STUDIES ON SEWER FLOW SYNTHESIS WITH SPECIAL ATTENTION TO STORM OVERFLOWS

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ABSTRACT

A model is developed, using a unit hydrograph approach for sewer flow synthesis and a simple mixing model to calculate the pollution load from combined sewer overflows, to simulate the long-term behaviour of storm overflows in combined sewerage systems. It is shown that this procedure synthesizes overflow operation characteristics to acceptable engineering accuracy, measured relative to the adopted standard for UK practice, namely predictions from the WALLRUS suite of engineer's software. This is achieved at only a small fraction of the computer run-time and so makes practicable a wide range of overflow performance and river impact studies using local rainfall records of unlimited extent. The model is applied successfully to three drainage networks. Results show that the model,COSSOM, achieves predictions with respect to runoff volume and overflow characteristics well within ±10 % of full WALLRUS applications.

Sensitivity studies demonstrate that performance of the model improves when catchment unit hydrographs are obtained, by preliminary application of WALLRUS using a rainfall intensity close to the maximum in the observed data and for rain duration close to the time of concentration of each sub-catchment under study. It is also shown that with little loss in accuracy relative to application of the WALLRUS approach for unit hydrograph development, COSSOM can be operated with other rainfall/runoff/pipeflow models.

CONTENTS

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NOTATIONS

A	Cross sectional area of the chamber
B	Surface width
C	Dimensionless runoff coefficient
I	Average rainfall intensity in mm/hr
L	Length
Q_{in}	Total discharge into the manhole
Q_{out}	Outflow from the manhole.
Q	Discharge
Q_p	Peak discharge
Q_{up}	Upstream discharges
Q_{dn}	Downstream discharges
Q_i	Inflow
Q_{con}	Continuation flow
R	Hydraulic radius
V	Chamber storage capacity
d	Pipe diameter
K_m	Loss coefficient for manholes
S	Reservoir storage
F_0	Froude number
S_0	Bottom slope
K_s	Roughness height
L_0	Length of overland flow plane
Y	Water level in the chamber
Q_o	Overflow discharge
$C_c(t)$	Flow of the pollutant at time t after the rain started
C_w	Concentration of the substance in the dry weather flow
Q_w	Dry weather flow
C_r	Concentration of the substance in the rain water runoff
$Q_r(t)$	Rainwater runoff at time t after rain start
$C_p(t)$	Concentration of the substance in the pass forward flow
$Q_p(t)$	Pass forward flow at time t after rain start

$P_o(t)$	Pollutant discharged through the overflow
$Q_o(t)$	Rate of overspill at time t after rain start
t_c	Time of concentration
c	Kinematic wave celerity
q_L	Lateral inflow
x	Spatial variable
i	Effective rainfall intensity
d_0	Normal depth
Δt	Time increment
q	Discharge per unit area
ω	Kinematic wave speed
g	Acceleration due to gravity
s	Hydraulic gradient.
Δh	Difference between the levels in the upstream and downstream manholes
λ	Darcy-Weisbach friction coefficient
DWF	Dry Weather Flow
UPM	Urban Pollution Management
f.c.f	free flow capacity
BOD	Biochemical Oxygen Demand
TSS	Total Suspended Solids
NH4-N	Ammoniacal Nitrogen
UCWI	Urban Catchment Wetness Index
SSD	Sewerage System Data

CHAPTER 1 INTRODUCTION

1.1 General Introduction

The primary reason for the development of sewer systems was to carry wastewater and the pollution associated with it away from cities. With the success of this came the possibility to drain the cities and avoid flooding during rain. Urban drainage systems were built for this purpose.

These systems may be broadly classified as 'separate' or 'combined'. The separate sewer systems consist of two networks, one for wastewater and the other for storm runoff. The foul sewers carry wastewater to treatment works while storm sewers convey surface runoff and generally discharge it to receiving waters without treatment.

Combined sewer systems are those in which sanitary sewage and stormwater are collected and disposed of through common sewers. In the past combined systems have been widely constructed because of economical reasons. In combined sewer systems, however, when it rains, the flows generated are very much greater than wastewater discharges and it is often impractical to carry such large flows to the treatment works. Therefore, part of the mixed sewage is sometimes directly discharged into receiving waters through overflow structures without treatment.

The problems associated with overflows in urban drainage networks which normally occur in densely urbanised areas of larger towns and cities are well recognised. These include pollution of receiving waters and may cause flooding or bank erosion in receiving rivers. Therefore, overflows from combined sewer systems must be limited to an acceptable value which depends on the receiving water in question.

Due to variability of rainfall and therefore, the quantitative and the qualitative overflow parameters, it is essential to be able to simulate the response of the sewer system to rainfall during quite a long period of time, otherwise the overflow parameters cannot be determined accurately. To achieve this objective with limited resources, application of complex sewer flow synthesis models is prohibitive for practical applications in many cases, simplifications are needed in the treatment of the flow process. A simple mathematical model is needed to enable synthesis of the pollution flow and their impact on receiving waters.

1.2 Aims and Objectives of the Research

This study has the aim to replace the detailed hydraulic models such as WASSP/WALLRUS (U.K.), MOUSE (Denmark), SWMM (U.S.A) etc., which deal with a number of problems involved in design and operation of sewer systems (and make great computational demands), by a simple and less time consuming model that can specifically deal with storm overflow operation and its impact on receiving water bodies.

To determine the overflow characteristics in a combined sewer systems a flow synthesis model has been developed which is based on unit hydrograph (TUH) approach for runoff simulation and a simple mixing model for pollution simulation. The sewer system is divided into a number of subsystems, each of them is characterized by its drainage area, unit hydrograph, dry weather flow, overflow storage volume and throughflow capacity, connection to other subsystems and mean event concentration of different pollution in rain water as well in dry weather flow. The rainfall data is fed to each subsystem to calculate runoff hydrograph at the downstream end and the continuity equation is used to calculate the overflow characteristics in terms of volume, duration, frequency and pollution load discharged.

On the basis of this synthesis, the information relating to overspill can be analyzed statistically or it can be used to appraise the benefits of increase in storage provision or throughflow setting.

The new model COSSOM is an extention and enhancement of the existing model 'FLOW 46'. The existing model deals with a single overflow structure in a catchment while COSSOM can calculate overflow characteristics at various locations and can also synthesise flows at selected sites in a catchment where overflow structures do not exist. The enhanced model can also be used to calculate pollution loads discharged from each CSO but only as simple mixing model. For one year rainfall data COSSOM synthesizes overflow operation characteristics to acceptable engineering accuracy, measured relative to WALLRUS for a sewerage network of 316 pipes within 1.3 hours (1 hr. set up time and 20 min. computational time) whereas full WALLRUS application requires 49 hours computational time.

As mentioned above, the model uses the unit hydrograph (TUH) approach to synthesize rainfall-runoff relationships. Therefore the sensitivity of the model with respect to the duration, T, of incremental rainfall, consideration of initial losses and the intensity of rainfall used to calculate the TUH, has been investigated.

1.3 Research Presentation

A review of rainfall-runoff modelling is presented in chapter 2. Mathematical models to calculate runoff from urban catchments and surface and below ground sewer routing has also been presented.

In chapter 3, Important urban drainage simulation models have been discussed.

Chapter 4 provides an introduction to storm water overflows and water quality problems associated with CSOs. Urban Pollution Management (UPM) approach and simplified quality modelling technique has also been discussed.

The basic methodology of building a long-term simulation model (COSSOM) is given in chapter 5, together with the description of computer programme developed.

In chapter 6 sensitivity of the model to the application of different rainfall intensities and durations when generating the unit hydrographs has been discussed.

The results of the model are presented and discussed in chapter 7. These results are based on three urban drainage networks and rain hyetographs selected from different rainfall time series. It also includes the comparison of these results with WALLRUS outputs as well as some observed data.

Chapter 8 gives the concluding remarks and some recommendations and suggestions for further work are made in chapter 9.

Tables and figures are provided at the end of each chapter. Drainage network data files are given in Appendix A, the Computer programme (COSSOM) listing is provided in Appendix B and User guide is given in Appendix C

CHAPTER 2 REVIEW OF STUDIES IN RAINFALL-RUNOFF MODELLING

2.1 Introduction

Throughout history, there have been periods when populations have tended to congregate together in towns and cities. Two great empires existed around two thousand years ago, one in the west the Roman Empire and the other in China. There is some evidence that, with the development of these cities, admirable drainage systems were built. How these systems were engineered is a subject of further research.

The industrial revolution and associated urbanisation initiated the modern urban storm drainage technology. The first step in the evolution of urban storm drainage technology was the systematic quantification of the drainage size to the area and location of the drains. This phase started around 1850. Typical example is the drainage tables for sewer sizes and slopes prepared by a London surveyor, John Roe in 1852 (Chow, 1962).

The second step of the advancement is the separate quantitative consideration of how much storm water should be drained and how to drain it. This phase started in the later half of the nineteenth century and lasted for almost one hundred years. Well known examples include the application of rational formula by Emil Kuichling (1889) during the period from 1877 to 1889 for sewer peak flow in Rochester, New York.

During the past one hundred years considerable efforts have been made on the techniques to determine a peak discharge for sizing the sewers, street gutters and other auxiliaries, i.e. a mere water quantity problem. The basic idea is that once a drain is sized to handle a design rain storm it will be able to handle all the smaller rain storms. Before the slowly growing science of urban drainage based on structural approach had a chance to mature, the scope of urban drainage was significantly expanded. With the Post-World War II rapid expansion of municipalities and industrial infrastructure, urban drainage is no longer just a water quantity problem. Water quality concerns are equally important. All rainfalls, large or small, contribute to urban runoff pollution.

The third step of advancement in urban storm drainage is the consideration of storm water quality in addition to its quantity. This phase started about mid-1960's. The nature of the problem changed from simply draining the water to how to dispose of it properly. Determination of a peak discharge from a design storm as in the traditional case of sizing sewer pipes no longer suffices.

Furthermore, in many municipalities, existing drainage facilities become inadequate because of the deterioration of the drains or urban expansion. Instead of building new sewers, detention or retention facilities offer possible remedies. Such alternatives require hydrologic information more than the design peak discharge. Quantitative knowledge of runoff volume and its distribution over time, i.e. the runoff hydrograph is required for the total management of drainage system.

A number of mathematical models have been developed for the calculation of runoff from urban catchments. These methods may be classified into those which provide the peak discharge only like rational method and those which also give the variation of discharge with time (runoff hydrograph) like the unit hydrograph method and kinematic wave approach. These methods are described in detail in the following sections.

2.2 Precipitation

During the nineteenth century, information on heavy rainfalls in short periods in the British Isles was collected by the British Rainfall Organisation, a group of volunteers and published by their founder, G.J. Symons, in an annual publication entitled British Rainfall. The British Rainfall Organisation published their first table of heavy rainfalls in short periods in 1888. These data, which were classified as either 'noteworthy' or 'exceptional', may be regarded as one of the first attempts to compile a rainfall depth-duration-frequency (DDF) relationship. With the introduction of autographic rainfall records during the 1920s, more reliable data began to be acquired and more statistical analyses permitted a more precise definition of DDF relationship. It has been thoroughly investigated by researchers, including Bilham (1935), Norris (1948), Rodda (1966), Folland et al. (1981), Arnell et al. (1984).

2.2.1 Rainfall Depth-Duration-Frequency Relationships

The relationships discussed here are statistical abstractions of point rainfall, i.e. precipitation as observed at a single raingage. These data are sufficient to allow the following generalisation to be made about the characteristics of storm rainfall.

1) As storm duration increases, the average rainfall intensity decreases for any given frequency of occurrence; and
2) As the frequency of occurrence decreases, the average rainfall intensity increases for any given duration

A study of the frequency of short-period continuous rainfall was conducted by Bilham (1935) and revised by Meteorological Office in 1962. Bilham assembled 10 years of autographic data from 12 sites representative of Midland and South-east of England with average annual rainfall under 35 inches and derived the following rainfall depth-duration-frequency relationship:

$$N = 1.25 * t\ (R+0.1)^{-3.55} \tag{2.1}$$

N is the number of occasions in 10 years in which the rain depth R mm is recorded within a duration t hours. The equation 2.1 was intended to be used for the durations between 5 and 120 minutes.

With the availability of more records of short duration rainfall, the Bilham's formula was modified by Holland (1964). This formula has received some criticism because no allowance was made for variations in the relation with geological location. It has been superseded by the recommendations made in the Flood Studies Report (NERC, 1975). This report provides the information on the variation of storm rainfall over areas of different sizes, and on the construction of storm profiles.

For the places without adequate rainfall records, Bell (1969) has derived very useful generalized depth-duration-frequency relationships by considering the data from U.S.A, former USSR and Australia. These analyses are confined to the rainfalls of up to 2 hours duration, since he assumes that intense rainfalls are most often of short duration.

2.2.2 Storm Profile

Storm profile is a distribution of rain intensity during the rainfall period. Initially the rainfall profiles were derived from the work of Bilham (1935) and published by the Road Research Laboratory (HMSO, 1963). These profiles vary only for return period and have a duration of 120 min (Price et al. 1978). With the publication of Flood Studies Report (NERC, 1975), it became possible to derive the profiles which vary for duration, location, peakedness, catchment area as well as return period. In Flood Studies Report (FSR) summer and winter storm profiles have been discussed separately.

The peakedness is the ratio of maximum to mean rainfall intensity. The distribution of 'percentile peakedness', i.e. the percentage of storms with a peakedness less than or equal to that of a given profile. Research has shown that percentile peakedness is an important parameter, and the variation in this parameter can cause significant variations in maximum flow. The 50 percent summer profile of such a duration that gives the peak flow is recommended for storm sewer design (HRS, 1981).

2.2.3 Annual Time Series Rainfall

Although design storms are still appropriate for design of drainage systems as well as for examination of existing systems, in terms of their surcharge or flooding performance, there are concerns and limitations over the use of these storms for water quality investigations. The Time Series Rainfall (TSR) was developed to address some of these limitations.

TSR is a sequence of historical rainfall events statistically representative of the precipitation patterns for a given location. Where the sequence is of one year duration it may be termed as annual Time Series Rainfall. The procedure for the development of these series involved the statistical analyses of long rainfall record from a range of sites within the UK.

Initially the total rainfall depths for each month of the record and the mean value for each of the 12 months of the year was calculated. Then with in every month the distribution of rainfall event by depth and duration was characterised. The selection of the 12 representative months was then made on the basis of monthly rainfall total, event duration/depth characteristics and inter event dry period characteristics. These selected months were then concatenated to form the annual series. This is more fully explained by Henderson (1986).

The annual Time Series Rainfall data is available in three forms:

1) chronological
2) ranked (by severity) over the full year and
3) ranked seasonal series (summer and winter)

The main applications of the annual TSR are in the areas of sewer quality modelling, overflow analysis, detention tank design and general analysis of the hydraulic performance of existing sewerage systems. The major drawbacks to these series are that the regionalisation procedure is relatively crude and the series do not contain very extreme events. (Cowpertwait et al. 1991).

2.2.4 Historical Rainfall Data

Design storms and annual Time Series Rainfall are the results of some statistical manipulation of the original rainfall data. This has been necessary to make the rainfall data accessible to the user. However, this statistical analysis has limited the use of these data. Many of these limitations can be overcome by working directly from long local historical rainfall records. Until recently, this option has not been possible because of lack of suitable long rainfall record or lack of processing software to handle the data. This problem has now been addressed to a large extent by the STORMPAC rainfall processing package (WRc, 1994). Continuous simulation of these records may prove expensive when sophisticated models are used. So for practical reasons gross simplifications in modelling are required.

2.3 Rainfall-Runoff Relationships

The derivation of relationships between the rainfall over a catchment area and resulting runoff is a complicated process. Runoff is a function of rainfall intensity, the storm duration, area of catchment, the infiltration capacity of the soil, the type of vegetation, distribution of storm with respect to time and space and several other factors. Because of these variables which are included in a completely deterministic runoff model, it is difficult to predict the rainfall-runoff relationship with certainty.

Figure 2.1 illustrates diagrammatically the various components of a catchment. Conceptually and qualitatively this system and its components processes may be described easily. However the development of an accurate mathematical model is complicated. The hydrological system is nonlinear, as was pointed out by Amorocho (1967) and Prasad (1967).

To overcome these problems some assumptions are needed and Dooge (1968) reported that if no assumptions are made about the nature of the system, then the problem of prediction is virtually insoluble. The more assumptions that are made about the system, the easier becomes the solution of the problem, but the greater the risk of the failure of the model system to accurately reflect the prototype.

There are numerous watershed models in use today. Some, if not all, make the assumptions like time invariance, linearity of the hydrologic subsystems and application of parameters, i.e assuming that parameter for rainfall, infiltration, interflow etc., is representation of an 'average' or net effect of the respective process over the entire catchment (Huggins and Monke, 1968).

There are few widely used methods relating rainfall to runoff. These methods have been derived by engineers for immediate practical use.

2.3.1 Rational Method

The rational method was introduced by Kuichling (1889) and has become the most widely used method for estimating peak runoff rates (for areas less than five square miles) in the design of urban drainage systems (Shaake et al. 1967) and is the following:

$$Q_p = \frac{1}{360} CIA \tag{2.2}$$

Where Q_p is peak discharge in m^3/sec., C is dimensionless runoff coefficient, I is average rainfall intensity in mm/hr for a duration equal to time of concentration t_c and A is area of the catchment in hectares (hac). t_c is the time taken by the runoff from the farthest point of the catchment to reach the point of interest.

The use of this formula is sometimes referred to as the Lloyd-Davies method because it was applied also to the sewer design calculations in England by Lloyd-Davies (1906). The rationale for the method lies in the concept that a steady and uniform rainfall intensity will produce maximum runoff when all parts of the catchment are contributing to the point of interest. This condition is fulfilled when the elapsed time is equal to the time of concentration t_c of the catchment.

In recent times, the rational method has been questioned. Shaake et al. (1967) tested the implicit assumption in the rational method that the frequency of peak runoff rate is the same as the frequency of design rainfall intensity. They studied sewer and inlet gauge data from 20 areas, ranging in size from 0.2 hac. to 150 hac. and concluded that the above assumption is approximately correct. They cautioned, however, that without further verification this conclusion should not be considered universally applicable.

Despite the simplicity of the rational method and its popularity, wide differences are found between discharges computed by different users (Ardis et al. 1969; McCuen et al. 1984). The source of these differences is believed to lie in the diversity of the methods for determination of the parameters C and t_c (McCuen et al. 1984).

2.3.2 Time-Area Method

This method is merely an extension of the rational method. The peak discharge Q_p is the sum of flow contribution from subdivisions of the catchment defined by time contours. These time contours are called isochrones and are lines of equal time-flow to the outfall where peak discharge is required. The flow from each subdivision is obtained from the product of the area ΔA and mean intensity of effective rainfall (i). Therefore Q_t , the flow at outfall at time t is given by

$$Q_t = \sum_{k=1}^{t} i_{(t-k)} \, \Delta A_{(k)} \tag{2.3}$$

To calculate the peak flow Q_p it is assumed that the whole catchment is contributing to the flow when t is equal to time of concentration (t_c) therefore

$$Q_p = \sum_{k=1}^{n} i_{(n-k)} \, \Delta A_{(k)} \tag{2.4}$$

Where n is the number of incremental areas between successive isochrones, and is given by $t_c/\Delta t$, and k is the counter. This method can be generalized by making the time increment Δt very small, and considering increases in the contributing area to be continuous with increasing time.

2.3.3 Unit Hydrograph Method

The unit hydrograph method was developed by Sherman in 1932. The general theory of unit hydrograph method is that at a given point in a catchment the base of the hydrograph of direct runoff from a storm of 'unit duration' is constant, regardless of the volume of runoff, while the ordinates of the hydrograph vary directly as the runoff. A unit hydrograph can, therefore, be the discharge hydrograph resulting from 'effective' rainfall falling uniformly over the area, at a uniform rate, and in a specified unit period of time. The effective rainfall is the rain remaining as runoff after all losses by infiltration, depression storage and interception have been allowed for. The magnitude of unit time depends on the size of the catchment and the response time.

The principles of the unit hydrographs forwarded by Sherman (1932) to convert rainfall excess or effective rainfall to a storm hydrograph are

1) Linear proportionality of the ordinates of the hydrograph to the depths of rainfall excess.
2) Equal time bases of hydrographs for equal durations of rainfall excess.
3) Superposition of hydrographs of incremental runoff to produce a storm hydrograph.
4) Time invariance of the rainfall-surface runoff relationship

In practice, a T hour unit hydrograph (TUH) is a hydrograph resulting from a unit depth of effective rainfall falling in T hr. over the catchment. The standard depth of effective rainfall was taken by Sherman to be 1 inch, but with metrication, 1 mm or sometimes 1 cm is used.

Figure 2.2 demonstrates the principles mentioned earlier. The hydrograph in fig. 2.2(a) is generated by 1 mm of rainfall excess falling in a unit of time T; fig. 2.2(b) shows a 2 mm rainfall having the same duration as fig. 2.2(a). This hydrograph demonstrates the principles 1 and 2. Fig. 2.2(c) illustrates principle 3, that is, for two successive amounts of excess rainfall , R_1 and R_2 each falling in T hr., the surface runoff produced is the sum of the component hydrographs due to R_1 and R_2 separately.

Chui and Bittler (1969) suggested that rainfall excess (rainfall occurring after surface saturation has been accomplished) should be the input, instead of observed rainfall data, and that baseflow should be removed from total runoff in development of the unit hydrograph.

The application of the unit hydrograph method requires a storm which displays linear responses. Viessman et al. (1977) suggested that in deriving a unit hydrograph for a particular catchment, one must select storms which occur individually (simple storm structure) and have uniform spatial distribution. In relating the effective rainfall to surface runoff, the amount of effective rainfall depends on the condition of the catchment just before the storm.

2.3.4 Kinematic Wave Theory

The concept of kinematic wave is well established among the existing methods to solve one dimensional flow problems. It is derived from the one dimensional momentum and continuity equations (St. Venant Equations) by assuming that changes in flow conditions at all locations are occurring so slowly that velocities may be satisfactorily estimated using steady state criteria. This means that the momentum equation collapses to a simple friction relationship and changes in flow conditions are then determined by the continuity equation. In open-channel flow modelling kinematic wave arises when the governing equations are simplified by neglecting the local inertia, convective inertia, pressure gradient and momentum-source terms (Lighthill and Whitham 1955).

From the physical standpoint, the kinematic wave assumption amounts to a uniform flow formula (such as Manning's or Chezy's) for the equation of motion. In essence, it says that as far as momentum is concerned, the flow can be considered steady.

From the mathematical standpoint, the kinematic wave assumption results in a considerable simplification of the equation of motion, reducing it to a statement of uniform flow (such as, for instance, the Manning equation). Combining this latter equation with the equation of continuity gives rise to the first-order partial differential equation, referred to as the kinematic wave equation

$$\frac{\partial Q}{\partial t}+c\frac{\partial Q}{\partial x}=cq_L \tag{2.5}$$

In which Q is discharge; c is kinematic wave celerity; q_L is lateral inflow; x is a spatial variable; and t is a temporal variable. This equation is applicable to streamflow modelling as well as to channel and gutter flow. For overland flow application, the kinematic wave equation is expressed in terms of unit-width discharge as follows:

$$\frac{\partial q}{\partial t}+c\frac{\partial q}{\partial x}=ci \tag{2.6}$$

In which q is unit-width discharge; i is effective rainfall intensity; c is celerity; and x and t are spatial and temporal variables respectively.

These are first-order differential equations, therefore, they can only describe convection but not diffusion, which is a second-order process. In practice this means that the kinematic wave equation can describe the travel of a flood wave, but not its attenuation as it propagates downstream.

The question of applicability of kinematic wave approach has interested many researchers and practitioners. Notable among these is the contribution made by Woolhiser and Liggett (1967) in the field of overland flow. They identified a parameter k defined as

$$k=\frac{S_0L_0}{d_0F_0^2} \tag{2.7}$$

Where S_0 is bottom slope; L_0 is length of overland flow plane; d_0 is normal depth; and F_0 is Froude number based on normal flow. The parameter k has been referred to in the literature as kinematic flow number (Liggett 1975).

This theory now forms the basis for many modern computer methods for storm drainage analysis (Alley et al. 1980). In 1984, D.K. Brady published a Microcomputer Model for impervious Runoff based on the same theory. The errors involved in using kinematic wave routing computations were discussed by Hromadke et al. in 1988. Dawdy (1990) and Woolhiser et al. (1990) also contributed to above discussion giving some valuable points and highlighting the usefulness of kinematic wave routing in comparison to the other available methods.

2.4 Overland Surface Flow

The urban runoff process may be seen as a two-phase phenomenon, incorporating both above-ground and below ground phases. There is no clear-cut interface between the two. However, the above-ground phase is very often taken to include the conversion of the rainfall on an element of catchment into the contribution to runoff at the manhole in the sewer system where the manhole is the collection point for the given element of the catchment. This phase includes not only behaviour of the water whilst above ground but also the routing the flows through gully traps and pipe runs to the manhole in the sewer system. The above-ground phase deals with the conversion of the rainfall hyetograph into the inlet hydrograph of the sewer system proper. The above ground model is divided into three sections. i) depression storage, ii) runoff volume, and iii) surface routing.

The overland flow process has been studied by many researchers. Initially such efforts were directed toward laboratory experiments, the objective of which was to understand the hydraulics of the process. Such investigations include those by Izzard (1944,1946), Yu & McNown (1964), Yen & Chow (1969), Kidd & Helliwell (1977), and Akan & Yen (1984).

In this study, drainage systems are analysed by WALLRUS-SIM, and the following sections are based on the Wallingford procedure (HRS 1981).

2.4.1 Depression Storage

When rainfall intensity exceeds the infiltration rate of the soil, depressions begin to fill. The depression storage used in the Wallingford Procedure (HRS 1981) is related to slope using data from British and Swedish catchments as :

$$DEPSTOG=C*SLOPE^{0.84} \tag{2.8}$$

Where DEPSTOG is the average depth of depression storage in mm, SLOPE is the average overland slope of the catchment (percent) and C is constant. A typical value of C is 0.71. However it can be varied according to the catchment characteristics (Kidd 1978, Pratt & Henderson 1981). Normally, the storage is assumed to be identical for paved and pervious areas, whereas sloping roofs are taken as having a fixed value of 0.4 mm.

2.4.2 Runoff Volume

The runoff volume submodel is applied to the rainfall to obtain the correct volume of runoff. As a first approximation, the runoff is assumed to be 100 % from impervious and zero from pervious surfaces. Departure from this assumption is then modelled by a constant correction factor to the rainfall hyetograph over the paved surfaces. The nature of this departure is a complex function of a large number of storm and catchment variables and lends itself better to a statistical approach than a deterministic one. Such statistical analysis have previously been done by the Institute of Hydrology (Stoneham & Kidd 1977, Kidd & Lowing 1979).

The runoff volume is expressed as percentage of storm rainfall and its variability with storm and catchment characteristics is expressed by regression equation as ; (HRS 1981)

$$PR = 0.829\ PIMP + 25.0\ SOIL + 0.078\ UCWI - 20.7 \tag{2.9}$$

Where PR is percentage runoff, PIMP is percentage of catchment area covered by impervious surfaces, SOIL is soil index based on the Flood Studies Report (NERC

1975) and UCWI urban catchment wetness index.

The UCWI value represents the wetness of the catchment at the start of the storm event. As UCWI rises so the PR rises which reflects the increased runoff to be expected from a wetter catchment. During a storm event the catchment wetness will increase, however, the PR value is kept constant. The UCWI value to be used in design application of equation 2.9 is obtained from the graph included in Wallingford Procedure, the value to be used in simulating an observed rainstorm is calculated from antecedent rainfalls and soil moisture deficit data.

The PR value obtained by equation 2.9 is then distributed to the three surface types: pervious, paved and roofed. If PR is less than 70% of PIMP, it is assumed that the pervious areas do not contribute and that all the runoff arises from the impervious areas. However, if PR is greater than 0.7 times the PIMP, the excess runoff is assumed to arise from both the pervious and impervious (paved or roofed) areas in the ratio of 0.3 to 1.0. Hence :

$$PR_{pav} = 70 + \frac{(0.3\ PR\ -\ 0.7\ PIMP)}{1\ -\ (0.7\ PIMP/100)} \tag{2.10}$$

$$PR_{perv} = \frac{PR\ -\ 0.7\ PIMP}{1\ -\ (0.7\ PIMP/100)} \tag{2.11}$$

These equations produce values of PR_{perv} which vary significantly with PIMP and are zero (since negative values have no meaning) over a wide range of catchment properties. Equations 2.10 & 2.11 have been revised (Orman 1985) and the new relationships produce markedly lower values of percentage runoff from pervious areas.

2.4.3 Surface Routing

The surface routing submodel takes the adjusted rainfall hyetograph and routes it over the particular surface to give the inlet hydrograph to the sewer system. This is achieved by a lumped reservoir, given by:

continuity $$\frac{\partial S}{\partial t} = i - q \qquad (2.12)$$

dynamic $$S = K\, q^{n} \qquad (2.13)$$

Where S is the reservoir storage; q is discharge per unit area; i is excess rainfall; and k and n are the two parameters of the model.

The above equations may be derived from the St. Venant equations (Akan & Yen 1981) applied to the overland flow phenomenon. Equation 2.13 is derived by ignoring the dynamic wave terms in St. Venant dynamic equation (in effect, taking a steady uniform flow condition). This kinematic wave approximation has been shown (Muzik 1974) to be reasonable where lateral inflow predominates (Woolhiser & Ligget 1967) and applies satisfactorily for both overland and channel flow.

A fixed set of k values in equation 2.13 corresponding to three classes of slope and three different classes of area (per gully) are used in Wallingford procedure routing calculation. This yields a standard set of nine inlet hydrographs (plus one for all pitched roofs) which can be applied to the respective surface areas in each subcatchment.

2.4.4 Modification to the Runoff Model of Wallingford Procedure

The modifications made to the modelling of rainfall runoff processes of the Wallingford Procedure and incorporated in WALLRUS software are in the runoff volume model and the surface routing model.

The runoff volume derived for the Wallingford Procedure gave the total runoff volume in terms of the total rainfall depth. This then required an adjustment to deal with subtraction of initial losses from the start of the rainfall. These losses had to be added back to the runoff during the rest of the storm (Wallingford Software 1991). The revised model subtracts the initial losses from the rainfall before calculating the runoff volume to give a net rainfall hyetograph. The following equation is then used to give the runoff volume in terms of net rainfall

$$Runoff\ Volume \ = \ Net\ Rainfall \ * \ Total\ Catchment\ Area \ * \ \frac{PR}{100} \qquad (2.14)$$

The regression equation 2.9 is applied separately to the contributing area for each pipe rather than the catchment as a whole to determine the percentage runoff (PR).

The spatial distribution of runoff volume between pervious and impervious areas is ignored in the revised model because it is dealt with by calculating runoff separately for each contributing area.

The surface routing non-linear reservoir model has been replaced by a simple linear reservoir model of the form:

$$S \ = \ k\ q \qquad (2.15)$$

Where S is reservoir storage, q is the runoff and k is a constant. The value of k varies with the catchment slope, the size of each contributing area and rainfall intensity. The relationship for k is:

$$k \ = \ c\ i^{-0.39} \qquad (2.16)$$

Where i is the rainfall intensity, and c is given by a regression equation on catchment slope and the size of the contributing area.

2.5 Sewer Flow Routing

Flow in sewers is more amenable to a physically-based modelling approach than runoff from contributing areas because of the simpler geometry. However, complications can arise where backwater effects are significant or where surcharging occurs. If the backwater effects are small, such as is generally the case for catchments with slope greater 0.001, flow routing can be confined to discharge alone coupled with a measure of manhole water levels to determine surcharge flow (Price et al. 1978).

A number of models can be used to compute the propagation of discharge hydrograph along a sewer, such as the time off-set model which simply translates the hydrograph without any change in the shape, or a storage routing model such as Muskingum-Cunge (Cunge 1969).

2.5.1 Free Surface Flow Routing

Free surface flow is calculated using Muskingum-Cunge technique. It is defined by the equations;

$$\frac{dS}{dt} = Q_{up} - Q_{dn} \tag{2.17}$$

$$S = \frac{L}{\omega}[\varepsilon Q_{up} + (1-\varepsilon)Q_{dn}] \tag{2.18}$$

$$\varepsilon = \frac{1}{2}[1 - \frac{Q}{BsL\omega}] \tag{2.19}$$

Where L and s are the length and gradient respectively, Q_{up} and Q_{dn} are upstream and downstream discharges, Q, B and ω are discharge at normal depth (h), surface width and kinematic wave speed along the pipe respectively. A value of ω can be found from the equation

$$\omega = \frac{1}{B}\frac{dQ}{dh} \tag{2.20}$$

with Q defined by the normal depth relationship of the Colebrook-White equation;

$$Q = A(32gRs)^{\frac{1}{2}}\log_{10}(\frac{14.8R}{K_s}) \tag{2.21}$$

Where g is the acceleration due to gravity, R is the hydraulic radius, A is x-section area of the pipe, K_s is the roughness height and s is hydraulic gradient.

The Muskingum-Cunge method ignores backwater effects from the downstream water level. So this method is applied for the flows where the backwater effects are not important, i.e. where the gradient of the pipe is more than 1:1000. For pipes with a gradient flatter than 1:1000 the convection diffusion equation is often used to calculate surface backwater (Osborn 1991).

2.5.2 Pressurised Pipe Routing

An advantage of the Muskingum-Cunge routing technique is that it may be applied to each pipe separately and in sequence down a branch of the network and manhole storage may be ignored. However, when a pipe or group of pipes become surcharged i.e. when incoming flow is greater than the just-full pipe capacity, or tail water level imposes a backwater effect, any change in one part of the surcharged system is propagated instantaneously throughout the system. Therefore, a surcharged group of pipes cannot be solved simultaneously (Bettess et al. 1978).

The head loss, Δh, along a surcharged pipe has two components; the loss due to friction in the pipe and the losses at the upstream and downstream manholes. Assuming that the manhole losses are proportional to the velocity head in the pipe; (HRS 1981)

$$\Delta h = \left(\frac{L\lambda}{d}+K_m\right)\frac{V^2}{2g}+\frac{1}{g}\frac{\partial v}{\partial t} \tag{2.22}$$

where Δh is the difference between the levels in the upstream and downstream manholes of the pipe, V is the velocity of flow in the pipe, L and d are length and diameter of the pipe, K_m is the loss coefficient for manholes and λ is the Darcy-Weisbach friction coefficient. Time dependent storage, S, in a manhole, including the water stored on the surface above the manhole, is described by the continuity equation;

$$\frac{dS}{dt} = Q_{in} - Q_{out} \tag{2.23}$$

Where Q_{in} is total discharge into the manhole and Q_{out} is outflow from the manhole.

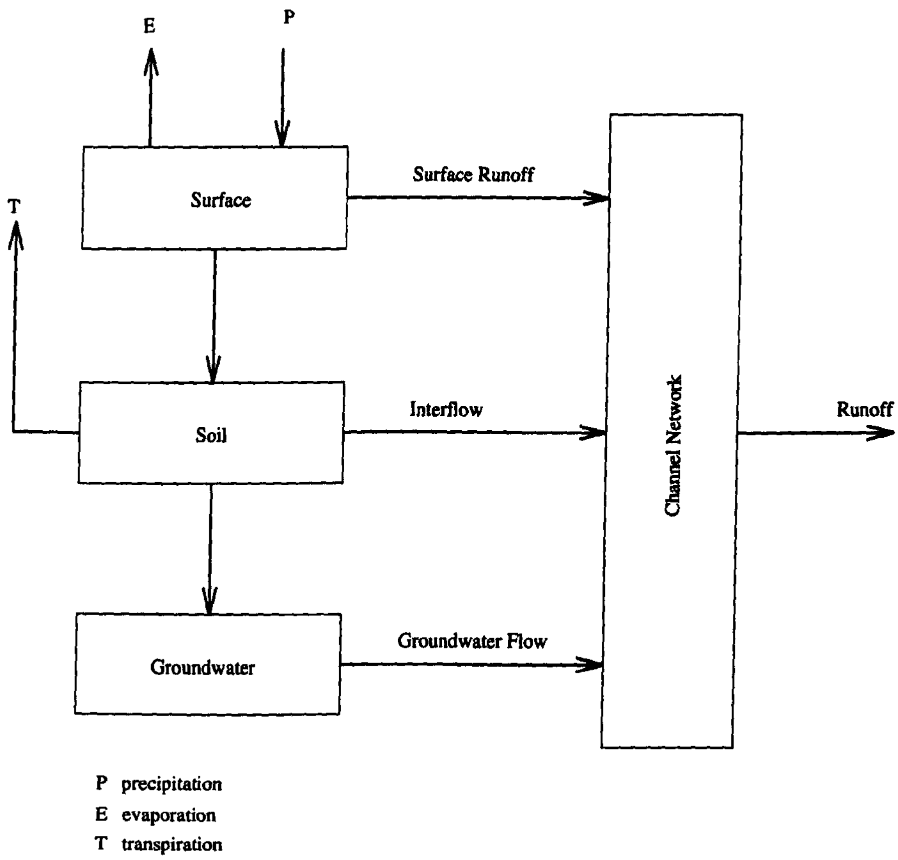


Figure 2.1 Catchment as a Closed System (Modified from Dooge (1981))

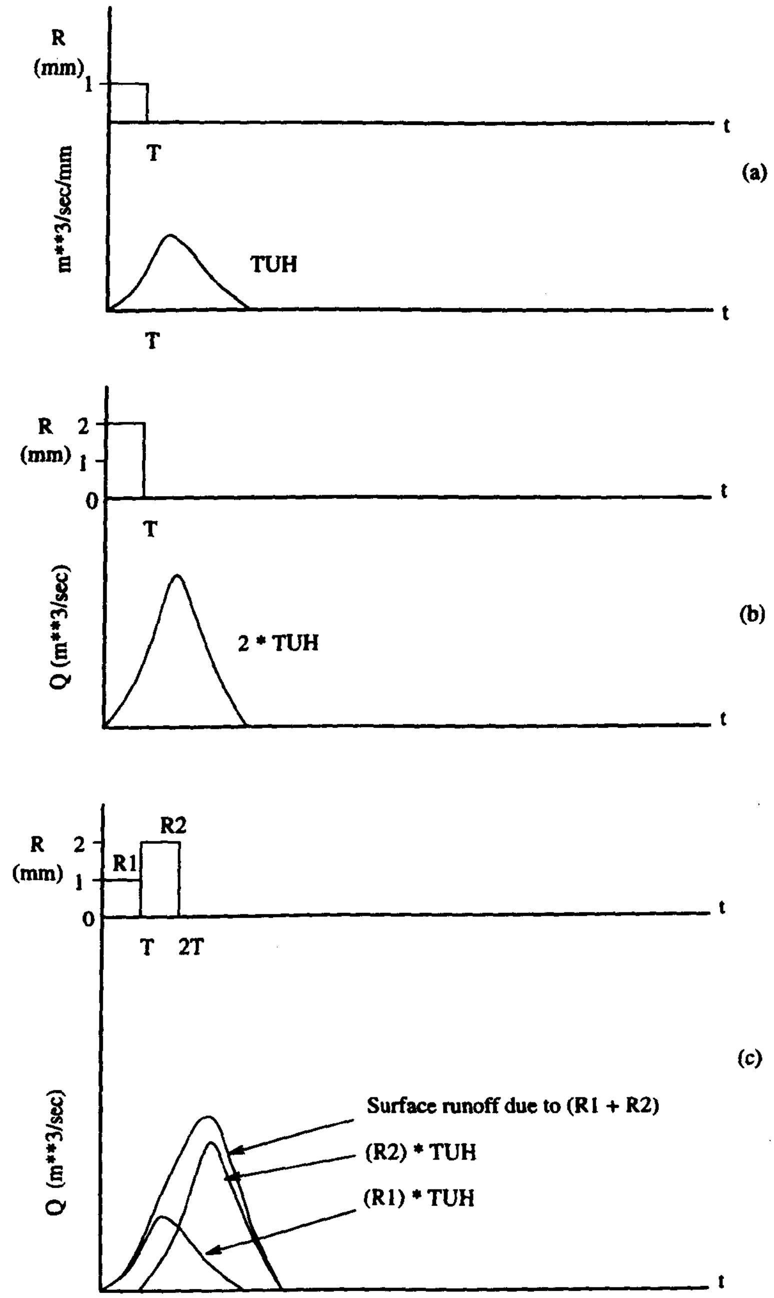


Figure 2.2 The Unit Hydrograph

CHAPTER 3 CONCEPTUAL MODELS OF URBAN CATCHMENTS

3.1 Introduction

When a catchment area is urbanised and the amount of impervious cover in the form of roofs, roads and pavements increases, the need inevitably arises for the natural drainage network to be supplemented or even replaced by man-made systems of pipes and paved gutters. The system of pipes or sewers generally assume a dendritic form in plan, similar to that of a network of natural channels. However, the hydrological design problems associated with sewerage, i.e. systems of sewers, differ from those concerned with channel works in that no measurement of surface water runoff are possible prior to construction. Design flood estimates for sewers must therefore be inferred from rainfall statistics using deterministic methods.

Sewerage systems, may be classified into three types,

(i) combined systems, in which both the stormwater drainage and the domestic wastes or sewage are conveyed in the same pipe network;

(ii) separate systems, in which the foul drainage is conveyed to the nearest treatment plant and the stormwater drainage is carried in its own system of sewers to the nearest watercourse; and

(iii) partially combined systems, in which some proportion of domestic sewage is carried by storm sewers

The problems of urban drainage design can range from the analysis of existing sewer networks to the design of entirely new systems, and the area served may vary in size from a small housing estate to a large conurbation. In order to cover the wide range of possibilities which occur, a design procedure incorporating a hierarchy of methods is required. There are many well-presented models and some of them are outlined in the following sections.

3.2 Transport and Road Research Laboratory Hydrograph Method (TRRL)

The TRRL method (Watkins 1962, 1970) is a conceptually simple model compared with other mathematical models, and has been used extensively as a design tool in Great Britain. Two main features of the model are that the areas which contribute storm runoff are taken to be only those impervious areas directly connected to the pipe system and these have a runoff coefficient of 100%. The former assumption has attracted most criticism of the model (Jones 1970, Linsley 1970, Snyder 1970).

Overland flow on these contributing areas is simulated by combining the rainfall hyetograph and a time versus contributing area diagram (time-area routing) to give an inflow hydrograph to the pipe under consideration. The TRRL method computer program supplied by the Transport and Road Research Laboratory assumes a linear time versus contributing area diagram for each inlet. The whole area contributes after the time of entry plus the time of travel at full-bore flow as calculated by the Colebrook-White formula. The time of entry at inlet is the time required for all the directly connected impervious area to contribute to runoff. It is assumed constant for any inlet and must be estimated externally and included as part of the input data.

The unique feature at the time of development of the TRRL method was its ability to design pipe diameters to avoid surcharging. This is carried out by successively increasing the pipe diameter and repeating the calculations until the peak of the outflow hydrograph (after storage routing) does not exceed the capacity of the pipe.

3.3 Illinois Urban Drainage Area Simulator (ILLUDAS)

Illinois Urban Drainage Area Simulator (ILLUDAS) is a single-event urban runoff model based on the TRRL method. ILLUDAS was developed by Terstriep and Stall in 1974. It differs from TRRL model, however, in that it computes runoff from pervious areas in addition to that from impervious areas.

Surface runoff hydrographs are computed for each specified subcatchment. These runoff hydrographs are then accumulated and routed downstream to the outlet. The pipe routing method is based on kinematic wave theory. Storage may be specified as a detention at any point, in which case the decrease in peak discharge will be reported, or alternatively a limiting discharge rate may be specified, in which case the required storage volume will be reported.

When the incoming flow is greater than the full-bore capacity, water accumulates in the upstream manhole until the incoming discharge has decreased below the capacity. ILLUDAS is relatively easy to use and is well documented.

3.4 Storm Water Management Model (SWMM)

Storm Water Management Model (SWMM) is a comprehensive model which was developed by a consortium of engineers for the US Environmental Protection Agency in 1971. It takes the rainfall data and catchment characteristics, determines the quantity and quality of runoff, routes the runoff through the sewer system and identifies the effluent impact on receiving waters. Thus it is a mathematical model capable of representing runoff quantity, quality, its treatment and impact on receiving waters (Torno 1975). The model is structured in four main computational blocks controlled by a fifth group of executive routines.

The RUNOFF block is concerned with the derivation of runoff hydrographs and their associated pollutant loadings for each specified subcatchment. Each subcatchment is characterized by its size, imperviousness, slope, infiltration potential, depression storage, and several factors relating to the accumulation of surface pollutants. Land use and other surface features are needed for quantifying pollution. For each time interval, a sequential computation is made of rainfall, infiltration, depression storage, net rainfall excess, and outflow rate according Manning's equation and the continuity equation.The hydrological model contained in the RUNOFF block was described by Chen and Shubinski (1971).

The TRANSPORT block accepts as input a geometric description of the sewer system and it combines and routes the various subcatchment hydrographs and pollutographs (time variations of individual pollutants) to the outlet. The routing of hydrographs is achieved by using kinematic wave approach. The water quality models incorporated into the model have been described by Lager et al. (1971) and are considered more fully by Jacobsen (1983) and Hall (1984).

The STORAGE block simulates the effect of any storage or treatment facility on the runoff hydrograph. This block can also calculate costs of selected treatment processes.

The EXTRAN block simulates the sediment build-up and subsequent erosion and calculates the pollution loads discharged.

The RECEIVING WATER block receives the output from TRANSPORT and STORAGE blocks and computes the effect on river or lake. Water level and pollutant concentration variations are solved using the equations of continuity, motion and conservation of mass.

The program does not simulate pressurised flow conditions, flows in excess of full capacity are assumed to be stored at the upstream manhole until conditions permit the accommodation of the volume stored. Only dendritic systems are considered and looped networks cannot be simulated.

3.5 Wallingford Procedure Storm Simulation Package (WALLRUS)

The Wallingford Procedure is an integrated approach to the design and analysis of urban storm drainage network. It is based upon the results of a research program carried out in the United Kingdom between 1974 and 1981 by the Hydraulic Research Station, the Institute of Hydrology and the Meterological Office. The work was coordinated by the National Water Council and the Department of the Environment and was monitored by the Working Party on the Hydraulic Design of Storm Sewers. The procedure was implemented by a package of computer based methods, WASSP, consisting of a Rational Design Method, a Hydrograph Design Method, an Optimising Method and a Simulation Method. This package was released in 1981. WASSP was transformed into a suite of programs for microcomputers and has subsequently been upgraded to WALLRUS. The new package WALLRUS has the following principal modules;

The MicroRAT Design Method is intended for use to design pipe or channel sizes and gradient using a modified rational method. Gradients are designed to give adequate self cleansing velocities at dry weather or storm flows. Sizes are designed to take the peak flows. The system may include overflow structures and detention storage. This is the simplest method in the package.

The Hydrograph Design Method determines the pipes or channel sizes for observed or synthetic rainfall events in a network with defined layout and levels. This method uses the linear reservoir model for overland flow and Muskingum-Cunge technique for pipe routing. The network may include overflows, storage tanks and pumping stations.

The Simulation Method (SIM) analyses the system performance for storm events, calculating discharges and water levels and checking surcharging and backwater effects. Ancillaries such as stormwater overflows, detention tanks, pumping stations and flap valves may also be taken into account.

The WALLRUS-VIS displays the results in schematic network format or long section plots highlighting details of surcharging pipes where required.

A separate module, MOSQITO, is also included in the WALLRUS suite. It uses different quality models to simulate the pollutant concentrations in a sewer system.

These methods may be applied to both combined and separate sewerage systems. To assist in the choice of appropriate methods for particular problems of design or analysis a flowchart is presented in figure 3.1.

The Simulation Method is mostly used in this research. The main difference of this method from the other methods i.e. the Hydrograph Method and the MicroRAT method lies in the modelling of the pipe flow (Bettess et al. 1978). Colebrook-White equation is used for velocity calculation and free surface flow routing in sewers is achieved by the Muskingum-Cunge method. The instantaneous discharges are calculated throughout the system at a given time increment instead of complete hydrographs being routed sequentially from one pipe to an other. The routing procedure for surcharged pipes is the same as described in section 2.5.2

3.6 The MOUSE System

The MOUSE System is a microcomputer software package developed by a consortium of Danish research engineers. The system contains a number of modules, of varying sophistication allowing for description of overland flow, pipe flows and pollution loads. Simplified as well as the most generalized equations have been used. There are three main menus INPUT, OUTPUT and COMPUTATION.

The INPUT menu assembles the details of rainfall data, hydrological and catchment data in different files. The OUTPUT menu provides the plots and print-outs of simulation results. It has also the facility to display lay-out of the pipe system and longitudinal profiles from catchment data base.

The COMPUTATION menu contains the following computational modules;

A runoff module describes the runoff process, and the user has the option to choose between a simplified and an advanced approach. The simplified approach combines a calculation of initial losses with time/area function. The advanced approach combines a calculation of all hydrological losses with a kinematic wave computation of surface runoff.

A pipe flow module provides the possibility of three different hydraulic descriptions (i) kinematic wave approach (ii) diffusive wave approach and (iii) dynamic wave approach. All three approaches simulate branched as well as looped systems. A Pollution module calculates pollutant loads to receiving water bodies from overflows.

3.7 Kinematic Wave Watershed Routing Model (KWRM)

The model, KWRM is based on an earlier program, KWIRM developed for impervious catchments by Brady in 1984 at University of Queensland, Australia in the computer BASIC language. Subsequently, the KWIRM model was rewritten in the FORTRAN language for microcomputers by Gunasinghe in 1990 and some modifications have been made to expand its applications to natural catchments including pervious areas. It is based on kinematic wave theory for flow routing. The Surface runoff calculations are based on catchment characteristics with introduction of runoff coefficient specification similar to that used in the Wallingford Procedure.

The catchment is defined in three type of flow segments, 1) overland flow segment, 2) collecting (and connecting) channel, and 3) reservoir storage segment.

The overland flow segment is assumed to be plane and is specified in terms of length, slope and Manning roughness coefficient. The width is determined by the length of the downstream collecting channel. This inherently assumes that the direction of surface flow is always normal to the collecting channel (sewer). The segment receives the rainfall and spills flow into downstream collecting channel. The program uses the same regression equation (equation 2.9) for percentage runoff (PR) prediction as is used in the Wallingford Procedure. Net rainfall on overland flow segments (RAINOF) for each rain interval (INTLEN) has been calculated by modifying the rainfall intensity to account for the simplified hydrological processes as (Gunasinghe 1990)

$$RAINOF = \frac{RAIN*60*PR*C_r}{INTLEN*100} \tag{3.1}$$

Where RAIN is rain depth in mm for each interval and C_r is the routing coefficient used in Wallingford Procedure.

The Collecting channel characteristics are specified in terms of length, slope, Manning roughness coefficient, channel section shape (e.g. circular, parabolic, triangular etc.) and particular dimension of the shape. It receives the spillage from overland flow segments connected directly to it, plus inflows from upstream channel or reservoir (if any) and carries the total flow to a downstream channel or reservoir. These channels are purely connecting channels if they do not have overland flow segments immediately upstream.

The reservoir storage segment is defined by the available storage volume, plan area of the lake and its percentage increment per unit increase in height above weir crest level and type and dimensions of overflow weir. Reservoirs are assumed to receive niether rainfall nor overland flow directly. If the reservoir actually receives a significant overland flow, this is modelled by introducing a small collecting channel to convey such flow to the reservoir.

3.7 A Comparative Evaluation of the Existing Flow Simulation Systems

The flow simulation models discussed in this chapter are but a few out of a whole range of simulation models which exist worldwide. These models have the capability to design and simulate sewerage systems on the basis of design rainfall event or analyse performance of existing systems for severe rainfall events. Increasing demand for better management of the water environment requires thorough investigation of pollution discharges related to combined sewer overflows which are the major source of pollution in receiving waters. Therefore, it is essential to quantify loads on the receiving waters from these overflows for representative periods of one year or more, to provide unbiased appraisal of pollution risk and river impact. Some of the models reviewed can be used for this purpose but the resources and cost involved for this extended simulation with these models is prohibitive for practical applications in many cases.

A flow synthesis model which can simulate the long-term behaviour of storm overflows in combined sewerage systems within limited resources, time and cost is needed.

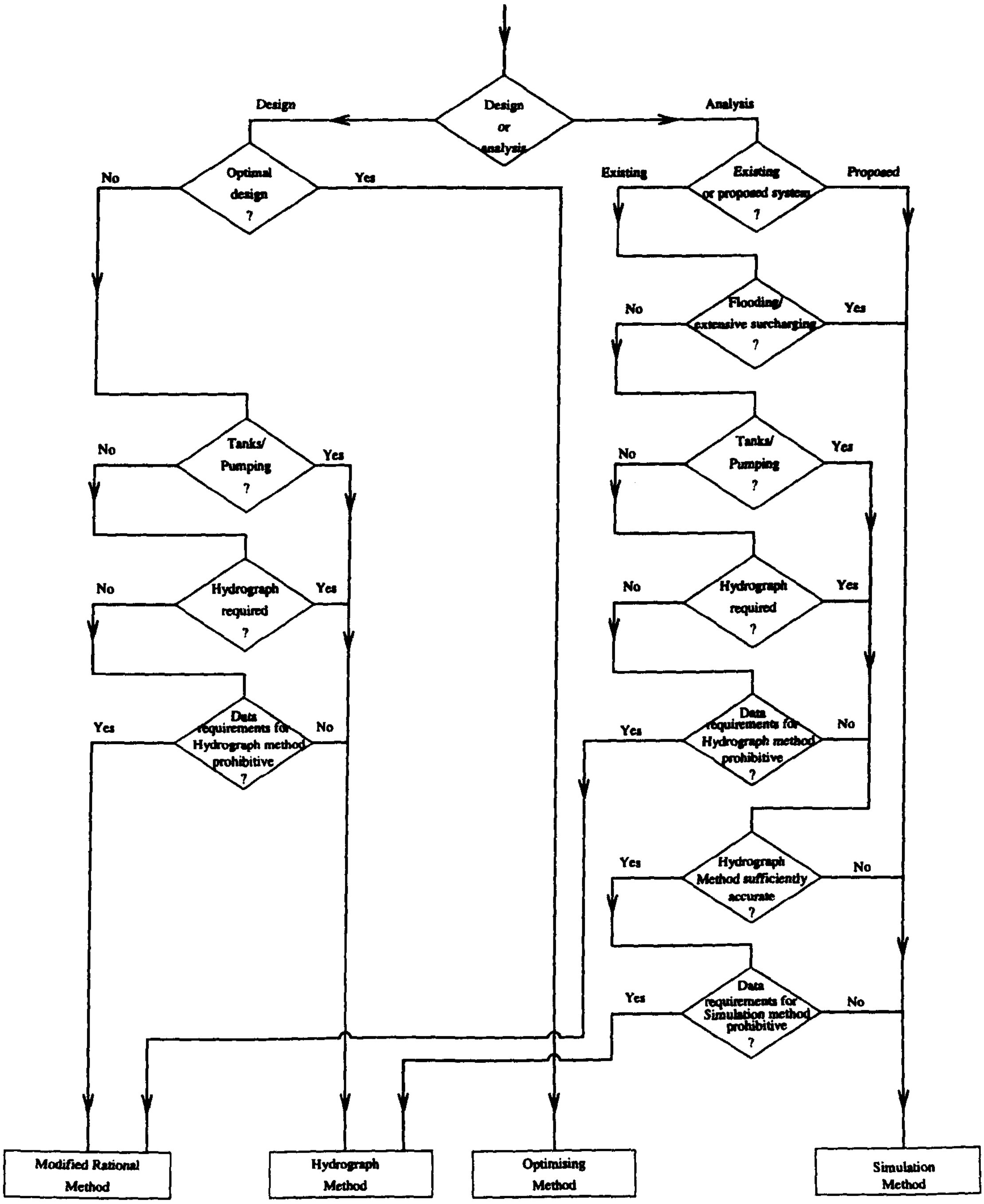


Figure 3.1 Selection of a method (Reproduced from HRS 1981)

CHAPTER 4 COMBINED STORM SEWAGE OVERFLOWS

4.1 Introduction

The flow in combined sewer systems is composed of rainfall runoff and dry weather flow (DWF). The dry weather flow may include domestic commercial and industrial wastewater and infiltration. During a rainfall event the flow in the combined sewer system can exceed the dry weather flowrate many fold. The downstream sewage works are built to a finite size because of economic and other constraints, typically dealing only with up to 6 times DWF. Therefore, to avoid the flooding of the sewage treatment works downstream, the flow must be split by some regulator structure, with part of it entering the works or interceptor sewer and the remainder exiting through the combined sewer overflow (CSO) outlet for relief discharge to watercourse. However, herein lies a pollution problem that sewers carry contaminated waters which together with deposits laying in or attached to the sides of the sewer are washed out in the overflow to the receiving water. It has been shown that storm sewerage overflows operating only 2-6 % of the time, can contribute as much as 45 % of the total annual BOD load to the receiving waters. (Aspinwall et al. 1986).

Lester (1967) reported that under intense rainfall conditions, streams have been found to become more heavily polluted, especially following longer periods of antecedent dry weather when deposits are removed from the sewer. The purpose of this chapter is to provide an introduction to combined sewer overflows and water quality modelling.

4.2 Historical Background

Many of the older communities in Europe and some other parts of the world have combined sewer systems. These systems tend to be concentrated in communities of large population. Some of these combined sewer systems were initially designed to carry storm runoff only. Due to increase in population, the problem of handling domestic wastewater became more difficult, and homes in some areas were connected to storm drains. These storm drains as well as those originally designed to carry combined wastewater, transported wastewater from their sources to the nearest surface water body for disposal. As population and waste quantities increased further, it became apparent that some degree of wastewater treatment would be required to protect public health and quality of receiving waters.

The interceptors or intercepting sewers were constructed to collect the discharges from combined sewer outlets in a community. These interceptors were designed to carry the peak dry weather wastewater and some portion of stormwater flow. The cost of constructing a treatment facility to cope with large quantities of storm water flows was considered prohibitive. These economic criteria together with the ability of a receiving water to have some assimilative capacity led to the wide-spread use of combined sewer overflows (CSOs) many of which are still in use. The overflow structures were constructed mostly at the junction of each combined sewer to the interceptor to relieve downstream pipes from overloading in certain communities.

As Britain was the first country to experience the pressure of urbanization, it was in the forefront of many of the earliest innovations. The Royal Commission on Sewage Disposal, which was set up in 1898, considered the question of the disposal of storm sewage and recommended in their Fifth Report (1908) that 'It is probably impractical to dispense altogether with storm overflows on branch sewers but in our opinion these should be used sparingly, and should usually be set so as not to come into operation until the flow in the branch sewer is several times the maximum normal dry weather flow in the sewer. The general principle should be to prevent such an amount of unpurified sewage from passing over to overflow as would cause nuisance'.

These recommendations did not include any value for the multiplier on dry weather flow. However the Local Government Boards did set a rule in the light of this report that the overflow setting should be 6 times average dry weather flow. The basis of this assumption was that once the flow had reached 6 DWF the sewage was sufficiently dilute that it would not cause problems (HRS 1993).

Technical Committee on Storm Overflows and Disposal of Storm Sewage was set up in 1955 to review the criteria. This Committee concluded that instead of simple multiplier on dry weather flow the overflow setting should be based on more realistic approach. That is the dry weather flow, the amount of storm flow to be retained in the sewers and industrial flows must be taken into account. These considerations led to Formula A which is

$$Q = DWF + 1360P + 2E \tag{4.1}$$

where Q is overflow setting (l/d), DWF is average daily rate in dry weather including infiltration and industrial discharge (l/d), P is population and E is average daily rate of industrial discharge (l/d).

In 1977 Scottish Development Department (SDD 1977) set up a Working Party on Storm Sewage to review the recommendations of the Technical Committee. The Working Party looked in particular at the use of storage tanks, and at the efficiency of overflows in retaining gross solids. They recommended an arbitrary amount of storage at overflow which depends on the dilution available in the river.

Further improvements in the CSO setting have been suggested in Urban Polluton Management Procedure (FWR 1994). In this procedure Environmental Quality Objectives (EQOs) are used to specify the desired uses of a water body. Environmental Quality Standards (EQSs) are then defined such that, when achieved, these EQOs are met and the desired uses are protected.

4.3 Rain Data for Estimation of Overflow Characteristics

If the combined sewerage system is not poorly designed and is well maintained overflow spills are caused only by rainfall. As rainfall is a random event this therefore means that overflow spills are also random. The rainfall input options to flow simulation models which are available include design storms, annual Time Series Rainfall (TSR) and continuous rain record or historical rainfall data.

Design rainfall, mostly used to design sewerage system is not appropriate to estimate overflow characteristics and ultimately their impact on receiving waters.

The annual TSR (Henderson, 1986) were developed by WRc to address some of the limitations of design storms. The use of the series in combined sewer overflow spill analysis is well appreciated in the U.K. For longer simulations only the very severe storms would be omitted and these may have only a minor effect on overall polluting effect on receiving waters.

Arnell. (1987) compared the results obtained by using design storms with those calculated from historical rainfall and concluded that good estimation of overspill volumes and other characteristics can only be done by using historical rainfall data. The use of historical data has a considerable advantage over design storms or annual TSR in that assumptions do not need to be made about storm shape, size or the pattern of the events. Also, the data are representative of the study area.

In the present study continuous rain data has been used to calculate the overflow characteristics. Although for the comparison of the results with WALLRUS the annual Time Series Rainfall data have also been used.

4.4 Water Quality Modelling

A considerable amount of research has been undertaken in recent years on qualitative assessment of polluting loads discharged from combined sewer overflows (CSOs). As overspills are a mixture of domestic sewage, industrial effluent and urban runoff there is a high degree of variability in their polluting characteristics. Intermittent discharge of such polluted waters causes a potential threat to the receiving water bodies. This has been reported by many researchers. Warwick in 1987 investigated the Little Juniata River (Pennsylvania, USA) and found that the water quality is very sensitive to CSO events.

Therefore, it is necessary to be able to quantify the polluting loads from CSOs to mitigate their impact on receiving waters. Different approaches are being used to model the performance of sewer systems in terms of the pollutant load discharged during rainfall event.

Detailed modelling is one of these approaches. In this approach attempts are being made to represent, to some extent, most of the physical processes involved in build-up and wash-off of surface and sewer sediments, foul inputs, and advection and dispersion of pollutants. Therefore, this type of modelling techniques are capable of producing detailed pollutographs for any part of the system during a simulated event. MOSQITO (Wallingford Software 1993) is an example of this type of model.

Another modelling approach is using a detailed hydraulic model to predict the spill volumes and durations. The volumes are then multiplied by standard values for event mean concentrations to give the total spill loads. In this technique it is assumed that the pollutant concentration could be represented by an average concentration which is constant throughout the spill and that it is the same in each rainfall event. These concentrations can be derived by measuring concentrations in a number of spill events at each overflow and calculating site specific average values. Threlfall et al. (1991) have recommended average determinand concentrations for storm sewage in combined sewer systems. The Constant Concentration Model (WRc 1986) is based on this approach. It uses the WALLRUS hydraulic model to predict the volume of overflow spill from the system during rainfall event and then by multiplying this volume with mean concentration of the pollutant it calculates the total pollutant load.

Simple tank simulation is another approach in which the flow processes are represented by a number of tanks in series and in parallel. Each tank receives foul flows and runoff from different subcatchments. Pollutants are modelled in different ways. One way is to assign the event mean concentration to foul flows and surface runoff, then by mass balance the loads are calculated at any point in the system. Another method has recently been used in Simplified Urban Pollution Modelling (SIMPOL) (FWR 1994). In this method BOD sediment store is represented in the sewer tanks and is eroded at a constant concentration by runoff. The concepts used in SIMPOL are described in the following section because it is only other software that can do what COSSOM can.

4.4.1 Simplified Urban Pollution Modelling (SIMPOL)

SIMPOL is a spreadsheat model. It has been developed by the Foundation For Water Research and Water Research Centre. In this model, the elements of a sewer system are represented by tanks. These tanks are connected together to build up whatever system configuration is required. Figure 4.1(a) illustrates the connections between different tanks of a sewer system. Figure 4.1(b) shows a typical subcatchment configuration which can be represented in SIMPOL. The model considers only one pollutant this is normally Biochemical Oxygen Demand (BOD). Ammonia can also be represented by adjusting the surface runoff and dry weather pollutant stores to zero.

The model runs on hourly time-steps, with hourly rainfall data. The surface tank converts the rainfall into runoff by using the percentage runoff equation used in WALLRUS. The runoff is mixed with foul flow, this volume is then passed forward to the downstream sewer tank at hourly time-steps. The sewer tank is assumed to have unlimited storage capacity. In addition, this also contains deposited BOD which can be eroded by runoff during storms. At each hour time-step the eroded BOD is fully mixed with the sewer tank contents and this mixture is then passed forward to the CSO tank. The CSO tank is a simple on-line storage tank with a maximum pass forward capacity. At each time-step a volume balance calculation is carried out to find the quantity spilled. It is assumed that the spill occurs at the inlet to the tank such that the pollutant concentration of the spill is equal to the pollutant concentration of the inflow. The concentration in the pass forward flow is taken to be the concentration in the tank after mixing.

The storm tank which is modelled as an off-line tank receives the pass forward flow from CSO tank at each time-step. Volumes are calculated as for CSO tanks. The concentration in spill flow is related to the concentration in the tank after mixing by an equation which allows some partitioning of BOD. The concentration in the pass forward flow is taken to be the concentration in the tank after mixing. A final balance gives the load left in the tank. In the following table a comparison has been made between SIMPOL and COSSOM.

Item	SIMPOL	COSSOM
Rainfall	STORMPAC produced rainfall events in hourly time step	Rainfall data in any time step
Runoff	Percentage runoff equation used in Wallingford Procedure	Unit hydrograph approach
Pass Forward Flow Routing	Routing is controlled by the equation $Q=aV^b$ where V is volume of water in sewer tank and a & b are attenuation factors	Time off-set method
Pollution Modelling	BOD loads by assuming unlimited store in sewer tank and erosion depends on runoff quantity. By assuming BOD store zero ammonia can be modelled.	Any pollutant can be modelled by using mean event concentration model and assuming complete mixing of the pollutant.
Environme-ntal Impact	By mixing the intermittent discharge with receiving water for six hours, the BOD concentration in receiving water is estimated	Not modelled
Results	Total spill volumes and pollution loads from CSO tanks and Storm tanks	Total spill volume, duration, number of spill events and pollution loads. Inflow and continuation flow hydrographs at each site.

4.4.2 Pollution in Combined Sewer Overflows

Pollution in combined sewer overflows can be explained mainly by the characteristics of the rainfall and the amount of pollutant that has accumulated on the catchment surface and in the sewer networks. In addition to these pollutants are those which are contributed by domestic and industrial waste water. Field (1972) summarizes the most important factors affecting the quality of CSO discharge; these are antecedent dry weather, land use of the catchment area, pollution accumulation and wash-off, street sweeping practices, soil erodibility, dry weather wastewater, solid deposition, scour in sewer system, and sewer system characteristics. Krejci et al (1987) investigated the different sources which contribute the pollutant loads in combined sewers and found that surface runoff, sewer deposits, slime and domestic wastewater contribute to the total pollutant load during the rain event.

A brief description of the pollutant sources build-up and their mobilization is given in the following paragraphs.

During dry weather flow the sediments accumulate on the surface of the catchment. The quantity and characteristics of these sediments depends on the land use and length of the dry weather period. In the event of rainfall these sediments and attached pollutants are washed-off the catchment surface and enter the combined sewer system. The quantity of these eroded sediments depends on the intensity of the rainfall and the total available quantities on the catchment surface.

When there is only dry weather flow in the sewer, the velocity of the flow is low, therefore, the heavier sediments tends to settle out of the sewer flow and deposit on the sewer bed. These sediments act as a store of pollutants. As the flow in the sewers increased during a storm event, the erosion begins. The rate of erosion depends on many factors like velocity of the flow, width of the sediment bed, shear strength etc. The movement of these sediments in sewers may be in suspension or as bed load. Finer, lighter materials tends to travel in suspension while the heavier material as bed load. The transport of the dissolved and suspended pollutants takes place by two main mechanisms, advection and dispersion.

Advection is the process by which the dissolved and suspended pollutant move in the same direction and at the same speed as the flow of water. Dispersion is a random process by which the pollutant move in such a way that the concentration gradient decreases along the sewer.

4.4.3 Effect of Combined Sewer Overflows on Receiving Waters

The combined sewer overflow (CSO) discharges consist essentially of the unpurified sewage and urban runoff. In addition to the organic matter associated with sewage, the constituents may include a diverse range of substances present in industrial and domestic effluent. Typically, CSO discharges are associated with increased biochemical oxygen demand (BOD) and chemical oxygen demand (COD), which can lead to oxygen depletion in the receiving water. CSO discharges may also contain ammonia, chloride, heavy metals, hydrogen sulphide, suspended solids, nitrites, and organic micro pollutants. Of the sewage constituents, heavy metal and organic micropollutants are mainly associated with industrial effluent, although runoff may also contain some metals (Clarke et al. 1992). The impacts of

CSOs discharges have therefore attracted more attention in recent years. The depletion in dissolved oxygen due to BOD is the main concern because it eliminates the aquatic life.

Sediments discharged from CSOs containing heavy organic and metallic contamination cause a persistent deterioration of the water body. A research on CSO discharge's influence on receiving waters has been conducted during 1982 and reported by Lavelle et al. in 1984. The study area was Quebec City in Canada. Results observed proved that CSO cause important shock load on the receiving water and long-term degradation of the river through sediment leakage.

Alongside the other problems, aesthetic pollution is also associated with CSO discharges. These often include colour, odours, scums etc. However, qualities such as these, which are associated with the discharge, are likely to be transient, whereas gross solids may persist and become stranded and have a high value of visual nuisance.

4.4.4 Urban Pollution Management Manual Approach

Urban Pollution Management (UPM) is the management of wastewater discharges from urban sewerage sewage treatment facilities under wet weather conditions. In particular, it is concerned with controlling the impact of these discharges on surface waters.

In the Urban Pollution Manual launched by the FWR in 1994 as a recomended practice in the U.K., an integrated approach is described to control the wet weather impacts. It brings together the different modelling tools within a single comprehensive planning framework referred to as the UPM procedure as illustrated in fig 4.2. The procedure guides the user in making appropriate use of these tools in different circumstances.

The primary purpose of this Manual is to help practitioners to develop such cost-effective UPM strategies by making use of new tools and procedures which are now available as a result of the UPM research programme (Clifforde et al. 1993). These include rainfall modelling, sewer quality modelling, sewage treatment quality modelling and river quality modelling. The following is a brief description of the function of these modelling tools and reference is made to the specific models developed under the UPM programme (FWR 1994).

Rainfall data are required to drive the models which simulate the wet weather performance of urban systems. Long time series of rainfall events provide a full account of the variability in rainfall. In absence of historical rainfall data, a model is required which can produce localised synthetic rainfall time series. STORMPAC (WRc 1994) is available which is capable of generating long time series of hourly rainfall for any location in the UK, selecting events from a series or from historical series based on user specified criteria and disaggregating the hourly values for selected events into five minute intensity values.

A sewer quality model which simulates the sewer performance in terms of the pollutant loads and is capable of producing detailed pollutographs for any location in the system during a rainfall event is required. MOSQITO (Wallingford Software 1993) is an urban drainage water quality simulation model which models build-up and wash-off of sediments, transport and behaviour of pollutants and sediments in sewers and in ancillaries and produces pollutographs to show the short term variations in flow quality during a storm event.

The dynamic sewage treatment works models represent the main physical, chemical and biological processes in a treatment works and are able to simulate their performance under varying input conditions. STOAT (Dudley and Dickson 1992) is a sewage treatment works simulation model which can handle varying flow and quality inputs e.g. from MOSQITO output.

To quantify the impact of wet weather discharges on rivers a dynamic river impact model is required. MIKE 11 (DHI 1992) is a one dimensional dynamic river quality model which can simulate all the important processes in a river prior to, during and after a storm discharge. It can accept MOSQITO and STOAT outputs representing urban discharges.

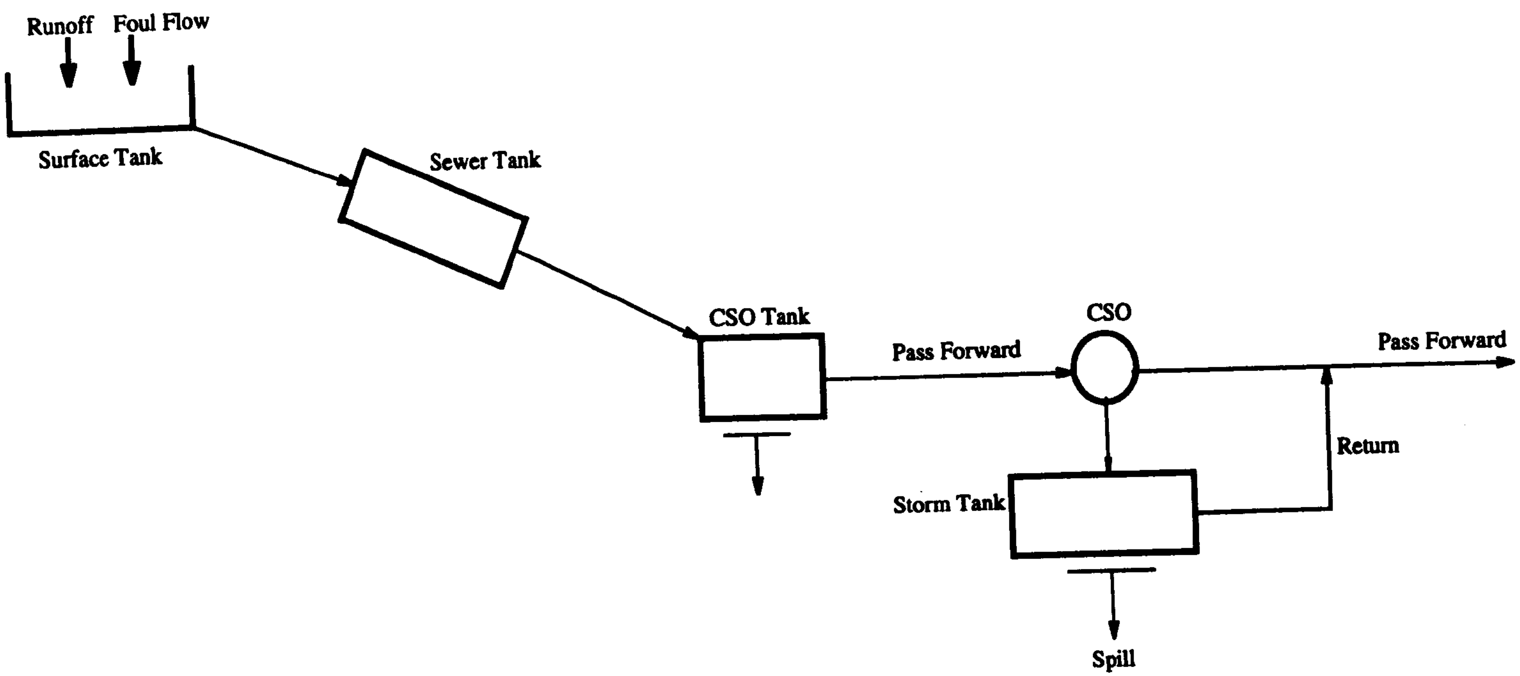


Figure 4.1(a) A Sewer Subcatchment in SIMPOL (Reproduced from FWR 1994).

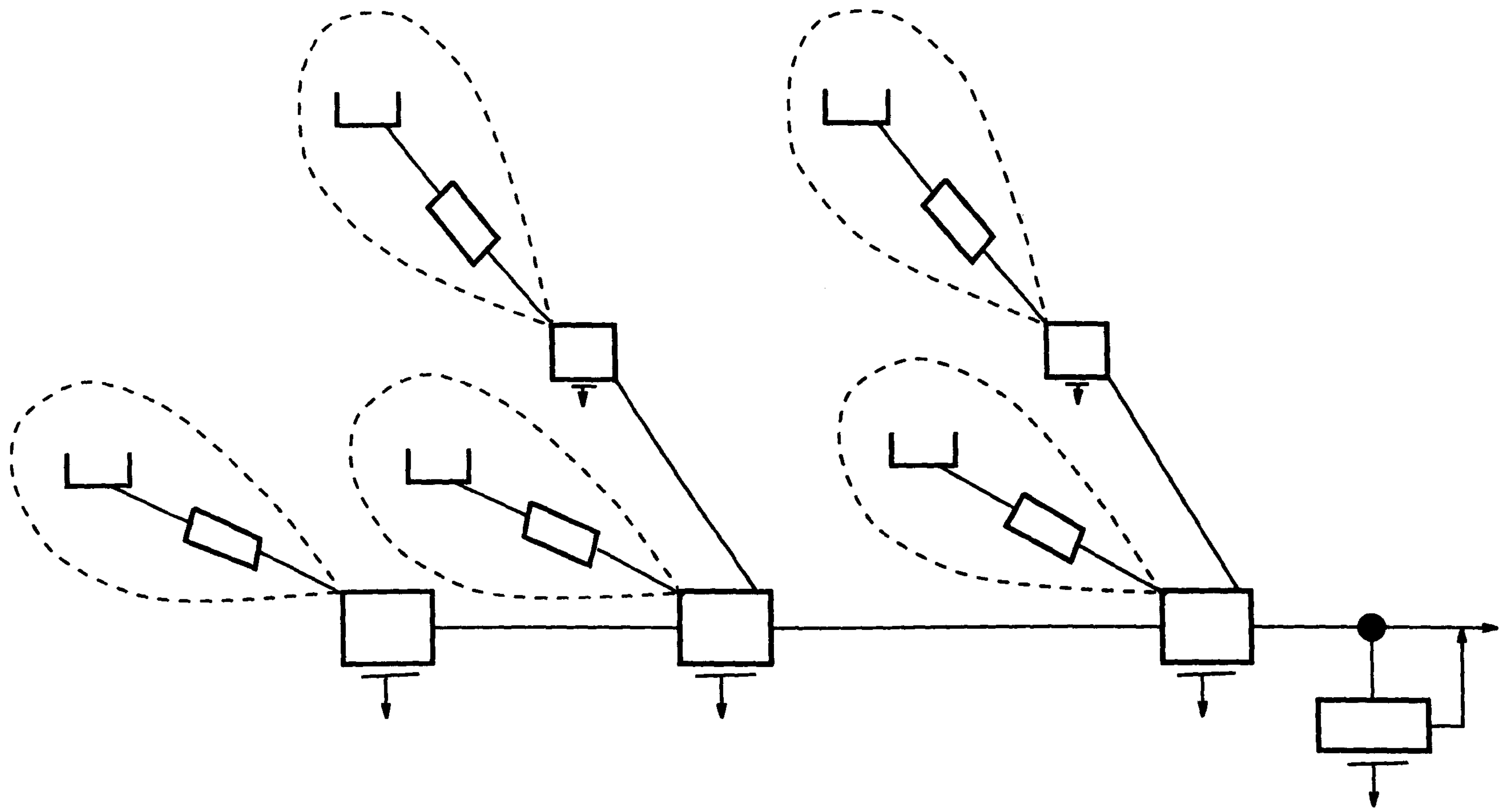


Figure 4.1(b) Typical Subcatchment Configurations which can be Represented in SIMPOL (Reproduced from FWR 1994).

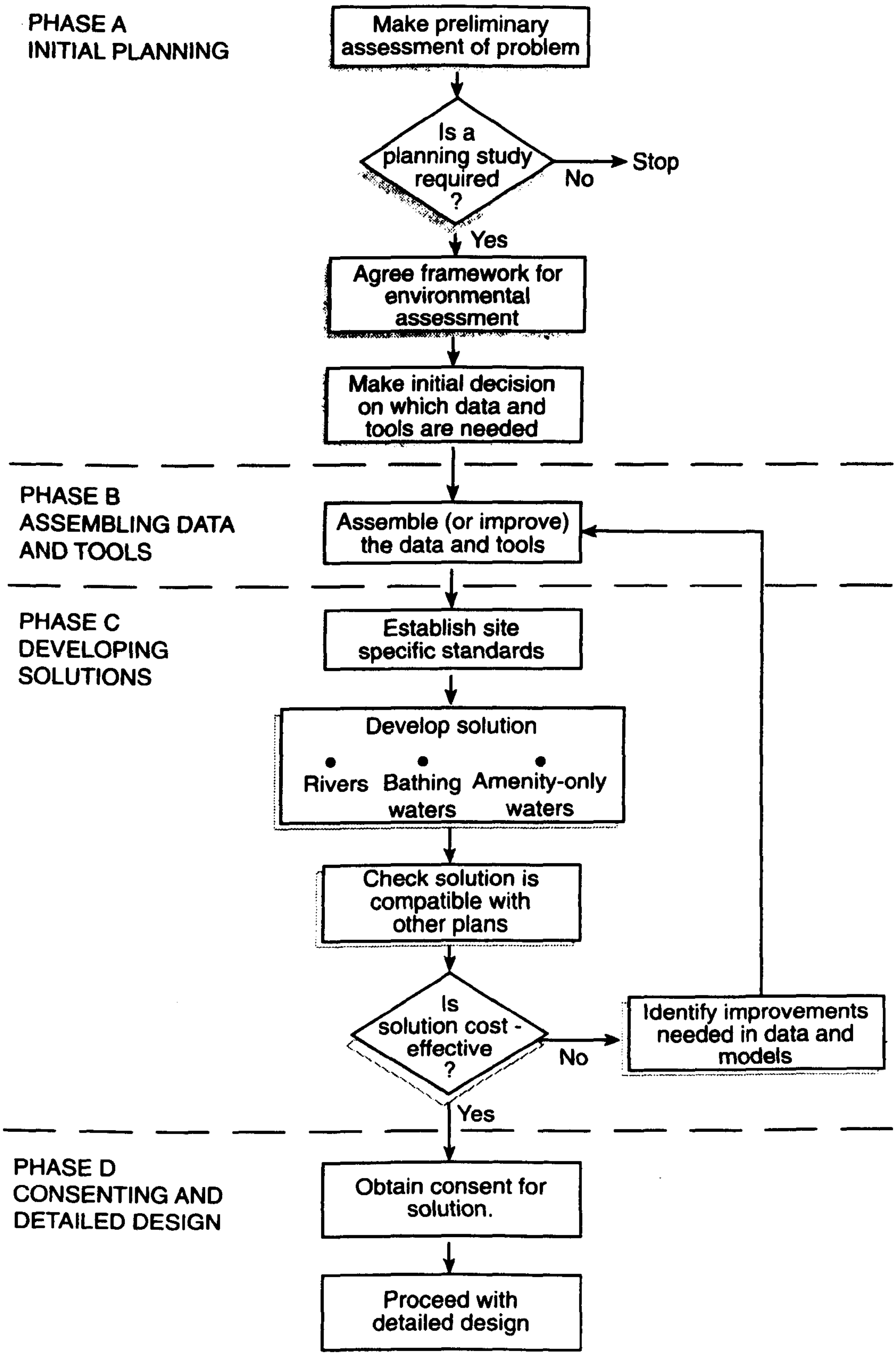


Figure 4.2 The UPM Procedure (Reproduced from FWR 1994)

CHAPTER 5 DEVELOPMENT OF THE LONG-TERM SIMULATION MODEL (COSSOM)

5.1 Introduction

It was realized in the last two decades that realistic conclusions concerning receiving water pollution from combined sewer overflows cannot be derived from rainfall-runoff measurements or simulations of singular events. To attain a degree of confidence in pollution control strategies, it is thought necessary to be able to simulate continuous rainfall data. The continuous (long-term) simulation is defined as the continual calculation of runoff based on rainfall records of several years. The aim is to apply a statistical analysis to the outcome of a long-term simulation to attain statements regarding runoff volumes and overspill volumes, frequencies and durations.

Long-term simulation theoretically can be done with any of the detailed hydraulic models discussed in chapter 3, but the computing time and other resources required are limiting factors. As far as the quality modelling is concerned there are several stormwater quality models which formulate water quality processes through the use of the concept of 'build-up' of pollutants on the land surface and in sewers during dry weather, followed by 'wash-off' through hydrodynamic processes during storm events. To calibrate these models for any particular catchment a large number of monitored water quality events is required, which if not impossible, is very complex, expensive and time consuming. MOSQITO is one example which requires an extensive data collection exercise and large amount of time to calibrate it. As MOSQITO is an event-based model (Ashley et al. 1992) its application is not justifiable for calculation of annual pollution loads from CSO's.

Therefore, simplifications are needed to overcome these limitations. On the other side these simplifications must not weaken the reliability of computed results. An effort has been made here to develop a simple mathematical model which incorporates the unit hydrograph approach for flow synthesis in combined sewer systems and a simple mixing model to calculate the pollution load from combined sewer overflows (CSO's). This simulation model, hereafter, is referred to as COSSOM (Combined Storm Sewage Overflow Model).

COSSOM is based on the model 'FLOW46' which was developed by Burrows (1987). The details of the original model 'FLOW46' and its modified version 'COSSOM' are described in the following sections.

5.2 Theoretical Basis of the Model

The unit hydrograph approach first introduced by Sherman (1932) and described in chapter 2 has been used as a basis to calculate runoff hydrograph at any point in a catchment. The unit hydrograph for a specified rain duration (TUH) can be estimated from rainfall runoff records for any particular catchment using the procedures described by Shaw (1994). In this research, however, the WALLRUS 'simulation method' is used to obtain unit hydrograph, any other detailed hydraulic model can also be used. The procedure applied in WALLRUS to synthesize rainfall, runoff and pipeflow processes is as follows.

The WALLRUS 'simulation method' uses urban catchment wetness index, percentage impermeable area and soil index to calculate percentage runoff for contributing area to each pipe as described in chapter 2. Rainfall event hyetograph is smoothed to represent average rainfall over the whole area of the catchment. To calculate a net rainfall hyetograph initial losses such as depression storage is subtracted from the average rainfall hyetograph. The net rainfall hyetograph is then converted into ten standard hydrographs using linear reservoir model for three characteristic slopes and the three paved areas (large, medium and small) and one for pitched roofs. Effective area is calculated by multiplying the percentage runoff value with the contributing area of each pipe. The appropriate standard hydrograph is then converted into ordinates of discharge by multiplying by the effective area.

For each time step the instantaneous runoff discharges from the contributing areas are introduced to the relevant manholes. Sewer Routing for free surface flow is achieved by the Muskingum-Cunge model. For surchaged pipes the programme calculates the volume stored in each surcharged manhole at the end of each time increment. New levels in the manholes and therefore discharges in the surcharged pipes are deduced from the volumes.

To derive a unit hydrograph which gives detailed description of the features like runoff, storage and routing, a rainfall event falling uniformly over the area, at a uniform rate and in a specified unit period of time (T) is considered. The appropriate magnitude of T depends upon the size, slope and area of the catchment as well as the rain intensity applied. Here, T is considered to be equal to the time of concentration of catchment and intensity as the maximum recorded value in the rain hyetograph data. Sensitivity analyses in chapter 6 have proved these values of duration and intensity as being appropriate.

A verified drainage network model of the sewerage system must be available in the format acceptable to the WALLRUS. To avoid any bias in results arising from allowance for initial losses incorporated in WALLRUS, the unit hydrograph is obtained as the difference between the hydrographs from two block rain events. The first event includes the desired uniform rainfall intensity of duration T, but preceded by a nominal antecedent rainfall intensity sufficient to satisfy the initial losses, and the second event includes only the antecedent rainfall. This is demonstrated in figure 5.1. Figure 5.1(a) shows the rainfall block of 20 mm/hr intensity for 15 minute duration preceded by a 5 mm/hr rain intensity for 5 minute and the resulted runoff hydrograph. Another event of 5 mm/hr intensity for 5 minute duration produced the runoff hydrograph shown in fig. 5.1(b). Subtracting the respective ordinates of hydrograph B from A results in the hydrograph shown in figure 5.1(c). This hydrograph is then divided by the rain depth applied to calculate the ordinates of the unit hydrograph (TUH) used in the COSSOM approach.

Once the TUH has been determined satisfactorily for a catchment, it can be used to calculate the runoff hydrograph from recorded rainfall data. The computation of a runoff hydrograph is demonstrated in Table 5.1, where a 10 minute unit hydrograph (U.H) is given at 5 minute intervals with U.H. values in m^3/sec/mm. Nine events with 10 minute time step and rainfall depths ranging from 5 to 15 mm are used as shown in figure 5.2(b). These events are multiplied to the ordinates of the TUH at their respective starting time. The columns 3 to 9 are added along each row to provide total surface runoff in the last column. These values are plotted on figure 5.2(c).

This runoff along with the dry weather flow and other flows in case of the presence of any upstream subcatchment forms the total flow arriving at the point under consideration. If the pass forward flow is restricted to a certain limit and an overflow structure exists, the overspill will start as soon as the overflow chamber is full and the inflow still exceeds the throughflow capacity. The throughflow capacity is defined by the multiple of dry weather flow (N*DWF). This process is shown diagrammatically in fig. 5.3.

To calculate overspill volume the continuity equation is applied at every time step. For the conditions when the incoming flow is less then or equal to the free flow capacity (f.c.f) and chamber is empty

$$Q_i - Q_{con} = 0 \tag{5.1}$$

Where Q_i is inflow and Q_{con} is continuation flow.

Filling of the overflow chamber starts as soon as the inflow exceeds the free flow capacity

$$A \frac{dY}{dt} = Q_i - Q_{con} \tag{5.2}$$

Where A is the cross sectional area of the chamber, Y is the water level in the chamber and t is the time step.

When Y is less then the chamber height and Q_{con} is less then N*DWF then

$$Q_{con} = m\ a\ \sqrt{2gh} \tag{5.3}$$

Where a is the cross-sectional area of the throttle pipe, h is the head difference between the water levels in the chamber and continuation pipe, g is acceleration due to gravity and m is the coefficient of discharge.

If the chamber is full and inflow still exceeds the throughflow capacity then overspill starts

$$Q_o = Q_i - Q_{con} \tag{5.4}$$

Where Q_o is the overflow discharge

The pollution concentration at the inlet of the structure is computed on the basis of a simple mixing model (Johansen et al. 1984). No sediment deposition is modelled in the overflow chamber and a uniform concentration of the pollutant is assumed throughout the chamber. The equation used to calculate the flow of pollution as function of time is as follows

$$C_c\ (t) = \frac{C_w * Q_w + C_r * Q_r\ (t)}{Q_w + Q_r\ (t)} \tag{5.5}$$

Where $C_c(t)$ is the flow of the pollutant at time t after the rain started, C_w is the concentration of the substance in the dry weather flow, Q_w is the dry weather flow, C_r is the concentration of the substance in the rain water runoff and $Q_r(t)$ is rainwater runoff at time t after rain start. Note that when the catchment under consideration receives pass forward flow from upstream catchment(s), equation 5.5 becomes

$$C_c(t) = \frac{C_w * Q_w + C_r * Q_r(t) + C_p(t) * Q_p(t)}{Q_w + Q_r(t) + Q_p(t)} \tag{5.6}$$

where $C_p(t)$ is the concentration of the substance in the pass forward flow ($Q_p(t)$) at time t after rain start, other terms used in the equation are the same as above. If there are more than one subcatchment upstream, additional terms are added following the same procedure.

The quantity of the pollutant discharged from the overflow is calculated by the equation

$$P_o(t) = C_c(t) * Q_o(t) \tag{5.7}$$

where $P_o(t)$ is pollutant discharged through the overflow and $Q_o(t)$ is the rate of overspill at time t after rain start.

The pollutant routing in the sewers is achieved by an advection process which assumes that the pollutants travel at the same speed as the flow of water. This is certainly true for the dissolved pollution and very fine sediments but it is not true for coarser sediments which are moved by being rolled along the invert of the pipes. The MOSQITO model (HRS 1993) which is based on the WALLRUS hydraulic simulation model uses the same assumption for the routing of the pollutants through the sewers. In this model it is assumed that in one time step Δt a parcel of water will move by a distance Δx. During this movement the concentration of pollutants in the parcel of water will be unchanged.

5.3 The Original Model

A simple procedure for long-term sewer flow synthesis from rainfall data, using the 'Rational method' and linear hydrographs was developed by Burrows (1987) to enable simulation of storm overflow operation. Later the 'Rational method' was replaced by a 'Unit Hydrograph' (U.H) approach (Burrows et al. 1991). This enhanced version of the model is referred to as "FLOW46". In the development stage only one catchment with single overflow structure was considered. The main features of the model are described below.

The model is written in the FORTRAN language. It receives the rainfall data recorded at any time steps and subsequently transforms this data into a selected time step. Data storage is minimized by omitting prolonged rainless periods whilst insertion of a special code ensures the separation of the storm events. Each consecutive rainfall 'event' is then transformed into sewer outflow on the basis of the unit hydrograph which is obtained by application of the WALLRUS 'simulation method'. Individual hydrographs are then combined by linear superposition to form the long-term stormwater runoff hydrograph, the methodology described earlier is depicted in figures 5.1-5.2 and table 5.1.

Dry weather flow (DWF) is added to the runoff hydrograph to synthesize the total sewer flow or overflow chamber inflow, Q_i, as shown in figure 5.4, which also illustrates the filling of the available storage and subsequent overspill during a single storm event. Overspill volume and peak discharge rate is also shown. The model permits the specification of throttle control on throughflow or hydraulic control by the continuation pipe, appropriate dimensions being input together with chamber storage capacity (V). For continuation pipe control, temporary detention in the chamber commences when flow rate Q_i exceeds the free flow capacity (f.c.f). Throughflow (Q_{con}) is modelled to vary with the water depth in the chamber, in accordance with the hydraulics of the control. Q_{con} would normally pass the setting flow (i.e. N*DWF) before first overspill (i.e. Q_i=N*DWF), then as Q_i increases further (above N*DWF), Q_{con} will continue to increase in accordance with the hydraulics of the structure's overflow weir etc. The flow continuity equation is used at each time step to establish changes in chamber water level and hence change in continuation pipe flow (Q_{con}). A flow chart of FLOW46 is shown in fig. 5.5.

Validation studies of the model have been conducted by Burrows et al. (1991). They compared results of the model with those obtained from the WALLRUS 'simulation programme'. A good agreement between two methods was reported.

5.4 The New Model

The original model FLOW46 has been extended and enhanced to relax its restriction to catchments with only a single overflow structure and also to attach a simple pollution model. These developments were considered necessary for several reasons. For large systems, there is often an engineering need to provide more than one overflow structure and single unit hydrograph representing the whole of a large catchment cannot be expected to provide equivalent accuracy, so it may be advantageous to divide the large catchment into number of subcatchments. The simple pollution model provides an estimate of pollution load discharged from the overflow structures, rather than the merely indicative measures of pollution impact offered by overflow spill volume and duration computation investigated previously.

Figure 5.6 shows a hypothetical drainage area divided into six subcatchments. The downstream end of each subcatchment is given a 'level' number as an indication of its position in the hierarchy of the system. The unit hydrographs at each level are then calculated by the application of the WALLRUS 'Simulation method' as described in section 5.2. A maximum of five hierarchial levels, including up to 20 overflow structures can now be treated in a single run using COSSOM in its present status. The Unit Hydrograph approach is applied to calculate the runoff hydrograph for each subcatchment at each level in the hierarchy working downstream. In stepping from one level to the next, contributions from upstream subcatchments (complete hydrograph or continuation flow, as relevant) are lagged and superimposed onto the runoff for the present subcatchment. A flow chart of the model COSSOM is shown in fig. 5.7.

The programme reads the rainfall data from data file which includes the number of the event, increment duration, index to identify the units of rainfall data i.e. intensity or depth and a symbol to check whether data is in mm or inches.

The programme then reads the number of subcatchments to be dealt with in a single run from system data file. Then for each subcatchment the following data are read from the same system data file:

1) index to identify whether the subcatchment has an overflow structure, 2) its position in the hierarchy of the system 3) drainage area, 4) unit rainfall duration 'T' of TUH 5) lag-time i.e. the time taken by the pass forward flow of the subcatchment to reach the next subcatchment in the hierarchy of the system, 6) dry weather flow, 7) ordinates of the unit hydrograph, 8) if the subcatchment contains overflow structure then the chamber storage volume and other specifications.

If the pollution load discharged from the overflows are required, the programme reads the mean event concentration of Biochemical Oxygen Demand (BOD), Total Suspended Solids (TSS) and Ammoniacal Nitrogen (NH4-N) in the rain water and the dry weather flow.

The programme then rearranges the rainfall data with time steps equal to 'T'. If the subcatchment has an overflow structure, the hydraulic specifications such as permitted throughflow and diameter of continuation and throttle pipes are given through the key board.

The programme then calculates the runoff hydrograph. All the previous pass forward flows (if any) are rearranged according to the present time steps. If the level of this subcatchment is greater than the previous level the hydrographs joining at this point are added together with respective lag-time. If the subcatchment under consideration has an overflow structure, the overspill characteristics are calculated otherwise the hydrograph data is stored in temporary arrays.

If the overflow characteristics are calculated and the pollution loads are required, the programme calculates the total quantity of pollution discharged. The pass forward flow and pollution conentration data are stored in temporary arrays. Results for the subcatchment are printed in output files.

Two output files are prepared. One includes the total results for each subcatchment in terms of inflow volume, overspill volume and duration, number of overspill events, maximum peak overflow rate and discharged pollution load for the three determinands. The second output file contains the time steps and inflow and continuation flow hydrographs for each subcatchment.

5.4.1 Estimation of Time of Concentration

In the present methodology a preliminary study is required to first estimate the time of concentration (t_c) for each subcatchment. Any available hydraulic model can be used and it is obtained here using the WALLRUS 'Hydrograph method' (HRS 1989). It is expected that t_c will be dependent on rainfall intensity and this is illustrated for the test system of fig. 5.8. As the rainfall intensity increases, the time of concentration decreases. This can be explained by the argument that with increase in depth, flow velocities increase and the response time decreases. In the later applications t_c has been calculated by using the most severe intensity observed on the (long-term) rainfall record. It has to be emphasised that t_c is not a parameter of the modelling procedure but is used only as a means for guiding selection of a suitable unit hydrograph duration, T, as described below.

5.4.2 Calculation of Lag-time

Additionally, it is necessary to establish a 'lag-time'. As described above it is the time taken by the pass forward flow from any subcatchment to reach the downstream end of the next subcatchment in the hierarchy of the system. In figure

5.6 the lag-time for the subcatchment 2 is the time taken by the continuation pipe flow to reach at downstream end i.e. level 3 of the subcatchment 3. The specific steps followed to calculate the lag-time in the present research were to run the WALLRUS simulation programme for the complete drainage network using the most severe rainfall event from the rain data set. The results of this simulation indicate the velocity in each pipe of the network. If only one pipe (ie same diameter and constant gradient) carries the 'pass forward' flows to the downstream end of the next subcatchment, the lag-time is calculated by using the length of the pipe and velocity in that pipe. If more than one pipe is involved and velocities vary, the lag-time is calculated by adding the travel time along each pipe.

5.4.3 Derivation of Unit Hydrograph

Derivation of the TUHs for each subcatchment are obtained herein by application of the WALLRUS 'Simulation method'. Each unit hydrograph was obtained as the difference between the hydrographs from two block rain events to eliminate the implicit allowance for initial losses, as explained in section 5.2. Division of the resulting hydrograph ordinates by the relevant rain depth applied yields the TUH ordinates. These ordinates, constructed at sub-intervals of T (i.e. $t = T/L$, $L=1,2,.........,6$) specify the unit hydrographs in their input into the sewer flow synthesis model (COSSOM).

5.4.4 Data Files

The model requires three data files, the rainfall data file, the system data file and pollutant data file. Details of the rainfall record such as total number of events and duration and depth or intensity of each event should be given in the rain data file. The program reads the rainfall data expressed in terms of depth (mm or inches) or intensity (mm/hr) and recorded at any time steps. This is then transformed into intensities at selected time steps to be used for the unit hydrograph analysis of the catchment. Note that different rain intervals T ($\approx t_c$) are selected for each subcatchment under study. The system data file includes the ordinates of the TUH for each subcatchment as well as other subcatchment characteristics such as area, lag-time, $T(\approx t_c)$, dry weather flow, chamber storage volume and other relevant control specifications. The pollutant data file includes concentration of pollutants for dry weather and stormwater runoff for each subcatchment.

5.4.5 Calculation of Overspill Characteristics

For each subcatchment the TUH and other specifications are read from the system data file. In each subcatchment the application of the TUH to each consecutive rainfall increment and employing superposition yields the long-term runoff hydrograph Q_i. Dry weather flow is then added to simulate the total flow reaching the storm overflow structure. Overflow characteristics are calculated in accordance with the chosen throughflow capacity and storage volume, section 5.3 and fig. 5.4

If the subcatchment under consideration has an overflow structure then the continuation pipe flow hydrograph is routed to the end of the downstream subcatchment where it is added to the other hydrographs joining at the same level. For the subcatchment without an overflow structure the total hydrograph (i.e. runoff hydrograph plus dry weather flow) is routed to the end of the downstream subcatchments. The routing of 'pass forward' flow hydrographs from upstream subcatchments is achieved here simply by shifting these hydrographs to the downstream end of the next subcatchment by the lag-time without any effect on their shape.

Similarly the hydrographs of other subcatchments joining at the same level are calculated and shifted to the point downstream with application of their respective lag-times. At this point all incoming hydrographs including the hydrograph of the last catchment are added to calculate the total inflow hydrograph to the overflow chamber. The overflow characteristics are then calculated at this level and the results for each subcatchment are stored in the output file. In the calculation sequence, a similar procedure is repeated for the other levels down the path. Note that all subcatchments upstream of that presently under investigation must have been synthesised before analysis can proceed. This is achieved by ensuring that subcatchments are treated in the sequence of their hierarchy level.

5.4.6 Calculation of Pollution Loads

The pollution loads spilled through each overflow structure are calculated by simply multiplying the overspill rate with inflow concentration of the substance as described in section 5.2.1. The remaining pollutants are carried forward by the continuation flow. The routing of these pollutants through the individual sewers is assumed to be by an advection process.

Three pollutants can be calculated at each overflow structure. These pollutants are

Biochemical oxygen demond (BOD)

Total suspended solids (SS)

Ammoniacal nitrogen (NH4-N)

The pollution data file must include the mean event concentration in the rain water as well as dry weather concentration for each of the pollutants and in the same order as the system data file.

Time	U.H (m^3/sec/mm)	5 mm	5 mm	15 mm	10 mm	5 mm	5 mm	10 mm	5 mm	5 mm	Total Runoff m^3/sec
0.00	0.000	0.000									0.000
5.00	0.056	0.280									0.280
10.00	0.107	0.535	0.000								0.535
15.00	0.021	0.105	0.280								0.385
20.00	0.004	0.020	0.535	0.000							0.555
25.00	0.002	0.010	0.105	0.840							0.955
30.00	0.000	0.000	0.020	1.605	0.000						1.625
35.00			0.010	0.315	0.560						0.885
40.00			0.000	0.060	1.070	0.000					1.130
45.00				0.030	0.210	0.280					0.520
50.00				0.000	0.040	0.535					0.575
55.00					0.020	0.105					0.125
60.00					0.000	0.020					0.020
65.00						0.010					0.010
70.00						0.000					0.000
75.00											0.000
80.00											0.000
85.00											0.000
90.00											0.000
95.00											0.000
100.00							0.000				0.000
105.00							0.280				0.280
110.00							0.535	0.000			0.535
115.00							0.105	0.560			0.665
120.00							0.020	1.070			1.090
125.00							0.010	0.210			0.220
130.00							0.000	0.040			0.040
135.00								0.020			0.020
140.00								0.000			0.000
145.00											0.000
150.00											0.000
155.00											0.000
160.00											0.000
165.00									0.000		0.000
170.00									0.280		0.280
175.00									0.535	0.000	0.535
180.00									0.105	0.280	0.385
185.00									0.020	0.535	0.555
190.00									0.010	0.105	0.115
195.00									0.000	0.020	0.020
200.00										0.010	0.010
205.00										0.000	0.000

Table 5.1 Runoff Hydrograph Caculations using Unit Hydrograph Approach

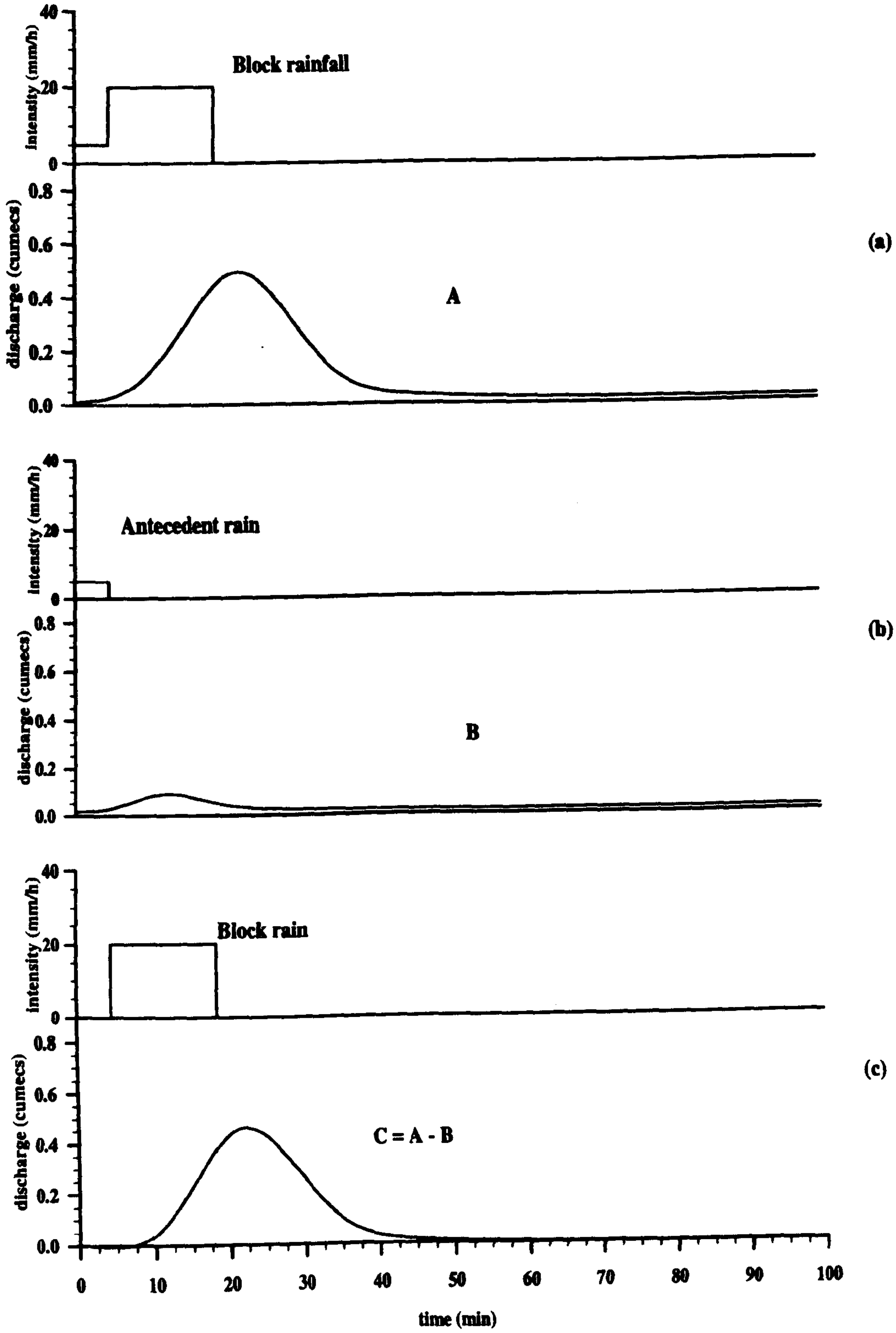


Figure 5.1 Procedure Adopted to Obtain Unit Hydrograph from WALLRUS.

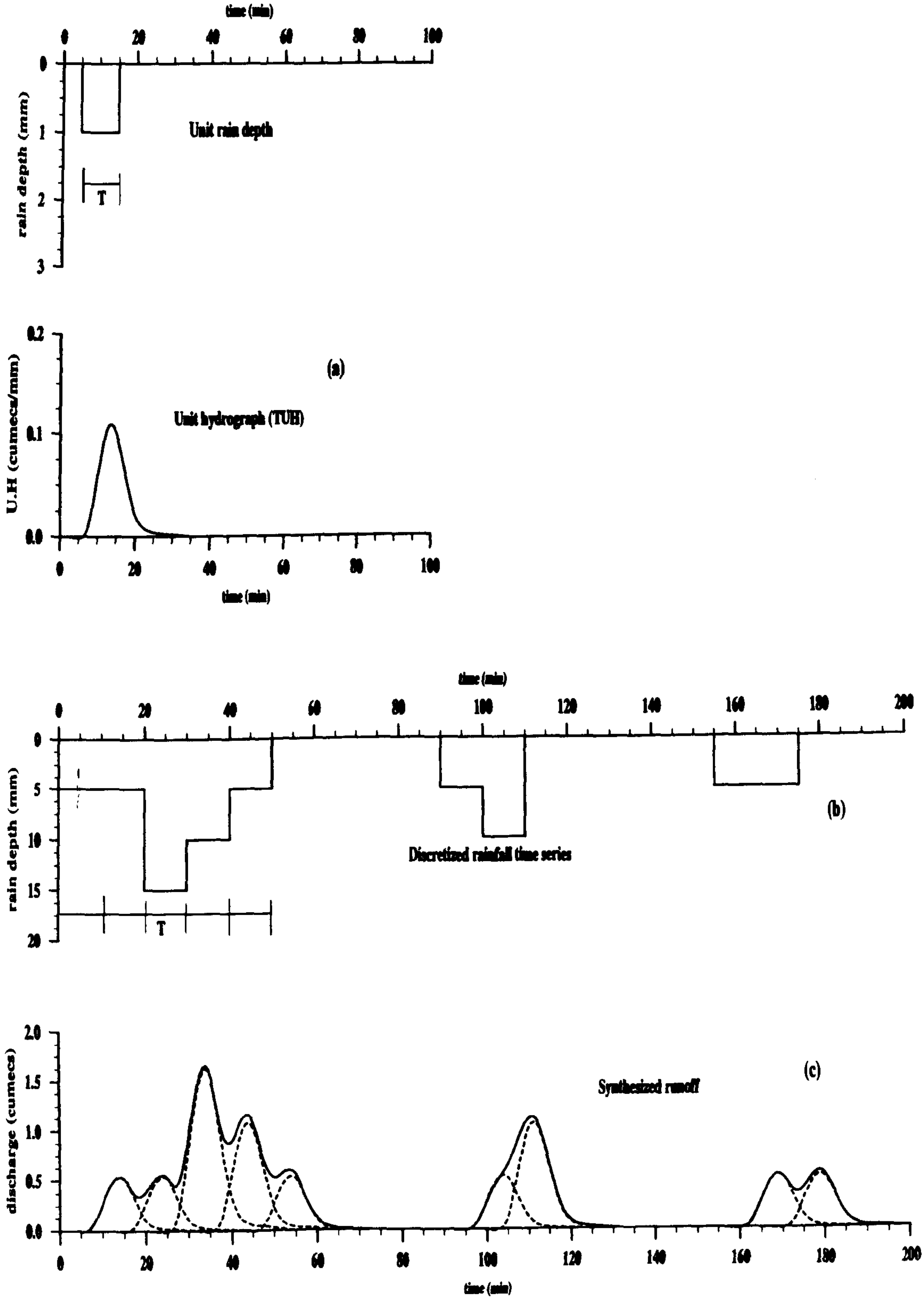


Figure 5.2 Runoff Synthesis Using the Unit Hydrograph Approach.

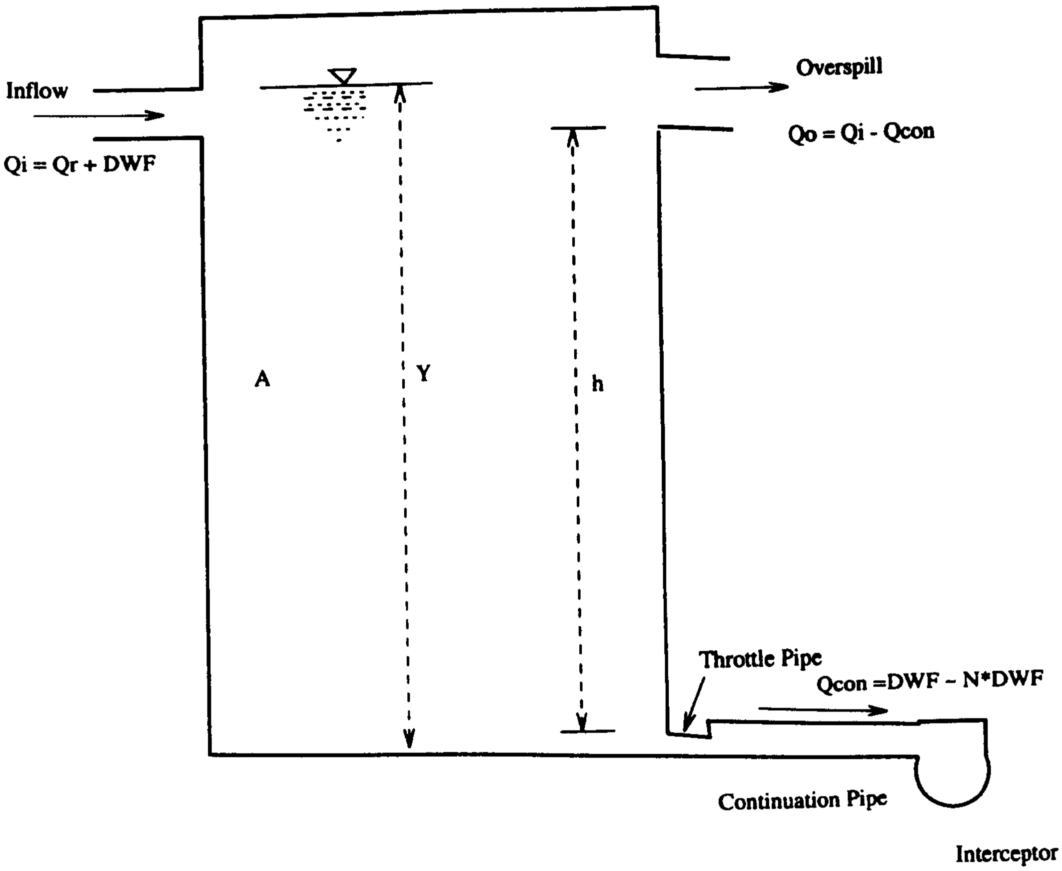


Figure 5.3 Overflow Operation

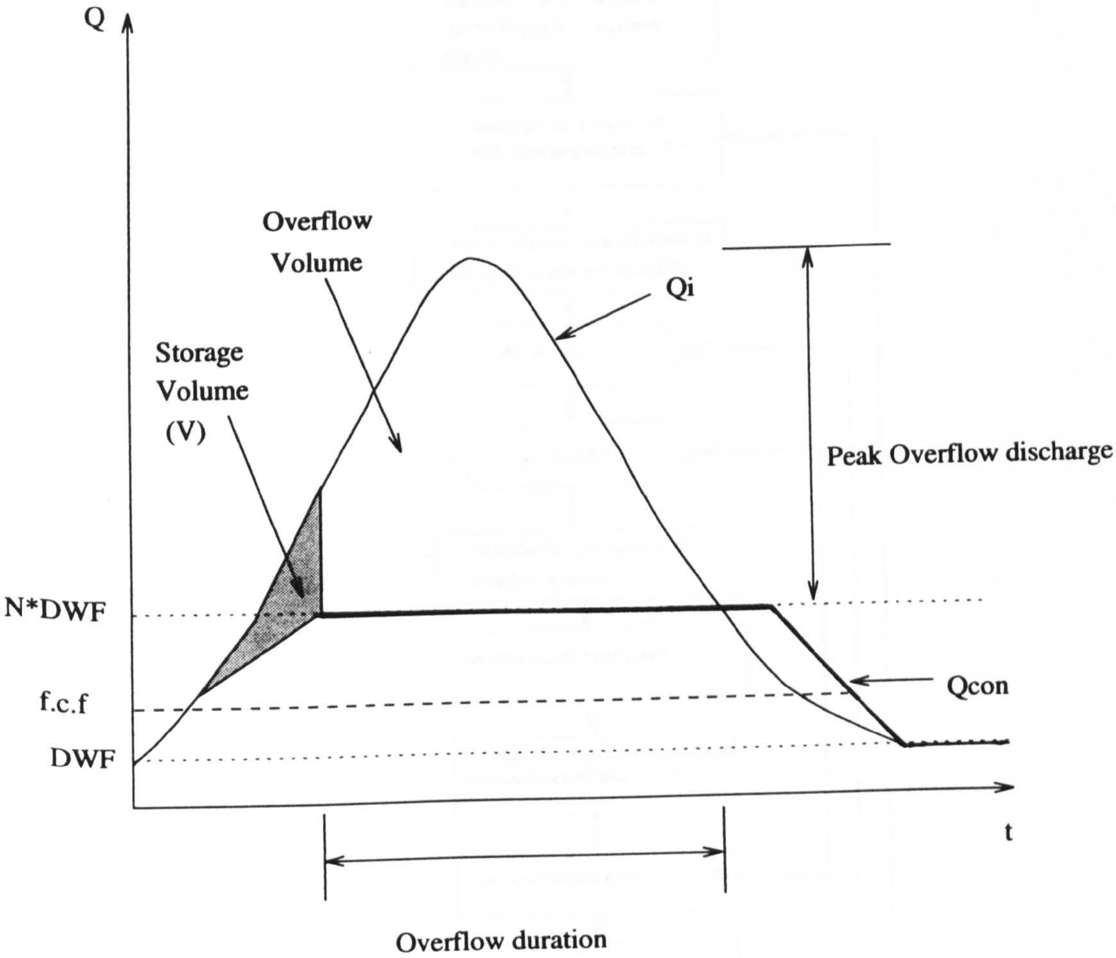


Figure 5.4 Schematic of Overflow Operation

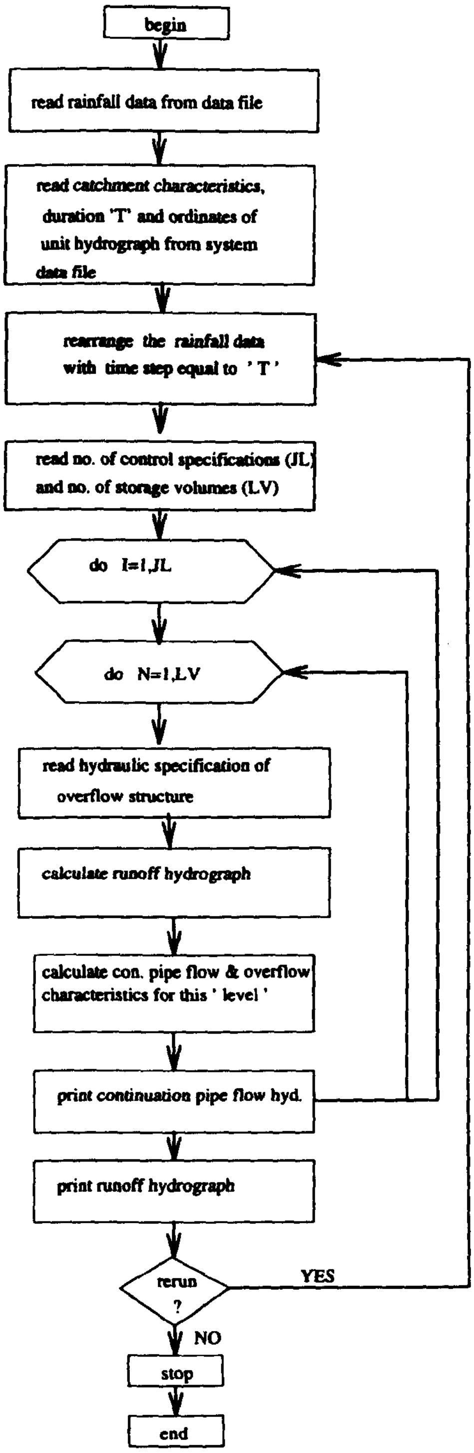


Figure 5.5 Flowchart FLOW46

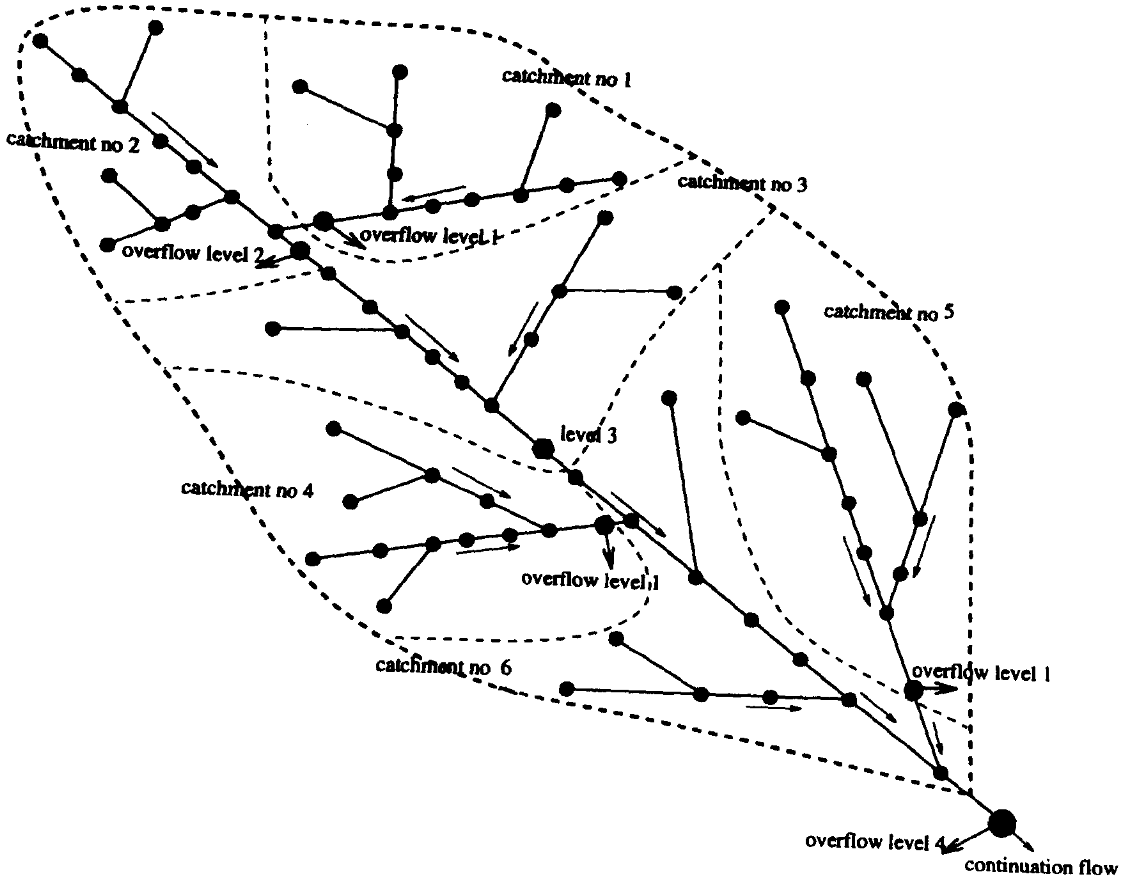


Figure 5.6 Test Sewerage System using Subcatchment Hierarchy and Overflow at Various 'Levels'.

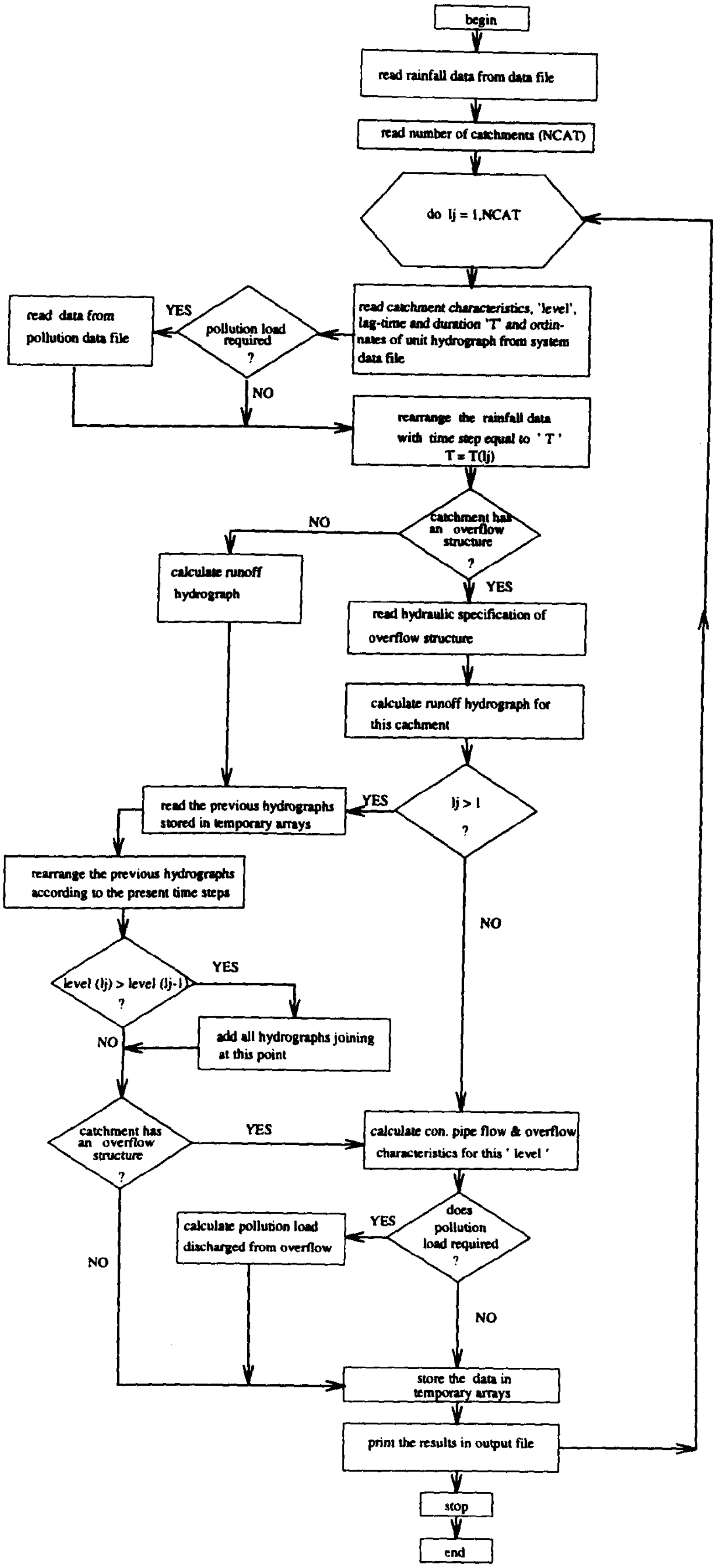


Figure 5.7 Flowchart COSSOM

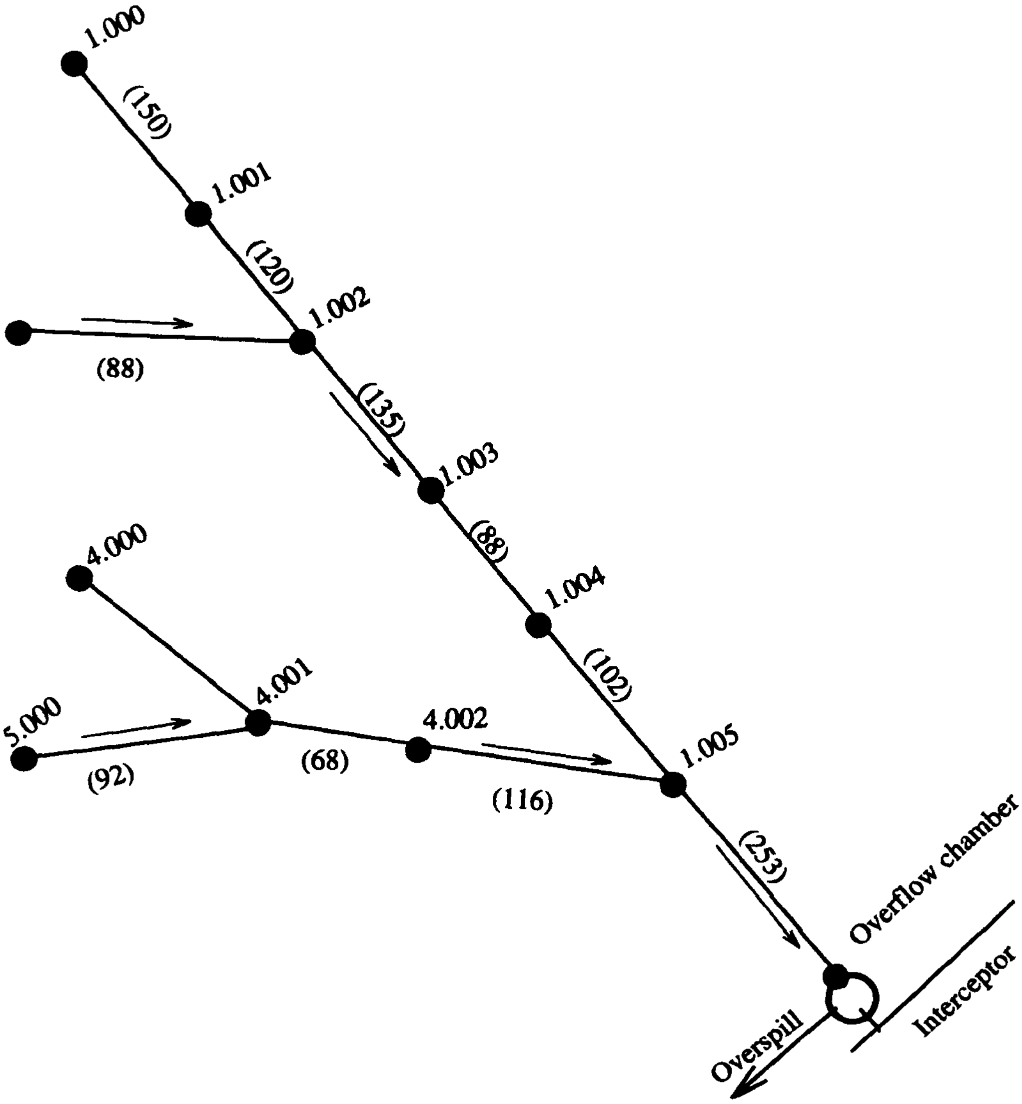


Figure 5.8 Test Sewerage System (Data File in Appendix A-1)

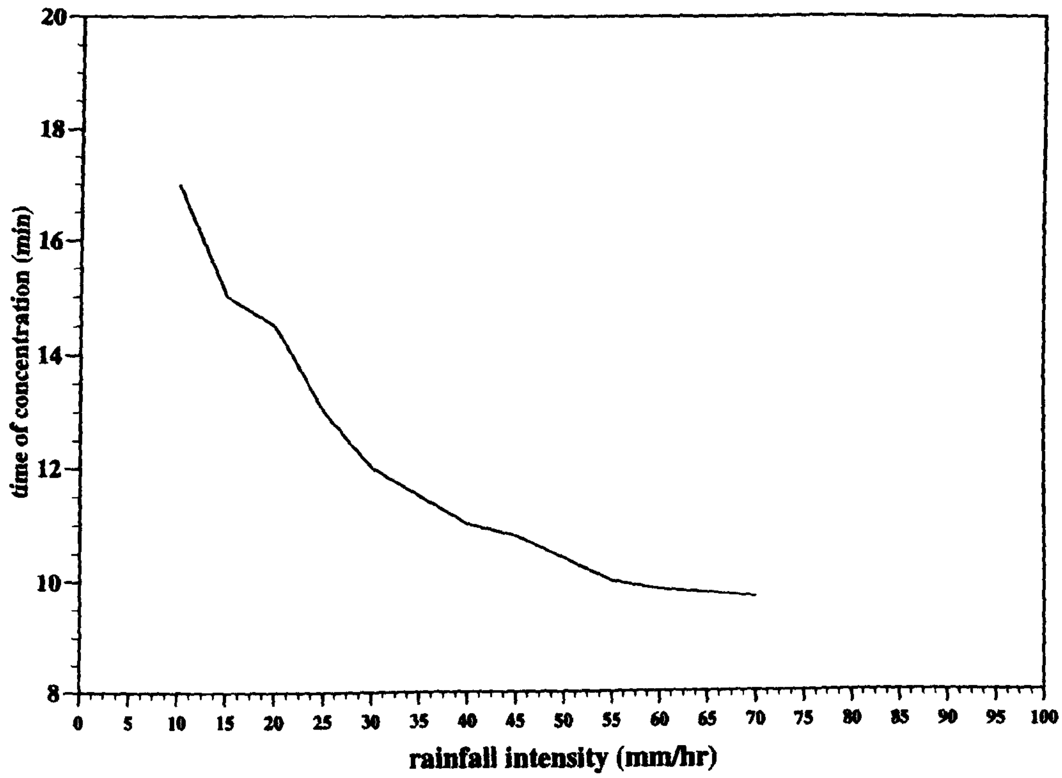


Figure 5.9 Variation of Time of Concentration.

CHAPTER 6 SENSITIVITY STUDIES ON THE MODEL

6.1 Introduction

As mentioned earlier, COSSOM uses the unit hydrograph approach to synthesize rainfall-runoff relationships. The procedure consists of adopting a unit hydrograph which results from a rainfall of specified duration and then calculating by convolution the runoff hydrograph which results from a given rainfall distribution. It is, then, the characteristics of the unit hydrograph which determine the rainfall-runoff transformation at any particular point in a catchment. If, presumably, the physical properties of the catchment remain constant then it might be expected that the characteristics of the storms might cause variations in the shape of the unit hydrograph. The storm characteristics are rainfall duration, intensity and areal distribution. Keeping in mind the relatively small area of urban catchments and the capability of the model (COSSOM) to deal with number of subcatchments, the areal variations will not be large enough to have any effect on the results.

Therefore the sensitivity of the model to the application of different rainfall intensities and durations when generating the unit hydrographs has been investigated. For these investigations a WALLRUS verified drainage network is used which is shown in fig. 5.8.

6.2 Sensitivity of the Model to the Unit Hydrograph of Different Rain Intensities

To investigate the sensitivity of the model to the TUH of various rain intensities a duration, T, equal to the mean time of concentration, t_c= 15 min, was first adopted. Different rainfall intensities are applied to the WALLRUS 'simulation method' to calculate the runoff hydrographs. The unit hydrographs are then obtained by dividing the ordinates of these hydrographs by the respective rainfall depths. These unit hydrographs are shown in fig. 6.1. It can be seen in the figure that no two unit hydrographs are identical, though they all have the same general shape. The peaks of unit hydrographs derived from smaller events occur slightly later and are lower than those derived from larger events.

This is partly because of the rainfall/runoff/pipeflow processes incorporated in WALLRUS software. The percentage runoff (PR) equation (section 2.4.2) used in WALLRUS 'simulation method' mainly depends on the antecedent conditions of the catchment. The urban catchment wetness index (UCWI) is an important parameter in the equation which governs the continuing infiltration losses. The runoff volume calculated applying this equation is then routed over the catchment surface by linear reservoir model (see section 2.4.4) which depends on storage constant k. The value of k varies with the rainfall intensity. This is why in fig. 6.1 the peaks occur earlier for higher rainfall intensities.

The difference in the peak values is because the runoff hydrograph for each rainfall intensity is divided by total depth instead of effective rainfall depth. For a small event after subtracting initial losses and applying PR equation the calculated runoff volume and hence the depth of water is relatively lower. Therefore, the time of concentration is increased as depicted in section 5.4.1 and fig. 5.8 (chapter 5). When the ordinates of the runoff hydrograph are divided by total depth of the rainfall the peak is under-estimated. For higher rainfall intensities these small variations have less effect on peak values.

These unit hydrographs are then applied to sample rainfall hyetographs using the model. The sample rain events are selected from the Time Series Rainfall (TSR) data for Liverpool (NW) region and Liverpool typical year rainfall data (1956). For each selected hyetograph the runoff hydrographs calculated by the model are compared with the output from the WALLRUS 'simulation method', some of these comparisons are shown in figures 6.2 and 6.3.

Figure 6.2 illustrates the responses of the catchment to rainfall hyetographs selected from TSR data. The peaks of runoff hydrographs show slight variation. The hydrographs compare reasonably well to the full WALLRUS simulation results for the application using TUHs from higher rain intensities.

Similarly for the results of other events the TUH modelling technique is found to show dependency on rain intensity selected in development of the unit hydrographs as shown in figure 6.3. However, when application is made with higher intensities good agreement between WALLRUS and COSSOM is achieved.

To evaluate how much error in flows might arise from selection of a given intensity for the TUH, the selected intensities and peak discharges simulated have been plotted, normalised with respective maximum values. Figure 6.4 shows the ratio ($Q_p/Q_{p\,max}$) against (I/I_{max}) for selected rainfall events. From these curves it can be seen that for the higher intensity TUHs the curves become relatively flat. Therefore for a real storm of varying intensity the TUH of relatively higher intensity rainfall would minimize the error in the predictions in comparison with the WALLRUS. The conclusion from this study is that flow predictions are not highly sensitive to the selection of the rainfall intensity (i.e. fig. 6.4 shows peaks within 20 % for I's over a wide range). As a guide selection of an intensity close to the maximum value in the observed data would appear to give the closest predictions on the basis of inspection of figures 6.2 and 6.3.

6.3 Sensitivity of the Model to the Unit Hydrograph of Different Rain Durations

It remains to investigate the sensitivity of the model to the choice of T, the rain increment duration of the TUH. Values ranging from 5 to 30 minutes are considered for the test system (fig. 5.8) with a time of concentration t_c~15 minute. In this case rainfall intensity applied for establishment of the TUH is in all cases taken as the highest present in the applied rainfall hyetographs. Resulting unit hydrographs are then applied to the model to calculate inflow volume and overflow characteristics such as overspill volume, peak discharge rate and duration. Figures 6.5 to 6.7 show flow hydrographs for selected events again in comparison against the full WALLRUS simulation.

For ease of presentation and assessment the overflow characteristics of some of these events are then normalised by dividing by those arising from selection of $T=t_c=$ 15 mins. These ratios, measuring the sensitivity of the method are shown in figure 6.8. In figure 6.8(a) Q_p indicates the ratio of maximum peak overflow rate for unit hydrographs of any duration T (Q_t) to maximum peak overflow rate for the unit hydrographs of duration equal to the time of concentration (Q_{tc}). Considerable instability is apparent for T less than t_c , whilst greater stability is evident when T approaches t_c. Similar behaviour is seen also in the total overflow volume ratios illustrated in figure 6.8(b) whilst total duration of overspill in figure 6.8(c) generally shows less sensitivity.

Use of unit hydrograph rain increment duration T close to t_c is shown to provide the closest approximation.

6.4 Consideration of Initial Losses

The methodology adopted in deriving unit hydrograph using WALLRUS is described in chapter 5. A nominal antecendant rain event is being used herein to satisfy the initial losses incorporated in the WALLRUS software and the sensitivity of the model has been tested to the consideration of this antecedent rain event.

Two unit hydrographs are calculated, one is based on the rain event which is preceded by an antecedent rain event as depicted in figure 5.1 (chapter 5) while in generating the second unit hydrograph this antecedent rain event is not considered. Figures 6.9 shows the results from COSSOM calculated using these two unit hydrographs for selected rainfall hyetographs. It can be seen in both the figures that the model shows some dependency on the consideration of initial losses i.e. it under estimates the runoff volumes and peak discharge. It shows that initial losses should be considered in the derivation of unit hydrographs for COSSOM when using the WALLRUS ' simulation method'. As far as the intensity of antecedent rain event is concerned this should be based on the catchment characteristics. Different intensities should be applied to the catchment using the WALLRUS 'simulation method'. The intensity which just produces a runoff hydrograph, showing that event is sufficient to fill the depression storage, should be selected as antecedent rain event intensity for the catchment.

6.5 Derivation of the Unit Hydrograph by Alternative Methods

As an alternative to the use of WALLRUS, the KWRM model, which is based on the kinematic wave theory as described in chapter 2, has been used to derive the unit hydrograph. The data for the drainage network (fig. 5.8) required for the KWRM are different from the SSD file format (see Appendix A.1) which is the requirement of WALLRUS. To prepare the KWRM data file the contributing area to each pipe in the network is considered as a rectangular overland flow segment with the length equal to the pipe length as shown in fig. 6.10 and the slope of segment normal to the pipe is taken as approximately 2.5 percent which is the value considered in Wallingford Procedure for catchments with medium slope. Other information such as soil index, urban catchment wetness index, percentage impermeable area and sewer dimensions are obtained directly from the SSD file.

The unit hydrograph is calculated using the same procedure as mentioned earlier in chapter 5. KWRM employs the percentage runoff equation used in calculating runoff volume, given in WALLRUS 'simulation method'. The treatment to the rainfall data prior to its application to calculate runoff volume is slightly different as described in chapter 2. The approximations made about the contributing area to each pipe and its slope clearly influence the unit hydrograph as illustrated in fig. 6.11, which shows that the peak of the unit hydrograph is lower than when using the unit hydrograph obtained from WALLRUS. The variation in the peak value and time to peak is because of the difference in sewer flow routing techniques and surface runoff collection procedure. In WALLRUS runoff from each contributing area is collected in each manhole whereas in KWRM surface runoff is distributed along the collecting pipe. However, the results from COSSOM based on these two unit hydrographs show reasonably good agreement as shown in fig. 6.12. Improvements can be made if data required by the KWRM is obtained directly from catchment survey.

Therefore, with little loss in accuracy relative to WALLRUS approach for unit hydrograph development, the model (COSSOM) can be operated with Rainfall/Runoff/Pipeflow models other than proprietary product.

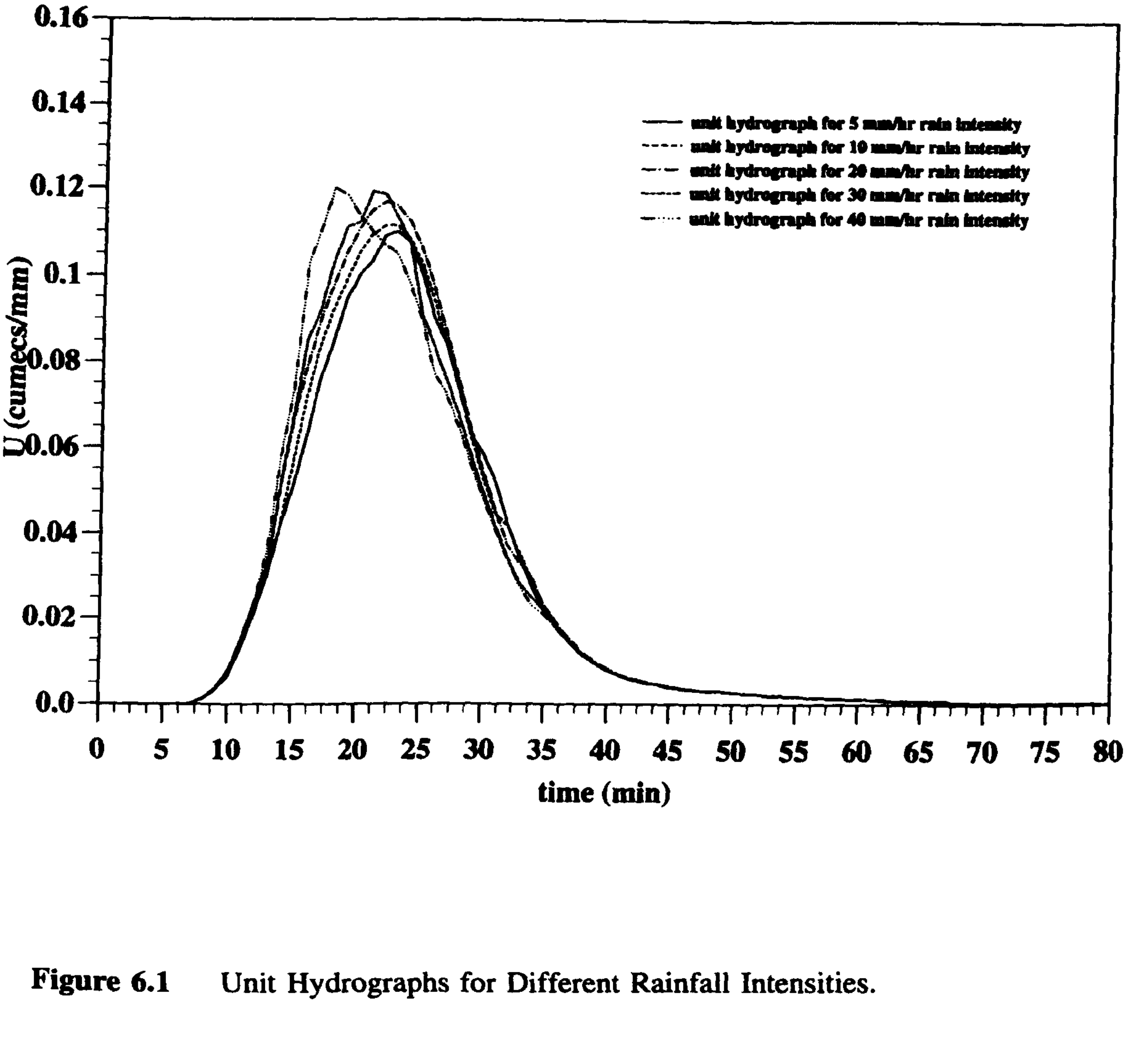


Figure 6.1 Unit Hydrographs for Different Rainfall Intensities.

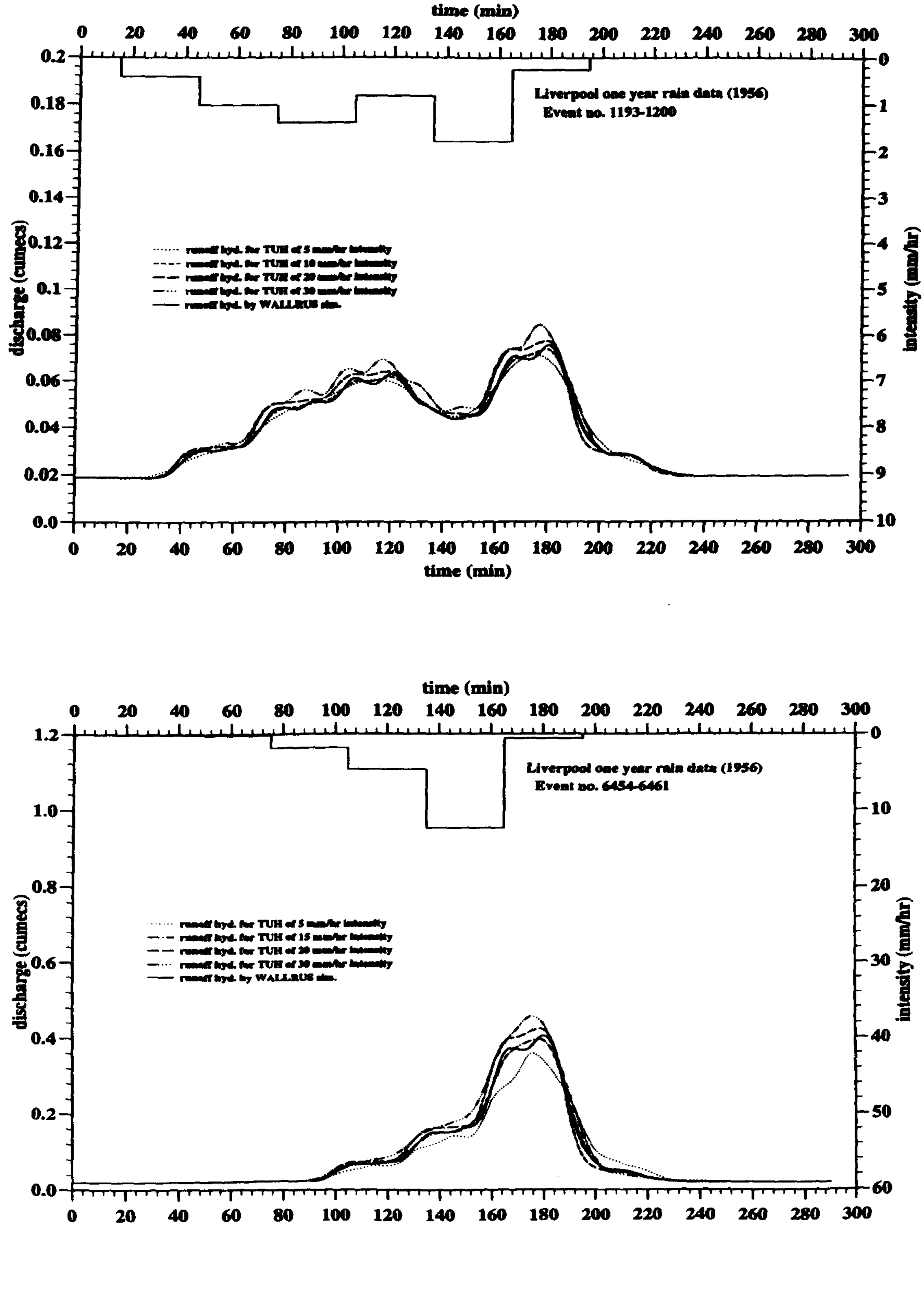
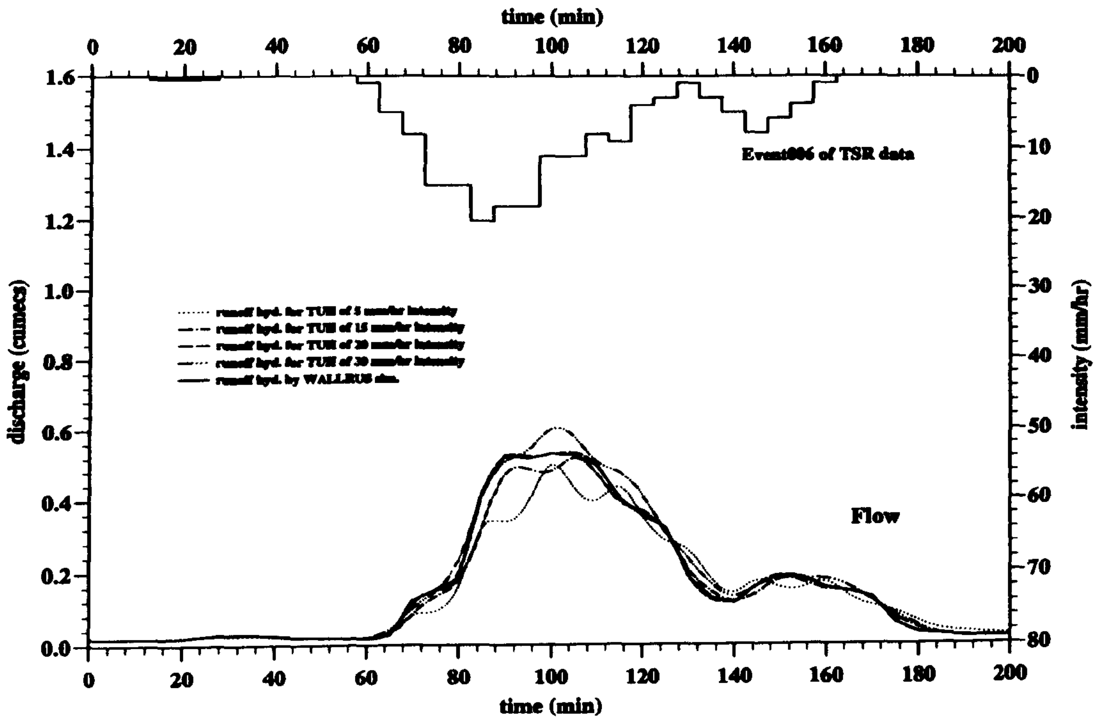


Figure 6.2 Sensitivity of Unit Hydrograph Approach to Selection of Rainfall Intensity.



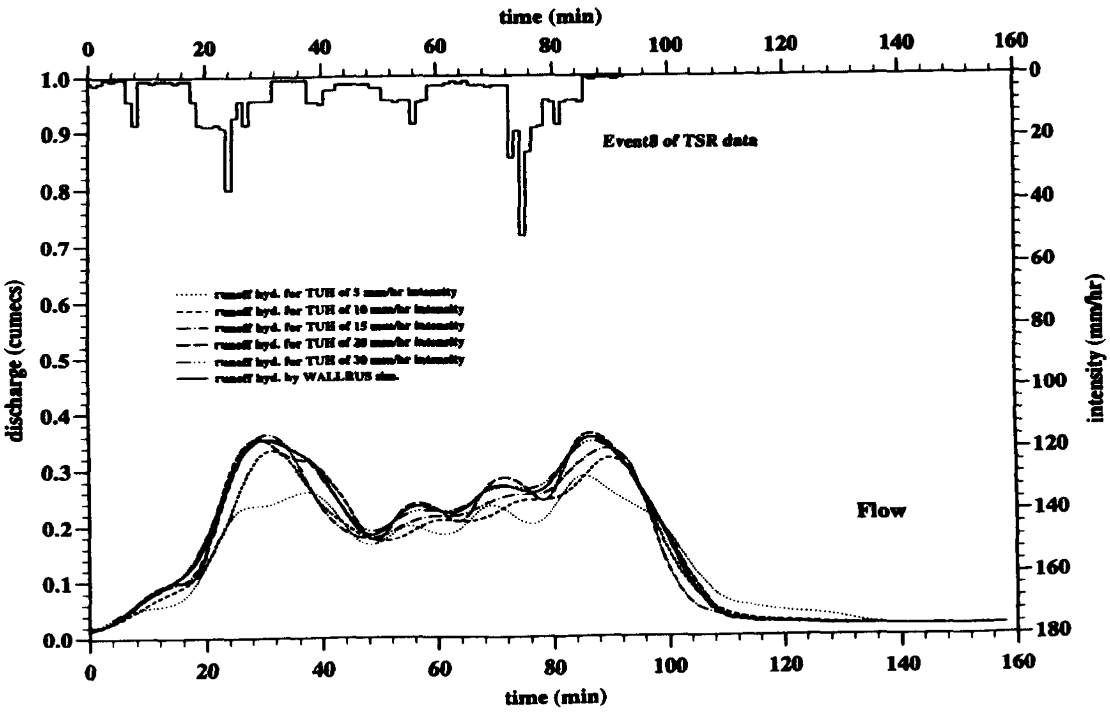


Figure 6.3 Sensitivity of Unit Hydrograph Approach to Selection of Rainfall Intensity.

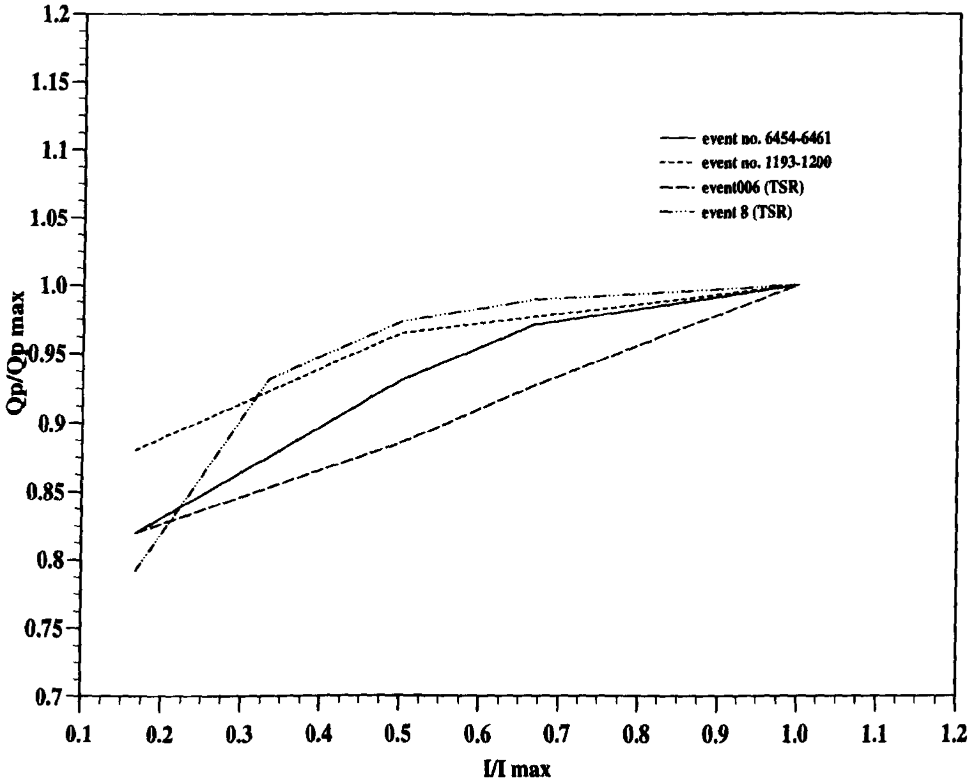


Figure 6.4 Relative Difference in Flows For TUH's of Different Rain Intensities.

Qp = Peak inflow
Qw = Peak inflow calculated by WALLRUS
I/Imax = Intensity maxima

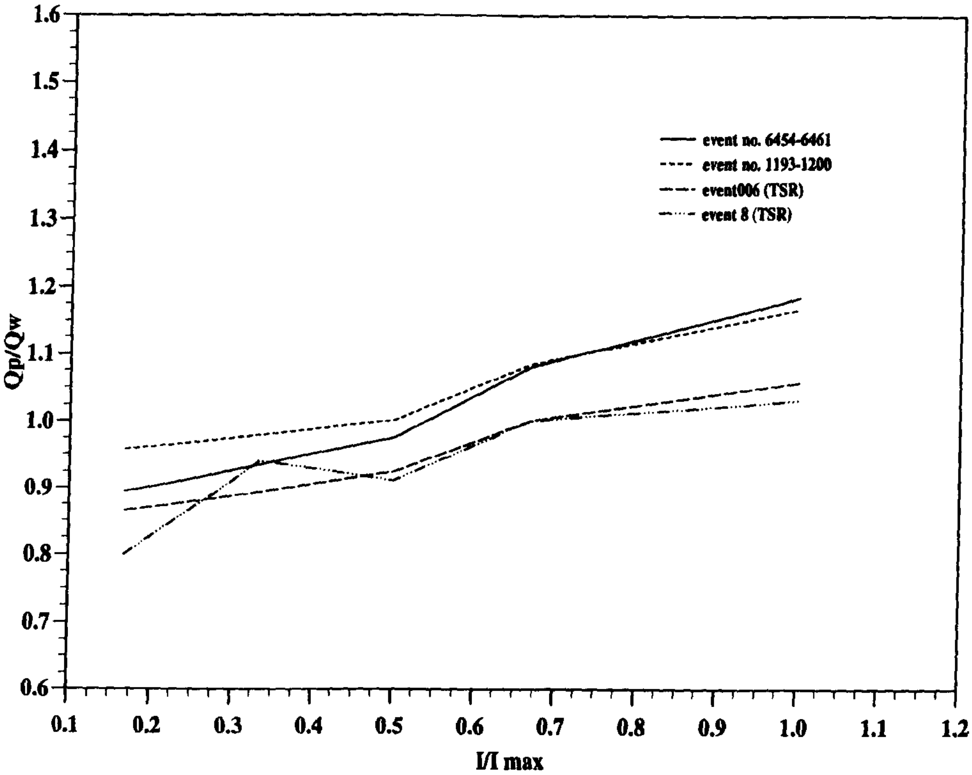


Figure 6.4(a) Relative Error in Flows Predicted by COSSOM for TUH's of Different Rain Intensities in Comparison to the WALLRUS results

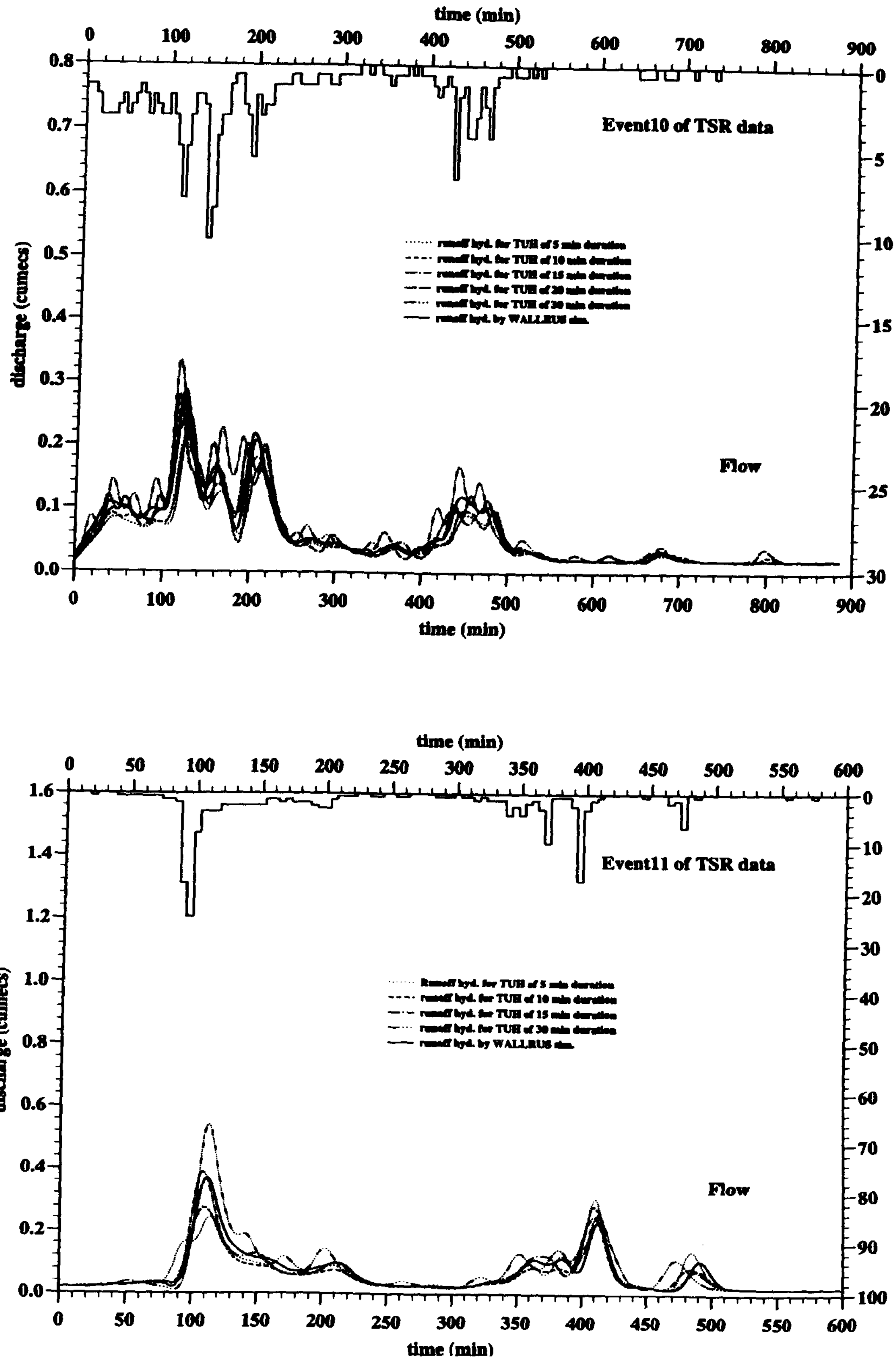
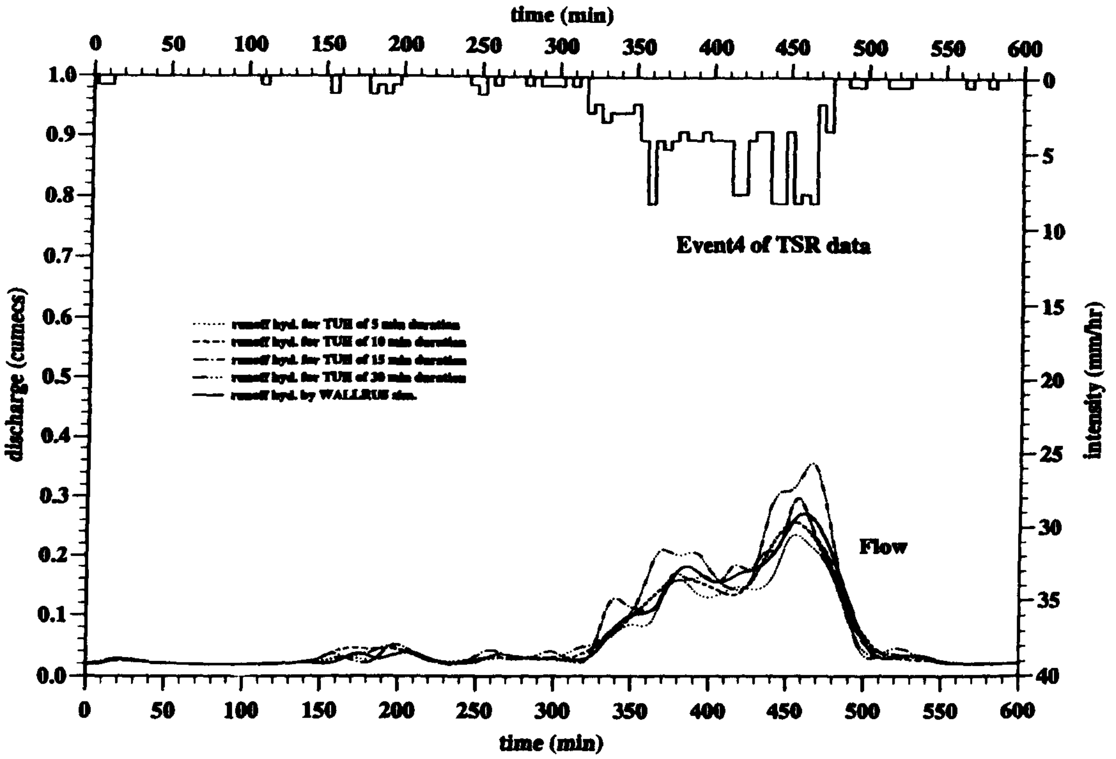


Figure 6.5 Sensitivity of Unit Hydrograph Approach to Selection of Rainfall Increment Duration.



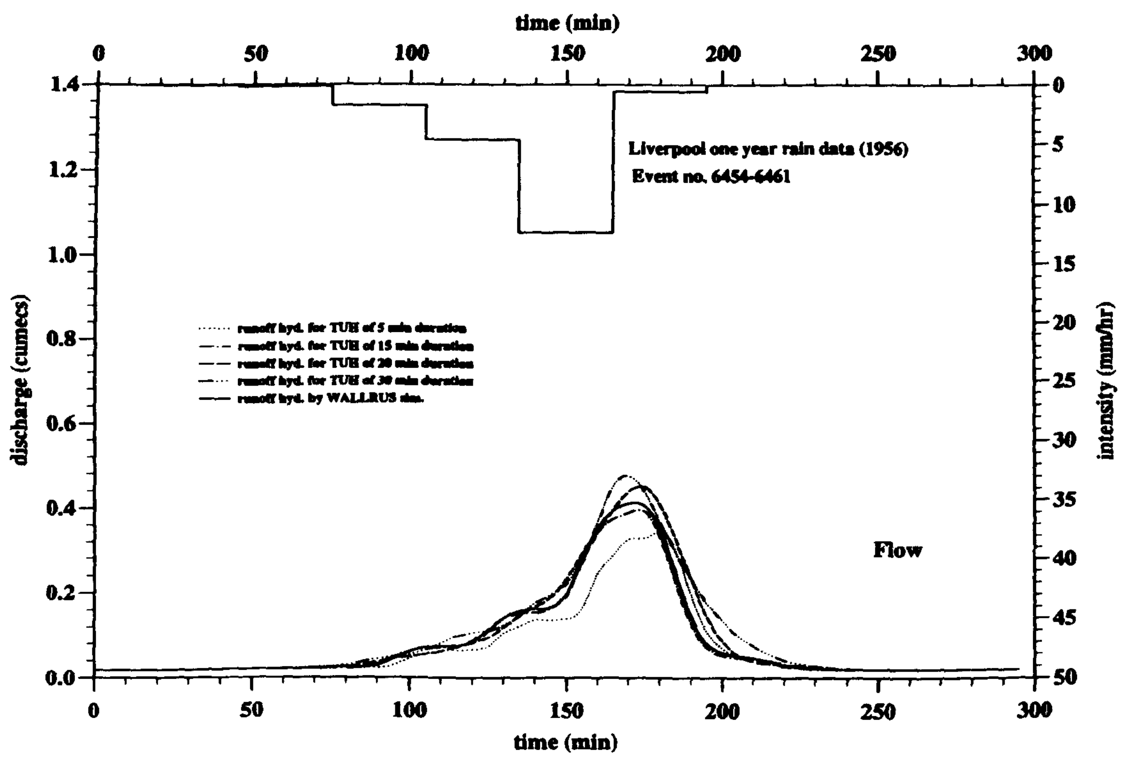
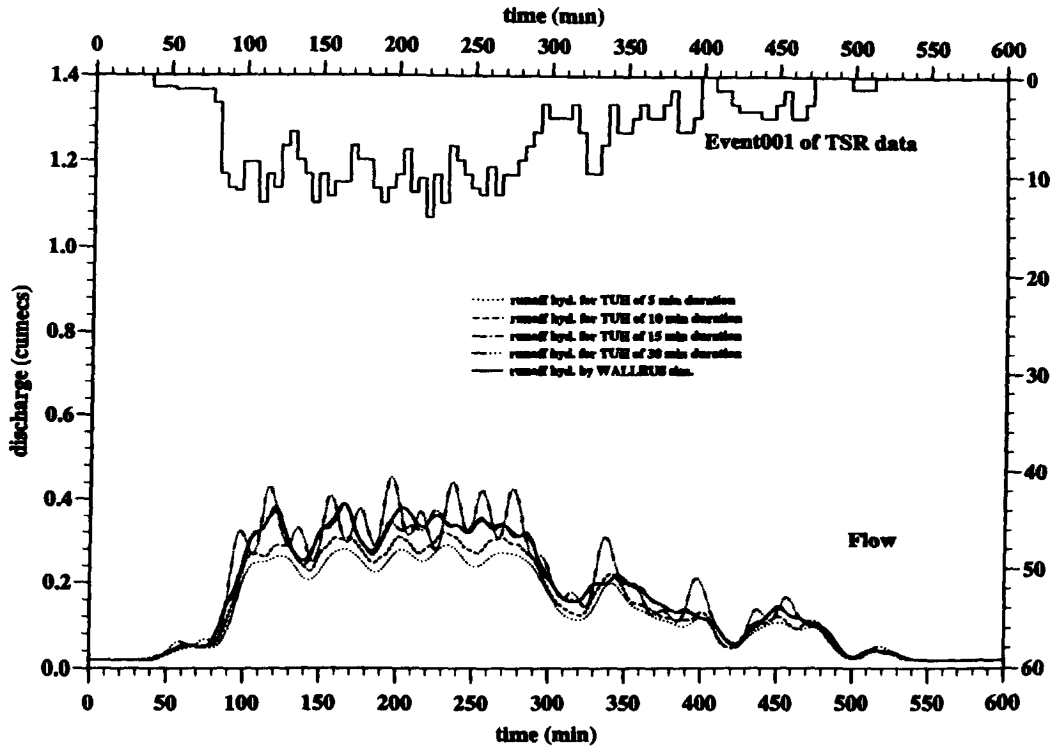


Figure 6.6 Sensitivity of Unit Hydrograph Approach to Selection of Rainfall Increment Duration.



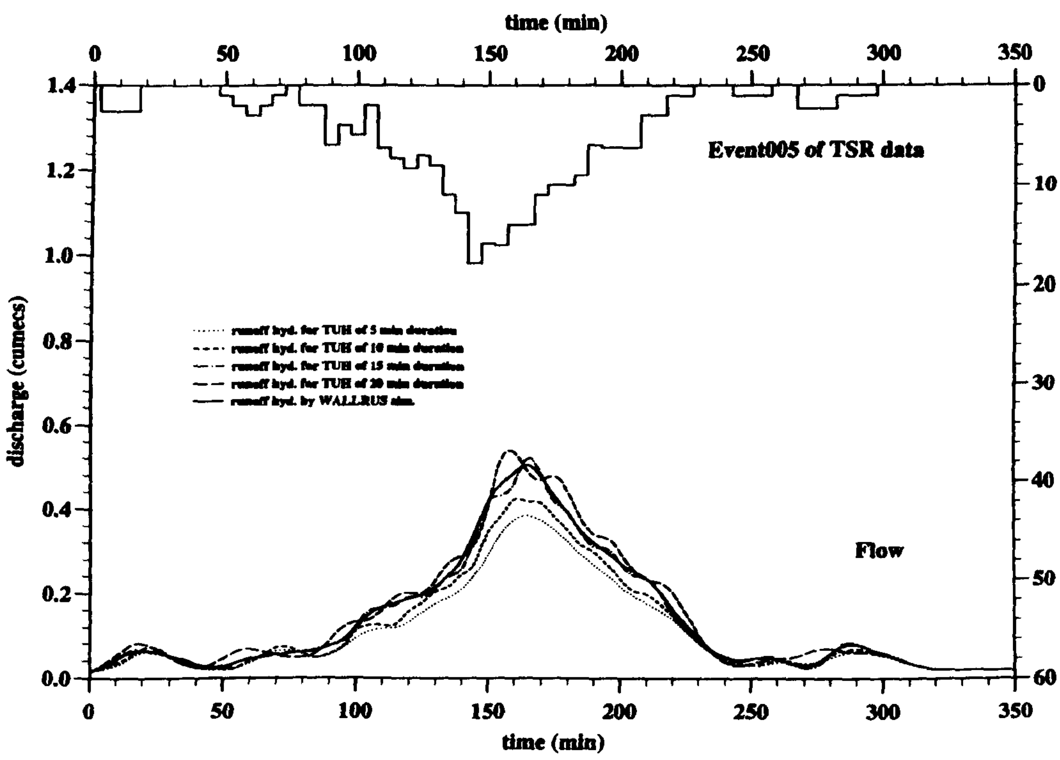


Figure 6.7 Sensitivity of Unit Hydrograph Approach to Selection of Rainfall Increment Duration.

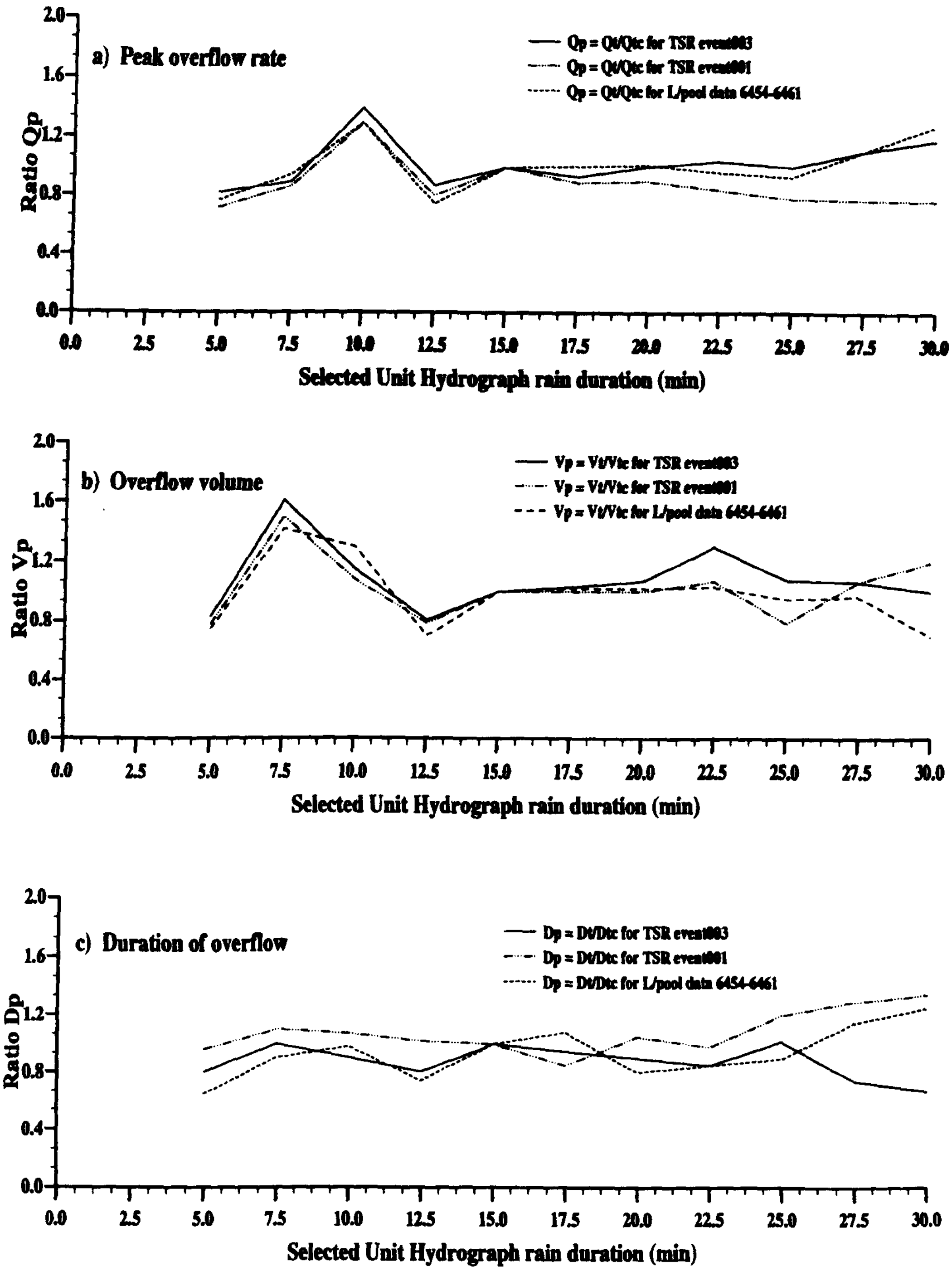
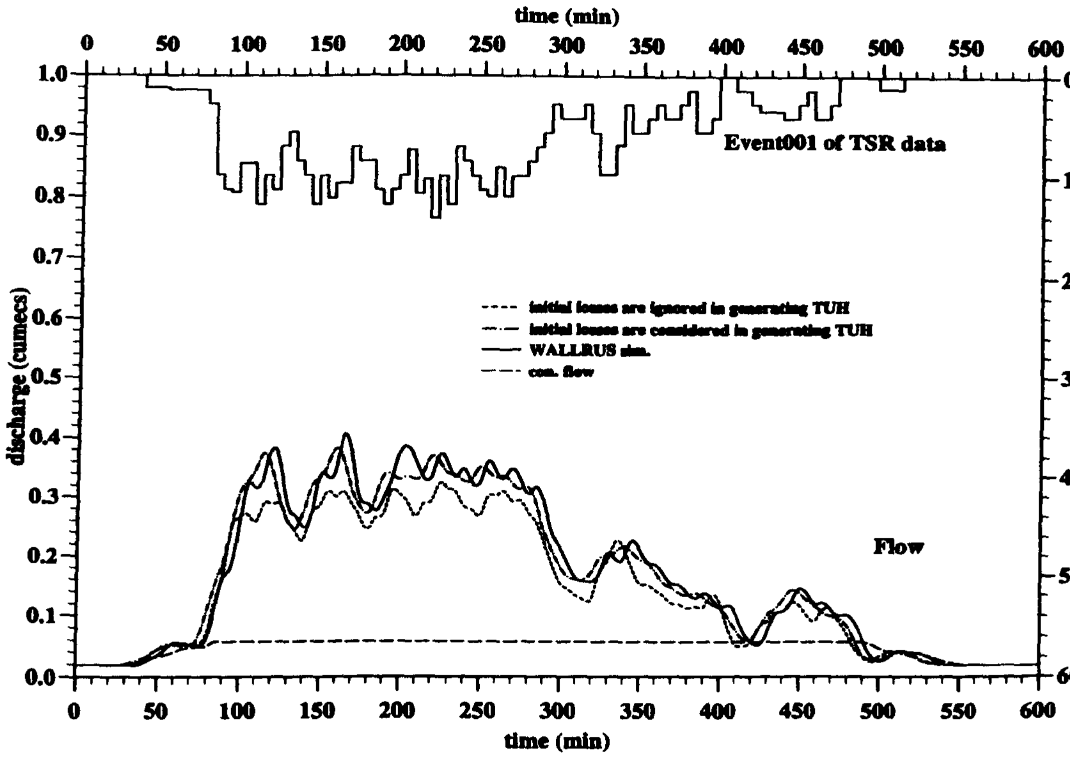


Figure 6.8 Influence of Choice of Rainfall Increment Duration on Overflow Operation Characteristics.



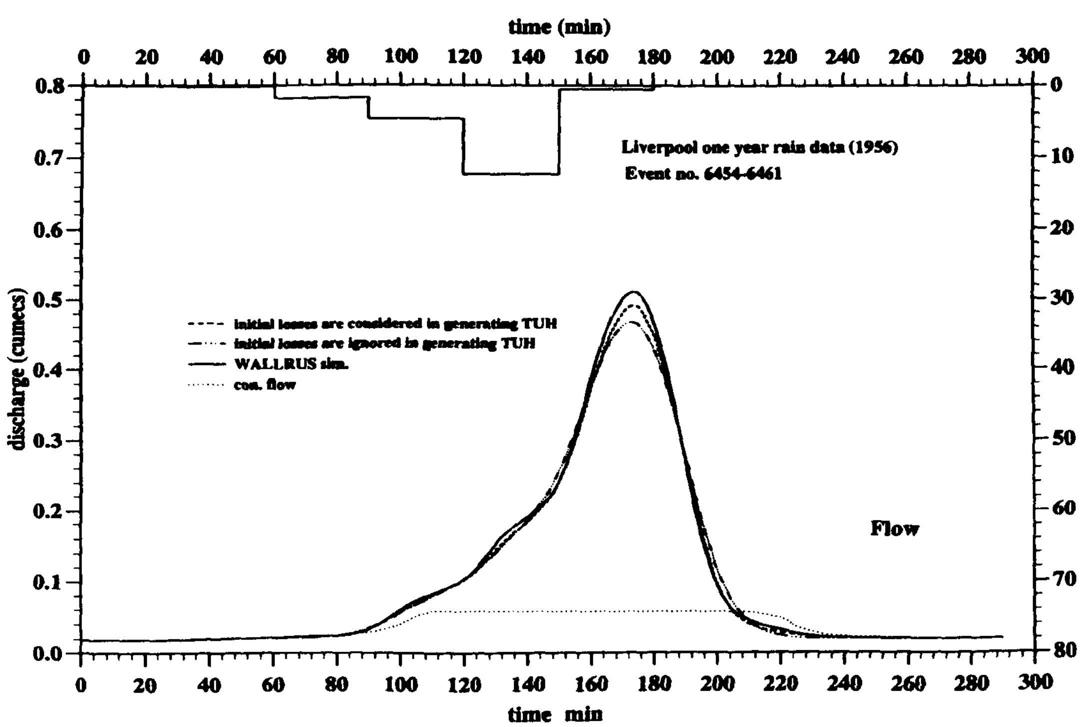


Figure 6.9 Sensitivity of Unit Hydrograph Approach to Consideration of Initial Losses.

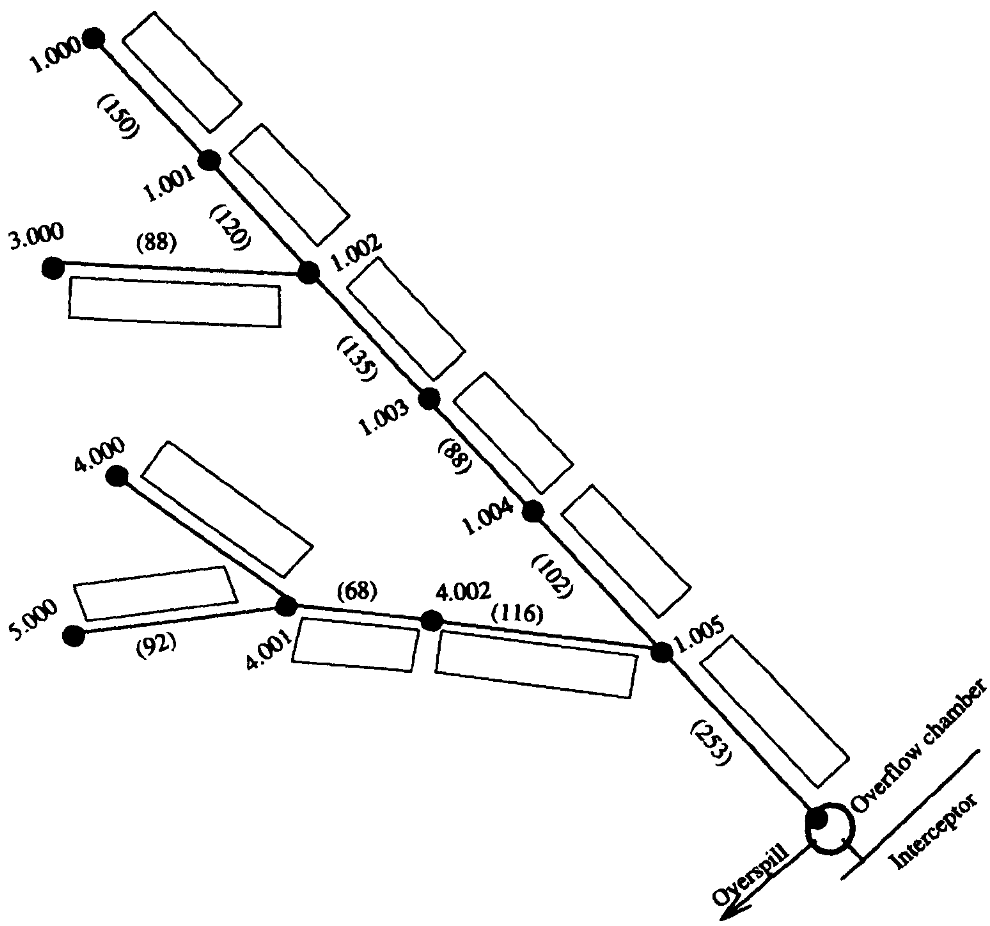


Figure 6.10 Test Sewerage System Layout for KWRM

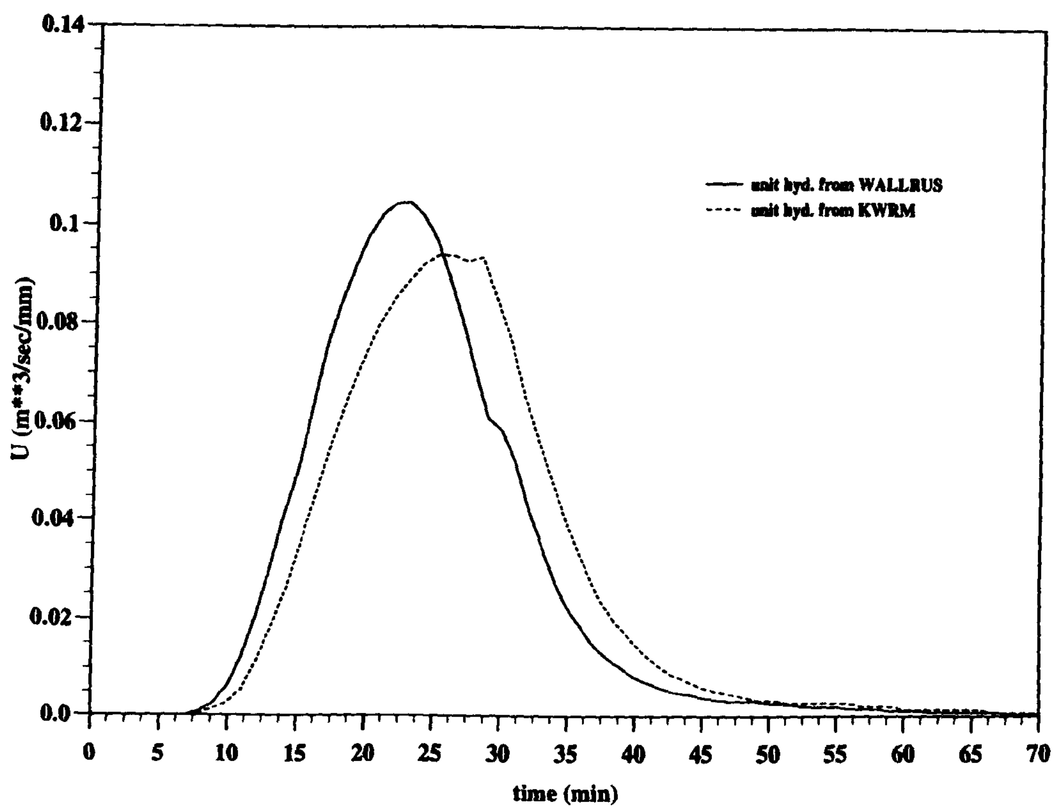
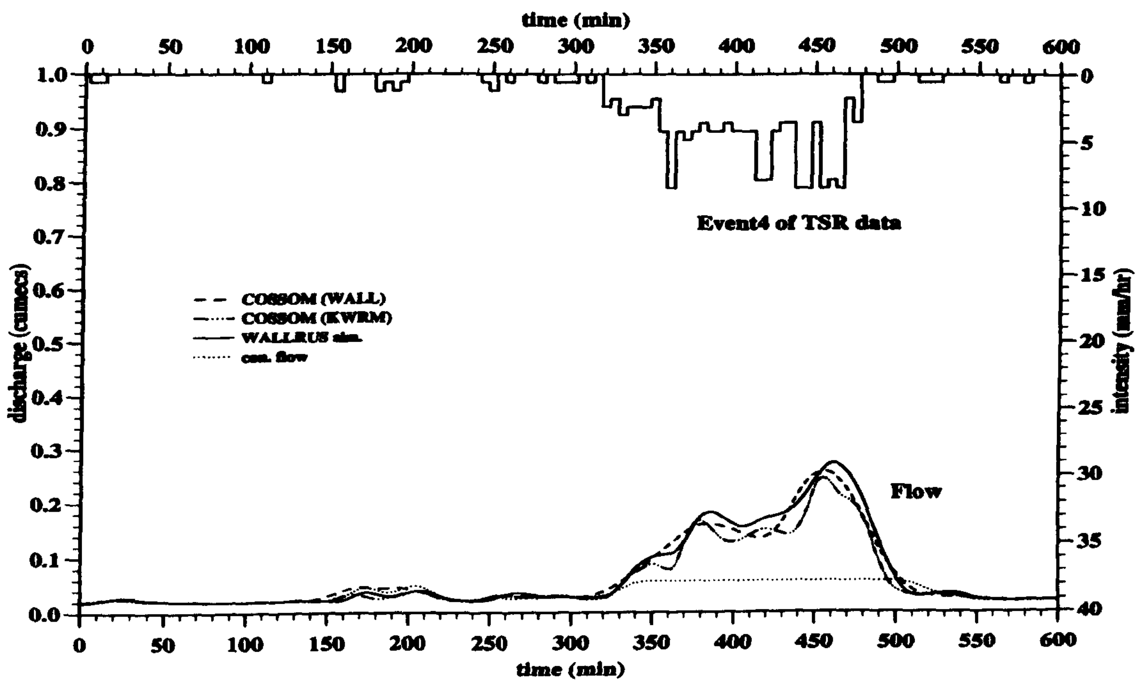


Figure 6.11 Comparison of Unit Hydrographs Obtained from WALLRUS and KWRM for Test Sewerage System.



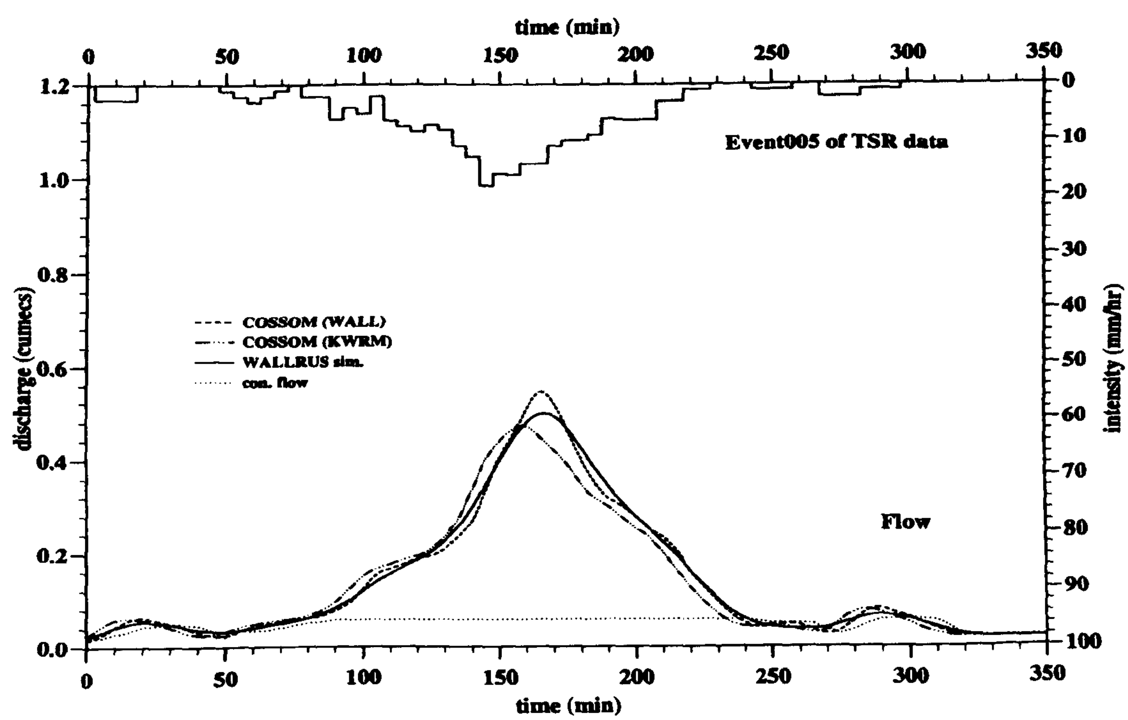


Figure 6.12 Comparison of Predicted Flows by WALLRUS Simulation Method and COSSOM (using TUH from WALLRUS and KWRM) for Test Sewerage System.

CHAPTER 7 VERIFICATION STUDIES

7.1 Introduction

The COSSOM is a simplified treatment of the rainfall, runoff and pipe flow processes, therefore it needs to be verified by comparison of its results with those obtained from the most detailed methods as well as observed data. Here verification studies are conducted by comparing the model results with WALLRUS predictions and field data obtained for Middlewood Road catchment area in Sheffield.

Three drainage networks, one hypothetical and other two existing networks are used. For hypothetical and Fleetwood (Blackpool) sewerage systems the comparison is made between the COSSOM and the WALLRUS results. The rain events are selected from annual Time Series Rainfall data for North west region and a one year rainfall record for Liverpool (1956). The application of Liverpool rainfall data to the Fleetwood catchment is only for illustrative purposes.

A verified sewerage system model of the Middlewood Road catchment area in Sheffield has also been used. For this catchment the observed runoff hydrographs from four real storms were available. Therefore, results of the model (COSSOM) based on TUHs from WALLRUS and KWRM are compared with observed hydrographs alongside the WALLRUS results. In the following sections these catchments are briefly described and presented results are discussed.

7.2 Catchment Description

7.2.1 Hypothetical Catchment

This is considered as an urban catchment with total area of 220.2 hectares out of which 97.93 hectares is total paved area. The sewerage system is assumed to be combined with a total dry weather flow 0.114 m^3/sec. It contains 74 sewers and five storm overflows at different locations. The network is shown in fig. 7.1 and the Sewerage System Data (SSD) file in WALLRUS format is included in Appendix A.3 which includes the slope, shape, diameter, contributing area, dry weather flow etc. for each pipe and also the details of overflow structures.

To obtain the data for COSSOM the catchment is divided into six subcatchments. The downstream end of each subcatchment is given a site number. The site 3 in the network is without an overflow structure. The unit hydrographs are obtained from WALLRUS application to these subcatchments individually. Other data such as area, dry weather flow, chamber storage volume and continuation pipe length,slope and diameter for each subcatchment is taken from the SSD file. The velocity in the pipe or group of pipes which carry pass forward flow down to next subcatchment in the hierarchy of the system is obtained from WALLRUS application to the complete network. This information is grouped in the system data file for COSSOM which is given in Appendix A.7.

7.2.2 Fleetwood Catchment

Fleetwood catchment area (NWW 1993) is located in Blackpool. It is a combined sewerage system which contains a total of 970 sewers. For this study only a part of this sewerage system is selected because the WALLRUS 400 pipe version package is used. Hereafter only this part will be discussed.

This part constitutes 316 sewers and five storm overflows. The sewers vary in diameter from 225 mm to 1000 mm. The total catchment area is 113 hectares out of which 73.45 hectares is paved. The drainage network is shown in fig. 7.2 and the Sewerage System Data (SSD) file is given in Appendix A. 4

For COSSOM application each overflow site is considered as the downstream end of the subcatchment as shown in fig. 7.2. Data is obtained following the same methodology as described above and is included in Appendix A. 8

7.2.3 Middlewood Road Catchment

The Middlewood Road catchment area is situated in Sheffield. The sewerage system model was developed in WASSP format which is an earlier version of WALLRUS software. This model was verified using the recorded data for four storms. The drainage network is shown in fig. 7.3 and the SSD file is given in Appendix A. 5.

The total area of the catchment is 272.1 hectares and total paved area is 106.1 hectares. It contains 227 sewers, 7 stormwater overflows and 3 balancing chambers. These balancing chambers operate during storm events and the excess water from these chambers is carried down the path by pipes which join back the main sewers before the next stormwater overflow structure. Therefore, these chambers are not considered for the COSSOM application and only six stormwater overflow sites are selected to check the validity of COSSOM in comparison with observed data along with the WALLRUS predictions.

7.3 Discussion

Three catchments described above are used to verify COSSOM. Rainfall series used for this verification study include annual TSR data, typical one year rainfall record for Liverpool (1956) and four observed storm events.

For hypothetical catchment shown in fig. 7.1 different rainfall events are applied to COSSOM and WALLRUS to calculate runoff hydrographs and overflow characteristics at various sites. The runoff hydrographs are shown in figures 7.4 to 7.24. Each rainfall hyetograph applied is also shown on the respective figure. The results are summerised in table 7.1. The COSSOM results show a close fit with the WALLRUS predicted hydrographs. Occasionally, slight departures during the build up and recession for the continuation hydrographs arise from residual differences in the hydraulic specification for the overflow operation between the two models but this is significant only to the moderate overspill events.

COSSOM predicted inflow volumes within ±3.5% of WALLRUS predictions as seen in table 7.1. The overflow volumes are added together to see the difference in total values which is found to vary within ±7.5 % of WALLRUS results. As far as peak overflow rates are concerned the difference is calculated for maximum peak overflow rates obtained from COSSOM and WALLRUS by considering all the sites. Both the models have consistently predicted maximum peak overflow rates at site 6. COSSOM predicted maximum peak overflow rates for all the events applied are within ±8 % of WALLRUS values.

Pollution loads discharged from these overflows are given in table 7.6. These loads are calculated by COSSOM and by the mean event concentration model which is incorporated in the WALLRUS software. For these calculations default values of concentrations of BOD, TSS, and NH4-N are used in both models. As these discharges are primarily dependent on overspill volumes therefore differences must be the same as in the volumes.

Table 7.2 presents results from application of the COSSOM to longer sub-sets of the 1956 data based on unit hydrographs corresponding to maximum intensity in respective sub-set. It is clearly seen that the COSSOM is able to synthesize catchment flows consistently close to the WALLRUS predictions. Whilst storm overflow volumes do deviate significantly, by as much as 10% for total volume from different sub-sets of the time series, and by greater margins for individual structures, the sense of the error appears to be partially compensatory and overall predictions are seen to be within 3% here.

Application of the COSSOM to the sub-sets using the unit hydrographs obtained from fixed rain intensities of 5 mm/hr, 10 mm/hr and 15 mm/hr intensities are also included in table 7.2. It can be seen that for long-term rainfall records the results show only slight sensitivity to the selection of rainfall intensity (for generating the unit hydrographs).

Application of selected rainfall hyetographs to the existing drainage network in Fleetwood, shown in figure 7.2, has also been made for validation. Some of the results are shown in figures 7.25 to 7.34. Summary of the results is included in table 7.3. From this table it can be seen that the inflow volumes and overspill volumes predicted by the different methods are well within ±5 % . Again the

COSSOM predicted peak overflow rates compare reasonably well with WALLRUS results.

Application has again been made using the chronological 1956 data set. Table 7.4 summarises results (for all overflow structures in the system) and percentages quoted indicate the departures of COSSOM from the WALLRUS results. The final column shows the TUH method to be within 4% of WALLRUS values for inflow volumes and, within 2% for total overflow volume. These results are achieved by COSSOM using less than 3% of the computer run time required by the full WALLRUS simulation. In this case, on a 66MH, 486DX2 PC computer, the one year WALLRUS simulation for the Fleetwood system is seen to have taken 49.2 hours computational time against 1.3 hours (1 hr. set up time and 20 min. computational time) for COSSOM.

COSSOM has also been used to reproduce runoff hydrographs from recorded storms on the Middlewood catchment in Sheffield. Results at different sites are compared with observed hydrographs as well as WALLRUS predictions in figures 7.35 to 7.46. Two COSSOM results are shown in each figure, for one result COSSOM utilises the TUH obtained from WALLRUS application and for other it uses the TUH obtained from KWRM application. Comparison between COSSOM and WALLRUS is reasonably close. Observed hydrograph do vary significantly in some cases and the predicted hydrographs differ as much as 50 % from observed data. These variations and inconsistencies are attributed to the underreading or overreading of the flow data and in some cases loss of reading during storm events. It is suggested in the final report by the supplier of the data (GCA 1990) that impervious areas allocated to some of the sites need further adjustments. The results are summarised in table 7.5.

Finally, figures 7.47 to 7.49 illustrate the storm overflow operation characteristics which can be established from a long rainfall sequence, in this case a one year (1956) simulation applied to the Fleetwood system. The influence of overflow chamber volumes is immediately apparent and similar relationships have been established for variation in throughflow setting as shown in figures 7.50 to 7.52. Such long-term performance synthesis capability is considered to be of potential value to decision making in the area of urban pollution management.

Item	Program	Location	Time Series Rainfall Data Regionalised for Liverpool from SW Series						Liverpool One Year Data (1956)	
			Eent001	**Event005**	**Event006**	**Event4**	**Event11**	**Event79**	**6454-6461**	**6500-6520**
Inflow Volume (m^3)	WALLRUS	Site 1	6183.00	3022.00	2100.00	2470.00	2770.00	1736.00	1409.00	2845.00
		Site 2	8801.00	4315.00	2921.00	4200.00	4765.00	3509.00	2303.00	4880.00
		Site 3	9185.00	5169.00	3392.00	5441.00	5893.00	5400.00	3248.00	5963.00
		Site 4	6192.00	3018.00	2098.00	2472.00	2768.00	1733.00	1407.00	2850.00
		Site 5	6190.00	3016.00	2100.00	2470.00	2770.00	1734.00	1409.00	2852.00
		Site 6	21297.00	11389.00	7481.00	11898.00	13002.00	11083.00	6177.00	13454.00
		Tot. Inflow	**47195.0**	**22647.0**	**15910.0**	**17948.0**	**19597.0**	**11412.0**	**10912.0**	**22702.0**
	COSSOM	Site 1	6017.00	2879.00	1929.00	2432.00	2636.00	1707.00	1451.00	2953.00
		Site 2	8696.00	4255.00	2766.00	4236.00	4592.00	3432.00	2340.00	4794.00
		Site 3	9905.00	5207.00	3434.00	5605.00	6115.00	5326.00	3172.00	6040.00
		Site 4	6017.00	2880.00	1929.00	2428.00	2634.00	1706.00	1451.00	2956.00
		Site 5	6017.00	2879.00	1933.00	2433.00	2636.00	1707.00	1451.00	2956.00
		Site 6	21777.00	11368.00	7549.00	12143.00	13178.00	10991.00	6001.00	13520.00
		Tot. Inflow	**47290.0**	**22316.0**	**15424.0**	**18159.0**	**19369.0**	**11346.0**	**10741.0**	**22631.0**
		Diff. %	**-0.20**	**+1.50**	**+3.10**	**-1.16**	**+1.18**	**+0.58**	**+1.59**	**+0.31**
Overflow Volume (m^3)	WALLRUS	Site 1	3449.00	1527.00	1200.00	713.00	841.00	0.00	584.00	1088.00
		Site 2	5255.00	2173.00	1608.00	1300.00	1584.00	119.00	954.00	1992.00
		Site 4	3399.00	1538.00	1198.00	695.00	833.00	0.00	579.00	1085.00
		Site 5	3287.00	1543.00	1200.00	710.00	835.00	0.00	582.00	1091.00
		Site 6	10508.00	4477.00	3223.00	2632.00	2502.00	210.00	2036.00	3992.00
		Total	**25898.0**	**11258.0**	**8429.0**	**6050.0**	**6595.0**	**329.0**	**4735.0**	**9248.0**
	COSSOM	Site 1	3365.00	1492.00	1105.00	662.00	698.00	0.00	618.00	1134.00
		Site 2	5158.00	2184.00	1552.00	1361.00	1431.00	133.00	982.00	1903.00
		Site 4	3367.00	1492.00	1106.00	662.00	698.00	0.00	618.00	1134.00
		Site 5	3367.00	1492.00	1105.00	662.00	698.00	0.00	618.00	1134.00
		Site 6	10256.00	4288.00	3007.00	2669.00	2666.00	222.00	1904.00	3806.00
		Total	**25513.0**	**10948.0**	**7875.0**	**6016.0**	**6191.0**	**355.0**	**4740.0**	**9111.0**
		Diff. %	**+1.51**	**+2.83**	**+7.44**	**+0.57**	**+4.39**	**-7.32**	**-0.11**	**+1.50**
Peak Overflow Rate (m^3/sec)	WALLRUS	Site 1	0.294	0.405	0.482	0.178	0.156	0.0	0.289	0.177
		Site 2	0.364	0.489	0.556	0.253	0.225	0.048	0.374	0.231
		Site 4	0.294	0.405	0.482	0.178	0.156	0.0	0.289	0.178
		Site 5	0.294	0.405	0.482	0.178	0.156	0.0	0.289	0.178
		Site 6	0.628	0.883	0.923	0.484	0.388	0.115	0.448	0.460
	COSSOM	Site 1	0.290	0.398	0.408	0.181	0.138	0.0	0.308	0.169
		Site 2	0.363	0.486	0.489	0.262	0.211	0.049	0.393	0.207
		Site 4	0.290	0.398	0.408	0.181	0.138	0.0	0.308	0.169
		Site 5	0.290	0.398	0.408	0.181	0.138	0.0	0.308	0.169
		Site 6	0.678	0.896	0.958	0.468	0.418	0.116	0.415	0.473

Table 7.1 Runoff and Overflow Calculations for Hypothetical Sewerage System (Fig. 7.1) for Selected Rainfall Events

			RESULTS FOR LIVERPOOL RAINFALL DATA (1956)													
			Rainfall Data Series													
Item	Program	Site Location	1 – 500	501 – 1000	1001 – 1500	1501 – 2000	2001 – 2500	2501 – 3000	3001 – 3500	3501 – 4000	4001 – 4500	4501 – 5000	5001 – 5500	5501 – 6000	6001 – 6520	Total
Rainfall Runoff Volume (m^3)	WALLRUS	Site 1	5078	5080	6504	6200	5472	5540	5122	7803	7801	6762	4807	5412	8832	80413
		Site 2	9887	9700	12175	11455	10664	10854	9614	13747	13589	12700	9145	10043	14967	148540
		Site 4	5078	5080	6504	6200	5477	5559	5134	7845	7870	6887	4918	5549	8867	80953
		Site 5	5087	5080	6504	6200	5477	5559	5134	7845	7870	6885	4920	5576	8891	81004
		Site 6	26813	25482	31915	28985	28429	29972	26468	33200	31471	32014	25611	26032	35310	381702
	COSSOM	Site 1	5242	5047	6482	6016	5364	5480	4999	7682	7490	6462	4597	5033	8622	78273
		Site 2	9713	9633	12020	11163	10268	10622	9455	13423	12941	11857	8848	9444	14437	143824
		Site 4	5242	5047	6482	6106	5364	5480	4999	7682	7490	6462	4597	5033	8622	78273
		Site 5	5242	5047	6428	6016	5364	5480	4999	7682	7490	6500	4597	5105	8713	78374
		Site 6	25984	25816	31204	28450	28004	29459	25927	32191	30728	30131	24817	25398	34872	371981
Overflow Volume (m^3)	WALLRUS	Site 1	266	502	997	1074	362	360	410	1688	1893	1100	324	613	2543	12132
		Site 2	1224	1635	2653	2400	1345	1120	1256	3746	4200	2500	777	1500	4200	28556
		Site 4	266	502	998	1046	361	355	409	1688	1893	1173	324	613	2543	12171
		Site 5	268	545	968	1060	372	363	423	1632	1800	1108	328	619	2543	12029
		Site 6	1385	1440	2229	2610	1250	713	1599	4007	4200	2700	918	1300	4000	28351
		Subtotal	**3409**	**4624**	**7845**	**8190**	**3690**	**2911**	**4097**	**12761**	**13986**	**8581**	**2671**	**4645**	**15829**	**93239**
	COSSOM	Site 1	252	456	938	1046	459	338	490	1937	2034	1061	341	622	2781	12755
		Site 2	1299	1504	2421	2511	1449	1329	1195	4031	4052	2735	833	1503	4318	29180
		Site 4	252	469	923	1055	464	331	499	1942	2050	1076	332	645	2782	12820
		Site 5	252	456	938	1046	459	338	490	1937	2034	1061	341	622	2781	12755
		Site 6	1150	1554	2372	2534	1253	787	1274	4160	4150	2766	836	1379	3931	28146
		Subtotal	**3055**	**4439**	**7592**	**8192**	**4084**	**3123**	**3948**	**14007**	**14320**	**8699**	**2683**	**4771**	**16593**	**95656**
		Diff. %	**-10.40**	**-4.03**	**-3.20**	**+0.20**	**+10.7**	**+7.20**	**-3.60**	**+9.70**	**+2.40**	**+1.40**	**+0.50**	**+2.70**	**+4.80**	**+2.60**
COSSOM results using TUH derived for 15 mm/hr intensity		**Subtotal**	**3211**	**4682**	**7678**	**8235**	**4120**	**3190**	**4201**	**14033**	**14348**	**8812**	**2797**	**4910**	**16593**	**96810**
		Diff. %	**-5.80**	**+1.25**	**-2.13**	**-0.55**	**+11.65**	**+9.60**	**+2.54**	**+9.96**	**+2.58**	**+2.69**	**+4.71**	**+5.70**	**+4.80**	**+3.83**
COSSOM results using TUH derived for 10 mm/hr intensity		**Subtotal**	**3165**	**4510**	**7500**	**8100**	**4084**	**3157**	**3960**	**13978**	**14207**	**8576**	**2703**	**4675**	**16203**	**94818**
		Diff. %	**-7.16**	**-2.46**	**-4.40**	**-1.10**	**+10.67**	**+8.45**	**-3.34**	**+9.54**	**+1.58**	**-0.06**	**+1.19**	**+0.65**	**+2.36**	**+1.69**
COSSOM results using TUH derived for 5 mm/hr intensity		**Subtotal**	**3055**	**4339**	**7426**	**8064**	**3978**	**3123**	**3843**	**13867**	**14001**	**8452**	**2681**	**4534**	**14741**	**92104**
		Diff. %	**-10.40**	**-6.16**	**-5.34**	**-1.54**	**+7.80**	**+7.28**	**-6.20**	**+8.67**	**+0.11**	**-1.50**	**+0.37**	**-2.38**	**-6.87**	**-1.22**
Run time (sec)	WALLRUS		2100	1980	2280	2520	2280	2400	1980	2100	2040	1800	1920	2520	2700	26838
	COSSOM		50	50	50	50	50	50	50	50	50	50	50	50	55	655

Table 7.2 Overflow Calculations for Hypothetical Sewerage System illustrated in Figure 7.1 for Liverpool One Year Rainfall Record (1956)

Item	Program	Overflow Location	Time Series Rainfall Data Regionalised for Liverpool from SW Series					Liverpool One Year Data (1956)	
			Eent001	**Event005**	**Event006**	**Event10**	**Event79**	**6454-6461**	**6450-6500**
Inflow Volume (m^3)	WALLRUS	Site 1	8466.00	3912.00	2642.00	3412.00	1621.00	1806.00	2891.00
		Site 2	2241.00	1066.00	722.00	1044.00	467.00	514.00	913.00
		Site 3	3417.00	1927.00	1242.00	2988.00	1934.00	1150.00	2655.00
		Site 4	920.00	426.00	291.00	387.00	186.00	203.00	342.00
		Site 5	16947.00	8204.00	5615.00	9029.00	5096.00	4208.00	8302.00
		Subtotal	**31991.0**	**15535.0**	**10512.0**	**16860.0**	**9304.0**	**7881.0**	**11993.0**
	COSSOM	Site 1	8480.00	3957.00	2797.00	3574.00	1669.00	1826.00	2918.00
		Site 2	2194.00	1030.00	727.00	981.00	482.00	486.00	878.00
		Site 3	3268.00	1860.00	1162.00	2856.00	2059.00	1058.00	2709.00
		Site 4	937.00	834.00	309.00	407.00	195.00	204.00	350.00
		Site 5	16529.00	8103.00	5179.00	9135.00	5277.00	3972.00	8200.00
		Subtotal	**31408.0**	**15784.0**	**10174.0**	**16953.0**	**9682.0**	**7546.0**	**11870.0**
		Diff. %	**-1.8**	**+1.5**	**-3.3**	**+0.54**	**+3.9**	**-4.4**	**+1.04**
Overflow Volume (m^3)	WALLRUS	Site 1	7049.00	3087.00	2098.00	1936.00	384.00	1328.00	1328.00
		Site 2	1592.00	666.00	498.00	322.00	0.00	278.00	278.00
		Site 3	974.00	350.00	206.00	159.00	0.00	89.00	89.00
		Site 4	699.00	291.00	211.00	144.00	0.00	120.00	120.00
		Site 5	10934.00	4495.00	3254.00	2463.00	170.00	1876.00	1876.00
		Subtotal	**21248.0**	**8889.0**	**6267.0**	**5024.0**	**554.0**	**3691.0**	**3691.0**
	COSSOM	Site 1	7141.00	3080.00	2265.00	1932.00	356.00	1283.00	1283.00
		Site 2	1581.00	667.00	516.00	321.00	0.00	276.00	276.00
		Site 3	1049.00	450.00	312.00	270.00	0.00	198.00	198.00
		Site 4	730.00	309.00	239.00	175.00	17.00	131.00	131.00
		Site 5	10774.00	4550.00	3092.00	2389.00	160.00	1782.00	1782.00
		Subtotal	**21275.0**	**9056.0**	**6415.0**	**5087.0**	**533.0**	**3670.0**	**3670.0**
		Diff. %	**+0.13**	**+1.8**	**+2.3**	**+1.2**	**-3.9**	**-0.57**	**-0.57**
Peak Overflow Rate (m^3/sec)	WALLRUS	Site 1	0.353	0.383	0.392	0.233	0.045	0.517	0.517
		Site 2	0.107	0.120	0.122	0.073	0.00	0.285	0.285
		Site 3	0.079	0.106	0.098	0.054	0.00	0.101	0.101
		Site 4	0.052	0.070	0.076	0.046	0.00	0.056	0.056
		Site 5	0.661	0.696	0.694	0.398	0.036	0.562	0.562
	COSSOM	Site 1	0.482	0.461	0.400	0.173	0.040	0.503	0.503
		Site 2	0.113	0.133	0.133	0.042	0.00	0.285	0.285
		Site 3	0.073	0.089	0.096	0.033	0.00	0.090	0.090
		Site 4	0.058	0.068	0.073	0.025	0.004	0.054	0.054
		Site 5	0.756	0.841	0.689	0.273	0.036	0.561	0.561

Table 7.3 Comparison of Runoff and Overflow Calculations obtained from WALLRUS and COSSOM for Fleetwood Sewerage System (Fig. 7.2) for Selected Rainfall Events

Item	Program	RESULTS FOR LIVERPOOL RAINFALL DATA (1956)													Total
		Rainfall data series													
		1 – 500	501 – 1000	1001 – 1500	1501 – 2000	2001 – 2500	2501 – 3000	3001 – 3500	3501 – 4000	4001 – 4500	4501 – 5000	5001 – 5500	5501 – 6000	6001 – 6520	
Rainfall Runoff Volume (m^3)	WALLRUS	52158	52145	59323	57667	53800	54226	51669	65765	64273	59266	49610	52102	69001	741012
	COSSOM	50607	50470	57406	55610	52023	52587	50198	63278	62367	57334	48300	50394	67779	718358
	Diff. %	**-3.0**	**-3.2**	**-3.2**	**-3.6**	**-3.3**	**-3.0**	**-2.8**	**-3.8**	**-3.0**	**-3.3**	**-2.6**	**-3.3**	**-1.8**	**-3.1**
Overflow Volume (m^3)	WALLRUS	1001	2071	4296	5576	2363	1739	1867	10128	9804	5073	893	2502	12901	60218
	COSSOM	1231	2321	4486	5406	2158	1633	1894	9178	9732	4645	1042	2596	12820	59145
	Diff. %	**+23.0**	**+12.1**	**+4.4**	**-3.0**	**-8.7**	**-6.1**	**+1.4**	**-9.4**	**-0.7**	**-8.4**	**+16.7**	**+3.8**	**-0.6**	**-1.8**
Run Time (sec)	WALLRUS	14040	14040	12360	13680	13500	13560	12120	15600	13980	12480	12120	14400	15300	177180
	COSSOM	80	80	80	80	80	80	80	80	80	80	80	80	85	1040

Table 7.4 Overflow Calculations for Fleetwood Sewerage System Illustrated in Figure 7.2 for Liverpool Typical Year (1956) Rainfall Record.

Rainfall Event	Site Location	Runoff Volume (m^3)				Peak Runoff Rate (m^3/sec)			
		Program			Observed	Program			Observed
		COSSOM (WALL)	COSSOM (KWRM)	WALLRUS Sim.		COSSOM (WALL)	COSSOM (KWRM)	WALLRUS Sim.	
Storm 1	Site 1	163.00	152.00	191.00	139.00	0.008	0.008	0.008	0.011
	Site 2	907.00	895.00	931.00	950.00	0.058	0.057	0.057	0.052
	Site 3	1594.00	1083.00	1460.00	1272.00	0.057	0.057	0.057	0.058
	Site 4	8337.00	8315.00	8308.00	14026.00	0.604	0.601	0.485	0.809
	Site 5	15308.00	15290.00	14669.00	7445.00	0.780	0.779	0.750	0.640
	Site 6	2276.00	2251.00	2278.00	2503.00	0.220	0.220	0.153	0.125
Storm 2	Site 1	115.00	110.00	134.00	130.00	0.009	0.008	0.010	0.008
	Site 2	731.00	704.00	726.00	648.00	0.058	0.058	0.057	0.053
	Site 3	1270.00	1042.00	1486.00	1100.00	0.058	0.056	0.063	0.056
	Site 4	6728.00	6681.00	6502.00	11287.00	0.500	0.490	0.540	0.921
	Site 5	12431.00	12474.00	11264.00	4533.00	0.821	0.823	0.790	0.451
	Site 6	1782.00	1690.00	1767.00	1855.00	0.172	0.178	0.189	0.125
Storm 3	Site 1	117.00	110.00	107.00	42.00	0.009	0.008	0.009	0.008
	Site 2	377.00	324.00	415.00	246.00	0.042	0.047	0.050	0.040
	Site 3	601.00	493.00	710.00	445.00	0.055	0.028	0.053	0.041
	Site 4	3872.00	3775.00	3944.00	5379.00	0.415	0.450	0.462	0.860
	Site 5	7207.00	7100.00	6668.00	1136.00	0.618	0.512	0.707	0.352
	Site 6	718.00	702.00	714.00	1602.00	0.154	0.154	0.175	0.148
Storm 4	Site 1	91.00	84.00	136.00	122.00	0.014	0.020	0.022	0.025
	Site 2	704.00	623.00	591.00	406.00	0.110	0.101	0.080	0.050
	Site 3	1046.00	907.00	1213.00	1101.00	0.119	0.093	0.138	0.138
	Site 4	5678.00	4351.00	5526.00	7052.00	1.025	0.851	1.022	1.250
	Site 5	9775.00	8864.00	9489.00	4869.00	0.721	0.718	1.100	0.628
	Site 6	1479.00	1341.00	1378.00	1165.00	0.408	0.338	0.3869	0.138

Table 7.5 Predicted by COSSOM and WALLRUS and Observed Runoff Volumes and Peak Runoff Rates for Middlewood Catchment (fig. 7.3)

Item	Overflow Location	Time Series Rainfall Data Regionalised for Liverpool from SW Series							
		Eent001		Event005		Event006		Event4	
		WALLRUS	COSSOM	WALLRUS	COSSOM	WALLRUS	COSSOM	WALLRUS	COSSOM
BOD (kg)	site 1	458.00	447.00	230.00	197.00	181.00	145.00	89.00	61.00
	site 2	800.00	725.00	387.00	301.00	297.00	215.00	165.00	140.00
	site 4	480.00	447.00	245.00	197.00	187.00	145.00	91.00	61.00
	site 5	466.00	447.00	232.00	197.00	189.00	145.00	95.00	61.00
	site 6	1258.00	1430.00	644.00	590.00	543.00	415.00	302.00	267.00
TSS (kg)	site 1	1469.00	1312.00	616.00	584.00	503.00	433.00	302.00	225.00
	site 2	2004.00	1973.00	933.00	829.00	620.00	597.00	519.00	453.00
	site 4	1538.00	1312.00	623.00	584.00	510.00	433.00	307.00	225.00
	site 5	1494.00	1312.00	620.00	584.00	511.00	433.00	310.00	225.00
	site 6	4030.00	3947.00	1770.00	1645.00	1207.00	1163.00	972.00	888.00
NH4-N (kg)	site 1	36.00	38.00	20.00	16.00	11.00	12.00	7.00	5.00
	site 2	64.00	66.00	31.00	27.00	20.00	19.00	16.00	11.00
	site 4	38.00	38.00	22.00	16.00	12.00	12.00	7.00	5.00
	site 5	37.00	38.00	21.00	16.00	13.00	12.00	8.00	5.00
	site 6	100.00	128.00	59.00	52.00	40.00	37.00	27.00	21.00

Table 7.6 Pollution Loads Calculated by COSSOM and WALLRUS for Hypothetical Catchment (fig 7.1)

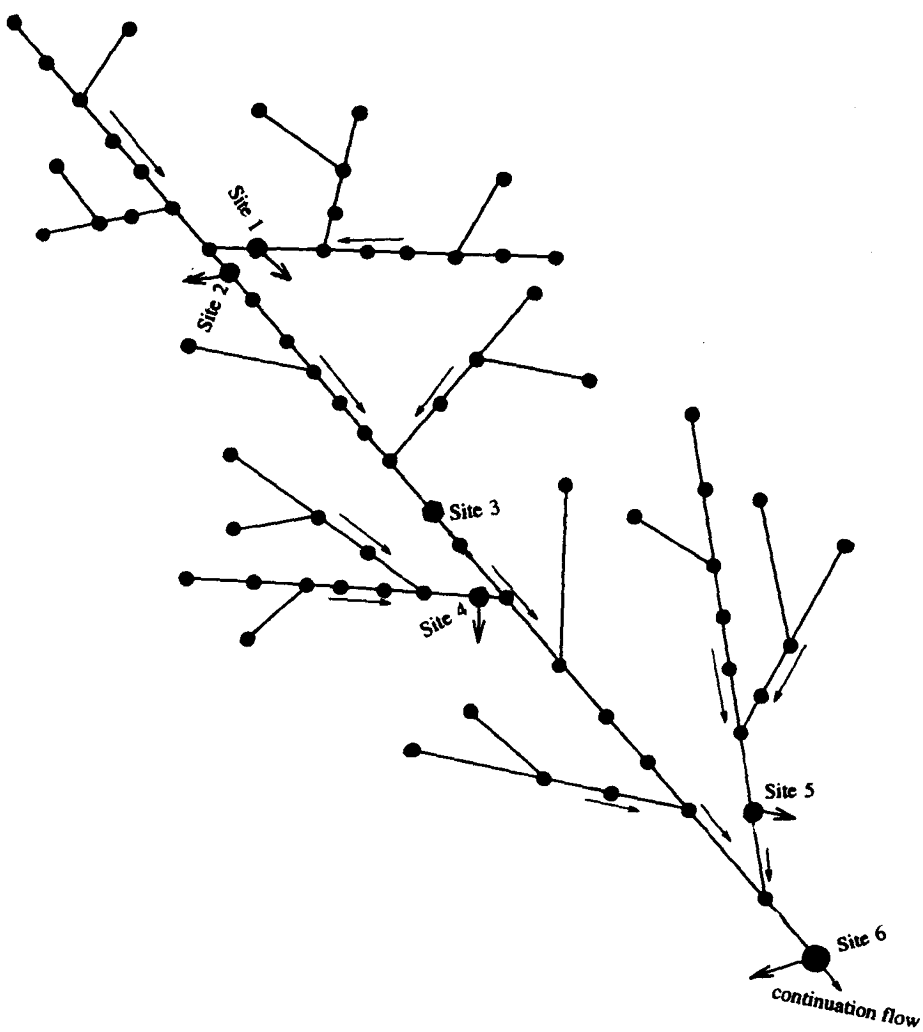


Figure 7.1 Hypothetical Sewerage System using Subcatchment Hierarchy and Overflows at Various 'Levels' identified by Site Numbers. (Data Files Appendix A-3).

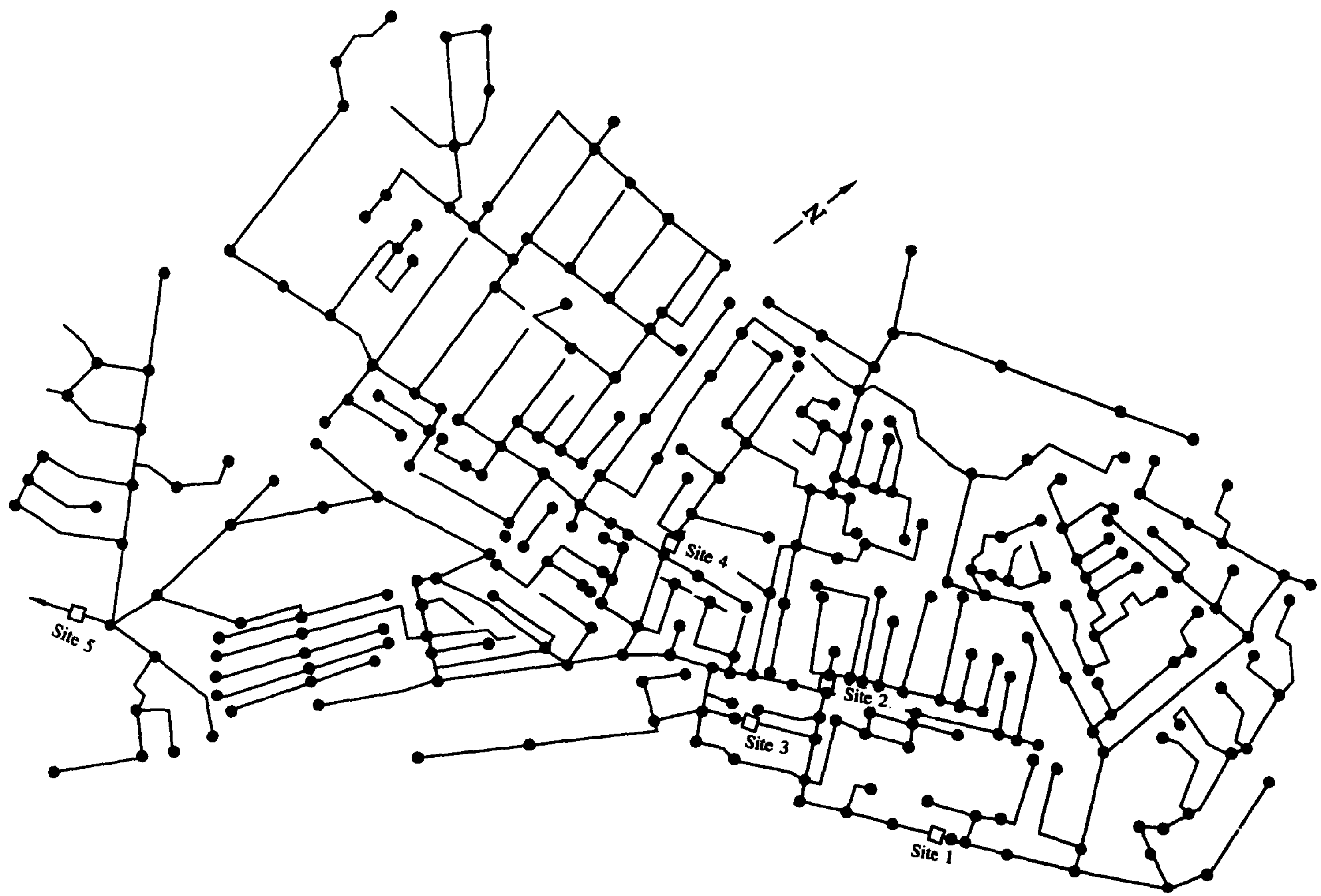


Figure 7.2 Fleetwood Sewerage System and Location of Overflows. (Data Files Appendix A-4).

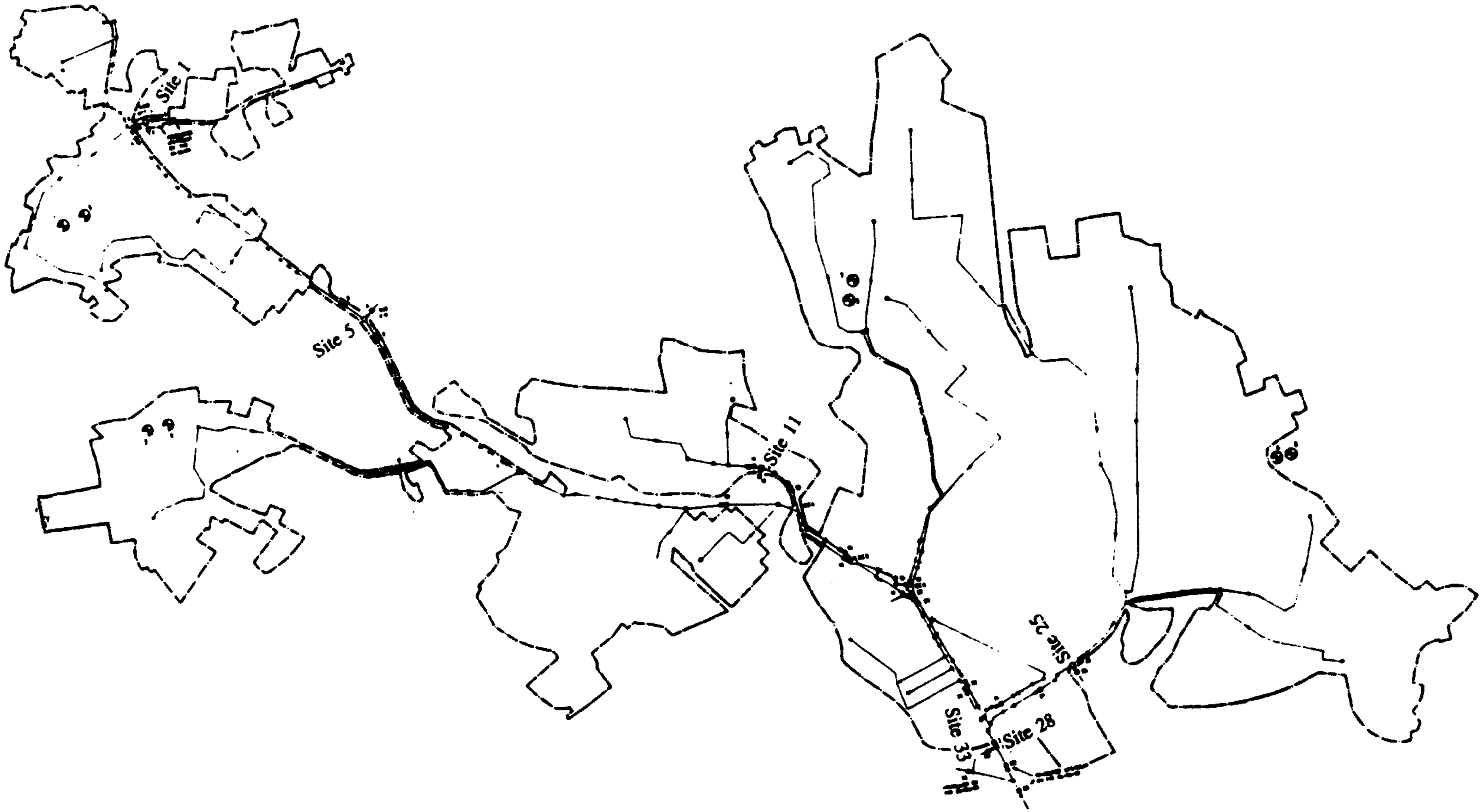
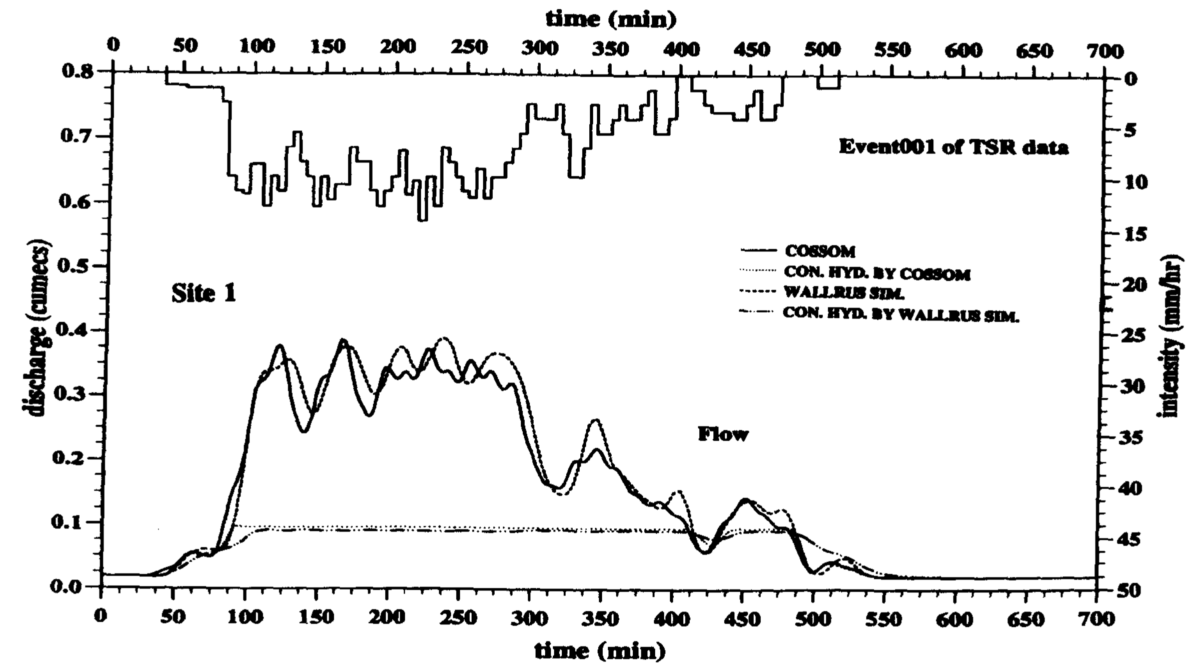


Figure 7.3 Middlewood Sewerage System and Location of Overflows (Data Files Appendix A-5).



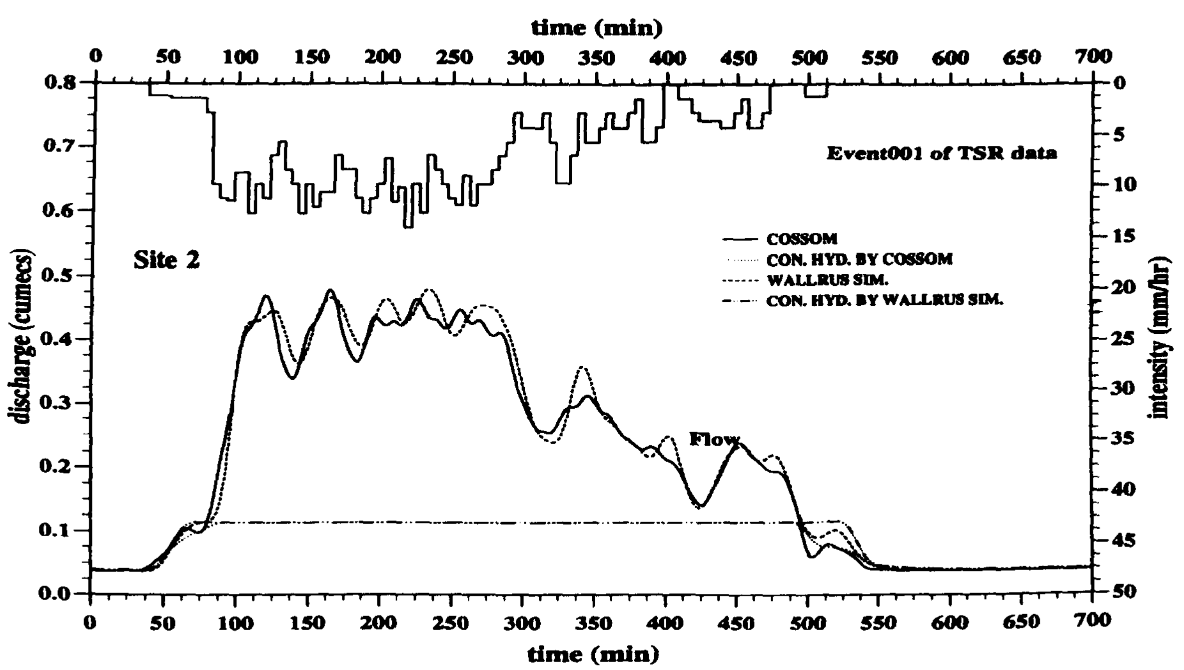


Figure 7.4 Comparison Between COSSOM and WALLRUS Computed Hydrographs of Chamber Inflow and Throughflow for Hypothetical Catchment at Sites 1 & 2.

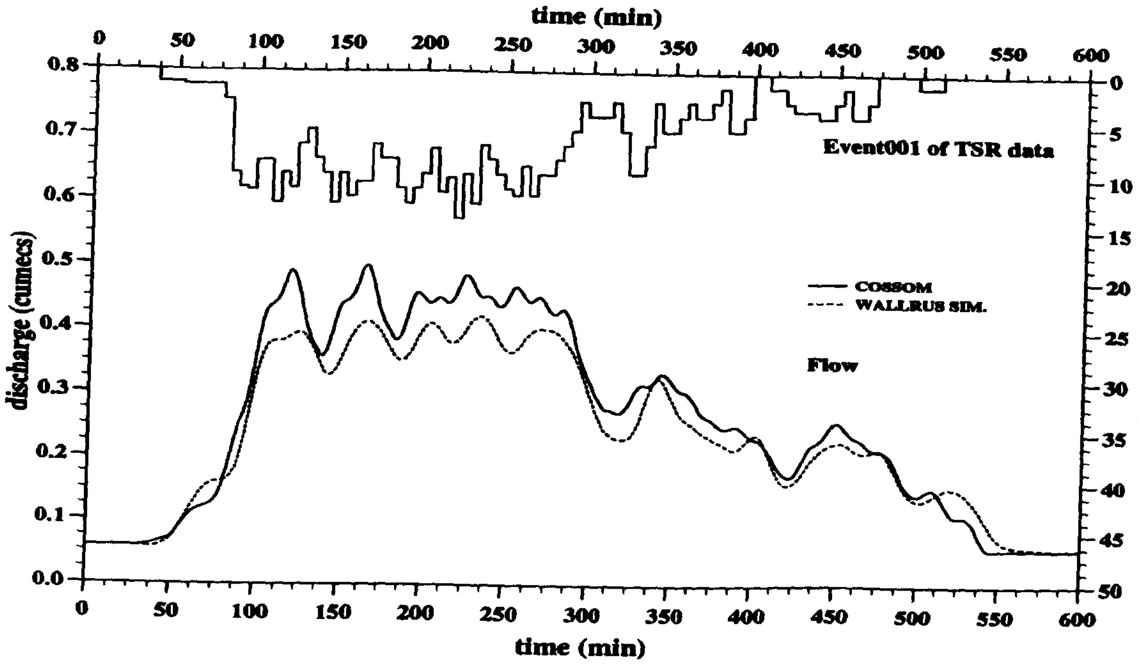


Figure 7.5 Comparison Between COSSOM and WALLRUS Predicted Flows for Hypothetical Catchment at Site 3.

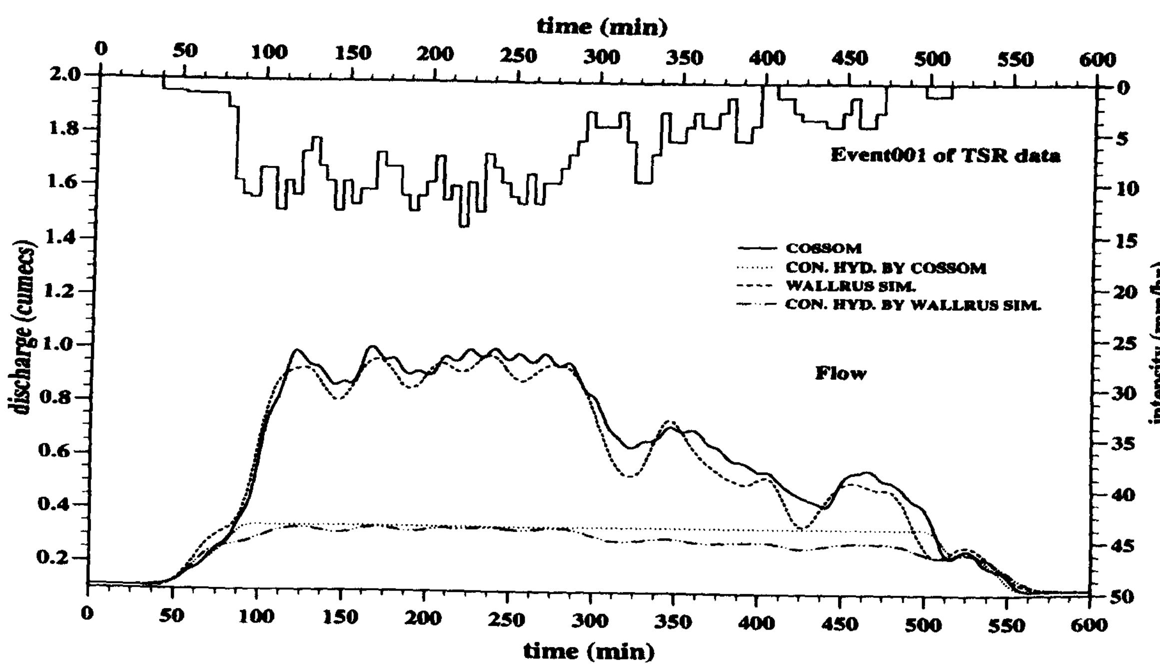
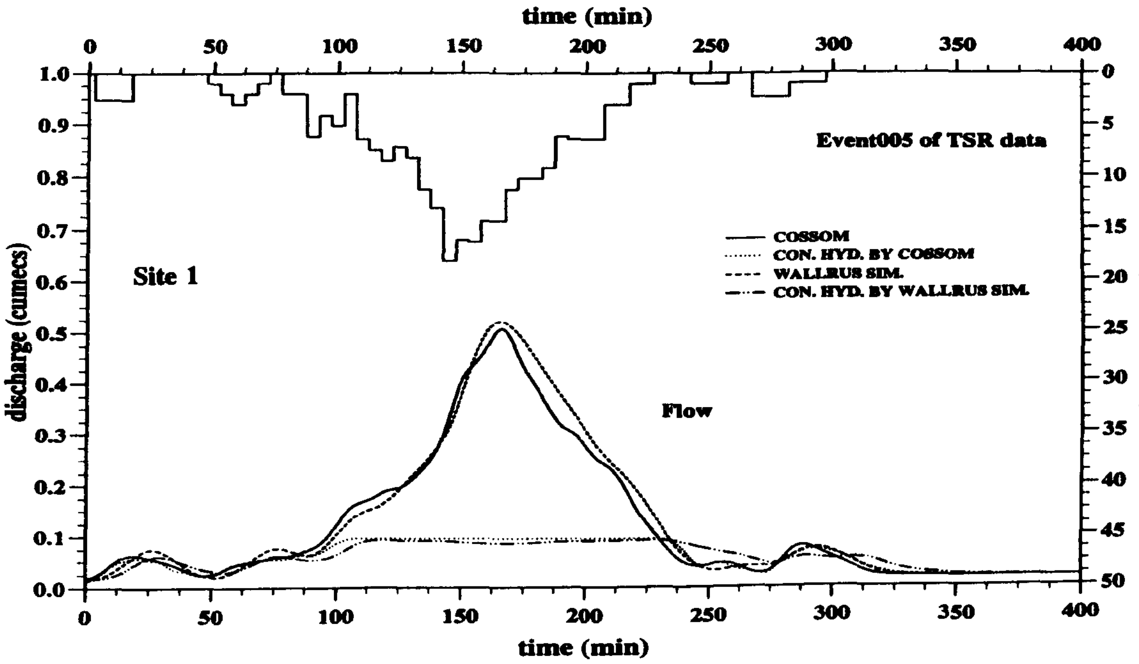


Figure 7.6 Comparison Between COSSOM and WALLRUS Computed Hydrographs of Chamber Inflow and Throughflow for Hypothetical Catchment at Site 6.



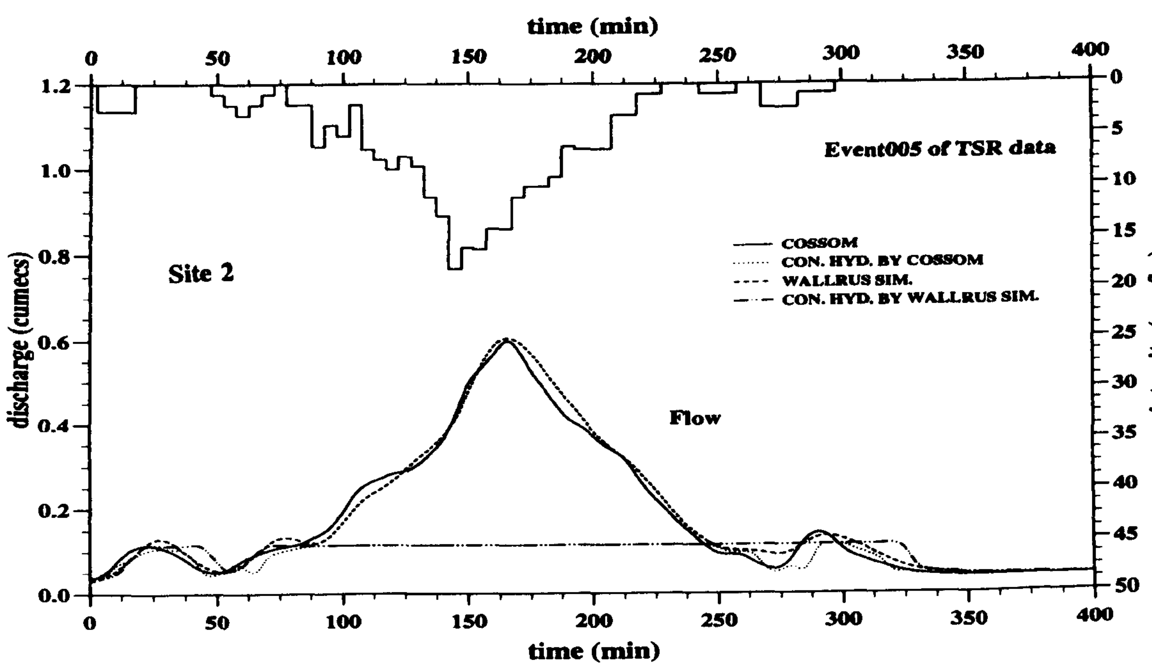


Figure 7.7 Comparison Between COSSOM and WALLRUS Computed Hydrographs of Chamber Inflow and Throughflow for Hypothetical Catchment at Sites 1 & 2.

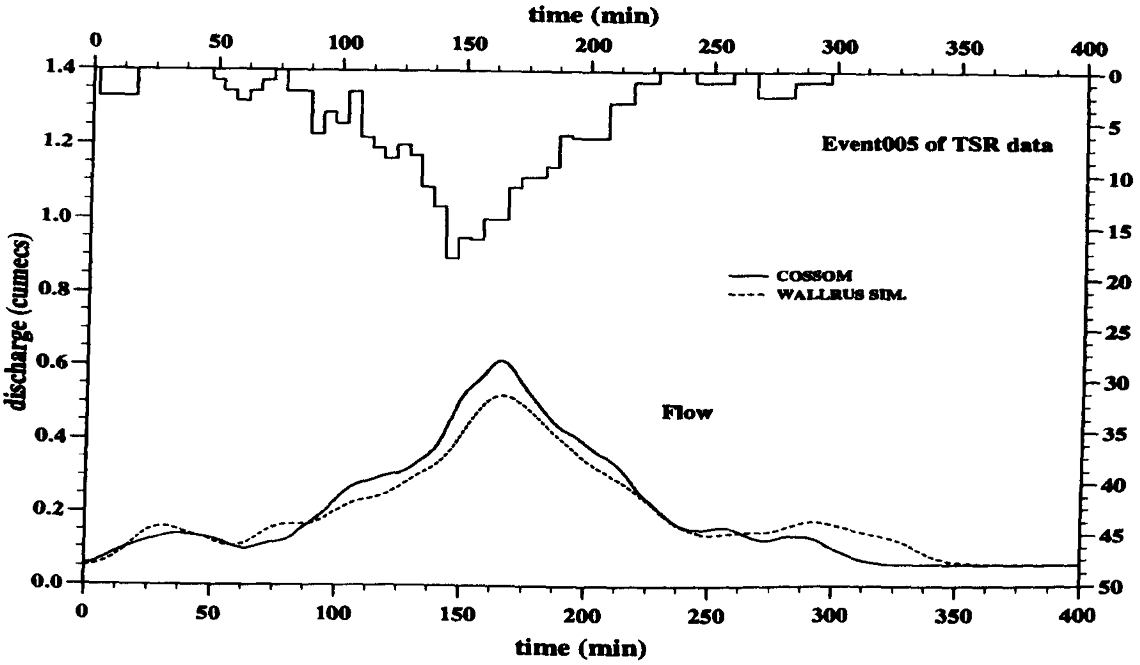


Figure 7.8 Comparison Between COSSOM and WALLRUS Predicted Flows for Hypothetical Catchment at Site 3.

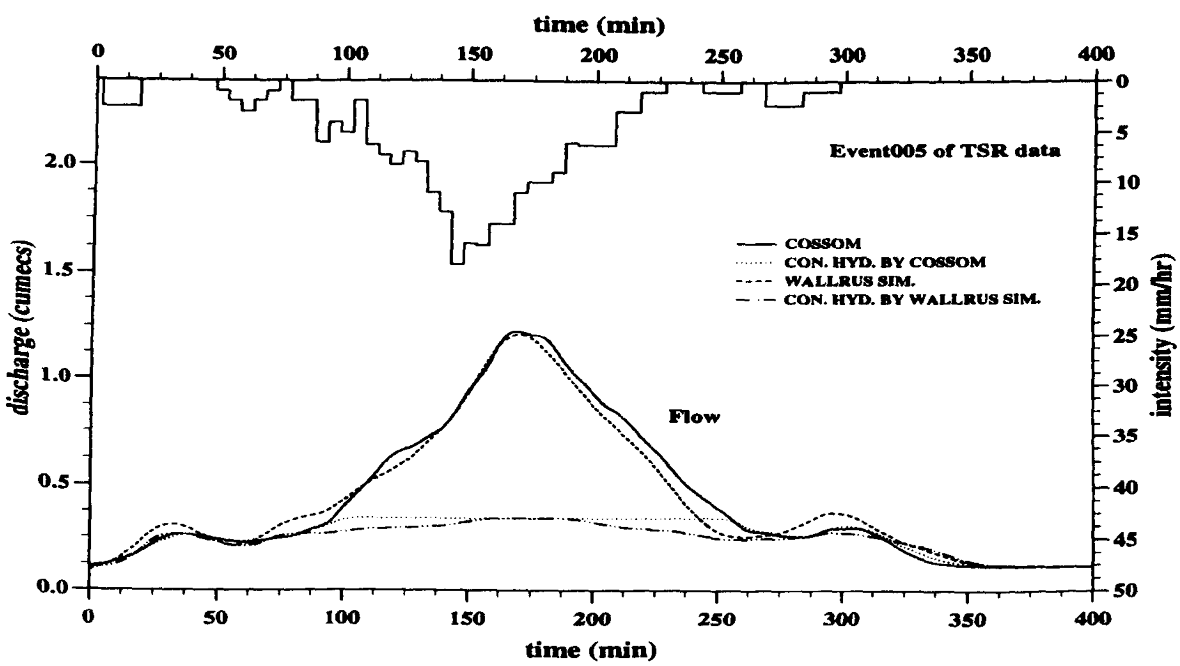


Figure 7.9 Comparison Between COSSOM and WALLRUS Computed Hydrographs of Chamber Inflow and Throughflow for Hypothetical Catchment at Site 6.

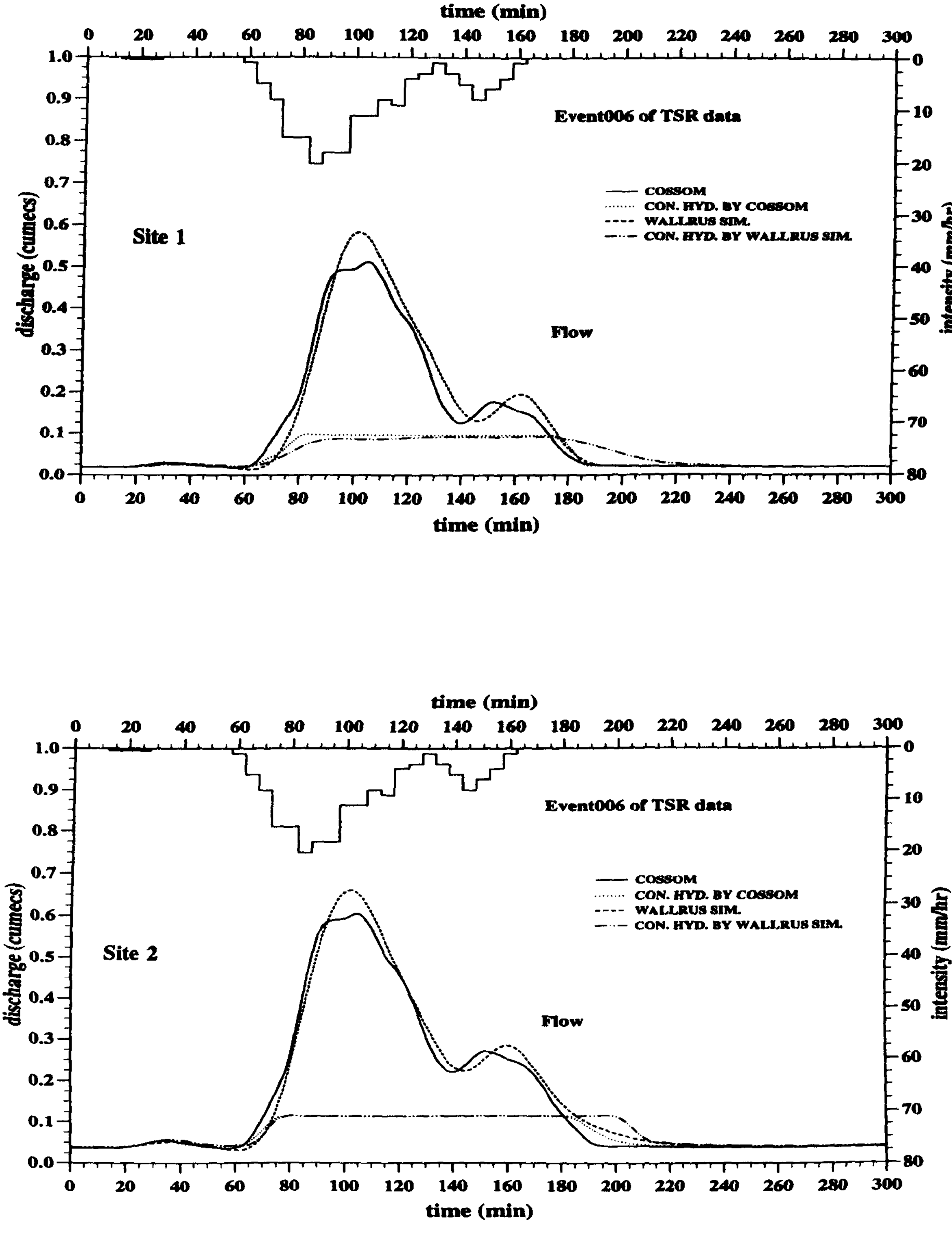


Figure 7.10 Comparison Between COSSOM and WALLRUS Computed Hydrographs of Chamber Inflow and Throughflow for Hypothetical Catchment at Sites 1 & 2.

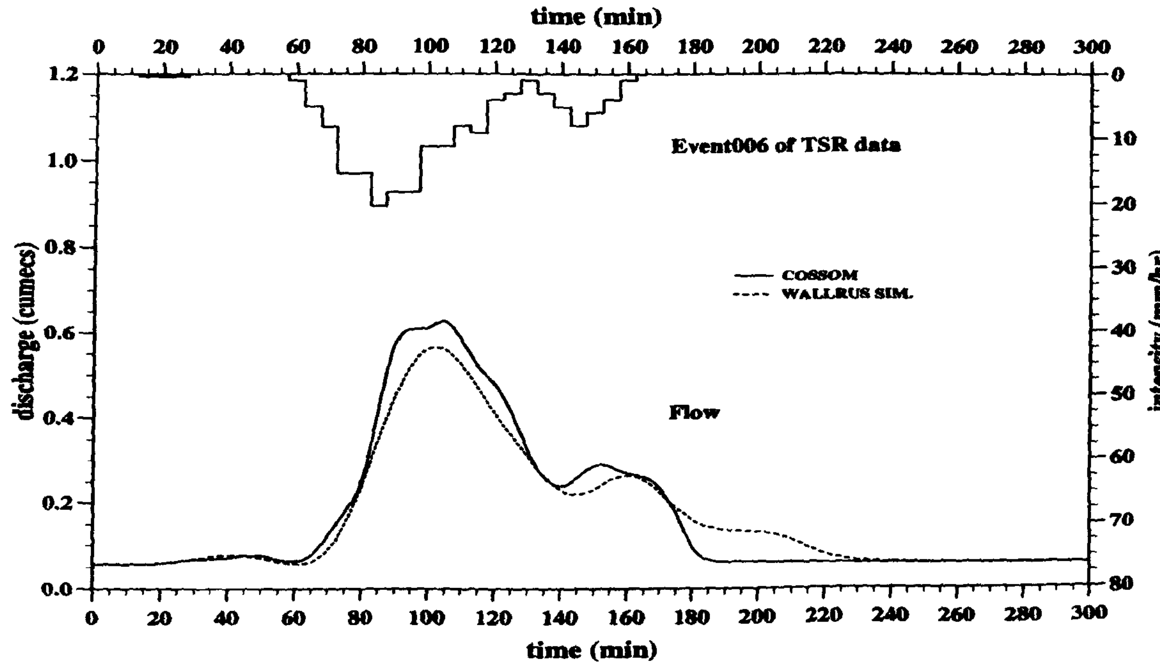


Figure 7.11 Comparison Between COSSOM and WALLRUS Predicted Flows for Hypothetical Catchment at Site 3.

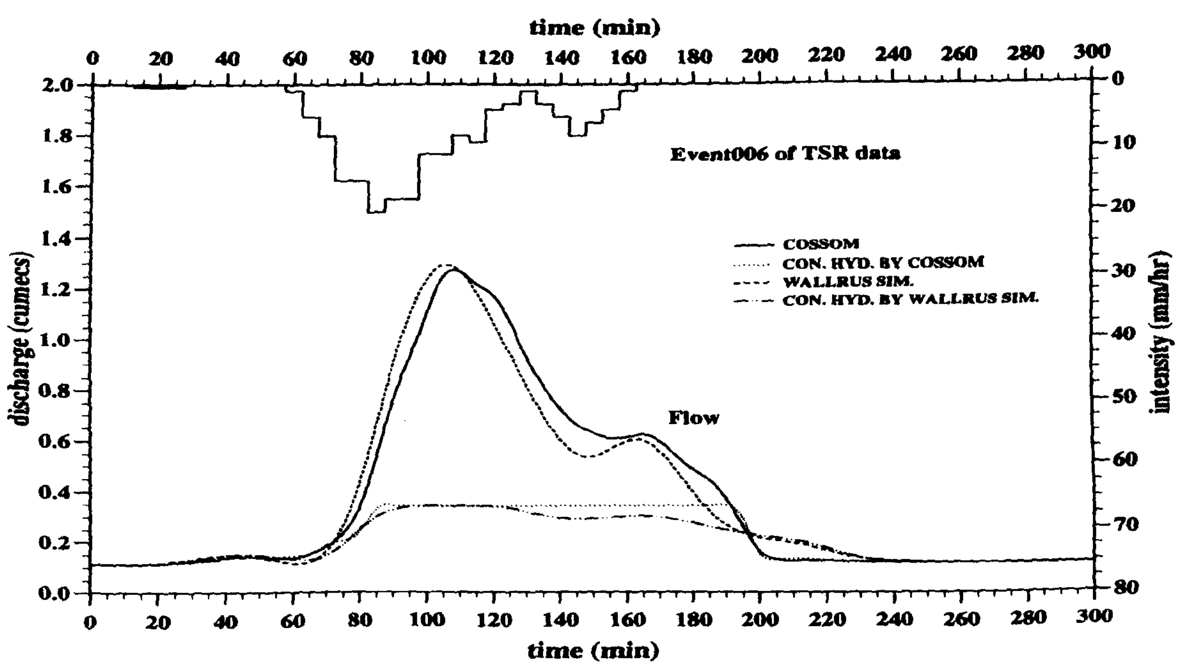
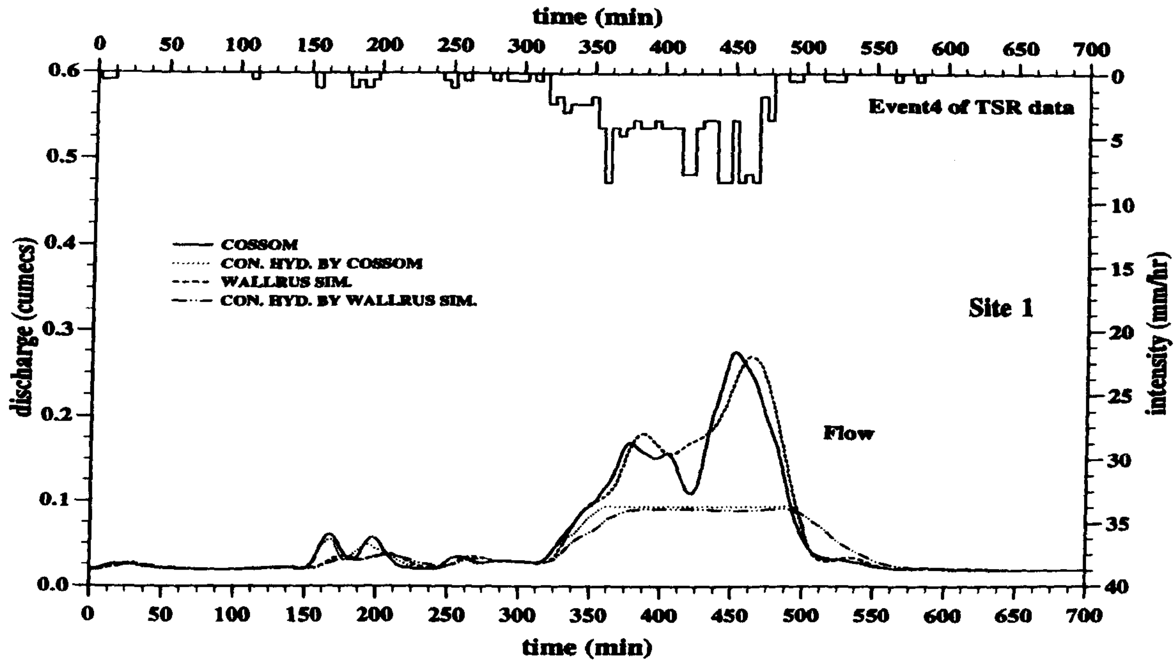


Figure 7.12 Comparison Between COSSOM and WALLRUS Computed Hydrographs of Chamber Inflow and Throughflow for Hypothetical Catchment at Site 6.



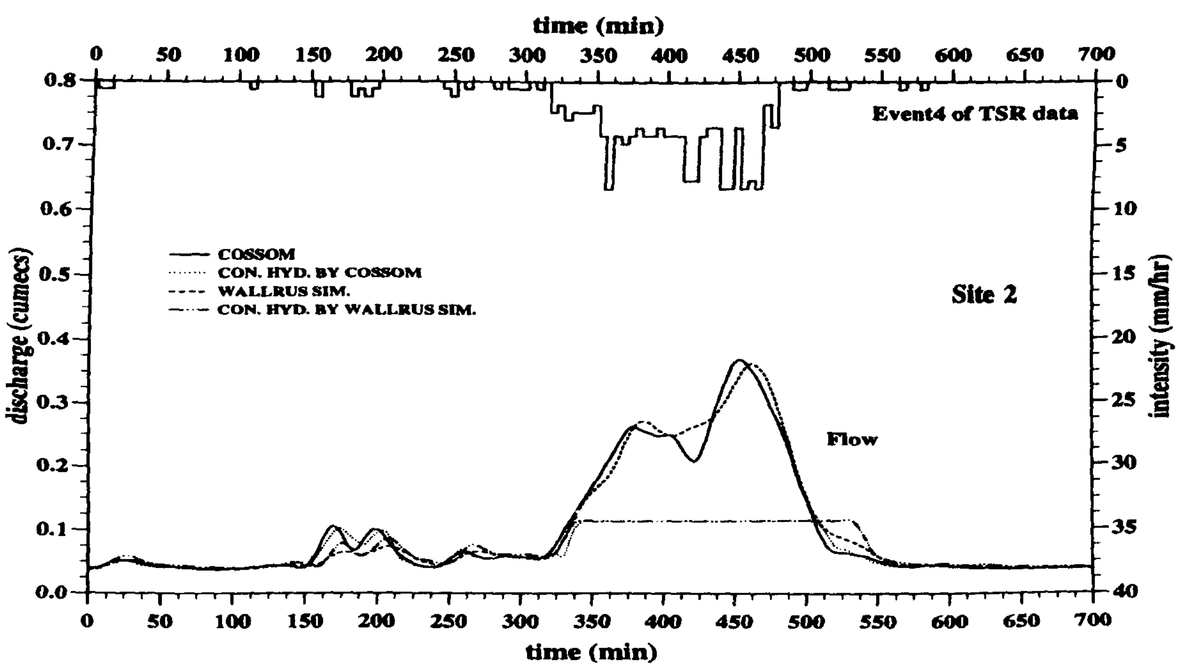


Figure 7.13 Comparison Between COSSOM and WALLRUS Computed Hydrographs of Chamber Inflow and Throughflow for Hypothetical Catchment at Sites 1 & 2.

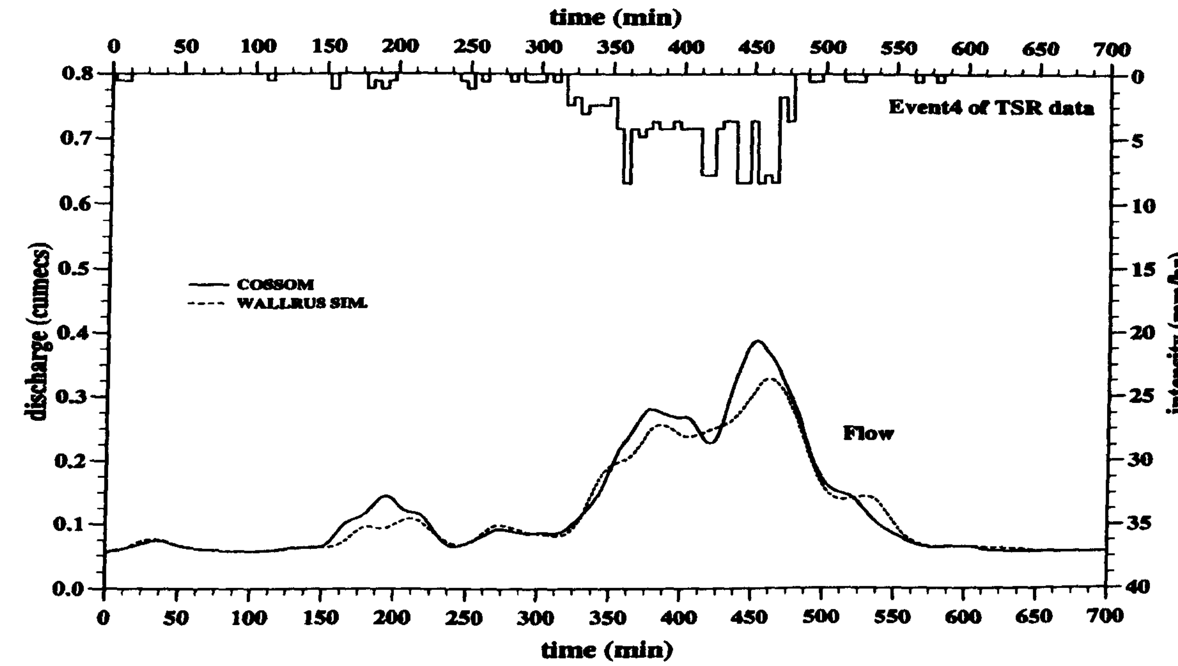


Figure 7.14 Comparison Between COSSOM and WALLRUS Predicted Flows for Hypothetical Catchment at Site 3.

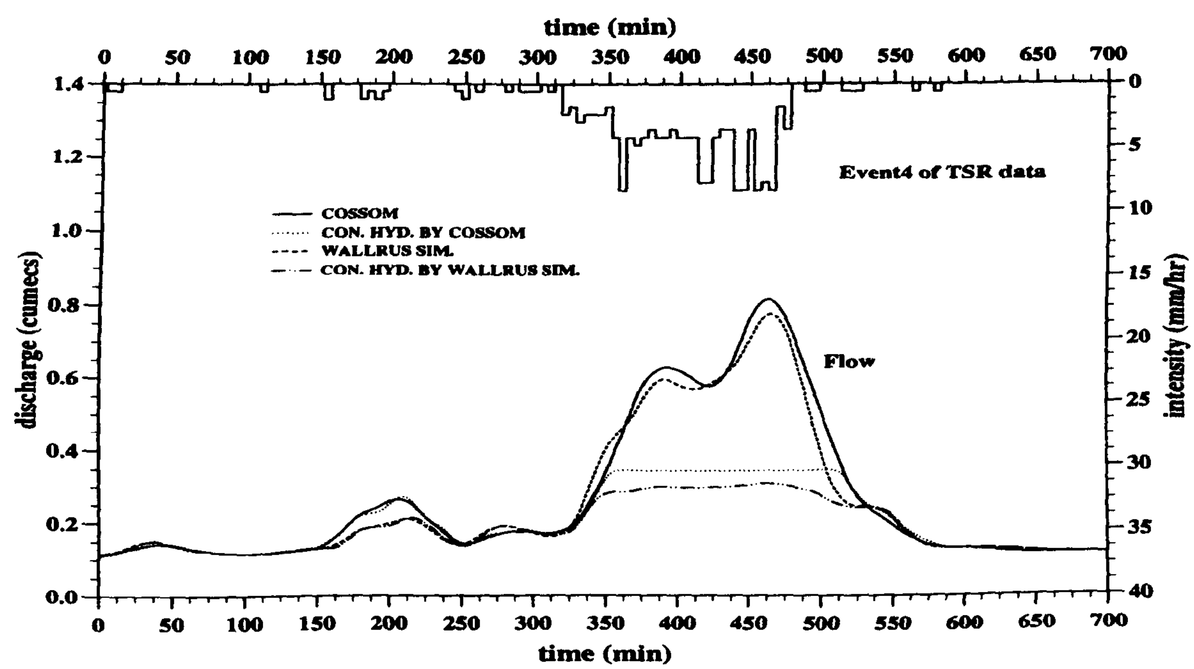
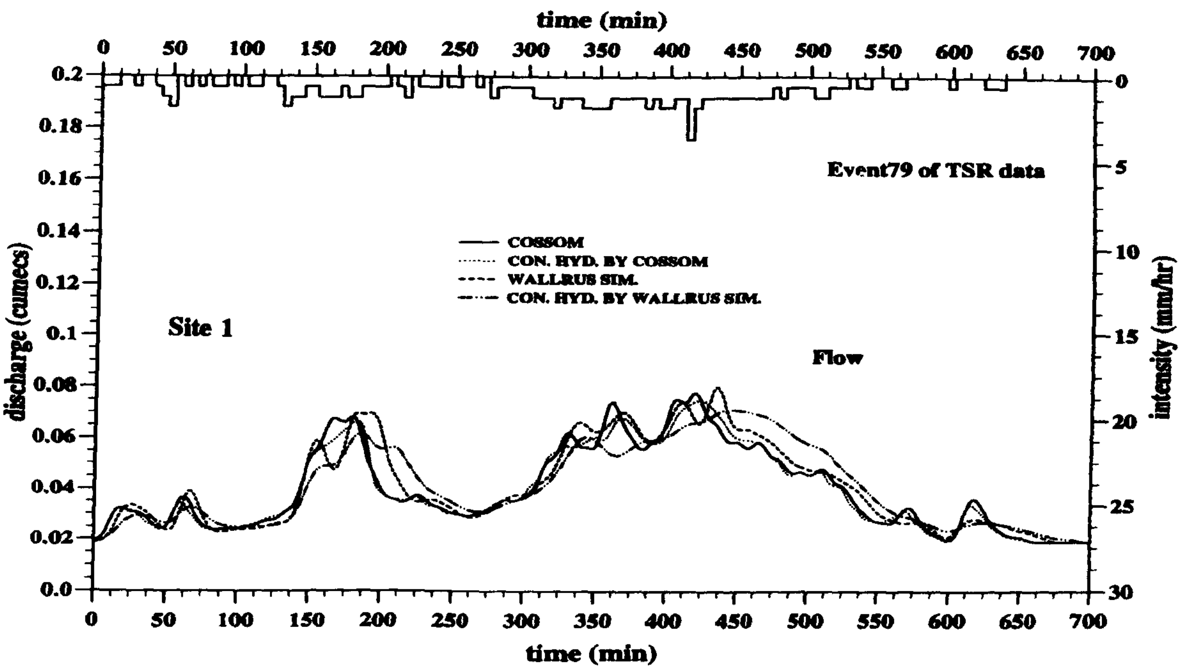


Figure 7.15 Comparison Between COSSOM and WALLRUS Computed Hydrographs of Chamber Inflow and Throughflow for Hypothetical Catchment at Site 6.



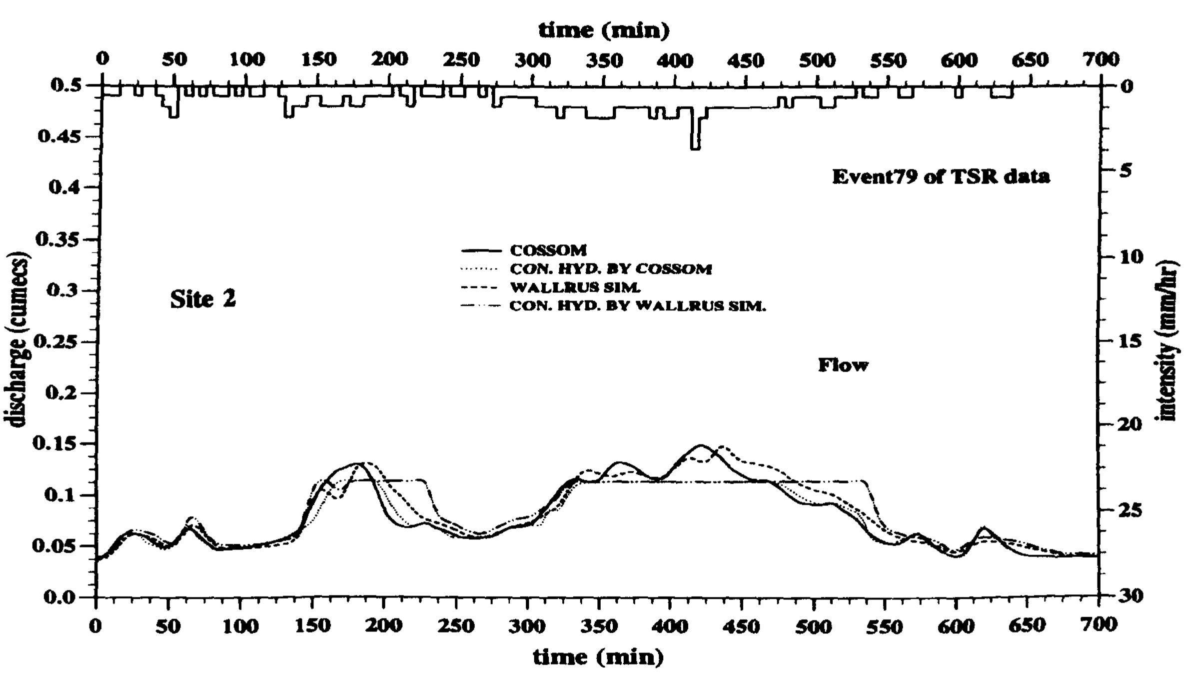


Figure 7.16 Comparison Between COSSOM and WALLRUS Computed Hydrographs of Chamber Inflow and Throughflow for Hypothetical Catchment at Sites 1 & 2.

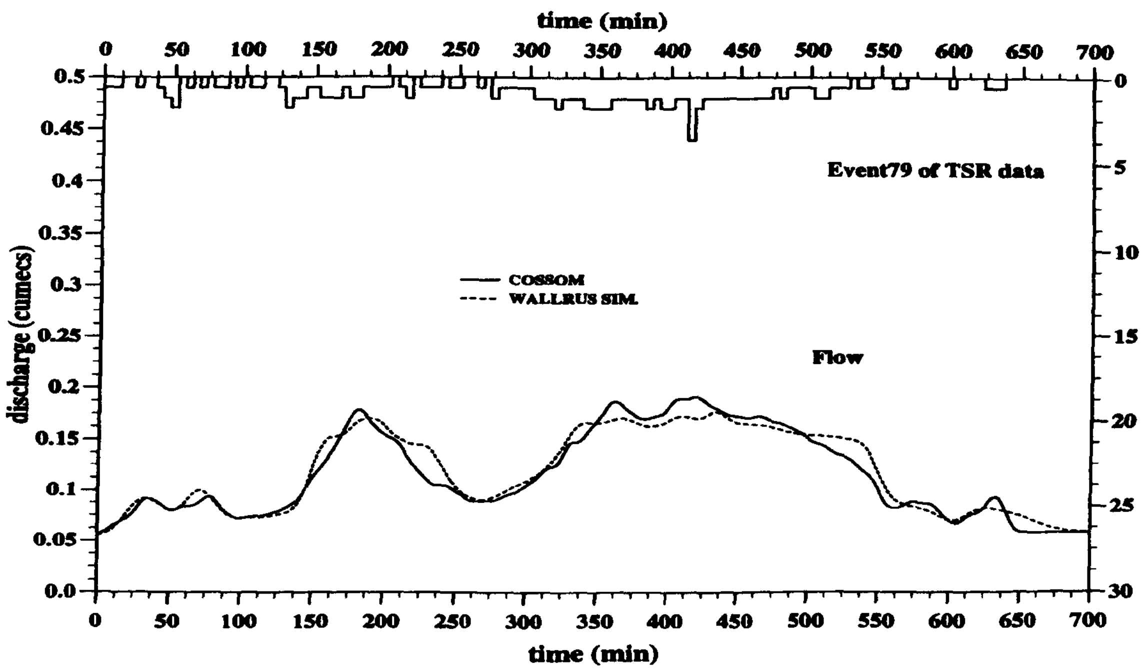


Figure 7.17 Comparison Between COSSOM and WALLRUS Predicted Flows for Hypothetical Catchment at Site 3.

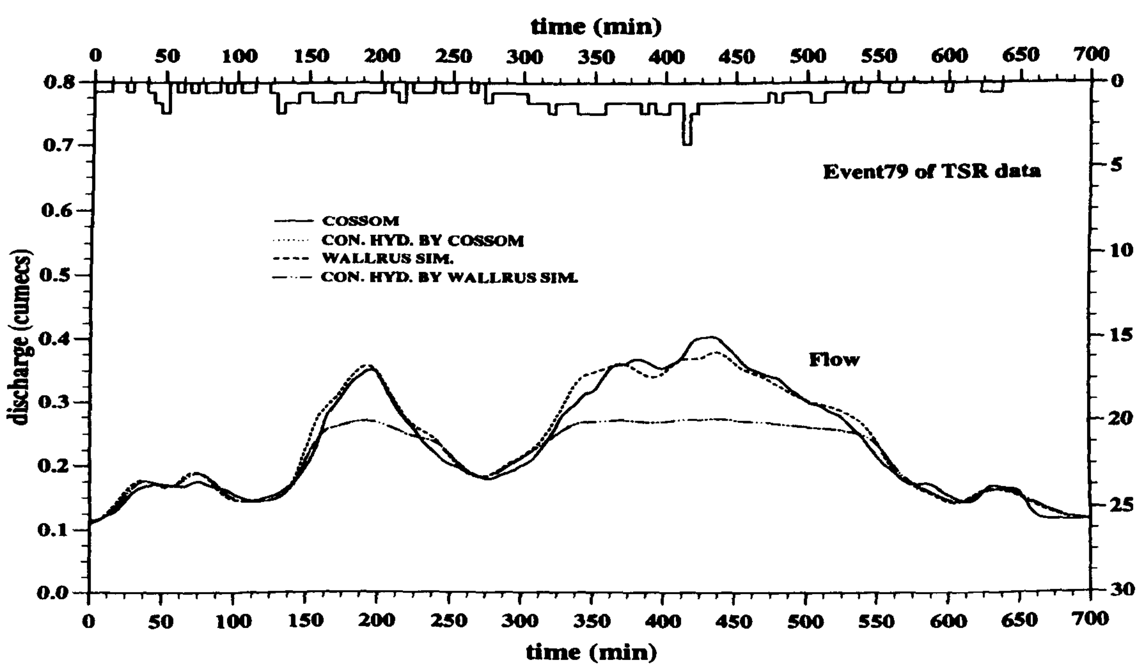
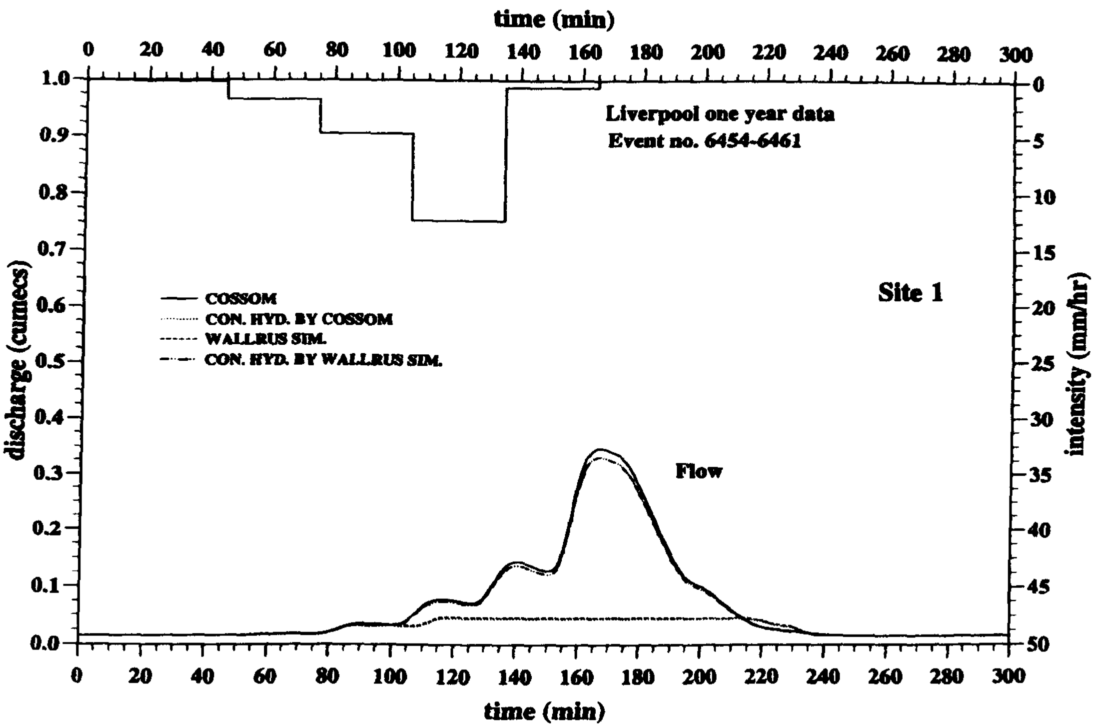


Figure 7.18 Comparison Between COSSOM and WALLRUS Computed Hydrographs of Chamber Inflow and Throughflow for Hypothetical Catchment at Site 6.



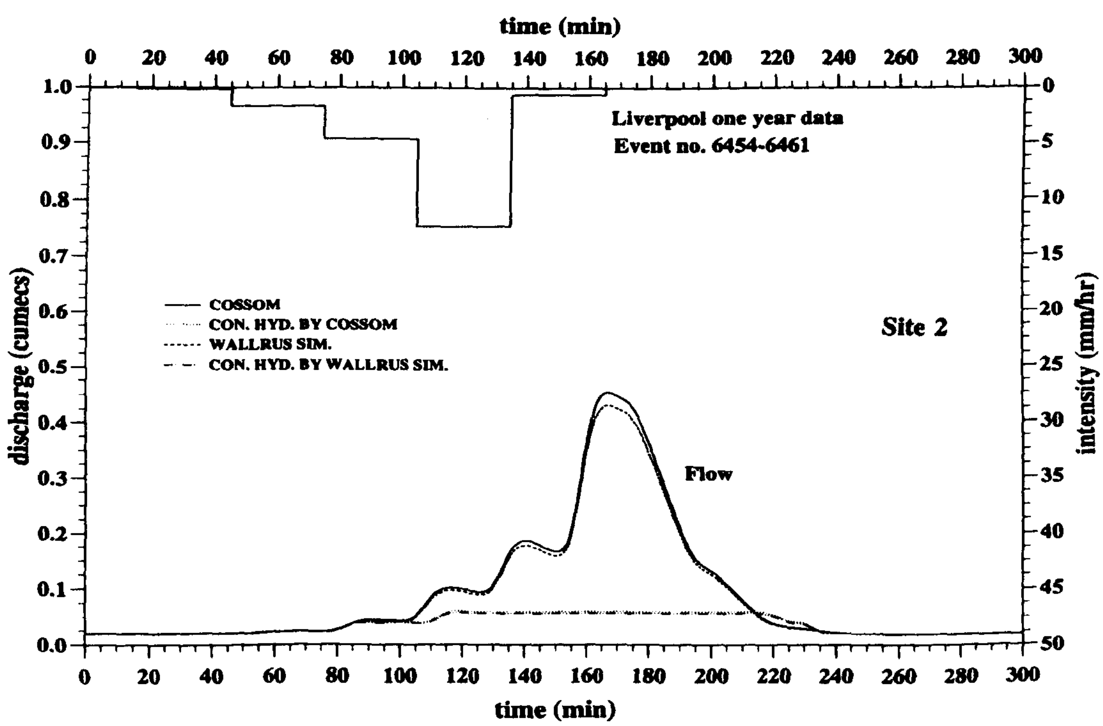


Figure 7.19 Comparison Between COSSOM and WALLRUS Computed Hydrographs of Chamber Inflow and Throughflow for Hypothetical Catchment at Sites 1 & 2.

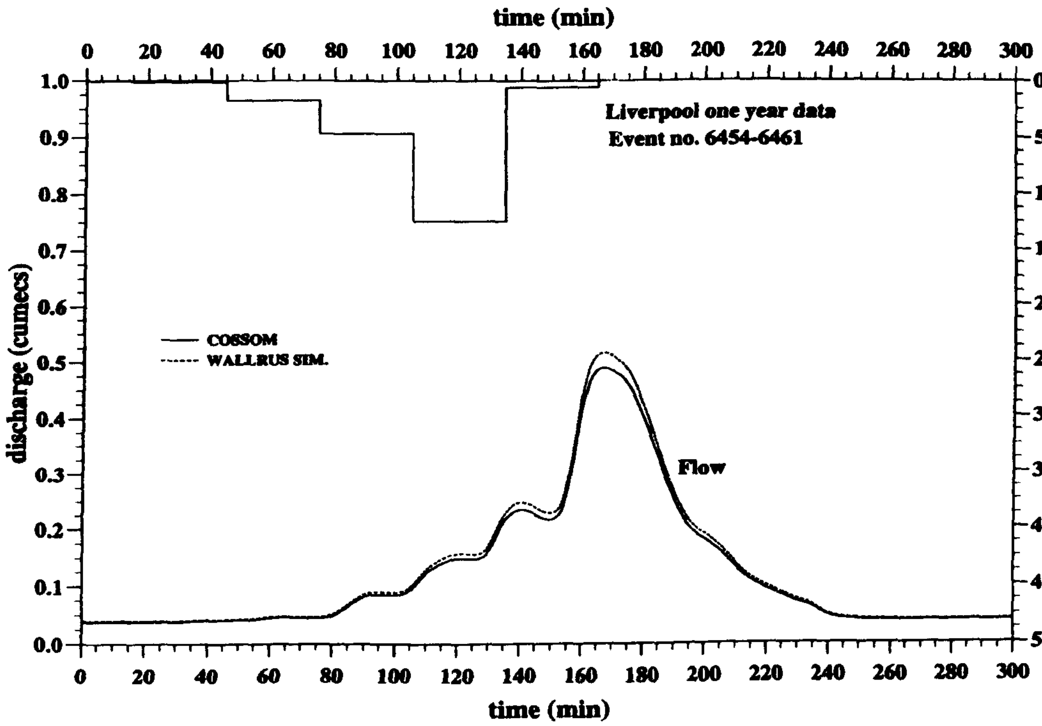


Figure 7.20 Comparison Between COSSOM and WALLRUS Predicted Flows for Hypothetical Catchment at Site 3.

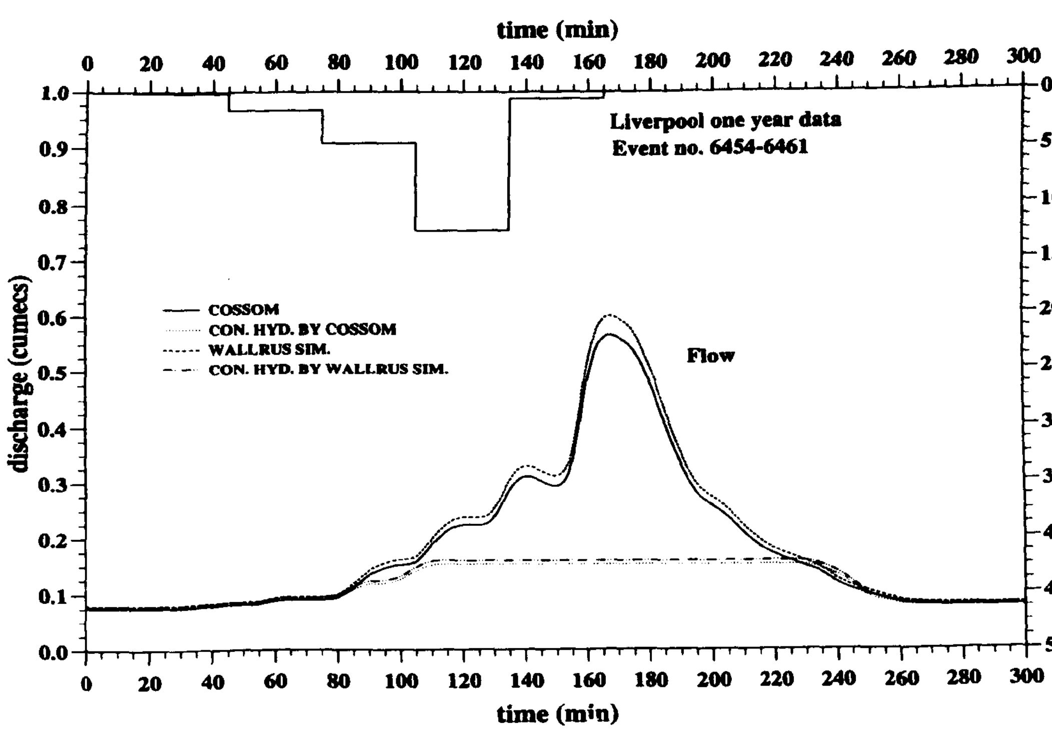
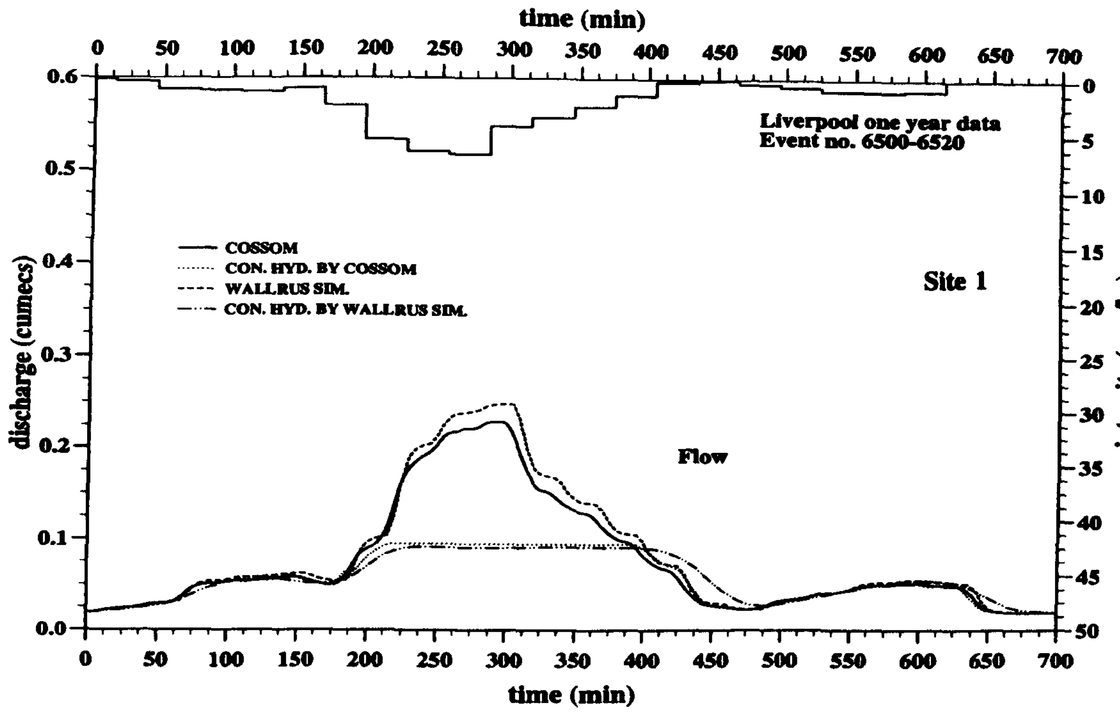


Figure 7.21 Comparison Between COSSOM and WALLRUS Computed Hydrographs of Chamber Inflow and Throughflow for Hypothetical Catchment at Site 6.



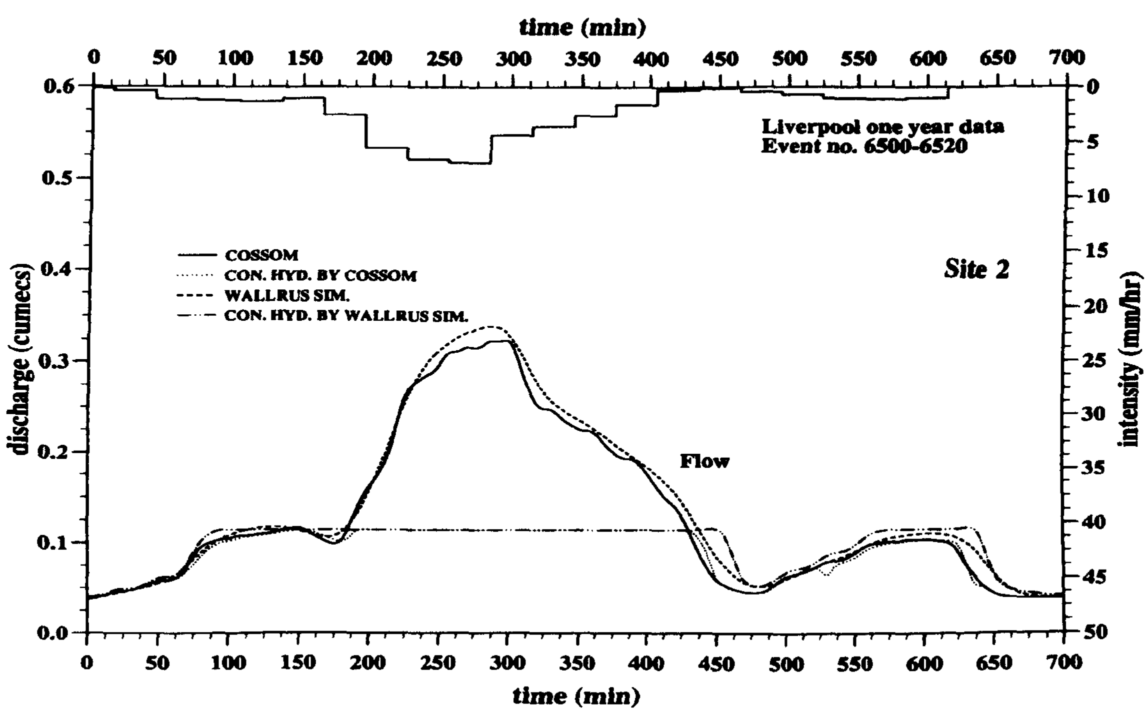


Figure 7.22 Comparison Between COSSOM and WALLRUS Computed Hydrographs of Chamber Inflow and Throughflow for Hypothetical Catchment at Sites 1 & 2.

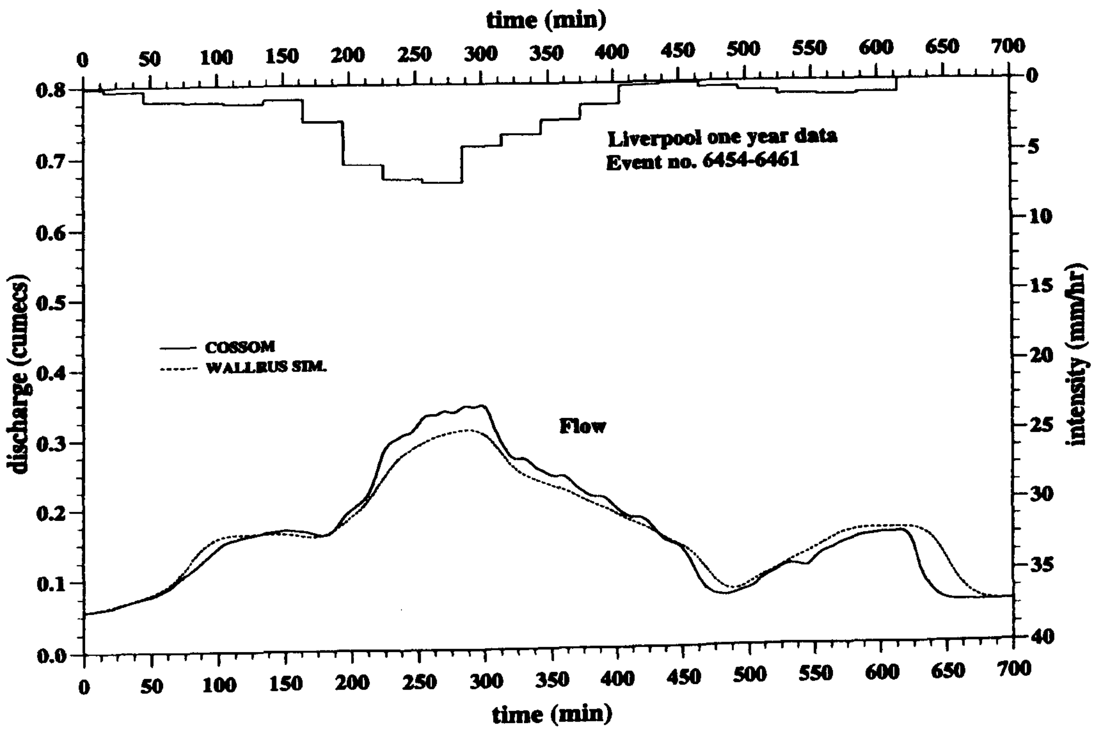


Figure 7.23 Comparison Between COSSOM and WALLRUS Predicted Flows for Hypothetical Catchment at Site 3.

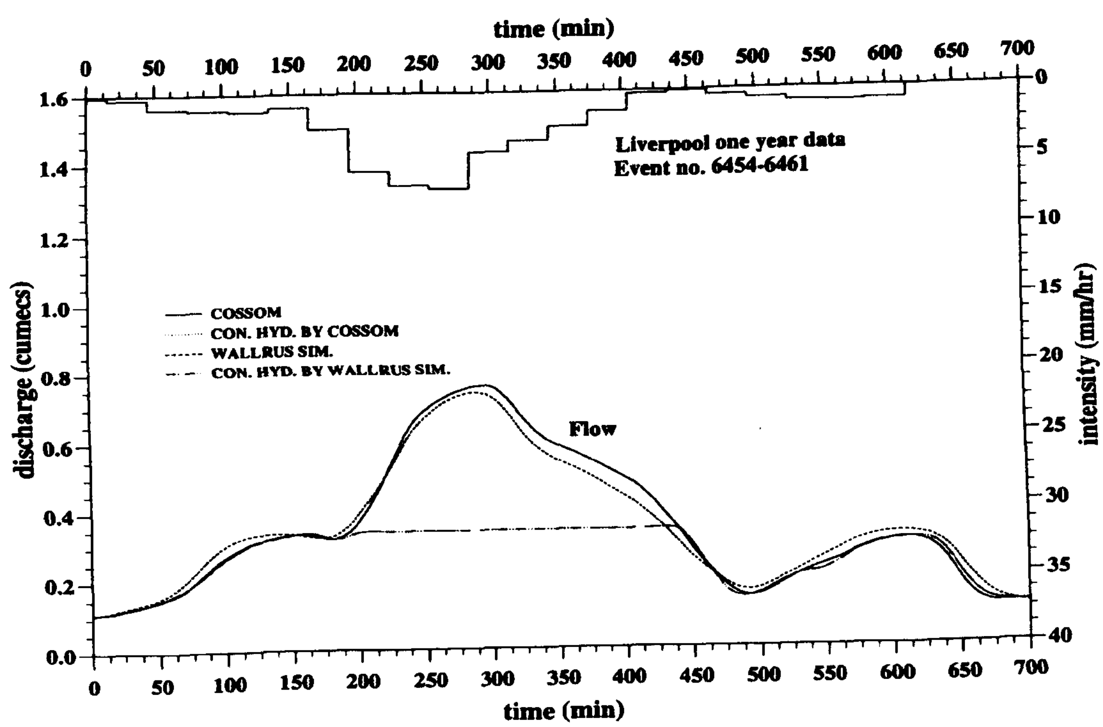
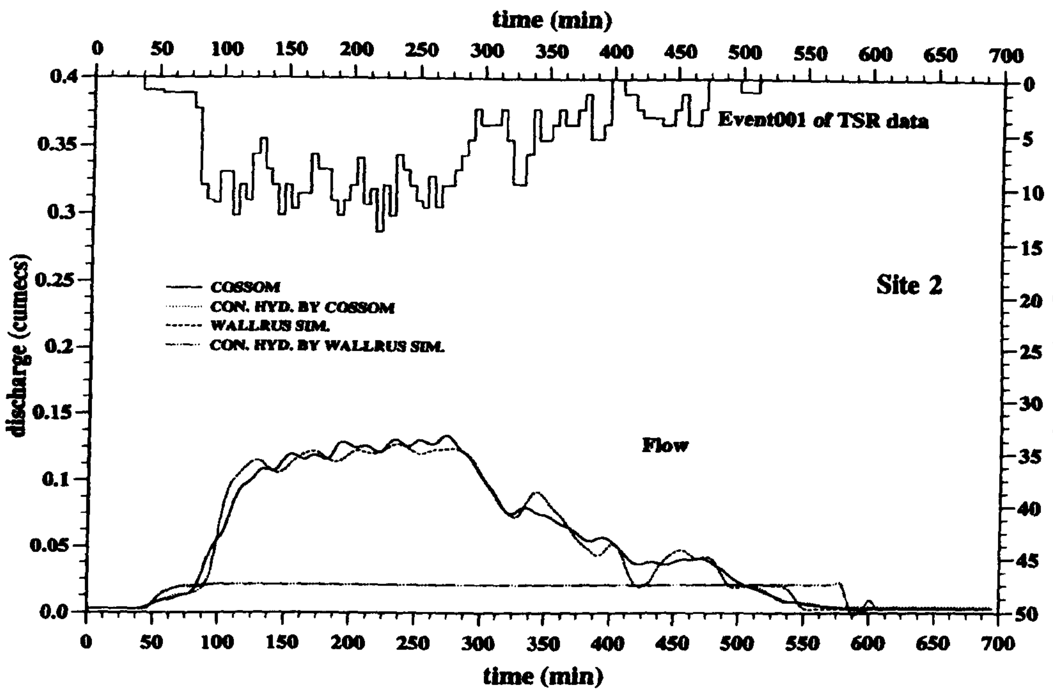


Figure 7.24 Comparison Between COSSOM and WALLRUS Computed Hydrographs of Chamber Inflow and Throughflow for Hypothetical Catchment at Site 6.



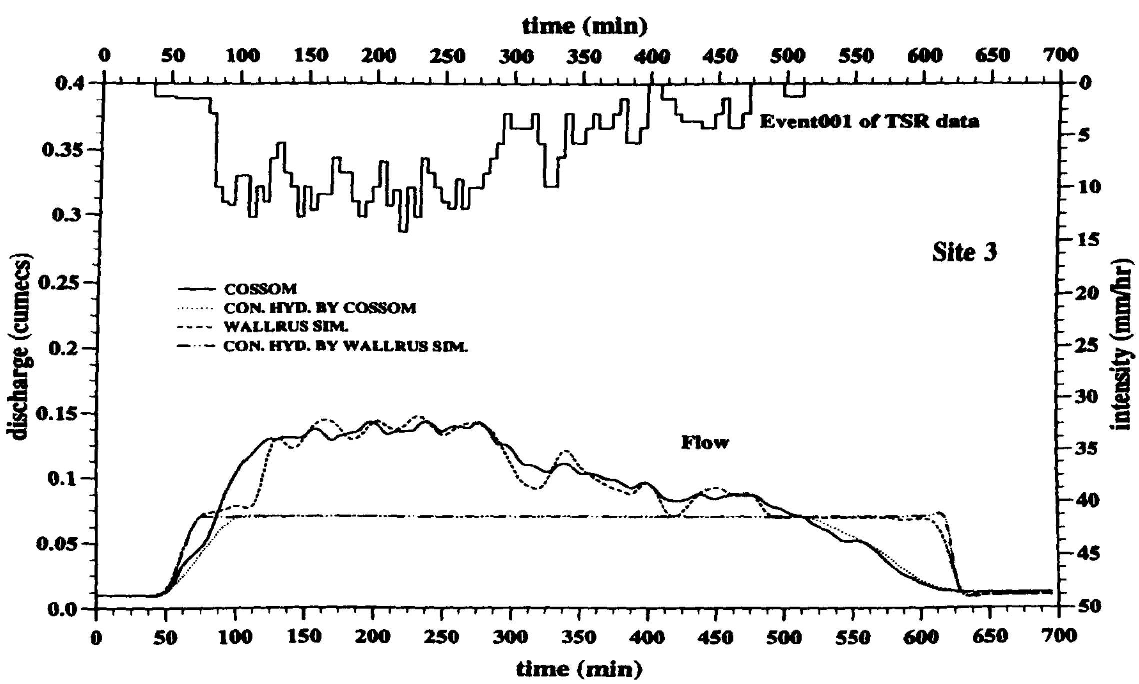
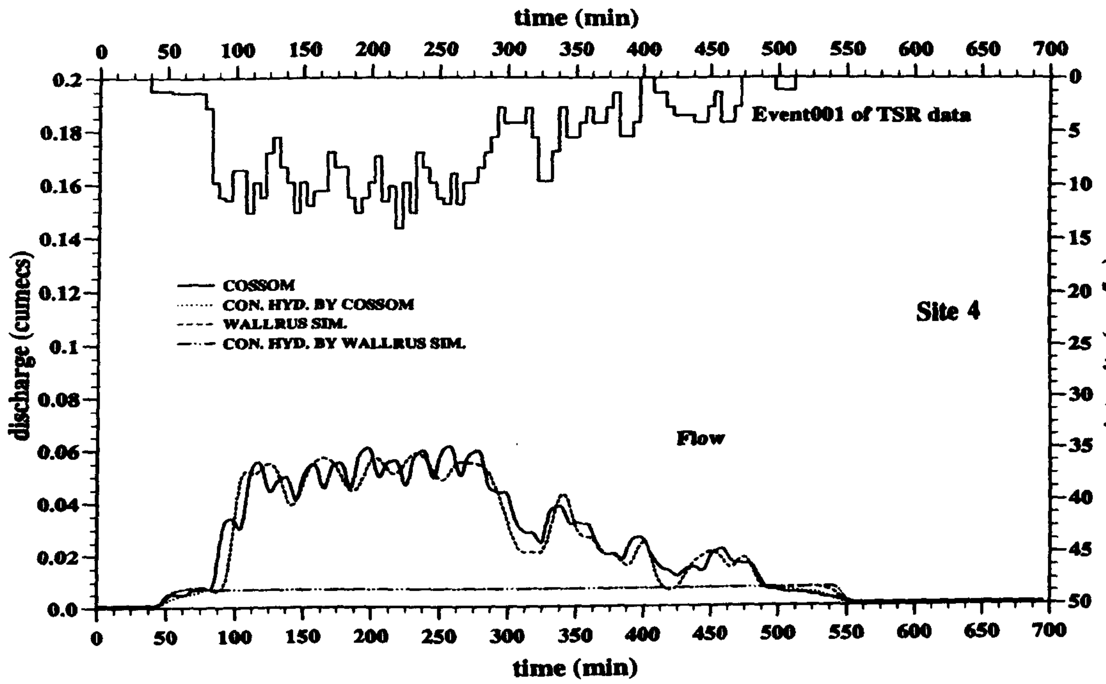


Figure 7.25 Comparison of COSSOM and WALLRUS Predicted Chamber Inflow and Throughflow for Fleetwood Catchment at Sites 2 and 3.



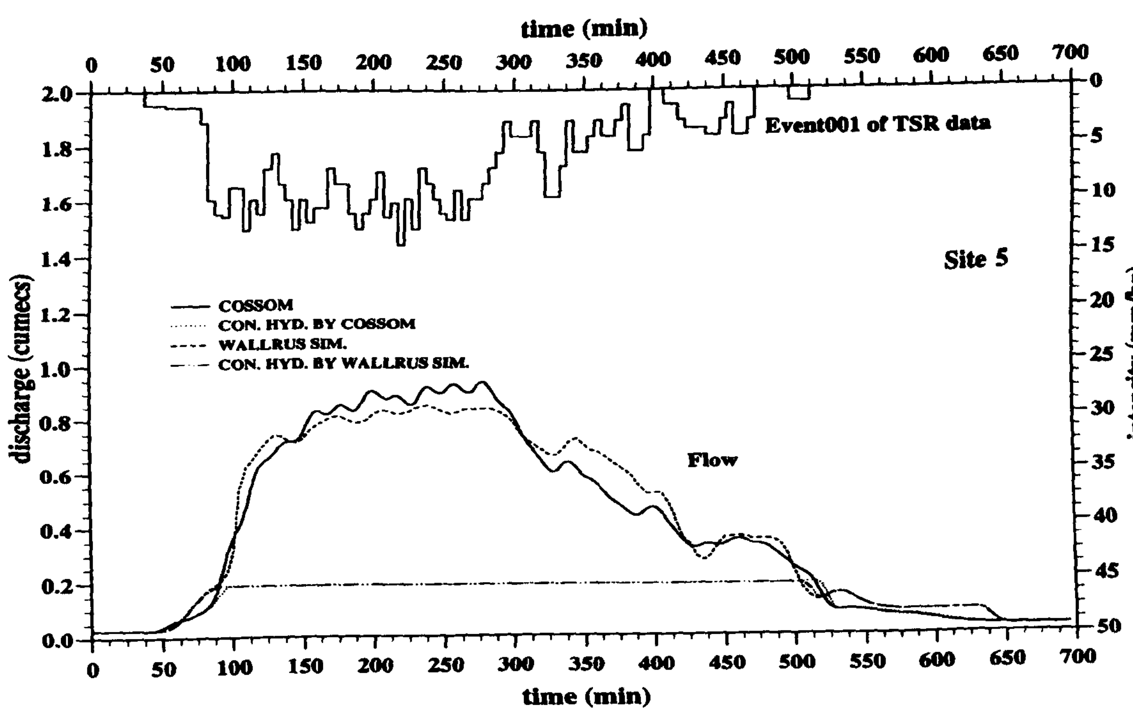
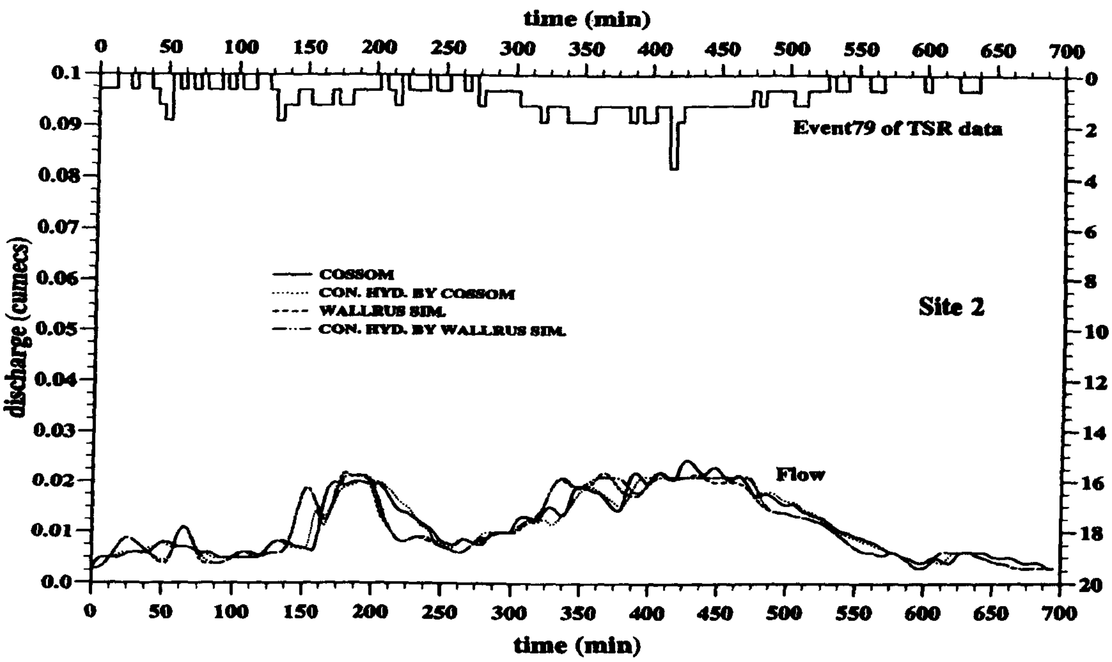


Figure 7.26 Comparison of COSSOM and WALLRUS Predicted Chamber Inflow and Throughflow for Fleetwood Catchment at Sites 4 and 5.



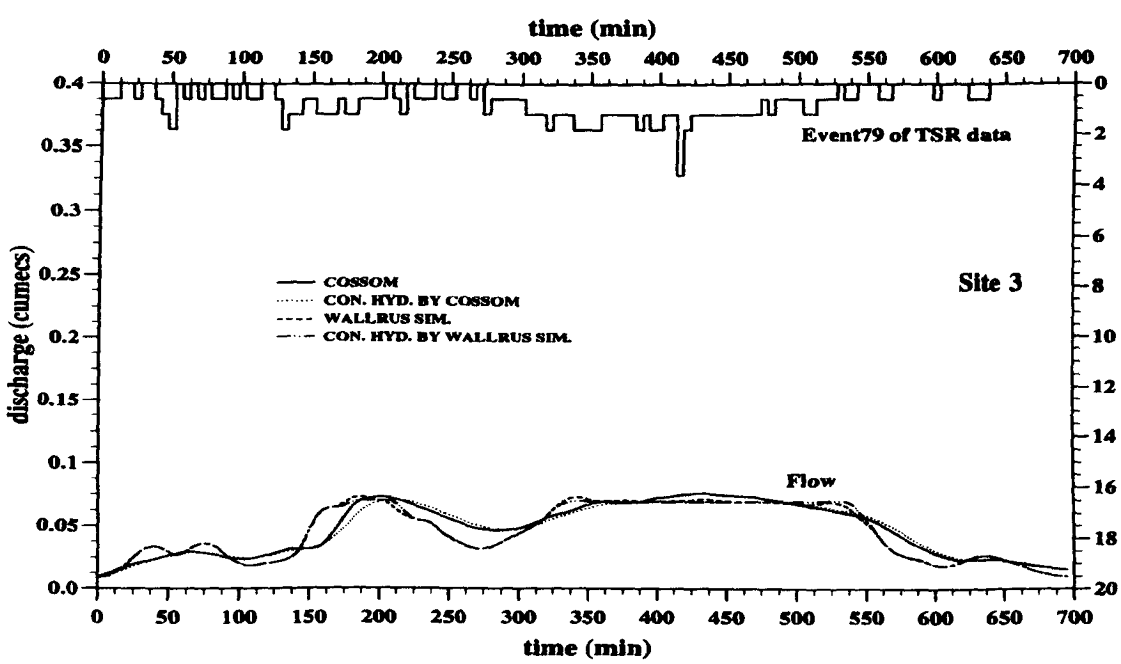
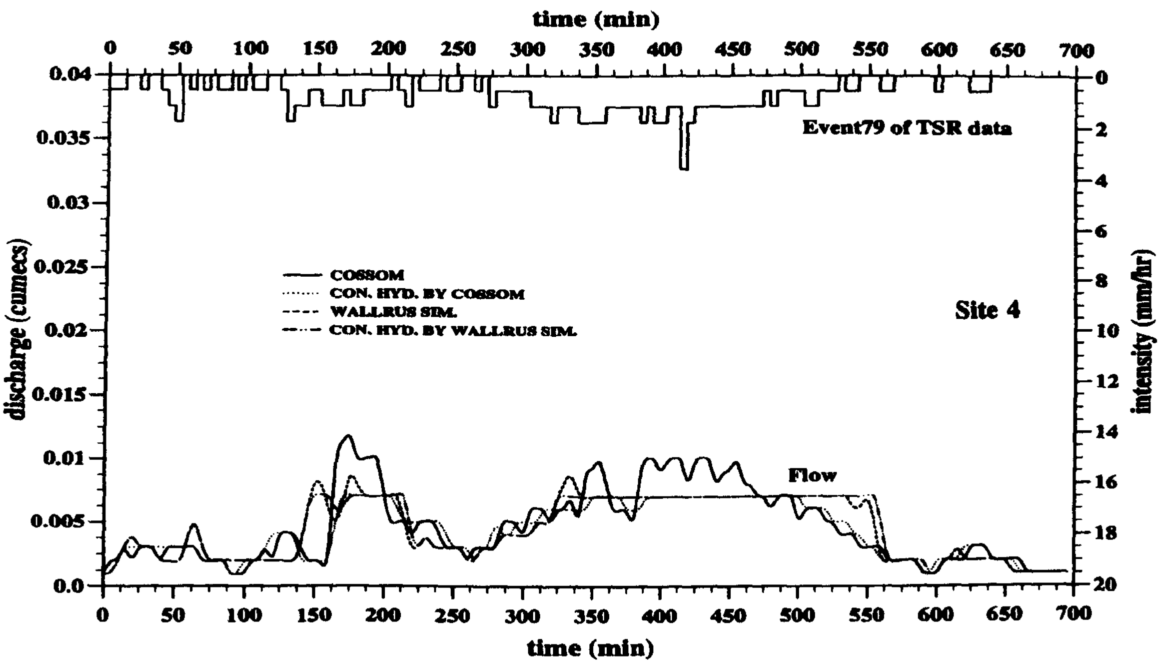


Figure 7.27 Comparison of COSSOM and WALLRUS Predicted Chamber Inflow and Throughflow for Fleetwood Catchment at Sites 2 and 3.



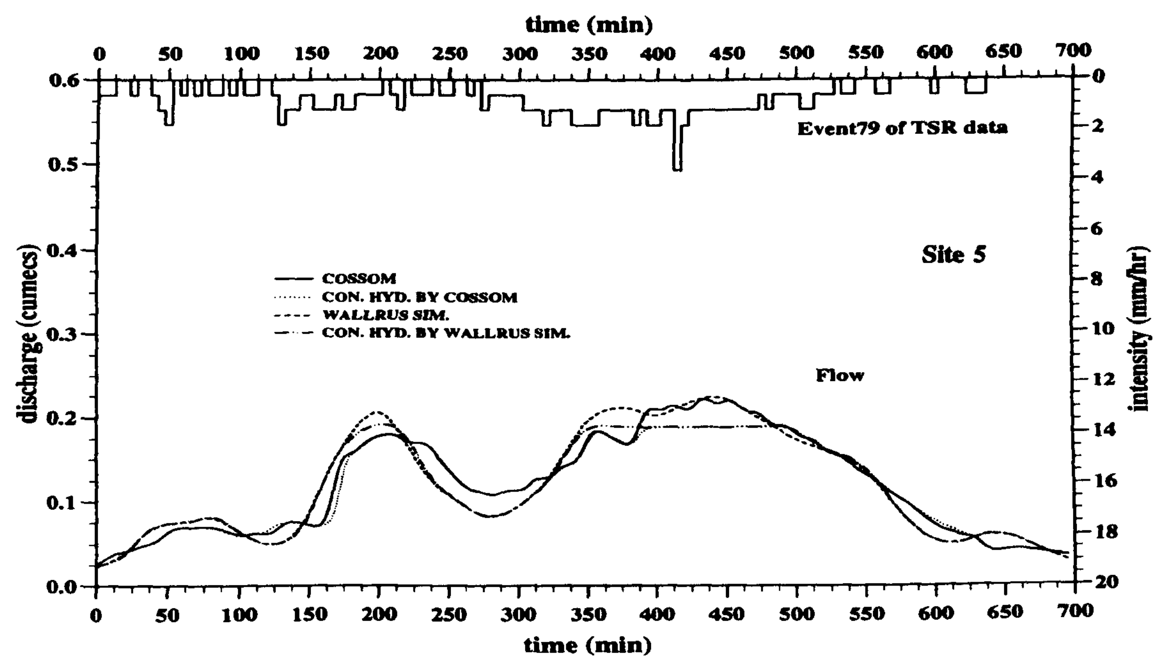
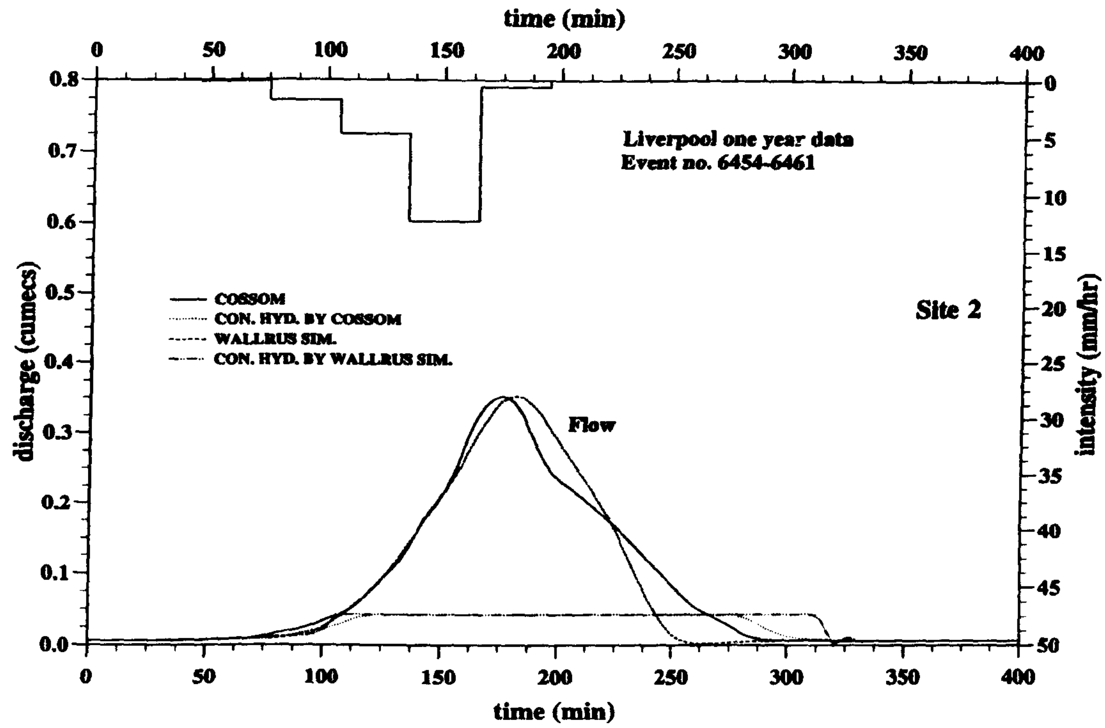


Figure 7.28 Comparison of COSSOM and WALLRUS Predicted Chamber Inflow and Throughflow for Fleetwood Catchment at Sites 4 and 5.



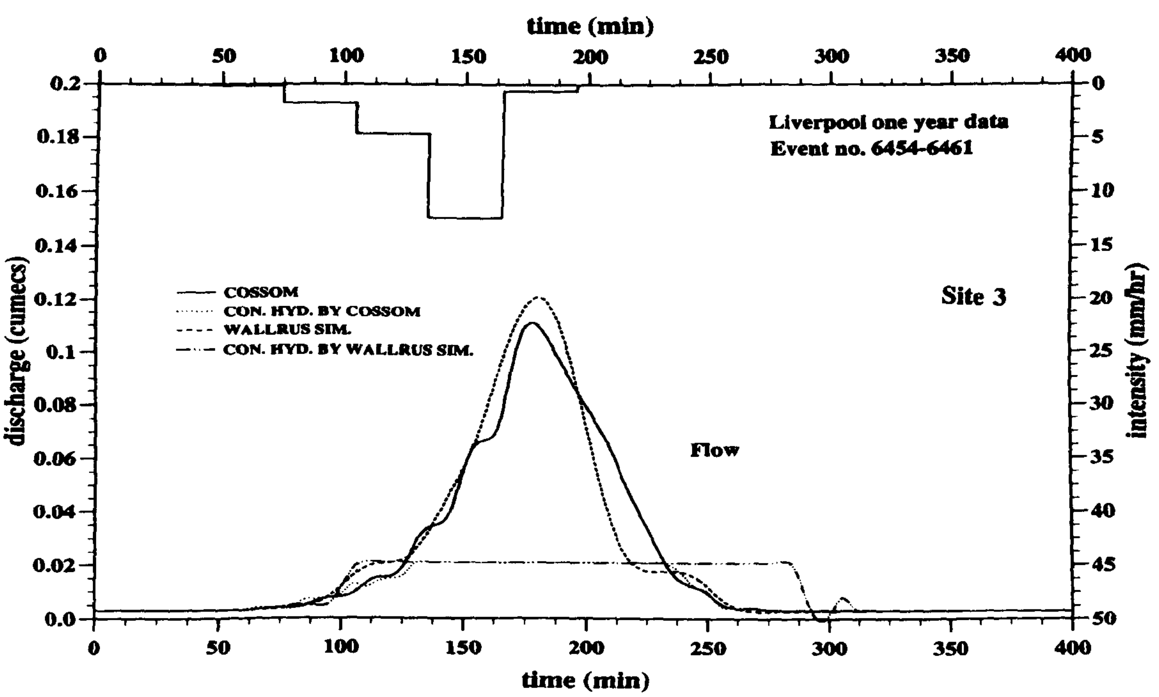
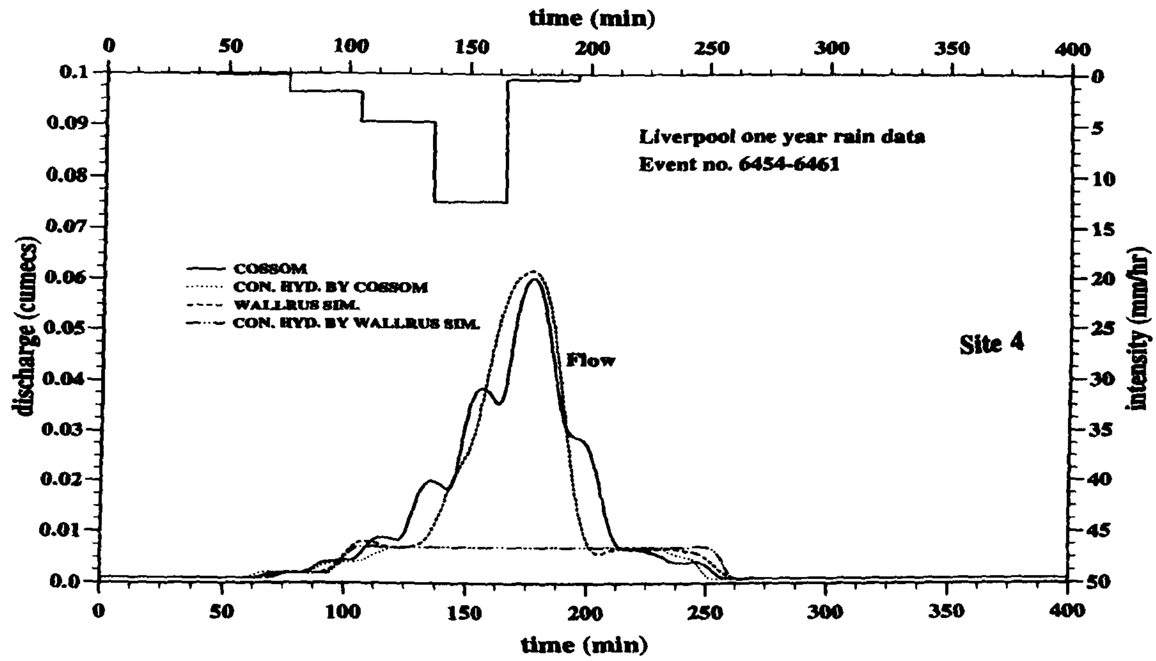


Figure 7.29 Comparison of COSSOM and WALLRUS Predicted Chamber Inflow and Throughflow for Fleetwood Catchment at Sites 2 and 3.



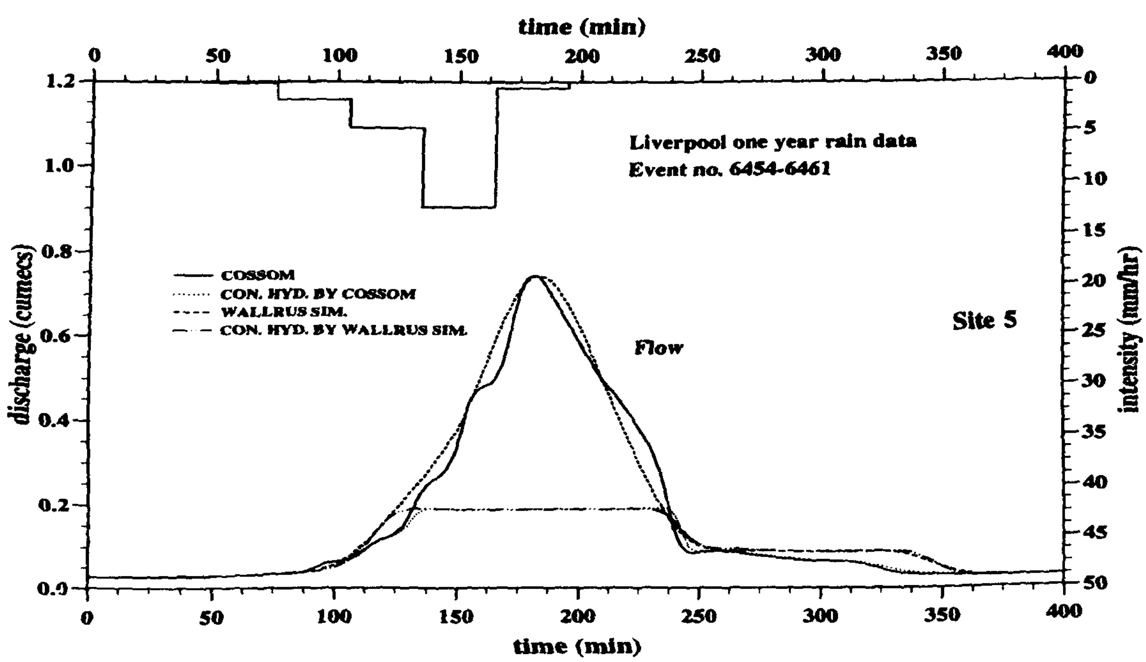
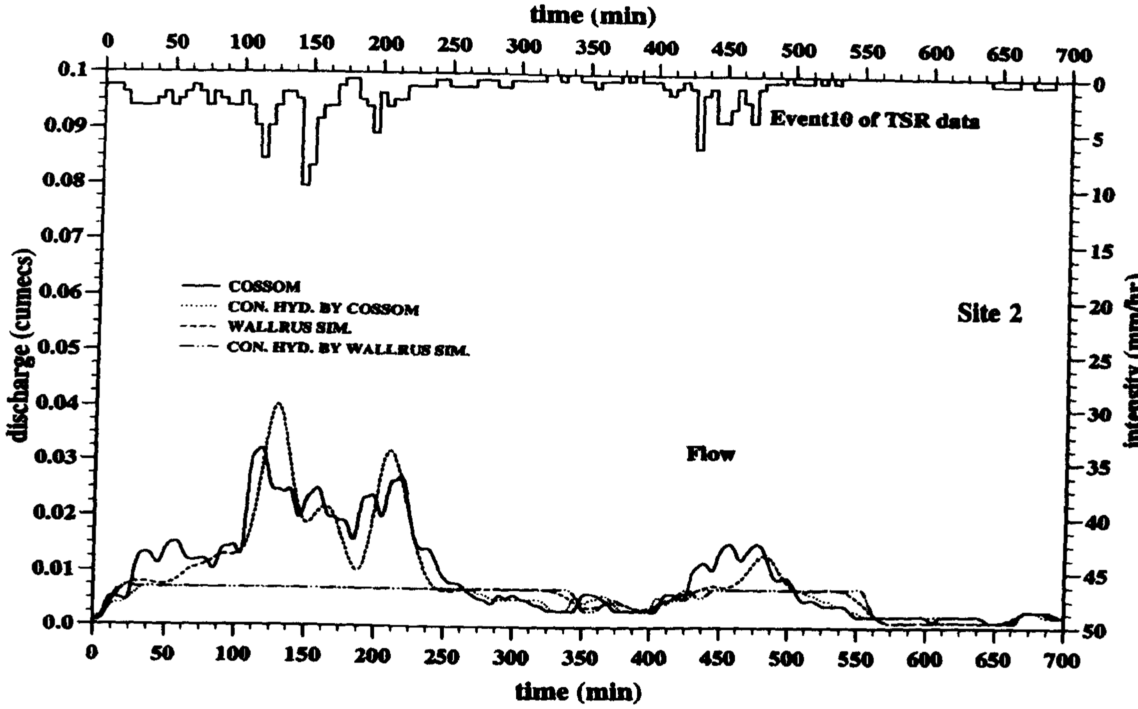


Figure 7.30 Comparison of COSSOM and WALLRUS Predicted Chamber Inflow and Throughflow for Fleetwood Catchment at Sites 4 and 5.



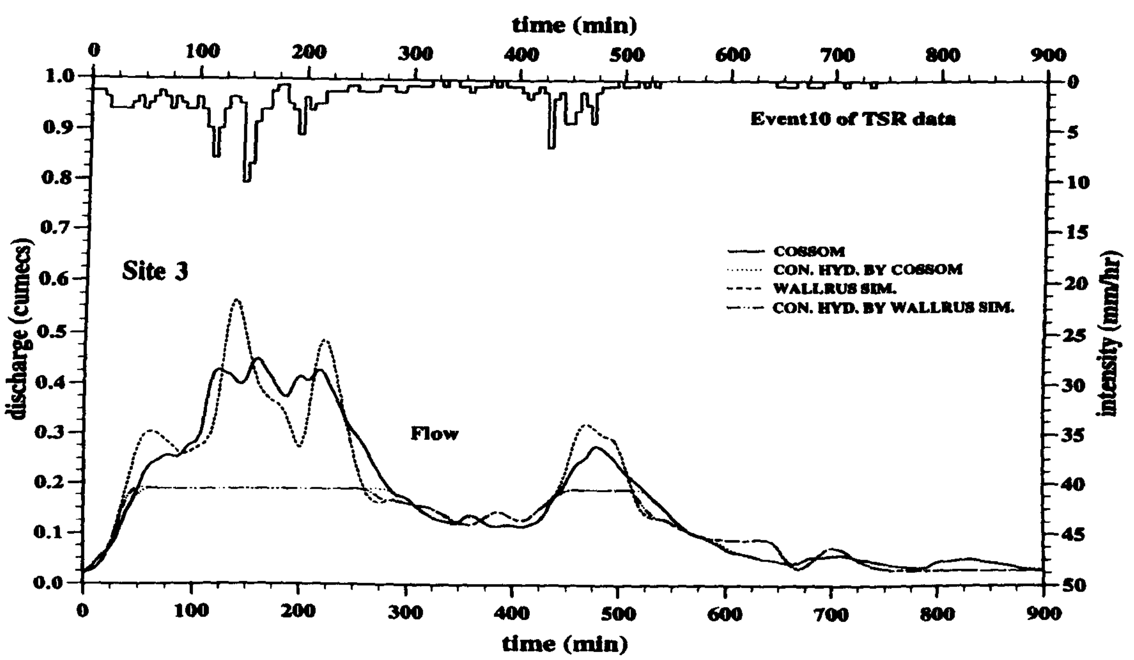
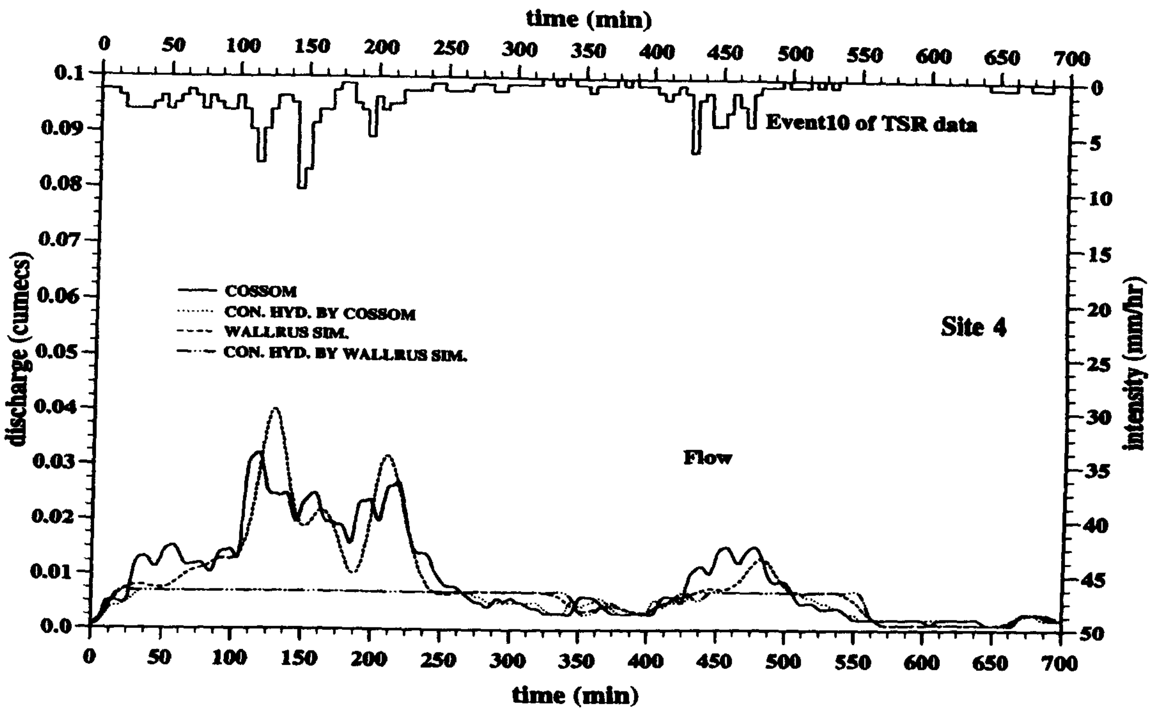


Figure 7.31 Comparison of COSSOM and WALLRUS Predicted Chamber Inflow and Throughflow for Fleetwood Catchment at Sites 2 and 3.



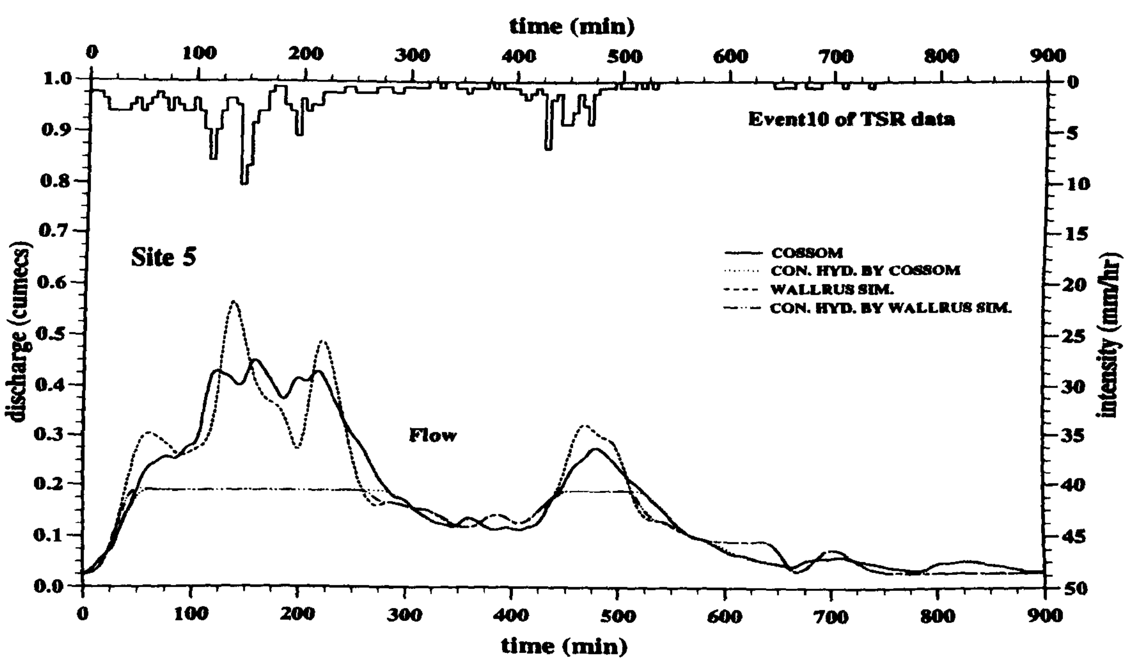
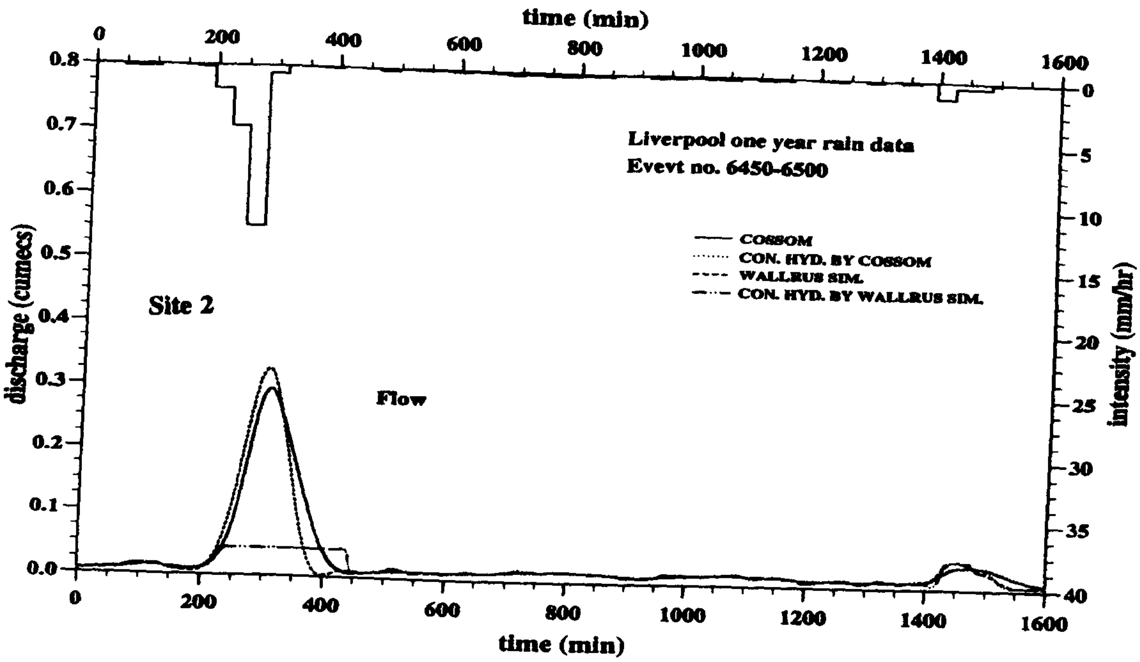


Figure 7.32 Comparison of COSSOM and WALLRUS Predicted Chamber Inflow and Throughflow for Fleetwood Catchment at Sites 4 and 5.



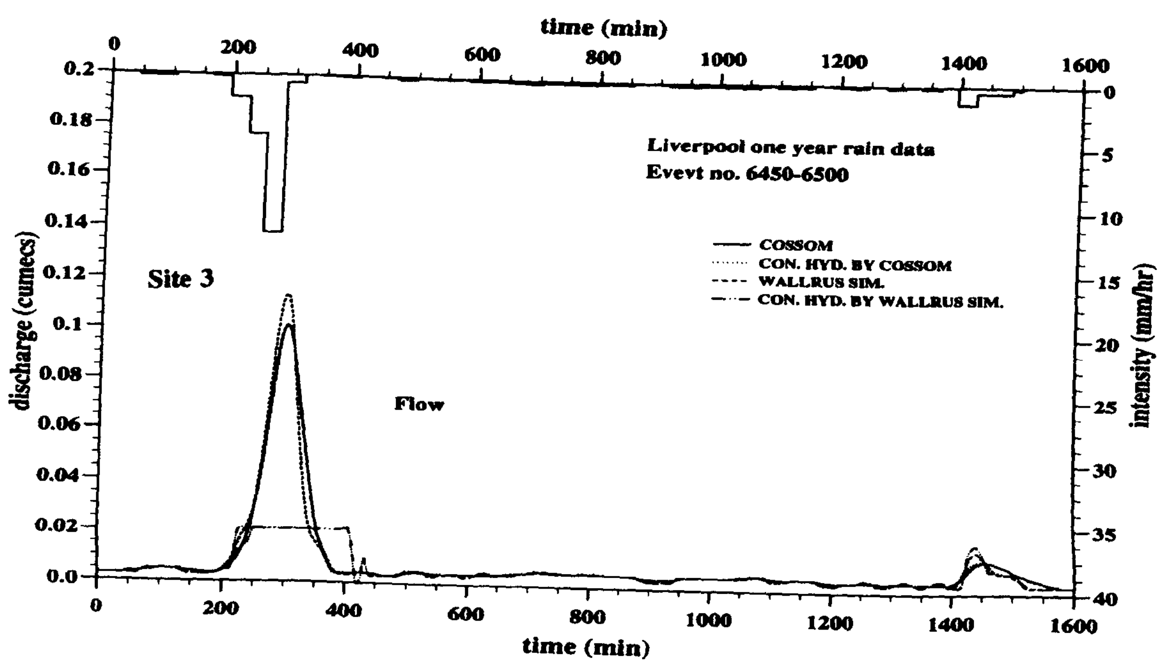
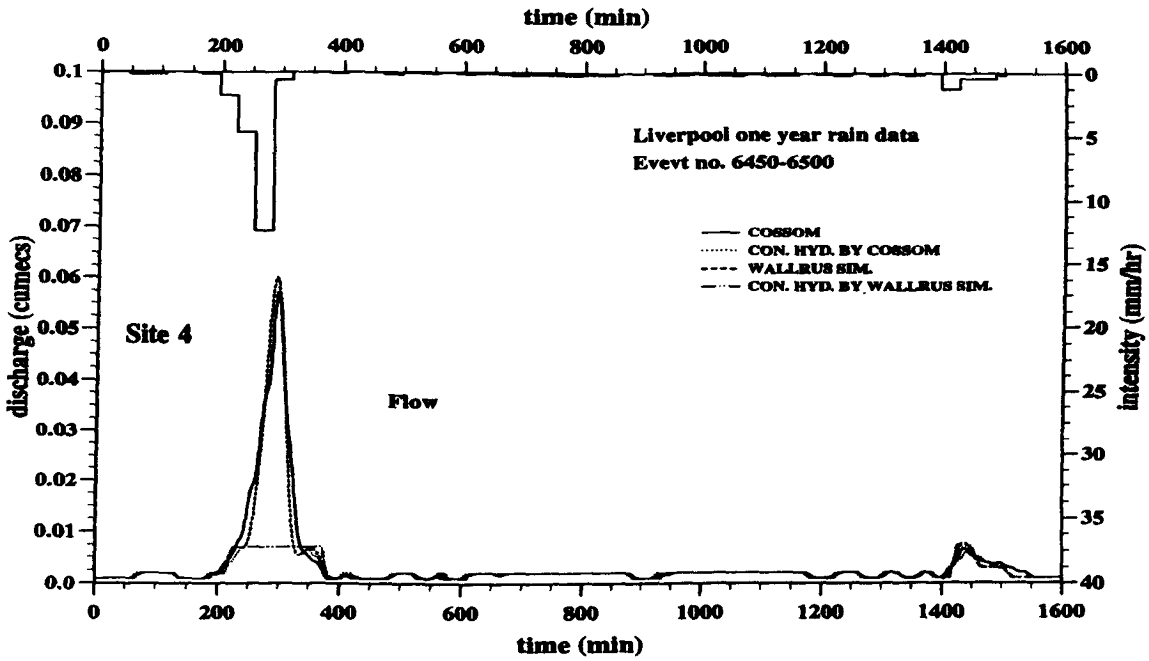


Figure 7.33 Comparison of COSSOM and WALLRUS Predicted Chamber Inflow and Throughflow for Fleetwood Catchment at Sites 2 and 3.



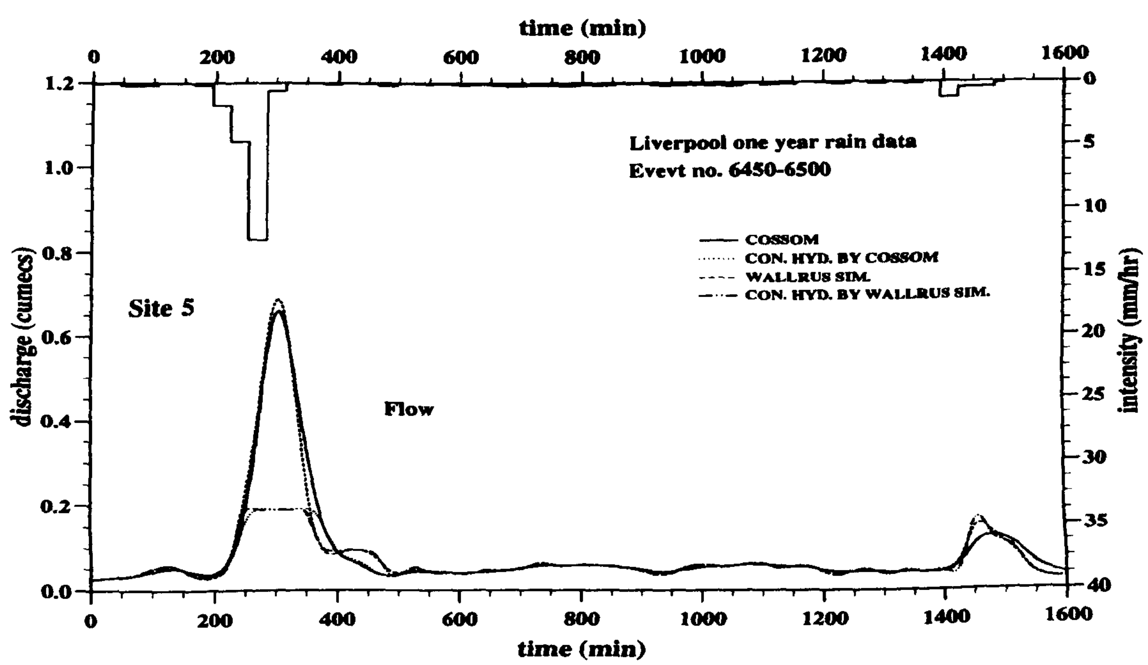
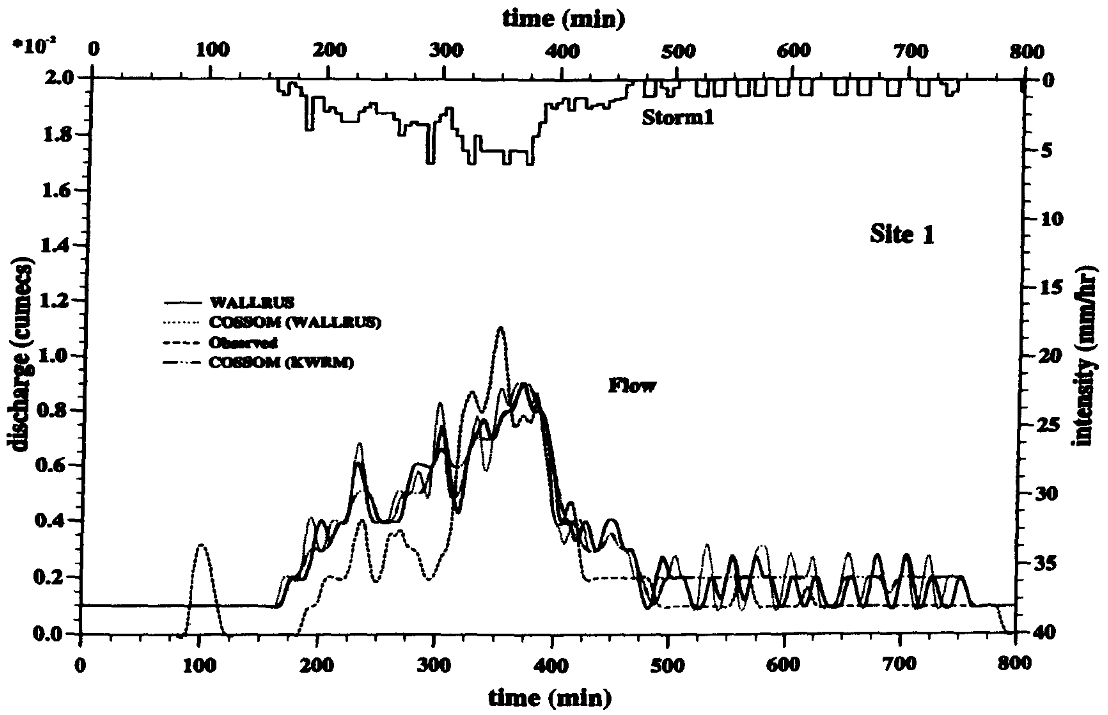


Figure 7.34 Comparison of COSSOM and WALLRUS Predicted Chamber Inflow and Throughflow for Fleetwood Catchment at Sites 2 and 3.



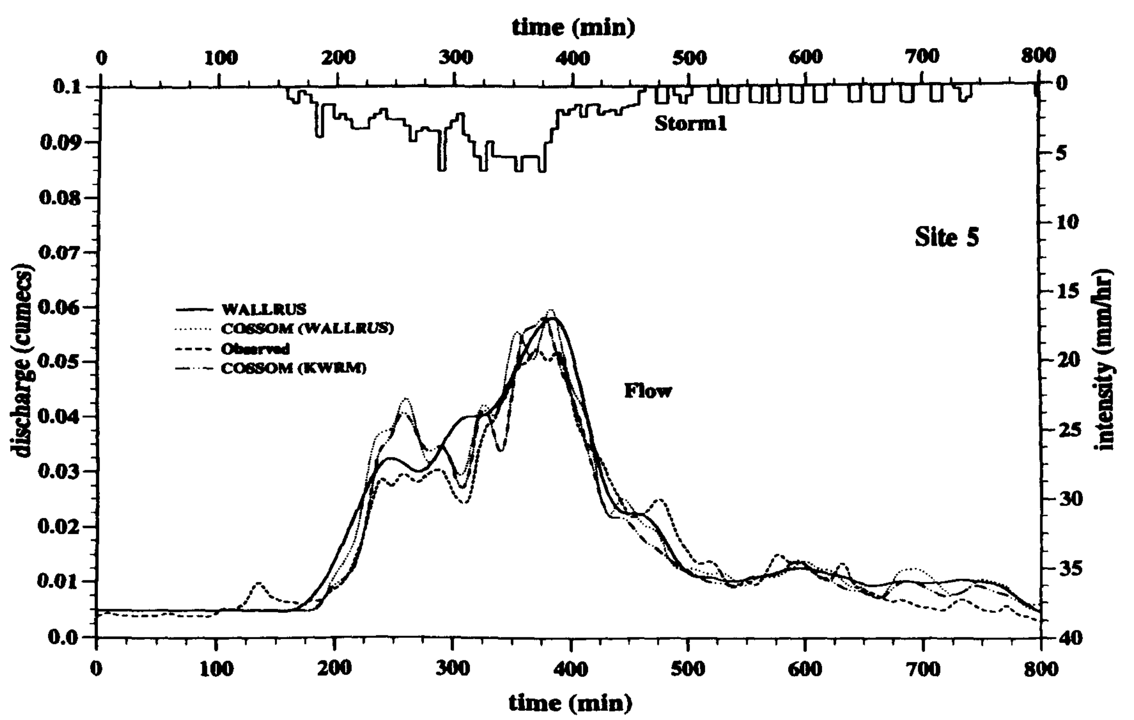
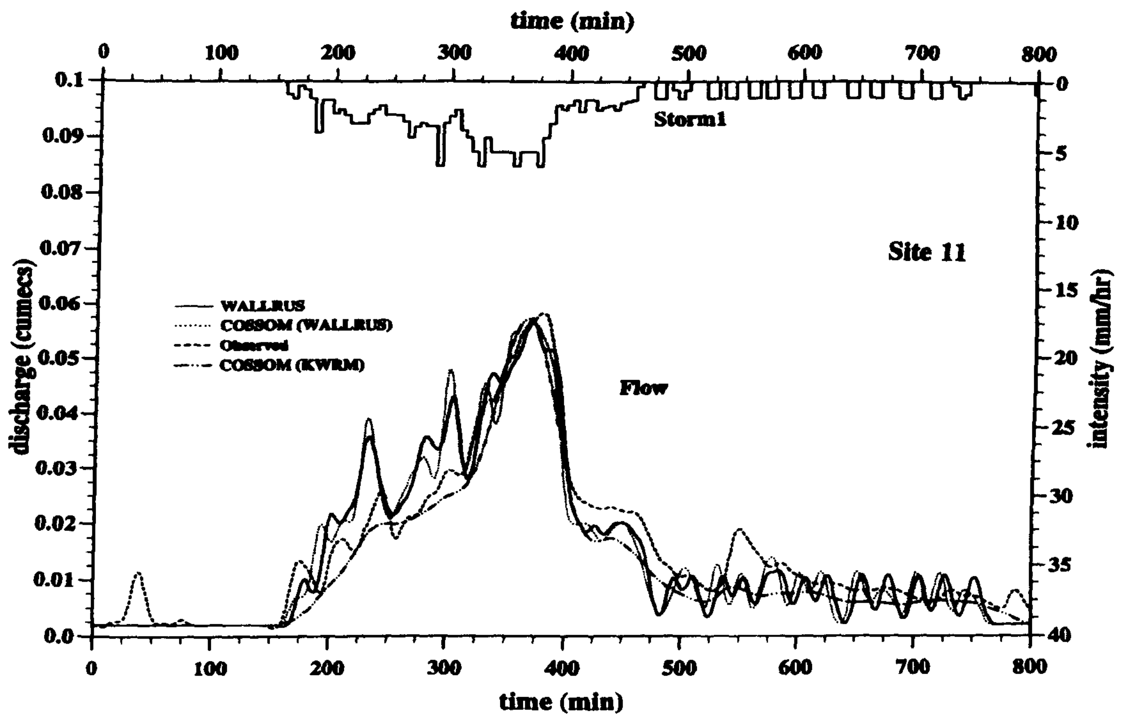


Figure 7.35 Comparison Between Observed and Computed by WALLRUS and COSSOM (using TUH from WALLRUS and KWRM) Flows at Sites 1 and 5 of Middlewood Sewerage System.



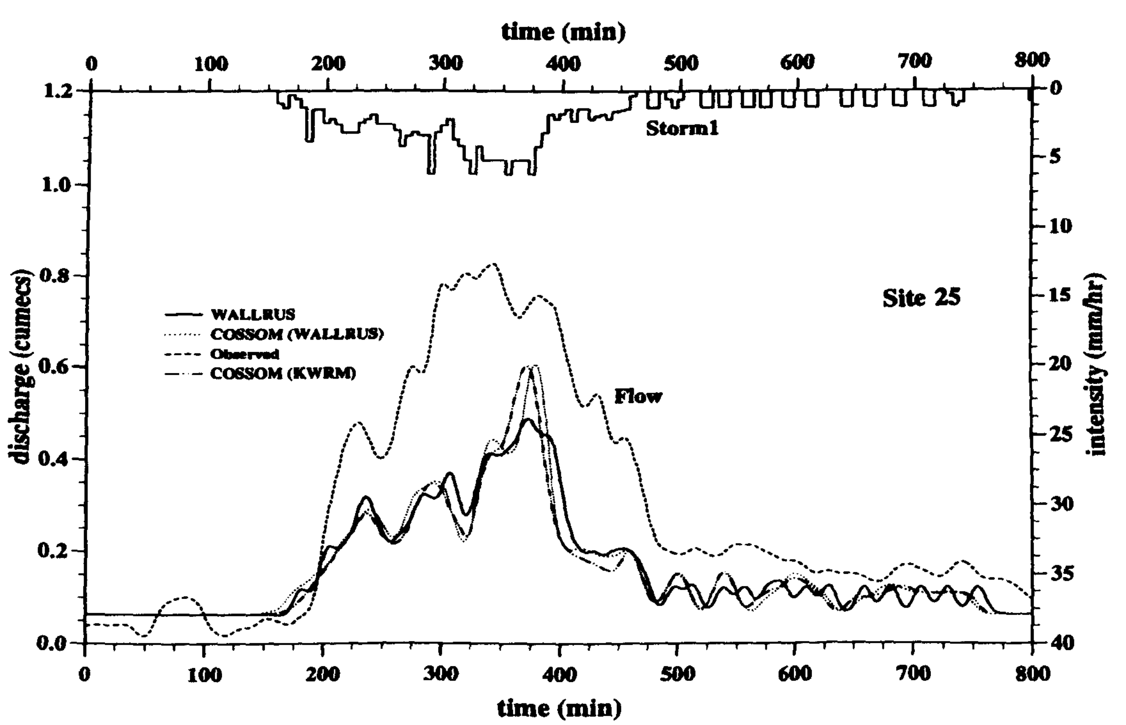
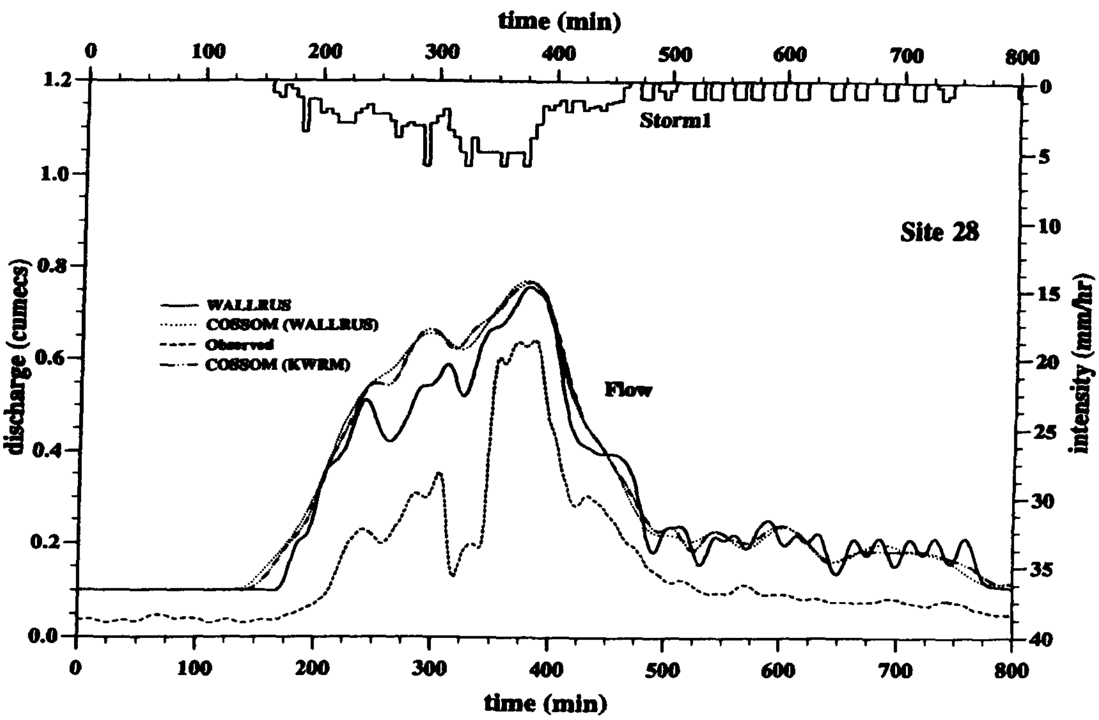


Figure 7.36 Comparison Between Observed and Computed by WALLRUS and COSSOM (using TUH from WALLRUS and KWRM) Flows at Sites 11 and 25 of Middlewood Sewerage System.



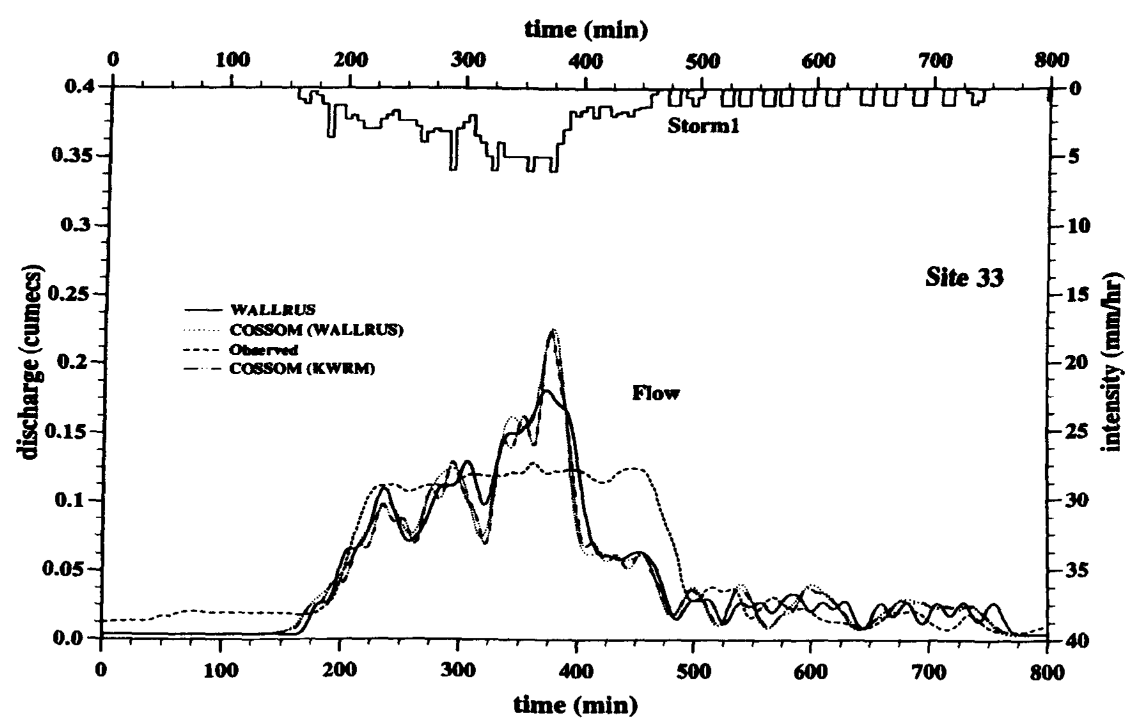
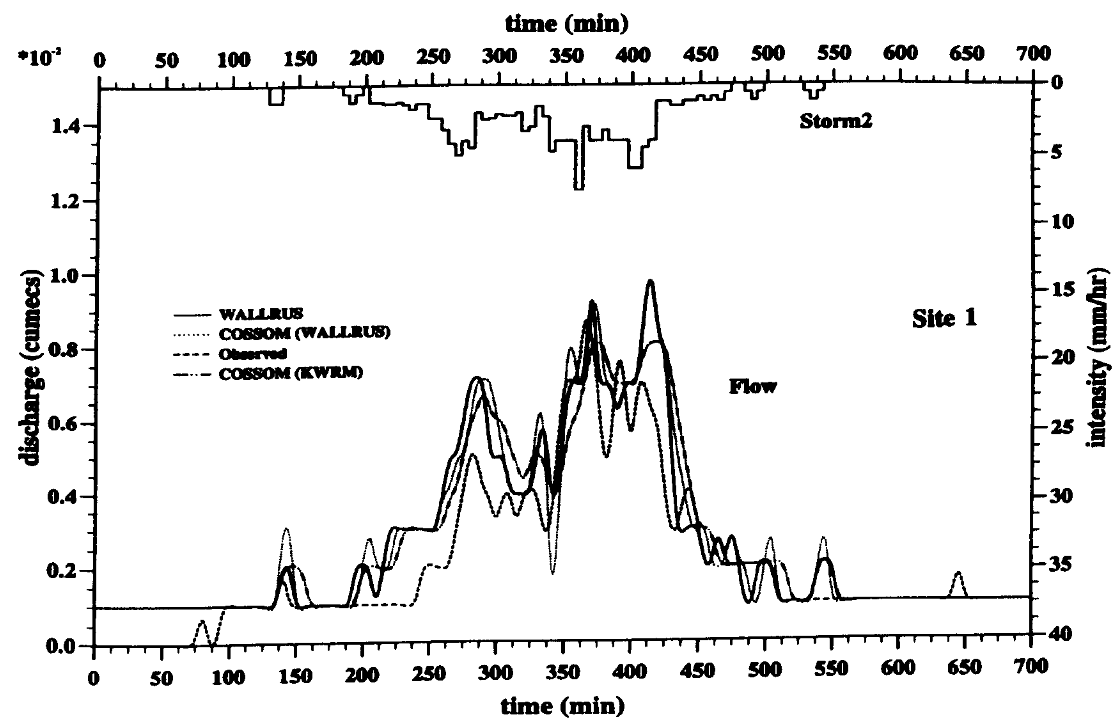


Figure 7.37 Comparison Between Observed and Computed by WALLRUS and COSSOM (using TUH from WALLRUS and KWRM) Flows at Sites 28 and 33 of Middlewood Sewerage System.



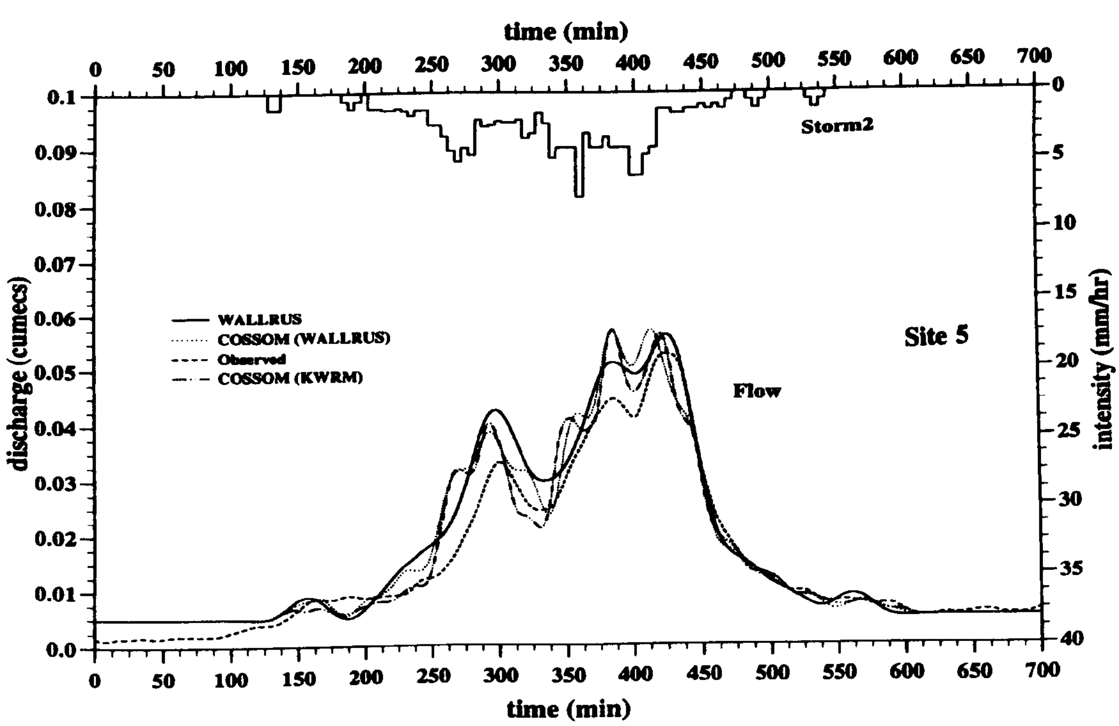
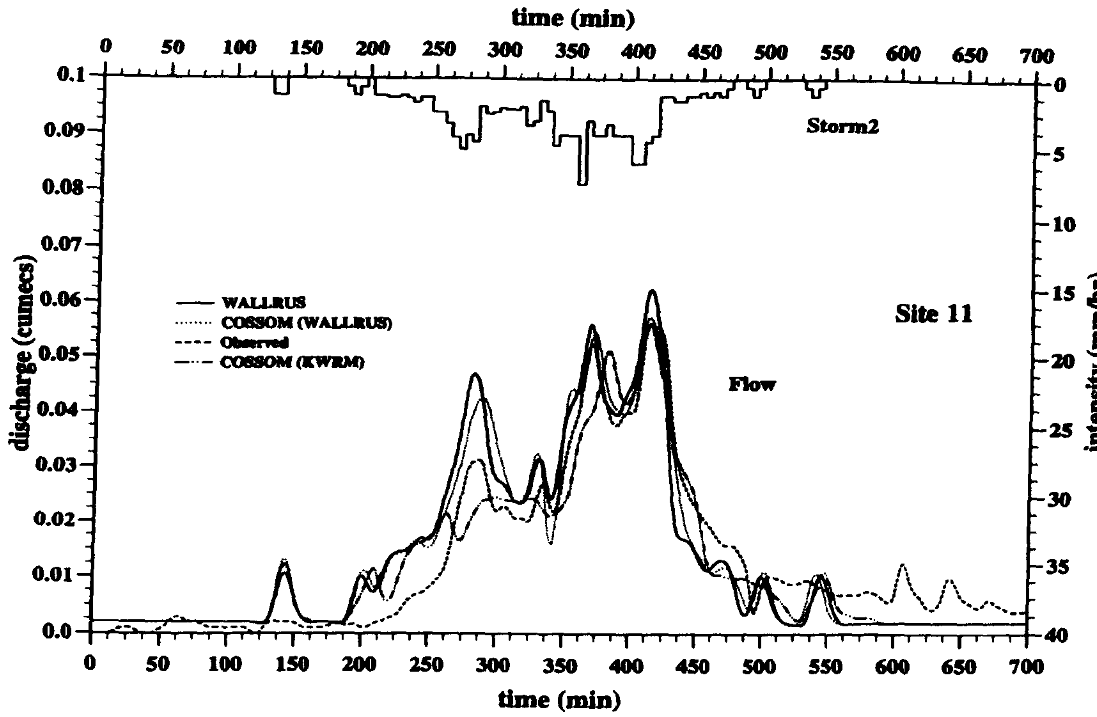


Figure 7.38 Comparison Between Observed and Computed by WALLRUS and COSSOM (using TUH from WALLRUS and KWRM) Flows at Sites 1 and 5 of Middlewood Sewerage System.



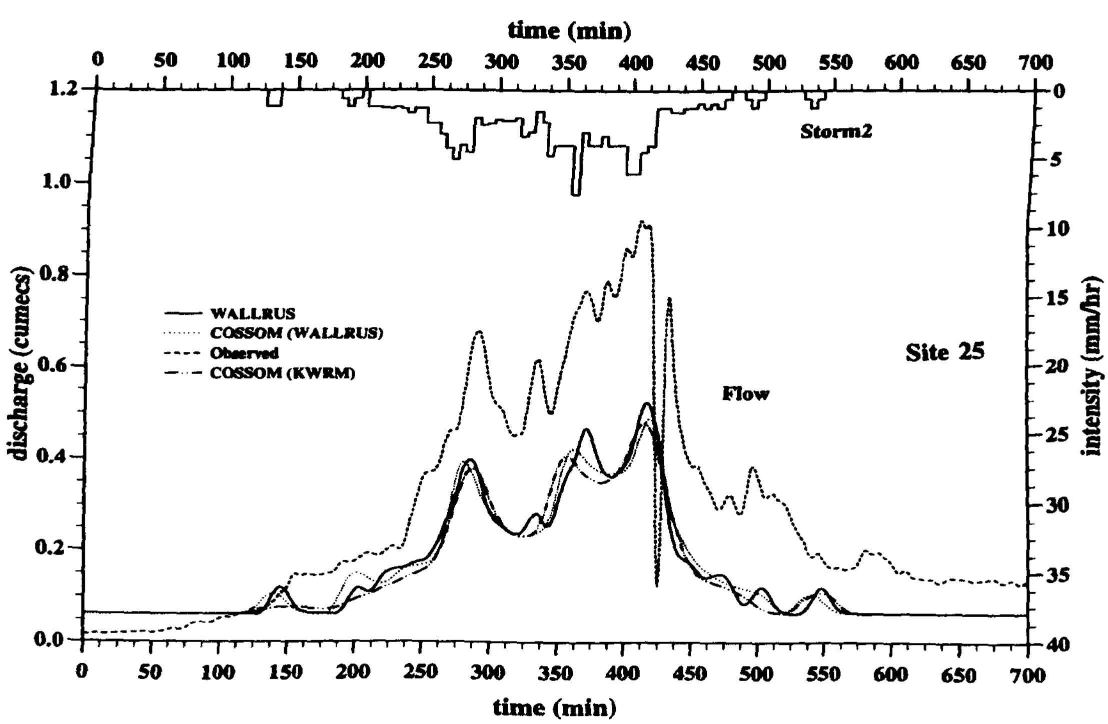
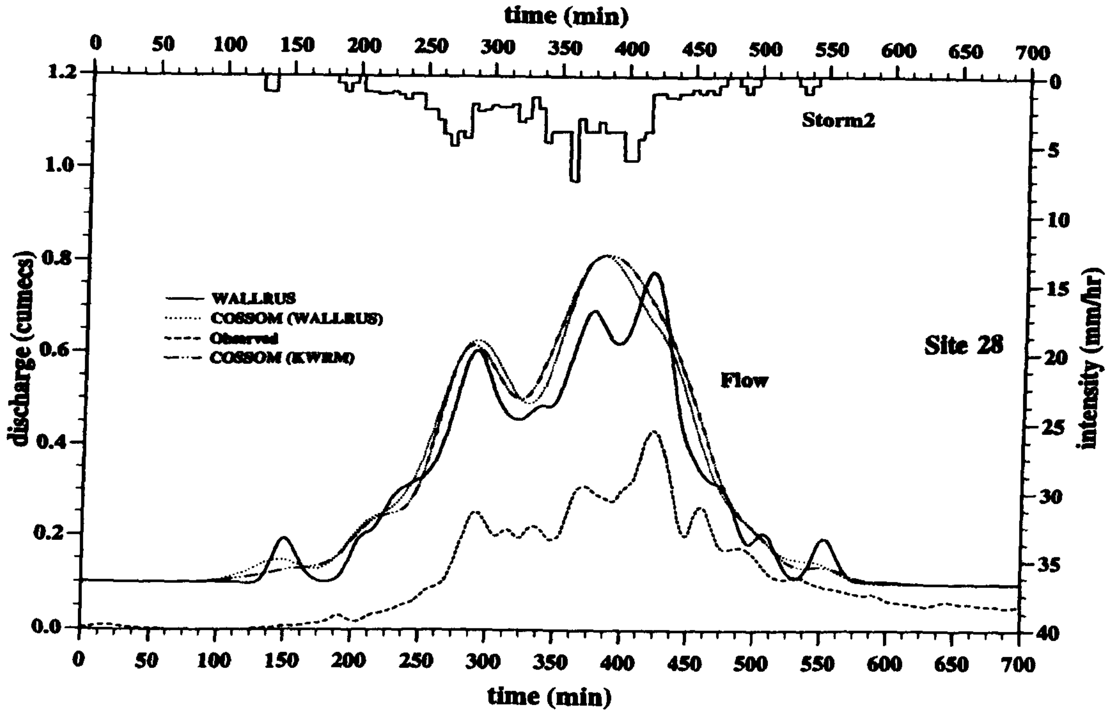


Figure 7.39 Comparison Between Observed and Computed by WALLRUS and COSSOM (using TUH from WALLRUS and KWRM) Flows at Sites 11 and 25 of Middlewood Sewerage System.



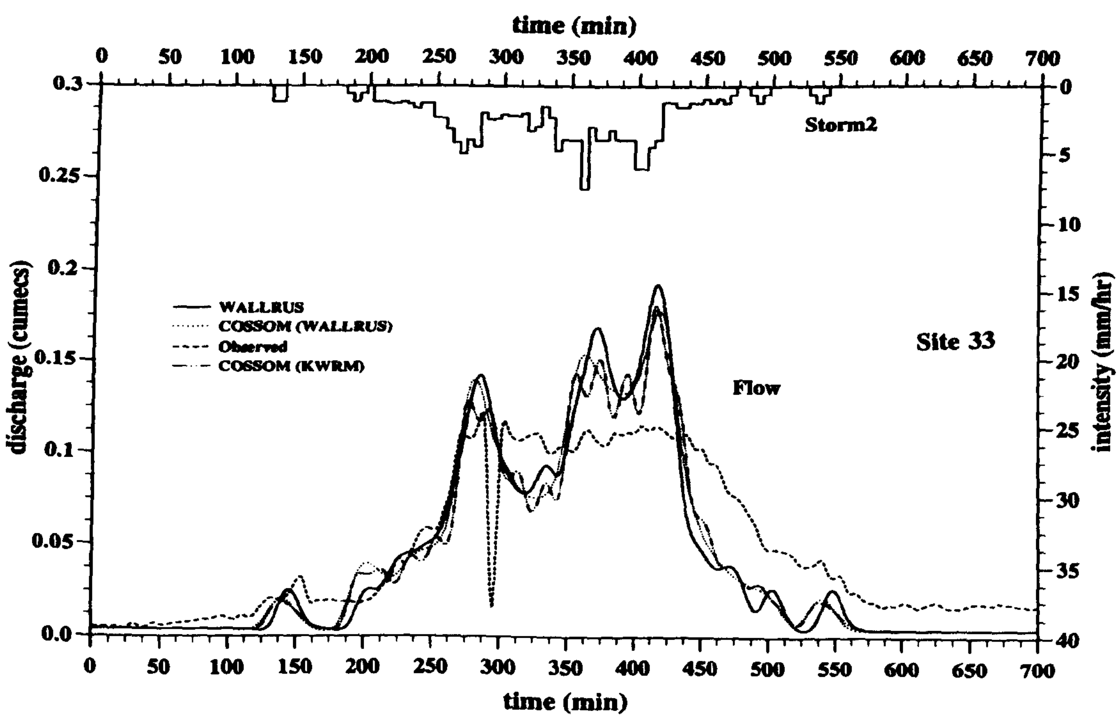
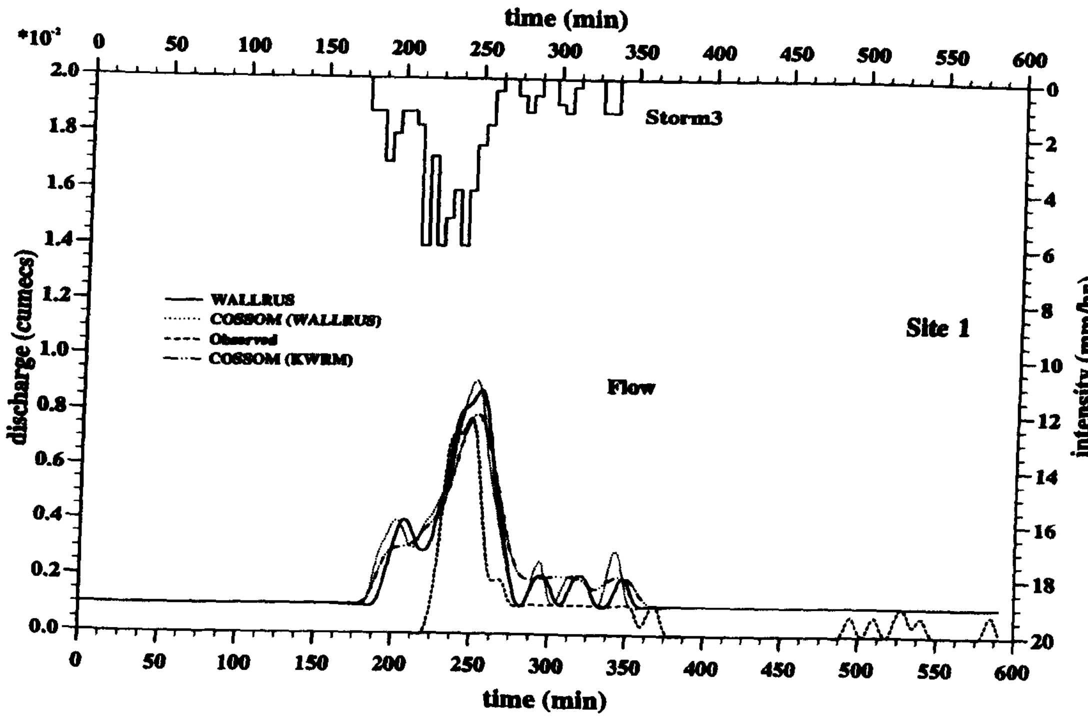


Figure 7.40 Comparison Between Observed and Computed by WALLRUS and COSSOM (using TUH from WALLRUS and KWRM) Flows at Sites 28 and 33 of Middlewood Sewerage System.



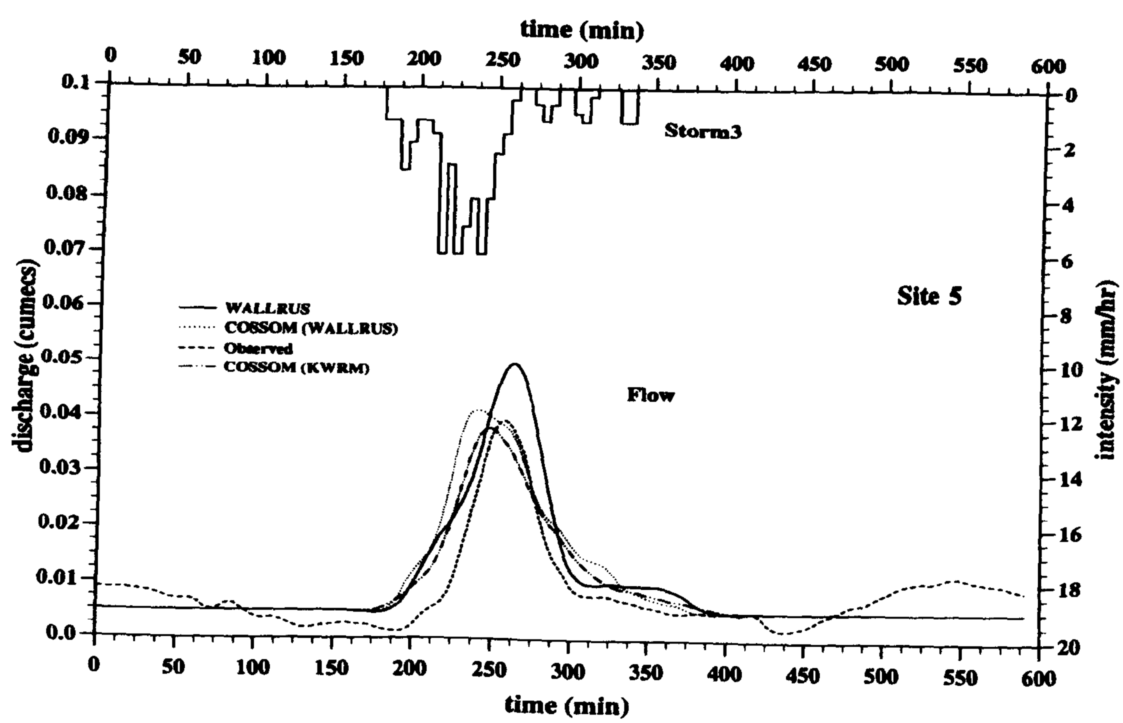
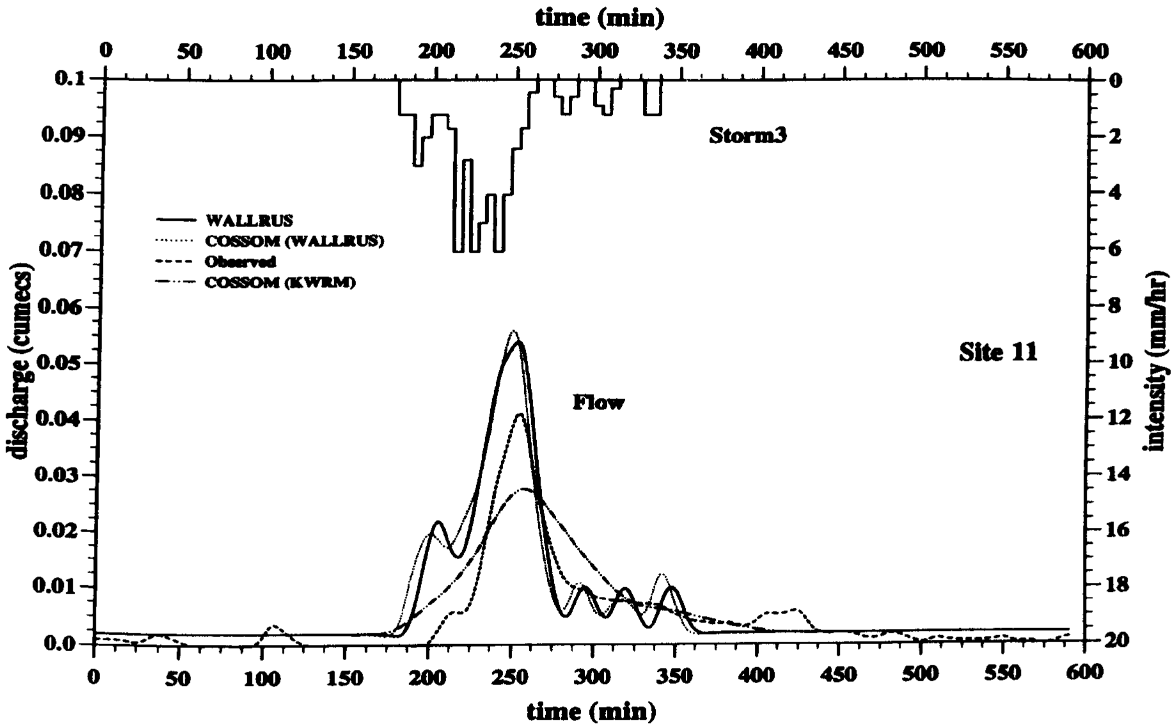


Figure 7.41 Comparison Between Observed and Computed by WALLRUS and COSSOM (using TUH from WALLRUS and KWRM) Flows at Sites 1 and 5 of Middlewood Sewerage System.



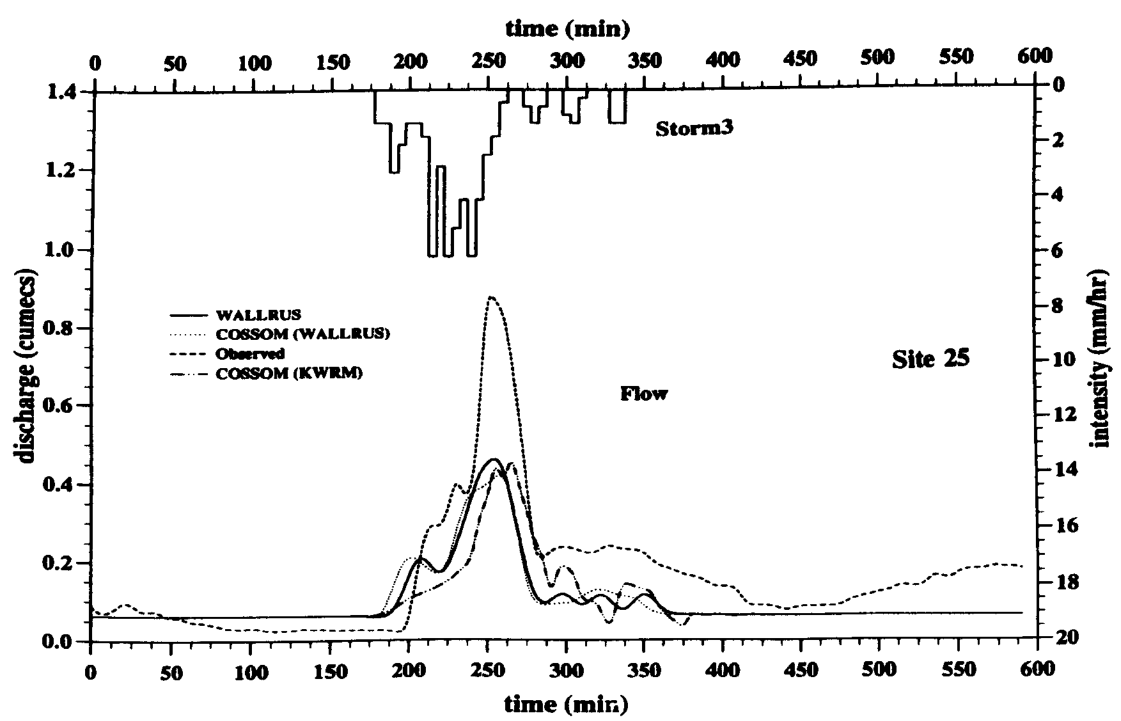
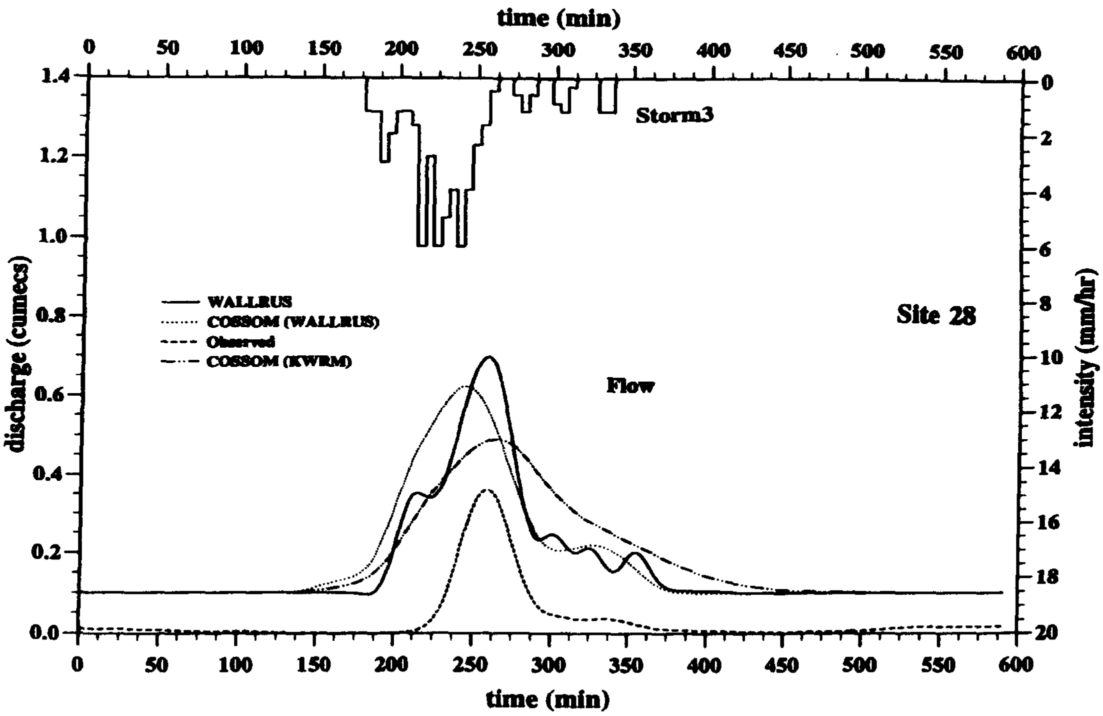


Figure 7.42 Comparison Between Observed and Computed by WALLRUS and COSSOM (using TUH from WALLRUS and KWRM) Flows at Sites 11 and 25 of Middlewood Sewerage System.



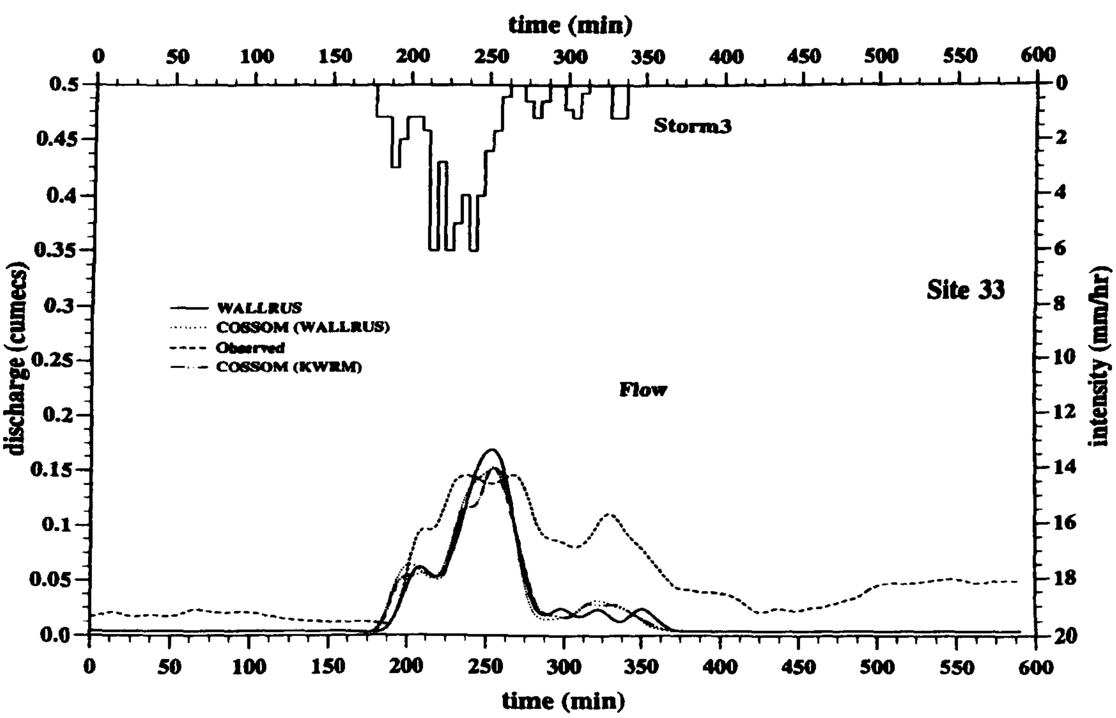
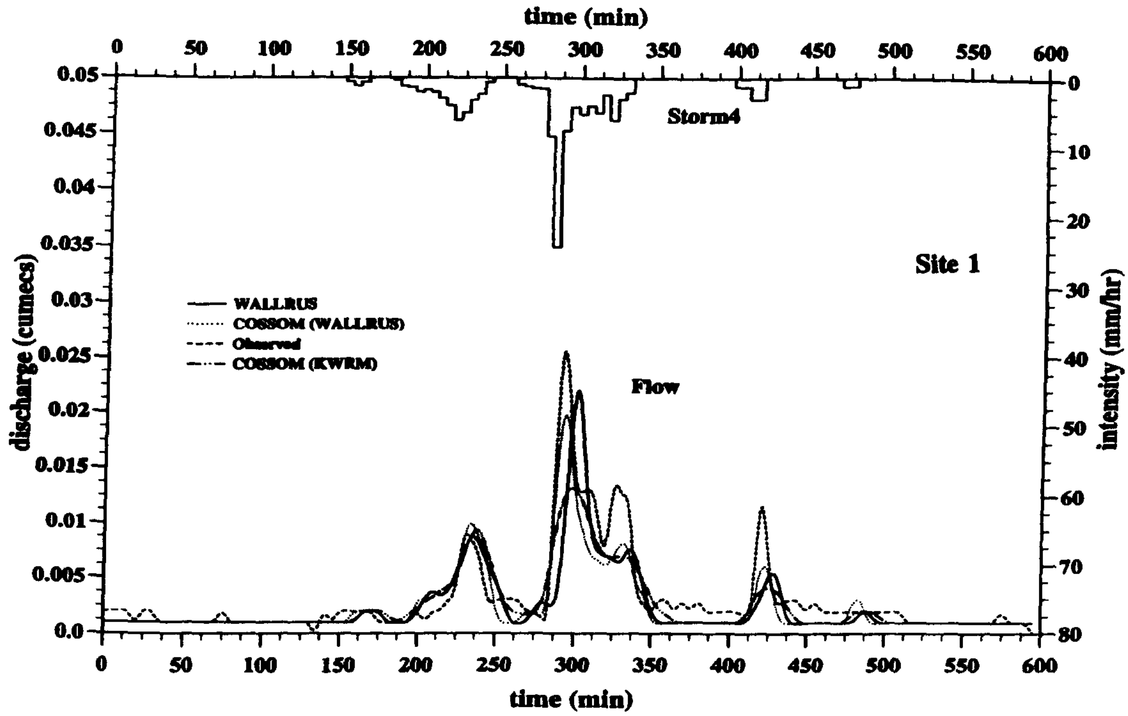


Figure 7.43 Comparison between Observed and Computed by WALLRUS and COSSOM (using TUH from WALLRUS and KWRM) Flows at Sites 28 and 33 of Middlewood Sewerage System.



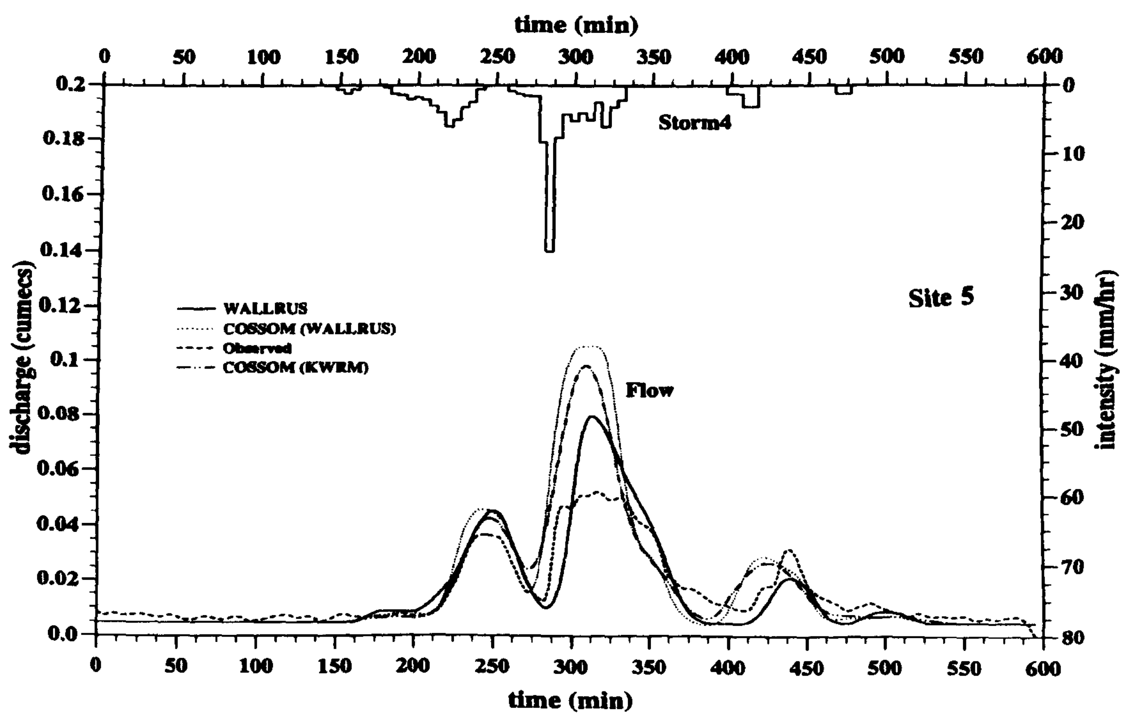
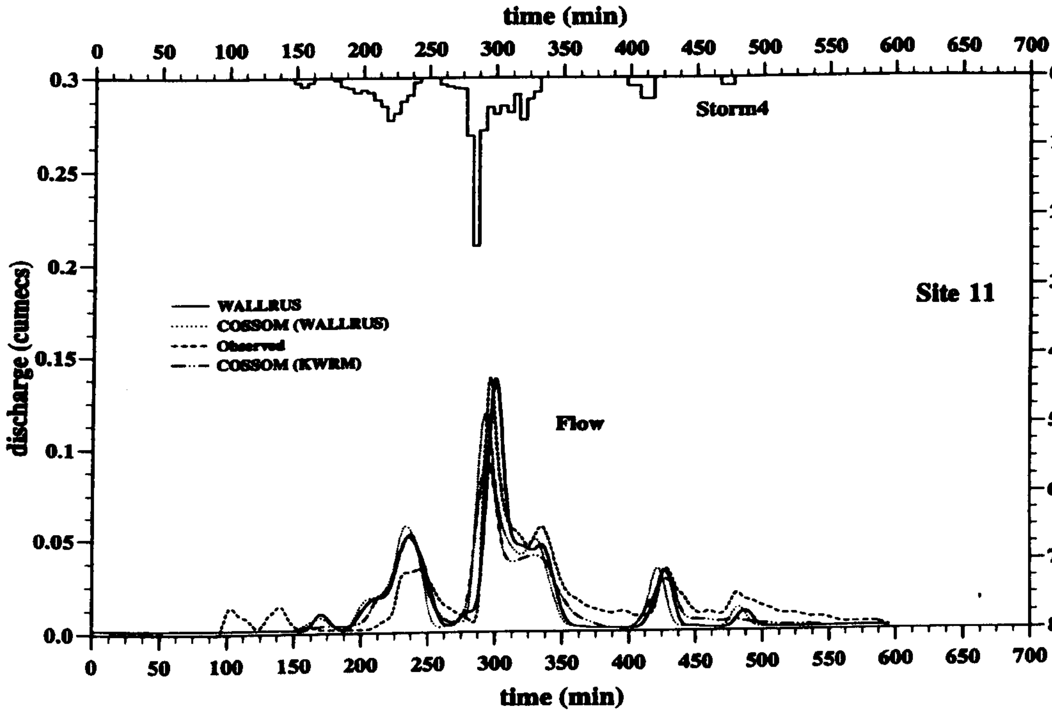


Figure 7.44 Comparison Between Observed and Computed by WALLRUS and COSSOM (using TUH from WALLRUS and KWRM) Flows at Sites 1 and 5 of Middlewood Sewerage System.



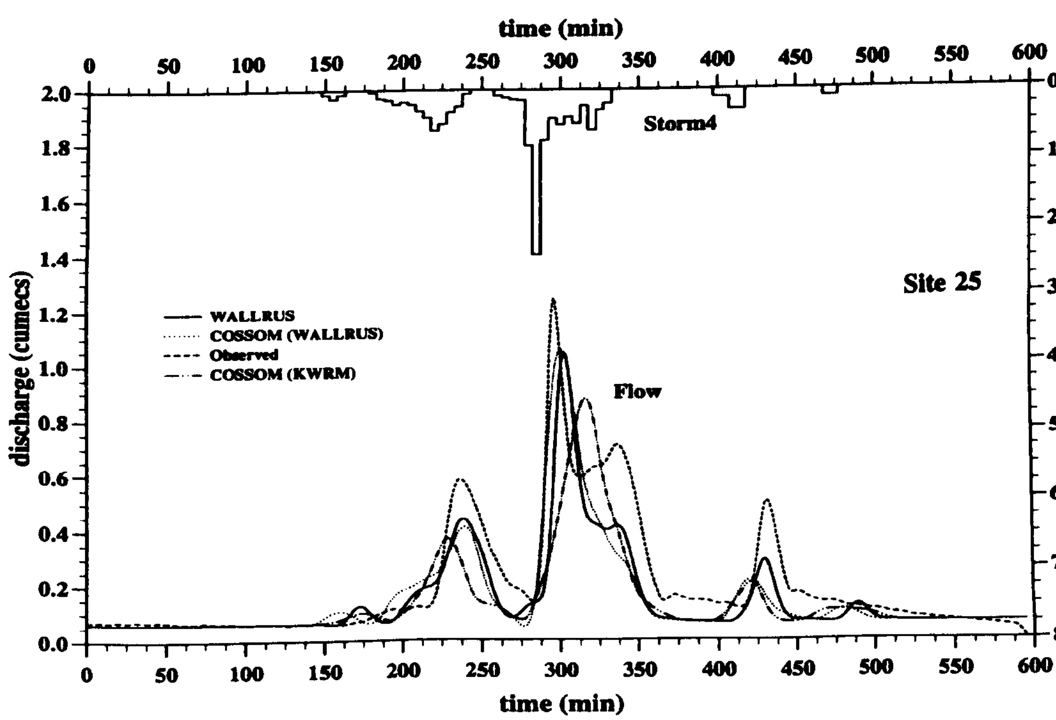
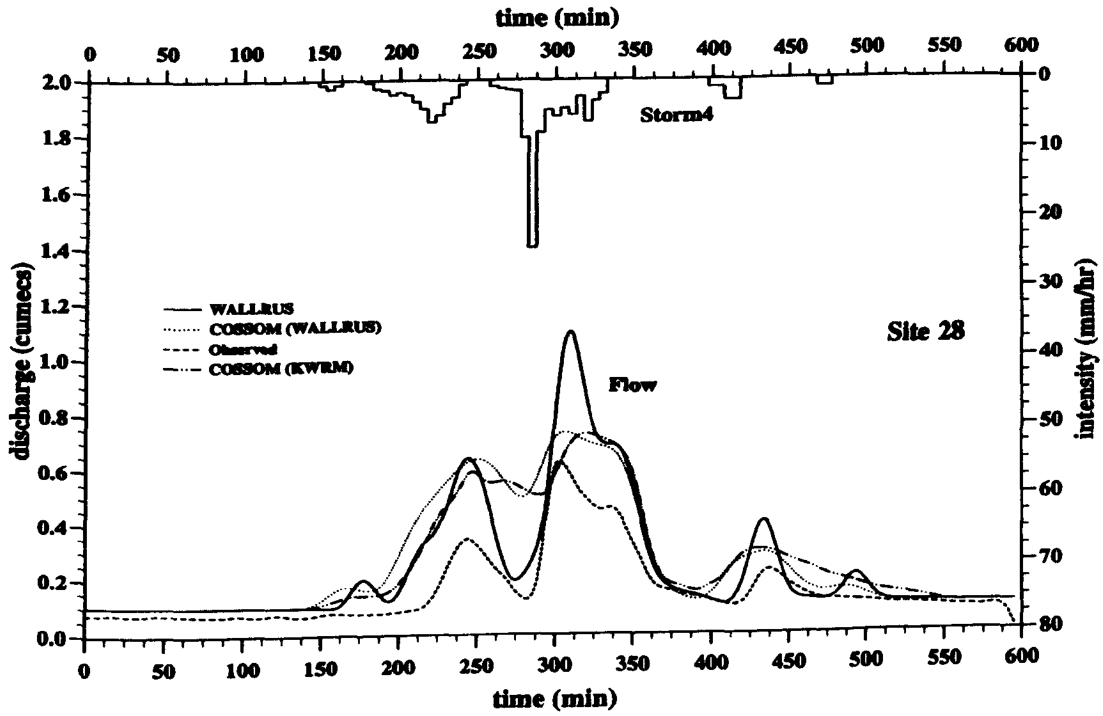


Figure 7.45 Comparison Between Observed and Computed by WALLRUS and COSSOM (using TUH from WALLRUS and KWRM) Flows at Sites 11 and 25 of Middlewood Sewerage System.



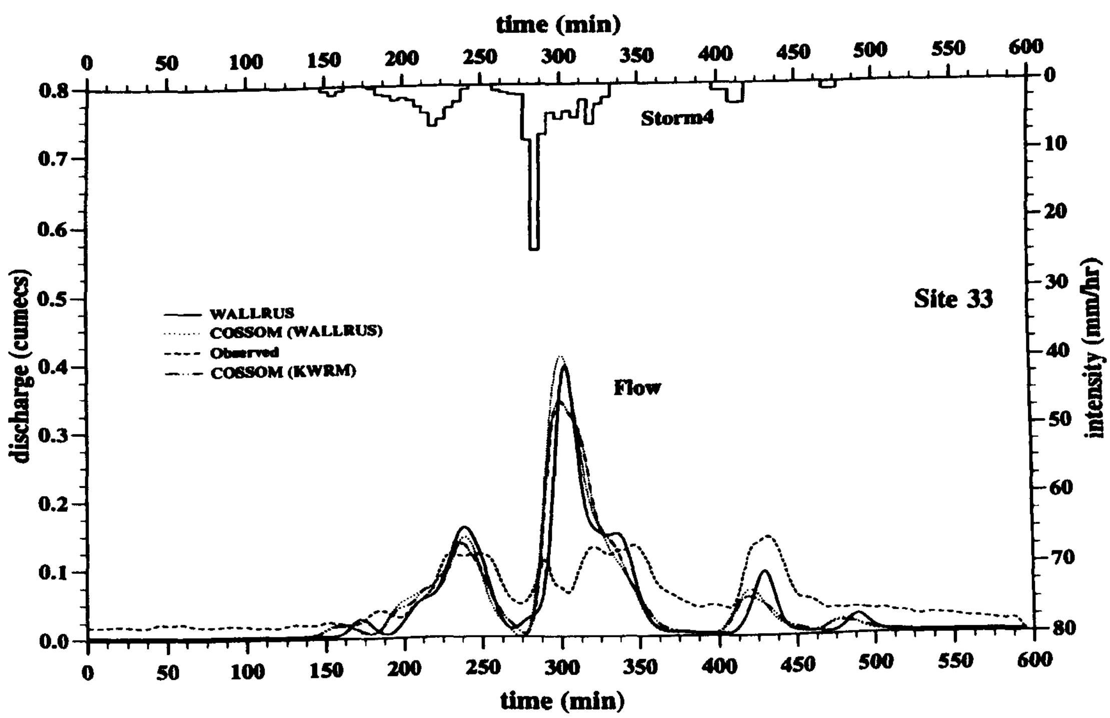
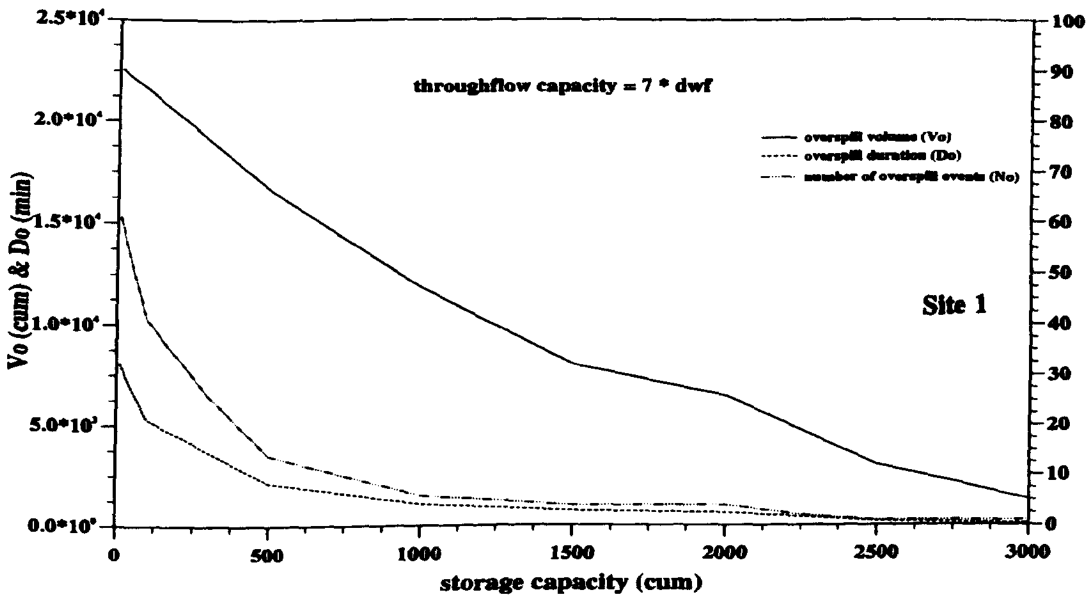


Figure 7.4C Comparison Between Observed and Computed by WALLRUS and COSSOM (using TUH from WALLRUS and KWRM) Flows at Sites 28 and 33 of Middlewood Sewerage System.



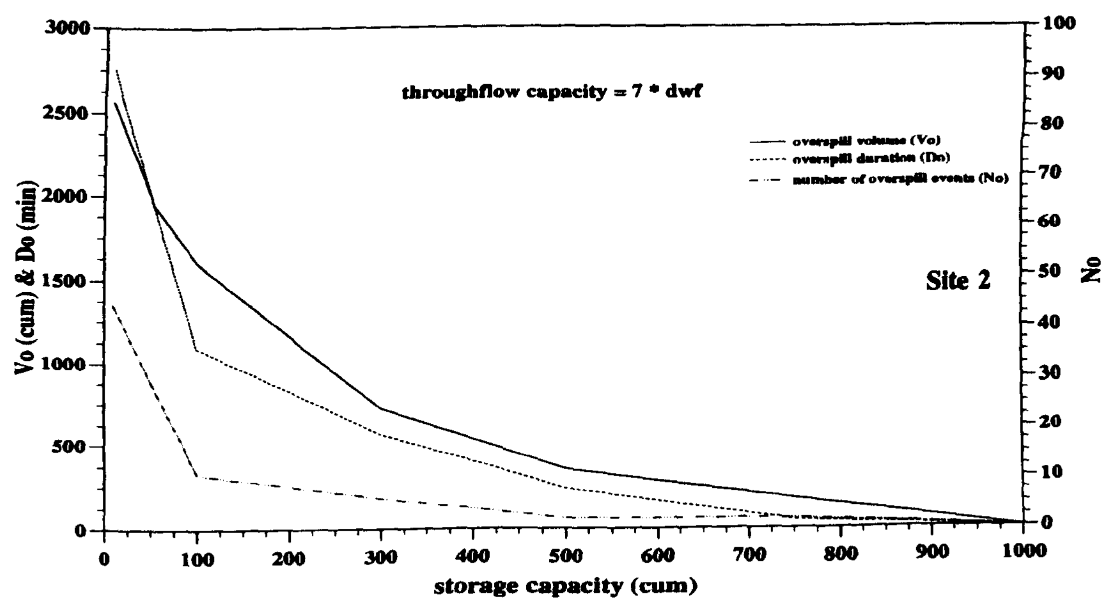
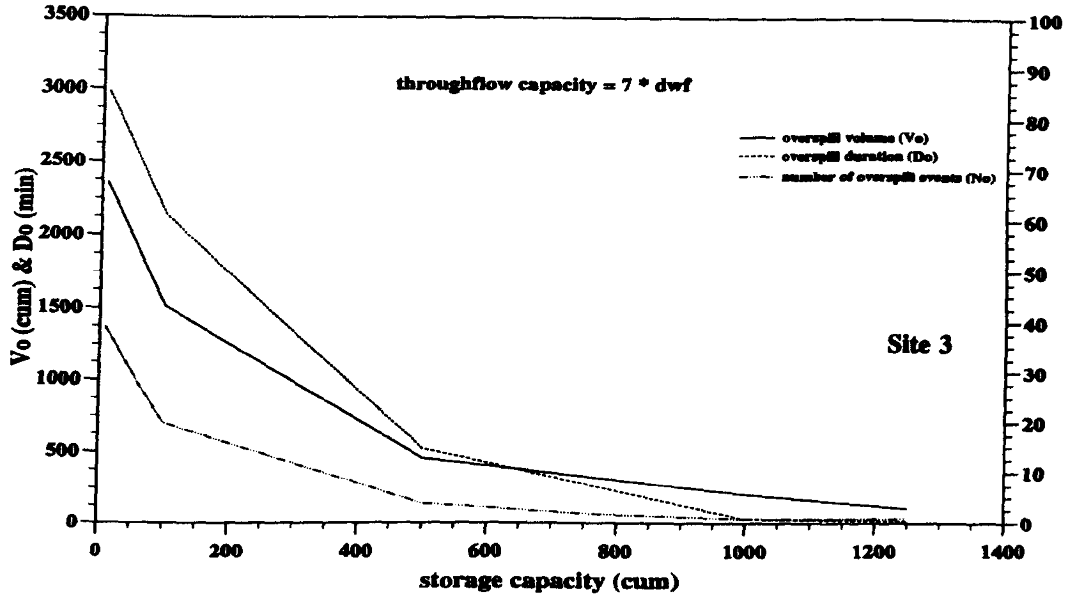


Figure 7.47 Annual Storm Overflow Operation Characteristics Synthesized for the Fleetwood Catchment at Sites 1 and 2 using One Year Liverpool Rainfall Records (1956).



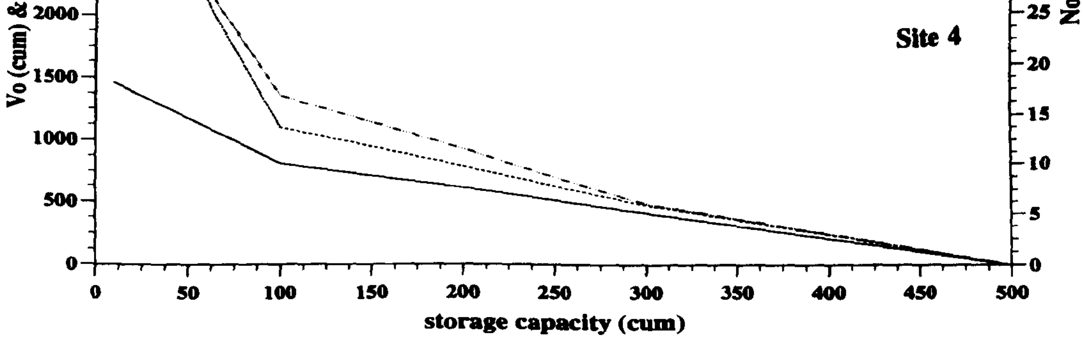
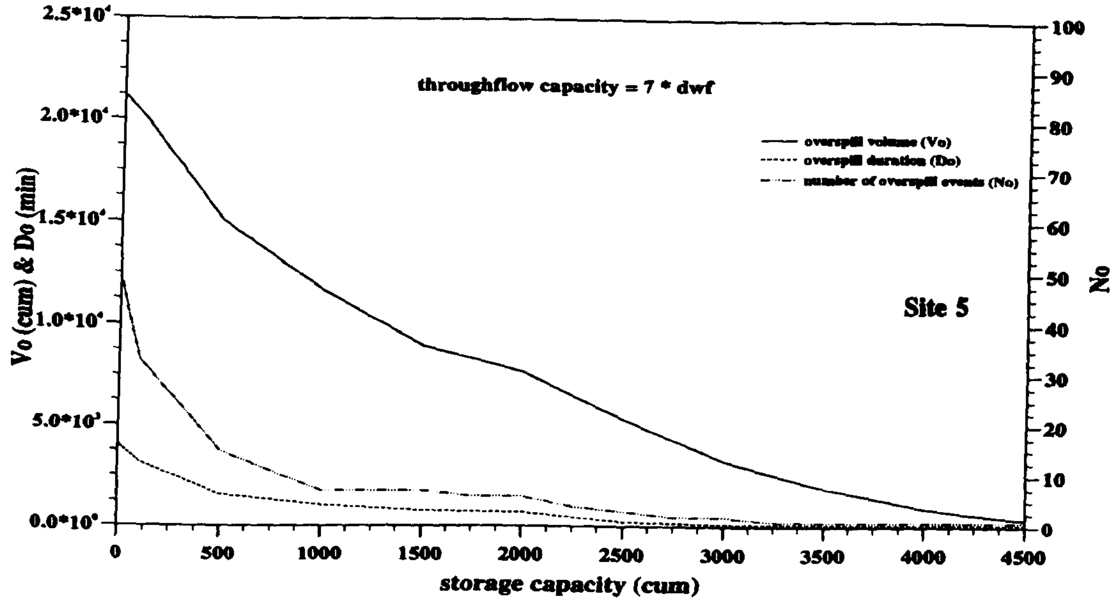


Figure 7.48 Annual Storm Overflow Operation Characteristics Synthesized for the Fleetwood Catchment at Sites 3 and 4 using One Year Liverpool Rainfall Records (1956).



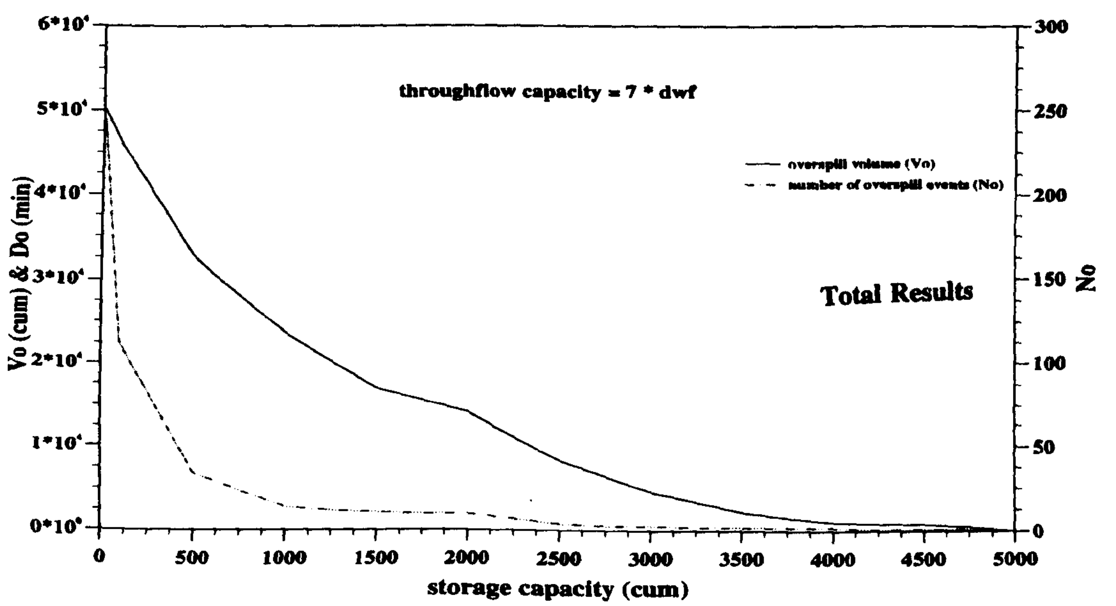
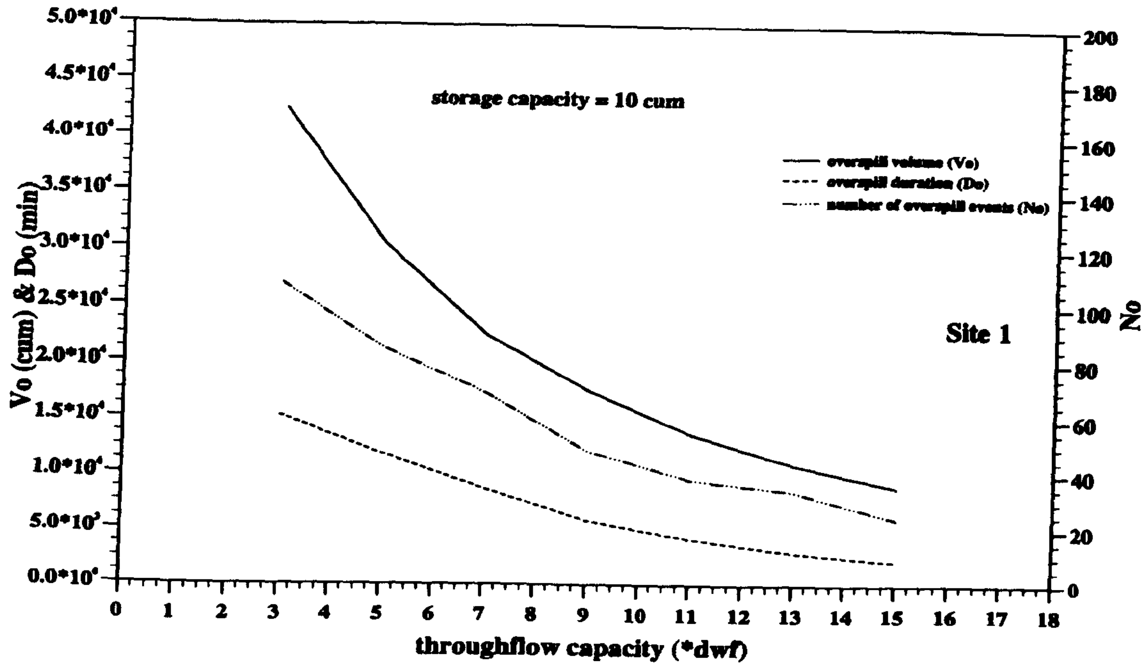


Figure 7.49 Annual Storm Overflow Operation Characteristics Synthesized for the Fleetwood Catchment at Site 5 and Total Results using One Year Liverpool Rainfall Records (1956).



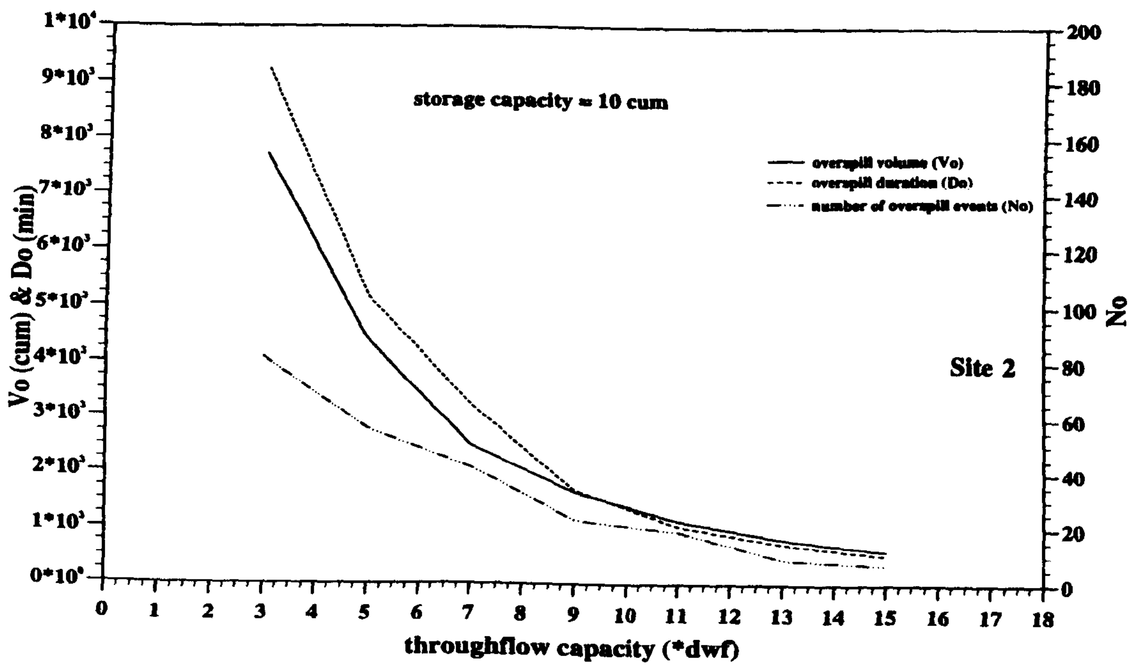
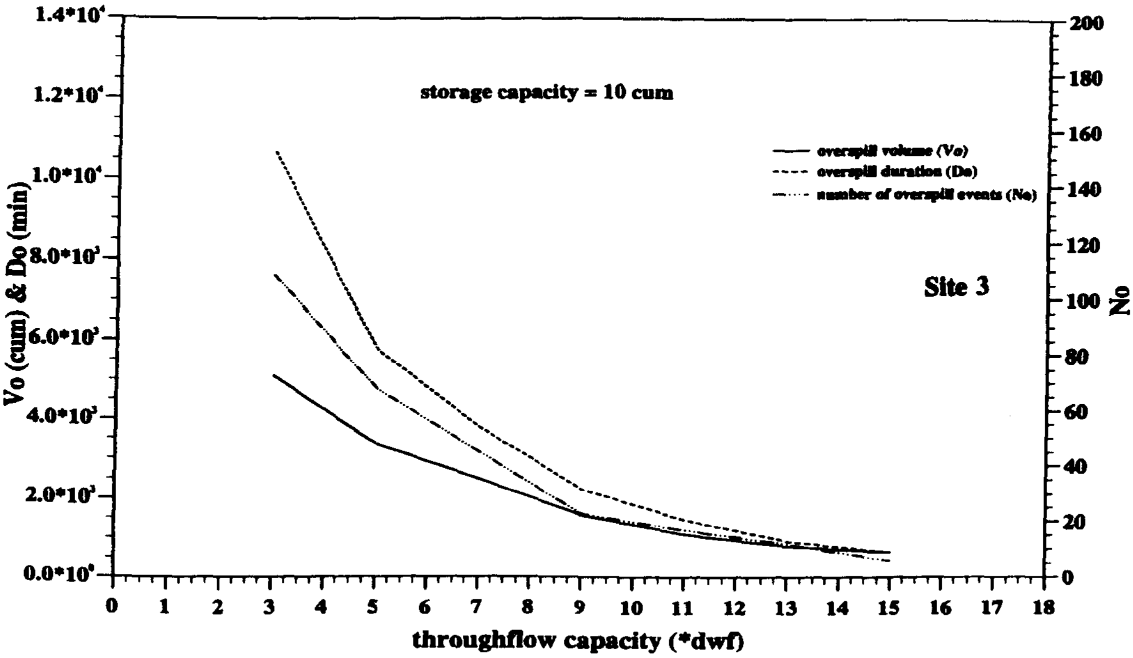


Figure 7.50 Annual Storm Overflow Operation Characteristics Synthesized for the Fleetwood Catchment at Sites 1 and 2 using One Year Liverpool Rainfall Records (1956).



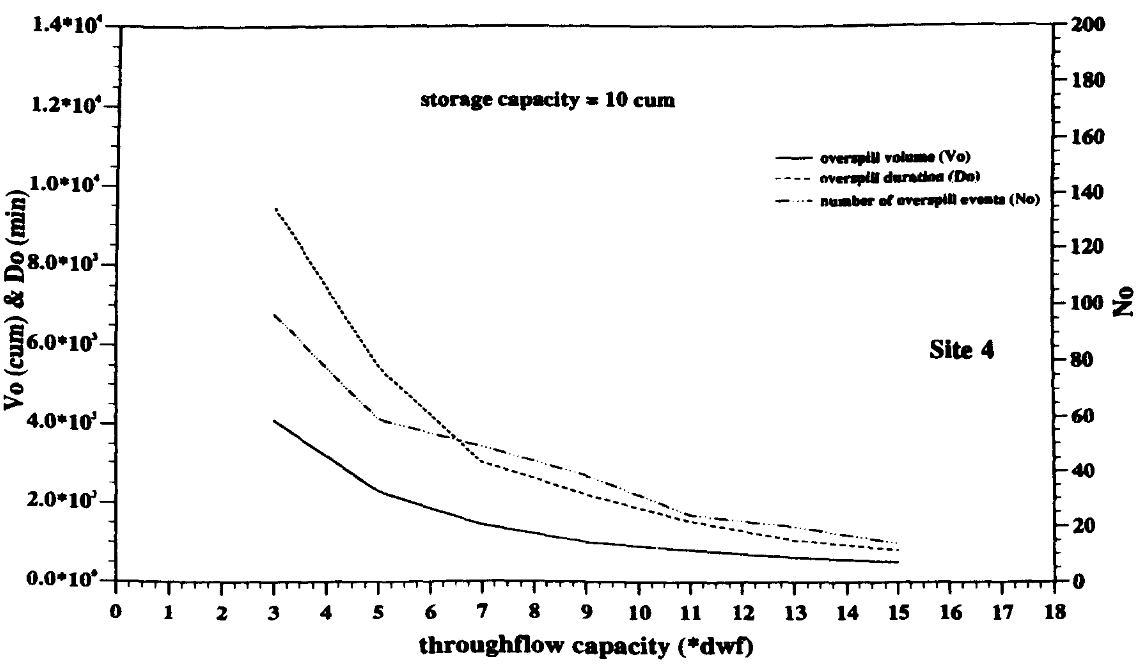
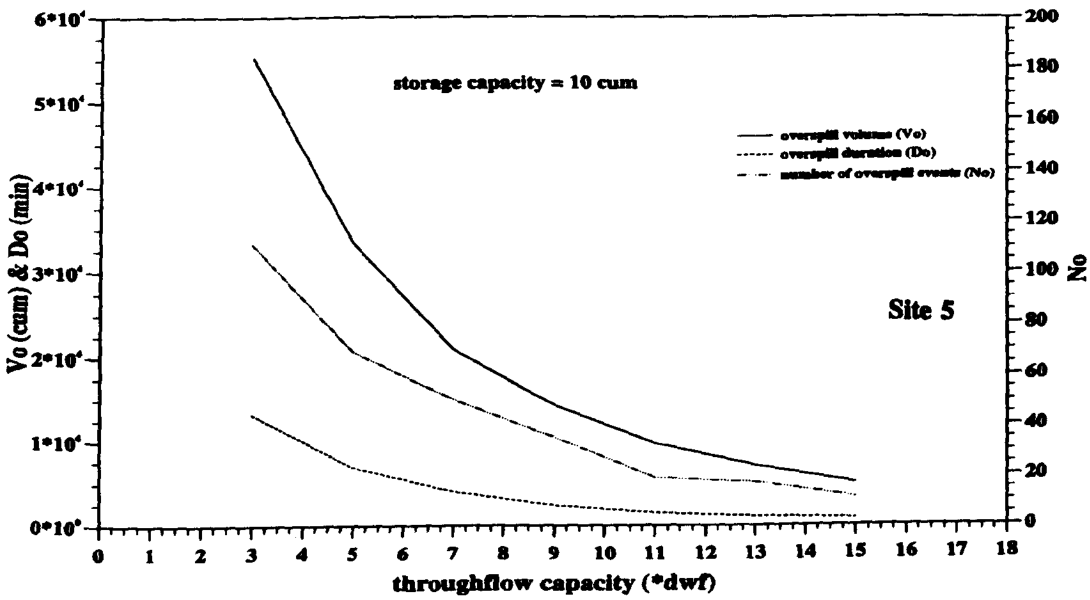


Figure 7.51 Annual Storm Overflow Operation Characteristics Synthesized for the Fleetwood Catchment at Sites 3 and 4 using One Year Liverpool Rainfall Records (1956).



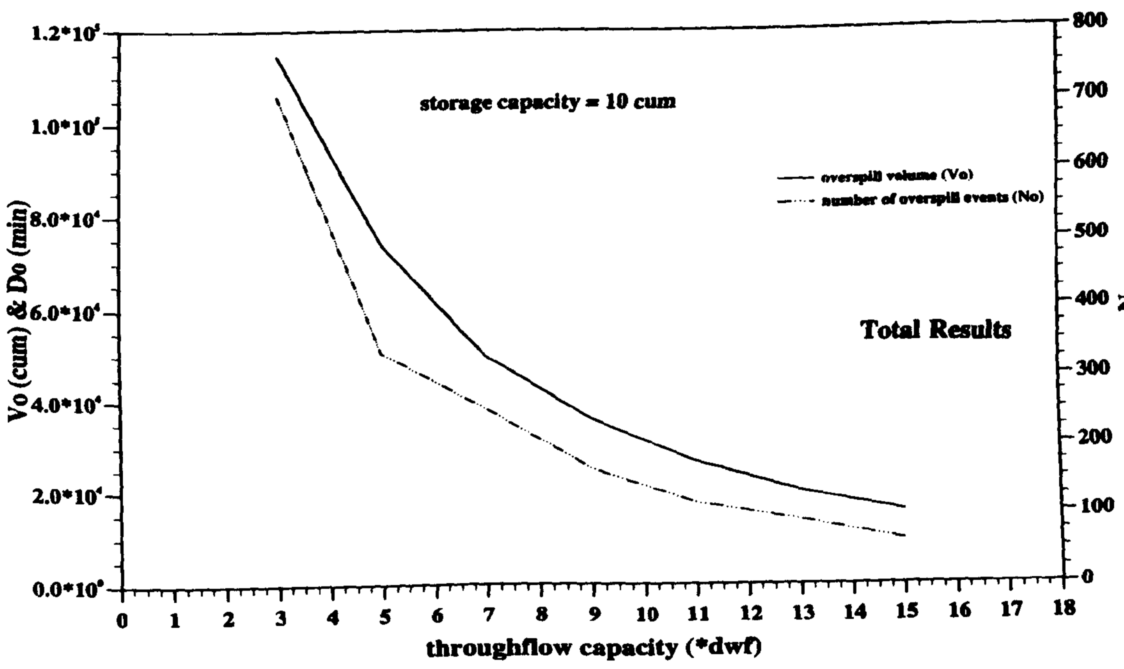


Figure 7.52 Annual Storm Overflow Operation Characteristics Synthesized for the Fleetwood Catchment at Site 5 and Total Results using One Year Liverpool Rainfall Records (1956).

CHAPTER 8 CONCLUSIONS

The following conclusions arise from this study:

1) On the basis of a unit hydrograph approach it has been possible to develop a flow synthesis model to simulate long-term rainfall series, for computation of overflow characteristics for each overflow structure in sewer network.

2) The model (COSSOM) can synthesize flows and predict storm overflow operation to an accuracy within acceptable engineering limits. This is achieved for long duration rainfall series at a small fraction of the computational effort required by a full hydrodynamic model such as WALLRUS.

3) The information relating to overspill can be analysed stastically in terms of spill event duration, volumes and peak flows or it can be used to appraise the effect of increase in storage provision or throughflow setting.

4) A simple mixing model provides an estimate of pollution load discharged from the overflow structures.

5) Performance of the model improves when catchment unit hydrographs are obtained by preliminary application of WALLRUS (or equivalent) using higher rainfall intensity i.e. close to the maximum in the observed rainfall data series and for rain duration close to the time of concentration of each subcatchment under consideration and when the implicit allowances for intial losses are accounted for.

6) With little loss in accuracy relative to application of the WALLRUS approach for unit hydrograph development COSSOM can be operated with Rainfall/Runoff/Pipeflow models other than a proprietary product. (i.e. KWRM)

7) The model has been applied successfully to three drainage networks. Results show that COSSOM predictions with respect to runoff volume and overflow characteristics are well within ±10 % of full WALLRUS applications for hypothetical catchment and Fleetwood catchment. Flows predicted by the two models for Middlewood catchment are consistent but show significant deviation from recorded values for certain of the storm events recorded. These discrepancies are likely to be caused by errors in observed data and sewer system model verification established therefrom.

8) There is a limit on maximum number of rainfall data (NR) that can be treated using COSSOM in its present form. It depends on the time step of rainfall data series (TR) and should be calculated as:

NR = time step of the ordinates of unit hydrograph * 10000 / TR

If a long-term rainfall series is required to be treated in sub sets because of this limit, this should be done by locating a rainless period in the series which is more than five times the time of concentration (t_c) of the catchment, to ensure that flow recession from the last rain event in one sub-set would not have figured in the flow synthesis of the first event of the next sub-set.

Application of COSSOM in its present status is subject to the following limitations

i) The model cannot account for the spatial variation of rainfall data.

ii) The model cannot perform flow routing in overflow structures, therefore for a chamber with large plan area the attenuation effects may not be modelled correctly

iii) Diurnal variation of dry weather flow cannot be accounted for.

iv) The model cannot simulate build-up and wash-off of pollution. The partitioning of pollution at overflow chambers is not considered.

v) The model can deal only with dendritict sewerage networks.

vi) COSSOM cannot simulate flows in surcharged pipes

CHAPTER 9 RECOMMENDATIONS

COSSOM utilizes the unit hydrograph generated by a detailed hydrodynamic model, therefore, it is essential that the sewer network is verified and any instability in the network model is carefully examined and removed before its application to calculate the unit hydrograph.

As most existing sewer systems are complicated, division of the main catchment into subcatchments must be achieved carefully, making sure that the contributing area for each subcatchment is calculated correctly and all the sewers carrying the flow to the overflow structure are included. A cross check should be made by comparing the sum of area of all subcatchments with the catchment area as a whole.

It is recommended that COSSOM should be applied to more existing sewer networks and compared with observed data to ensure that the performance of the model is robust. COSSOM predicted pollution discharges need to be verified with observed data.

Further improvements in the model can be made by extending it to allow simulation of flows through pumps.

Pollution modelling can be improved by linking mean event concentration to antecedent conditions. This can be done by incorporating a subroutine in COSSOM to keep record of the length of rainless period and later using this record as the antecedent period in the selection of corresponding mean event concentration would improve pollution predictions.

A final goal of future research should be the further enhancement of COSSOM to represent the behaviour of pollutants at overflow structures such as sediment deposition and retention time and subsequent difference in concentrations of pollutants in throughflow and overflow discharge.

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APPENDIX A

SEWERAGE SYSTEM DATA FILES IN STANDARD WALLRUS FORMAT AND SYSTEM DATA FILES FOR COSSOM

Appendix A. 1

WALLRUS 'DEMO' system shown in figure 5.8

```
 Pipe      Pipe Ground U/S   D/S        Pipe                     Cont.
 label     leng. level level level      dia.                     area
            (m)  (mod)  (mod) (mod)     (mm)                     (hac.)
 1.000 0   150 30.10 28.615 26.630      375      0         0 01  9.20402000031000.00218
 1.001 0   120 28.05 26.630 24.122      375      0         0 02  2.80401000021000.00318
 2.000 0    67 26.95 25.544 24.600      300      0         0 01  4.65401500031000.00218
 1.002 0   135 26.15 24.122 23.097      525      0         0 02  3.20501500021000.00118
 1.003 0    88 24.80 23.097 22.294      525      0         0 01  1.55401000021000.00118
 1.004 0   102 24.25 22.294 21.829      600      0    2    0 01  1.00401000021000.00218
 4.000 0    92 25.94 24.136 23.134      300      0         0 02  5.30501000031000.00318
 5.000 0    77 26.03 24.650 23.450      225      0         0 01  2.60501000021000.00218
 4.001 0    68 24.98 23.134 22.566      450      0 0.6     0 01  2.15401500011000.00118
 4.002 0   116 24.55 22.566 22.029      525      0 0.6     0 02  3.3540 500011000.00118
 1.005 2   253 23.88 21.829 21.180      825      0         0 03  0.9099 000011000.00118
 100         1                 1     12.00     19.550       0.076                   9
   2.000                             0.500     21.180      3.2500      1.500        10
 1.006 0    10 22.00 19.900 19.700      350      0         0 01-1.000 0 0000        18
-1.000           23.56                                                              15
```

Appendix A. 3

Multi-level hypothetical test system shown in figure 7.1

```
                                                            Cont.
Pipe     Pipe Ground U/S   D/S        Pipe                  area
label    leng. level level level      dia.                  (hac.)
          (m) (mod)  (mod) (mod)      (mm)
1.000 0   150 30.10 28.615 26.630     375     0        0 01  9.2040200003l000.00218
1.001 0   120 28.05 26.630 24.122     375     0        0 02  2.8040100002l000.00318
2.000 0    67 26.95 25.544 24.600     300     0        0 01  4.6540150003l000.00218
1.002 0   135 26.15 24.122 23.097     525     0        0 02  3.2050150002l000.00118
1.003 0    88 24.80 23.097 22.294     525     0        0 01  1.5540100002l000.00118
1.004 0   102 24.25 22.294 21.829     600     0   2    0 01  1.0040100002l000.00218
4.000 0    92 25.94 24.136 23.134     300     0        0 02  5.3050100003l000.00318
5.000 0    77 26.03 24.650 23.450     225     0        0 01  2.6050100002l000.00218
4.001 0    68 24.98 23.134 22.566     450     0 0.6    0 01  2.1540150001l000.00118
4.002 0   116 24.55 22.566 22.029     525     0 0.6    0 02  3.3540 50001l000.00118
1.005 0   253 23.88 21.829 21.180     825     0        0 03  0.9099 00001l000.00118
6.000 0   150 30.10 28.615 26.630     375     0        0 01  9.2040200003l000.00218
6.001 0   120 28.05 26.630 24.122     375     0        0 02  2.8040100002l000.00318
7.000 0    67 26.95 25.544 24.600     300     0        0 01  4.6540150003l000.00218
6.002 0   135 26.15 24.122 23.097     525     0        0 02  3.2050150002l000.00118
6.003 0    88 24.80 23.097 22.294     525     0        0 01  1.5540100002l000.00118
6.004 0   102 24.25 22.294 21.829     600     0   2    0 01  1.0040100002l000.00218
8.000 0    92 25.94 24.136 23.134     300     0        0 02  5.3050100003l000.00318
9.000 0    77 26.03 24.650 23.450     225     0        0 01  2.6050100002l000.00218
8.001 0    68 24.98 23.134 22.566     450     0 0.6    0 01  2.1540150001l000.00118
8.002 0   116 24.55 22.566 22.029     525     0 0.6    0 02  3.3540 50001l000.00118
6.005 2   253 23.88 21.829 21.480     900     0        0 03  0.9099 00001l000.00118
100             6            1      10.00     20.500      0.095                     9
    0.800                           0.400     21.500    3.2500      1.500          10
6.006 0    10 23.00 21.200 21.100     300     0         0 01-1.000 0 00000         18
1.006 2    50 23.00 21.180 21.100     900     0         0 01-1.000 0 00000         18
110             1             1     10.00     20.100      0.114
9
    0.800                           0.400     21.100    3.2500      1.500          10
1.007 0   150 23.10 20.500 18.515     450     0        0 01  9.2040200003l000.00218
1.008 0   120 20.00 18.515 16.007     450     0        0 02  2.8040100002l000.00318
11.000 0   67 17.95 16.952 16.007     300     0        0 01  4.6540150003l000.00218
1.009 0   135 18.01 16.007 14.983     600     0        0 02  3.2050150002l000.00118
1.010 0    88 16.48 14.983 14.179     600     0        0 01  1.5540100002l000.00118
1.011 0   102 16.18 14.179 13.715     675     0   2    0 01  1.0040100002l000.00218
12.000 0   92 17.00 16.364 15.362     300     0        0 02  5.3050100003l000.00318
13.000 0   77 18.44 16.500 15.300     225     0        0 01  2.6050100002l000.00218
12.001 0   68 17.00 15.362 14.566     375     0 0.6    0 01  2.1540150001l000.00118
12.002 0  116 17.50 14.566 13.715     450     0 0.6    0 02  3.3540 50001l000.00118
1.012 0   253 17.00 13.715 13.178     900     0        0 03  0.9099 00001l000.00118
14.000 0  150 22.10 20.615 18.630     375     0        0 01  9.2040200003l000.00218
14.001 0  120 20.05 18.630 16.122     375     0        0 02  2.8040100002l000.00318
15.000 0   67 18.95 17.544 16.600     300     0        0 01  4.6540150003l000.00218
14.002 0  135 18.15 16.122 15.097     525     0        0 02  3.2050150002l000.00118
14.003 0   88 16.80 15.097 14.294     525     0        0 01  1.5540100002l000.00118
14.004 0  102 16.25 14.294 13.829     600     0   2    0 01  1.0040100002l000.00218
16.000 0   92 17.94 16.136 15.134     300     0        0 02  5.3050100003l000.00318
17.000 0   77 18.03 16.650 15.450     225     0        0 01  2.6050100002l000.00218
16.001 0   68 16.98 15.134 14.566     450     0 0.6    0 01  2.1540150001l000.00118
16.002 0  116 16.55 14.566 14.029     525     0 0.6    0 02  3.3540 50001l000.00118
14.005 2  253 15.88 13.829 13.200     825     0        0 03  0.9099 00001l000.00118
 120            14           1      10.00     12.000      0.095                     9
    0.800                           0.400     13.000    3.2500      1.500          10
14.006 0   10 15.00 13.200 13.178     450     0         0 01-1.000 0 00000         18
 1.013 2   10 15.00 13.178 13.000     900     0         0 01-1.000 0 00000         18
 130            1            1      10.00     12.000      0.228                     9
    0.800                           0.400     13.000    3.2500      1.500          10
```

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 1.014 0  150 15.10 12.975 11.015     525     0        0 01  9.20402000031000.00218
 1.015 0  120 13.02 11.015  8.507     525     0        0 02  2.80401000021000.00318
19.000 0   67 11.45  9.451  8.507     300     0        0 01  4.65401500031000.00218
 1.016 0  135 10.51  8.507  7.482     600     0        0 02  3.20501500021000.00118
 1.017 0   88  9.00  7.483  6.680     600     0        0 01  1.55401000021000.00118
 1.018 0  102  8.68  6.679  6.214     750     0    2   0 01  1.00401000021000.00218
20.000 0   92  8.50  8.250  7.248     300     0        0 02  5.30501000031000.00318
21.000 0   77  8.90  8.448  7.248     225     0        0 01  2.60501000021000.00218
20.001 0   68  7.89  7.248  6.680     450     0 0.6    0 01  2.15401500011000.00118
20.002 0  116  8.77  6.680  6.214     525     0 0.6    0 02  3.3540 500011000.00118
 1.019 0  253  8.21  6.214  5.565     900     0        0 03  0.9099 000011000.00118
22.000 0  150 14.10 12.615 10.630     375     0        0 01  9.20402000031000.00218
22.001 0  120 12.05 10.630  8.122     375     0        0 02  2.80401000021000.00318
23.000 0   67 10.95  9.544  8.600     300     0        0 01  4.65401500031000.00218
22.002 0  135 10.15  8.122  7.097     525     0        0 02  3.20501500021000.00118
22.003 0   88  8.80  7.097  6.294     525     0        0 01  1.55401000021000.00118
22.004 0  102  8.25  6.294  5.829     600     0    2   0 01  1.00401000021000.00218
24.000 0   92  9.94  8.136  7.134     300     0        0 02  5.30501000031000.00318
25.000 0   77 10.03  8.650  7.450     225     0        0 01  2.60501000021000.00218
24.001 0   68  8.98  7.134  6.566     450     0 0.6    0 01  2.15401500011000.00118
24.002 0  116  8.55  6.566  6.029     525     0 0.6    0 02  3.3540 500011000.00118
22.005 2  253  7.88  5.829  5.180     825     0        0 03  0.9099 000011000.00118
 140        22                1      10.00    4.170     0.095                      9
     0.800                           0.400    5.170    3.2500      1.500          10
22.006 0   10  7.00  5.600  5.565     375     0        0 01-1.000 0 00000         18
 1.020 2   10  7.00  5.565  5.545     975     0        0 01-1.000 0 00000         18
 150         1                1      10.00    4.000     0.342                      9
     0.800                           0.400    5.000    3.2500      1.500          10
 1.021 0   10  6.00  5.500  5.475     675     0        0 01 0.000 0 00000         18
-1.000                                                                            15
```

Appendix A. 4

Fleetwood sewerage system data file shown in figure 7.2

Pipe label	Pipe leng. (m)	Ground level (mod)	U/S level (mod)	D/S level (mod)	Pipe dia. (mm)			Cont. area (hac.)	
1.000	45	8.93	5.960	5.690	225		1	0.800 89900	18
2.000	110	12.08	9.070	7.480	300		55	0.726809900	.000218
2.010	85	10.70	7.430	6.450	380		45	0.717809900	.000218
3.000	120	10.18	8.290	6.660	300		75	1.140859900	.000118
2.020	95	9.42	6.450	5.690	380		41	0.433859900	018
1.010	100	9.01	5.640	5.340	380	40	25	0.350859900	018
4.000	124	8.68	7.000	6.480	225		21	0.450859900	.000118
5.000	100	9.05	7.250	6.520	225		45	0.400859900	.000318
4.010	80	9.11	6.440	6.210	300		35	0.440809900	018
6.000	65	9.24	7.860	6.410	225		21	0.440809900	.000118
4.020	61	8.98	6.210	5.630	300		21	0.300809900	18
1.020	275	8.83	5.340	4.980	380	40	61	0.850859900	018
7.000	175	12.38	10.220	8.630	300		51	0.998809900	018
7.010	90	11.30	8.630	6.850	300		55	0.231859900	018
7.020	161	8.36	6.850	6.320	300		31	0.618859900	018
7.030	65	7.63	6.320	6.050	300		11	0.273759900	018
8.000	60	8.58	6.980	6.600	225		54	0.467759900	.000118
8.010	99	8.06	6.600	6.290	225		104	0.487759900	.000318
8.020	35	7.44	6.290	6.140	300		21	0.056859900	.000118
9.000	105	8.20	6.510	6.270	300		55	0.386859900	.000218
10.000	84	8.20	6.510	6.270	300		41	0.196859900	.000218
9.010	25	7.72	6.270	6.140	300		11	0.034859900	018
8.030	30	7.81	6.140	6.050	300		21	0.139859900	018
7.040	65	7.82	6.050	5.810	300		11	0.225859900	018
7.050	120	7.60	5.810	5.410	300		11	0.534859900	018
11.000	68	9.95	7.800	7.080	225		45	0.443809900	.000218
12.000	75	8.96	7.600	7.080	225		35	0.331759900	.000218
11.010	48	8.21	7.080	6.870	300		11	0.101809900	018
13.000	75	8.43	7.110	6.870	225		45	0.288759900	.000218
11.020	26	8.40	6.870	6.780	300		21	0.050759900	.000118
14.000	66	8.65	7.300	6.780	225		21	0.194859900	018
11.030	33	8.43	6.780	6.560	300		11	0.186859900	018
15.000	95	8.65	7.260	6.560	300		55	0.331759900	.000218
11.040	78	8.15	6.560	5.980	300		37	0.264809900	018
16.000	171	8.53	6.860	5.980	300		67	0.640759900	.000318
11.050	60	8.20	5.980	5.437	300		11	0.215859900	018
17.000	98	8.16	6.530	5.430	300		56	0.427759900	.000218
11.070	20	7.78	5.430	5.410	300		13	0.060902000	018
7.060	80	7.63	5.410	5.059	300		11	0.255802000	018
19.000	100	9.25	7.250	5.880	300		35	0.484702000	018
19.010	125	8.42	5.880	5.160	300		77	0.848702000	.000318
20.000	42	8.99	7.010	5.500	450		34	0.235702000	.000418
19.020	35	7.61	5.160	5.100	450		25	0.698752000	018
7.070	30	7.33	5.059	4.980	450		11	0.058852000	018
1.030	120	7.34	4.980	4.410	450		25	0.610802000	018
21.000	160	6.70	5.500	4.410	300		157	0.810702000	.000518
1.040	30	7.16	4.410	4.270	450		46	0.365752000	018
22.000	162	8.77	7.760	5.960	300		37	0.795802000	.000218
23.000	95	8.53	7.686	6.180	225		45	0.110852000	.000118
22.010	95	8.59	5.960	5.590	300		31	0.569752000	.000218
24.000	115	8.16	6.480	5.890	300		45	0.597752000	.000218
22.020	20	8.44	5.590	5.560	300		13	0.092752000	018
25.000	95	7.90	7.190	6.120	225		55	0.347802000	.000118
22.030	90	8.23	5.560	5.120	300	30	24	0.474802000	.000118

22.040	45	8.59	5.120	5.030	300		30 15 0.367802000	018
22.050	110	8.30	5.030	4.780	300		76 0.850852000	.000218
22.060	94	8.30	4.780	4.300	380		45 0.360802000	18
22.070	140	8.32	4.300	3.940	380		14 0.417802000	018
1.045	92	7.30	3.320	3.170	600		11 0.366852000	018
1.050	75	6.68	3.170	3.000	600		11 0.291852000	018
26.000	110	6.59	5.520	4.990	300		64 0.730802000	.000118
27.000	93	6.49	5.460	4.990	300		81 0.910802000	.000218
26.020	45	6.48	4.990	4.720	300		24 0.213852000	018
1.055 2	10	6.68	3.000	2.980	1000		1 -1.0009020	018
100	1			1	2.00	2.97	0.042	9
2.000					0.050	3.970	1.2500 1.500	10
1.060	115	6.54	2.980	2.740	600		11 0.259852000	018
1.070	65	6.43	2.740	2.610	600		11 0.137852000	018
28.000	82	6.10	3.950	2.700	300		24 0.242802000	.000118
1.080	70	6.21	2.610	2.460	600		11 0.140852000	018
1.090	30	6.18	2.460	2.330	600		24 0.045852000	018
30.000	95	6.20	4.650	3.640	225		64 0.512802000	18
29.000	65	6.27	4.760	4.540	225		11 0.320802000	.000118
29.005	35	6.18	4.540	4.320	225		15 0.040902000	018
29.010	30	6.35	4.320	4.210	225		33 0.510902000	18
29.020	40	6.10	4.210	4.090	225		43 0.300902000	18
29.030	160	6.07	4.090	3.480	300		85 0.530802000	.000218
1.100	71	5.94	2.330	2.210	600		11 0.148852000	018
31.000	30	6.73	5.350	5.320	225		31 0.743852000	018
31.005	30	6.50	5.320	5.290	225		15 0.060902000	018
32.000	70	6.79	5.360	5.290	225		11 0.404802000	018
31.010	125	6.75	5.290	4.600	225		21 0.240852000	018
31.020	135	6.14	4.600	4.160	225		21 0.220802000	018
33.000	115	6.89	5.680	5.080	300		104 0.493752000	.000518
34.000	80	7.19	6.010	5.150	225		21 0.537802000	018
33.010	30	6.46	5.080	4.930	300		11 0.060752000	018
35.000	150	7.56	6.340	4.990	225		51 0.380752000	.000418
33.020	65	6.41	4.930	4.660	300		21 0.200852000	.000118
36.000	144	6.80	5.650	4.810	225		61 0.860802000	.000218
33.030	28	6.25	4.660	4.500	300		14 0.066852000	018
37.000	91	6.22	4.950	4.500	225		11 0.273752000	018
33.040	20	6.07	4.500	4.480	300		14 0.047752000	018
38.000	148	6.23	5.420	4.620	225		41 0.379752000	.000218
33.050	16	6.09	4.480	4.390	300		24 0.042752000	.000118
39.000	210	6.39	6.010	4.390	300		224 0.620752000	.000618
33.060	26	6.21	4.390	4.280	300		14 0.039752000	018
40.000	55	6.50	5.160	4.280	225		11 0.328752000	018
41.000	155	6.55	5.780	4.280	300		104 0.589802000	.000318
33.070	25	6.11	4.280	3.840	300		14 0.156802000	018
31.025 2	10	6.10	3.840	3.830	300		14-1.000 0 000	018
120	31			1	2.50	3.82	0.021	9
2.000					0.500	4.820	1.2500 1.500	10
31.030	37	5.95	3.830	3.600	480		24 0.145802000	18
42.000	100	5.09	4.480	3.960	300		55 0.323802000	.000118
31.040	28	6.11	3.600	3.240	480		11 0.039852000	018
1.110	125	6.11	2.030	1.800	600		14 0.328852000	018
1.115 2	10	5.99	1.800	1.790	600		11-1.000 0 000	018
130	1			1	6.00	1.780	0.070	9
2.000					0.600	4.780	3.2500 1.500	10
1.120	30	5.39	1.790	1.720	400		11 0.037852000	018
44.000	73	5.20	3.440	3.200	225		11 0.210802000	18
44.010	63	4.81	3.200	2.520	225		24 0.360802000	.000118
44.020	70	4.63	2.520	1.720	300		14 0.280802000	18
45.000	70	5.09	3.100	1.720	225		15 0.310802000	.000118
1.130	60	4.85	1.720	1.660	600		14 0.125852000	018
46.000	10	5.95	4.230	4.060	225		11-1.000 020	18
46.010	99	5.95	4.060	2.160	225		14 0.154852000	018
47.000	100	10.36	8.790	8.290	225		11 0.470802000	018
47.005	174	9.89	8.250	7.500	225		21 1.010552000	018
47.010	165	9.31	7.500	5.620	225		31 0.301902000	018
48.000	133	6.74	6.090	5.620	225		21 0.025802000	18
47.020	60	8.71	5.620	4.480	225		11 0.222802000	.000118
49.000	157	7.68	6.250	4.960	225		66 0.829802000	.000218
49.010	115	8.18	4.960	4.480	225		34 0.648752000	.000118
47.030	35	9.33	4.480	3.980	225		11 0.052852000	018

50.000	81	8.36	7.010	3.980	225	
51.000	88	6.96	5.430	3.980	225	
47.040	70	7.94	3.980	3.770	225	
52.000	60	6.37	5.000	4.270	225	
52.010	35	5.97	4.270	4.050	225	
53.000	85	5.60	4.900	4.050	225	
52.020	35	6.20	4.050	3.770	225	
47.050	60	6.47	3.770	3.470	300	
55.000	83	7.75	6.240	4.180	225	
56.000	95	6.59	5.290	4.180	225	
55.020	30	6.61	4.180	4.040	225	
57.000	45	7.75	5.780	4.040	225	
55.030	30	6.56	4.040	3.756	225	
58.000	90	7.16	5.580	3.756	225	
55.040	30	6.07	3.756	3.470	225	
47.060	63	5.70	3.470	3.330	375	
59.000	100	5.58	4.430	3.330	225	
47.070	25	5.24	3.330	3.220	375	
60.000	130	5.60	4.000	3.220	225	
47.080	85	5.38	3.220	2.680	380	
61.000	155	7.24	5.760	4.700	225	
61.030	30	6.50	4.700	4.570	225	
61.040	57	6.25	4.570	2.680	225	
65.000	100	5.43	4.590	3.630	225	
65.010	88	5.58	3.630	2.680	300	
47.090	97	5.39	2.680	2.460	450	
66.000	140	4.63	4.010	2.460	225	
47.100	125	5.24	2.460	2.160	450	
46.020	30	5.23	2.160	1.860	450	
68.000	70	4.92	2.670	2.400	225	
69.000	110	5.01	3.100	2.400	225	
68.010	25	5.16	2.400	1.860	225	
46.030	30	5.03	1.860	1.660	450	
1.140	60	5.11	1.660	1.370	615	
1.150	60	5.13	1.370	1.250	650	
70.000	125	6.96	5.430	3.140	225	
71.000	85	6.68	5.070	4.180	225	
71.010	125	5.70	4.180	3.140	225	
70.010	65	4.77	3.140	2.780	225	
72.000	112	5.26	3.690	2.780	225	
73.000	70	4.60	3.070	2.780	225	
70.020	65	4.37	2.780	2.540	300	
70.025 2	10	5.20	2.540	2.530	300	2.50
140	70			1	2.00	3.500
					0.500	
2.000						
70.030	30	5.20	2.530	2.360	225	
74.000	125	4.37	2.830	2.360	225	
70.040	35	4.21	2.360	1.810	375	
75.000	30	4.32	3.140	3.010	225	
75.010	65	4.41	3.010	2.360	225	
77.000	40	4.35	3.350	2.880	225	
77.010	35	4.43	2.880	2.470	225	
77.020	50	4.54	2.470	2.040	225	
78.000	125	5.01	3.100	2.260	225	
78.010	60	4.58	2.250	1.960	225	
70.050	115	4.30	1.810	1.580	375	
76.000	125	4.59	3.400	1.820	225	
70.060	40	4.82	1.580	1.520	375	
1.160	85	4.08	1.250	1.150	720	
79.000	135	4.56	2.870	1.500	225	
1.170	45	4.38	1.150	1.050	720	
80.000	165	4.14	2.730	1.950	300	
1.180	180	4.08	1.050	0.840	720	
81.000	145	7.47	5.860	4.860	225	
81.010	60	6.37	4.860	4.140	225	
81.020	135	5.76	4.140	3.070	300	
81.030	115	4.66	3.070	2.710	300	
82.000	210	6.95	5.940	4.030	225	
82.010	105	5.51	4.030	2.710	300	
81.040	45	4.66	2.710	2.230	300	
83.000	10	4.45	2.630	2.580	225	

41	0.395852000	018
24	0.231752000	.000118
25	0.247702000	018
54	0.331852000	.000218
14	0.100702000	018
53	0.091702000	.000218
11	0.060852000	018
11	0.169852000	018
54	0.583752000	.000318
24	0.414702000	.000118
14	0.045802000	018
21	0.225702000	018
11	0.047702000	018
31	0.402752000	.000218
11	0.060752000	018
11	0.125752000	018
76	0.400752000	.000318
14-1.000 020		018
15	0.364752000	.000218
14	0.284752000	.000218
116	0.720702000	.000318
14	0.310852000	018
14	0.247852000	.000118
71	0.301752000	.000318
11	0.255752000	.000218
24	0.252852000	018
136	0.490802000	.000318
15	0.383852000	018
11	0.048852000	018
22	0.330802000	.000118
54	0.330802000	.000218
11	0.060802000	018
11	0.181852000	018
11	0.125852000	018
11	0.275852000	018
21	0.580852000	018
41	0.472852000	.000218
77	0.585852000	.000218
11	0.138852000	018
46	0.570352000	.000118
21	0.577392000	18
15	0.097752000	018
1	-1.0008020	018
0.007		9
1.2500	1.500	10
13	0.039802000	018
35	0.550502000	.000218
15	0.220802000	.000118
11	0.090802000	018
95	0.470802000	.000318
21	0.081852000	.000118
11	0.040802000	018
14	0.330852000	018
55	0.420802000	.000118
44	0.275852000	018
15	0.200852000	018
65	0.430802000	.000318
11	0.040802000	018
11	0.284852000	018
36	0.450852000	018
11	0.137902000	018
31	0.434652000	.000318
31-1.000 020		018
44	0.411652000	.000318
21	0.157602000	.000118
41	0.314602000	.000118
24	0.500552000	.000118
50	0.920602000	018
21	0.430602000	018
14	0.098702000	018
11-1.000 020		18

83.010	72	4.54	2.580	2.280	225
84.000	35	4.34	2.720	2.650	225
81.050	75	4.66	2.140	1.800	300
85.000	224	7.06	5.540	4.490	225
86.000	155	7.06	5.560	4.840	225
86.010	72	6.35	4.840	4.490	225
85.010	75	5.89	4.490	4.132	225
87.000	180	7.40	5.260	4.340	225
88.000	135	7.47	5.160	4.340	225
87.010	35	6.44	4.340	4.070	225
89.000	65	5.94	4.520	4.130	225
85.020	90	5.53	4.040	3.630	300
90.000	60	6.37	4.990	4.770	225
90.005	145	6.41	4.770	3.630	225
85.030	130	5.46	3.630	2.480	300
91.000	135	5.53	4.060	3.280	225
92.000	30	5.08	3.380	3.280	225
91.010	37	5.19	3.280	3.000	225
93.000	50	5.36	3.200	3.000	225
91.020	35	4.73	3.000	2.480	225
94.000	125	4.97	3.600	2.480	225
85.040	43	4.62	2.480	2.140	375
95.000	75	6.22	3.570	3.300	375
95.010	75	6.64	3.300	3.070	375
96.000	255	6.08	3.850	3.070	225
107.000	87	5.88	4.530	3.510	225
108.000	25	5.91	3.635	3.510	225
107.010	60	5.91	3.510	3.070	225
95.020	75	6.78	3.070	2.890	380
97.010	130	6.27	4.700	4.210	225
98.000	160	6.23	4.960	4.210	225
99.000	160	5.97	4.910	4.210	225
97.020	85	5.91	4.210	3.970	300
97.030	40	6.06	3.970	3.850	300
100.000	203	6.54	4.930	3.850	225
97.040	73	6.08	3.850	3.690	300
101.000	73	6.54	5.030	4.620	225
102.000	45	6.50	4.750	4.620	225
103.000	75	6.50	5.030	4.620	225
101.010	160	6.63	4.620	3.870	225
101.020	33	6.11	3.870	3.690	225
97.050	55	6.08	3.690	3.540	300
104.000	73	6.40	4.900	3.630	225
97.060	192	5.83	3.540	2.930	300
95.030	42	6.68	2.850	2.680	380
109.000	95	6.11	4.050	3.490	225
110.000	60	5.26	3.670	3.490	225
109.010	30	6.01	3.490	2.680	225
95.040	30	6.46	2.680	2.520	380
105.010	135	6.15	4.340	2.520	225
95.050	70	6.36	2.520	2.340	380
112.000	145	5.39	4.230	2.340	225
95.060	75	5.19	2.340	1.660	380
81.060	85	4.62	1.660	1.530	450
111.010	170	4.80	3.210	1.530	225
81.065	20	4.70	1.530	1.280	450
81.070	36	4.18	1.280	1.240	525
113.000	233	4.76	3.210	2.090	225
114.000	175	4.63	3.150	2.090	225
113.010	155	4.53	2.090	1.450	225
81.080	85	3.72	1.240	1.110	525
1.190	30	4.38	0.840	0.760	800
115.000	200	4.25	2.740	1.820	225
115.010	50	4.19	1.820	1.610	300
116.000	85	4.00	2.420	1.610	225
115.020	25	4.17	1.610	1.460	300
117.000	130	4.14	2.474	1.460	225
118.000	100	4.49	2.900	1.460	225
115.030	45	4.20	1.460	1.280	300
119.000	100	4.14	2.690	1.280	225
115.040	35	4.27	1.280	1.220	300

11	0.298602000	018
34	0.184652000	18
14	0.267702000	018
44	1.310462000	.000218
41	0.897402000	.000318
14	0.316352000	.000118
14	0.480292000	018
34	1.000432000	.000218
44	0.965552000	.000318
14-1.000 020		018
11	0.210552000	.000118
34	0.340392000	.000118
31	0.460552000	.000118
15	0.840552000	.000118
21	0.724552000	018
24	0.620482000	.000118
21	0.161392000	018
14	0.048512000	.000118
21	0.230392000	.000218
34	0.703702000	018
44	0.894192000	.000418
11	0.067702000	018
51	0.131482000	.000518
11	0.709312000	018
31	1.550322000	.000218
21	0.428382000	.000218
11	0.200442000	018
14	0.278382000	.000118
11	0.220482000	018
55	0.672302000	.000218
31	0.710322000	.000118
155	1.860272000	.000318
35	0.320282000	.000118
24	0.212382000	18
93	1.800392000	.000418
61	0.164672000	.000418
11	0.320482000	018
11	0.179572000	018
11	0.300412000	.000118
34	1.030402000	.000218
11	0.187362000	.000118
14	0.310662000	018
14	0.270432000	.000118
81	1.130352000	.000318
11	0.160572000	018
11	0.280502000	.000118
11	0.220512000	.000118
14	0.052672000	18
11	0.100582000	.000118
15	1.020372000	018
13	0.240492000	.000118
107	0.628682000	.000418
11	0.289632000	018
21-1.000 020		018
76	0.762532000	.000318
11-1.000 020		18
15	0.240322000	018
55	1.240262000	018
31	0.600222000	18
31	0.520632000	018
31-1.000 020		018
13	0.070752000	018
30 41	0.350852000	018
55	0.396752000	.000118
11	0.170852000	018
15-1.000 02000		018
35	0.420752000	.000218
56	0.420702000	.000218
15	0.060852000	018
57	0.380702000	.000218
15	0.040852000	018

```
  1.200    170  4.38  0.760  0.590    800              23-1.000 020          018
120.000    160  4.39  2.790  2.160    225              55 0.470702000     .000318
121.000     90  4.43  2.680  2.160    225              11 0.170852000        018
122.000     90  4.43  2.860  2.160    225              21 0.650702000         18
120.010     20  4.40  2.160  2.000    225              14 0.017902000        018
123.000    115  4.39  2.840  2.000    225              41 0.290702000     .000318
124.000    120  4.48  3.010  2.000    225              21 0.212702000     .000218
120.020     25  4.39  2.000  1.840    300              14 0.012902000        018
125.000    120  4.36  2.830  1.840    225              21 0.234852000        018
126.000    125  4.49  3.020  1.840    225              21 0.250852000        018
120.030     10  4.34  1.840  1.830    300              13 0.015902000        018
127.000    115  4.36  2.870  1.830    225              41 0.340702000     .000318
120.040     30  4.43  1.830  1.770    300              12 0.025902000        018
130.000    135  4.48  3.190  2.500    225              21 0.510702000        018
129.000     70  4.42  3.270  2.910    225              11 0.156752000        018
  1.215     60  4.42  0.530  0.470    800              63-1.000 020          018
  1.220     60  4.47  0.470  0.405    800              22-1.000 020          018
  1.230     33  4.50  0.405  0.370    800              13-1.000 020           18
  1.235 2   15  4.51  0.370  0.220   1000              13-1.000 020           18
 200         1                1      12.00     0.100   0.189                     9
    2.000                            0.500     1.100  4.2500       1.500        10
  1.236     10  3.50  0.110  0.085    500              11-1.000 0 000           18
 -1.000                                                                         15
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Appendix A. 5

Middlewood Rood Catchment Shown in Figure 7.3

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                                                              Cont.
Pipe     Pipe Ground U/S     D/S      Pipe                    area
label    leng. level level   level    dia.                    (hac.)
         (m)  (mod)  (mod)   (mod)    (mm)          0 00         0 00000100    .018
1.000     15101.79  98.68    97.87    152           0 00         0 00000100 .00018
1.010     53 99.42  97.87    97.44    229           0 00         0 00000100 .00018
2.000    210123.01 121.88    97.45    152           0 00         0 00000100 .00018
1.020     98 99.36  97.44    95.26    229           0 00         0 00000100 .00018
1.030    104 97.27  95.26    94.39    229           0 00         0 00000100 .00118
3.000    350123.66 121.50    94.39    152           0 00         0 00000100 .00018
1.040     37 96.39  94.39    91.97    229           0 00         0 00000100 .00018
1.050     50 94.79  91.97    90.06    229           0 00         0 00000100 .00018
1.060     39 92.02  90.06    87.89    229           0 00         0 00000100    .018
1.070     25 90.10  87.89    86.00    229           0 00    2.9253 00000100 .00118
5.000    353172.80 171.36   143.87    229           0 00         0 00000100 .00018
5.010    285145.94 143.87   114.65    229           0 00         0 00000100 .00118
5.020    321118.71 114.65    86.00    229           0 00         0 00000100    .018
1.080     13 88.93  86.00    85.70    305           0 00    1.2456 00000100 .00118
6.000    514162.10 160.37   104.31    229           0 00         0 00000100 .00018
6.010    216106.29 104.31    86.69    229           0 00         0 00000100 .00018
6.020     77 88.80  86.69    85.76    235           0 00         0 00000100 .00018
6.030 2   18 88.29  85.76    85.46    229                                          9
 17    0    6  100            1      2.00    85.44                                10
       1   85.44                     0.30    85.63    1.00
                                     240                0 00         0 00000100 .00118
6.040 0   45 86.61  85.44    85.04    229               0 00         0 00000100    .018
6.050      8 88.53  85.04    84.87    305               0 00         0 00000100 .00018
1.090     40 88.38  84.87    84.72    305               0 00         0 00000100    .018
1.100     84 87.78  84.72    84.62    305               0 00    0.4123 00000100    .018
1.110     90 87.40  84.62    84.22    305               0 00    0.3023 00000100    .018
1.120     52 86.81  84.22    83.92    305               0 00    0.2223 00000100    .018
1.130     62 86.66  83.92    83.63    305               0 00    0.3223 00000100    .018
1.140     73 91.07  83.63    83.27    305               0 00    0.3823 00000100    .018
1.150     68 94.68  83.27    82.93    229               0 00    0.9723 00000100    .018
7.000    132105.01 102.05    82.93    305               0 00    0.6623 00000100    .018
1.160     64 95.27  82.93    82.86    305               0 00    0.6223 00000100    .018
1.170     63 94.23  82.86    82.70    152               0 00    3.0023 00000100    .018
8.000    504170.00 168.40   120.84    229               0 00         0 00000100    .018
8.010    145122.44 120.84   107.16    229               0 00    5.7523 00000100    .018
8.020    139108.75 107.16    92.60    305               0 00    0.2623 00000100    .018
1.180     69 94.20  82.70    82.30    305               0 00    0.2123 00000100    .018
1.190     64 92.51  82.30    81.99    305               0 00    0.9523 00000100    .018
1.200     74 90.30  81.99    81.77    305               0 00    0.5323 00000100    .018
1.210     67 88.15  81.77    81.47    305               0 00    0.1423 00000100    .018
1.220    142 87.04  81.47    80.90    305               0 00    0.0970 00000100    .018
1.230 2   91 84.53  80.90    80.52    305                                          9
 18    0    1  200            1      2.00    80.52                                10
     1.24  80.52                    -0.06    80.77    0.073
1.240     93 82.58  80.52    80.12    305               0 00    0.1370 00000100    .018
1.250     33 83.75  80.12    80.06    305               0 00         0 00000100    .018
1.260    131 83.66  80.06    79.67    305               0 00    0.1370 00000100    .018
1.270    119 84.47  79.67    79.28    305               0 00    0.1270 00000100    .018
1.280    166 83.37  79.28    78.77    305               0 00    0.1670 00000100    .018
1.300     65 84.96  78.77    78.51    305               0 00    0.1970 00000100    .018
9.000    486229.24 228.02   191.31    229               0 00    2.1665 00000100 .00118
9.010    748193.50 191.31   120.73    229               0 00         0 00000100 .00218
9.020     55122.77 120.73   113.60    225               0 00         0 00000100 .00018
9.030    273115.64 113.60    78.51    229               0 00         0 00000100    .018
1.320     70 94.89  78.51    78.27    305               0 00    0.2250 00000100    .018
1.330    131 82.33  78.27    77.45    305               0 00    0.3950 00000100    .018
1.340     51 80.80  77.45    76.69    305               0 00    0.0770 00000100    .018
```

```
 10.000      259 94.79  92.69  76.69    229            0 00  0.9050 00000100   .018
  1.350       70 80.20  76.69  76.06    310            0 00       0 00000100   .018
  1.360      112 79.26  76.06  74.74    305            0 00       0 00000100 .00018
  1.370       33 77.46  74.74  73.28    305            0 00       0 00000100   .018
  1.380      137 76.04  73.28  71.67    305            0 00       0 00000100 .00018
  1.390      145 74.59  71.67  69.48    305            0 00       0 00000100 .00018
  1.400      127 72.88  69.48  68.76    305            0 00       0 00000100 .00018
 12.000 0    900155.00            11    305            0 00  5.7484 00000100 .00118
  1.410      146 71.32  68.76  67.80    380            0 00       0 00000100 .00018
  1.420      191 70.31  67.80  66.70    381            0 00       0 00000100 .00118
 13.000      402 77.70  75.40  66.70    229            0 00       0 00000100 .00118
  1.430       78 68.66  66.70  66.21    533            0 00       0 00000100 .00018
 14.000      300100.00  98.00  75.81    381            0 00  6.6248 00000100 .00118
 14.010       96 78.16  75.74  75.17    457            0 00       0 00000100 .00018
 14.015       58 78.30  75.09  74.60    533            0 00       0 00000100 .00018
140.000      246 91.03  89.10  74.60    381            0 00  3.0059 00000100 .00118
 14.020 2    118 77.77  74.60  73.67    535            0 00       0 00000100 .00018
   90    0    14  300           1      2.00   73.65                                 9
         2     73.65                   0.01   73.95     2.44                       10
 14.025       52 75.33  73.65  72.25    381            0 00 11.5367 00000100 .00418
 14.030       68 74.60  72.25  70.48    381            0 00       0 00000100 .00518
 14.040       28 72.98  70.48  69.65    380            0 00       0 00000100 .00218
 14.050 2     80 72.17  69.65  66.81    381            0 00       0 00000100 .00018
    4    0     1   15           1      2.00   66.17                                 9
         1     66.17                 -0.008   66.17    0.114                       10
  1.440       16 69.62  66.17  66.11    686            0 00       0 00000100   .018
  1.450       34 69.36  66.11  65.89    686            0 00       0 00000100 .00018
  1.460       22 69.23  65.89  65.78    686            0 00       0 00000100 .00018
  1.470       76 69.14  65.78  65.35    686            0 00       0 00000100 .00018
  1.480       77 68.85  65.35  64.96    680            0 00       0 00000100 .00018
  1.490       47 68.17  64.96  64.63    686            0 00       0 00000100   .018
 15.000       58 69.46  66.21  65.94    381            0 00       0 00000100   .018
 15.010      102 69.16  65.94  65.52    381            0 00       0 00000100   .018
 15.020       99 68.00  65.52  64.94    381            0 00       0 00000100 -1.018
 15.030 2     23 67.91  64.94  64.68    381            0 00       0 00000100   .018
    5    0     1   17           1      2.00   64.63                                 9
         1     64.63                  0.375   65.01      1.5                       10
  1.500       91 67.82  64.63  64.15    762            0 00       0 00000100   .018
  1.510       65 67.23  64.15  63.82    762            0 00       0 00000100   .018
  1.520       23 67.20  63.82  63.80    762            0 00       0 00000100   .018
  1.530       51 66.95  63.80  63.42    760            0 00       0 00000100   .018
  1.540       15 67.03  63.42  63.36    762            0 00       0 00000100 .00018
 16.000      907181.37 178.77 129.03    305            0170 11.8029 00000100 .00118
 16.010      779131.38 128.65  78.00    610            0190  4.6935 00000100 .00118
161.000     1000148.79 146.30  78.00    457            0170  9.6150 00000100 .00118
 16.015      222 80.70  78.00  66.34    686            0 30  1.6535 00000100 .00018
 16.018       61 69.81  66.34  63.40    835            0 00       0 00000100 .00018
 16.020       72 67.55  63.40  62.95    838            0 00       0 00000100 .00118
160.000      403161.83 159.13 128.97    305            0 70  4.2262 00000100 .00218
160.010      721131.35 128.94  77.96    381            0110  2.3562 00000100 .00318
160.015      182 80.70  77.96  67.96    457            0 30  5.6262 00000100 .00118
160.018      157 71.76  67.96  63.39    455            0 00       0 00000100 .00118
160.020 2     16 66.73  63.39  63.27    610            0 00       0 00000100 .00018
    6    0     1   18           1      3.00   62.65                                 9
         1     62.65                  -0.75   63.11    0.292                       10
  1.550       60 66.54  62.65  61.24    910            0 00       0 00000100 .00118
  1.560       70 65.69  61.24  60.51   1065            0 00       0 00000100   .018
  1.570       85 64.52  60.51  59.57   1065            0 00       0 00000100   .018
  1.580       87 63.23  59.57  59.10   1650            0 00       0 00000100   .018
  1.590       69 62.38  59.10  58.95   1650            0 00       0 00000100   .018
  1.600        5 62.12  58.95  58.93   1650            0 00       0 00000100   .018
  1.610       20 62.07  58.93  58.89   1675            0 00       0 00000100   .018
  1.620      105 62.08  58.89  58.68   1650            0 00       0 00000100   .018
  1.625       52 61.88  58.68  58.62   1650            0 00       0 00000100   .018
 23.000      508 64.71  63.44  60.12    229            0 00       0 00000100 .00118
 23.010       62 64.12  59.95  59.79    305            0 00       0 00000100 .00018
 23.020       64 63.32  59.79  59.63    305            0 00       0 00000100 .00018
 23.030       20 63.01  59.63  59.49    381            0 00       0 00000100   .018
 23.040       77 62.82  59.49  59.18    370            0 00       0 00000100 .00018
 23.050       14 62.32  59.10  59.00    381            0 00       0 00000100   .018
 23.060       30 62.25  59.00  58.95    370            0 00  5.9229 00000100   .018
```

```
  23.070      18 62.00  58.95  58.89     381              0 00        0 00000100   .018
   1.630      20 62.10  58.62  58.59    1650              0 00        0 00000100   .018
  26.000    1000166.53 164.64 106.93     381              0180 16.0941 00000100 .01318
  26.005     588110.71 106.91  88.97     686              0100 17.2341 00000100 .00718
  26.010     498 91.65  88.97  78.18     915              0 90  4.5347 00000100 .00618
  27.000     503122.58 120.43 100.77     381              0 70  9.3747 00000100 .00618
  27.010     650102.79 100.75  78.18     610              0100 20.9731 00000100 .00818
  26.020      47 83.21  78.18  76.90    1067              0 00        0 00000100 .00118
  28.000     612121.10 119.93 102.70     457              0130 15.3037 00000100 .00718
  29.000     668142.66 140.86 102.70     457              0160 19.8341 00000100 .00818
  28.010     332105.03 102.64  76.90     610              0 30        0 00000100 .00418
  26.030     281 80.60  76.90  66.04    1067              0 00        0 00000100 .00318
  26.035      14 70.05  66.04  65.33    1070              0 00        0 00000100 .00018
  26.040 2    18 69.01  65.33  65.31    1067              0 00        0 00000100   .018
    95    0    26  400             1    2.82     64.96                                  9
          2      64.96                  1.70     65.21       3.20                      10
  26.050      66 67.96  64.96  62.12     457              0 00        0 00000100   .018
  26.060       6 65.45  62.12  61.91     457              0 00        0 00000100   .018
  26.070     109 65.35  61.91  61.01     530              0 00        0 00000100   .018
  26.080     100 63.42  61.01  60.37     533              0 00   0.3830 00000100   .018
  26.090      53 62.82  60.37  59.97     533              0 00        0 00000100   .018
  26.100      73 62.45  59.97  58.62     533              0 00        0 00000100   .018
   1.635 0     8 62.40  58.59  58.58    1650              0 00   0.00 0 00000100   .018
  17.000     210 67.82  64.68  63.22     380              0 00        0 00000100 -1.018
  17.005      36 66.62  63.22  62.87     381              0 00        0 00000100 .00018
  18.000      32 66.54  63.11  62.47     610              0 00        0 00000100 -1.018
  17.010       7 66.24  62.47  62.45     610              0 00        0 00000100   .018
  19.000     153 66.21  63.74  62.65     229              0 00   0.8127 00000100 .00018
  17.020      83 66.14  62.45  60.69     610              0 00        0 00000100 .00018
  17.030     105 64.57  60.69  59.51     610              0 00        0 00000100 .00018
  17.040      15 63.21  59.51  59.38     610              0 00        0 00000100   .018
  17.050      41 63.03  59.38  59.26     610              0 00   0.1434 00000100 .00018
  20.000     205 64.92  61.82  59.29     305              0 00   1.3227 00000100 .00018
  17.060      50 62.62  59.26  59.12     610              0 00   0.1834 00000100 .00018
  21.000     190 64.62  61.92  59.19     305              0 00   0.6927 00000100 .00018
  17.070      50 62.30  59.12  58.97     610              0 00   0.1834 00000100 .00018
  22.000     555 65.96  63.17  59.20     381              0130   4.9827 00000100 .00118
  17.080      38 62.19  58.97  58.91     610              0 00   0.1334 00000100 .00018
  17.090     133 62.09  58.91  58.66     610              0 00   0.2270 00000100   .018
  17.110      26 61.95  58.66  58.56     610              0 00   0.0570 00000100   .018
   1.640 2    56 62.42  58.56  58.48    1370              0 00        0 00000100   .018
    94    0    1  500              1    2.98     58.33                                  9
          1     58.33                   0.80     58.65        6.70       2.0           10
   1.650      34 63.30  58.33  56.76    1078  6862        0 00        0 00000100   .018
   1.660     142 63.30  56.76  56.63    1070              0 00        0 00000100   .018
  30.000     470145.98 143.23 120.16     305          4   0 00   2.12 0 00000100 .00118
  31.000     140130.13 127.73 120.16     305          3   0 00   0.42 0 00000100 .00018
  30.010     185122.95 120.16 103.80     305          3   0 00   0.97 0 00000100 .00018
  32.000     540128.26 125.82 103.80     305          6   0 00   3.53 0 00000100 .00118
  30.020     100106.51 103.80  95.63     305          1   0 00   0.45 0 00000100 .00018
  33.000     280108.62 106.01  95.63     305          3   0 00   2.35 0 00000100 .00018
  30.030     320 98.16  95.63  88.37     381          5   0 00   1.81 0 00000100 .00018
  34.000     420173.65 171.41 139.18     381         14   0 00   6.1038 00000100 .00118
  34.010     330142.58 139.39 114.06     381          5   0 00   1.5644 00000100 .00018
  35.000     130133.15 130.65 129.21     229          3   0 00   0.8734 00000100 .00018
  35.010     255132.29 129.21 117.27     305          3   0 00   0.3943 00000100 .00018
  36.000     125127.13 124.77 117.27     305          1   0 00   0.6538 00000100 .00018
  35.020      45120.07 117.18 114.06     305          1   0 00   0.3940 00000100 .00018
  34.020      30117.07 114.06 111.21     381          0   0 00   0.0650 00000100   .018
  37.000     190146.73 144.21 129.69     229          2   0 00   0.6958 00000100 .00018
  38.000     155147.00 145.00 129.69     381          2   0 00   0.6250 00000100 .00018
  37.010     290132.29 129.69 117.22     381          2   0 00   1.2850 00000100 .00018
  34.030      25114.01 110.80 109.00     381          0   0 00   0.0630 00000100   .018
  39.000     195125.81 123.84 109.00     229          3   0 00   0.5950 00000100 .00018
  34.040     140111.55 109.00  97.84     458          2   0 00   0.7357 00000100 .00018
  40.000     190120.56 118.63 117.46     229          6   0 00   0.2249 00000100 .00018
  41.000     195134.77 133.09 117.46     229          4   0 00   0.5833 00000100 .00018
  40.010     195119.43 116.99  97.84     229          2   0 00   0.9150 00000100 .00018
  34.050      20 99.84  97.84  96.06     458          0   0 00   0.0395 00000100   .018
  42.000     355125.29 121.29  96.06     229         10   0 00   1.7441 00000100 .00118
  34.060     230 98.91  96.06  88.37     458          6   0 00   0.2249 00000100 .00018
```

```
  43.000     240128.26 126.44 107.80     229         5   0 00  1.2232 00000100 .00018
  44.000     270111.56 109.26 107.80     229         5   0 00  1.4040 00000100 .00018
  45.000     330110.51 108.97 107.80     229         8   0 00  1.2950 00000100 .00018
  43.010     220109.83 107.80  88.37     305         5   0 00  1.0255 00000100 .00018
  30.040     340 91.11  88.37  70.13     610         5   0 00  2.3660 00000100 .00018
  46.000     227 77.91  75.39  73.61     305         0   0 00  1.7435 00000100 .00018
  47.000     238 79.00  77.00  73.61     305         9   0 00  1.3870 00000100 .00018
  46.010     200 75.61  73.61  70.13     305         2   0 00  0.2480 00000100 .00018
  30.050     210 73.03  70.13  63.84     610         4   0 00  0.8380 00000100 .00018
  48.000      95146.73 144.21 135.97     229         0   0 00  1.20 0 00000100 .00018
  48.010     290138.82 135.97 125.32     305         1   0 00  1.20 0 00000100 .00018
  48.020     285127.76 125.32 101.16     381         3   0 00  1.00 0 00000100 .00018
  48.030      90130.16 101.16  80.86     381         1   0 00  0.60 0 00000100 .00018
  48.040      50 83.60  80.86  74.11     381         0   0 00  0.82 0 00000100 .00018
  48.050     170 77.11  74.11  71.71     381         3   0 00  1.36 0 00000100 .00018
  49.000     175 91.92  88.68  71.71     305         2   0 00  4.52 5 00000100 .00018
  48.060     330 74.67  71.71  67.98     381         7   0 00  3.2927 00000100 .00018
  50.000     250 91.92  88.68  82.06     305         3   0 00  0.94 0 00000100 .00018
  51.000     115 85.66  82.96  82.06     305         1   0 00  0.32 0 00000100 .00018
  50.010     354 84.86  82.06  68.50     305         5   0 00  2.3327 00000100 .00018
  52.000     354 73.73  71.89  68.96     305         7   0 00  0.3046 00000100 .00018
  53.000     265 85.66  82.97  68.96     229         4   0 00  1.55 0 00000100 .00018
  52.010      55 71.89  68.96  68.50     305         0   0 00  0.1847 00000100 .00018
  50.020      15 71.61  68.50  67.98     305         0   0 00  0.0150 00000100   .018
  48.070     160 71.01  67.98  63.85     381         2   0 00  1.1060 00000100 .00018
  30.060 2    10 65.97  63.84  62.79     610         1   0 00  0.9860 00000100   .018
     91    0    30    0          1      4.8     62.48                                9
       0.708     62.48                  1.5     63.63       4.94                    10
  30.070      10 66.65  62.48  62.16     229         0   0 00      0 0 00000100   .018
  30.080      10 65.37  62.16  61.16     229         0   0 00      0 0 00000100   .018
  30.090      17 65.43  62.16  61.79     610         0   0 00        0 00000100   .018
  30.100      76 65.78  61.79  60.50     610         0   0 00  0.9855 00000100 .00018
  30.110      39 63.56  60.50  59.87     610             0 00        0 00000100   .018
  30.120     122 63.04  59.87  57.78     610         0   0 00        0 00000100   .018
   1.670 0    45 61.41  56.63  56.59     580  0.51       0 00        0 00000100   .018
   1.680 2   566 61.50  56.59  55.54     610    1        0 00        0 00000100   .018
    10     0     1    0          1      4.00     55.54        0.20
9
           2      55.54                 0.42    57.54        2.0                    10
   1.690      35 61.25  55.54  54.98     375                 0 00        0 00000100   .018
 100.000       7 86.61  85.15  84.95     615                 0 00        0 00000100   .018
 100.010      50 86.90  84.95  78.00    1067                 0 00        0 00000100   .018
 200.000      35 82.58  80.77  78.00     305                 0 00        0 00000100   .018
 100.020      50 81.00  78.00  71.50    1067                 0 00        0 00000100   .018
 300.000       5 75.33  73.28  72.00     455                 0 00        0 00000100   .018
 100.030      50 74.00  71.50  61.50    1067                 0 00        0 00000100   .018
 400.000      26 67.96  64.46  62.14    1105                 0 00        0 00000100   .018
 100.040      50 64.00  61.50  58.00    1372                 0 00        0 00000100   .018
 500.000      20 63.30  58.41  58.35    1220                 0 00        0 00000100   .018
                                                                                    15
  -1.000
```

Appendix A. 6

COSSOM System Data File for Network shown in Figure 5.8

```
     1
    1         1
   1.00      36.70      15.00       1.00
  0.019      50.0      0.0197
 10.000
 94.000      3   19
 0.0000     0.0000     0.0070     0.0562     0.1002     0.1067     0.0612     0.0214
 0.0078     0.0039     0.0026     0.0017     0.0011     0.0007     0.0004     0.0002
 0.0002     0.0002     0.0000
```

Appendix A. 7

COSSOM System Data File for Hypothetical Catchment Network shown in Figure 7.1

```
  6
   1         1
  1.00     36.70     15.00      1.00
  0.019    20.0     0.0050
 20.000
 65.000    5  22
 0.0000    0.0011    0.0131    0.0435    0.0797    0.1051    0.1112    0.0941
 0.0635    0.0421    0.0232    0.0120    0.0072    0.0048    0.0035    0.0027
 0.0021    0.0016    0.0013    0.0008    0.0008    0.0000

   1         2
  1.00     36.70     15.00     13.00
  0.038    79.0     0.0050
 20.000
 65.000    5  22
 0.0000    0.0011    0.0131    0.0435    0.0797    0.1051    0.1112    0.0941
 0.0635    0.0421    0.0232    0.0120    0.0072    0.0048    0.0035    0.0027
 0.0021    0.0016    0.0013    0.0008    0.0008    0.0000

   0         3
  1.00     36.70     15.00     17.00
  0.057    20.0     0.0050
 20.000
 67.000    5  22
 0.0000    0.0011    0.0131    0.0435    0.0797    0.1051    0.1112    0.0941
 0.0635    0.0421    0.0232    0.0120    0.0072    0.0048    0.0035    0.0027
 0.0021    0.0016    0.0013    0.0008    0.0008    0.0000

   1         1
  1.00     36.70     15.00     15.00
  0.019    20.0     0.0050
 20.000
 67.000    5  22
 0.0000    0.0011    0.0131    0.0435    0.0797    0.1051    0.1112    0.0941
 0.0635    0.0421    0.0232    0.0120    0.0072    0.0048    0.0035    0.0027
 0.0021    0.0016    0.0013    0.0008    0.0008    0.0000

   1         1
  1.00     36.70     15.00      5.00
  0.019    10.0     0.0050
 20.000
 67.000    5  22
 0.0000    0.0011    0.0131    0.0435    0.0797    0.1051    0.1112    0.0941
 0.0635    0.0421    0.0232    0.0120    0.0072    0.0048    0.0035    0.0027
 0.0021    0.0016    0.0013    0.0008    0.0008    0.0000

   1         4
  1.00     36.70     15.00      1.00
  0.114    79.0     0.0050
 20.000
 67.000    5  22
 0.0000    0.0011    0.0131    0.0435    0.0797    0.1051    0.1112    0.0941
 0.0635    0.0421    0.0232    0.0120    0.0072    0.0048    0.0035    0.0027
 0.0021    0.0016    0.0013    0.0008    0.0008    0.0000
```

Appendix A. 8

COSSOM System Data File for Fleetwood Catchment Network shown in Figure 7.2

```
    5
          1           1
   1.00     28.86      20.00       10.00
  0.006    115.0     0.0021
  2.000
149.000    4   30
 0.0000    0.0000     0.0045     0.0263     0.0398     0.0438     0.0424     0.0377
 0.0353    0.0330     0.0298     0.0286     0.0274     0.0263     0.0253     0.0242
 0.0232    0.0221     0.0206     0.0187     0.0160     0.0132     0.0095     0.0084
 0.0077    0.0069     0.0051     0.0005     0.0001     0.0000

      1           1
   1.00      5.07      10.00       10.00
  0.003      37.0     0.0062
  2.500
 69.000    2   14
 0.0000    0.0000     0.0001     0.0139     0.0141     0.0128     0.0120     0.0114

 0.0091    0.0076     0.0037     0.0024     0.0016     0.0000

     1            2
   1.00      6.64      20.00       25.00
  0.010      30.0     0.0023
 18.000
 79.000    4   16
 0.0000    0.0000     0.0029     0.0066     0.0103     0.0102     0.0120     0.0068
 0.0065    0.0064     0.0062     0.0060     0.0065     0.0055     0.0014     0.0000

    1        1
   1.00      4.64      10.00       20.00
  0.001      30.0     0.0057
  2.000
 41.000    5   21
 0.0000    0.0000     0.0005     0.0084     0.0097     0.0102     0.0081     0.0061
 0.0056    0.0055     0.0036     0.0007     0.0006     0.0006     0.0005     0.0006
 0.0006    0.0006     0.0005     0.0006     0.0000

          1           3
   1.00     87.86      30.00        1.00
  0.027      10.0     0.0025
  6.000
139.000    6   28
 0.0000    0.0000     0.0007     0.0140     0.0739     0.0860     0.0905     0.0834
 0.0761    0.0679     0.0637     0.0596     0.0553     0.0495     0.0447     0.0405
 0.0341    0.0322     0.0240     0.0171     0.0132     0.0103     0.0069     0.0046
 0.0023    0.0006     0.0001     0.0000
```

Appendix A. 9

COSSOM System Data File for Middlewood Road Catchment shown in Figure 7.3

```
        6
        1        1
     1.00     1.24    10.00    25.00
    0.001     45.0   0.0090
    2.000
   59.000   2   12
   0.0000   0.0000   0.0008   0.0068   0.0076   0.0016   0.0004   0.0002
   0.0001   0.0001   0.0000   0.0000

        1        2
     1.00    17.73    30.00    40.00
    0.005     93.0   0.0040
    2.000
   99.000   6   20
   0.0000   0.0000   0.0003   0.0019   0.0061   0.0107   0.0120   0.0132
   0.0136   0.0124   0.0104   0.0092   0.0079   0.0040   0.0015   0.0005
   0.0003   0.0001   0.0001   0.0000

        1        1
     1.00     9.62    10.00    30.00
    0.002     52.0  0.00270
    2.000
   59.000   2   12
   0.0000   0.0000   0.0128   0.0476   0.0420   0.0104   0.0028   0.0012
   0.0008   0.0004   0.0004   0.0000

        1        1
     1.00   103.32    20.00    20.00
    0.063     66.0   0.0043
    2.820
   99.000   4   20
   0.0000   0.0000   0.0074   0.1194   0.1990   0.2200   0.2118   0.1026
   0.0322   0.0142   0.0086   0.0054   0.0036   0.0022   0.0014   0.0008
   0.0006   0.0004   0.0002   0.0002

        1        3
     1.00    76.68    50.00     1.00
    0.101     34.0   0.0046
    2.980
  129.000   5   13
   0.0000   0.0014   0.0428   0.0770   0.0830   0.0843   0.0835   0.0465
   0.0118   0.0035   0.0008   0.0002   0.0000

        1        1
     1.00    62.52    20.00     1.00
    0.004     10.0   0.0032
    4.800
   99.000   4   20
   0.0000   0.0000   0.0104   0.0518   0.0826   0.0918   0.0836   0.0424
   0.0144   0.0064   0.0034   0.0020   0.0012   0.0008   0.0004   0.0004
   0.0002   0.0002   0.0000   0.0000
```

APPENDIX B LISTING OF THE PROGRAMME (COSSOM)

APPENDIX B

```
C
C
C
C
C
C   THIS PROGRAMME IS USED ON PC COMPUTER.
C   THE OPEN STATEMENTS SHOULD FIRST BE CHECKED IF THE NAMES OF DISK
C   DRIVE ARE CORRECT.
C   THIS PROGRAMME ANALYZES A COMBINED SEWER SYSTEM WITH A ON-LINE
C   CHAMBER.
C   AFTER GIVING DATA OF THE SYSTEM AND RAINFALL, THE PROGRAMME OUTPUTS
C   OVERFLOW EVENTS, VOLUMES, DURATIONS AND PEAK FLOW RATES AS FUNCTIONS
C   OF THE CHOSEN THROUGH FLOW CAPACITY AND STORAGE VOLUME AVAILABLE IN
C   THE CHAMBER.THE PROGRAM ALSO CALCULATES THE OVERSPILL POLLUTION
C   DISCHARGED, IF IT IS REQUIRED.
C
C
C
C         DATA REQUIRED AND DEFINITIONS OF MAIN VARIABLES
C           (IN ORDER OF INPUT OR APPEAR IN STATEMENTS):
C
C
C                RAINFALL DATA FILE
C
C    NR3--------NO. OF ORINGINAL RAINFALL DATA (<=10000)
C    UNIT-------SYMBOL OF UNIT OF RAINFALL DATA: 1.0 FOR MM,
C            25.4 FOR IN.
C    TR---------TIME STEP OF ORINGINAL RAINFALL DATA IN MIN.
C    INDEX------INDEX=0 IF THE RAINFALL DATA ARE DEPTHES
C            INDEX=1 IF THE RAINFALL DATA ARE INTENSITIES
C    QQ(N)------TEMPORARY ARRAY TO STORE ORIGENAL RAINFALL
C    AI(N)------RAINFALL DATA IN DEPTH IN MM OR IN
C                  OR IN INTENSITY IN MM/HR
C            AFTER BEING TREATED THEY BECOME
C            RAINFALL DATA DISCRETIZED INTO SEQUENCES OF
C            RAINFALL DEPTH AND ITS DURATION EQUAL TO THE
C            UNIT RAINFALL DURATION( T ),IN MM.
C
C               SYSTEM DATA FILE
C
C   NCAT-------NUMBER OF SUBCATCHMENTS
C   INDEXR-----INDEXR=0  (SUBCATCHMENT WITH OUT OVERFLOW
C                  STRUCTURE)
C           INDEXR=1  (SUBCATCHMENT WITH OVERFLOW STRUCTURE)
C   IB(NCAT)---LEVEL OF SUBCATCHMENT IN DRAINAGE SYSTEM
C   CV---------RUNOFF COEFFICIENT (WHEN USE UNIT HYDROGRAPH
C            T U H ,COMING FROM WALLRUS: CV=1.0 )
C   A----------DRAINAGE AREA (HA.)
C   T----------UNIT RAINFALL DURATION OF  T U H ,IN MIN.
C   TTR--------LAG-TIME(MIN)
C   DWF--------DRY WEATHER FLOW IN (CUMECS)
C   CONL-------CONTINUATION PIPE LENGTH (M)
C   CONI-------GRADIENT OF CONTINUATION PIPE
C   V----------GIVEN STORAGE VOLUME OF CHAMBER (CUMECS)
C   PLT--------DURATION OF UNIT HYDROGRAPH (MIN)
C   LD---------DIVIDING OF NUMBER OF T (<=6)
C   NP---------NO. OF ORDINATES OF UNIT HYDROGRAPH
C   TUH(I)-----ORDINATES OF THE UNIT HYDROGRAPH (CUMECS/MM)
```

```
C                  (TIME STEP: TC=T/LD )
C
C
C
C
C                POLLUTION DATA FILE
C
C      CBD-------BOD CONCENTRATION IN DRY WEATHER FLOW (MG/L)
C      CBR-------BOD CONCENTRATION IN RAIN WATER (MG/L)
C      CSD-------TSS CONCENTRATION IN DRY WEATHER FLOW (MG/L)
C      CSR-------TSS CONCENTRATION IN RAIN WATER (MG/L)
C      CND-------NH3-N CONCENTRATION IN DRY WEATHER FLOW (MG/L)
C      CSR-------NH3-N CONCENTRATION IN RAIN WATER (MG/L)
C
C
C
C                KEY BOARD
C
C      NR1,NR2----RAINFALL NO. YOU WANT TO CALCULATE FROM AND TO
C      PDATA------VARIABLES OF CHARACTER (Y OR N)
C      FLOW-------VARIABLES OF CHARACTER (Y OR N)
C      UZ---------VARIABLES OF CHARACTER (Y OR N)
C      POL--------VARIABLES OF CHARACTER (Y OR N)
C      NO---------GIVEN INTERCEPTING FACTER
C      TSP--------TIME STEP USED IN ANALYSIS OF CONTINUATION PIPE
C              HYDROGRAPH, IN MIN.( >=0.1,<=0.5)
C      COND-------DIAMETER OF CONTINUATION PIPE(M)
C              CHOOSE FROM: 0.150,0.225,0.300,0.375,0.450,
C                      0.525,0.600,0.675,0.750...
C      DTHR-------DIAMETER OF THROTLE PIPE ( <= COND )
C      DEPTH------VARIABLES OF CHARACTER ( Y OR N )
C      HYD--------VARIABLES OF CHARACTER (Y OR N)
C
C
C
C      TC----------------TIME STEP OF INFLOW
C      NREAD2------------NO. OF RAINFALL DATA WHICH WILL BE CALCULATED
C      DO(JL)------------DIMETRES OF CONTINUE PIPE (M)
C      Q(I),QU,QU2,QL----INFLOW RATE FROM RAINFALL
C      NOVER-------------VARIABLE OF NO. OF OVERFLOW EVENTS
C      NOVER1------------TOTAL OF TIMES OF OVERFLOW
C      QOF(NOVER)--------PEAK OF OVERFLOW
C      ODU(NOVER)--------OVERFLOW DURATION
C      CUMOV(NOVER)------OVERFLOW VOLUME
C      AOFR(NOVER)-------OVERFLOW RATE
C      ADU(LV)-----------AVERAGE OVERFLOW DURATION
C      AVOL(LV)---------      „     VOLUME
C      TOTVAL(LV)--------TOTAL OVERFLOW VOLUME
C      TOTDU(LV)---------     „     DURATION
C
      DIMENSION DU(1600),CDV(1600),CUMV(1600),QOF(1600),BD(10),DB(10)
      DIMENSION CUMOV(1600),ODU(1600),DDUR(1600),DUR(1600),BR(10),SD(10)
      DIMENSION AOFR(1600),TOTVOL(8),QQL(5000),SR(10),TND(10),V(8)
      DIMENSION TOTDU(8),AVOL(8),ADU(8),QQ(-100:10000),QC1(-100:10000)
      DIMENSION AI(-20:10000),Q(0:100),TUH(0:100),NX(-6:50),TNR(10)
      DIMENSION BN(-21:1),QCONS(0:601),QS(1:5,0:10000),QP(0:10000)
      DIMENSION IB(0:20),TCT(0:10),NWT(0:20),NT(0:20),TOTV(20),QPP(0:20)
      DIMENSION NNR(0:20)
C
      CHARACTER*1 UZ,PDATA,FLOW,DEPTH,POL,HYD
      CHARACTER*72 DATAFN1,DATAFN2,OUT5,OUT2,DAT1
      PRINT *, 'ENTER THE NAME OF SYSTEM DATA FILE WITH PATH'
      READ '(A)',DATAFN1
      PRINT *, 'ENTER THE NAME OF RAIN DATA FILE WITH PATH'
```

```
      READ '(A)',DATAFN2
      PRINT *, 'ENTER THE NAME OF OUTPUT FILE FOR OVERFLOW EVENT DETAILS'
      READ '(A)',OUT1
      PRINT *,'ENTER THE NAME OF OUTPUT FILE FOR INFLOW AND OVERFLOW RESULTS'
      READ '(A)',OUT2
      PRINT *, 'ENTER THE NAME OF OUTPUT FOR LIST OF FLOW'
      READ '(A)',OUT5
      OPEN(3,FILE=DATAFN1,STATUS='OLD')
      OPEN(4,FILE=DATAFN2,STATUS='OLD')
      OPEN(9,FILE=OUT1,STATUS='UNKNOWN')
      OPEN(10,FILE=OUT2,STATUS='UNKNOWN')
C
C
      READ(3,*)NCAT
 5005 READ(4,*)NR3,UNIT,PTR,INDEX
 5003 READ(4,*)(QQ(N),N=1,NR3)
 2702 FORMAT(F8.3)
 9000 WRITE(6,5001)
 5001 FORMAT('INPUT 2 NUMBER WHICH YOU WANT TO CALCULATE DATA FROM NO.1
     *TO  NO.2 ')
      WRITE(6,5007)
 5007 FORMAT('    **** NOTE: (NO.2-NO.1)*(TR/T) MUST <=10000 *****')
      READ(5,5002)NR1,NR2
 5002 FORMAT(I5)
      DO 5004 I=NR1,NR2
      J=I-NR1+1
      AI(J)=QQ(I)
 5004 QQL(J)=AI(J)
      JLM=NR2-NR1+1
      NLV=1
               WRITE(6,5008)
 5008 FORMAT('     CHECK YOUR DATA WANTED')
                  PRINT*,NR1,AI(1),NR1+1,AI(2)
                  PRINT*,NR2-1,AI(J-1),NR2,AI(J)
 5006 NREAD2=J
      WRITE(6,450)
  450 FORMAT(45H DO YOU WANT TO PRINT RAIN DATA? TYPE:Y OR N )
      READ(5,451)PDATA
  451 FORMAT(A1)
      WRITE(6,452)
  452 FORMAT('DO YOU WANT TO PRINT A LIST OF FLOW?  TYPE:  Y OR N')
      READ(5,453)FLOW
  453 FORMAT(A1)
      WRITE(6,455)
  455 FORMAT('DO YOU WANT A LIST OF OVERFLOW & DURATION FOR EACH OVERFLO
     &W EVENT? TYPE: Y OR N')
      READ(5,510)UZ
      WRITE(6,456)
  456 FORMAT('DO YOU WANT TO CALCULATE POLLUTANTS DISCHARGED FROM OVERFL
     *OW ?  TYPE: Y OR N')
      READ(5,510)POL
  510 FORMAT(A1)
      IF(POL.EQ.'Y')THEN
      PRINT *, 'ENTER THE NAME OF POLLUTION FILE WITH PATH'
      READ '(A)',DAT1
      OPEN(2,FILE=DAT1,STATUS='OLD')
      OPEN(14,FILE='OUT6',STATUS='UNKNOWN')
      END IF
      WRITE(6,95)
   95 FORMAT('INPUT TIME STEP FOR CONTINUATION PIPE FLOW ANALYSIS: >0.1
     *AND < 0.5 (MINUTE)')
      READ(5,*)TSSP
      DO 4491 I=1,10
      BD(I)=0.0
```

```
      BR(I)=0.0
      TND(I)=0.0
      TNR(I)=0.0
      SD(I)=0.0
      SR(I)=0.0
4491  CONTINUE
      DO 449 I=1,5
      DO 447 J=0,10000
      QS(I,J)=0.0
 447  CONTINUE
 449  CONTINUE
      WRITE(6,454)
 454  FORMAT(' THIS PROGRAM USES T U H METHOD TO CALCULATE RUNOFF ')
      WRITE(6,*)
      WRITE(6,*)
      TDWF=0.0
      WRITE(6,5422)
5422  FORMAT(22(/))
      WRITE(6,5434)
5434  FORMAT(55X,'PLEASE WAIT')
      DO 1234 LJ=1,NCAT
      DO 448 J=1,1600
      DU(J)=0.0
      CDV(J)=0.0
      CUMV(J)=0.0
      CUMOV(J)=0.0
      ODU(J)=0.0
      DDUR(J)=0.0
      DUR(J)=0.0
      QOF(J)=0.0
 448  CONTINUE
      DO 201 I=0,100
 201  TUH(I)=0.0
      DO 213 I=-20,10000
 213  AI(I)=0.0
      DO 633 I=1,JLM
 633  AI(I)=QQL(I)
      TCON=0.0
      MODV=1
      READ(3,*)INDEXR,IB(LJ)
      READ(3,*)CV,A,T,TTR
      READ(3,*)DWF,CONL,CONI
      IF(INDEXR.EQ.1)READ(3,*)V(1)
      READ(3,*)PLT,LD,NP
      IF(POL.EQ.'Y')THEN
      READ(2,*)CBD,CBR,CSD,CSR,CND,CNR
      END IF
      T=T*60.0
      TCON=TCON*60.0
      PLT=PLT*60.0
      NOVER2=0
C
C                   CALCULATING TIME STEP OF HYDROGRAPH
C
      NK=1
      TC=T/LD
      NR=INT(PLT/TC)
      IF((NR+1).LT.NP)THEN
      WRITE(6,720)
 720  FORMAT(10X,'ERROR IN SYSTEM DATA FILE,E.G.PLT,NP,ETC')
      GOTO 716
      END IF
      READ(3,506)(TUH(I),I=0,NR)
      DURAT=0.0
```

```
      TR=PTR*60.0
      IF(INDEXR.NE.0)THEN
      WRITE(6,93)
   93 FORMAT('INPUT VALUE OF N TO DEFINE N*DWF')
      READ(5,*)NO
      TSP=TSSP
      DO 3506 I=0,NR
 3506 TUH(I)=TUH(I)*CV
      TSP=TSP*60.0
      JTP=INT(TC/TSP)
      END IF
      WRITE(9,648)
  648 FORMAT(21X,'*-*--*--* LIST OF RESULTS (COSSOM.FOR) *--*--*-*')
      WRITE(9,649)
  649 FORMAT(1X)
      WRITE(9,605)CV,A,T/60.0,DWF,NREAD2
      WRITE(9,*)
      IF(LJ.GT.1)GOTO 31
      IF(PDATA.EQ.'N')GOTO31
      IF(INDEX.EQ.0.AND.UNIT.LT.25.0)WRITE(9,650)
      IF(INDEX.EQ.0.AND.UNIT.GT.25.0)WRITE(9,652)
      IF(INDEX.EQ.1)WRITE(9,653)
  650 FORMAT(15X,'----------RAINFALL DATA  ( MM )----------')
  652 FORMAT(15X,'----------RAINFALL DATA  ( IN )----------')
  653 FORMAT(15X,'----------RAINFALL DATA  ( MM/HR )-----------')
      WRITE(9,*)
      WRITE(9,702)(AI(N),N=1,NREAD2)
C
C                 REORGANIZING RAINFALL DATA
C
C                  (1)    PREPARING
C
   31 IF(INDEXR.EQ.3)GOTO 234
      MINNO=NO
   58 CONTINUE
      MAXV=V(1)
      NO1=MINNO-1
      DWFN=FLOAT(NO1)*DWF
      MAXT=MAXV/DWFN
  234 MAXV=V(1)
      DO 50 LV=2,NLV
      IF(MAXV.LT.V(LV))MAXV=V(LV)
   50 CONTINUE
      IF(INDEX.EQ.0)THEN
      DO 80 N=1,NREAD2
   80 AI(N)=AI(N)*UNIT/TR
      ELSE
      DO 79 N=1,NREAD2
   79 AI(N)=AI(N)/3600
      END IF
C
C             (2)  CONDENSING THE RAINFALL DATA
C
      NREAD=NREAD2
      NAI0=0
      II=1
      AI(II)=AI(1)
      IJ=0
      TCR=0.0
      DO 53 J=2,NREAD2
      II=II+1
      AI(II)=AI(J)
      IF(AI(J).GT.0.0)TCR=0.0
      GOTO 53
```

```
      IF(AI(J).LE.0.0000001)THEN
      TCR=TR+TCR
      IF(TCR.GT.(100.0*TCON))THEN
      IF(AI(J).LT.0.0000001.AND.AI(J-1).LT.0.0000001)THEN
      NAI0=NAI0+1
      IF(NAI0*TR.GT.MAXT)THEN
      IF((NAI0-1)*TR.GT.MAXT)THEN
      IJ=IJ+1
      ELSE
      IJ=IJ+NAI0-1
      END IF
      IM=J-IJ
      AI(IM)=0.0
      NREAD=NREAD2-IJ
      II=IM
      END IF
      END IF
      END IF
      GOTO 53
      END IF
      NAI0=0
   53 CONTINUE
      IF(AI(NREAD).LT.0.0)AI(NREAD)=0.0
      DO 81 N=1,NREAD
      QQ(N)=AI(N)
      QQ(N)=QQ(N)*3600.0
   81 CONTINUE
      IF(PDATA.EQ.'N')GOTO 76
      IF(LJ.GT.1)GOTO 76
      WRITE(9,722)
  722 FORMAT(15X,'----- RAINFALL INTENSITY ( MM/HR)(CONDENCED)-----')
      WRITE(9,721)(QQ(N),N=1,NREAD)
  721 FORMAT(8F10.4)
C
C             (3) RE-ARRANGING THE DATA
C
   76 QQ(1)=AI(1)
      ACQQ=QQ(1)*T
      ACAI=AI(1)*TR
      II=1
      IF(T.GT.TR)GOTO60
      NS=2
      IS=0
      IN=0
   52 DO 51 N=NS,NREAD
      IF(AI(N).LT.0.0)THEN
   54 CONTINUE
      IF(((N-IN-1)*TR-(II-IS)*T).LT.T)THEN
      II=II+1
      QQ(II)=(ACAI-ACQQ)/T
      ELSE
      II=II+1
      QQ(II)=AI(N-1)
      ACQQ=ACQQ+QQ(II)*T
      GOTO54
      END IF
      II=II+1
      QQ(II)=AI(N)
      II=II+1
      QQ(II)=AI(N+1)
      ACQQ=QQ(II)*T
      ACAI=AI(N+1)*TR
      NS=N+2
      IS=II-1
```

```
  IN=N
  GOTO52
  END IF
  IF(((N-IN-1)*TR-(II-IS)*T).LT.T)THEN
  II=II+1
  QQ(II)=(ACAI-ACQQ+AI(N)*((II-IS)*T-(N-IN-1)*TR))/T
  ACQQ=ACQQ+QQ(II)*T
  ELSE
  II=II+1
  QQ(II)=AI(N-1)
  ACQQ=ACQQ+QQ(II)*T
  END IF
  IF((TR*(N-IN)-T*(II-IS)).GT.T)THEN
  NS=N
  GOTO52
  END IF
  ACAI=ACAI+AI(N)*TR
  IF(N.EQ.NREAD)THEN
55 CONTINUE
  IF(((N-IN-1)*TR-(II-IS)*T).LT.T)THEN
  II=II+1
  QQ(II)=(ACAI-ACQQ)/T
  ELSE
  II=II+1
  QQ(II)=AI(N)
  ACQQ=ACQQ+QQ(II)*T
  GOTO55
  END IF
  END IF
51 CONTINUE
  GOTO59
60 ACAI=0.0
  JTS=NINT(T/TR+0.5)
  LT=0
  JJ=0
  II=0
  N99=0
  I99=0
  DO 57 N=1,NREAD
  IF(AI(N).LT.0.0)THEN
  II=II+1
  QQ(II)=ACAI/T
  II=II+1
  QQ(II)=0.0
  ACAI=0.0
  JJ=0
  LT=0
  N99=N
  I99=II
  GOTO56
  END IF
  JJ=JJ+1
  IF(JJ.LT.JTS)THEN
  IF((T-LT).GT.TR)THEN
  ACAI=ACAI+TR*AI(N)
  GOTO56
  ELSE
  ACAI=ACAI+(T-LT)*AI(N)
  END IF
  ELSE
  ACAI=ACAI+AI(N)*((T-LT)-(JJ-1)*TR)
  END IF
  II=II+1
  QQ(II)=ACAI/T
```

```
      LT=(N-N99)*TR-(II-I99)*T
      ACAI=AI(N)*LT
      JJ=0
   56 IF(N.EQ.NREAD.AND.ACAI.GT.0.0)THEN
      II=II+1
      QQ(II)=ACAI/T
      END IF
   57 CONTINUE
   59 NREAD=II
      DO 78 N3=1,NREAD
      IF(LJ.GT.1)GOTO 7846
      IF(QQ(N3).LT.0.0)QQ(N3)=0.0
 7846 CONTINUE
      QQ(N3)=(QQ(N3)*T)
      IF(QQ(N3).LT.0.0)QQ(N3)=0.0
   78 AI(N3)=QQ(N3)
      IF(PDATA.EQ.'N')GOTO77
      IF(LJ.GT.1)GOTO 77
      RDEP=0.0
      DO 9723 N=1,NREAD
 9723 RDEP=RDEP+QQ(N)
      WRITE(10,9722)RDEP
 9722 FORMAT(1X,'TOTAL RAIN DEPTH IS ',F4.1,' (MM)')
      WRITE(10,*)
      WRITE(10,*)
      WRITE(9,718)
  718 FORMAT(15X, '....RAINFALL DATA AFTER REORGANIZED ( MM )....')
      WRITE(9,702)(AI(I),I=1,NREAD)
      WRITE(9,696)
      WRITE(9,*)
C
C                 (4) TO GET EFFECTIVE RAINFALLLS IN MM
C
   77 DO 3 N3=1,NREAD
      AI(N3)=AI(N3)*CV
    3 CONTINUE
C     NOTATION:- CUMOV=TOTAL OVERFLOW VOLUME
C               ODU=TOTAL OVERFLOW DURATION
C               NOVER=NO. OF OVERFLOW EVENTS
      NTOTL=NREAD
      NREAD1=NREAD+1
      IF(INDEXR.EQ.0)THEN
      JLEND=1
      GOTO 1112
      END IF
      IB(0)=1
      IF(IB(LJ).EQ.IB(LJ-1))TDWF=TDWF+DWF
      JLEND=1
  792 FORMAT(3X)
      WRITE(10,793)LJ
  793 FORMAT(2X,' RESULTS  FOR SUBCATCHMENT   NO. ',I2)
 1112 JQ=0
      CONTINUE
      JL=1
      LV=1
      IF(INDEXR.EQ.0)GOTO 1114
      NOF=NO
      NO1=NOF-1
      DWFM=FLOAT(NO1)*DWF
      DWFMT=DWFM
 1113 CONTINUE
      CD=0.0
      COND1=(0.044917*DWF/CONI**0.5)**0.375
   98 WRITE(6,96)COND1
```

```
   96 FORMAT('INPUT DIAMETER OF CONTINUATION PIPE: FREE FLOW FOR DWF
     * COND>= ',F6.3)
      READ(5,*)COND
      CQCON=22.2631*COND**2.6667*CONI**0.5
      IF(CQCON.GT.NOF*DWF)THEN
      WRITE(6,5015)
 5015 FORMAT('DIAMETER OF CONT. PIPE IS TOO LARGE, TRY AGAIN!')
      GOTO98
      END IF
      WRITE(6,5010)
 5010 FORMAT('INPUT DIAMETER OF THROTLE PIPE ( <=DIAMETER OF THROTLE
     *PIPE )')
      READ(5,*)DTHR
      RATCT=COND/DTHR
      IF(RATCT.GE.5.0)THEN
      ATA=0.89
      ELSE IF(RATCT.LT.5.0.AND.RATCT.GE.4.0)THEN
      ATA=0.85
      ELSE IF(RATCT.LT.4.0.AND.RATCT.GE.3.0)THEN
      ATA=0.77
      ELSE IF(RATCT.LT.3.0.AND.RATCT.GE.2.5)THEN
      ATA=0.69
      ELSE IF(RATCT.LT.2.5)THEN
      ATA=0.55
      END IF
      ECONL=CONL+(1+(0.5+ATA)*RATCT**4.0)*49.95*COND**1.3333
      HH=0.00201756*ECONL*(NOF*DWF)**2.0/COND**5.3333
      HH1=HH+COND-CONL*CONI
      IF(HH1.LT.COND)THEN
      WRITE(6,99)
   99 FORMAT(' THE GIVEN DIAMETER OF CONTINUATION PIPE OR THROTLE PIPE
     *IS TOO LARGE. TRY AGAIN!')
      GOTO98
      END IF
      WRITE(6,97)HH1
   97 FORMAT('WATER DEPTH IN CHAMBER=',F10.5,' IS IT OK? TYPE: Y OR N')
      READ(5,510)DEPTH
      IF(DEPTH.EQ.'N')GOTO 98
      WRITE(9,*)
      WRITE(9,75)NOF,NOF*DWF
      WRITE(9,690)V(LV),HH1
      WRITE(9,698)COND,DTHR
      WRITE(9,*)
   75 FORMAT(5X,16H MAX.CONT.FLOW= ,I3,4H*DWF,2H= ,F8.4)
      OPEN(8,FILE='OUT4',STATUS='UNKNOWN')
      TOTVOL(LV)=0.0
      TOTDU(LV)=0.0
      NOVER=1
      DU(1)=0.0
      CDV(1)=0.0
      DDUR(1)=0.0
      QOF(1)=0.0
      NQOF=0
      NCD=0
      ORV=V(LV)
      RQCON=CQCON-DWF
      IF(MODV.EQ.0)THEN
      ARCH=ORV/HH1
      V(LV)=ORV-COND*ARCH
      ELSE
      ARCH=ORV/(HH1-COND)
      END IF
      H1=COND
 1114 IF(FLOW.EQ.'N') GOTO 688
```

```
300 FORMAT(40X,'TIME STEP = ',F8.2,' SECOND')
688 NCV=INT(PLT/T)
   NWS=0
   JQC=0
   QC1(-1)=0.0
   QC1(0)=0.0
   DO 1145 N=0,10000
1145 QP(N)=0.0
   ILJ=IB(LJ)
   IB(0)=1
   IF(ILJ.GT.IB(LJ-1))TCT(ILJ)=TC
   IF(ILJ.EQ.1)THEN
   IF(LJ.EQ.1.OR.IB(LJ-1).GT.1)THEN
   TCT(ILJ)=TC
   END IF
   END IF
   IF(INDEXR.LT.2.AND.LJ.GT.1)THEN
   IF(ILJ.GT.IB(LJ-1))ILJ=ILJ-1
   DO 626 N=1,ILJ
   TB=TCT(N)
   JQL=1
   LEV=NWT(N)
   IF(TC.EQ.TB)GOTO 626
   DO 624 I=1,LEV
621 CONTINUE
   IF(TB.GT.TC)THEN
   TT1=I*TB
   IF(I*TB.GT.JQL*TC)THEN
   SLOP=(QS(N,I+1)-QS(N,I))/TB
   QP(JQL)=QS(N,I)+SLOP*(TB-(TT1-JQL*TC))
   JQL=JQL+1
   GOTO 621
   ELSE
   TT2=(I+1)*TB
   SLOP=(QS(N,I+2)-QS(N,I+1))/TB
   QP(JQL)=QS(N,I+1)+SLOP*(TB-(TT2-JQL*TC))
   JQL=JQL+1
   END IF
   END IF
   IF(TC.GT.TB)THEN
   IDST=(TC*I)/TB+1
   SLOP=(QS(N,IDST+1)-QS(N,IDST))/TB
   QP(JQL)=QS(N,IDST+1)+SLOP*(I*TC-(IDST)*TB)
   JQL=JQL+1
   IF(I*TC.GT.LEV*TB-TC/TB)GOTO 325
   END IF
624 CONTINUE
325 DO 622 I=1,JQL
   QS(N,I)=QP(I)
622 CONTINUE
   NWT(N)=JQL
626 CONTINUE
   NWT(0)=0
   ILJ=IB(LJ)
   IF(IB(LJ).GT.IB(LJ-1))THEN
   DO 638 N=1,ILJ-1
   IF(ILJ.GT.1)THEN
   IF(NWT(N).LT.NWT(N-1))NWT(N)=NWT(N-1)
   END IF
638 CONTINUE
   DO 628 N=1,ILJ-1
   LEV=NWT(N)
   DO 629 I=1,LEV
   QS(ILJ,I)=QS(ILJ,I)+QS(N,I)
```

```
  629 CONTINUE
  628 CONTINUE
      DO 2345 I=1,LEV
 2345 QP(I)=QS(ILJ,I)
 1123 JQP=0
      LDD=LD
      NRUN=INT((NWT(ILJ-1))/LDD)
      NREAD1=NRUN+1
      NREAD=NREAD1-1
      QS(ILJ-1,0)=0.0
      DO 7 N=1,NREAD
      DO 8 I=1,LDD+1
    8 QPP(I)=QS((ILJ),(JQP+I))
      QPP(0)=QS((ILJ),JQP)
      IF(LDD.LT.6)THEN
      DO 9 I=LDD+2,7
    9 QPP(I)=0.0
      END IF
      DO 10 I=0,7
      IF(QPP(I).LT.0.0)QPP(I)=0.0
   10 CONTINUE
      JQP=JQP+LDD
      WRITE(8,689)(QPP(I),I=0,7)
      IF(N.EQ.NREAD)THEN
      MPS=JQP-2
      WRITE(8,689)(QS((ILJ),K),K=MPS,MPS+7)
      END IF
    7 CONTINUE
      REWIND 8
      IF(ILJ.GT.1)THEN
      DO 2343 N=1,ILJ
      DO 2344 I=1,10000
      QS(N,I)=0.0
 2344 CONTINUE
 2343 CONTINUE
      END IF
      END IF
      END IF
      NREAD1=MAX(NTOTL+1,NREAD1)
      OPEN(11,FILE='OUT5',STATUS='UNKNOWN')
      DO 116 N3=1,NREAD1
      DO 210 I=0,60
  210 Q(I)=0.0
      IF(N3.LT.2)THEN
      QCON=-1.0
      QCONS(0)=CQCON
      END IF
  189 FORMAT(40X,3HN3=,I5)
      IF(V(LV).LT.0.0001.AND.NOF.GT.1.0)DDUR(NOVER)=1.0
      QU=0.0
      QL=0.0
      QU2=0.0
      DUI=0.0
      DV=0.0
      TY=0.0
      QF=0.0
      IF(INDEXR.EQ.1.AND.IB(LJ).GT.IB(LJ-1))THEN
      IF(LJ.GT.1)THEN
      IF(N3.GT.NTOTL)THEN
      READ(8,689)(QPP(N),N=0,7)
      DO 101 N=0,7
  101 Q(N)=QPP(N)
      GOTO 7654
      END IF
```

```
      END IF
      END IF
C
C         TO PREPARE TREATING AI(I)
C
      DO 200 I=-LD,NCV*LD,LD
      NX(I)=N3-I/LD
      IF(NX(I).LT.0) NX(I)=0
      IF(NX(I).EQ.0) AI(NX(I))=0.0
  200 CONTINUE
      DO 218 K=-21,1
  218 BN(K)=0.0
      N3C=N3
      IF(N3.EQ.NREAD1)THEN
      N3C=NREAD1
      GOTO209
      END IF
C
C         TO TREAT AI(I)
C
      IF(AI(N3+1).LT.0.0)THEN
      BN(1)=AI(N3+1)
      AI(N3+1)=0.0
      END IF
      DO 215 I=0,NCV
      IAI=N3-I
      IF(AI(IAI).LT.0.0)THEN
      DO 214 K=IAI,N3-NCV,-1
      J=K-IAI
      BN(J)=AI(K)
  214 AI(K)=0.0
      GOTO 219
      END IF
  215 CONTINUE
C
C         TO FORM HEADS OF TUHS
C
  219 DO 202 I=0,LD+1
      Q(I)=0.0
      DO 203 J=0,NCV*LD,LD
      Q(I)=Q(I)+AI(NX(J))*TUH(J+I)
  203 CONTINUE
      IF (I.GT.LD) THEN
      Q(I)=Q(I)+AI(N3+1)*TUH(1)
      END IF
  202 CONTINUE
      GOTO208
C
C         TO TREAT AI(I)
C
  209 NRF=NREAD
      IF(N3C.EQ.NREAD1)NRF=N3-1
      NWS=NWS+1
      JE=NRF-NCV
      DO 222 I=1,NCV
      IAI=N3-I
      IF(AI(IAI).LT.0.0)THEN
      DO 223 K=IAI,N3-NCV,-1
      J=K-IAI
      BN(J)=AI(K)
  223 AI(K)=0.0
      GOTO224
      END IF
  222 CONTINUE
```

```
C
C        TO FORM TAILS OF TUHS
C
  224 DO 204 I=0,NR-LD+1
      Q(I)=0.0
      JJ=0
      DO 205 J=NRF,JE,-1
      JJ=JJ+1
      JM=I+JJ*LD
  205 Q(I)=Q(I)+AI(J)*TUH(JM)
  204 CONTINUE
C
C        TO RESUME AI(I)
C
  208 IF (BN(1).LT.0.0)AI(N3+1)=BN(1)
      DO 220 I=0,-NCV,-1
      IF(BN(I).LT.0.0)THEN
      DO 207 K=IAI,N3-NCV,-1
      J=K-IAI
      AI(K)=BN(J)
  207 CONTINUE
      GOTO221
      END IF
  220 CONTINUE
  221 LDD=LD
 7654 CONTINUE
      IB(0)=1
      IF(INDEXR.LT.2.AND.IB(LJ).GT.IB(LJ-1))THEN
      IF(LJ.GT.1)THEN
      IF(N3.LE.NTOTL)THEN
      READ(8,689)(QPP(N),N=0,7)
      DO 103 N=0,7
  103 Q(N)=Q(N)+QPP(N)
      END IF
      END IF
      END IF
      IF(N3.EQ.NREAD1)THEN
      LDD=NR-LD
      LDT=LDD
      END IF
      IF(FLOW.EQ.'N')GOTO681
      IF(AI(N3).LT.0.0)N3C=N3
      IF(N3C.GT.NREAD)N3C=NREAD
      IF(N3.EQ.NREAD1)THEN
      PTS=INT((NR-14)/6)+1
      SPM=6
      IF(INDEXR.LT.2.AND.IB(LJ).GT.IB(LJ-1))THEN
      K=6
      DO 13 N=0,7
      K=K+1
   13 QPP(K)=QPP(N)
      DO 12 N=SPM,SPM+7
   12 Q(N)=Q(N)+QPP(N)
      END IF
  301 SPM=SPM+6
      END IF
  680 FORMAT(5HRAIN(,I5,2H):,8F8.4)
      IF(JL.EQ.JLEND.AND.LV.EQ.NLV)THEN
      DO 211 I=1,LDD
      JQ=JQ+1
      IF(JQ.GT.10000)GOTO6818
  211 QQ(JQ)=Q(I)
      END IF
 6818 IF(INDEXR.EQ.0)GOTO 1654
```

```
C
C       TO CALCULATE OVERFLOWS
C
 681  DO 1000 IJ=1,LDD
      QU=Q(IJ)
      QU2=Q(IJ+1)
      QL=Q(IJ-1)
      IF(QCON.LT.0.0)THEN
      IF(QU.GT.RQCON.AND.QL.LE.RQCON)QCON=RQCON
      END IF
      IF(QCON.GE.RQCON)THEN
      DWFM=QCON
      Y=3.0/8.0*QL+3.0/4.0*QU-1.0/8.0*QU2
      DVS=((QL+QU)/6.0+2.0*Y/3.0-DWFM)*TC
      G=(QU-QL)/TC
      GR=(QL-QU)/TC
      IF(ABS(QU-QL).LT.0.0001)GOTO 1007
      IF(QU.LT.QL)GOTO 1011
      IF(QU.GT.QL.AND.QU.GT.QU2)GOTO 1009
C
C     GRAD, +VE,G
C
      IF(QU.LE.DWFM)GOTO 20
      IF(QU.GT.DWFM.AND.QL.LE.DWFM)GOTO 1003
      IF(QU.GT.DWFM.AND.QL.GT.DWFM)GOTO 1005
 1003 DUI=(QU-DWFM)/G
      TK=TC-DUI
      IF(DWFM.LT.0.00001.AND.DWFM.GT.-0.00001)GOTO 25
      IF(CDV(NOVER).LT.0.00001.AND.CDV(NOVER).GT.-0.00001)GOTO 25
      DV=(DWFM-QL)*(TK/2.0)*(-1.0)
      CDV(NOVER)=CDV(NOVER)+DV
      IF(CDV(NOVER).LE.0.0) CDV(NOVER)=0.0
   25 DV=(QU-DWFM)*DUI/2.0
      CDV(NOVER)=CDV(NOVER)+DV
      IF(CDV(NOVER).LE.V(LV))GOTO 1002
      IF(DDUR(NOVER).GT.0.0)GOTO 1004
      C1=V(LV)-CDV(NOVER)+DV
      DDUR(NOVER)=SQRT(2.0*C1*DUI/(QU-DWFM))
 1004 CONTINUE
      IF(H1.GE.HH1)DU(NOVER)=DU(NOVER)+DUI
      GOTO 1002
   20 DV=(((DWFM-QU)*TC)+((QU-QL)*TC/2.0))*(-1.0)
      CDV(NOVER)=CDV(NOVER)+DV
      GOTO 90
 1005 CDV(NOVER)=CDV(NOVER)+DVS
      IF(CDV(NOVER).LE.V(LV))GOTO 1002
      IF(DDUR(NOVER).GT.0.0)GOTO 1006
      C1=V(LV)-CDV(NOVER)+DVS
      DDUR(NOVER)=TC*(-QL+DWFM+SQRT((QL-DWFM)**2.0+4.0*(QU-QL)/2.0/
     &TC*C1))/(QU-QL)
 1006 CONTINUE
      IF(H1.GE.HH1)DU(NOVER)=DU(NOVER)+TC
      GOTO 1002
C
C     QU=QL
C
 1007 IF(QU.LE.DWFM)GOTO 91
      CDV(NOVER)=CDV(NOVER)+DVS
      IF(CDV(NOVER).LE.V(LV))GOTO 1002
      IF(DDUR(NOVER).GT.0.0)GOTO 1008
      C1=V(LV)-CDV(NOVER)+DVS
      DDUR(NOVER)=C1/(QU-DWFM)
 1008 IF((QU-QU2).GT.0.0001)QF=QU-DWFM
      IF(QF.GT.QOF(NOVER))THEN
```

```
      QOF(NOVER)=QF
      NQOF=N3-1
      END IF
      IF(H1.GE.HH1)DU(NOVER)=DU(NOVER)+TC
      GOTO 1002
   91 DV=(DWFM-QL)*TC*(-1.0)
      CDV(NOVER)=CDV(NOVER)+DV
      GOTO 90
C
C     PEAK
C
 1009 IF(QU.LE.DWFM)GOTO 48
      IF(QU.GT.DWFM.AND.QL.GT.DWFM)GOTO 1010
      DUI=(QU-DWFM)/G
      DV=(QU-DWFM)*DUI/2.0
      CDV(NOVER)=CDV(NOVER)+DV
      IF(CDV(NOVER).LE.V(LV))GOTO 1002
      IF(DDUR(NOVER).GT.0.0)GOTO 5000
      C1=V(LV)-CDV(NOVER)+DV
      DDUR(NOVER)=SQRT(2.0*C1*DUI/(QU-DWFM))
 5000 QF=QU-DWFM
      IF(QF.GT.QOF(NOVER))THEN
      QOF(NOVER)=QF
      NQOF=N3-1
      END IF
      IF(H1.GE.HH1)DU(NOVER)=DU(NOVER)+DUI
      GOTO 1002
   48 DV=(((DWFM-QU)*TC)+((QU-QL)*TC/2.0))*(-1.0)
      CDV(NOVER)=CDV(NOVER)+DV
      GOTO 90
 1010 CDV(NOVER)=CDV(NOVER)+DVS
      IF(CDV(NOVER).LE.V(LV))GOTO 1002
      IF(DDUR(NOVER).GT.0.0)GOTO 6000
      C1=V(LV)-CDV(NOVER)+DVS
      DDUR(NOVER)=TC*(-QL+DWFM+SQRT((QL-DWFM)**2.0+4.0
     &*(QU-QL)/2.0/TC*C1))/(QU-QL)
 6000 QF=QU-DWFM
      IF(QF.GT.QOF(NOVER))THEN
      QOF(NOVER)=QF
      NQOF=N3-1
      END IF
      IF(H1.GE.HH1)DU(NOVER)=DU(NOVER)+TC
      GOTO 1002
C
C     GRAD-VE
C
 1011 CONTINUE
      IF(QL.LE.DWFM)GOTO 92
      IF(QU.GE.DWFM)GOTO 1012
      IF(QU.LT.DWFM.AND.QL.GT.DWFM)GOTO 1014
 1012 CDV(NOVER)=CDV(NOVER)+DVS
      IF(CDV(NOVER).LE.V(LV))GOTO 1002
      IF(DDUR(NOVER).GT.0.0)GOTO 1013
      C1=V(LV)-CDV(NOVER)+DVS
      DDUR(NOVER)=TC*((QL-DWFM)-SQRT((QL-DWFM)**2.0-2.0*(QL-QU)*C1/TC))
     &/(QL-QU)
C
C     COMPUTE PEAK FLOW
C
 1013 QF=(QL-QU)*(TC-DDUR(NOVER))/TC+QU-DWFM
      IF(QF.GT.QOF(NOVER))THEN
      QOF(NOVER)=QF
      NQOF=N3-1
      END IF
```

```
      IF(H1.GE.HH1)DU(NOVER)=DU(NOVER)+TC
      GOTO 1002
 1014 DUI=(QL-DWFM)/GR
      DV=(QL-DWFM)*DUI/2.0
      CDV(NOVER)=CDV(NOVER)+DV
      IF(CDV(NOVER).LE.V(LV))GOTO42
      IF(DDUR(NOVER).GT.0.0)GOTO 1015
      C1=V(LV)-CDV(NOVER)+DV
      DDUR(NOVER)=DUI*((QL-DWFM)-SQRT((QL-DWFM)**2.0-2.0*(QL-DWFM)*C1/
     &DUI))/(QL-DWFM)
 1015 QF=(QL-DWFM)*(DUI-DDUR(NOVER))/DUI
      IF(QF.GT.QOF(NOVER))THEN
      QOF(NOVER)=QF
      NQOF=N3-1
      END IF
      IF(H1.GE.HH1)DU(NOVER)=DU(NOVER)+DUI
      GOTO 39
   92 DV=(((DWFM-QL)*TC)+((QL-QU)*TC/2.0))*(-1.0)
      CDV(NOVER)=CDV(NOVER)+DV
      GOTO 90
   39 CONTINUE
      IF((HH1-H1).GT.0.1)CDV(NOVER)=0.0
      IF(CDV(NOVER).LE.V(LV))GOTO42
C
C     TOT. VOL. & DURATION FOR EACH OVERFLOW EVENT
C
      IF(V(LV).EQ.0.000001.AND.NOF.GT.1.0)DDUR(1)=0.0
      IF(H1.LT.HH1)DDUR(NOVER)=0.0
      CUMOV(NOVER)=CDV(NOVER)-V(LV)
      ODU(NOVER)=DU(NOVER)-DDUR(NOVER)
C
C     COMP. AV. OVERFLOW RATE FOR EACH EVENT
C
      IF(ODU(NOVER).GT.0.1)AOFR(NOVER)=CUMOV(NOVER)/ODU(NOVER)
      IF(NQOF.GT.NREAD)NQOF=NREAD
      IF(NCD.GT.NREAD)NCD=NREAD
      IF(UZ.EQ.'N')GOTO 131
      IF(QU.LT.DWFMT.AND.QL.GT.DWFMT)THEN
      WRITE(9,8787)NOVER
 8787 FORMAT(20X,'EVENT NO. ',I2)
      WRITE(9,*)
      WRITE(9,687)
  687 FORMAT(6X,13HPEAK OVERFLOW,6X,8HDURATION,7X,12HOVERFLOW VOL
     &,7X,13HOVERFLOW RATE,6X,20H AFTER NEW RAIN NO. )
      CALL TPRINT(AOFR(NOVER),CUMOV(NOVER),ODU(NOVER),QOF(NOVER),NQOF)
      END IF
  131 TOTVOL(LV)=TOTVOL(LV)+CUMOV(NOVER)
      TOTDU(LV)=TOTDU(LV)+ODU(NOVER)
      IF(CD.LT.QOF(NOVER))THEN
      CD=QOF(NOVER)
      NCD=NQOF
      END IF
      IF(QU.LT.DWFMT.AND.QL.GT.DWFMT)THEN
      NOVER1=NOVER
      NOVER=NOVER+1
      CDV(NOVER)=CDV(NOVER1)
      END IF
   42 DU(NOVER)=0.0
      DDUR(NOVER)=0.0
      QOF(NOVER)=0.0
      TZ=TC-DUI
      DV=(DWFM-QU)*TZ/2.0*(-1.0)
      IF(CDV(NOVER).GT.V(LV))CDV(NOVER)=V(LV)
      CDV(NOVER)=CDV(NOVER)+DV
```

```
 90  IF(CDV(NOVER).LE.0.0)CDV(NOVER)=0.0
 1002 CONTINUE
      END IF
C
C          TO CALCULATE FLOW OF CONTINUATION PIPE : QC1(JQC)
C
      IF(FLOW.NE.'N')THEN
      JQC=JQC+1
      IF(JQC.LT.10001)THEN
      QC1(JQC)=QCONS(0)-DWF
C          TO ESTIMATE  QC1(JQC)
      IF(QCON.LE.RQCON)THEN
      QC1(JQC)=QU2
      IF(QU.GE.QL)THEN
      QC1(JQC)=QU
      IF(QU.GT.RQCON)QC1(JQC)=(QL+RQCON)/2.0
      END IF
      IF(QC1(JQC-2).GT.QC1(JQC-1))THEN
      QC1(JQC)=(QC1(JQC-1)+QU)/2.0
      IF(QU2.GT.QU)QC1(JQC)=QU
      END IF
      END IF
      END IF
      END IF
      KKC=0
 44   QUS=QU
      DEQ=(QU2-QU)/JTP
      JTPS=JTP
      IF(QCON.GE.RQCON)THEN
      IF(KKC.EQ.0)THEN
      IF(QL.LT.RQCON.AND.QU.GT.RQCON)THEN
      IF(QU.GT.QL.OR.QU.LT.QL)THEN
      DET=(QU-RQCON)*TC/(QU-QL)
      ELSE
      DET=TC
      END IF
      JTPS=INT(DET/TSP)
      IF(JTPS.EQ.0)JTPS=1
      DEQ=(QU-RQCON)/JTPS
      QUS=DEQ+RQCON
      QCONS(0)=CQCON
      END IF
      END IF
      QCON=0.0
      DO 40 IT=1,JTPS
      DEH=(QUS+DEQ*(IT-1)+DWF-QCONS(IT-1))*TSP/ARCH
      H1=H1+DEH
      IF(H1.GT.HH1)H1=HH1
      IF(H1.GE.COND)THEN
      SCON=(H1-COND+CONL*CONI)/ECONL
      QCONS(IT)=22.2631*COND**2.6667*SCON**0.5
      IF(QCONS(IT).LT.CQCON)QCONS(IT)=QCONS(IT-1)
      ELSE
      QCONS(IT)=QU2+DWF
      H1=COND
      END IF
 40   QCON=QCON+QCONS(IT)-DWF
      QCON=QCON/JTPS
      QCONS(0)=QCONS(IT-1)
      IF(QL.LT.RQCON.AND.KKC.EQ.0)THEN
      IF(JQC.LT.10000)QC1(JQC)=QCONS(0)-DWF
      KKC=1
      GOTO44
      END IF
```

```
      ELSE
      QCON=(QU+QU2)/2.0
      END IF
 1000 CONTINUE
 1654 CONTINUE
  116 CONTINUE
      REWIND 8
      IF(INDEXR.EQ.0)GOTO 1111
      IF(NOVER.EQ.1)THEN
      NOVER1=NOVER-1
      WRITE(9,693)NOVER1
      GOTO1021
      END IF
  689 FORMAT(2X,8F8.4)
      WRITE(9,693)NOVER1
      IF(NOVER1.EQ.0)GOTO 1018
C
C     AV. OVERFLOW VOL. & DUR. FOR EACH STORAGE VOL.
C
      AVOL(LV)=TOTVOL(LV)/FLOAT(NOVER1)
      ADU(LV)=TOTDU(LV)/FLOAT(NOVER1)
      GOTO 1019
 1021 TOTVOL(LV)=CDV(NOVER)-V(LV)
      IF(TOTVOL(LV).LT.0.0) TOTVOL(LV)=0.0
      TOTDU(LV)=DU(NOVER)-DDUR(NOVER)
      AVOL(LV)=TOTVOL(LV)
      ADU(LV)=TOTDU(LV)
      GOTO 1019
 1018 AVOL(LV)=0.0
      ADU(LV)=0.0
 1019 WRITE(9,697)CD,NCD
      WRITE(9,691)ADU(LV),AVOL(LV)
      WRITE(9,695)TOTVOL(LV),TOTDU(LV)
      WRITE(9,696)
  795 FORMAT(10X,I3,4H*DWF,1H=,F6.4,12X,F8.1,20X,I5)
 1111 IF(FLOW.NE.'N')THEN
      IF(INDEXR.EQ.0)THEN
      WRITE(10,*)
      WRITE(10,*)
      WRITE(10,793)LJ
      END IF
      NW=(NREAD1-NWS)*LD+NWS*(NR-LD)
      IF(NW.GT.10000)NW=10000
 2321 IF(INDEXR.EQ.0)THEN
      DO 7664 I=1,NW
 7664 QC1(I)=QQ(I)
      END IF
      END IF
 5454 FORMAT(40X,'TOTAL . VOL.=',1X,F10.1)
      NWJ=NW
      TTR=60*TTR
      JTR=TTR/TC-1
      IF(JTR.GT.0)THEN
      DO 7890 KI=-JTR,0,1
      QC1(KI)=0.0
 7890 CONTINUE
      END IF
      IF(INDEXR.LT.2)THEN
      JKL=JTR
      KL=NW+JKL+1
      DO 799 I=1,KL
      ILJ=IB(LJ)
      QS(ILJ,I)=QC1(I-JKL-1)+QS(ILJ,I)
  799 CONTINUE
```

```
      TCT(ILJ)=TC
C
C     CALCULATION OF CONTINUATION VOLUME
C
      TCT(ILJ)=TC
      END IF
      ORV1=V(LV)
      V(LV)=ORV
      NT(LJ)=KL
      NWT(ILJ)=KL
      IF(LJ.GT.1.AND.IB(LJ).EQ.IB(LJ-1))THEN
      NWT(ILJ)=MAX(NT(LJ),NT(LJ-1))
      END IF
 9898 CONTINUE
 1001 CONTINUE
 716  IF(JQC.GT.10000)THEN
      WRITE(6,441)
 441  FORMAT(' WARNNING: JQC>10000  AND  NW>10000,')
      WRITE(6,442)
 442  FORMAT('    SO  QC1(JQC) AND QQ(I) DID NOT BE CALCULATED MORE')
      END IF
      CHAM=0.0
      CHAM1=0.0
      DO 6859 I=1,NW
      AIT=(QQ(I)-QC1(I))
      IF(AIT.LT.0.0)AIT=0.0
      IF(AIT.GT.0.0.AND.CHAM.LT.ORV1)THEN
      IF(QQ(I).GT.RQCON)THEN
      CHAM=AIT*TC+CHAM
      AIT=0.0
      END IF
      END IF
      IF(QC1(I).LT.DWFMT.AND.CHAM1.GE.ORV1)THEN
      QCC=DWFMT-QC1(I)
      QCV=QCC*TC
      CHAM=CHAM-QCV
      IF(CHAM.LT.0.0)CHAM=0.0
      QC1(I)=QC1(I)+QCC
      END IF
      CHAM1=CHAM
      AI(I)=AIT
      IF(QQ(I).LT.QC1(I).OR.QC1(I).LT.DWFMT)AI(I)=0.0
 6859 CONTINUE
      ORVOL=0.0
      POR=0.0
      QMR=0.0
      QQC=0.0
      DO 6950 I=1,NW
      IF(AI(I).GT.POR)POR=AI(I)
      ORVOL=ORVOL+AI(I)*TC
      QMR=QMR+(QQ(I)+DWF)*TC
      QQC=QQC+(QC1(I)+DWF)*TC
      QQC=QMR-ORVOL
      IF(AI(I).GT.0.0)DURAT=DURAT+TC
      IF(AI(I).GT.0.0.AND.AI(I-1).EQ.0.0)NOVER2=NOVER2+1
 6950 CONTINUE
      IF(INDEXR.EQ.1)THEN
      DURAT=TOTDU(LV)
      ORVOL=TOTVOL(LV)
      END IF
      WAQAT=DURAT
      WRITE(10,5455)QQC
 5455 FORMAT(25X,'CONTINUATION FLOW VOLUME (CUMECS)  = ',F12.3)
      WRITE(10,5457)ORVOL
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 5457 FORMAT(25X,'OVERSPILL VOLUME (CUMECS)        = ',F12.3)
      WRITE(10,5456)QMR
 5456 FORMAT(25X,'TOTAL INFLOW VOLUME (CUMECS)      = ',F12.3)
      TOTV(LJ)=ORVOL
      IF(INDEXR.EQ.0)GOTO 9586
 7915 FORMAT(5X,I4,8X,F10.2,4X,F10.2,6X,F10.4)
      IF(POL.EQ.'Y')THEN
      PBOD=0.0
      PTSS=0.0
      PTNH3=0.0
      WRITE(14,9235)LJ
      WRITE(14,*)
      WRITE(14,9237)
      WRITE(14,9236)
      DO 6006 I=1,NW
      IF(IB(LJ).EQ.IB(LJ-1).OR.IB(LJ).EQ.1)THEN
      BOD=(DWF*CBD+QQ(I)*CBR)/(QQ(I)+DWF)
      TSS=(DWF*CSD+QQ(I)*CSR)/(QQ(I)+DWF)
      TNH3=(DWF*CND+QQ(I)*CNR)/(QQ(I)+DWF)
      BD(IB(LJ))=(BD(IB(LJ))+CBD)/2.
      BR(IB(LJ))=(BR(IB(LJ))+CBR)/2.
      SD(IB(LJ))=(SD(IB(LJ))+CSD)/2.
      SR(IB(LJ))=(SR(IB(LJ))+CSR)/2.
      TND(IB(LJ))=(TND(IB(LJ))+CND)/2.
      TNR(IB(LJ))=(TNR(IB(LJ))+CNR)/2.
      END IF
      IF(IB(LJ).GT.IB(LJ-1))THEN
      ILJ=IB(LJ-1)
      BOD=(DWF*CBD+QQ(I)*CBR+QP(I)*BR(ILJ)+TDWF*BD(ILJ))/(QQ(I)+
     *DWF+TDWF+QP(I))
      TSS=(DWF*CSD+QQ(I)*CSR+QP(I)*SR(ILJ)+TDWF*SD(ILJ))/(QQ(I)+
     *DWF+TDWF+QP(I))
      TNH3=(DWF*CND+QQ(I)*CNR+QP(I)*TNR(ILJ)+TDWF*TND(ILJ))/(QQ(I)+
     *DWF+TDWF+QP(I))
      END IF
      BOD=BOD*AI(I)
      PBOD=PBOD+BOD*TC
      TSS=TSS*AI(I)
      PTSS=PTSS+TSS*TC
      TNH3=TNH3*AI(I)
      PTNH3=PTNH3+TNH3*TC
      WRITE(14,9234)BOD,TSS,TNH3
 9234 FORMAT(5X,3F13.3)
 9235 FORMAT('CATCHMENT NO.',I3,3X,'POLLUTION DISCHARGED FROM OVERFLOW')
 9237 FORMAT('CONCENTRATION')
 9236 FORMAT(10X,' BOD (MG/L) ',' TSS (MG/L) ',' NH4-N (MG/L)')
 6006 CONTINUE
      PBOD=PBOD/1000.
      PTSS=PTSS/1000.
      PTNH3=PTNH3/1000.
      WRITE(14,*)
      WRITE(14,9238)PBOD,PTSS,PTNH3
      WRITE(10,9239)PBOD,PTSS,PTNH3
      END IF
 9239 FORMAT(3X,'BOD (KG) =',F10.3,4X,'TSS (KG) =',F10.3,4X,'NH3-N (KG)
     *= ',F10.3)
      WRITE(10,*)
      WRITE(10,*)
 9238 FORMAT(2X,'TOTAL = ',3F13.4)
 9004 FORMAT(3F8.3)
 9586 IF(INDEXR.EQ.0)THEN
      WRITE(10,*)
      WRITE(10,*)
      TOTV(LJ)=0.0
```

```
      END IF
      WRITE(11,9017)NW,TC
      DO 9005 I=1,NW
      QQ(I)=QQ(I)+DWF
      QC1(I)=QC1(I)+DWF
      WRITE(11,9004)QQ(I),QC1(I),AI(I)
 9005 CONTINUE
 9017 FORMAT(I8,F8.3)
      DO 1235 I=-100,10000
      QQ(I)=0.0
 1235 QC1(I)=0.0
 3156 FORMAT(33X,'END OF CATCHMENT (',I2,' )')
 1234 CONTINUE
      WRITE(6,5422)
      VOLUME=0.0
      DO 5113 I=1,NCAT
 5113 VOLUME=VOLUME+TOTV(I)
      WRITE(10,*)
      WRITE(10,*)
      WRITE(10,5114)VOLUME
 5114 FORMAT(10X,'TOTAL OVERFLOW VOLUME (CUMECS) = ',F14.3)
      REWIND 11
      IF(NW.LT.500)THEN
      WRITE(5,5668)
 5668 FORMAT('DO YOU WANT TO PREPARE DISCHARGE HYDROGRAPH DATA FILE?  TY
     *PE Y OR N')
      READ(5,5667)HYD
 5667 FORMAT(A1)
      IF(HYD.EQ.'Y')THEN
      OPEN(16,FILE='TEMP.HYQ',STATUS='UNKNOWN')
      NREAD=INT(TC)
      IWT=(PTR*60*JLM)/NREAD+50
      REWIND 11
      TCT(0)=0.0
      NNR(0)=0
      NT(0)=0
      DO 1906 N=0,10000
      QQ(N)=0.0
      QC1(N)=0.0
      AI(N)=0.0
      QP(N)=0.0
 1906 CONTINUE
      JQL=1
      DO 17 N=1,NCAT
      READ(11,*)NNR(N),TCT(N)
      DO 6231 IN=1,NNR(N)
      READ(11,515)QQ(IN),QC1(IN)
 6231 CONTINUE
      TC=NREAD
      TB=TCT(N)
      NT(N)=NNR(N)
      IF(TC.EQ.TB)GOTO 1626
      DO 1624 I=1,NNR(N)
 6217 CONTINUE
      IF(TB.GT.TC)THEN
      TT1=FLOAT(I)*TB
      IF(I*(TB).GT.JQL*(TC))THEN
      SLOP=(QQ(I+1)-QQ(I))/TB
      AI(JQL)=QQ(I)+SLOP*(TB-(TT1-FLOAT(JQL)*TC))
      SLOP=(QC1(I+1)-QC1(I))/TB
      QP(JQL)=QC1(I)+SLOP*(TB-(TT1-FLOAT(JQL)*TC))
      JQL=JQL+1
      GOTO 6217
      ELSE
```

```
      TT2=FLOAT(I+1)*TB
      SLOP=(QQ(I+2)-QQ(I+1))/TB
      AI(JQL)=QQ(I+1)+SLOP*(TB-(TT2-FLOAT(JQL)*TC))
      SLOP=(QC1(I+2)-QC1(I+1))/TB
      QP(JQL)=QC1(I+1)+SLOP*(TB-(TT2-FLOAT(JQL)*TC))
      JQL=JQL+1
      END IF
      END IF
      IF(TC.GT.TB)THEN
      IDST=(TC*FLOAT(I))/TB+1.0
      SLOP=(QQ(IDST+1)-QQ(IDST))/TB
 AI(JQL)=QQ(IDST+1)+SLOP*(FLOAT(I)*TC-FLOAT(IDST)*TB)
      SLOP=(QC1(IDST+1)-QC1(IDST))/TB
      QP(JQL)=QC1(IDST+1)+SLOP*(FLOAT(I)*TC-FLOAT(IDST)*TB)
      JQL=JQL+1
      IF(FLOAT(I)*TC.GT.FLOAT(NNR(N))*TB)GOTO 1325
      END IF
 1624 CONTINUE
 1325 NT(N)=JQL
      JQL=1
      DO 1622 I=1,NT(N)-1
      QQ(I)=AI(I)
      QC1(I)=QP(I)
 1622 CONTINUE
 1626 CONTINUE
      NNWT=MAX(NT(N),NT(N-1))
      IF(IWT.GT.NT(N))THEN
      DO 191 I=NT(N),IWT
      QQ(I)=QQ(NT(N))
  191 QC1(I)=QC1(NT(N))
      END IF
      DO 19 IN=1,IWT
      WRITE(16,536)QQ(IN),QC1(IN)
   19 CONTINUE
   17 CONTINUE
      REWIND 16
      REWIND 11
      OPEN(11,FILE=OUT5,STATUS='UNKNOWN')
      DO 14 I=1,IWT
      DO 15 K=1,NCAT
      READ(16,515)QQ(K),QP(K)
      DO 16 LN=2,IWT
      IF(K.LT.NCAT)READ(16,*)
   16 CONTINUE
   15 CONTINUE
      REWIND 16
      DO 1503 K=1,I
 1503 READ(16,*)
      WRITE(11,536)(QQ(K),QP(K),K=1,NCAT)
   14 CONTINUE
      END IF
  515 FORMAT(2F8.3)
  536 FORMAT(20F8.3)
 1563 CONTINUE
      END IF
  500 FORMAT(I5)
  501 FORMAT(8F10.3)
  502 FORMAT(4F10.2)
  503 FORMAT(2I3)
  504 FORMAT(F10.3,2I5)
  505 FORMAT(I5,F5.1,F10.1,I5)
  506 FORMAT(8F10.6)
  507 FORMAT(10F8.4)
  509 FORMAT(F10.3,I5,I5,F10.1,F10.4)
```

```
590  FORMAT(8F10.1)
605  FORMAT(   3X,3HC= ,F5.2,3X,3HA= ,F6.2,3X,3HT= ,F6.2,3X,6HDWF=
    *,F6.4,3X,16HRAINFALL NUMBER=,I5)
690  FORMAT(   5X,16H STORAGE VOLUME= ,F6.1,5X,29H MAX.WATER DEPTH IN
    *CHAMBER= ,F6.3)
698  FORMAT(6X,'DIAMETER OF CONTINUATION PIPE=',F6.3,10X,'DIAMETER OF
    *THROTLE PIPE=',F6.3)
691  FORMAT( 5X,18H AVERAGE DURATION= ,E12.5,2X,28H AVERAGE OVERFLOW
    &VOLUME= ,E12.5)
692  FORMAT( 15X,F8.4,10X,E12.5,16X,E12.5)
693  FORMAT( 10X,30H TOTAL NO. OF OVERFLOW EVENTS= ,I4)
695  FORMAT(5X,23H TOTAL OVERFLOW VOLUME= ,E12.5,2X,26H TOTAL OVERFLOW
    &DURATION= ,E12.5)
696  FORMAT(3X)
697  FORMAT(5X,'MAXIMUM PEAK OVERFLOW= ',F10.7,' CUMECS'
    &,5X,'AFTER NEW RAIN NO.',I5)
701  FORMAT( 10X,30H TOTAL NO. OF OVERFLOW EVENTS= ,I4)
702  FORMAT(8F10.3)
7133 FORMAT(10X,'*--*OVERFLOW HYDROGRAPH RESULTING FROM RAINFALL*--*')
713  FORMAT(10X,'*--*--* HYDROGRAPH RESULTING FROM RAINFALL *--*--*')
714  FORMAT(15X,'( FLOW UNIT: CUMECS, TIME STEP = ',F8.1,' SECOND )')
717  FORMAT(10X,'  <<<<<<<<  CONTINUE PIPE HYDROGRAPH FROM RAINFALL
    * >>>>>>>> ')
719  FORMAT(5X,'NOMAL FULL FLOW IN CONTINUATION PIPE =',F8.4,
    *' (INCLUDES DWF',F8.4,'+SOME RAINFALL FLOW',F8.4,' )')
730  FORMAT('   WATER DEPTH IN CHAMBER=',F10.5,'      ACTIVE DEPTH=',
    *F10.5,'      ACTIVE VOLUME=',F10.5)
731  FORMAT( '   DIAMETER OF CONTINUATION PIPE=',F6.3,'    DIAMETER OF
    *THROTLE PIPE=',F6.3)
4323 continue
     STOP
     END
C*****************************************************************
     SUBROUTINE TPRINT(AOFR,CUMOV,ODU,QOF,NQOF)
C*****************************************************************
     WRITE(9,715)QOF,ODU,CUMOV,AOFR,NQOF
715  FORMAT(8X,F8.4,6X,E12.5,5X,E12.5,8X,F10.5,13X,I5)
     RETURN
     END
```

APPENDIX C USER GUIDE

USER GUIDE

1 Prepare rainfall data file by specifying the total number of rain events, index to identify the units (1 for mm and 0 for inches), duration of each event in min. and symbol to specify whether depth or intensity (1 for intensity and 0 for depth)

2 From sewerage system layout locate the overflow structures and assign them site numbers in non-upstream order. The system data file for COSSOM should appear in the same order.

3 Now give a level number to each overflow structure adopting the following procedure

if an overflow structure receives runoff only from its own subcatchment and there is no other flow from upstream subcatchment joining at the same point assign it Level 1. if an overflow structure receives pass forward flow from upstream subcatchment (identified by Level 1) in addition to the flows from its own subcatchment give it Level 2. Next overflow down the path in the heirarchy of the system should be given Level 3 and so on.

4 Prepare the pollution data file by giving the mean event concentration in rain water and dry weather flow for each subcatchment in the same sequence as site numbers.

5 For each subcatchment calculate unit hydrographs and other parameters as follows

a) If WALLRUS software is used

i) Examine the SSD file for the sewerage system, identify the pipes contributing to each overflow structure and prepare SSD files for each subcatchment.

ii) Apply WALLRUS simulation method to calculate the pipe full velocities in those pipes which carry pass forward flows from upstream subcatchment to the end of downstream subcatchment. Using these velocities calculate the lag-time for each subcatchment.

iii) Calculate the time of concentration (t_c) for each subcatchment using WALLRUS hydrograph method and for rain intensity close to the maximum in rainfall record.

iv) Apply a nominal rainfall event to WALLRUS simulation method which just produces a runoff hydrograph (A).

v) Apply a block rain event of intensity close to the maximum in rainfall record and duration (T) close to the time of concentration (t_c) and preceded by the nominal antecedent rain event to WALLRUS simulation method to produce another runoff hydrograph (B).

vi) Subtract the ordinates of the hydrograph A from B to obtain hydrograph C. Divide the ordinates of hydrograph C by the total depth of block rainfall applied. Resulting ordinates are constructed at interval t, (t=T/L, L=1,2,...6) to give the TUH.

vii) Repeat steps iv, v & vi above for all subcatchments

viii) Prepare system data file for COSSOM by specifying number of subcatchments and then for each subcatchment define the following parameters in the sequence: level of subcatchment in the system, area, time T of TUH, lag-time, dry weather flow, length of continuation pipe, slope of continuation pipe, overflow chamber volume, base width of the unit hydrograph, dividing factor (L), number of ordinates of the unit hydrograph, ordinates of unit hydrograph

ix) Run COSSOM using prepared system data file, rain data file and pollution file.

x) Follow the instructions that appear on the screen

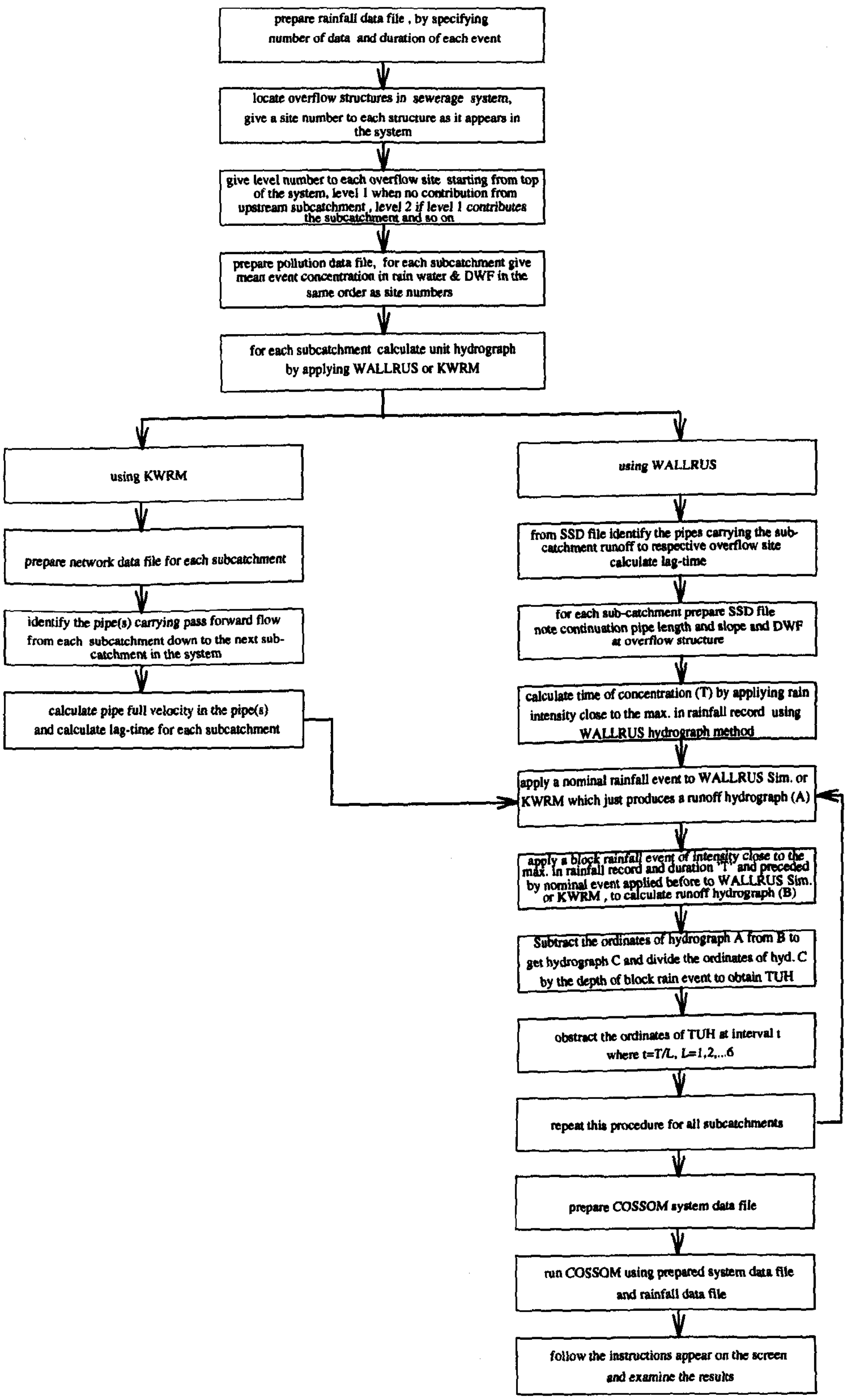
b) If KWRM is used to calculate the unit hydrographs and other parameters.

i) prepare network data file for each subcatchment using KWRM programme. The programme instructs the user to define the network. Once the file is prepared it can be saved for future applications.

ii) From layout of the system identify the pipes which carry pass forward flows. Using KWRM calculate the velocities in the pipes and obtain the lag-time from these velocities.

iii) Follow the procedure described in steps (iv) to (x) above. The only difference in these steps is the use of KWRM instead of the WALLRUS simulation method.

USE OF THE COSSOM



Flowchart