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A REVIEW OF STORMWATER QUALITY MODELS

by

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Abstract This review report presents an overview of current stormwater models for the simulation of the runoff quantity and quality from urban catchments. Among the models considered in this study are AUSQUAL, HSPF, INFOWORKS CS, MOUSE, MUSIC, STORM, SWMM, and XP-AQUALM. These models are selected based on their capabilities of simulating stormwater quality processes in addition to runoff quantity modelling. It is concluded that deficiencies can still be found in these models with flaws and limitations in the simulation techniques adopted. Alternative modelling approaches and model improvements need to be introduced, which have to be accompanied by ample water quantity and quality data to confirm the validity of the enhanced model.		
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A REVIEW OF STORMWATER QUALITY MODELS

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1. INTRODUCTION

The impacts of urbanisation on urban stormwater quality have resulted in the need to implement various stormwater pollutant control structures developed to prevent further deterioration of the downstream receiving waters quality and protect the ecosystem. The major causes of the stormwater borne pollution can be traced back to the disposal of pollutants from both point and non-point sources within urban catchments. Of these sources, the latter (i.e. non-point sources) have been found to be the main contributor. In spite of the significance of this problem, little progress has been made in fully understanding the water quality processes taking place during a runoff event (Huber, 1992) and this deficiency is continued in the process models that form part of the stormwater quality models. As a result, current models are not able to reproduce the historical pollutographs or loadographs accurately or reliably. This is further compounded by the limited information relating to pollutant loads on catchment surfaces (Ball, 2000).

In Australia, the variability of the rainfall and runoff makes water management very challenging for local urban planners and engineers. Thus, a newfound concept of Water Sensitive Urban Design (WSUD) is gaining popularity as increased efforts are put into providing a more sustainable use of water and maintaining water quality at pre-development conditions (http://www.melbournewater.com.au) or even improving existing water quality. In light of this integrated best management practice approach to urban stormwater management, it is necessary to investigate the contribution of individual land surfaces such as roofs and roads to urban pollution in order to facilitate the implementation of the appropriate WSUD applications. The formulation of a model that is capable of differentiating these distinct sources and simulating the generation, collection and transportation of pollutants from these surfaces will be valuable for the exercise.

When conducting stormwater management studies, it is also important to comprehend phenomena such as the first flush effect, which can only be simulated with a description of the temporal and spatial distribution of sediment deposits on the catchment surface and in the urban drainage system. Unfortunately, the available data indicates that little has been known about the spatial and temporal distribution of pollutants on these surfaces especially for roofs whereas the simulation models lack the capabilities of modelling the intricate nature of the urban drainage systems with high degree of accuracy, particularly with respect to stormwater quality.

There are numerous approaches to simulate stormwater quality processes taking place within the urban environment. One can either formulate a conceptual model from scratch or adopt an existing modelling package to facilitate the task. The main purpose of this review therefore is to give an overview of current stormwater modelling packages, with particular preference to those that fulfil the following criteria:

- Has been applied in the Australian context, or suitable for implementation in local conditions especially in urban areas;
- Available to Australian modellers, which include commercial models and those found in the public domain; and
- Capable of simulating the various stormwater quality processes such as build-up and washoff of pollutants in the catchment, in addition to the normal hydrological and hydraulic functions.

This review attempts to identify and scrutinize the model components responsible for simulating water quantity and quality for the selected models, assessing their capabilities in addressing the issues mentioned previously, and determining their suitability in stormwater management applications.

Among the models that will be discussed herein are:

- AUSQUAL
- HSPF
- INFOWORKS CS
- MOUSE
- MUSIC
- STORM
- SWMM
- XP-AQUALM.

There are several segments to the following discussions for each model. Firstly, the purpose for which the model is developed for and the main model attributes are presented. In the same section, a brief history of the model development is outlined and information in regards to the availability of the model source code and user's manual is included. In view of the possibility of investigating and subsequently modifying the model code to suit different simulation objectives, the programming languages in which the model was developed are also stated. On the other hand, the water quantity and quality simulation components of the model are examined in the subsequent sections, and categorised according to the modular format of a catchment modelling system as introduced by Ball (1992):

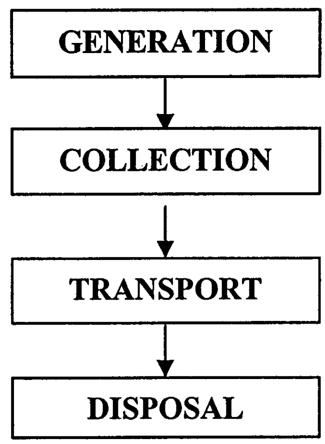

Figure 1: Conceptual components of a catchment modelling system.

The four conceptual modules as shown in Figure 1 are:

- **Generation** – Concerned with modelling the spatial and temporal variation of rainfall, the availability of pollutant constituents, and any models associated with control parameter estimation.
- **Collection** – Concerned with the accurate prediction of the temporal variation of the stormwater quantity and quality flux at the entry points to the transport module of the system. This module generally is considered to be the hydrologic component of the system.
- **Transport** – Concerned with the routing of stormwater runoff quantity and quality through the physical links in the drainage system. This module generally is considered to be the hydraulic component of the system.
- **Disposal** – Concerned with the manner by which the stormwater quantity and quality is discharged into the receiving waters.

Hence, the process models for these different conceptual components found in an individual model are considered, with the exception of the disposal component. In the final part of the discussion, comments are given regarding the suitability of these process models in performing the tasks that were mentioned earlier.

2. MODELS

2.1 AUSQUAL (*AUS*tralian water *Q*uality model using *U*nit *A*rea *L*oadings)

2.1.1 Model Objectives and Features

AUSQUAL was developed as a problem-solving tool in the auditing and management of non-point source pollution within catchments. It was named to indicate its nature; *AUS* for Australian conditions, *Q* as it is substantially a quality model and *UAL* because it is based on unit area loadings of constant concentration (White and Cattell, 1992). As this model relates pollutant generation directly to land use, the effects on water quality of projected changes in the catchment can be modelled easily. Moreover, it has the benefit of producing results from a limited database, yet capable of detailed calibration of quantity and quality if sufficient data are available.

The main proprietor of this model is Gamtron Pty Ltd, a firm based in Sydney from whom the program and operational manual (Gamtron, 1990) can be obtained. The model comes in executable form only.

AUSQUAL models the land use interactions through two main components; the hydrologic model and the water quality model. Presently it accepts five different user defined land use categories and four different pollutants for a single run. Data required for the exercise will include rainfall, catchment characteristics, hydrologic and pollutant characteristics of each land use type, and specifications of the stormwater drainage system. The model can also be set up in four different ways:

- For calculating the total mass export only, usually in an annual basis
- For simple event analysis with uniform rainfall hyetograph
- For event analysis with varying hyetograph
- For calculating total mass export using daily rainfall.

For each land use type, AUSQUAL allocates a coefficient for imperviousness, continual rainfall loss and pollution availability. On the other hand, for each subcatchment, weightings can be allocated for runoff continual loss, point source and areal loadings for pollutants, and percentage for different land uses. The results of this simple and data efficient type of modelling exercise have been effective for calculating simple hydrology, gross export of pollutants and pollutograph shape for urban catchments in Sydney. The main intention of the developers in creating this model was to reproduce or predict pollution loadings with sufficient accuracy to enable the assessment of alternative management options for the catchment.

All in all, AUSQUAL is not as comprehensive as other models, and generally has been designed for professionals responsible for mitigating non-point sources of pollution many of whom will lack a detailed knowledge of hydrology, hydraulics and water pollution.

2.1.2 Programming Language

BASIC

2.1.3 Modelling Water Quantity

As with most hydrologic based models, AUSQUAL requires the modeller to partition the catchment into a number of subcatchment determined by hydrologic boundaries. Land use divisions must then be determined within each of the subcatchments. Subsequently, runoff coefficients need to be provided for the pervious and impervious fractions of each land use and the same is done for unit area pollutant loadings.

For each defined subcatchment, AUSQUAL determines the hydrologic response of the catchment and predicts a runoff hydrograph using a time-area model. This particular hydrological model actually forms the basis of many runoff models and has been found to reproduce the stormwater runoff hydrographs adequately for urban catchments where surface storage effects are not prominent (Ball, 1992). Then again, AUSQUAL uses the time-area model based on the use of a runoff coefficient in place of consideration of the rainfall excess. Modification of this runoff coefficient will be necessary as most subcatchments comprise more than one land use. This rational type of hydrologic analysis has revealed adequate responses for quality modelling where small events are modelled (White and Cattell, 1992).

After generation of the individual subcatchment hydrographs, each hydrograph is routed to the catchment outlet by applying the appropriate time lag, which is generally derived from a representative flow velocity and the flow length. One assumption in using this technique is that the attenuation of the unsteady flow is not expected to occur. Typically, this would be used in hydraulically steep channels.

2.1.4 Modelling Water Quality

The water quality component is based on the assumption that land use activities can be identified with areas within subcatchments and that each of these areas can be assigned an export coefficient. These average export coefficients for the model are estimated in terms of concentrations. For most Australian urban streams this seems a reasonable approximation although some studies have shown that constant concentration is inappropriate. Nonetheless, this component relies heavily on the output from the hydrologic model. Each ordinate on the predicted runoff hydrograph is multiplied by the pollutant unit loading for the land use within the subcatchment area. These pollutant mass fluxes are then routed to the downstream catchment boundary where they are converted to pollutographs through consideration of the principle of mass conservation. Generally, the event based pollutant transport is generated from unit area loadings derived from both the export coefficients and the point source emissions.

Although developed originally for urban stormwater problems, this model should be equally applicable to diffuse runoff from non-urban catchments. Appropriate export concentration will need to be assigned to the various rural land uses similarly to those in urban catchments.

2.1.5 Applicability of Model

The simplistic nature of the model prevents detailed analysis of the stormwater systems, from hydrologic routing along the surfaces to generation and collection of pollutants from the subcatchments. Limitations on the use of this model relate primarily to its genesis as a decision support system rather than a broad and complete model for the prediction of the quality and quantity of runoff from a catchment. Hence, it is inappropriate for detailed stormwater quality simulation as the model is mainly suited for providing rough predictions of the effects of urbanisation on the catchment and the effectiveness of various stormwater measures taken to overcome the problem. This is evident from the adoption of the time-area method which simulates linear catchment response to any rainfall and also the event mean concentration method to predict the water quality constituents. Furthermore, rigorous testing of AUSQUAL on gauged catchments should be undertaken to ascertain the order of accuracy for the predicted pollutant loadings and the sensitivity of the predictions of parameter values (Ball, 1992).

2.2 HSPF (*H*ydrological *S*imulation *P*rogram – *F*ORTRAN)

2.2.1 Model Objectives and Features

The Hydrological Simulation Program - FORTRAN (HSPF) is a software package that can simulate the hydrologic and associated water quality processes on pervious and impervious land surfaces, and in streams and well-mixed impoundments (Bicknell *et al.*, 2001). This model is mainly suited for application in agricultural and rural watersheds but urban catchments can also be simulated. It is considered to be one of the most comprehensive and flexible models of watershed hydrology and water quality available (Zoppou, 2001). In addition, it allows continuous modelling for a wide range of time steps, and performs simulation not only of land and soil contaminant runoff processes but also in-stream hydraulic and sediment-chemical interactions.

The formulation of the HSPF model started with the development of the Stanford Watershed Model in the early 1960's (Crawford and Linsley, 1966), which provide the basis for the runoff quantity prediction component. Subsequently, a number of alternative quality models were developed to incorporate water quality processes in the 1970's, with the noteworthy one being the model presented by Huff (1967) who initiated the first serious attempt to develop an integrated model for runoff quantity and quality. Development of a FORTRAN version incorporating several related models using software engineering design and development concepts was funded by the USEPA in the late 1970's. In the 1980's, pre-processing and post processing software, algorithm enhancements, and use of the USGS WDM system were developed jointly by the USGS and USEPA. The most recent release is version 12, with the manual and code were prepared under the sponsorship of the USEPA. Furthermore, HSPF has been incorporated into Better Assessment Science Integrating Point and Nonpoint Sources (BASINS), a software developed by the USEPA that comprises a suite of interrelated components for performing the various aspects of environmental analysis (USEPA, 2001). It can be accessed via the *WinHSPF* interface.

This model generally requires meteorological and hydrologic data to develop the simulation and to compute the streamflow hydrograph and pollutograph. There is no predefined temporal increment during the calculation; this variable can be defined in accordance to the information available and to the problem being assessed. Additional information that can be used for simulation of the runoff processes include temperature, snow cover, water yield, ice content of snow and solar radiation intensity.

HSPF is comparable to SWMM (which will be discussed later in the report) in terms of its comprehensiveness and the number of conceptual components considered. It does include the algorithms for the generation, collection, transportation and disposal of the water quantity and quality from the catchment. Moreover, there is the option available for the modeller to define additional or alternative module that will suit the requirements of the problem being investigated as the source code is supplied and available in the public domain. The modules are operated in series whereby the prediction of one module is assessed prior to moving onto the next one, thus enable the user to follow the program operation relatively easy. Furthermore, it was developed in a manner where only relevant parts of the model need to be implemented depending on the problem at hand. Full model description and details can be found in the user manual by Bicknell *et al.* (2001).

HSPF is generally used to assess the effects of land-use change, reservoir operations, point or nonpoint source treatment alternatives, flow diversions, etc. Programs are available separately to support data pre-processing and post processing for statistical and graphical analysis of data saved to the Watershed Data Management (WDM) file. Even though this model is widely applied and tested in the United States, its suitability for local Australian conditions is still relatively unknown other than for rural catchments, such as the studies done by Ball *et al.* (1993), Perrens *et al.* (1991) and Rahman and Salbe (1995). While the data requirements can be quite extensive, HSPF is thought to be the most accurate and appropriate management tool presently available for the continuous simulation of hydrology and water quality in watershed (Bicknell *et al.*, 2001).

2.2.2 Programming Language

FORTRAN

2.2.3 Modelling Water Quantity

For runoff simulation, HSPF categorises the subcatchment areas into two components: pervious and impervious areas. Both runoff quantity and quality are simulated through separate modules for the different land surfaces (*PERLND* for pervious and *IMPLND* for impervious). Then the runoff quality and quantity are routed to the receiving waters via the transport component (*RCHRES*).

Modelling of the catchment processes by HSPF requires the subdivision of the catchment into individual land segments with the boundaries defined according to the user's needs, but generally based on similar hydrological characteristics. Runoff is then routed through each land segment by treating the overland flow as a turbulent flow process. It is simulated using the Chezy-Manning equation and an empirical expression that relates outflow depth to detention storage. Generally the subroutines in this section for both land segments are similar except for the omission of the infiltration function and subsurface flows for the impervious module.

The transportation and receiving water components are modelled using completely mixed reactors with the runoff hydrographs routed through the channel or reservoir segments using storage routing or kinematic wave techniques. This routing approach should be acceptable in the upper reaches of a catchment where the gravitational and frictional forces are the dominant forces influencing the motion of the unsteady flows (Ball, 1992). However, it is important to note that the flow is assumed to be unidirectional in the transportation module.

2.2.4 Modelling Water Quality

The bases of the water quality models included in HSPF are the Agricultural Runoff Management (ARM) model (Donigian-Jr. and Crawford, 1976b) and NonPoint Source (NPS) model (Donigian-Jr. and Crawford, 1976a). Both models are actually based on representation of the physical and chemical processes involved with the generation and removal of pollutant mass from the surface of agricultural catchments. The only change necessary for alternative land uses is the definition of the importance of the different processes involved.

HSPF has different sets of water quality modules for simulating sediments or solids and various other quality constituents for the two distinct land segments. The total sediment can be categorized into three components: sand, silt and clay, which can be inorganic, organic or both. The removal of sediment by water is simulated as washoff of detached sediment in storage and scour of the soil matrix. The washoff process involves two parts: the detachment or attachment of sediment from the soil matrix and the transportation of this sediment by overland flow. Detachment of soil is only possible via rain impact on wet days whereas reattachment occurs on dry days. On the other hand, the transport of detached sediment is based on the transport capacity of the overland flow compared to the mass of sediment available for transport. Alternative means of estimating the transport capacity of the flow are available but the use of a dimensionally non-homogeneous method is recommended.

Therefore, the main influences on the sediment washoff rate considered are:

- Detachment or attachment of sediment from the soil matrix
- Impact energy of rainfall
- Transport of detached sediment by overland flow.

With respect to the quality constituents, simple relationships with water or sediment yield can be formulated to predict the water quality constituents or pollutants in the outflows from the subcatchments. Two methods are available in the model to determine the quantities of the constituents in the surface flow:

- Simulate the constituent by association with sediment removal
- Simulate using atmospheric deposition or basic accumulation and depletion rates together with depletion by washoff, in other words the constituent outflow from the surface is a function of the water flow and constituent in storage.

In general, contaminants and nutrients removed from the surface are assumed to be a function of the sediment removed from the land segment surface. This requires the definition of a potency factor that will relate the contaminant or nutrient mass to the sediment mass, which is analogous to the first method. For the second method, storage of the quality constituent on the land surface is simulated, whereby the constituent can be accumulated and removed by processes which are independent of storm events such as cleaning, decay, wind erosion and deposition, or it can be washed off by overland flow.

Generation of pollutants on the catchment surface are derived from a number of sources including:

- Land use within the land segment
- Atmospheric fallout
- Land management practices
- Vegetation
- Rainfall.

Separate modules are also available for different constituents with distinct characteristics when modelling the water quality transportation component. The constituent can either be in the dissolved state or sediment-associated. For the particulate form, it can further be divided and linked to cohesive sediments such as silt and clay, or non-cohesive sediments such as sand and gravel. Generally in HSPF, the subroutines that are executed for sediment-associated constituent include:

- Advection of the adsorbed suspended material
- Deposition and scour of adsorbed material with sediment
- Decay of suspended and bed material
- Adsorption/desorption between dissolved and sediment-associated phase.

The simulation of the sediment-associated constituent is preceded by the module that simulates the transportation, deposition, and scouring of inorganic sediment.

On the contrary, if the constituent is not associated with sediment, the module only considers:

- Advection of dissolved material
- Decay processes
- Production of a constituent as a result of decay of another.

Transformation of the pollutants by means of hydrolysis, oxidation, photolysis, biodegradation, volatilisation and sorption is also possible. Most of these reactions, however, are based on simple first-order equations and do not consider the total transformation. The current HSPF only includes detailed degradation methods for the dissolved state of the quality constituent. Nonetheless, it is important to note that the model was developed such that the necessary processes can be modelled and subsequently the effects of alternative land use management practices can be ascertained.

2.2.5 Applicability of Model

HSPF is a lumped parameter watershed model that simulates non-point source runoff and pollutant loadings for a watershed and performs flow and water quality routing in reaches. All pertinent hydrologic processes can be simulated with HSPF but many of the parameters that control system responses are empirical (non-physically based) and are determined through calibration. Its ability to represent most of the hydrologic regimes and also the various pollutant processes taking place within a catchment, starting from the generation component to the receiving waters will consequently lead to a better prediction of the catchment response. However, the increase in comprehensiveness of the model resulted in more parameters to be calibrated and the uncertainties associated with these parameters may not be easily ascertained.

The runoff component in HSPF does not model the flow depth and spatial variation along the subcatchment surface. This might have some implications on the accuracy of runoff estimation as well as the water quality simulation results. Additionally, flow between different subcatchments or land uses cannot be modelled; yet these phenomena are common in urban catchments during storm events.

Nevertheless, in comparison with other conceptual models available in the market, HSPF presents a useful tool for carrying out the water quality simulation exercise as the modules incorporated in the model allow both particulate and dissolved form of pollutants to be modelled along with their individual processes. A wide range of sub processes can be simulated including the decay of the quality constituent but this advantage may not present significant benefits to the project. Also, the quality processes are described using empirical expressions that may not be applicable for different catchment conditions other than the ones in which they were developed from.

On the other hand, the transportation component of the model is set up as a series of completely mixed reactors and modelled using the kinematic wave approximation. This may lead to significant errors when dealing with low channel slopes, significant backwater conditions, or reversals in channel flow. Also, surface water structures can be simulated using fixed stage-discharge-storage relationships but they cannot be dynamically changed during a simulation. Thus, unlike models that are developed mainly for urban stormwater studies like SWMM, HSPF would fare poorly in system with pumps or flow regulators.

2.3 INFOWORKS CS (*C*ollection *S*ystem)

2.3.1 Model Objectives and Features

InfoWorks is a suite of softwares developed to undertake hydrological modelling of the complete urban water cycle, from supply and distribution, urban drainage and wastewater management through to river management modelling (Wallingford Software Ltd, 2005). InfoWorks CS, as part of the software package, is the system responsible for the simulation of the stormwater collection system, and provides a practical tool for the operational control and planning of the urban drainage systems. Other applications of this model include urban flooding and pollution prediction, and the modelling of water quality and sediment transport throughout the wastewater network.

The current version of the model, InfoWorks version 6.5 comes from a long pedigree of development and improvement by Wallingford Software Ltd, a company based in the United Kingdom. It is actually a compilation of its predecessors, including WASSP (rainfall-runoff model), WALLRUS (simple pipe routing model), SPIDA (full dynamic pipe routing model), MOSQITO (water quality module), and HydroWorks. InfoWorks CS also supports the import and consolidation of existing models directly from HydroWorks, MOUSE and SWMM. Presently, the model is only commercially available and the user's manual is available upon request. Data requirements are generally similar to other models such as SWMM. Both event based simulation and continuous simulation over long time periods can be performed.

InfoWorks CS is not used widely throughout Australia due to its limited availability compared to stormwater models found in the public domain. However, one notable feature of this system is that it provides fast, accurate and stable modelling of the key elements of stormwater and combined drainage systems. In addition to that, the software incorporates full solution modelling of backwater effects and reverse flow, open channels, trunk sewers, complex pipe connections and complex ancillary structures. Hence, it has been adopted by local councils for asset planning and management, and design of water and wastewater distribution systems.

2.3.2 Programming Language

C++ and FORTRAN

2.3.3 Modelling Water Quantity

Similar to other modelling exercises, a network that consists of manholes, pipes, channels, and subcatchment areas has to be defined before proceeding any further. The overall catchment model is then divided into a series of subcatchments, with each of them further subdivided into distinct surface types. Each subcatchment can use up to 12 of the defined surface types.

On another aspect, both synthetic and historical rainfall data can be used as input into the model. An empirical relationship can be utilised to determine the average spatial rainfall over a catchment using rainfall intensity and a spatial smoothing factor.

The expressions for water quantity simulation mainly stemmed from the Department of Environment (1983) rainfall-runoff models, used in the United Kingdom for both urban and rural catchment areas. Rainfall runoff is represented by three model components:

- Initial losses (depression storage)
- Continuing losses (infiltration)
- Overland flow routing.

Initial losses including wetting and depression storage depend on surface type and slope, and can be calculated using a regression equation or specified as an absolute value. Although this is dominated by depression storage on paved surfaces, other losses such as surface wetting, infiltration and evapotranspiration all have an impact on the value of the initial loss. There are three available types of initial losses in the model:

- Slope - depression storage is related to ground slope by an expression
- Absolute – a depression storage depth is given
- SCS - the value is a proportion of the storage depth that is retained.

On the other hand, the overland flow of the runoff into the drainage system is modelled separately for each type of surface, using simple reservoir-based models instead of more complex, distributed models like the kinematic wave approximation. There are a number of routing models that can be adopted to simulate the overland runoff on the catchment:

- Desbordes model
- Double Linear Reservoir (Wallingford) model
- Large Contributing Area model

- SPRINT model
- SWMM model.

All of these models are either empirical or conceptual. The basis of both the Desbordes and SPRINT model is the single linear reservoir routing technique. On the other hand, the Double Linear Reservoir (Wallingford) model is based on the use of a double quasi-linear reservoir model whereas the Large Contributing Area model is the modified version of this model. The USEPA's SWMM runoff block provides the last alternative option. In addition, a time delay can be introduced so that the peak runoff lags the peak rainfall.

Next, several infiltration models are available for selection to describe the infiltration processes, which include the Green-Ampt model, Horton Infiltration model, and Constant Infiltration model. Depending on the modeller, other non-routing models such as the New U.K. PR model, Wallingford Procedure model and the U.S. SCS model can be adopted to predict storm flow volumes rather than runoff rates.

The Muskingum–Cunge method and the solution of the full shallow water wave equations are the options for routing flows through the stormwater network. Both defined and user-specified pipes and channels can be used. 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 then used to solve the equations.

2.3.4 Modelling Water Quality

With respect to water quality, the pollutants that can be modelled using this model are total suspended solids (TSS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), ammonia, total Kjeldahl nitrogen, total P and four arbitrary conservative pollutants. Each pollutant can be modelled as a dissolved pollutant, or as pollutant attached to one or both sediment fractions using a potency factor. Also, it is assumed that there is no interaction between pollutants and their environment, or between one pollutant and another.

All in all, the InfoWorks CS water quality module allows simulation of the build-up of sediment in the network and the movement of sediment and pollutants through the drainage system during a rainfall event. Among the physical process models included within the water quality module are a surface pollutant build-up model, surface pollutant washoff model, gully pot model, wastewater profile generator, sediment transport model and an in-pipe water quality model. Generally the water quality model involves a separate calculation process that effectively occurs in parallel with the hydraulic modelling calculations, with the runoff module providing data to the washoff module at each time step. At the same time, a pollution index that defines the water quality parameters of the entire subcatchment is assigned to each particular land use in order to facilitate the simulation exercise.

The model treats sediments and attached pollutants separately from dissolved pollutants:

- Sediments, and any pollutants attached to sediments, build up on the catchment surface during dry weather periods. During a period of rainfall they are washed off the surface into the drainage system by surface runoff. This process is simulated by the Washoff Model.
- Dissolved pollutants build up in gully pots between periods of rainfall. During a rainfall period, surface runoff entering the drainage system washes these dissolved pollutants into the network. This process is simulated by the Gully Pot Model.

These two processes are modelled independently by the surface pollutant model of InfoWorks CS.

The build-up equation is based on the hypothesis that on a clean surface the pollutant accumulation rate is linear but as surface mass increases the accumulation rate decays exponentially. This empirical expression is used to determine the mass of sediment build-up only whereas the mass of attached pollutant is determined by multiplying sediment mass by a potency factor as discussed before. As for gully pot pollutant build-up, the basic hypothesis is similar, with a time-linear accumulation of each pollutant in the gully pot. Besides, the build-up of sediment and pollutants continues during both storms and subsequent dry weather periods.

On the other hand, the rate at which eroded sediment runs off into the drainage system is calculated using either the Desbordes model (the single linear reservoir runoff routing model) or other chosen hydraulic runoff model. InfoWorks CS assumes that the pollutant flow at the subcatchment outlet is proportional to the quantity of pollutant dissolved or in suspension in the storm water present on the subcatchment, which is by and large analogous to a first-order decay model. Thus, the model calculates:

- The amount of sediment eroded from the surface and held in suspension in the storm water (TSS). This erosion is proportional to rainfall intensity and it is also a function of the mass of deposit on the ground.
- The amount of sediment washed into the drainage network using the single linear reservoir routing model.

- The amount of each pollutant attached to the sediment entering the drainage network. This is also proportional to rainfall intensity.

No sediment deposition or erosion is modelled by the gully pot model and only dissolved pollutants are introduced to the drainage network using this model. The underlying assumption behind the concept is even mixing of the pollutant mass in the gully-pot and that resulting from surface washoff. The resulting pollutant flow therefore depends on the inflow from the runoff module.

Next, the transportation module carries out calculations in three stages for each time step:

- The Network Model calculates the concentration of dissolved pollutants and suspended sediment at all nodes using a conservation of mass equation
- The Conduit Model calculates the concentration of dissolved pollutants and suspended sediment along each conduit
- The Conduit Model then calculates the erosion and deposition of sediment in each conduit.

In general, the network model is used to generate the concentration of dissolved pollutants and suspended sediment at the nodes. Conversely, the conduit model is used to calculate the transport of suspended sediment and dissolved pollutant, and the erosion and deposition of sediment, in conduits. The transport process and the sediment erosion and deposition process are solved separately within each time step. The advection equation is then solved in each conduit via the Holly-Preissmann scheme (Holly and Preissmann, 1977). However, the diffusion processes are ignored.

2.3.5 Applicability of Model

As a commercial model, InfoWorks offers a user friendly modelling environment and various helpful features that simplify the entire simulation exercise. Even though this would lead to reduced modelling time for the users, the accuracy of the results is not further improved as minor changes to the adopted expressions are implemented.

In generating hydrographs or predicting runoff rates, this model utilises simple linear or non-linear reservoir model to carry out the task. The downside of using such models is that the spatial variation of the runoff on the catchment cannot be determined and this would lead to inaccuracy in the water quality predictions that rely on accurate water quantity simulation. Moreover, empirical expressions are used to model sediments build-up and washoff for the water quality module and these algorithms are deemed not suitable for local Australian conditions considering the fact that they are developed in accordance to overseas catchment characteristics, and largely also for combined drainage systems. Nevertheless, this model allows the separate prediction of the dissolved contaminants component and its hydraulic model is on par with other established stormwater models, and hence is suitable for modelling wastewater and stormwater collection networks.

2.4 MOUSE (*M*odeling *O*f *U*rban *SE*wers)

2.4.1 Model Objectives and Features

MOUSE is a comprehensive surface runoff, open channel and pipe flow, water quality and sediment transport modelling package for urban drainage systems, stormwater sewers and sanitary sewers (DHI Water & Environment, 2004). It combines the simulation of complex hydrology, hydraulics, water quality and sediment transport in a completely graphical, easy-to-use interface. This is further supplemented by various pre-processing and post processing softwares such as MIKE View and MOUSE GIS, all of which are developed by DHI Water and Environment.

Back in the early 1980s, MOUSE pioneered the application of numerical models on DOS-based personal computers. The evolution of MOUSE has been firmly linked to the improvements of the PC's computational power, the operating systems and the standards set for the user interface. The model has been used for a number of years for examining flows in sewers and pipe systems especially in urban environments. Most of its development is influenced by other hydrological or hydrodynamic models like MIKE11 and MIKE STORM. As a result, overlapping of the model components is common.

This proprietary software is developed and distributed by DHI Water and Environment, a firm based in Denmark. Product support and training for this model is readily available since the program is continually being enhanced by the same company. Several user guidelines are also available for different modules featured in the model. General data requirements for running the model include the network and operational data, meteorological information, hydrological and catchment morphological conditions, pollutant and sediment data.

The model system is organised in several modules of varying sophistication:

- MOUSE Runoff: surface runoff models for urban catchment applications
- MOUSE HD: hydrodynamic network model with some limited options of flow regulation
- MOUSE RDI: advanced hydrological model for continuous simulation
- MOUSE RTC: advanced reactive RTC capabilities for MOUSE pipe models

- MOUSE LTS: long-term hydraulic simulations with statistics
- MOUSE TRAP: containing sub-modules like:
    - MOUSE SRQ: pollutants build-up and transport on catchment surfaces
    - MOUSE AD: pollutants advection-dispersion in drainage networks
    - MOUSE WQ: water quality processes in drainage networks
    - MOUSE ST: sediment transport in drainage network.

These modules not only form the backbone of MOUSE, the underlying concepts were also adopted and incorporated in models such as MIKE STORM and MIKE URBAN.

Typical applications of MOUSE include studies of combined sewer overflows (CSO), sanitary sewer overflows (SSO), complex Real Time Control (RTC) schemes development and analysis, design of new site developments, regulatory consenting procedures and analysis and diagnosis of existing stormwater and sanitary sewer systems. In Europe, this model is one of the most widely used tools for the analysis of urban drainage problems, and it is also used extensively in Australia (Urbonas and Stahre, 1993).

2.4.2 Programming Language
DELPHI, FORTRAN and C++

2.4.3 Modelling Water Quantity
MOUSE, as a numerical modelling tool, works with a schematized representation of the urban drainage system; a set finite number of well-defined interconnected elements appropriate for the computations of the relevant physical, chemical and biological processes. Basically the urban drainage system is divided into two parts: the catchment and the drainage network, which can be considered as being the collection and transport components outlined earlier. The runoff processes are computed by one of the MOUSE runoff models, and the hydrodynamic pipe flow model computes the network flows. The hydrodynamic computations are then used as a basis for the computation of other relevant processes (e.g. sediment transport, advection-dispersion and water quality).

Different surface runoff computation concepts are available as four different runoff models:

- Time-area method
- Non-linear reservoir method (kinematic wave)
- Linear reservoir method, in two sub-variants:
    - Dutch runoff model
    - French runoff model
- Unit hydrograph model (UHM).

Runoff computed by any of the surface runoff models except UHM can be complemented by a continuous runoff component, i.e. rainfall-induced infiltration can be added to the computed surface runoff hydrographs using the MOUSE Rainfall Dependent Infiltration (RDI) module.

For the time-area method, the runoff hydrograph is controlled by the concentration time and the time-area (T-A) curve. In contrast, the non-linear reservoir model produces runoff hydrographs that are controlled by the catchment parameters length, slope and roughness of the catchment surface. These parameters form the base for a kinematic wave computation using Manning's equation. The third surface runoff computation method is founded on the routing of the runoff through a linear reservoir. This means that the catchment surface runoff is proportional to the current water depth on the catchment. The implemented two versions of the model are equivalent to the surface runoff models used in the Netherlands and in France. Lastly, the UHM module simulates the runoff from single storm events using the SCS-dimensionless hydrographs or the Snyder Unit Hydrograph. The unit hydrograph model calculates the excess rainfall assuming that the losses to infiltration can be described as a fixed initial and constant loss, a proportional loss (the rational method) or by the U.S. Soil Conservation Service (SCS) curve number method. The flexibility of choosing the best model for the task is governed by the amount of information available. The computed hydrographs are then used as input to the pipe flow model.

The hydrological model includes simulation of both direct surface runoff and indirect runoff. Each catchment is described by its total area, the distribution of the area between the direct and indirect runoff components, and the relevant hydrological parameters.

The Hydrodynamic Pipe Flow model (HD) in MOUSE solves the complete St. Venant (dynamic flow) equations throughout the drainage network (looped and dendritic), which allows for modelling of backwater effects, flow reversal, surcharging in manholes, free-surface and pressure flow, tidal outfalls and storage basins. The program has been designed to handle any type of pipe network system with alternating free surface and pressurized flows as well as open channel network. It provides for three different hydraulic descriptions:

- Kinematic wave approach
- Diffuse wave approach
- Dynamic wave approach.

All three approaches can simulate branches as well as looped systems. The dynamic description is recommended in all cases except where it can be proved that either diffusive or kinematic descriptions are adequate. On the other hand, the diffusive and kinematic waves are actually truncated versions of the dynamic wave and the only motivation for the choice of these simplified descriptions is because of their faster computation speed.

Also, the computational scheme uses an implicit, finite-difference numerical solution of the St. Venant flow equations. The numerical algorithm uses a self-adapting time step, which provides efficient and accurate solutions in multiple connected branched and looped pipe networks. This scheme is applicable to unsteady flow conditions that occur in pipes ranging from small-profile collectors for detailed urban drainage, to low-lying, often pressurized, sewer mains affected by varying outlet water levels. Both subcritical and supercritical flows are treated by means of the same computational scheme that adapts to the local flow conditions. In addition, flow phenomena such as backwater effects and surcharges can be precisely simulated.

2.4.4 Modelling Water Quality

For this model, water quality is simulated via an add-on module known as MOUSE TRAP. Under this common name, several modules are provided for the simulation of sediment transport and water quality for both urban catchment surfaces and drainage systems. Since pollutants are mainly carried by sediment, sediment transport processes and water quality in drainage systems are closely interconnected. This is important for understanding phenomena like the first flush effect, which can only be simulated with a description of the temporal and spatial distribution of sediment deposits on the catchment surface and in the drainage system. MOUSE can model these complex mechanisms using its Surface Runoff Quality (SRQ), Pipe Sediment Transport (ST), Pipe Advection-Dispersion (AD), and Pipe Water Quality (WQ) modules. Output from these modules can then be applied directly to models like MIKE 11 and MIKE 21, which would enable the water quality assessment of receiving water bodies.

The primary role of the Surface Runoff Quality (SRQ) module is to provide a physically-based description of the relevant processes associated with sediments and pollutants due to surface runoff. This would generate input for the sediment transport, advection-dispersion or water quality computation in the underlying pipe model. The processes that can be accounted for are as follow:

- Build-up and washoff of sediment particles on the catchment surface
- Surface transport of pollutants attached to the sediment particles
- Build-up and washout of dissolved pollutants in potholes and stilling basins.

The build-up and washoff model consists of two sub-models: a model for replicating the accumulation process of particles on the catchment and a model for the description of the detachment of particles by rainfall and subsequent washoff by the overland flow. The model works with both fine and coarse sediment fractions, with each fraction being characterised by its mean diameter. Generally, the build-up function available in the model is mainly suited for the finer sediments and can be defined as a linear build-up function or an exponential function. The washoff function on the contrary is assumed to be dependant on the erosion by rain drops, which is governed by the rain intensity and a detachment rate, utilizing an approach presented by Svensson (1987). The transport of the coarse sediment is limited by the transport capacity of the overland flow, whilst the transport of the fine sediment only is limited by the rainfall erosion rate and the sediment mass available on the surface.

Like other stormwater models, the surface sediment transport model is linked to the hydrological models available in MOUSE. Hence, the sediment is routed according to the hydrological description in the surface runoff models. There is also the Sediment and Pollutants model that describes the attachment of pollutants to the sediment whereas a Gully Pot model to describe the release of polluted water from gully pots, which under some circumstances contributes significantly to a first foul flush. Analogous to INFOWORKS CS, the data supplied to the Gully Pot model facilitate description of the build-up of dissolved pollutants in the gully pots during dry weather and the dissolved pollutants washoff from the gully pots during storm events.

Sediment deposits can greatly reduce the hydraulic capacity of drainage pipes by restricting their flow area and increasing the bed friction resistance. The Pipe Sediment Transport (ST) module thus accounts for these problems by simulating pipe drainage network sediment transport including deposition and erosion from non-uniform (graded) sediments. Contributions from rainfall washoff and dry weather wastewater flow can be included. This module runs in conjunction with the dynamic flow routing, thereby simulating dynamic deposition of sediment and providing feedback due to the change in pipe area and resistance caused by sediment deposition.

Additionally, the Advection-Dispersion (AD) module simulates the transport of dissolved substances and suspended fine sediments in pipe flow. Conservative materials as well as those that are subject to a linear decay can be simulated. Moreover the computed pipe flow discharges, water levels, and cross-sectional flow areas are used in the AD module computation. The solution of the one-dimensional advection-dispersion equation is obtained using an implicit, finite difference scheme that has negligible numerical dispersion. Concentration profiles with very steep fronts can also be accurately modelled. The computed results can be displayed as longitudinal concentration profiles and pollutographs, which later could be used as the inflow to a sewage treatment plant or an overflow structure.

Last but not least, the Pipe Water Quality (WQ) module works in conjunction with the AD module, thereby providing many options for describing the reaction processes of multi-compound systems including degradation of organic matter, bacterial fate, exchange of oxygen with the atmosphere and oxygen demand from eroded sediments. The AD module simulates the transport process while the WQ module deals with the simultaneous transforming processes of the biological constituents and chemical compounds in the drainage system. This allows realistic analysis of complex phenomena related to water quality in drainage systems. The sediment types included in the interaction with the WQ module are foul flow organic sediments, and fine and coarse mineral in-pipe sediments originating from catchment runoff, potholes and stilling basins. The WQ module therefore accounts for:

- Decay of BOD or COD in biofilm and water phase
- Hydrolysis of suspended matter
- Growth of suspended biomass
- Oxygen consumption from decay of BOD or COD, biofilm and erosion of sediment
- Reaeration
- Bacterial fate
- Interaction with sediments for nutrients and metals.

All in all, the SRQ module can be used by itself to study water quality and sediment transport processes on catchments. The result can then be used as input to a river model like MIKE11 or to the MOUSE TRAP modules which deal with processes in the pipe model. If only dissolved pollutants are of concern, it is sufficient to utilize the AD module, possibly in conjunction with the WQ module. If the pollutants attached to sediment are to be modelled it is recommended that the ST, AD and WQ modules be employed simultaneously. Finally, if sediment transport is the only modelling purpose, the ST module can be adopted separately.

2.4.5 Applicability of Model

There are many similarities between MOUSE and other models like INFOWORKS CS and SWMM. However, common limitations that would lessen the accuracy of predictions are also found in this model. The use of simple rainfall routing methods like the time-area method to slightly more complex approaches like the non-linear reservoir method would not provide the capabilities of simulating the necessary temporal and spatial variation found in catchment surface runoff. Adding to that, the water quality processes are either based on a linear or exponential function, or from an empirically-derived expression. Overall, MOUSE does not provide as much descriptions of the physical processes taking place within the catchment like HSPF does and many of the expressions developed are founded on overseas catchments which may not be applicable for local conditions.

2.5 MUSIC (*M*odel for *U*rban *S*tormwater *I*mprovement *C*onceptualisation)

2.5.1 Model Objectives and Features

MUSIC is a model that provides the ability to simulate both runoff quantity and quality from various catchments, and the effect of a wide range of treatment facilities on the quantity and quality of runoff downstream (MUSIC Development Team, 2005). It helps predicts the performance of stormwater quality management systems, and facilitates the planning and design of appropriate urban stormwater management systems for catchments, usually at the conceptual level.

The pilot version of MUSIC was released in March 2001 for beta testing before actually being distributed to the stormwater industry at large few months later. The model gathers years of research and testing carried out by the Cooperative Research Centre for Catchment Hydrology (CRCCH), which is based in Australia to address the deficiencies in knowledge concerning diffuse sources of pollution and performance of stormwater treatment measures (Wong *et al.*, 2002). The latest version, MUSIC version 3 introduces the Life Cycle Costing module, which allows the lifecycle costs of a treatment train to be estimated and analysed. The various features and instructions on model usage are included in the user guide by the MUSIC Development Team (2005). Presently, this model is only commercially available from CRCCH.

Data requirements for this model include rainfall and meteorologic data that are available from the Australian Bureau of Meteorology, catchment characteristics (i.e. area, land use, impervious area etc.) and conceptual design of stormwater treatment measures (i.e. type, size etc.). Both historical and stochastically generated data of flow and pollutant concentration can be adopted when running the model.

The model runs on either an event or continuous basis, allowing rigorous analysis of the merit of proposed strategies over the short-term and long-term. Furthermore, it can perform simulation for catchment areas from 0.01 km^2 to 100 km^2, with the modelling time steps ranging from 6 minutes to 24 hours to match the range of spatial scale. The model's algorithms are based on known performance characteristics of common stormwater quality improvement measures. Hence, by simulating the performance of stormwater quality improvement measures, MUSIC is able to determine whether the proposed systems can meet the specified water quality objectives. MUSIC also provides the ability to compare the observed and simulated data on time series graphs.

The development of MUSIC provides urban catchment managers with an easy to use decision support tool by which they can evaluate and compare alternative strategies aimed at protecting aquatic ecosystems from the impacts of urbanisation. The results of MUSIC simulations can be used to inform the decision making process associated with the economic risk analysis, prioritising and staging of the stormwater quality management strategy for the catchment. Many catchment managers in Australia are now adopting the model to assist with both their strategic catchment planning as well as their assessment of urban development applications submitted by land developers.

Lastly, it is important to note that this model is not a detailed design tool, but a more conceptual design tool as the necessary algorithms for detailed sizing of the various stormwater facilities are not included. Moreover, it does not include all aspects of stormwater management that decision-makers must consider particularly during Water Sensitive Urban Design applications.

2.5.2 Programming Language

FORTRAN and DELPHI

2.5.3 Modelling Water Quantity

The algorithm adopted to generate urban runoff is based on the model developed by Chiew and McMahon (1997). The model was a simplified description of the rainfall-runoff processes in catchments involving the definition of the impervious area and two soil moisture storages. It was initially developed using a daily time step, but has been modified for incorporation into MUSIC to allow disaggregation of the generated daily runoff into sub-daily temporal patterns.

Similar to the others, this model allows for separate runoff generation processes on impervious and pervious portions of the catchment. The impervious area has depression storage only with no infiltration, and quickly produces surface runoff during an event. Water in the depression storage is lost to evapotranspiration daily. On the contrary, the pervious area represents the fraction of the source node in which infiltration occurs, with the infiltration rate of the soil being defined as an exponential function of the soil moisture storage. Runoff then occurs when the rainfall exceeds the infiltration rate of the soil and when the soil moisture store has reached its maximum capacity. On the other hand, water that is stored in the pervious storage can be lost to evapotranspiration at any time and to groundwater when the volume in store exceeds the field capacity.

The passage of a stormwater wave through a link between two nodes is computed in MUSIC using the Muskingum-Cunge method of stream routing, based on the continuity of mass equation within a channel reach. This method is used to compute the outflow hydrograph and pollutograph from those entering the link.

The various default values adopted for this model are based on the calibration of the model to Brisbane and Melbourne urban catchments. Consequently, it is imperative that the rainfall-runoff model be calibrated to local conditions whenever possible. It should also be noted that the volume of runoff generated and the stormwater runoff time series from an urban catchment are not very sensitive to variation in the parameters defining the pervious area response to rainfall, and the model is significantly more sensitive to the accurate definition of the fraction imperviousness and the selection of simulation time step.

2.5.4 Modelling Water Quality

Analogous to SWMM, MUSIC is also a link-node model, with separate source nodes for urban, agricultural and forested subcatchments. Each of these three source nodes has its own default pollutant concentrations. Therefore, to represent a subcatchment made up of differing component land uses, separate source nodes much be created to represent each of these dominant land uses.

A comprehensive review of stormwater quality in urban catchments was undertaken by Duncan (1999) and this study forms the basis for default values of event mean concentrations for Total Suspended Solids (TSS), Total Phosphorus (TP) and Total Nitrogen (TN) adopted in MUSIC. Currently these water quality constituents together with the gross pollutants are the only pollutants modelled. The pollutant generation rates are then determined via statistical analysis with the TSS, TP and TN concentrations generated using a stochastic process involving cross correlation (between TSS and TP) and serial correlation of water quality time series.

The algorithm for routing contaminants through a channel reach in MUSIC is similar to the flow routing method adopted whereby it is based on the continuity of contaminant mass equation.

On the other hand, MUSIC incorporates the ability to display the predicted probabilistic water quality conditions at source nodes (e.g. urban subcatchment), treatment nodes (e.g. wetland) or receiving nodes, against local or regional water quality standards. In addition to that, among the treatment devices that can be incorporated into the modelling system include gross pollutant trap, wetland, buffer strip, vegetated swale, bioretention system, infiltration system, pond, sediment basin, and rainwater tank. MUSIC uses the Universal Stormwater Treatment Model (USTM) to calculate the treatment processes that take place in these devices, and the performance of these measures is simulated in a two-stage process (MUSIC Development Team, 2005). The hydrodynamic behaviour of the stormwater treatment facility is first modelled by describing this behaviour as a series of well-mixed water bodies notionally located within the physical configuration of the stormwater treatment system. The pollutant reduction within each of these well-mixed water bodies is then computed using a first-order decay algorithm. The mechanisms promoted in the removal of stormwater pollutants encompass physical, chemical and biological processes.

2.5.5 Applicability of Model

As discussed earlier, MUSIC is a highly conceptual model; therefore any detailed analysis of the urban stormwater system is inhibited. In view of the nature of the rainfall-runoff model that obtains rainfall data derived from the disaggregation of the generated daily runoff, plus the fact that the water quality component is wholly based on event mean concentrations, the resulting prediction of water quality flowing from different land uses will almost certainly be inaccurate compared to results from process-based, deterministic models like HSPF. Moreover, the modelling concepts developed for the model are akin to those from a typical water balance model, with particular focus on satisfying the mass balance rather than reproducing the hydrographs or pollutographs.

Other weaknesses of the model include the inability to simulate spatial and temporal variation of water quantity and quality on the catchment surface, absence of hydraulic analysis of the stormwater drainage system, and lack of actual data to validate the accuracy of this relatively new model. The model can only provide a guide to the probable range of diffuse pollution load generated from the catchments. Nevertheless, MUSIC provides an efficient model by which the performance of stormwater treatment measures during storm events can be predicted and evaluated (Wong *et al.*, 2002).

2.6 STORM (*S*torage *T*reatment *O*verflow *R*unoff *M*odel)

2.6.1 Model Objectives and Features

The Storage Treatment Overflow Runoff Model is an analysis tool for estimating runoff quantity and quality from urban and non-urban watersheds (HEC, 1977). To accomplish this task, the model considers the interaction of rainfall or snowmelt, dry weather flow, pollutant accumulation and washoff, land surface erosion, treatment processes, runoff and detention reservoir storage. Subsequently, this would aid in the sizing of storage and treatment facilities to control the quantity and quality of stormwater runoff and land surface erosion.

The model was originally developed in the early 1970s by Water Resources Engineers, Inc. (WRE) of Walnut Creek, California as part of a project for the Hydrologic Engineering Centre of the U.S. Army Corps of Engineers. It has since been updated by both the Hydrologic Engineering Centre and Resource Analysis Inc. of Cambridge, Massachusetts. Detailed descriptions of the model components are provided by HEC (1977). However, the emergence of better and more up-to-date models has lead to the demise of this model. Nevertheless, variants such as MIKE STORM and XP-STORM have been developed but the fundamental concepts found in these models are different altogether.

Basic data required for operation of the model include hourly precipitation records, land use data including runoff parameters, pollutant accumulation and washoff data, and land surface erosion data. It is mainly a continuous simulation model using hourly time steps and it can be used for single events. There is a clear indication in the user's manual that this model is only suitable for prediction of runoff quantity and quality at the downstream boundary of large catchments where the catchment processes have significantly attenuated and delayed localised peaks in both the runoff pollutograph and hydrograph. For this reason, the computational time step used in the program is fixed at one hour (Ball, 1992).

Among the main functionalities of the model include the computation of runoff quantity and quality, computation of treatment, storage, and overflow, and computation of land surface erosion. The basic approach adopted in this program recognizes not only the properties of storm duration and intensity, but also the storm spacing and storage capacity of the stormwater systems.

In general, this model can be adopted for use in two important planning components of a stormwater study. First is the prediction of wet weather pollutographs for use in a receiving water assessment model, whereby the impact of any land use changes can be evaluated.

The other application is in the preliminary sizing of storage and treatment facilities to satisfy desired criteria for control of stormwater runoff. Statistical information in regards to the quantity and quality of pollutants washoff, soil erosion and storage overflows can then be obtained herein.

2.6.2 Programming Language

FORTRAN

2.6.3 Modelling Water Quantity

Three alternative models are available for estimation of runoff quantity, these being the coefficient method, the U.S. Soil Conservation Service Curve Number technique, and a combination of the two. The coefficient method uses a volumetric runoff coefficient to estimate the average depth of runoff over the catchment during the simulation period. In other words a certain fraction of rainfall will run off each hour of each rainfall event. This runoff coefficient accounts for the losses due to infiltration. On the other hand, the S.C.S. method is based on a curvilinear relationship between accumulated runoff and accumulated rainfall, taking into consideration the antecedent conditions at the same time. For the last option which uses a combination of these two methods, the former approach is applied to the impervious surfaces whereas the latter method is used on the pervious surfaces.

It can be inferred from the previous approaches that there is no attempt to route the runoff through the catchment. In order to eliminate the restriction of having to adopt the model for small subcatchments only where the routing effects can be neglected, a unit hydrograph procedure was introduced in STORM that would provide a means of routing rainfall excess to the outlet of each subcatchment. A Soil Conservation Service triangular unit hydrograph is thus employed, with additional variables introduced such as the time of concentration of the subcatchments and also the ratio of time of recession to time to peak of the unit hydrograph. This unit hydrograph method can then be employed for both the coefficient method and the S.C.S. method of runoff computation.

2.6.4 Modelling Water Quality

With respect to water quality, loads and concentrations of six basic water quality parameters are computed including suspended and settleable solids, biochemical oxygen demand, total nitrogen, orthophosphate and total coliform. There are two components involved in predicting runoff quality: accumulation and washoff of the pollutants.

The accumulation process can be modelled via two methods: dust and dirt method, which assumes all pollutants are associated with the accumulation of dust and dirt on the catchment surface (more applicable for urban catchments), and daily pollutant accumulation method (more suitable for rural catchments). For the former, the amount of pollutants washed into the storm drains and eventually to the treatment facilities or receiving waters is dependent on several factors such as the rainfall intensity, runoff rate, accumulation of dust and dirt on the watershed and the frequency and efficiency of street sweeping. These pollutants are expressed as fractions of the dust and dirt for each land use, similar to the approach taken by other models. The second method however requires only the average daily accumulation rates for each pollutant, with the omission of street sweeping. The washoff of pollutants is then simulated using a decay function and the rate is proportional to the amount of pollutant remaining. No runoff treatment is assumed to occur in storage.

Besides, land surface erosion can be modelled independently of the pollutant accumulation and washoff through the use of the Universal Soil Loss Equation (USLE) presented by Wischmeier and Smith (1958). This empirical relationship takes into account the rainfall factor, soil properties, length-slope factor, cropping management factor, erosion control practice factor and the sediment delivery ratio. The option is intended for use only when the sediment production is to be studied.

2.6.5 Applicability of Model

STORM is a lumped conceptual model that has been mainly adopted for use in modelling the main processes of stormwater flow such as runoff generation, collection, storage, treatment, and discharge to receiving waters. Most of the computational algorithms derived are based on simple linear relationships or first order models that would result in rough estimates of the resulting runoff quantity and quality. Moreover, some of the empirical expressions are formulated based on U.S. catchment characteristics and may not be suited for local Australian conditions. Support for the use of this model however is no longer available and its development has been halted long before the creation of personal computers. Considering the lack of model testing and validation in the literature, and also the simplification of the routing procedures implemented, this model is not regarded as being suitable for current stormwater management studies.

2.7 SWMM (*S*torm *W*ater *M*anagement *M*odel)

2.7.1 Model Objectives and Features

The USEPA Storm Water Management Model (SWMM) is a dynamic rainfall-runoff simulation model used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas (Rossman, 2005). It performs hydrology, hydraulics and quality analysis of natural and stormwater drainage systems including sewage treatment plants, water quality control devices and Best Management Practices (BMPs) (Wong, 2005). All aspects of the urban hydrologic and quality cycles can be simulated, including rainfall, snowmelt, surface and subsurface runoff, flow routing through drainage network, storage and treatment.

SWMM was originally developed in 1971 and has undergone several major upgrades since then. It was the first comprehensive model of its type for urban runoff analysis. Up till now, it continues to be widely used throughout the world for planning, analysis and design of combined and separated stormwater systems in urban areas, sometimes in non-urban areas as well. The latest edition of the model, version 5, which is produced by the USEPA, provides an integrated, Windows-based environment for editing input data, running hydrologic, hydraulic and water quality simulations, and viewing the results in a variety of formats.

Basically, the model consists of a number of components known as modules or "blocks", which can be linked to run sequentially so that the output of one module provides input to another. For hydrologic simulation in the *RUNOFF* Block, data requirements include area, imperviousness, slope, roughness, width, depression storage, and infiltration parameters for up to 100 subcatchments. Additional data are required if simulation of snowmelt, subsurface drainage, and infiltration or inflow options are employed. On the other hand, flow routing can be performed in the *RUNOFF*, *TRANSPORT* and *EXTRAN* (*EXTENDED TRANSPORT*) Blocks, with input data such as shape and dimensions of the closed conduits or open channels, slope, roughness etc. The *STORAGE* or *TREATMENT* Block then characterizes the effects of control devices upon flow and quality.

Stormwater quality processes are initiated in the *RUNOFF* Block and include options for constant concentration, regression of load vs. flow, and build-up washoff, with the latter requiring the most data. Additional options include street cleaning, erosion, and quality contributions from precipitation, catch basins, adsorption, and base flow. The dynamic flow routing module, *EXTRAN* nevertheless is the only block that does not simulate water quality. As with other comprehensive models, input data requirements can be minimal to extensive depending upon the simulation objective. Lastly, calibration data that consist of measured hydrographs and pollutographs are needed for use in establishing values of input parameters for which a priori estimates are insufficient.

Because of its public domain status whereby the source code for the model is provided, extensive feedback has been received from users on needed corrections and enhancements, thus further improving the model. Full description and details of the model can be found in the user manual by Rossman (2005). In addition to the original model, various customized versions have been developed such as PCSWMM, XP-SWMM, and MIKE-SWMM that integrate pre-processing and post processing softwares and graphical user interface with the initial version.

SWMM was created to provide a tool capable of modelling the full hydrological cycle of stormwater and wastewater flow, from generation of pollutant to simulation of hydraulics in any drainage system of open or closed conduits. Typical SWMM applications include design and sizing of drainage system components for flood control, generating non-point source pollutant loadings for waste load allocation studies, evaluating the effectiveness of BMPs for reducing wet weather pollutant loadings etc. Due to its popularity and proven track record, it has been used in thousands of sewer and stormwater studies throughout the world (Rossman, 2005).

2.7.2 Programming Language

FORTRAN (version 4.4h) and C (version 5)

2.7.3 Modelling Water Quantity

Water quantity is modelled using several components. The runoff component operates on a collection of subcatchment areas that receive precipitation, generate runoff and pollutant loads. The routing portion of SWMM transports this runoff through a system of pipes, channels, storage or treatment devices, pumps, and regulators. The model also tracks the quantity and quality of runoff generated within each subcatchment, and the flow rate, flow depth, and water quality in each pipe and channel during a simulation period comprised of multiple time steps.

Similar to HSPF, the area of the subcatchments can be categorised as pervious and impervious segments, and it is up to the modeller to divide the study area into an appropriate number of subcatchments and identify the outlet point for each of them. Surface runoff can infiltrate into the upper soil zone of the pervious area, but not through the impervious area. On the other hand, impervious areas can be further divided into two areas; one that contains depression storage and another that does not.

For this model, surface runoff is based on rainfall intensities, antecedent 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. Overland flow hydrographs may be generated using Manning's equation and lumped continuity equation. On the other hand, infiltration of rainfall from the pervious area of a subcatchment into the unsaturated upper soil zone can be described using three different models:

- Horton infiltration
- Green-Ampt infiltration
- SCS Curve Number infiltration.

Furthermore, spatial variability in all of these processes is achieved by dividing the study area into a collection of smaller, homogeneous subcatchment areas, each containing its own fraction of pervious and impervious sub-areas. Overland flow can then be routed between sub-areas, between subcatchments, or between entry points of a drainage system.

Different flow routing options can be utilized in SWMM and they are:

- Steady Flow routing
- Kinematic Wave routing
- Dynamic Wave routing.

The former is the simplest type whereas the last produces the most theoretically accurate results since this routing method solves the complete one-dimensional Saint Venant flow equations. Generally, this is carried out by the stand-alone module, *EXTRAN* which 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, thus facilitates accurate simulation of backwater, looped connections, surcharging, and pressure flow.

2.7.4 Modelling Water Quality

SWMM is also used in a wide variety of water quality studies. The processes that can be simulated include pollutant build-up, washoff during rainfall, transport, advection, sedimentation, and biochemical processes. Generally the user defines the constituents involved and the surface water quality is computed based on one of the following approaches:

- Build-up and washoff process
- Rating curve washoff
- Event mean concentration (EMC) method.

Moreover, co-pollutants that are related to the primary pollutants modelled can also be defined in SWMM.

Pollutant build-up and washoff from subcatchments are associated with the land uses assigned to the subcatchment. Examples of land use activities are residential, commercial, industrial, and undeveloped areas whereas different land surface characteristics might include rooftops, lawns, paved roads, undisturbed soils, etc. Hence spatial variability of the pollutants can be incorporated in the catchment modelling system. Input loadings of pollutants to the drainage system can also originate from external time series inflows as well as from dry weather inflows. Build-up is then continuously depleted as washoff proceeds, and washoff ceases when there is no more build-up available. The build-up process is a function of the precedent dry weather days and can be computed using the following functions:

- Power function
- Exponential function
- Saturation function.

On the other hand, the washoff process occurs during wet weather periods and can be described via the following functions:

- Exponential washoff
- Rating curve washoff
- Event mean concentration method.

Besides, periodical reduction in dry-weather build-up due to street cleaning can also be incorporated.

Pollutant loads are then routed through the drainage system using a modified kinematic wave approximation and assuming complete mixing. Although a plug flow reactor assumption might be more realistic, the differences will be small if the travel time through the conduit is on the same order as the routing time step. The routing also becomes closer to pure advection (plug flow) as the number of conduits is increased. Each constituent may be subjected to first order decay during the routing process. Nonetheless, the decay of one constituent has no effect on other constituents present.

On another aspect, erosion and sedimentation are also often cited as a major problem related to urban runoff. However, in keeping with the simplified quality procedures included in the rest of the *RUNOFF* block, a widely-used empirical approach known as the Universal Soil Loss Equation (USLE) has been adapted for use in SWMM, instead of more sophisticated calculations that demand additional calibration data. This equation is developed by Wischmeier and Smith (1958) as an estimate of the average annual soil erosion from rainstorms for a given upland area.

2.7.5 Applicability of Model

SWMM is a conceptual stormwater model often adopted for urban stormwater management. Most of the processes that are part of the urban hydrological cycle are represented using power or exponential functions, especially those involving water quality simulations. This approach is fairly reasonable considering the fact that processes controlling pollutant erosion and transport are poorly understood (Huber, 1992). Moreover, this would reduce the number of parameters that needs to be calibrated during the modelling exercise.

As with other models, a number of assumptions are made in formulating SWMM. One of the assumptions inherent in the model is that there is no interaction among the quality processes. The repercussion of this might not be detrimental as the response time of urban catchments is generally too short for any interaction between the pollutants. But more importantly, SWMM does not have the capability to model sediment transport to a high degree of accuracy. Firstly, the depth of flow can only be assumed constant across the whole catchment due to the non-linear reservoir routing approach adopted. Eventually this will lead to error in estimating the amount of sediment pollutants being removed from the catchment (Ferguson and Ball, 1994). Secondly, the conceptual equations developed for the water quality simulations will not be as accurate as those physically based ones.

Version 5 of SWMM is a significant improvement to the model whereby friendly user interface and graphical output are introduced, hence eliminating one of the biggest impediments to model usage. Even though this latest release includes almost all of the previous functionalities, there are exceptions such as the plug flow and sedimentation theory in treatment units, erosion off subcatchments, and scour-deposition in channels and conduits (http://ccee.oregonstate.edu). These however are included in the unofficial release version, 4.4h. Hence, the modeller might have to resort to the latter version if detailed simulations of erosion, scouring and deposition processes are required. Nevertheless, the reliability of SWMM and its availability in the public domain have lead to the widespread use of this model, earning recognition as one of the better models for urban stormwater management studies.

2.8 XP-AQUALM (Networked Stormwater Quality Model)

2.8.1 Model Objectives and Features

XP-AQUALM is a comprehensive water resources quality management package with components for generating surface and subsurface runoff, non-point source and point source pollutant export (Phillips *et al.*, 1993), pollutant transport and routing (http://www.xpsoftware.com). It is an integrated suite of stormwater quality and stream flow models that is implemented under the *EXPERT* (XP) graphical user environment (Phillips *et al.*, 1992). Besides, it analyses the pollutant transport in a combination of watersheds and river reaches, and optimises the design of pollution control devices for the mitigation of pollutants.

Essentially, this software package is an enhanced and improved version of POLLUTE, a model developed by WP Software Pty Ltd (Ball, 1992). The major enhancements introduced are the ability to network a number of subcatchments to form a larger catchment and the inclusion of stream and lake routing of quality and quantity constituents. In addition, the latest version incorporates a friendly, object-oriented Graphical User Interface with a range of decision support functions. Currently, the program and manuals are available from XP Software Pty Ltd of Canberra, Australia, by which the model comes in executable form only. Typical data needed to run and calibrate the model include various meteorologic and rainfall data, land use, pollutant export data, water balance parameters and information on the drainage network.

Components within XP-AQUALM include:

- Rainfall-runoff module
- Non-point source pollutant export module
- Water quality inlet/gross pollutant trap and water pollution control ponds module
- Lake loading module
- River quality module.

The suite has two modes of operation. Under the *EXPORT* mode of operation, the networked system generates runoff and pollutant exports on a continuous daily basis and routes these flows and pollutants through gross pollutant traps or water pollution control ponds. Up to eight different categories of land use and up to ten different pollutants can be modelled. On the other hand, the *RIVER* mode of operation routes the runoff and pollutants generated from the *EXPORT* model through lakes and river systems, and calculates expected microphyte and algal growths within river reaches and eutrophication states within lakes.

XP-AQUALM allows the planner or engineer to analyse and optimize a range of catchment management options in a networked environment, with consideration towards total water cycle management involving stormwater, secondary water supply as well as industrial and municipal point source effluent. Other recommended uses of this model include prioritisation of land uses and "hot spots" for targeted management action, runoff and water quality assessments, and creation of data for input into detailed process models for analysis of the performance of ponds and wetlands (Wong, 2005).

2.8.2 Programming Language

C++, .NET and FORTRAN

2.8.3 Modelling Water Quantity

Daily runoff is simulated using a comprehensive rainfall-runoff model utilising a water balance description throughout the catchment. This continuous daily runoff model is based on a simplified version of the model developed by Lawrence and Lansdown (1977) for Lake Ginninderra and subsequently modified by GH&D (1981) for the Tuggeranong Creek catchment. It predicts runoff from rainfall based on an accounting of interception, evapotranspiration, surface and soil moisture storages. The parameters for the model must be defined separately for each category of land use ranging from highly urban to rural and forested sub-basins.

The transportation component of XP-AQUALM for the runoff quantity has not been defined in the technical literature available.

2.8.4 Modelling Water Quality

This model does not allow pollutants to build-up on the catchment surface; rather it assumes that there is sufficient pollutant mass available for export during the storm event being considered. Simulation of non-point source pollution is based on the total daily runoff predicted by the runoff model. A power relationship between the pollutant mass per unit area exported and the daily runoff is assumed. Various components of runoff including surface runoff, through flow and total runoff can adopt the same expression. Since the pollutant export is related to the daily runoff from each individual land use, it is necessary to obtain calibrated runoff parameters for each individual land use in each subcatchment.

An additional option available in this model for the prediction of pollutant loadings is the use of the Event Mean Concentration (EMC) method. Calibration of this option requires coefficients and loading rates obtained by either transposition from similar catchments or recorded events. Also, mean and standard deviation data can be applied to simulate statistical concentration distributions.

The quality aspect of the conceptual transport component has been outlined in concept and is based on a steady state assumption inclusive of decay of pollutant constituents to account for the loss in constituent mass flow with flow downstream.

Even though the model is designed to operate at a daily time step, an hourly estimate of rainfall temporal variation can be applied for further analysis of small control structures like Water Quality Inlets (WQI's). Additionally, the soil grading for each land use can be used to predict export of sediment and to track the grading as it passes through the drainage network and control devices. Scour and deposition of sediment can also be modelled along a river reach, utilising algorithms similar to those employed by SWMM.

2.8.5 Applicability of Model

Similar to MUSIC, XP-AQUALM is a highly conceptual water balance model that is generally adopted for setting out management strategies rather than for detailed design of stormwater drainage systems. The runoff is based upon an equation which has no direct relationship with the catchment impervious area. Hence it will not be sufficient when more physically based algorithms are needed to simulate the complex water quality processes and also when smaller operating time steps are required to achieve a higher level of accuracy. Moreover, further detailed testing of the model on gauged catchments by other than its developers is required to assess its sensitivity to alternative parameter values, and its ability to distinguish between alternative management practices for catchments. This is due to the fact that there are limited literature available to justify the model's reliability and applicability in various Australian catchment conditions.

3. CONCLUSIONS AND RECOMMENDATIONS

Inherent flaws and limitations can still be found in most of the water quality models available in the present market. From this study, it would appear that the developers have not progressed far in improving the various models that would replicate the actual physical processes taking place during a rainfall storm event albeit significant improvements to the graphical user interface of the models, pre-processing and post processing of the collected data and modelled results respectively. Justified by the fact that limited water quality data are readily available when performing most of the catchment modelling exercise, simple and straightforward expressions are still commonly used to estimate the stormwater flows and water quality pollutants contained in the runoff. Moreover, some only have the capabilities of simulating total load or flow volume of a rainfall event even though it is necessary to model the spatial and temporal distribution of pollutants in order to fully understand phenomena such as the first flush effect. Most, if not all, necessitate calibration and validation to local data available before deemed to be suitable for application in local catchment conditions.

In view of the increasing popularity of designing urban stormwater systems using the WSUD approach, it is essential to adopt a modelling approach that would differentiate the various sources of pollutants such as roofs, roads and other effective impervious areas. Since the build-up and washoff processes are distinct from different parts of the catchment, i.e. between roofs and roads, and the transportation pathway may differ slightly, there exists a need to further refined the model so as to account for these disparities and at the same time, improve on the accuracy of the water quality modelling results. Current models are considered to be not up to the task yet as many of the existing models are neither capable of differentiating the sources of these constituents nor able to accurately and reliably reproduce the observed pollutographs. Hence, further research and investigation in this area should be prompted, and more distributed and process-based models ought to be introduced, which will be accompanied by ample water quantity and quality data to confirm the validity of the developed model.

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APPENDIX

1	Model	**AUSQUAL**
	Version	N/A
	Developer	Gamtron Pty Ltd
	Manual	Gamtron (1990)
	Language	BASIC
	Availability	Commercial
		Executable form only
	Water Quantity	Time-area model based on runoff coefficient
		Apply time lag for routing
	Water Quality	Unit area loadings derived from export coefficients and point source emissions
		Based on land use
2	Model	**HSPF**
	Version	12
	Developer	USEPA
	Manual	Bicknell *et al.* (2001)
	Language	FORTRAN
	Availability	Public domain, downloadable from USEPA website
		Source code available
		Incorporated in BASINS
	Water Quantity	Using Chezy-Manning equation and empirical expression that relates outflow depth to detention storage
		Overland flow treated as a turbulent flow process
		Completely mixed reactors for transportation and receiving water components
		Storage routing or kinematic wave techniques
	Water Quality	Detachment or attachment of sediment from the soil matrix and transportation by overland flow
		Quality constituents simulated by association with sediment removal (use of a potency factor) or as a function of the water flow
		Simulate advection, adsorption/desorption, decay, deposition/scour

3	Model	**InfoWorks CS**
	Version	6.5
	Developer	Wallingford Software Ltd
	Manual	Wallingford Software Ltd (2005)
	Language	C++ and FORTRAN
	Availability	Commercial Executable form only
	Water Quantity	Single linear reservoir routing technique (Desbordes, SPRINT), double linear reservoir (Wallingford, Large Contributing Area), SWMM model New U.K. PR model, Wallingford Procedure model, U.S. SCS model to predict flow volumes instead of runoff rates Muskingum–Cunge method and shallow water wave equations for routing flows Pressurised pipes modelled with St. Venant equations using a Preissmann slot or with the local acceleration term neglected
	Water Quality	Simulate dissolved pollutant or pollutant attached to sediment using a potency factor Washoff Model used to simulate sediments and attached pollutants build-up during dry weather periods and washoff during rainfall Gully Pot Model used to simulate dissolved pollutants build-up in gully pots and washoff during rainfall Sediment erosion rate simulated using the Desbordes model or other hydraulic runoff models Network model and Conduit model used in the transportation module Advection equation solved in each conduit via the Holly-Preissmann scheme
4	Model	**MOUSE**
	Version	2005
	Developer	DHI Water and Environment
	Manual	DHI Water and Environment (2004)
	Language	DELPHI, FORTRAN and C++
	Availability	Commercial Executable form only
	Water Quantity	Time-area method, non-linear reservoir method, linear reservoir method (Dutch, French), unit hydrograph model Hydrodynamic Pipe Flow model to solve the St. Venant equations Using dynamic wave, diffusive wave and kinematic wave approximation
	Water Quality	Utilizing an add-on water quality module known as MOUSE TRAP Surface Runoff Quality (SRQ) module simulates build-up and washoff of sediments and attached pollutants, and build-up and washout of dissolved pollutants in gully pots Pipe Sediment Transport (ST) module for simulating pipe sediment transport including deposition and erosion Advection-Dispersion (AD) module to simulate transport of dissolved substances and suspended fine sediments in pipe flow Pipe Water Quality (WQ) module deals with the simultaneous transformation of the biological constituents and chemical compounds

5	Model	**MUSIC**
	Version	3
	Developer	CRCCH
	Manual	MUSIC Development Team (2005)
	Language	FORTRAN and DELPHI
	Availability	Commercial
		Executable form only
	Water Quantity	Based on urban runoff model by Chiew and McMahon (1997), allowing disaggregation of daily runoff into sub-daily temporal patterns
		Use of an impervious area and two soil moisture storages
		Muskingum-Cunge method for stream routing
	Water Quality	Using event mean concentrations from the study by Duncan (1999)
		Pollutant generation rates determined via statistical analysis from the same study
		Routing of contaminants based on the continuity of mass equation
		Universal Stormwater Treatment Model (USTM) to evaluate performance of stormwater treatment devices

6	Model	**STORM**
	Version	N/A
	Developer	Hydrologic Engineering Center of the U.S. Army Corps of Engineers
	Manual	Hydrologic Engineering Center (1977)
	Language	FORTRAN
	Availability	Commercial
		Executable form only
		No longer available, variants include XP-STORM, MIKE STORM
	Water Quantity	Runoff quantity estimation via the coefficient method, U.S. Soil Conservation Service Curve Number technique, and combination of both
		Soil Conservation Service triangular unit hydrograph method can also be employed to perform runoff routing
	Water Quality	Predicting both pollutants accumulation and washoff
		Accumulation process described using dust and dirt method and daily pollutant accumulation method
		Pollutants washoff simulated using a decay function and rate is proportional to the amount of pollutant remaining
		Land surface erosion modelled using Universal Soil Loss Equation (USLE)

7	Model	**SWMM**
	Version	4.4h, 5
	Developer	USEPA
	Manual	Rossman (2005)
	Language	FORTRAN (4.4h) and C (5)
	Availability	Public domain, downloadable from website Source code available Variants include XP-SWMM, MIKE SWMM
	Water Quantity	Simple non-linear reservoir storage to simulate rainfall-runoff processes Overland flow hydrographs generated using Manning's equation and lumped continuity equation Flow routing options include steady wave, kinematic wave and dynamic wave routing
	Water Quality	Computed using build-up and washoff process, rating curve washoff or event mean concentration method Pollutant build-up and washoff based on land use Pollutant loads are routed through drainage system using modified kinematic wave approximation and assuming complete mixing Soil erosion modelled using Universal Soil Loss Equation (USLE)
8	Model	**XP-AQUALM**
	Version	N/A
	Developer	XP Software Pty Ltd
	Manual	www.xpsoftware.com
	Language	C++, .NET and FORTRAN
	Availability	Commercial Executable form only
	Water Quantity	Continuous daily runoff model based on a water balance description Predicts runoff from rainfall based on an accounting of interception, evapotranspiration, surface and soil moisture storages No transportation component
	Water Quality	A power relationship between the pollutant mass per unit area exported and the daily runoff Or event mean concentration method, coefficients and loading rates obtained by transposition from similar catchments or recorded events Conceptual transport component based on steady state assumption, inclusive of decay of pollutant constituents to account for losses