly, procedures to mitigate quantity and quality are often complimentary. For example, a retarding basin operates to reduce flood peaks as well as serve as a sediment trap. In a few urban storm water models, greater emphasis is placed on modelling pollutants rather than accurately modelling storm water flows. It is important to have a realistic hydraulic or hydrologic models which have the appropriate spatial and temporal resolution required for the problem.

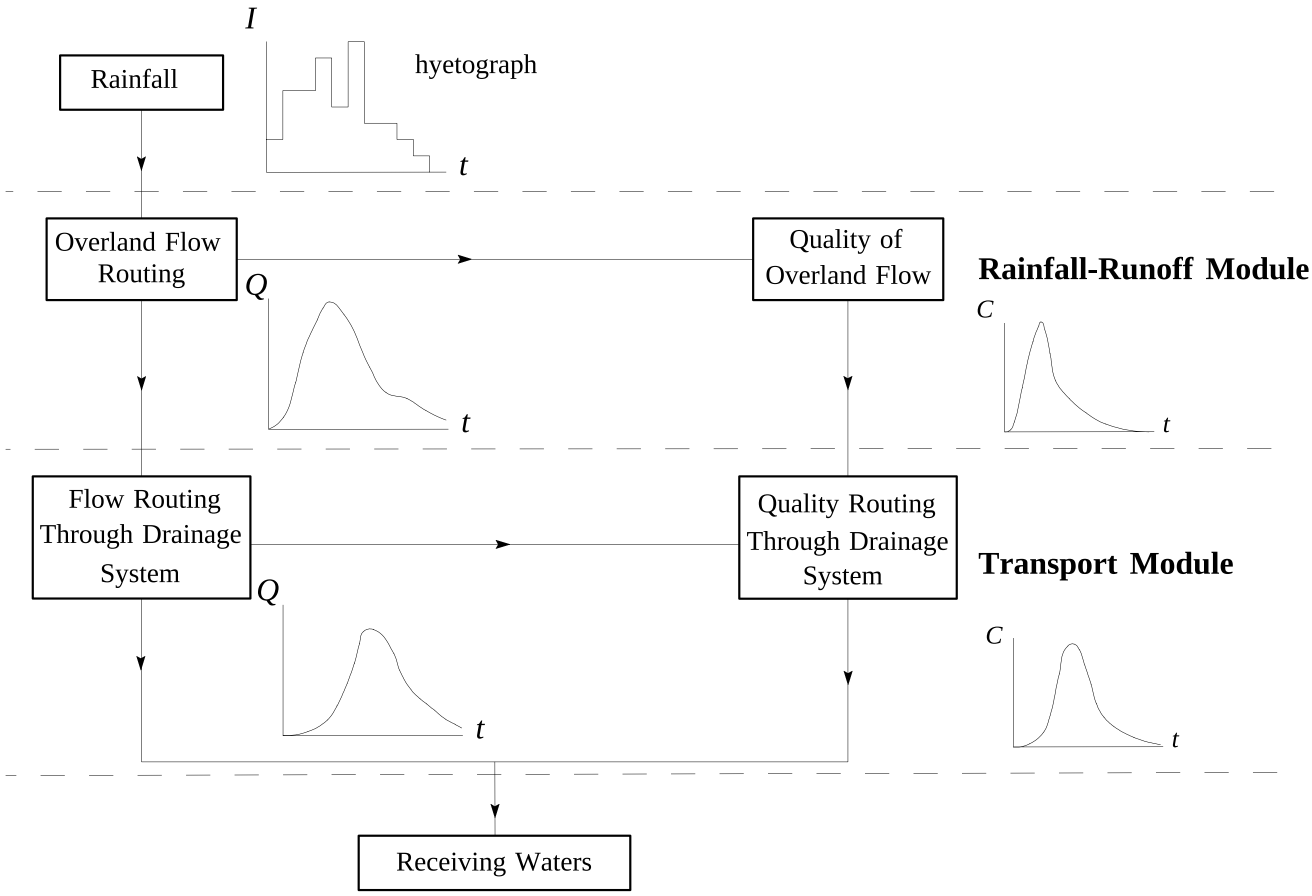

Figure 1. Overview of Processes Incorporated in a Storm Water Model

3.1 The Quantity of Storm Water

The hydrological cycle begins with precipitation. Precipitation in the form of rain falling on the land surface is subject to evaporation and initial loss due to interception by vegetation. The excess rainfall is available for *infiltration*, *overland flow* and *depression storage*. Depression storages are small pore and depressions on the land surface, which temporarily store water. Infiltrated water may flow through the upper layer of the soil which is generally the *unsaturated zone* of the soil, or flow deeper into the soil reaching the *groundwater*, or *saturated zone*. Water, which has infiltrated the soil and moves through the unsaturated zone and later becomes surface water, is known as *interflow*. In some urban storm water models, sub-surface flows are not modelled. One reason why sub-surface hydrology is not included in some urban storm water models is that a large proportion of the urban catchment is impervious, with little or no sub-surface flows. Unfortunately, accurate representation of the hydrological cycle is important for the accurate simulation of both runoff and its quality.

The two most important problems associated with the quantity of water are; *flooding* and *water supply*. These problems are relevant in varying degrees to both urban and rural catchments. Alterations to the form of the landscape by human activity results in increasing runoff volumes, reduced times for flows to reach their maximum and the increase in peak flow rates. Consequently, urban areas are more susceptible to flooding affecting all land use activities. Provision of storm water infrastructure, which may consist of a network of drainage pipes, channels and retarding basins is essential to protect both property and lives from flooding. In many instances, the infrastructure is only designed for a particular storm event, usually the 1 in 10 year storm event.

The concentration of human activity in a small area also creates problems for supplying water of suitable quality. Water supply problems relate to the allocation of available water to satisfy various types of water uses, such as industrial, residential and agricultural. This involves the design of a supply and treatment infrastructure such as reservoirs, pumps, pipes, reticulation systems and water treatment plants to meet the required demands. Therefore, models developed to simulate storm water flows from urban areas differ from models developed to estimate flows in rural areas. Models of urban areas are generally more complicated because they must include additional factors such as gutters, streets, sewers, overflows, surcharging, closed conduits under pressure, storm water drainage networks, culverts, open channels, roof top storage, open and natural watercourses and storages. *Surcharges* occur when a closed conduit, which would normally act as an open channel, becomes full and acts a conduit under pressure. Under some circumstances, this is desirable because it has the potential to increase the capacity of the storm water drain. If there is sufficient pressure so that the water rises above the ground level, then overflow occurs where the excess volume of flow becomes surface runoff. Urban catchments respond considerably faster to rainfall than rural catchments. Therefore, models developed for an urban catchment must be able to capture the rapid response of the catchment to storm events.

Another main objective of the analysis of storm water flows is to determine inputs of pollutants to receiving waters. Flowing water is the main mechanism, along with the impact of rain for transporting pollutants in the urban catchment.

3.2 The Quality of Storm Water

The five natural processes, which affect the movement and transformation of pollutants in an urban catchment are; *chemical*, *physicochemical*, *biological*, *ecological* and *physical*. Chemical processes involve the reaction of two or more compounds with each other to form one or more different compounds. An example of a chemical process in a natural system is the transformation of SO_2 into SO_3 and eventually H_2SO_4 (sulfuric acid) in the atmosphere. Biochemical processes are a result of chemical transformations taking place within a biological organism, such as bacterial decomposition of organic material and photosynthesis. Physicochemical processes involve the chemistry and physics of molecules interacting with their surroundings. The most important physicochemical processes are; *adsorption*, *desorption* and *absorption*. Adsorption is the adhesion of a substance to the surface of a solid or liquid. Adsorption is an important process because many pollutants such as nitrogen, phosphorous, various pesticides and heavy metals attach themselves to sediment particles and are in turn transported with the particles in flowing water. The quantities of pollutants that become attached to sediment particles are a function of the concentration of pollutants in the runoff and temperature. Desorption is the release of pollutants from sediment particles. Absorption is the penetration of a substance into or through another. It usually takes place at the air-water interface where gases are absorbed into water. This is the primary mechanism whereby receiving water bodies obtain oxygen. Ecological processes involve interactions between different organisms in the food chain. This includes consumption, growth, mortality and respiration from organisms. Transport or physical processes describe the movement of pollutants by fluid motion. This is primarily by the action of *advection*, the fluid moving and *diffusion*, the motion of molecules and turbulent fluctuations in the fluid dispersing material. The transport process acts independently of the transformations of nonconservative substances and is equally valid for both conservative and nonconservative substances. Materials that are not transformed chemically while being transported are termed *conservative substances*, otherwise they are *nonconservative substances*. For example, dissolved salts are conservative because, generally they do not interact with other substances. Nitrogen, in its ionic state will undergo chemical, physicochemical and biological transformation in a water body.

Major water quality problems in urban storm water are produced by; salinity, temperature, sedimentation, dissolved oxygen, toxic substances and biological effects. Temperature has impacts on; physicochemical reactions, biochemical reactions, biological processes and on the behavioural pattern of organisms. Temperature can also result in synergistic effects. For example, higher water temperatures exacerbate the adverse effects of low dissolved oxygen concentrations. Salinity problems are associated with high concentrations of total dissolved salts. Salinity affects aquatic organisms as well as uses of water withdrawn from receiving water. Sedimentation is a natural process, which has been accelerated in many areas by man’s activities. Suspended sediments in high concentrations diminish light penetration, thereby inhibiting photosynthesis by aquatic organisms. Sediments that are deposited can smother plants and organisms and destroy fish spawning grounds. Sediments entering receiving waters can also carry attached nutrients, pesticides and heavy metals. Sediments can also clog water treatment plant filters, block channels and pipes. Dissolved oxygen is important as an indicator of water quality. Organisms in aquatic systems must have oxygen to survive. The primary demand for oxygen in receiving waters is by decomposing organic material. Three indicators used in relation to oxygen demand are; *biochemical oxygen demand* (BOD), *chemical oxygen demand* (COD) and *total organic carbon* (TOC). TOC and COD are an indicator of the total amount of organic material present. BOD is a measure of the total amount of oxygen required to biochemically oxidise organic matter at a specific temperature and time. It is generally considered a major indicator of the health of a water body. Toxic substances include; herbicides, insecticides, pesticides, heavy metals, radioactive materials, oils and reduced ions. The sources, health and environmental consequences of a variety of pollutants that can occur in urban storm water are given in Table 3.1.

The rates at which chemical, physicochemical and biochemical reactions occur are important in understanding ambient water quality. However, due to the short response times in urban runoff, impacts of chemical and biochemical processes on urban runoff quality are usually negligible, the only exception being storages that are used as wetlands. Hence, these processes are neglected in most urban runoff models.

Modifications which man has made to the land surface have exacerbated physicochemical and transport processes in many regions, thereby increasing the quantity of pollutants and altering both the types of pollutants and the time pattern of flows. Consequently, in order to estimate the quantity and quality of water from an urban area, these processes must be included in a storm water model.

3.3 Approaches to Storm Water Quantity Estimation

Nix (1994) uses three categories (*i*) *simple,* (*ii*) *simple routing* and (*iii*) *complex routing* models to categorise models. Each category has different demands on data and computing resources and provides results at different time scales and spatial resolution. In simple models, no routing is performed, little data is required, calculations are not repetitive and a computer may not be required to perform the calculations. These models provide very little detail of the behaviour of the flow or pollutant. In general, these models are used to provide long-term averages or peak values. They are specific to a particular site and catchment behaviour. Empirical models could be considered as simple models. Although some statistical models are based on complicated techniques, they only reflect the current behaviour of a catchment at a particular site. Some empirical models involve very simple expressions that do not require the use of a computer. Both simple and complex routing models are based on physical laws describing the flow within the catchment. Although, they are deterministic models, they describe the behaviour of the catchment at different complexities. The complexity of a model has implications on the computational resources required, limitations of the model and the reliability of the results produced by the model.

The most sophisticated models are capable of producing the same information as simpler models at a price, however the converse is not generally true. Simple storm water models do not simulate some important processes. For example, the commonly used storage routing technique is a lumped model. Processes that are time dependent, such as the decay of some pollutants cannot be modelled because processes are assumed to occur instantaneously. To overcome this problem, models incorporate time, such as a lag in the routing process. This introduces another subjective parameter for the user to estimate and this approach is independent of the behaviour of the process being modelled. Lumped models are usually used in planning models where the time steps are much larger than the time scale of the transients that occur through the system. Therefore, they use average values for the various processes. This ignores the temporal and spatial variability of the system, which are required to test the integrity of the storm water system. The spatial and temporal variability must be artificially introduced into the modelling process. For example, a planning model for allocating potable water may use an average monthly demand to test a water allocation strategy. However, peak demands are required to test the integrity of the water supply infrastructure. The assessment of the integrity of the infrastructure is integral to the success of the water allocation strategy and cannot be performed independent of the water allocation analysis. Therefore, an empirical relationship between peak and average demands must be established. This adds additional subjectivity and uncertainty in the modelling process. These problems could be overcome by using models that are more complicated, but at a cost.

The importance of selecting a quantity model with the appropriate temporal and spatial resolution is not emphasised in other reviews. If flow is not modelled adequately, then water quality predictions will not reflect the true behaviour of the catchment.

Table 3.1 Sources, Health and Environmental Consequences of various Contaminants

Contaminant	Sources, Health and Environmental Consequences
Nitrogen	Amongst the major point sources of nitrogen in water bodies are; municipal and industrial waste water and septic tanks. Diffuse sources of nitrogen include fertilisers, animal wastes, leachate from landfill and atmospheric fall out. Nitrates become toxic only under conditions in which they are reduced to nitrites. In high concentrations nitrate is known to cause methemoglobinemia in bottle fed infants.
Phosphorous	In the elemental form, phosphorous is highly toxic. Phosphorous as phosphate is one of the major nutrients required by plants. Phosphorous is not the sole cause of eutrophication, but it is a limiting factor for aquatic plants. Phosphates enter waterways from several different sources. These include human and animal excreta, surface runoff and atmospheric fallout. High concentrations of total phosphate may interfere in water treatment plants. Algal growth imparts undesirable tastes and odours to water, interferes with water treatment and becomes aesthetically unpleasant.
Copper	Prolonged excessive quantities of copper may result in liver and kidney damage. Copper may impart some taste to water. The toxicity of copper to aquatic life is dependent on alkalinity. The lower the alkalinity, the more toxic copper is to aquatic life. It is rapidly adsorbed to sediments. It is highly toxic to most aquatic plants as well as most freshwater and marine invertebrates. It is considered more toxic to freshwater fish than any other heavy metal except mercury. Major sources of copper occur in; steel production, sewage treatment plant wastes, corrosion of brass and copper pipes. It is used in electrical wiring, plumbing and the automobile industry. Copper sulfate has been widely used in the control of algae in water supplies.
Coliforms	Coliforms are an indicator organism for faecal coliforms, steptococcal and other pathogenic bacteria. Sewage and animal wastes are the major sources of coliform bacteria. Possible chronic health effects of coliform bacteria include; gartroenteritis, salmonella infection, dysentery, typhoid fever and cholera.
Chromium	Chromium was used in making paint pigment, textile colouring and tanning. More recently, it is used in the production of stainless steel, photoelectric cells and ceramic glazes. The principal emissions of chromium into surface waters are from electroplating, waste incineration, contaminated laundry detergent and bleaches and septic systems. Toxicity of chromium to humans and aquatic organisms is generally low. Under most conditions, mercury, cadmium and copper are more toxic than chromium. Soluble compounds can cause liver, kidney and lung damage.
Cadmium	Cadmium is toxic to man, causing chronic kidney and liver disease. It is deposited and accumulates in various human body tissues. Its major source is industrial production such as; electroplating, pigments, plastic stabilisers, discarded batteries, paints, corrosion of galvanised pipes, fertilisers and sewage sludge. In aquatic systems, it is adsorbed to sediment particles. Certain invertebrates and fish are very sensitive to cadmium. Increased hardness and alkalinity decreases the toxicity of cadmium for aquatic organisms.
Iron	Pollution sources of iron are industrial wastes, iron-bearing groundwater and leaching from cast iron pipes in water reticulation systems. In the presence of dissolved oxygen, iron will precipitate as a hydroxide, forming gels or flocs. These may be detrimental to fish and other aquatic life as they settle over stream beds smothering invertebrates, plants and spawning grounds. In water supplies, it affects taste and stains clothes and plumbing fixtures. For some industries, low concentrations of iron are required. These include paper manufacturing and flood processing.
Lead	Lead is used in storage batteries, pipes, paint, petrol additive, solder and fusible alloys. Combustion of oil and petrol is the major source of lead absorbed by humans. Lead enters the aquatic environment through precipitation, leaching of soil, street and municipal runoff, corrosion of lead pipes, discarded storage batteries, lead-soldered pipe joints and industrial waste discharges. It is a toxic metal that accumulates in the tissue of organisms by ingestion or inhalation of dust or fumes. It results in irreversible nerve and brain damage in infants. Kidney damage, blood disorders and hypertension are symptoms of health problems associated with lead. The major toxic effects of lead include anaemia, neurological dysfunction and renal impairment. Lead is less toxic to invertebrates than copper, cadmium, zinc and mercury.
Mercury	Mercury is highly toxic to aquatic plants, organisms and humans. It can accumulate by; ingestion, skin adsorption and inhalation of vapour. Long-term exposure can produce brain, nerve and kidney damage. Birth defects and skin rash have also been attributable to exposure to mercury. Sources of mercury include; amalgams, electrical equipment, fungicides, mirror coatings and sewage. In the aquatic environment, mercury associates strongly with suspended solids.
Suspended solids	For aquatic life, suspended solids can reduce light penetration, which will adversely affect photosynthetic activity. Suspended sediments provide areas where microorganisms do not come in contact with chlorine disinfectant. Therefore, it can influence the efficiency of water treatment processes such as coagulation, sedimentation, filtration and chlorination.
Zinc	Zinc is used in brass, galvanising, die-casting and leaching of galvanised pipes and fittings. It is an essential element in human metabolism. It has however, a bitter or astringent taste. Toxic concentrations of zinc compounds cause adverse changes in the morphology and physiology of fish. The toxicity of zinc is dependent on pH and water hardness. Under most circumstances, mercury and copper are more toxic to aquatic plants and invertebrates than zinc, whereas chromium, cadmium, nickel and lead may be more or less toxic, depending on conditions (Moore and Ramamoorthy 1984). Mercury and copper are more toxic to fish than zinc. The rare toxicity of zinc arises from its synergistic interaction with other heavy metals.

3.3.1 Statistical and Empirical Models

Statistical models that have been used for estimating storm water flows and water quality loads, are usually based on regression models. These relate measured quantities, such as water quantity with measurable physical parameters that are considered important in a particular process. Regression models are an example of a stochastic modelling approach. These may include climatic characteristics, such as rainfall intensity and catchment parameters (impervious area, land-use and catchment slope). For example, the nonlinear regression model

$$Y = \beta_0 \prod_{i=1}^{n} X_i \beta_i$$

in which Y is the dependent variable, X_i are the *explanatory* or observer variables and β_i are the unknown regression coefficients, is a common statistical model used for modelling both water quality and quantity. Other regression models include simple linear, multiple linear, semi-log transform and the log-log transform (see, for example Bidwell 1971, Jewell and Adrian 1981). Examples of statistical models used in urban watershed modelling can be found in Jewell and Adrian (1981), Driver and Tasker (1988) and Yao and Terakaura (1999). It is recognised that linear regression is inadequate in urban catchment modelling (Jewell and Adrian 1981). The most important limitation of statistical models is that the statistical relationship developed from a given set of data reflects a particular spatial arrangement. For any markedly different spatial patterns and processes, new data and a new statistical relationship must be developed. Because of these limitations, the statistical approach has been primarily used only for crude analysis or in situations where deterministic approaches cannot be used because of insufficient data or resources. Driver and Tasker (1988) describe regression models as sufficient for planning purposes only.

An example of a regression method for analysing runoff is based on the *antecedent precipitation index* (API). It is the most frequently used and important explanatory variable in surface water runoff. The antecedent precipitation index is essentially the summation of the precipitation amounts occurring prior to the storm, weighted according to the time of occurrence. An example of a quantity antecedent regression model is (Betson *et al*. 1969)

$$C = c + (a + dS)\exp(-bA),$$

$$Q = (i^n + C^n)^{1/n} - C$$

in which Q is the surface runoff, C runoff coefficient, S a seasonal index parameter, A antecedent precipitation index, i rainfall and a, b, c, d and n are model coefficients to be determined from the data using regression analysis.

Empirical models involve a functional relationship between a dependent variable and variables that are considered germane to the process. These variables are chosen from knowledge of the physical processes involved and from empirical measurements. An example of an empirical approach for estimating runoff is the *rational formula*

$$Q = CiA.$$

The rational method is the simplest approach to modelling peak runoff volumes, which are important for storm water infrastructure design. The rational method is a simple relationship between flow Q, the catchment area A, the rainfall intensity i, and a runoff coefficient C where $0 \le C \le 1$.

3.3.2 Deterministic Models

Deterministic models are based on conservation laws, which govern the behaviour of a fluid. These laws generally involve the *conservation of flow*, known as *continuity*, the *conservation of momentum* or the *conservation of energy*. In almost all cases, one-dimensional flow analysis is undertaken. Deterministic models used in storm water modelling can be classified as either *hydrologic* or *hydraulic* models. Hydrologic models usually satisfy the continuity equation only. Hydraulic models solve the continuity equation as well as either the momentum or the energy equations as a coupled system of equations. The major difference between these modelling approaches is that hydraulic models describe the spatial behaviour of a process. It is the momentum equation that defines the speed at which a process can occur.

Many engineers in Australia do not make this distinction. The distinction between hydrology and hydraulics is determined by the process that is being modelled. For example, rainfall-runoff process is considered as a hydrological process and modelling flows through open channels is a hydraulic problem. This distinction is due to the historical development of models used to simulate overland and open channel flows. Traditionally, due to the complexity of overland flow, only the continuity equation was solved. The dynamic equations (momentum or energy) are considered of secondary importance. As techniques emerge for simulating overland flow by solving simultaneously the continuity and dynamic equations, this distinction is not clear. Therefore in this report, the distinction between hydrologic and hydraulic models is based on the equations that are used to describe a process and not the process that is being modelled.

3.3.2.1 Hydraulic Models

For very simple problems, analytical solutions are available for the solution of the governing equations. Generally, numerical schemes are used to solve these equations. Hydrological methods have a greater scope for solution using analytical methods. In complicated problems, numerical schemes such as *finite differences*, *finite elements* or the *method of characteristics* are used. Finite differences are the most commonly used approach and these can be either *implicit* or *explicit* schemes. In explicit schemes, a single unknown value can be written in terms of known values. This produces a large number of simple linear equations that can be solved directly for the unknown. In implicit schemes, a number of unknowns at a particular time are written in terms of the knowns, established previously as well as unknowns at the current time. This results in a system of coupled simultaneous equations that must be solved. The major advantage with implicit schemes is that they are unconditionally stable. They are stable for any computational time step used in the model. Therefore, the additional computational effort required to solve a system of equations is compensated for by a relaxation in the restriction in the time step that can be used in the simulation. However, the adequate description of boundary conditions and truncation errors, due to the finite difference approximations, may preclude the use of very large time steps in an implicit finite difference scheme. This is in contrast to explicit schemes, where there is a severe restriction on the time step that may be employed. Although the time step restriction is directly proportional to the speed of the transients being modelled, this may not be a disadvantage in modelling rapidly varying transients. Here a small time step is required to adequately capture the behaviour of the transient. Rapidly varying transients are common in urban watershed problems, such as overland flow and flash flooding.

3.3.2.1.1 Shallow Water Wave Equations

The conservative form of the one-dimensional continuity and momentum equations can be written as

$$\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{F}}{\partial x} = \mathbf{S} \qquad (1)$$

where **U** is a vector of conservative variables

$$\mathbf{U} = \begin{bmatrix} A \\ Q \end{bmatrix}$$

F is the flux vector

$$\mathbf{F}(\mathbf{U}) = \begin{bmatrix} Q \\ \dfrac{Q^2}{A} + gI_1 \end{bmatrix}$$

and **S** represents the source vector

$$\mathbf{S} = \begin{bmatrix} qA \\ gA(S_0 - S_f) + gI_2 \end{bmatrix}$$

in which A is the water depth, Q is the discharge, q is the lateral inflow, x is the distance, t is the time, g is the acceleration due to gravity, S_0 is the bed slope, S_f is the friction slope and I_2 is given by

$$I_1 = \int_0^{y(x)} (y(x) - \xi)B(\xi)d\xi.$$

The effects of forces exerted by contraction or expansion of the channel walls on the flow is described by

$$I_2 = \int_0^{y(x)} (y(x) - \xi)\left[\frac{\partial B(\xi)}{\partial x}\right]_{y(x)=y_0} d\xi$$

which is zero for a uniform channel, where, B is the width of the channel, y is the water depth and y_0 is a constant water depth. These equations are known as the *shallow water wave equations* or the *St. Venant equations*.

The shallow water wave equations written in non-conservative form with the flow velocity $u = Q/A$ and y as the dependent variables are; for the continuity equation

$$\frac{\partial y}{\partial t} + \frac{\partial (uy)}{\partial x} = q \tag{2}$$

and for the momentum equation

$$\frac{1}{g}\frac{\partial u}{\partial t} + \frac{u}{g}\frac{\partial u}{\partial x} + \frac{\partial y}{\partial x} = S_0 - S_f - \frac{q}{g}\frac{u}{y}. \tag{3}$$

The friction slope $S_{f\,,}$ is approximated using either the Manning or Chezy equations. The Manning equation is given by

$$S_f = K^2Q^2 = \frac{u|u|\eta^2}{R^{4/3}}$$

in which η is the Manning resistance coefficient and R is the hydraulic radius, defined by $R = A/P$ with P the wetted perimeter and K is known as the *conveyance*. The Chezy equation is given by

$$S_f = \frac{u|u|}{cR}$$

in which c is the Chezy resistance coefficient. In both equations, the absolute sign for the velocity will ensure that the friction always opposes the flow.

The continuity equation, (2) is based on the law of conservation of mass in a fluid element. It simply states that the rate of change in water depth with time in a fluid element is equal to the net inflow into the fluid element. The momentum equation, (3) is a mathematical expression for the conservation of momentum within a fluid element. It simply states that the rate of change in momentum of a fluid element is equal to the sum of forces acting on the element. It is the momentum equation that determines the velocity or speed of the fluid element.

The shallow water wave equations are *hyperbolic* and it is this feature that distinguishes them from other methods of routing, which are generally sub-sets of these equations. The distinguishing feature of the shallow water wave equations is that they have two characteristics. These characteristics represent the directions that information can travel. In the case of the shallow water wave equations, depending on the flow conditions, information can propagate both upstream and downstream. This is important because downstream obstructions will influence the flow upstream of the obstruction. For example, flow upstream of a weir will be influenced by the weir. This influence can only be simulated if there is an interaction of information travelling both upstream and downstream of the weir or obstruction to the flow.

The shallow water wave equations can be used to simulate unsteady one-dimensional gradually and rapidly varying flows, if (1) is used (see, for example Zoppou and Roberts 1999) in open and natural channels and in pressurised closed conduits using the Priessmann slot (Abbott 1979). Two-dimensional overland flows can also be simulated using the shallow water wave equations.

Under steady flow conditions, the continuity equation is simply $Q = q$, and the momentum equation becomes

$$S_f - S_0 = \frac{d\left(y + u^2/2g\right)}{dx} \tag{4}$$

which is used to calculate the water surface profile in an open channel upstream of an obstacle? This type of analysis is referred to as *backwater analysis* and it involves the solution of (4) using an iterative scheme (see, for example Henderson 1966).

In (3) the *local acceleration slope*, $1/g\ \partial u/\partial t$ is the same order of magnitude but opposite in sign to the *convective acceleration slope*, $u/g\ \partial u/\partial x$. Both of these terms are generally an order of magnitude smaller than the *pressure slope*, $\partial y/\partial x$.

This is demonstrated by routing the discharge hydrograph illustrated in Figure 2 through a rectangular channel and plotting the individual terms in the momentum equation. In this example, the channel has a length of 10*kms* is 7*m* wide, with a bed slope, $S_0 = 0.005$ and the Manning resistance coefficient equal to 0.015. The downstream boundary condition is a uniform rating curve. A model using a fully implicit finite difference approximation to (2) and (3), in which the computational time step, $\Delta t = 60s$ and the computational distance step, $\Delta x = 1000m$ was used to rout the hydrograph. The individual terms in the momentum equation as a function of time at the location, $x = 5000m$ are shown in Figure 3. In this simple example, the local and convective acceleration terms have opposite signs and are smaller than the pressure slope. The pressure slope plays an important role in the friction slope. Its influence depends on the bed slope and the shape of the inflow hydrograph. It should only be neglected for very steep bed slopes.

Because of the relative magnitude of these terms, some are neglected to produce approximations to the shallow water wave equations. In addition, the relative computational effort required to solve the shallow water wave equations is greater than its simplified counterparts. Two well known and extensively used, simplified versions of the shallow water wave equations are the *kinematic* and the *diffusion wave* equations. The kinematic wave routing assumes that there are no backwater influences and that the local and convective acceleration and the pressure terms in (3) are small compared to the bed slope. The diffusion wave equations assume that the local and convective acceleration terms can be neglected in (3).

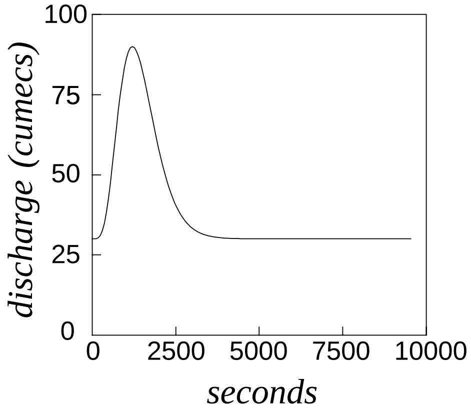

Figure 2. Discharge Hydrograph Used as the Upstream Boundary Condition in the Hypothetical Example

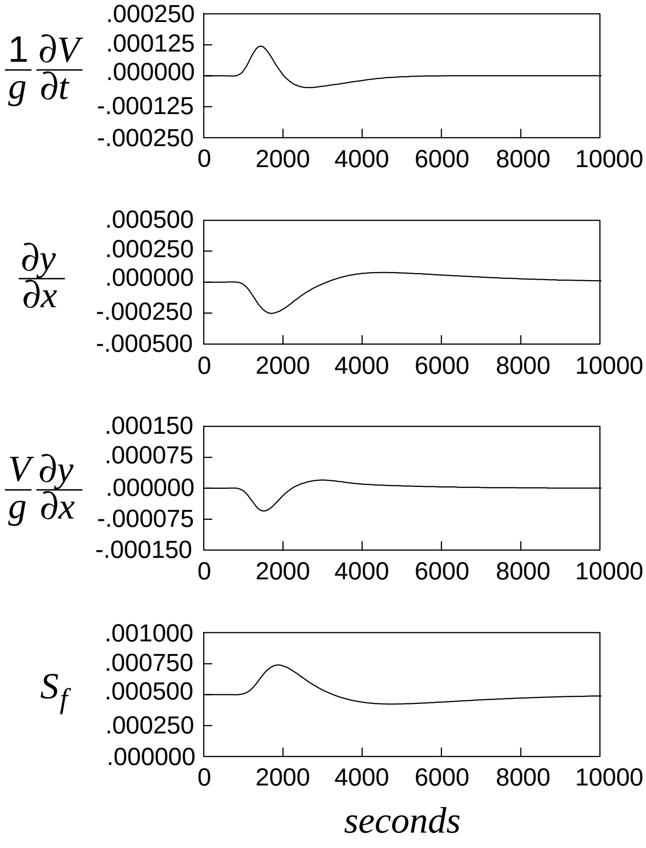

Figure 3. Magnitude of the Individual Terms in the Momentum Equation

Approximations to the shallow water wave equations only possess one set of characteristics, which always travel downstream. For example, the influence of a weir on the upstream water level and flow cannot be simulated by the kinematic or diffusion wave equations. This may have serious implications in the design of storm water infrastructure.

Transients can move rapidly through an urban catchment. To accurately capture these transients using the shallow water wave equation, very small time steps may be required of the order of seconds, minutes or hours. For larger time steps, days, weeks or months, transients may have passed through the system. The computational effort required to solve the shallow water wave equation for a complicated network of channels or pipes can be resource intensive. Therefore, hydraulic models based on the solution of the shallow water wave equations are usually restricted to event based or operation modelling. Solving the shallow water wave equations provides detailed information on the behaviour of the watershed and produces a more accurate representation of the interaction of the flow and the water depth than other approximate models. The water depth and flow are parameters that are important in the detailed design of storm water infrastructure. However, simplified and hydrological models only provide information about one of these variables, which is usually flow. To obtain the water depth from the flow, an empirical relationship between flow and water depth is required. For gradually varying flows, this relationship is not unique and can represent a significant source of error (see, for example Henderson 1966). Therefore, models, which solve the shallow water wave equations, are generally used to design storm water infrastructure.

Data required for the solution of the shallow water wave equations includes cross-sectional information, roughness coefficients, boundary conditions and any internal structures. For some catchments, this information may not be available. Generally, approximations to the shallow water wave equations will require less demanding data requirements.

3.3.2.1.2 Kinematic Wave Model

The kinematic wave model assumes that the local, convective and pressure slopes in the momentum equation can be neglected. It assumes that the friction slope balances the bed slope only, so that $S_f = S_0$. This assumption is generally valid for overland flow only. With a monotonic relationship between flow and water depth the kinematic wave is based on the solution of

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \tag{5}$$

and

$$Q = f(y).$$

The continuity equation, (5) can be written as

$$\frac{\partial Q}{\partial t} + \frac{dQ}{dA}\frac{\partial Q}{\partial x} = 0.$$

Recalling that

$$\frac{\partial Q}{\partial t} + \frac{dx}{dt}\frac{\partial Q}{\partial x} = \frac{dQ}{dt}$$

then the kinematic wave equation is given by

$$\frac{\partial Q}{\partial t} + V\frac{\partial Q}{\partial x} = 0$$

in which the kinematic wave speed, V is given by

$$V = \frac{dQ}{dA} \tag{6}$$

which is known as *Kleitz-Sneddon law*. The kinematic wave speed can be obtained by differentiating the functional form of the monotonic relationship between Q and y, given by (6). The kinematic wave does not experience any attenuation, however, it does steepen with time. In practical problems, this equation is solved numerically. The numerical scheme introduces truncation errors due to the finite difference approximations. These are not to be confused with roundoff errors, which are associated with machine precision. The numerical scheme introduces numerical diffusion, which results in attenuation of the simulated hydrograph. This diffusion has no physical justification, it is dependent on the computational time and distance steps used in the model.

A major advantage with this and other approximations to the shallow water wave equations is that detailed information on the catchment is not required. In this model, the kinematic wave speed is required, which can be calculated from channel properties or estimated from observed data. Since this approximation possesses one system of characteristics, then only one boundary condition is required for its solution. This is considerably less information than is required for the shallow water wave equations, which requires two boundary conditions.

3.3.2.1.3 Diffusion Wave Model

In the diffusion wave analogy, only the convective and local acceleration terms in the momentum equation are ignored. Therefore, the diffusion wave is based on

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \tag{7}$$

and

$$S_f = S_0 - \frac{\partial y}{\partial x} \tag{8}$$

in which the lateral inflow has been reintroduced into (7). The diffusion wave equation is capable of simulating the attenuation in the flow because the pressure slope is included in the momentum equation.

If the channel is rectangular, then $A = By$. Differentiating (7) with respect to x then

$$B\frac{\partial^2 y}{\partial x \partial t} + \frac{\partial^2 Q}{\partial x^2} = 0.$$

Differentiating (8) with respect to t then

$$\frac{\partial^2 y}{\partial x \partial t} = -\frac{2Q}{K^2}\frac{\partial Q}{\partial t} + \frac{2Q^2}{K^3}\frac{\partial K}{\partial t}.$$

Eliminating the second derivative of the flow depth between these equations yields

$$\frac{\partial^2 Q}{\partial x^2} = \frac{2QB}{K^2}\frac{\partial Q}{\partial t} + \frac{2Q^2B}{K^3}\frac{\partial K}{\partial t}. \tag{9}$$

Using the continuity equation then

$$\frac{\partial K}{\partial t} = \frac{dK}{dy}\frac{\partial y}{\partial t} = \frac{dK}{dy}\left(\frac{q}{B} - \frac{1}{B}\frac{\partial Q}{\partial x}\right)$$

and substituting into (9) results in an equation in terms of Q as

$$\frac{\partial Q}{\partial t} + V\frac{\partial Q}{\partial x} = D\frac{\partial^2 Q}{\partial x^2} + S$$

in which V is the wave speed and D is a diffusion coefficient, has the form of an advective-diffusion model. The coefficients are given by

$$V = \frac{Q}{KB}\frac{dK}{dy}, D = \frac{K^2}{2QB} \text{ and } S = \frac{q}{KB}\frac{dK}{dy}.$$

For nearly prismatic channels, with the assumption that the pressure slope is small, then V is given by the Kleitz-Sneddon law and the diffusion equation is simply given by (6).

Price (1973) provides values for these coefficients for an irregular channel, which are functions of the channel properties. The diffusion wave equation is capable of approximating the physical attenuation experienced by the flow because the pressure slope is included in the momentum equation.

Cunge (1969) showed that an implicit finite difference approximation of the kinematic wave equation is a second-order approximation of the diffusion equation. He equated the numerical diffusion and wave speed in the kinematic wave approximation with the corresponding coefficients in the diffusion equation using a Taylor series expansion of the finite difference equations. This provides expressions for the computational distance step and a finite difference weighting coefficient in terms of channel parameters and the computational time step used in the model. This produced the well-known *Muskingum-Cunge* method.

3.3.2.2 Hydrological Models

Hydrological methods ignore the spatial variability in the problem. They are generally based on the conservation of mass only. The unit hydrograph, lumped continuity or storage models, the Muskingum method and nonlinear storage are considered here to be hydrological methods. Some hydrological models can be interpreted as hydraulic models. The Muskingum method is one approach that can be described as an approximation to the shallow water wave equations or in terms of the conservation of mass.

3.3.2.2.1 Unit Hydrograph

For a storm of given duration, the unit hydrograph is defined as the hydrograph resulting from direct runoff produced by a unit of rainfall excess over a catchment. Hydrographs for storms of the same duration but different intensity can be obtained from the unit hydrograph by assuming a linear relationship between the hydrographs. The ordinates of the unit hydrograph are multiplied by the actual excess runoff depth for the storm. These unit hydrographs can be measured from individual catchments. More commonly, the unit hydrograph is obtained using analytical techniques. For example, the linear instantaneous unit hydrograph assumes that the catchment acts as a reservoir and the outflow is a linear function of storage, so that

$$S = KO$$

in which S is the storage, O is the outflow and $K > 1$ is a constant storage coefficient. Combined with the continuity equation for the reservoir

$$\frac{dS}{dt} = I - O$$

where I is the inflow, the exponential form of the instantaneous unit hydrograph for a single linear storage is (Chow 1964)

$$O(t) = \frac{1}{K}\exp(-t/K).$$

A large catchment can be subdivided into equal sub-catchments with each sub-catchment considered as a separate linear storage. The instantaneous unit hydrograph for a cascade of n linear reservoirs is given by (Nash 1957)

$$O(t) = \frac{1}{K(n-1)!}\left(\frac{t}{K}\right)^{n-1}\exp(-t/K)$$

which resembles a Gamma function. This model is linear because K is constant and does not consider translation of the flow. Nonlinear models (Kulandaiswamy 1964) and models which include translation, (Dooge 1959) have been developed.

3.3.2.2.2 Lumped Continuity or Storage Models

Lumped continuity or storage models simply satisfy the conservation of mass. The catchment response is instantaneous because the momentum equation is completely ignored. Replacing the spatial derivatives in (5) with finite differences so that $\partial Q/\partial x = (I - O)/\Delta x$ then

$$\frac{dS}{dt} = I - O$$

in which the storage $S = A\Delta x$. This equation is known as the *storage equation* which is used in simple routing methods. If the flow is assumed to be steady, then $dS/dt = 0$ and the flow model is simply a mass balance ($I = O$).

The Modified Puls method solves the storage equation, which is expressed over a finite time interval, Δt as

$$\Delta t(I_1 + I_2) + S_1 - \Delta t O_1/2 = S_2 + \Delta t O_2/2. \qquad (10)$$

All the unknowns are on the right hand side of the equation. This method only requires the construction of two curves, S and $S + \Delta tO/2$ as a function of O. For an initial outflow O_1, the storage S_1 is obtained from the $S - O$ curve and the quantity $S_1 - \Delta tO_1/2$ can be computed. The average inflow plus the quantity $S_1 + \Delta tO_1/2$ gives the quantity $S_2 + \Delta tO_2/2$. Thus the outflow O_2 corresponding to $S_2 - \Delta tO_2/2$ can be determined from the $S + \Delta tO/2 - O$ curve. Colon and McMahon (1987) found that this routing method produced significant errors in the simulated reservoir water depth, the discharge from the reservoir and in the duration of a flood. This was most pronounced under severe flood or reservoir release and during non-uniform spatial and temporal precipitation distributions. Under these conditions, the solution of the shallow water wave equations would be more appropriate.

3.3.2.2.3 Muskingum Method

In the Muskingum method, it is recognised that the storage in a river or reservoir depends on the inflow as well as the outflow. It is assumed that the storage is a linear function of inflow and outflow, such that

$$S = K(XI + (1 - X)O)$$

in which K and X are empirical constants to be determined by trial and error. Substituting into (9) and after simplifying

$$O_2 = C_1 I_2 + C_2 I_1 + C_3 O_1$$

in which

$$C_1 = \frac{KX - \Delta t / 2}{\alpha},\ C_2 = \frac{KX + \Delta t / 2}{\alpha},\ C_3 = \frac{KX - \Delta t / 2}{\alpha} \text{ and } \alpha = K(1 - X) + \Delta t / 2.$$

3.3.2.2.4 Nonlinear Storage

In the nonlinear storage methods, the storage is expressed as a nonlinear function of outflow so that

$$S = KO_w^m$$

where

$$O_w = XI + (1 - X)O$$

and m is some power. Substituting into the discretised storage equation (9), then

$$O_2 \Delta t + 2KO_{w_2}^m = (I_2 + I_1 - O_1)\Delta t + 2KO_{w_1}^m .$$

All the terms on the right hand side are known. Since this equation is nonlinear, an iterative scheme is required for its solution. If $m = 1$ then the model is identical to the linear Muskingum method.

3.4 Approaches to Storm Water Quality Modelling

Water quality modelling approaches are very similar to those used to model water quantity. Statistical and empirical models are also relevant for the modelling of pollutants. In deterministic models however, the transport of pollutants is modelled using a single equation, the conservation of mass, which includes the two fundamental transport processes, *advection* and *diffusion*. Advection describes the process by which pollutants are conveyed by moving water. Diffusion is the transportation of pollutants in the direction of decreasing gradient by molecular processes or turbulent fluctuations in the water. This process can occur in quiescent fluid. In general, turbulent diffusion is much larger than molecular diffusion. The transport of pollutants is dominated by the advection by flowing water. Diffusion is a secondary process. A one-dimensional analysis of the transport of pollutants is usually undertaken in urban catchments where the concentrations represent cross-sectional averages (Fisher *et al*. 1979).

In storm water modelling, pollutants are treated as neutrally buoyant material, which are transported by fluid motion. The behaviour of the fluid is assumed to be unaffected by the pollutant and can therefore be calculated independently of the pollutant transformations. This is not the case for example, with a thermal power station discharging highly saline water into a freshwater body. The difference in density between the two bodies of water may induce density currents in the flow. In this case, the flow and pollutant models are coupled and must be solved simultaneously. Sediment transport is another example where the flow and sediment transport should be modelled as a coupled system. However, this is seldom done.

3.4.1 Statistical and Empirical Approaches

Statistical models for estimating storm water quality are also based on regression analysis between water quality and relevant explanatory variables (see, for example Driscoll *et al*. 1979 and Driver and Tasker 1990, Driver and Troutman 1989). Regression models have been widely used to describe event mean concentrations (EMC) and total storm event load (Huber 1992a).

An important phenomenon relating to solids accumulation and to pollutant generation and discharge from impervious surfaces is the *first flush*. The first flush relates to the high concentrations of pollutants, especially solids, which often occur in the early portion of a runoff event. Material that has accumulated on a surface during dry weather and material that has previously been deposited in channels and pipes and is scoured by the flow are primary sources of pollutants in the first flush. The impact of higher rainfall intensities at the beginning of a storm dislodges particles and as the storm continues, less pollutant is available to be conveyed by the runoff. This also contributes to the first-flush effect. The wash-off of pollutants is therefore greater near the beginning of a storm. Between storm events, pollutants accumulate on impervious surfaces. This is known as the *buildup* process. Urban runoff quality models attempt to incorporate the build up and wash-off process using an empirical exponential *washoff* and the *buildup functions*. In the washoff model, the rate at which a pollutant is washed off the surface is assumed to be proportional to the availability of the pollutant on that surface. A typical washoff function is

$$\frac{dP_w}{dt} = -k_w r P_w$$

in which $P_w(t)$ is the mass of pollutant at time t, k_w is an empirical pollutant removal coefficient and r is the runoff flow rate. It has the following solution

$$P_w(t) = P_w(0)\exp(-k_w rt)$$

where $P_W(0)$ is the initial pollutant concentration. The buildup function suggested by Novotny (1995) is

$$\frac{dP_B}{dt} = I - k_B P_B$$

which has the following analytical solution

$$P_B(t) = I(1 - \exp(-k_B t)) / k_B + P_B(0)\exp(-k_B t)$$

in which $P_B(t)$ is the buildup of pollutant load at time t, I is the accumulation of pollutant between storms and k_B is the coefficient of pollutant buildup. The coefficients for both functions are determined from measured concentrations.

3.4.2 Mass Transport Equation

The basic equations that incorporates the *advection* and *diffusion* processes and is used to describe the behaviour of a pollutant in a stream, is the one-dimensional conservative advective-diffusion equation

$$\frac{\partial(A_x C)}{\partial t} = \frac{\partial}{\partial x}\left(A_x D_x \frac{\partial C}{\partial x}\right) - \frac{\partial}{\partial x}\left(uA_x \cdot C\right) \pm S(C,x,t)$$

in which, C is the thermal energy or constituent concentration, t the time, x is distance, u is the advection velocity, A_x the cross-sectional area, D_x the diffusion coefficient and $S(C,x,t)$ are all sources and sinks. This equation includes the advection of pollutant by the flowing water, diffusion of pollutant in the stream, constituent reactions, interactions and sources and sinks. Assuming that A_x and D_x are constant and using the flow continuity equation

$$\frac{\partial(A_x C)}{\partial t} + \frac{\partial}{\partial x}\left(uA_x\right) = 0$$

then

$$\frac{\partial C}{\partial t} = D_x \frac{\partial^2 C}{\partial z^2} - u\frac{\partial C}{\partial z} \pm S$$

which is the form of the advective-diffusion equation used in models like HEC – 5Q and WQRRS which are included in this review. The source term includes sinks and sources for conservative pollutants. For non-conservative pollutants, it can also include a production or loss of a pollutant, with or without interaction with another pollutant. This is known as a *kinetic process*. These include the chemical and physicochemical processes. The general form of such terms is

$$\frac{dC_i}{dt} = f(C_i, C_j, T) \quad \forall\ j$$

in which the rate of change in pollutant C_i is dependent on C_i and other pollutants C_j and temperature T. Generally kinetic processes are adequately described by first-order relationships of the form

$$\frac{dC}{dt} = -KC$$

in which K is the first-order rate coefficient and the negative sign indicates decay or loss. Zero-order processes are described by expressions of the form, $dC/dt = -K$. Second-order processes involve $dC/dt \propto C^2$. Higher-order or more complicated expressions could also be used. Chemical reactions can be described by zero-order, first-order, second-order or third-order processes. Generally, first-order processes are used. Due to the complex interactions in ecological processes, (see for example Jogenson 1982,1988) second and third-order kinetics is used to describe them.

Some pollutants are usually coupled, that is when one pollutant decays another may be formed or degrade. This will lead to a set of simultaneous equations. The advantage of first-order processes, which are coupled, is that the overall first-order rate coefficient is the sum of the first-order rates for the individual pollutants. The dissolved oxygen sag is a good example. Receiving water experiences a depletion of dissolved oxygen due to the inflow of organic material. The sag curve is due to two competing processes. BOD causes the level of dissolved oxygen to drop and re-aeration replaces dissolved oxygen from the atmosphere. Therefore, two interacting relationships are required to model the sag curve. The advective diffusion equation is written for each pollutant. These are

$$\frac{\partial C_{BOD}}{\partial t} = D_x \frac{\partial^2 C_{BOD}}{\partial z^2} - u \frac{\partial C_{BOD}}{\partial z} + \frac{dC_{BOD}}{dt} \pm S_{BOD}$$

$$\frac{\partial C_{DO}}{\partial t} = D_x \frac{\partial^2 C_{DO}}{\partial z^2} - u \frac{\partial C_{DO}}{\partial z} + \frac{dC_{DO}}{dt} \pm S_{DO}$$

in which C_{BOD} is the concentration of BOD, C_{DO} is the concentration of DO and S represents sources or sinks. The term dC/dt represents kinetic processes. Generally, these are described by first-order kinetic relationships. The time rate of change in BOD is assumed to be governed by

$$\frac{dC_{BOD}}{dt} = -(K_1 + K_3)C_{BOD}$$

in which K_1 is the first-order BOD reaction coefficient and K_3 is the first-order decay coefficient for the removal of BOD by sedimentation and adsorption. The term $-K_1C_{BOD}$ governs the rate of removal of BOD which is exactly equal to the rate of removal of dissolved oxygen. In addition, there is a saturation threshold for dissolved oxygen. Therefore, a suitable first-order reaction for DO is

$$\frac{dC_{DO}}{dt} = -K_2(Cs_{DO} + C_{DO}) - K_1C_{DO}$$

in which K_2 is the first-order re-aeration coefficient and Cs is the saturated dissolved oxygen concentration. The equation for BOD concentration can be solved independently of the DO equation. However, the DO equation cannot be solved until C_{BOD} is known. Therefore, the equations can be solved either simultaneously, using an implicit finite difference scheme or in a two step process using an explicit finite difference scheme, solving for BOD then for DO.

This simple example illustrates a way in which chemical and the transport process are combined. This is a common approach adopted in many water quality models.

The above transformations are not restricted to the advective-diffusion equation. They can be used with any transport equations. As with the hydraulic analysis, many water quality models use simplifications to the advective diffusion equation. These include *completely mixed reactor* and *plug flow*.

3.4.3 Completely Mixed Flow

A completely mixed reactor flow is based on the continuity equation only. This simplification is analogous to the storage equation in the hydraulic analysis. Complete mixing occurs instantaneously. The rate of change in mass of a pollutant is given by

$$V\frac{\partial C}{\partial t} = \frac{\partial (QC)}{\partial x} - KCV \pm S$$

in which V is the volume of the conduit and the equation contains a first-order decay and source term.

3.4.4 Plug Flow

Plug flow satisfies the continuity equation and includes travel time in the transport process. This is achieved by assuming that the input of flow over any time step behaves as a plug of fluid with homogenous quality travelling through a storage or along a channel. The storage consists of a series of these plugs and their retention time in the storage is determined by the amount of outflow from the storage. Changes in concentration between the plugs can occur during the retention time. The rate of change with time of a pollutant in plug flow is given by (Tchobanoglous and Schroeder 1987)

$$\frac{\partial C}{\partial t} = -\frac{Q}{A}\frac{\partial C}{\partial x} - KC \pm S$$

4. OTHER ASPECTS OF URBAN STORM WATER MODELLING

Water resources management planning involves the identification and evaluation of various management alternatives that satisfy certain objectives. These objectives might involve (*i*) economic factors, often expressed in terms of costs and (*ii*) water quality goals, which are often water quality standards imposed by regulatory authorities. Water resources management models usually include a water quality and quantity modelling component. In addition to describing the behaviour of the flow and water quality in a catchment, they may also include cost functions for alternative management strategies. Given the large number of alternative management strategies and constraints that must be satisfied, some models include an *optimisation* technique. Optimisation is used to determine optimum values for a given set of decision variables that will maximise or minimise an objective function, usually cost.

Planning decisions are greatly enhanced if confidence limits, which reflects the uncertainty in the decision making process can be placed on the results of a model. This uncertainty may arise from; (*i*) natural or inherent uncertainty (random variability in the hydrological processes or in costs), (*ii*) model uncertainty (from the use of a simplified model to describe a complex physical process) and (*iii*) parameter uncertainty (model parameters are not known with certainty). *Uncertainty analysis* is a technique that can be used to quantify uncertainty in the modelling results. Uncertainty analysis can be used to identify the dominant sources of uncertainty affecting the reliability of the results from a model. This will focus both data gathering and research activities in an attempt to reduce the uncertainty in these parameters and in the modelled results.

4.1 Optimisation

Optimisation provides a mechanism to automate a systematic series of executions of a model in search of an optimum solution from a range of possible outcomes. The best solution may be a minimum in the least cost sense or the largest improvement for a given investment. This is defined mathematically by the *objective function*. The coupling of a storm water model with an optimisation technique represents an important and powerful tool for the management of urban storm water. Optimisation techniques available include; (*i*) linear programming, (*ii*) nonlinear programming, (*iii*) dynamic programming and (*iv*) simulated annealing. Simulated annealing (Kirkpatrick *et al*. 1983) is not commonly employed in water resources problems, with other approaches being more common. Examples in water resources projects where optimisation techniques have been reported are; Allen and Bridgeman (1986), Behera *et al*. (1999), Brendecke *et al*. (1989), Carriaga and Mays (1995), Chu and Yeh (1978), Chung *et al*. (1989), Diaz and Fontane (1989), Ford *et al*. (1981), Labadie *et al*. (1980), Lansey and Basnet (1991), Lindell *et al*. (1987), Martin (1983, 1987), Nitivattananon *et al*. (1996) and Ostfeld and Shamir (1996).

Optimisation is also used in some models to *calibrate* model parameters. This is a process whereby the model response is fitted to an observed catchment response by adjusting a number of model parameters. This is done in an automatic and systematic way using an optimisation procedure.

4.1.1 Linear Programming

The general form of the linear programming problem is as follows

$$\text{minimize (or maximize)} \quad Z = \sum_{j=1}^{n} c_j x_j$$

$$\text{subject to} \quad \sum_{j-1}^{n} a_{ij} x_j \le b_i \quad \text{for} \quad i = 1,2,\ldots,m$$

$$\text{and} \quad x_j \ge 0 \quad \text{for} \quad j = 1,2,\ldots,n$$

in which Z is the objective function, x_j are the decision variables, c_j, a_{ij} and b_i are constants, n is the number of decision variables and m is the number of constraints. The problem consists of minimising a linear objective function subject to a set of linear constraints. Their advantage is that simple and efficient solution algorithms exist, such as *the simplex algorithm* (Press *et al*. 1992). It is relatively simple to include the nonegativity constraint. This is important when dealing with physical quantities, for example, the number of pipes must have a positive value. The linearity restriction of linear programming restricts its applicability. Nevertheless, many water resources problems can be described realistically by linear objective functions and constraints.

4.1.2 Dynamic Programming

The dynamic programming approach involves decomposing a complex problem into a series of simpler sub-problems, which are solved sequentially by transferring information from one level to the next level of the computations. These stages can represent different points in space or time or activities with a decision required at each stage. For an N-stage problem, the order of the *forward* computation is

$$f_1(x_1) \rightarrow f_2(x_2) \rightarrow \cdots \rightarrow f_{i-1}(x_{i-1}) \rightarrow f_i(x_i) \rightarrow \cdots \rightarrow f_N(x_N)$$

in which $f_i(x_i)$ is the cumulative optimum return for stages 1,2,…, and i given the state of the system is x_i. This pattern can be written as a recursive equation relating the states $f_i(x_i)$ to $f_{i-1}(x_{i-1})$ as

$$f_1(x_1) = \max_{\substack{m_1 \\ c_{1,m_1} \le x_1}} \{R_{1,m_1}\}$$

and

$$f_i(x_i) = \max_{\substack{m_i \\ c_{i,m_i} \le x_i}} \{R_{i,m_i} + f_{i-1}(x_i - c_{i,m_i})\}, \quad i = 1,2,\ldots,N$$

in which c_{i,m_i} is the penalty for alternative m_i for state i and R_{i,m_i} is the *return function* of a decision. The conversion from x_{i-1} to x_i is usually referred to as *state transformation*. Each stage must have a number of other states associated with it. The states describe the possible conditions in which the system might be at that stage of the computations. The effect of a decision at each stage of the problem is to transform the current state of the system into a state associated with the next stage. The connection between various states is defined by a decision. The *state* of the system represents the link between successful stages so that when each stage is optimised separately, the resulting decision is automatically feasible for the entire problem. It also allows for the optimum decision to be made for the remaining stages without checking the effect future decisions have on decisions made previously. A return function is the utility or cost of each potential state transformation. The optimality of the decision required at the current stage is judged in terms of its impact on the return function for the current stage and all subsequent stages.

The recursive equations are the only unifying theory for dynamic programming, it does not provide details on how the optimisation for each sub-problem is solved. In addition, there is no guarantee that each sub-problem can be solved. Dynamic programming, although considered as a powerful technique, is generally more difficult to learn and understand than linear programming.

4.1.3 Nonlinear Programming

Many problems in water resources are nonlinear. In some instances, the problem may be linearised and linear programming is employed in an iterative scheme where the solution is refined with each iteration. Robust methods are available for optimising nonlinear functions. Nonlinear optimisation algorithms can be classified broadly as search methods. The algorithm systematically and automatically searches through all feasible solutions and finds a solution, which satisfies the objective function. Search techniques such as conjugate gradient and pattern search methods, are simple to implement with complex models. In many nonlinear programming techniques, the search direction is governed by the local slope of the function being optimised. Successful moves are generally in a downhill direction. Unfortunately, this strategy may only locate a local and not the global minimum and the iterative nature of the approach means that nonlinear programming can be computationally expensive.

4.2 Uncertainty Analysis

Uncertainty analysis can be performed analytically or numerically. For complex problems, numerical techniques are exclusively used. Numerical reliability techniques include, in order of accuracy; (*i*) *sensitivity analysis*, (*ii*) *mean value first-order second moment analysis* (*iii*) *point estimate method*, (*vi*) *Monte Carlo simulation* and (*v*) *Mellin transform*. There are very few applications of the point estimate and Mellin transform to water resources problems. The point estimate is a relatively new technique and the Mellin transform is restricted to certain functional relationships not generally satisfied in complicated models. Examples of the application of uncertainty analysis to water resources problems can be found in Burges and Lettenmaier (1975), Chatterton *et al*. (1982), Jaffe and Parker (1984), Melching and

Yoon (1996), Melching *et al.* (1991), Scavia *et al.* (1981), Reddy *et al.* (1996), Tung (1987, 1989,1990), Warwick and Wilson (1990), Willey (1986), Xu and Goulter (1998), Yeh and Tung (1993) and Zoppou and Li (1992, 1993).

4.2.1 Sensitivity Analysis

Sensitivity analysis is simply establishing the change in model response, ***Y*** due to a small perturbation in each k independent model variables $\mathbf{x} = (x_1,\ldots,x_k)$. The model is considered most sensitive to the parameters that produce the greatest model response. This is equivalent to estimating the derivative

$$\frac{\partial Y_j}{\partial x_i} \quad \forall \ i.$$

Greater resources should be allocated to those parameters that produce the greatest model response. To effectively compare the sensitivity of a model to various parameters the derivative must be normalised. Therefore, the normal sensitivity coefficient S_{ij} for output Y_j to input x_i is given by

$$S_{ij} = \frac{\Delta Y_j \,/\, Y_j}{\Delta x_j \,/\, x_j}$$

in which Δx and Δy are the magnitudes of the perturbations and x_j and Y_i are the reference values for the output and input variables respectively. Sensitivity analysis does not consider the variability in a parameter. A highly sensitive parameter that is relatively well defined may have less influence on the reliability of the results from a model than a much less sensitive parameter that has large uncertainties. In this case, parameter uncertainty must be considered.

4.2.2 Mean Value First-order Second Moment Analysis

Consider a model response that is a function of a single variable, x so that $Y = f(x)$. The function can be expanded as a Taylor series around $x = \mu_x$, where μ_x is the mean value of x to give

$$Y = f(\mu_x) + \frac{df}{dx}(x - \mu_x) + \frac{1}{2}\frac{d^2 f}{dx^2}(x - \mu_x) + \cdots$$

where the derivatives df/dx, d^2f/dx^2,… are evaluated at $x = \mu_x$. If second and higher-order terms are neglected, the resulting *first-order* expression for Y is

$$Y \approx f(\mu_x) + \frac{df}{dx}(x - \mu_x).$$

Taking the expectation of both sides, then

$$\mu_Y = E[Y] = f(\mu_x)$$

That is the expected value of $E[Y]$ is the mean value of Y and is obtained by evaluating $f(x)$ using the mean value of $x = \mu_x$. Combining the above results, the variance of Y defined by

$$\sigma_Y^2 = E[(Y - \mu_x)^2]$$

can be approximated by

$$\sigma_Y^2 \approx E\left[\left(\frac{df}{dx}(x - \mu_x)\right)^2\right] = \left(\frac{df}{dx}\right)^2 \sigma_x^2$$

in which σ_x^2 is the variance of x. If $\boldsymbol{Y}$ is dependent on k mutually independent variables $\mathbf{x} = (x_1,\ldots,x_k)$ it can be shown that

$$\mu_Y = f(\mu_{x_1},\ldots,\mu_{x_k}) \text{ and } \sigma_Y^2 = \sum_{i=1}^{k}\left(\frac{df}{dx_i}\right)^2 \sigma_{x_i}^2$$

The components of the output variance represent weights of the input variances multiplied by the square of the sensitivity of the model output to the input. Therefore, it is relatively simple to extend sensitivity analysis to perform mean value first-order second moment analysis. The only additional information that is required is the standard deviation of the input variables, which is a measure of what is not known about the variable. Correlated random variables can be considered in first-order second moment analysis. Implicit in mean value first-order second moment analysis is that the model response is linear or approximately linear near the perturbed values. Since only the mean and variance of the model response is provided in mean value first-order second moment analysis, only a two parameter distribution can be fitted to the model response so that confidence limits can be inferred from the fitted distribution.

4.2.3 Monte Carlo Simulation

In Monte Carlo simulation, variables are sampled at random from pre-defined probability distributions, with or without correlation and the distribution of the model response is obtained from repeated simulations. The validity of this model is not affected by non-linearities in the water quality model. Comparing the standard deviation estimates from Monte Carlo simulations with those from first-order second moment analysis, provides an indication of the model non-linearity. The major drawback with Monte Carlo simulation is that the probability distribution of the uncertain parameters must be known or assumed. This may not be possible if there is insufficient data to establish these distributions. The other major problem with Monte Carlo simulation is that it can be computationally expensive. In some problems 1000’s of repeated simulations of the model are required.

Monte Carlo simulation has the advantage of estimating model frequency distributions, but it is computationally expensive if a large number of random variables are involved in the problem. The cumulative frequency distribution of the model response is useful in evaluating overall dispersion in the model predictions and in assessing the likelihood of violating a water quality standard.

The US Environmental Protection Agency (Salhotra *et al.* 1988) has developed a generic Monte Carlo module for use with any transport model. The generator can sample from, Normal, log Normal, uniform, exponential, empirical, triangular and Johnson *SB* and *SU* distributions. Correlated random variables can also be generated.

4.3 Economic Analysis

Water resources managers must be able to identify the best management strategy from a number of alternative scenarios. The best management strategy could be chosen from those alternatives that do not compromise the storm water infrastructure using hydraulic analysis. Water quality objectives could be used to select the best management strategy. Economic analysis provides another method for assessing alternative storm water management options. Traditionally, economic analysis generally involved a cost-benefit analysis. The use of cost-benefit criteria as a decision-making tool is a matter of expediency, since they primarily deal with tangible and quantifiable factors and hence they can be analysed objectively. These tangible factors are commonly referred to *as life-cycle* costs and include such things as: maintenance, capital, operating, replacement, disposal and land acquisition costs.

Economists often lump criteria that are difficult to assign a monetary value as *externalities*. Externalities might include social well being, national security, regional growth and stability, preservation of natural areas and risk management costs. It is clear that society also has constraints it wants to impose on projects that do not necessarily have a monetary value. Traditional cost-benefit analysis does not consider these factors. The problem is that externalities are intangible and non-quantifiable, hence would be treated rather subjectively. The real question is not whether externalities should be considered as a planning objective, but rather how they should be considered objectively within the planning framework. These objectives are not mutually exclusive, in fact they are often conflicting. Contributions to one may only be made at the expense of the other. For example, the cost of increasing the capacity of a waste water infrastructure to eliminate overflows may be significantly greater than the cost associated with the overflow. Using cost-benefit analysis to eliminate overflows in a design may not be economically feasible. However, social acceptance of overflows may reverse the decision based on a cost-benefit analysis alone. The problem is how a trade-off should occur. Does an intangible social dis-benefit, in terms of environmental degradation for example, provide sufficient justification for rejecting a project, irrespective of the cost-benefit objective?

Fortunately, planners do not make the final decision, nor do they pass legislation that may influence planning decisions. The real decision-making lies with politicians. Planners do however, demonstrate the cost-effectiveness, the social, environmental and technical feasibility of a project. Therefore, the impacts of life-cycle costs and externalities should be considered in project design and ranking. An economic analysis of various management strategies can be misleading if the infrastructure modelling is inadequate.

5. URBAN STORM WATER MODELS

There are literally hundreds of models developed by academic institutions, regulatory authorities, government departments and engineering consultants that are capable of simulating water quality and quantity in an urban catchment. The twelve models chosen represent a wide range of capabilities, spatial and temporal resolutions. In addition, they have been chosen to demonstrate how the features described in the previous sections, have been incorporated into stormwater models. Eight models were specifically designed to simulate urban storm water quantity and quality. DR_3M – QUAL (Alley and Smith 1982a, 1982b), HSPF (Bicknell *et al.* 1993, Johanson *et al.* 1980, Johanson *et al.* 1984), MIKE – SWMM, QQS (Geiger and Dorsch 1980), STORM (Hydrologic Engineering Center 1977), SWMM (Huber and Dickinson 1988, Huber *et al.* 1984, Roesner *et al.* 1988), SWMM Level 1 (Heaney *et al.* 1976) and the Wallingford Model (Bettess *et al.* 1978, Price 1978, Price and Kidd 1978). The remaining four models are capable of being adapted for use in urban storm water problems, and are; BRASS (Colon and McMahon 1987, McMahon *et al.* 1984), HEC – 5Q (Hydrologic Engineering Center 1986), QUAL2E – UNCAS (Brown and Barnwell 1987) and WQRRS (Hydrologic Engineering Center 1978).

These models have been classified according to (a) the type of modelling that the model can perform, (b) how the water quality and quantity components are simulated in the model, (c) the water quality constituents that are modelled, (d) additional features that a model may posses and (e) the accessibility of the model.

(a) Modelling Scale

Table 5.1 indicates which models can be used as planning, operational and design models. Models which are capable of simulating single or continuous events are shown in Table 5.3.

(b) Water Quantity and Quality Components

The models that are capable of simulating flows in common infrastructure components, such as pipes, open channel, retarding basins and natural channels are given in Table 5.2. Other infrastructure components that can be simulated by these models are also given in Table 5.2. Most of the models simulate the rainfall runoff process, see Table 5.2. The type of routing that is employed in a model; simple storage, hydrologic and hydraulic routing is given in Table 5.3. The transport processes that are used by each model to rout pollutants are shown in Table 5.3. These include the use of the advective diffusion equations, plug flow or assuming that complete mixing has occurred. The method used in the model for transforming pollutants include; empirical, using a buildup and washoff processes or modelling the adsorption and desorption with sediment (soil loss).

(c) Water Quality Constituents

The types of pollutants that are modelled are shown in Table 5.4. Although not explicitly included in this table, heavy metals are generally modelled as conservative pollutants adsorbing to suspended and settleable solids.

(d) Other Model Characteristics

Several models also have the capability of undertaking uncertainty analysis, optimisation and costs. Of the models reviewed, those capable of performing these functions are shown in Table 5.3. None of the models considered includes all these capabilities. None of the urban storm water models includes uncertainty analysis and only two consider cost as an important component in urban storm water management. Two models include parameter optimisation.

(e) Accessibility

Most of the models have been developed by United States government funded agencies. These models are made available at a nominal cost with very little support. However, some of these models have gained wide acceptance with user groups formed to overcome the poor documentation and support. These groups are a valuable source of information experience on the use of these models. In contrast, commercially available models are supported by their developers, but they are expensive. In general, source code for public domain software is available. Commercial software is distributed as executable files. This makes it very difficult to modify, enhance and develop interfaces with commercial software.

A more detailed description of the capabilities of these models is provided below.

DR$_3$M - QUAL (Alley and Smith 1982a, 1982b)

In US Geological Survey's Distributed Routing Rainfall-Runoff model (DR$_3$M) an urban drainage basin is represented by an overland flow element, a channel element, pipe elements and reservoirs. Soil moisture conditions between storms are considered in the rainfall runoff modelling. Interflow and base flows are not simulated. Rainfall excess is calculated using soil moisture, evaporation, pervious and impervious areas, length and slope of the subcatchment and parameter optimisation. Kinematic wave, which is used to route overland and channel segments is solved using either, characteristics, implicit or explicit finite difference schemes with time steps as small as a minute. Two soil types can be defined, each with up to six soil moisture and infiltration parameters. Reservoir storage is simulated using linear storage or the modified Puls method. Up to 99 flow planes, 3 rainfall gauges and up to 60 storms, spanning up to 20 years can be accommodated by the model. Channels, pipes, reservoirs and junctions may be used to define the catchment. Surcharges in pipe networks are also handled. Quality is simulated for arbitrary parameters using exponential build-up and wash-off functions. Removal of accumulated surface pollutants can occur in dry weather by street cleaning. Erosion is simulated using empirical equations relating sediment yield to peak runoff and its volume. Up to four pollutants can be simulated, however interactions between pollutants are not permitted. Concentrations of other pollutants are assumed proportional to the sediment concentration. Plug flow with no decay is used to rout pollutants through the drainage network and storage basins. The model can be executed using any time step over any time.

HSPF (Bicknell *et al.* 1993, Johanson *et al.* 1980, Johanson *et al.* 1984)

The US Environmental Protection Agency, Hydrological Simulation Program – Fortran (HSPF) was developed in the mid 1970's to model a broad range of hydrologic and water quality processes in agricultural and rural watersheds. Urban watersheds can also be simulated. It is considered the most comprehensive and flexible model of watershed hydrology and water quality available. It is a continuous watershed hydrology and water quality simulation package using hourly time steps. Land and soil contaminant runoff processes and in-stream hydraulic and sediment-chemical interactions are simulated.

For overland flow temperature, DO, CO_2, (at saturation levels) coliform, nitrogen, phosphorus, pesticides and arbitrary conservative pollutants are modelled using empirical relationships between pollutant and water as well as sediment yield. Rainfall-runoff modelling includes snowmelt, water balance in the upper and lower soil storage and groundwater storage for both pervious and impervious surfaces. Interception, evaporation and evapotranspiration are included in the water balance along with displacement of soil by rainfall. Deep groundwater storage can become base flow to a stream. Total stream flow is a combination of overland and base flow. Washoff quality is estimated using linear buildup with washoff

Table 5.1 Functionality and Accessibility of Representative Models

Program Name	Functionality			Accessibility	
	Planning	Operational	Design	Public Domain	Commercial
Urban Models					
DR_3M – QUAL	✔		✔	✔	
HSPF	✔		✔	✔	
MIKE – SWMM	✔	✔	✔		✔
QQS	✔		✔	?	
STORM	✔			✔	
SWMM	✔		✔	✔	
SWWM Level 1	✔			✔	
Wallingford Model	✔	✔	✔		✔
Non-Urban Models					
BRASS		✔	✔	?	
HEC – 5Q	✔	✔		✔	
QUAL2E – UNCAS	✔			✔	
WQRRS	✔		✔	✔	
				✔	

Table 5.2 Components in the Quantity Analysis in Representative Models

Program Name	Model Quantity Component					
	Pipes	Open Channel	Retarding Basins	Others	Natural Streams	Rainfall Runoff
Urban Models						
DR_3M – QUAL	✔	✔	✔		✔	✔
HSPF	✔	✔	1		✔	✔
MIKE – SWMM	✔	✔	✔	2-7	✔	✔
QQS	3	✔	✔	2		✔
STORM						
SWMM	✔	✔	✔	4		✔
SWMM Level 1						✔
Wallingford Model	4	✔	✔	2-5		✔
Non Urban Models						
BRASS		✔	1	7	✔	✔
HEC – 5Q			1		✔	
QUAL2E – UNCAS					✔	
WQRRS		✔	1		✔	✔

1 reservoir module
2 weirs and pumps
3 pressurised pipes
4 gutter and pumps
5 surcharges
6 bridges
7 overland flow

Table 5.3 Characteristics of Representative Models (adapted from Nix 1991)

Model Characteristics

Model	**Routing Level**			**Time Modelling Scale**		**Pollutant Predictive Method**			**Pollution Transport**			**Optimisation**				**Uncertainty Analysis**			**Costs**	
	Simple Storage	**Hydrologic**	**Hydraulic**	**Continuous**	**Event**	**Empirical**	**Buildup and Washoff**	**Soil Loss**	**Advective Diffusion Equation**	**Completely Mixed Reactor**	**Plug Flow**	**Analytical**	**Linear Programming**	**Non-Linear Programming**	**Dynamic Programming**	**Sensitivity Analysis**	**First-Order Second Moment**	**Monte Carlo**	**Life Cycle**	**Externalities**
Urban Models																				
DR_3M – QUAL	✔	✔	✔		✔	✔	✔	✔			✔			✔						
HSPF	✔	✔		✔	✔	✔	✔	✔		✔	✔									
MIKE – SWMM	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔									
QSS	✔	✔	✔	✔	✔	✔	✔				✔	✔								
STORM	✔				✔		✔	✔		✔										
SWMM Level 1				✔		✔						✔							✔	
SWMM	2	✔	3		✔	✔	✔	✔		✔	✔								✔	
Wallingford Model	✔	✔	✔	✔	✔	✔	✔		4						✔				5	
Non-Urban Models																				
BRASS			✔	✔	✔															
HEC – 5Q	✔	✔		✔		✔			✔	✔			✔						1	
QUAL2E – UNCAS	✔			✔		✔			✔							✔	✔	✔		
WQRRS		✔	✔	✔	✔	✔			✔	✔										

1 flood damages
2 flow balance only
3 with EXTRAN module
4. advection only
5 labour, material and plant costs

rates directly proportional to runoff. Separate washoff functions are used for each pollutant. Pollutants that can be simulated with the runoff include; temperature, pesticides, sediments, nitrogen, phosphorous, ammonia and conservative pollutants. Absorption and desorption of pollutants between bed sediments and water is allowed. Settling and re-suspension of sand, clay and silt sediments are possible. Re-suspension and settling of silts and clays are based on bed shear stress. Absorption and desorption of many of these pollutants is optional via first-order kinetics. For impervious surfaces, empirical relationships are used for the washoff, which is a function of runoff and street cleaning. The advection of pollutant is estimated using plug flows and complete mixing in storages. Overland flow, open and closed channel flow and sewer routing is with the modified kinematic wave equation incorporating the Manning equation. It flags surcharges in the sewer system and reservoir routing can be included. Total dissolved solids, chlorides, pesticides, temperature, sediment scour and deposition, pH, CO_2, algae, nitrate, nitrite, orthophosphorous, total inorganic carbon, DO, BOD, ammonia, photoplankton, zooplankton and attached algae can be modelled in streams and in storages.

Table 5.4 Water Quality Parameters Modelled

Water Quality Parameter

Model	**Temperature**	**Inorganic Suspended Solids**	**Organic Sediment**	**Inorganic Sediment**	**BOD**	**Total Coliform**	**Total Inorganic Carbon**	**Ammonia**	**Total N**	**Total P**	**Dissolved Oxygen**	**Alkalinity**	**pH**	**Suspended Solids**	**Soil Erosion**	**Total Dissolved Solids**	**Others**
Urban Models																	
DR_3M – QUAL																	7,9
HSPF	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	1,2,7,9,10
MIKE - SWMM	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓			✓	✓		10
QQS					✓	✓			✓	✓					7		9
STORM					✓	✓			✓	6					7		
SWMM					✓	✓			✓	✓				✓	✓		3,7,8
SWMM Level 1					✓				✓	✓				5			
Wallingford Model					✓			✓	✓	✓	3			7			9
Non Urban Models																	
BRASS																	11
HEC – 5Q	✓				3			✓	1	2	✓						9,10
QUAL2E – UNCAS	✓				✓	✓		4	1	2	✓						9,10
WQRRS	✓	✓	✓	✓	✓	✓	✓	✓	1	2	✓	✓	✓	✓			9,10

1 nitrates and nitrites
2 phosphorous
3 CBOD
4 ammonia as N
5 suspended and volatile solids
6 orthophosphates
7 suspended and settleable solids
8 oil/grease
9 arbitrary pollutants
10 aquatic organisms
11 no water quality modelled

MIKE - SWMM

This package combines MIKE 11 (Havno *et al*. 1995) and the well known SWMM (Huber *et al*. 1984, Huber and Dickinson 1988, Roesner *et al*. 1988) models. The merger is intended to use the strengths of MIKE 11 in one-dimensional unsteady flow modelling, which solves the shallow water wave equations using an implicit finite difference scheme, replacing the temperamental EXTRAN module in SWMM. The combined model can perform hydrologic, hydraulic and water quality analysis of storm water and waste water drainage systems, including sewage treatment plants and water quality control devices. Pipes, pumps, culverts, retarding, detention ponds, pressurised flow in looped connections and overflows from sewers can be modelled.

Mass balance is used for runoff computations, which include surface detention, lower soil storage and upper and lower groundwater storage. Runoff consists of overland and base flow. Two-dimensional overland flooding can also be simulated using the shallow water wave equation. A sediment budget accounts for erosion and deposition. The advective diffusion equation is used to simulate the transport of pollutants, which are subject to first-order kinetics. It is also solved using an implicit finite difference scheme. Dissolved and suspended sediments, BOD, DO, nutrients, macrophytes and plankton can be simulated.

MIKE – SWMM can interface with the full suite of Danish Hydraulic Institute models. They have been linked with STORMPAC, a rainfall generation program, the urban sewer network model, MOUSE (Lindberg *et al.* 1989), MIKE 21 (Dudley *et al*. 1994) for modelling of estuaries, lagoons and coastal areas, including water quality and STOAT to assess treatment plant performance. Water quality parameters include; total coliform, total P, total N, DO, temperature, ammonia, nitrate, heavy metals using kinetic descriptions of absorption/desorption to particles, suspended sediments and bed sediments and BOD as both dissolved and attached to suspended sediments. Sediments are defined as either cohesive or non-cohesive according to their size and behaviour. The dynamics of primary production by photoplankton and the grazing by zooplankton are described. Primary production by benthic vegetation can also be modelled. MOUSE can perform real-time control simulations and sediment transport in pipe networks. All these models are capable of simulating water quality and quantity at any temporal and spatial scale. They can be used in design, management and operation of a diverse range of water resource problems.

QQS (Geiger and Dorsch 1980)

The Quality-Quantity Simulator (QQS) can perform continuous or single event simulation using five-minute time intervals. It can simulate flows in pipes and channels using an implicit finite difference approximation of the kinematic wave equations, storage routing, backwater analysis and pipes under pressure. Looped networks, weirs and pumps can be simulated. Dry weather flow and quality based on empirical relationships, have a diurnal and population dependency. Washoff function is dependent on the accumulation of dust and the time interval between storms and street sweeping. Quality routing through channels and pipes, storage units and receiving water is performed using plug flow. Up to four arbitrary conservative pollutants can be routed. Empirical washoff functions are available for BOD, COD, suspended solids, settleable solids, total nitrogen, total P and faecal coliform.

STORM: (Hydrologic Engineering Center 1977)

The US Corps of Engineers, Storage, Treatment, Overflow, Runoff Model is capable of simulating runoff and pollutant loads from urban and rural watersheds in response to precipitation. It is a continuous model using hourly time steps and it can be used for single events. Using hourly precipitation, runoff from a catchment is simply the accumulation of runoff from upstream sub-catchment. There is no attempt to rout the runoff through the catchment. Three methods are available for calculating the hourly runoff; coefficient method, soil-complex-cover method and the unit hydrograph method. The runoff coefficient method is identical to that used in SWMM Level 1. Runoff is a linear relationship between runoff and the precipitation minus rainfall interception. However, here the impervious and pervious runoff coefficients and the fraction of impervious area are variable and not fixed. Erosion is estimated using an empirical relationship. Two methods are available to simulate pollutant accumulation. The pollutant accumulation is proportional to the dust and dirt accumulated or a simpler linear function of time. Washoff is proportional to the amount of pollutant remaining. Pollutants that are treated as conservative include; suspended and settleable solids, BOD, total nitrogen and orthophosphates. Coliforms are also modelled. No treatment is assumed to occur in a storage.

SWMM (Huber *et al*. 1984, Huber and Dickinson 1988, Roesner *et al*. 1988)

SWMM simulates both water quality and quantity of urban storm water runoff and combined sewer overflow. This is both a continuous and single event models. Surface runoff is based on rainfall intensities and antecedent moisture conditions, land use and topography. A simple nonlinear reservoir storage is used to simulate the rainfall-runoff process, which includes infiltration depression storage, evaporation and surface runoff. Infiltration is routed through upper and lower subzones and may return as runoff. Surface pollutant allows both linear and nonlinear accumulation with time. Washoff is simulated as a simple function of runoff or as a first-order decay relationship. Sewer flows are generated using land use, population density and other factors. Infiltration into the sewer system is dependent on the sewer condition and groundwater levels. Flows and pollutants are routed through the sewer system using a modified kinematic wave approximation and assuming complete mixing. Hydrographs along the sewer system are modified to represent storage and treatment effects. This includes retention time, treatment efficiency as well as estimating costs. Surcharging is not included. Pollutants in storage systems can be modelled as either complete mixing or plug flow. The stand-alone module EXTRAN permits SWMM to rout inflow hydrographs through open channel and a closed conduit system using an explicit numerical solution of the shallow water wave equations. Unfortunately, routing of pollutant loads, sewer infiltration and dry-weather flows are not currently modelled. Eight conservative pollutants are; suspended solids, settleable solids, BOD, COD, total nitrogen, total P, oil/grease, total coliforms as well as an arbitrary pollutant and erosion simulated in surface runoff.

SWMM Level 1: (Heaney *et al*. 1976)

SWMM Level 1 estimates average annual runoff from a watershed with the minimum of input data. The average annual runoff is a simple linear function of the average annual precipitation. Losses from rainfall interception are considered. The runoff coefficient is a function of pervious and impervious areas, with the latter a function of population. Simple relationships are used to estimate the annual load of pollutant. The pollutants are treated as independent and they are directly proportional to the average annual precipitation, population density, the effectiveness of street sweeping and the catchment area. Land uses considered are residential, commercial, industrial and other developed areas. Pollutants considered are; BOD, suspended solids, volatile solids, total P and total N. Preliminary estimates for costs of storing and treating storm water pollutants have been included in SWMM Level 1. This is a simple linear function with constant costs for treatment and storage. The simple cost function is solved analytically to provide a function representing the least cost combination of storage and treatment required satisfying a certain level of pollutant removal. SWMM Level 1 is not implemented on a computer, it is applied with tables and nomographs. It is part of the EPA's SWMM package.

Wallingford Model (Price 1978, Price and Kidd 1978, Bettess *et al*. 1978)

The Wallingford model is a suite of models developed at the Hydraulics Research Institute, Wallingford, United Kingdom. It includes a rainfall-runoff model (WASSP), a simple (WALLRUS) and full dynamic pipe routing model (SPIDA) and a water quality module (MOSQITO). The model can be applied to storm water or sewer systems or to the combined system using 15 minute time steps. It has been used for real time operational, design and planning simulations.

Hyetographs can be defined as input if required. Alternatively, synthetic rain storms can be generated using a variety of techniques including; depth-duration-frequency relationships and the modified Chicago method. An empirical relationship is used to determine the average spatial rainfall over a catchment using rainfall intensity and a spatial smoothing factor. The rainfall-runoff model employs a modified rational method, which is essentially the same as the rational method with the inclusion of a routing coefficient. The routing coefficient incorporates the proportion of impervious area, soil type, evapotranspiration and antecedent conditions. Five antecedent moisture models are provided. The runoff is estimated by distributing rainfall between impervious, roofs and pervious areas. The amount of runoff from these areas is based on area type, catchment slope, initial loss to depression storage and continuing loss by infiltration. The attenuation caused by surface storage is simulated by a non-linear reservoir storage model. Two empirical runoff routing models available. One is for catchments up to 1ha and up to 100ha. The latter relationship is nonlinear relationship and uses area, slope and length of the catchment. Due to the size of a large catchment, the runoff is also lagged. The time delay is also a nonlinear empirical relationship based on area, bed slope and length of the catchment. For small catchments, overland flow is routed using two equal linear reservoirs in series with routing coefficients dependent on rainfall intensity, contributing area and surface slope. The use of SWMM's runoff model is optional. Four other runoff modelling approaches are available which utilise simple storages. A time delay is also introduced so that the peak runoff lags the peak rainfall.

The Muskingum-Cunge method and the solution of the full shallow water wave equations are options for routing flows through the storm water network. Both defined and user-specified pipes and channels are options. Pressurised pipes are modelled with either the St. Venant equations using a Preissmann slot or the St. Venant equations with the local acceleration term neglected. An implicit finite difference scheme is used to solve the equations. The advection equation is used in the pollution transport process, while diffusion is ignored. Erosion and deposition processes are modelled, including sedimentation in pipes. Manholes, overflows, tanks, pump wells or storages can be modelled in the pipe network. Suspended sediments in tanks are assumed to be well mixed with a layer of cleaner water available at the top of the tank for overflow. Water quality pollutants that can be modelled are BOD, COD, ammonia, kjeldahl nitrogen, total P and four arbitrary conservative pollutants that may be attached to sediments or in solution.

Buildup of pollutants on impervious surfaces is an empirical relationship, which is based on time. Washoff is also a first-order decay model that is a function of rainfall intensity. Pollutants that are available to be washed off impervious surfaces are BOD, COD, total N, ammonia, total P and four arbitrary pollutants. Washoff pollutants can be transported by absorption to sediments or in solution.

A dynamic programming technique is used to determine the minimum construction costs of a storm water network using pipe diameter, trench depth and gradient as the optimised variables. Both existing and proposed designs can be simulated by taking into account; storm water overflows, on-line and off-line detention storages and pumping stations. The Wallingford model includes a module for calculating life cycle costs. The cost modelling includes, labour, plant and materials costs. A number of construction costs such as; excavations, pavement destruction, bedding, backfill etc. are included in the labour costs.

6. OTHER URBAN STORM WATER QUANTITY AND QUALITY MODELS

A number of publications have compared and summarised the capability of a number of urban storm water models. These include (Brandstetter 1976, Chu and Bowers 1977, Dendrou 1982, DeVries and Hromadka 1992, Hall 1984, Huber 1986, 1992b, Huber and Heaney 1982, Reckhow *et al*. 1985, Whipple *et al*. 1983 and Wurbs 1994). A useful bibliography on urban storm water modelling can be found in Duncan (1995).

This review is by no means a comprehensive list of urban storm water models. It is meant to provide a brief summary of the capability and approaches adopted to simulate storm water quantity and quality by a few well, and not so well known models.

Other urban storm water models include;

(a) Simple models

Regional Hydrologic Regression and Network Analysis Using Generalised Least Squares (GLSNET) (Tasker and Stedinger 1989)

(b) Continuous models

- Precipitation-Runoff Modelling Systems (PRMS) (Leavesley *et al*. 1983)
- The Hydrologic Modeling System (HEC-HMS) (Charley *et al*. 1995)

(c) Single event models

- US Geological Survey Rainfall Runoff Model for Peak Flow Synthesis (Dawdy *et al.* 1972, Dawdy and O’Donnell 1965)
- Kinematic Wave Generation Model (Woolhiser 1977, Rovey and Woolhiser 1977)
- Battelle Urban Wastewater Management Model (Brandstetter *et al*. 1973, Brandstetter 1976)

- Computer Augmented Treatment and Disposal System (Leiser 1974)
- Distributed Routing Rainfall-Runoff Model: Version II (Alley and Smith 1982a)
- Illinois Storm Sewer System Simulation Model (Sevuk *et al*. 1973)
- Illinois Urban Drainage Area Simulator (ILLDAS) (Terstriep and Stall 1974)
- SOGREAH (SOGREAH 1977)
- Sacramento Catchment Model (Peck 1976)
- TOMCAT (Brown, 1986)
- KINEROS – A Kinematic Runoff and Erosion Model (Woolhiser *et al*. 1990)
- MIKE – SHE (Danish Hydraulics Institute 1990)

7. OTHER MODELS CAPABLE OF SIMULATING URBAN STORM WATER QUANTITY AND QUALITY

The models described above have been developed specifically for the modelling of water quality and quantity in an urban environment. There are other water quality and quantity models of watersheds that are capable of modelling various components of the urban water problem. Some of these models are described as follows.

BRASS (McMahon *et al*. 1984, Colon and McMahon 1987)

The Basin Runoff and Streamflow Simulation (BRASS) was developed by the US Army Corps of Engineers to provide flood management decision support for the operation of a reservoir system in both real-time and as a design model. Continuous and event based simulations can be performed. It is an interactive hydrologic/hydraulic simulation model, which includes rainfall-runoff modelling, storage routing through regulated reservoirs and dynamic streamflow routing capabilities. BRASS incorporates the National Weather Service Operational Dynamic Wave Model (DWOPER) (Fread 1978) which computes unsteady flows in open channels and due to dam failures. It can be used as a continuous or event based model for design and real time simulations. The model can handle 15 rivers or tributaries, 90 sub-areas and it can provide hourly runoff and routing for up to 30 days. In continuous simulation, 100 days of rainfall records from a total of 20 rainfall gauges can be simulated. The rainfall-runoff modelling incorporates; evaporation, infiltration, baseflow, spatial and temporal rainfall distribution. It requires user specified unit hydrographs and infiltration losses to determine runoff hydrographs from sub-catchments. Infiltration is a function of rainfall, evaporation and soil moisture. Baseflow is a simple exponential recession, which is a function of time. Storage routing is used to rout sub-area outflows and shallow water wave equations are used to rout these flows through river channels. The full dynamic analysis includes; bridges, embankments overtopping and flows through control structures and through a dentric system. The shallow water wave equations are solved using the stable implicit finite difference scheme. Missing rainfall data is accommodated in BRASS by interpolation from neighbouring rainfall gauges. No water quality modelling is performed by BRASS.

HEC – 5Q (Hydrologic Engineering Center 1986)

The Simulation of Flood Control and Conservation Systems (Including Water Quality Analysis) model, HEC – 5Q, has the ability to decide how to regulate a complex network of reservoirs. The model will define the optimum system operation for water quality and quantity. The decision criteria consider flood control, hydropower, instream flow (municipal, industrial, irrigation, water supply, fish habitat) and water quality requirements. The model uses linear programming to evaluate the optimum reservoir operating rules. Up to ten reservoirs and up to thirty control points can be considered. Temperature and up to three conservative and three non conservative water quality constituents can be modelled using

$$V\frac{\partial C}{\partial t} = \Delta x Q_x \frac{\partial C}{\partial x} + \Delta x A_x D_c \frac{\partial^2 C}{\partial x^2} + Q_i C_i - Q_0 C \pm VS.$$

A phytoplankton option requires eight constituents; temperature, total dissolved solids, nitrate nitrogen, phosphate phosphorous, CBOD, ammonia nitrogen and dissolved oxygen. Non-conservative constituents are replaced by first-order kinetic decay formulations. The model simulates either daily or monthly data. Therefore, its use is restricted to large catchments. Hydrological streamflow routing methods such as modified Puls and Muskingum are used in HEC – 5Q. This model also includes the capability to modify the flows to improve water quality at control points using linear programming. HEC – 5Q provide economic evaluation capabilities for computing average flood damage.

QUAL2E - UNCAS (Brown and Barnwell 1987)

This is a US Environmental Protection Agency model for simulating stream water quality. It was intended for use as a planning tool and can simulate steady and unsteady transport of pollutants. However, it assumes steady flow. It can simulate the interaction of up to 15 water quality constituents. These include; dissolved oxygen, BOD, temperature, algae as chlorophyll a, organic nitrogen as N, ammonia as N, nitrite as N, nitrate as N, organic phosphorous as P, dissolved phosphorous as P, coliforms, arbitrary non-conservative constituent and three conservative constituents. All parameters can be simulated as either steady state or dynamic conditions. Diurnal variations in meteorological data on water quality only can be studied. Other dynamic forcing functions such as flow variations cannot be modelled. Uncertainty analysis can be performed. This includes sensitivity analysis, first-order and Monte Carlo analysis. This is only applied to the steady state simulations. A maximum of 25 river reaches containing no more than 20 computational elements per reach are permitted. Only six river junctions and seven headwater elements and up to 25 input and withdrawal nodes are allowed. Flow balance is the only routing that is performed by this model. Storage within an element is ignored and flow is considered as steady. The water depth is estimated by solving the Manning equation.

The basic equation that is used to describe the behaviour of a pollutant in a stream is the one-dimensional conservative advective-diffusion equation

$$A_x \frac{\partial C}{\partial t} = \frac{\partial}{\partial x}\left(A_x D_c \frac{\partial C}{\partial x} \right) - \frac{\partial}{\partial x}\left(u A_x C \right) + \frac{dC}{dt} \pm S(C,x,t)$$

in which, C is the thermal energy or constituent concentration, t the time, x is distance, u is the advection velocity, A_x the cross-sectional area, D_x the diffusion coefficient, $S(C,x,t)$ are all sources and sinks and the term dC/dt defines the first-order kinetics for non-conservative constituents. Coliforms are modelled as non-conservative constituents. These and arbitrary non-conservative constituents are modelled as first-order decaying constituents dependent on temperature and do not interact with other constituents. Sensitivity analysis of model to individual parameters can be performed using the UNCAS extension to QUAL2E. In first-order analysis and Monte Carlo simulations, the variables are assumed to be independent.

WQRRS (Hydrologic Engineering Center 1978)

The US Army Corps of Engineers, Water Quality for River-Reservoir Systems (WQRRS) was designed to model water quality and quantity within an entire catchment. It consists of three independent modules; a reservoir module (WQRRSR), a stream hydraulic module (SHP) (Hydrologic Engineering Center 1988) and the stream quality module (WQRRSQ), that can be coupled if necessary. The model is capable of simulating 18 different physical, chemical and biological water quality parameters in a river or reservoir or a river-reservoir system. It has the capability to rout flows on open channels using the shallow water wave equations, kinematic wave equations, Muskingum method or using the modified Puls method. Steady flows using either stage-flow relationships or backwater analysis can also be performed.

Conservative water quality parameters are modelled using the advective diffusion equation

$$V\frac{\partial C}{\partial t} = \Delta x Q_x \frac{\partial C}{\partial z} + \Delta x A_x D_C \frac{\partial^2 C}{\partial x^2} + Q_i C_i - Q_0 C \pm VS$$

in which, C is the thermal energy or constituent concentration, V is the volume, t is the time, x is the space coordinate (vertical for the reservoir and horizontal for the stream), Q_x is the advective flow, A_x is the surface area, D_c is the effective diffusion coefficient, Q_i is the lateral inflow, C_i is the inflow thermal or concentration, Q_0 is the lateral outflow and S are all the sources and sinks. It is interesting to note that this equation is not conservative unless the advection is assumed to be constant. The source and sink term is limited to external heat fluxes for temperature. It includes settling, first-order decay, reaeration, chemical transformation, biological uptake and release, growth, respiration and mortality including predation. For constituents that affix to the bottom or are mobile, their transformation is governed by

$$V\frac{\partial C}{\partial t} = \pm VS$$

The biological and chemical constituents considered are; fish, aquatic insects, benthic animals, zooplankton, phytoplankton, benthic algae, detritus, organic sediments, inorganic suspended solids, inorganic sediments, dissolved phosphate, total inorganic carbon, dissolved ammonia, dissolved nitrates, dissolved nitrates, BOD, coliform bacteria, total alkalinity, total dissolved solids, pH and unit alkalinity. All chemical and biological rate processes occur in an aerobic environment. In addition to the transport processes, advection and dispersion, other processes included in WQRRS are shown in Table 7.1. The interdependence of constituents as represented in WQRRS are given in Table 7.2.

Table 7.1 Basic Processes Influencing Constituents

Constituent	Process				
	Conservative Constituent	**Mass Increased by By-Products with Other Constituents**	**Exchange through Air-Water Interface**	**Rates are Temperature Dependent**	**Mass Decreases by Decay**
Temperature			✔		
BOD				✔	✔
Phosphorous		✔		✔	
Ammonia		✔		✔	
Nitrate		✔		✔	
Nitrite		✔		✔	
Total Carbon		✔	✔	✔	
Organic Sediments		✔		✔	
Alkalinity	✔				
TDS	✔				
Oxygen		✔	✔	✔	
Suspended Solids				✔	
Inorganic Sediments		✔			
Coliforms				✔	✔

8. SUMMARY

Urban storm water models should be capable of simulating flows and the transport of pollutants over impervious and pervious areas, through channel and pipe networks and through storages. They should be able to produce results summarising the behaviour of the catchment response as a function of time and at several locations throughout the catchment. Due to the amount of data required and the complexity of some of these models, the simulation requires the use of a computer. Very few serious models of urban storm water rely on statistical techniques, such as regression analysis. Generally, they are based on deterministic modelling approach.

There are numerous models capable of simulating urban water quantity and quality employing diverse approaches to handling the problem. However, there seems to be a number of deficiencies that are common to most of these models. The following is a summary of the conclusions from the review of eight models that are specifically designed to model urban storm water and four models capable of modelling urban storm water .

- Due to the complexity of the urban flow and water quality processes, many urban watershed models have evolved over several years or decades.

- Many of the models described in this review can be used to model either storm water, waste water or water supply infrastructure. However, none consider integrated storm water, water supply and waste water infrastructure. Many simply consider only one component, although in the United States, storm water and waste water can share the same infrastructure and are modelled as a combined system.

Table 7.2. Interdependence of Constituents (WQRRS)

															Constituent								
Constituent	**Temperature**	**Fish**	**Benthic Animals**	**Zooplankton**	**Aquatic Insects***	**Phytoplankton**	**Benthic Algae***	**Detritus**	**Toxicity***	**Inorganic Suspended Solids**	**Organic Sediment**	**Inorganic Sediment**	**BOD**	**Coliform Bacteria**	**Total Inorganic Carbon**	**Ammonia**	**Nitrate**	**Nitrite**	**Phosphate**	**Oxygen**	**Alkalinity and**	**Carbon Dioxide**	**pH**
Temperature				K		K		K		K										G			
Fish			D	D	D		D		I		D									G			
Benthic Animals		L							I		D									G			
Zooplankton		L				D			I											G			
Aquatic Insects*		L					D	D	I		D				D	D		D	D				
Phytoplankton				L					I						D	D		D	D				
Benthic Algae*		L			L				I														
Detritus		E		E,L	E		J	J															
Inorganic Suspended Solids												J											
Organic Sediments	A		E			J																	
Inorganic Sediments									J	J													
BOD	A																			G			
Coliform Bacteria	A																						
Total Inorganic Carbon			B	B	B	B	B	B			B		B							G		M	
Ammonia	A		B	B	B	B	B	B			B												
Nitrate	A															B				G			
Nitrite	A																B			G			
Phosphate			B	B	B	B	B	B			B												
Oxygen	F	C	C	C	C		C	C			C		C				C	C					
Alkalinity and TDS																							
Carbon Dioxide	F,H														M						H		M
pH	H														H						H	H	

A affects rate of decay, respiration, growth or mortality
B by-Product of decay or respiration
C consumed by decay and respiration
D prey or nutrients required for growth
E by-product of growth
F affects reaeration rates and saturation
G limits growth or decay if out of acceptable range

H affects chemical Equilibrium
I affects mortality
J source through sedimentation or scour
K limits energy input by affecting light penetration
L consumed by growth of other constituents
M at chemical equilibrium with other constituents
* stream module only

- All the urban storm water models can be used as planning models with some as design tools and very few as operational tools, see Table 5.1. A reason why few urban storm water models are designed as operational models is that in an urban environment, the transients are very rapid, making it difficult to implement complicated models and collect data in real-time. Most of the models are capable of simulating single events, see Table 5.3. Those that are capable of simulating continuous and single events are also used to design urban storm water infrastructure.

- Planning models are continuous models that use simple hydrological approaches to simulate the behaviour of flows in an urban catchment.

- All urban storm water models incorporate a rainfall runoff model.

- Spatial distribution of rainfall is not considered in many of these models. Rainfall is assumed to be uniformly distributed in a subcatchment. The development of a model to interpolate, both spatially and temporally, rainfall data collected at rainfall gauges, which are sparsely distributed within a catchment, would be a huge advancement in rainfall runoff modelling.

- For overland flow, the linear storage method is the most popular approach. The shallow water wave equations or their approximations are seldom employed, although their popularity is increasing.

- Washoff and buildup of pollutants on impervious areas is described by empirical relationship based on first-order kinetic type relationships.

- Buildup and washoff of pollutants is not very well understood. The simple exponential relationship that is generally used is not reliable and there are very few data sets available to verify or establish new empirical relationships. More studies, such as those undertaken by Mackay (1999) are required to establish new or verify these relationships.

- In general, water quality modelling involves first-order kinetics, with adsorption to sediments being a major component. Very few models have a sediment transport model. This is a conservation of sediment equations which is solved simultaneously with the shallow water wave equations.

- Simple storage is the most common approach to routing flows. There is a trend towards the use of hydraulic analysis of storm water infrastructure, with many of the more recently developed models including a number of hydraulic routing techniques as options.

- The most common water quality parameters that are modelled in urban water storm water models are: BOD, total coliforms, total P and N and both suspended and bed sediment transport. The non-urban models include arbitrary conservative pollutants and the modelling of aquatic organisms. Because the effect of pollutants on organisms is important, temperature, DO and ammonia are also included in non-urban models.

- Design models employ hydraulic modelling for runoff simulation and model the behaviour of storm water flows. More recently, the St. Venant equations have been solved. This is not due to new techniques being developed to solve these equations but to the availability of cheaper and more powerful computers making the solution of large systems of equations more tractable.

- Very few of the models examined have the capability of modelling flash flooding in urban areas. Only MIKE – SWMM seem to be capable of modelling two-dimensional overland flow.

- Very few model reviews mention the implications of using approximations to the shallow water wave equations. The shallow water wave equations are capable of simulating the effect of obstacles to the flow, loops in the network and pressurised pipe flows. The diffusion wave and kinematic wave equations possess one set of characteristics which travel downstream. Therefore, these models are not capable of simulating backwater effects from channel and pipe junctions and obstacles to the flow. In addition, the kinematic wave is not capable of simulating the attenuation in the flow. The diffusion wave equation approximates the physical attenuation of the flow. This may be a serious limitation if these models are being used to design storm water infrastructure. Lumped models, which include many hydrological models, ignore the spatial variability of the problem. This approach assumes that the behaviour of the catchment is instantaneous. This has serious implications in water quality modelling and other processes that are time dependent.

- Only one of the urban storm water models solves the advective diffusion equation for the transport of pollutants in pipes, channels or storages. All the others use simpler techniques, such as plug flow or assuming simply that the pollutant is completely mixed. This is in contrast to the non-urban models which all use the advective diffusion equation for the transport of contaminants. Two reasons why the advective-diffusion equation is not solved for urban problems are: Due to the rapid response of an urban catchment, the transport of contaminants by diffusion is considered to be insignificant compared to the influence of advection in the transport of these contaminants. Urban storm water infrastructure networks are generally more complicated than river networks. The numerical solution of the advective-diffusion equation for complicated networks may be computationally expensive.

- Reliability is another aspect of modelling that is very seldom found in watershed modelling. In view of the uncertainties in estimating empirical coefficients and the assumed water quality transformation, placing confidence limits on the model outputs due to these uncertainties should be important and should be an integral part of the decision making process. Beven (1989) suggests that reliability estimation is a requirement for watershed models. Risk analysis is a relatively new development in water resources models. The most popular approach is sensitivity analysis followed by first-order analysis and Monte Carlo simulation.

- Very few storm water models include an economic analysis of alternative storm water strategies. Those that do include an economic analysis are based only on life cycle costs, externalities are ignored.

- A number of models incorporate an optimisation technique. These are generally used for parameter estimation. Nonlinear and dynamic programming are almost exclusively used in water resources problems. Only one model examined uses optimisation to design storm water infrastructure.

- Orlob (1982) commented, that in the late 1970s the technology of modelling, at least that of water quality, reached a point where advancement seems to depend more on the availability of reliable data from the field than on the ingenuity of the modeller or on the computer. It seems that this situation has not improved.

9. OPPORTUNITIES IN STORM WATER MODELLING

This review has highlighted potential research opportunities in *storm water modelling*, *process understanding* and *data management*. The implementation of many of these research opportunities in a modelling framework is currently achievable.

(a) Modelling

- Rapidly Varying Flows and Flows over a Dry Bed

One-dimensional unsteady flow models have matured and there have been very few innovative advancements in these models over the past few years. They are robust, efficient and suitable for simulating gradually varied flows in well defined channels or conduits. This is not the case for rapidly varying flows and unsteady flows over a dry bed. One and two-dimensional algorithms for handling these type of flows are emerging. The simulation of flash flooding and storm water infrastructure failure, which are increasing problems in urban areas, can be modelled with such algorithms. Accurate modelling of two-dimensional unsteady flows over steep slopes and dry beds is an emerging area of research. These models will also gain prominence in modelling two-dimensional overland flow.

- Sediment Transport

Adsorption to sediments is a major component in the transport of pollutants. Some models use algorithms that are abstract. Whilst these may be intuitive, they are often difficult to relate to physical measurements. Sediment transport models should be more physically based. Sediment transport and flow are co-dependent, therefore the sediment and flow equations should be solved simultaneously. Very few models solve these equations simultaneously.

- Rainfall Interpolation

Failures in storm water infrastructure are generally associated with high intensity rainfall. The spatial and temporal variability in rainfall is not adequately considered in rainfall-runoff models. Tools that can accurately interpolate both spatial and temporal variability in rainfall would provide more reliable estimates of point rainfall and consequently runoff.

- Integrated Water System

Storm water is only one component of the urban water system. Very few models integrate water resources systems. They do not include storm water, waste water and potable water systems. Therefore, it is not possible to consider water reuse in options or the impact of one system on another.

- Economic Analysis

The few storm water models that include economic analysis are based only on life cycle costs. Externalities are ignored. The occurrence of rare events that result in the failure of urban infrastructure is another emerging aspect of urban storm water management. Assessing the costs associated with infrastructure failure is seldom included in an economic analysis of urban systems. For example, flash flooding is disruptive, destructive and places life and property at risk. Recent events in major city centres in Australia have demonstrated the huge costs associated with the inadequacy of urban infrastructure to convey storm water. The costs associated with infrastructure failure are seldom included in the cost of storm water infrastructure.

- Risk analysis

Uncertainty analysis is not adequately addressed in modelling. Placing confidence limits on the model results, which reflect the uncertainties in a model, is extremely important. With the model uncertainties quantified, its results can be viewed in perspective.

- Optimisation

Optimisation has been used in urban storm water models for a number of years. However, they are generally used for model parameter estimation. There are opportunities for the use of optimisation for the selection of storm water infrastructure. An obvious example is the use of simulated annealing to size storm water infrastructure.

(b) Process Understanding

- Head Losses in Manholes

Manholes and drop structures in a storm water network can have a significant impact on the behaviour of flow through these systems. Hydraulic models generally treat these structures as internal boundary conditions. However, their behaviour under varying flow is not well understood. Laboratory experiments are required to establish the empirical relationships that accurately reflect the impact of these structures on the flow.

- Buildup and Washoff Function

Most model development activity has been devoted to porting models to personal computers, improving the numerical procedures or improving their “user friendliness”. This diverts effort from enhancing our understanding of urban runoff and of better ways to model it. This is particularly true for the accumulation and subsequent transport of pollutants by runoff. There is a limited knowledge of buildup and washoff of pollutants and methods for simulating the accumulation and washoff of surface pollutants have not been verified (Nix 1994). The simple exponential relationship that is generally used is not reliable and there are very few data sets available to verify or establish new empirical relationships. More studies, such as those undertaken by Mackay (1999), are required to establish new or verify existing relationships.

- Water Quality Interactions

There are numerous algorithms to handle various facets of water quality modelling. Few, if any, are capable of studying a particular facet with scientific rigour. The interaction of various water quality parameters may have a more significant influence on an aquatic system that the individual parameters in isolation. Most water quality models ignore or restrict the interaction of water quality parameters. A greater understanding of the significance of the interaction between water quality parameters is necessary before reliable algorithms can be developed to describe these interactions.

(b) Data Management

- Expert System for Model Selection

There are numerous urban storm water models. The level of apparent detail in a model may lead some user to believe that the results are equally impressive. This is simply not the case. What is required is an expert system that can be used to assist the user in selecting a model that will balance the modelling effort with the needs of the study.

- Data Archives

Models move ahead of the database available to support them (Nix 1994). Large runoff models require large amounts of expensive data. What is lacking is an intelligent system that streamlines the management of data. The provision of interfaces with popular data base management software and spreadsheets will increase the utility of existing models and data.

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