Hydraulics Research
Wallingford

MODELLING OF STORMWATER QUALITY INCLUDING TANKS AND OVERFLOWS (MOSQITO) - DESIGN SPECIFICATION

by

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This report describes work carried out under contract No PECD 7/7/053 in the development of a sewer quality sub-model for the Wallingford Storm Sewer package, funded by the Department of the Environment from April 1985 to March 1988.

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ABSTRACT

This report details the design specification of the sewer quality model under development at Hydraulics Research Limited and funded by the Department of the Environment. This report is an update of a previous report providing further details of the model that has been developed during the period Autumn 1986 to Spring 1988. Following a summary of the requirement specification for the model, which was defined by the River Basin Management Programme at the behest of the UK Water Industry, two particular elements of the model design are discussed. First, an appropriate methodology for simulating pollutant discharges from urban sewered systems is introduced. This together with details of various aspects of software design is discussed as part of the "non-procedural" aspects of the design. Secondly, particular sub-models and algorithms for simulating the behaviour of pollutants and sediments within an urban drainage system are detailed. Definition of the elements to be included within the final model form a major part of the "procedural" aspects of the design. Finally, a timetable of the various milestones in the development of the model is also outlined together with future developments of the model integrated within the River Basin Management Programme.

Abbreviations

USWQM	Urban Storm Water Quality Model
COD	Chemical Oxygen Demand
BOD	Biological Oxygen Demand
SS	Suspended Solids
CSO	Combined Sewer Overflow
SSO	Stormwater Sewer Overflow

Models

SWWM3	StormWater Management Model III (US EPA)
QQS	Quality Quantity Simulation (Dorsch Consult)
DR3M-QUAL	United States Geological Survey
SAMBA	Danish quality model
STORM	Storage, Treatment Overflow Runoff Model (US Army Corps)
WASSP-SIM	The Wallingford Procedure - Simulation Programme

CONTENTS

1 INTRODUCTION

Storm overflows have been identified as one of the major causes of poor receiving water quality within the United Kingdom (Clifforde et al., 1986; Crabtree, 1986). Economic constraints, however, dictate that a large number of these overflows will have to remain in operation for the foreseeable future (Ministry of Housing and Local Government, 1970; Scottish Development Department, 1977; Clifforde et al., 1986). Therefore, to limit pollutant discharges from overflows, structural amendments will need to be made to urban drainage systems usually in the form of increased storage. The efficient design of such rehabilitation measures, in order to both limit the receiving water impact as well as the flooding hazard, requires a collection of analytical tools. Presently available tools for considering storm overflow settings and sewer rehabilitation are unable to fulfil this task; see for example the 'Ministry of Health Requirements', 'Formula A', and WASSP-SIM. Hence a rational procedure is required for the design of sewerage rehabilitation structures (Clifforde et al., 1986). This procedure has been defined to consist of four major elements:

(i) appropriate rainfall inputs to sewer flow simulation models;

(ii) a sewer flow quality model;

(iii) a river impact model;

(iv) a comprehensive river classification scheme.

This document details the development of the sewer-flow quality model and its incorporation, together with an existing sewer flow quantity model

(WASSP-SIM; National Water Concil, 1981), into a software package for the analysis of the pollutant behaviour of urban stormwater drainage systems.

The design of software can be viewed in general as a 'top-down' process (Spriet and Vansteenkiste, 1982), in which the design requirements, design specifications and the final implementable program are all derived from an initial definition of the problem to be tackled (Figure 1). It is the customer, in this instance the UK Water Industry represented by the Water Research Centre (WRc), who by examination of the problem provides a detailed design requirement. This should consist of two major parts: the 'functional requirements' describing what the software must be able to do; the 'attributes' of the software constraining how it should operate. Chapter 2 provides a short summary of the requirement specification (Appendix B contains the requirements specified by WRc).

Chapter 3, then, develops the non-procedural design detailing the methodological principles upon which the model itself is founded and the major components of the model. These elements together with the properties of the software identified from the attributes, comprise the 'static' design specification of the software which remains invariant during software development.

The 'dynamic' design specification comprises the actual procedures, and algorithms, which are incorporated into the software. By testing each component individually, if possible, or by testing the overall behaviour of the model, the non-procedural design can be transformed into the 'procedural' design and, then, eventually into a preliminary version of the required software. This, itself, must undergo considerable verification tests to eradicate malfunctions and errors. Chapter 4 details the procedural design phase of this strategy; Appendix A provides an overview of the major functional subroutines within the model and their procedural relationship.

The final chapter, Chapter 5, provides an outline of the development schedule of the program as well as the data requirements necessary for model development. These latter requirements are specified to take into account not only existing data-collection programmes but, also, to recommend either modifications to these programmes or the initiation of new efforts.

2 REQUIREMENT SPECIFICATION FOR THE SEWER QUALITY MODEL

The requirement specification of the sewer quality model has been defined by WRc. These are described within two documents (see Appendix B): one describing the reasons for developing a sewer quality model and the other providing a short functional specification of the model. Distillation of the elements within these documents provide the following requirement specification.

1. Determinands

   Determinands to be simulated are:

   (a) Suspended solids (SS);

   (b) Dissolved oxygen (DO);

   (c) Biological oxygen demand (BOD) or chemical oxygen demand (COD);

(d) Ammoniacal nitrogen (NH_4-N);

(e) Hydrogen sulphide (H_2S);

(f) Sediments - large sediment fractions.

2. Complexity of simulation.

Time-varying pollutant levels are required; that is, the model must be capable of simulating pollutographs. This stipulation dictates that the model must be able to represent the time-varying behaviour of contaminant interaction and transport both upon catchment surfaces and within the sewer system, itself.

3. Verification

The model when used must be capable of producing accurate simulations of both total event loadings and within-event loadings of the various contaminants without the need for parameter calibration. Model verification will consist of the measurement of dry-weather flows and, possibly, sampling of a limited number of pollutant levels as part of an extended flow-survey study. It is conceivable, however, that this exercise may involve the comparison of pollutants/determinands against related variables; for example, suspended solids can be calibrated by the measuring turbidity levels within the runoff. It must be stated at this juncture that this level of calibration is apposite to that currently recommended in the use of comparable modelling procedures and may place a limit on overall model accuracy.

3 THE NON-PROCEDURAL DESIGN SPECIFICATION

The development of a new model for predicting urban sewer water quality is only justified when current models are unable to fulfil the defined modelling purposes adequately. Even if it can be shown that present models are, indeed, inadequate it is important to note that any new model consists of no more than addendums to previously constructed models, or the collection together of previously validated component models. The selection of which models and algorithms to incorporate within the overall model can be divided into two steps within the general modelling process (Figure 3.1). First, a general class of models is selected based on the interaction of theory and practice (largely 'a priori' knowledge). Then having decided on the general methodology to be employed, and employing direct knowledge of the system in question, those subclasses, components and algorithms offering parsimonious solutions to the particular problem (Box and Jenkins, 1970) are identified. Within this document the former step has been designated as the non-procedural design incorporating the static design specifications which will remain largely invariant during the course of model development. The latter step, embodied within the procedural design (Chapter 4), incorporates much of the iterative aspects of the design specification in which competing models and algorithms are selected upon the basis of both 'a priori' validation and 'a posteriori' verification. This chapter considers the selection of a model type given the prescribed requirements specified in the previous chapter (and Appendix B) and the limit of current knowledge of the interactive processes between water, sediment and pollutants within urban catchments and sewerage systems.

3.1 Selection of a model type

In order to select a general class of model for urban runoff pollutant simulation it is necessary to possess a rudimentary classification of model types. Urban runoff models may be distinguished upon a multiple of grounds; foremost amongst these for this discussion are the degree of stochasticity treated by the model, the level of application to which the model is suited (sometimes synonymous with model complexity), and the degree of simplification of the simulation period (that is continuous or event-based modelling). These elements, although highly interrelated, are nevertheless considered separately below.

(a) Stochastic/Deterministic

A general model of catchment behaviour may be portrayed thus:

y (output(s)) = f(input(s), catchment characs, ...) + errors

The functional relation, f(x1,x2, ...) is commonly regarded as the 'function of the determinist' while the error term is the 'function of the statistician' (Clarke, 1973). Typical urban runoff models (SWWM3, WASSP-SIM, ILLUDAS, QQS) are all deterministic models, in that no allowance is made for probabilistic or stochastic influences upon model parameters. However, as a model can not be a perfect representation of reality, then some error will always have to be entertained in the output from a runoff simulation. In the situation where the quantity of urban runoff is being simulated, say for the design of a new pipe system or the analysis of old systems to assess their flooding attributes, magnitudes of errors between observed and simulated results will not be too large (e.g. no more than 10%). However, in the simulation of water quality, by the use of deterministic models, errors are likely to be much greater. Without extensive calibration typical USWQMs have been described as of little use in the prediction of absolute contaminant magnitudes (Huber, 1986). This is a feature of the influence of imperfect knowledge of the behaviour of pollutants within the urban hydrological system, and the influence of seemingly random process operations. Furthermore, the calibration of models such as SWWM3 to a variety of catchments has illustrated the need for specific data with which to define the parameters of the model as well as to select the functional relationships used within the model (Jewell and Adrian, 1981; Huber, 1986). Calibration procedures within this modelling exercise have been restricted to dry weather flow sampling with possibly a small number of samples obtained during wet weather; this is a much more restricted calibration period than that required by the use of SWWM3 and other similar USWQM.

(b) Level of application

It is generally recognised that urban runoff models operate at three levels (McPherson, 1975):

(i) planning level;

(ii) design/analysis level;

(iii) operational level.

The urban runoff quality model will by definition have to operate at the second of these levels thus requiring commensurably more detailed computation than a model that operated at the planning level. Hence, a model similar to SWWM3 (or its ilk) is needed for analysis purposes; models such as STORM and SAMBA (simple planning type models) would not satisfy the design requirements of this exercise. However, the latter group of models are useful in conjunction with more detailed analysis models, especially in highlighting particular events from a long rainfall time-series, which it would be too time-consuming to run through an analysis-type model.

(c) Event/Continuous Simulation

A continuous record of precipitation over a period such as one year or ten years consists of periods of wet and dry-weather; in event-based modelling the model simulates only the processes operative during the course of an event, whereas in continuous simulation the model will operate during both dry and wet-weather periods. In the simulation of flooding in urban catchments, the difference between these two modelling procedures has become enhanced by the nature of the rainfall input. Hence, with event-based simulation of future flooding potential in urban catchments it is common to use a statistical representation of the rainfall record (the well-known intensity duration frequency curve and associated design storms); in continuous simulation the rainfall record is directly input into the model. The assumption in the former approach is that:

urban runoff frequency = rainfall frequency

This equivalence is sometimes 'forced' to take into account the probabilistic nature of antecedent conditions and their resultant influence upon rainfall excess determination; but is nevertheless the overriding doctrine in conventional urban runoff simulation. Within continuous simulation no such assumption is made; however, considerably more effort is expended in obtaining an estimate of flooding behaviour suitable for design purposes. Furthermore, it has never been proved that the above assumption is significantly incorrect for the prediction of flood levels.

However, for the prediction of the polluting effect of SSO discharges upon receiving streams **it is clear that the use of traditional event-based modelling incorporating design-storms is inappropriate.** Primary amongst the reasons for this assertion are:

1. Although data sources are limited and as of yet there is no long time series of rainfall, runoff and urban water-quality, evidence does suggest that the magnitude-frequency relationships of urban pollutant discharge bears little relationship to the magnitude frequency relationships of rainfall or runoff (Huber, 1986). Added to this is the recognition that the magnitude-frequency relations of individual pollutants will be different (Geiger, 1986); that is, different storms will produce the critical event for different pollutants. This reflects the varying influence of antecedent periods upon the behaviour of each pollutant.

2. The magnitude-frequency relationships of receiving water behaviour will not in general be related to those of the incident rainfall employed within urban runoff simulation. It is true that the pollutional response of small rivers will be dominated by the behaviour of the discharging outfall; for larger rivers behaviour will be a

combined effect of river and catchment response.

3. Pollution events occurring within some receiving waters may be occurring a number of times per year; this is not commensurate with the return period of design storms used for flooding prediction.

4. Although the primary focus of this procedure is to aid the amelioration of short term effects upon receiving waters, longer-term effects arising from SSO discharges may become an important consideration in future scenarios; it would appear appropriate that the capability must exist to simulate the influence of pollutants that are accumulative within the receiving water.

These considerations indicate that the sewer quality model must explicitly consider the influence of the antecedent period. This effect can be considered either by the use of a continuous simulation model or the use of an event model with simple antecedent indices. Unfortunately, the definition of appropriate antecedent indices with significant explanatory power to describe the build-up of pollutants within an urban drainage system would appear difficult to achieve; the use of a continuous simulation model in this case would seem warranted. However, to simulate a long-term series of rainfall events will undoubtedly be prohibitive in terms of computational costs. A procedure for reducing these costs has been advocated elsewhere (Harremoes et al., 1984); the technique consists essentially of running a long rainfall time-series through either a simpler model (a planning model) or through a simplified representation of the sewer system itself, identifying those events/periods of rainfall that lead to potential design problems, and, then, run these events/periods of rainfall through a more complex model with appropriately defined antecedent conditions to produce results amenable for the re-design of a system. Figure 3.2 compares this approach with the more traditional design storm methodology.

3.2 The non-procedural design

The following paragraphs provide a detailed specification of the non-procedural aspects of the sewer quality model divided into the functional specifications and the attributes of the software.

(a) Functional Specifications

It is apparent from the foregoing discussion that the sewer quality model will have a number of properties:

1. The ability to simulate both the stochastic and deterministic behaviour of all the pollutants considered in the design specification.

2. The ability to operate in a continuous fashion in order to simulate pollutant discharges derived from urban sewer systems over a wide variety of time periods.

3. The ability to simulate pollutant behaviour within an urban catchment from a planning aspect in order to identify critical pollution events generated by the rainfall time-series, and from a more precise design aspect to aid in the assessment of various sewer rehabilitation structures.

Appendix B provides greater detail of some of the functional specifications of the sewer quality model. In concept the model will operate on two levels: a screening-level, where the complex geometry of the sewer system is dramatically simplified, analogous to the 'sewered sub-area' model currently incorporated within WASSP-SIM; a design-level, which operates over a period encompassing a 'pollution event', as defined in the description below. In both instances it is envisaged that a form of error analysis will be employed to characterise uncertainties in pollutant simulation; a first-order error error analysis will be employed for these purposes. Use of these procedures within 'design mode' will enable the engineer to assign probabilistic risks to his/her rehabilitation scheme.

As intimated above, the definition of a critical pollution event will not be achieved by the use of the sewer quality model alone. Sewer rehabiltitation for controlling pollutant discharges will be assessed in terms of critical pollutant events within the receiving water. Not only will these events not be related to rainfall event frequency, but individual rainfall events may not be necessarily associated with individual pollution events. Temporal response within the receiving water may be such that a number of individual rainfall events may cause, by accumulative effects over a short period, pollutant events within the receiving water. This dictates that the planning model of the sewer quality model will have to be run to provide input to the river impact model. Identified pollution events will be assessed in terms of a short-term receiving water criteria. Critical events are then used to assess the relative performance of different rehabilitation measures again in terms of receiving water impacts.

(b) Attributes of the software

The need to ensure ready access by drainage engineers to the software dictates that the primary hardware environment in which the software should be employed is the micro-computer or workstation as opposed to the mainframe environment. Although, the computing power of the former has increased dramatically over the years, and will no doubt continue to do so, it is still envisaged that computer run-time, and hence computing costs, will be a major constraint. This is again a reason for dividing the modelling procedure into a first-level screening approach and a second-level design approach. However, the use of micro-computer systems does enable a greater deal of flexibility in the use of graphics and interactive input-output procedures. These aspects are particularly important in order to ease the use of the model as a number of concepts contained within the model will, in general, be new to the engineer. Specific details of the software specification are detailed below:

(i) Hardware requirements

The program will be specifically aimed at the micro-computer and workstation environment. Specific machines upon which its use will be recommended are the Intel 80286 range of micro-computers with a maths co-processor (IBM-PC/AT and compatibles; Apricot XEN's) operating within DOS; workstations including the Apollo Domain series, Micro-VAX II, and Sun workstations operating either as DOS-workalikes or within a UNIX-based system. In each case a hard-disk storage of at least 10Mbytes will be required together with a printer and a mouse (optional). There is a strong possibility that as machines based on the Intel 80386 processor become more widely used, these machines will be preferable to machines with the 80286 processor.

(ii) Display layouts and report layouts

Displays will in general follow the format associated with current software (e.g. WASSP) and future released software (e.g. WALLRUS and SPIDA). Specific displays relevant to the water quality software will involve the input of various factors associated with each pollutant simulated by the model. This will be achieved by the use of a spread-sheet type approach; associated with each element of the spread-sheet will be a help-screen containing the default values and a range of likely values for the parameters to be entered.

Results will be placed into a file in a similar format to depth and discharge data as produced currently by WASSP; it will also be possible to plot out data for comparison with observed pollutant data and to analyse computed results in terms of critical events likely to cause damage to the receiving water ecosystem.

(iii) Error handling

In general, errors in data-input should be trapped before passage to the major part of the software utilising a check program similar to that currently used by WASSP. Other errors, such as using too large a time-step for simulation and unreasonable input parameter values, will be accounted for by the use of specific ranges for these parameters above or below which data will not be allowed to be input. Help-screens associated with each parameter value will give guidance as to the likely range of values.

4 THE PROCEDURAL DESIGN SPECIFICATION

4.1 Introduction

It has been identified that a mixed deterministic-stochastic approach to modelling stormwater quality runoff from urban catchments is appropriate. Furthermore, for practical purposes it will be desirable to operate the model in both a long-term and a short-term mode. This chapter details the individual components to be included within the final model to fulfil both the design requirements of the UK Water Industry (Chapter 2 and Appendix B) and to follow the general methodology introduced in Chapter 3.

In order to characterise the response of a variety of sewer systems adequately, an urban water quality model must be formed from a set of component models. Within urban catchments two major component models can be recognised, one representing the accumulation, generation and transport of pollutants upon catchment surfaces, the other representing the behaviour of pollutants within the sewer system. Within the sewer system pollutants are obtained from both the foul-water flow (in the case of combined sewer systems) and from the sediments deposited within the pipe-network, which takes place during both dry-weather periods and during falling stages of a stormwater hydrograph. The basic principle in simulating outflow discharges from a combined sewer system consists of the amalgamation of these flows by the use of a simple mixing model applied at various nodes within the sewer network (Figure 4.1). The background and specification of the two systems defined above are described here and in Appendix A.

The model as indicated in Chapter 3 will operate on a continuous basis over a period incorporating a collection of individual events. However, it is important to define appropriate initial conditions to operate the model. Furthermore, in running an extended period of rainfall events, it is necessary to simplify either the modelling procedure or the system characteristics to ensure economic model application. These aspects of the water quality model are discussed in later sections of this chapter together with a definition of the treatment of uncertainty in model output predictions associated with both model uncertainties and input-data uncertainties.

4.2 The Surface Sub-System

The surface sub-system is defined to consist of subcatchment surfaces and gully-pots. The behaviour of both sediments and pollutants are simulated within a continuous mass balance framework (Fig 4.2). The model first defines the behaviour of solids (dissolved and suspended) within this system. Pollutants are then related to these solids by simplified means. Particular sub-models within MOSQITO can be related to

(i) Surface accumulation and solids pollutant relationships;

(ii) Removal by surface runoff;

(iii) Behaviour of gully-pots

(i) Surface accumulation and solid pollutant relationships

As stated above the general procedure in simulating the discharge of pollutants from urban catchments is to link their behaviour directly to certain determinands. The determinands used within MOSQITO are

1. Suspended solids;
2. Dissolved solids or individual dissolved pollutants;
3. Dissolved oxygen

No distinct models are used within MOSQITO to represent the accumulation or presence of these determinands. For suspended solids it is generally assumed that there is an unlimited supply of these materials, although a nominal threshold can be applied.

Dissolved solids or pollutants have a fixed initial mass. In the former case, this is comprised of the fixed initial masses of dissolved BOD and NH_4-N.

Dissolved oxygen within runoff is assumed to be at saturation on entry into the storm sewer system and is obtained by using a relationship of the form

$$\begin{aligned} C_{do} = & - 139.34411 + (1.575701 + 10^5/T) \\ & - (6.642308 \times 10^7/T^2) + (1.2438 \times 10^{10}/T^3) \\ & - (8.621949 \times 10^{11}/T^4) \\ & - Chl \times \left[(3.1929 \times 10^{-2}) - (1.929 \times 10^{-2}) - \right. \\ & \left. (1.9428 \times 10/T + (3.8673 \times 10^3/T^2)\right] \qquad (4.1) \end{aligned}$$

where C_{do}, s = saturation level of DO
T = temperature, kelvin
Chl = chlorinity, parts per thousand

The relationship between pollutants (BOD and NH_4-N) and solids on the catchment surface is described by the use of potency factors. In this approach the concentration, or mass, of pollutant i is related to solid k by a fixed ratio, p_{ik}, that is

$$M_i = p_{ik} . M_k \qquad (4.2)$$

where p_{ik} = potency factor between pollutant i and solid k

M_i = mass of pollutant i

M_k = mass of solid k

These factors are input by the model user, although a range of values is to be defined for use in the U.K. This approach is used throughout MOSQITO. However, in other sub-systems solids potency can be variable with respect to time. Potency of solids on catchment surface however is constant and does not vary with respect to time.

(ii) Surface washoff

Removal of solids from the catchment surface is represented within MOSQITO by separate models for the removal of suspended solids (considered to be non-cohesive) and dissolved solids. These two models operate on each surface type defined within a subcatchment; WALLRUS-SIM allows three surface types to be characterised for each subcatchment. The two models incorporated within MOSQITO are described below.

(a) Removal of suspended solids

The removal of suspended solids from catchment surfaces is represented by a modified form of the model first developed by Price and Mance (1978). This model was derived by consideration of mass conservation of suspended solids on a hypothetical 'catchment element' or 'conceptual strip' (Fig 4.4). If M_s is the instantaneous mass of suspended solids per unit area, then the rate of change of M_s with respect to time can be given by

$$\frac{dM_s}{dt} = \text{erosion by raindrop impact } (E_i)$$
$$+ \text{ erosion by overland flow } (E_f)$$
$$- \text{ deposition from overland flow } (D_f)$$
$$- \text{ removal from conceptual strip } (R_s) \qquad (4.3)$$

Each of the terms on the R.H.S of Eq 4.3 can be represented by separate rate equations (Fig 4.3). However, within MOSQITO input of suspended solids from rainwater is assumed to be negligible and thus only four terms are included on the R.H.S of Eq 4.3. The original model was developed to model the total load of suspended solids; the new model has the facility to consider particular size fractions within the particle size distribution.

Specific terms on the R.H.S of Eq 4.3 are

1. Erosion of raindrop impact given by

$$E_i = a_i \, i^{\gamma} \qquad (4.4)$$

where a_i = constant obtained by calibration

$\gamma = 1.5$

2. Erosion by overland flow

$$E_f = a_e \, (\tau - \tau_{ce}) \qquad (4.5)$$

where a_e = constant obtained by calibration

τ = flow shear stress

τ_{ce} = critical shear stress for removal of sediment fraction

3. Deposition from overland flow

$$D_f = a_d (\tau_{cd} - \tau) \tag{4.6}$$

where a_d = constant obtained by calibration

τ_{cd} = critical shear stress for deposition of a sediment fraction

4. Removal from conceptual strip

$$R_s = \frac{M_s q}{Kq + h} \tag{4.7}$$

where q = discharge per unit area over strip

k = linear reservoir storage coefficient

h = depression storage

Thus, the differential equation used for representing suspended solids removal from catchment surfaces is

$$\frac{dM_s}{dt} = a_i i^\gamma + a_e (\tau - \tau_{ce}) - a_d (\tau_{cd} - \tau) - \frac{M_s q}{Kq + h} \tag{4.8}$$

This equation is solved numerically at each time step by use of Euller's method (Chapra and Canale, 1985), that is

$$M_{t + \Delta t} = M_t + \Delta t \text{ (R.H.S of Eq 4.8)} \tag{4.9}$$

where M_t = Mass of suspended sediments per unit area at time t.

Removal from the strips at each time step is then calculated by means of Eq 4.7. Three points with respect to the solution of this model require further clarification.

First, it is possible to define an upper limit or threshold to the amount of sediment removed during a single rain event. The cumulative amount of material removed at each time step is compared against this value, if it exceeds this value then no more erosion is allowed to take place.

Second, the boundary shear stress τ acting on the sediment surface is calculated by

$$\tau = \frac{\rho f V^2}{8} \qquad (4.10)$$

where ρ = density of water

f = Darcy - Weisbach friction due to grain resistance

V = flow velocity

Values of f are obtained by assuming laminar overland flow conditions over rough surfaces (Woolhiser, 1976) and are set up within the model.

Third, critical shear stresses for erosion and deposition are obtained by interpolation of Shield's curve (Graf, 1970).

(b) Removal of dissolved solids

Dissolved solids are simulated within MOSQITO by a similar model to that used for suspended solids. Again, if M_d is the instantaneous mass of dissolved solids per unit area, then the mass rate is given by

$$\frac{dMd}{dt} = \text{input from rainfall} \quad (I_r)$$

$$+ \text{ diffusion to and from bed } (D_b)$$

$$- \text{ removal from conceptual strip } (R_d) \qquad (4.11)$$

Specific terms on the R.H.S of the above equations are:-

1. Input from rainfall

$$I_r = \frac{-dm_r}{dt} \qquad (4.12)$$

where m_r = mass of dissolved solids in rainfall

Following Price and Mance (1978)

$$\frac{dm_r}{dt} = \frac{m_r i}{t_r i_r} \qquad (4.13)$$

where $t_i i_r$ is some fixed depth of rainfall

m_r is then given by

$$m_r = \bar{m}_r \exp \left\{- \int_o^t \frac{idt}{t_r i_r}\right\} \qquad (4.14)$$

where $\bar{m}_r$ = initial mass of dissolved solids in atmosphere per unit area of surface (Kg).

2. Diffusion to and from bed

Diffusion to and from bed is given by the concentration gradient between the dissolved solids in the bed and those in the water, that is

$$D_b = a_f \ (C_b - C_f) \tag{4.15}$$

where a_f = a diffusion coefficient obtained by calibration

C_b = concentration of dissolved material in bed

C_f = concentration of dissolved material in flow

3. Removal from conceptual strip

$$R_d = \frac{M_d \ q}{Kq + h} \tag{4.16}$$

as before.

Thus the differential equation used for representing dissolved solids removal from catchment surfaces is

$$\frac{d \ M_d}{dt} = a_f \ (C_b - C_f) - \frac{dm_r}{dt} - \frac{M_d \ q}{Kq + h} \tag{4.17}$$

Again, this model is solved over finite time steps using

$$M_{t + \Delta t} = M_t + \Delta t \ (\text{R.H.S of Eq 4.17}) \tag{4.18}$$

(iii) Behaviour of Gully-pots

Gully pots act as storage devices during dry-weather flow conditions. During storm periods these materials are released into the stormwater flow. This behaviour is modelled by considering that each individual gully-pot behaves as a constantly stirred tank reactor. Thus both suspended and dissolved solids concentration within the gully pot are given by

$$\bar{V}_g \frac{dC}{dt} = \text{mass flow into pot } (M_i)$$

$$- \text{ mass flow out of pot } (M_o)$$

$$- \text{ transfer to bed } (T_f)$$

$$+ \text{ transfer from bed } (T_b)$$

$$- \text{ change in volume of water head } (V_{gc}) \qquad (4.19)$$

Individual terms on the R.H.S of Eq 4.19 are given below

1. Mass flow rate into pot

$$M_i = \sum_{j=1}^{3} M_j \qquad (4.20)$$

where M_j = mass flow from surface j of subcatchment contributing to gully-pot.

2. Mass flow out of pot

$$M_o = \left[\overline{C_\ell . Q_o}\right] \qquad (4.21)$$

C_ℓ = concentration of solid within gully-pot liquor

Q_o = discharge from gully-pot

3. Transfer to and from bed

For suspended solids transfer considered in terms of a settling velocity, v_s, and an uplift velocity v_u. Hence,

$$T_f = v_s \bar{C}_\ell \tag{4.22}$$

and

$$T_b = v_u \bar{C}_b \tag{4.23}$$

where C_b = concentration of solid within gully-pot bed.

For dissolved solids a 'diffusion-like' relationship is used

$$T = T_b + T_f = D_g (\bar{C}_b - \bar{C}_f) \tag{4.24}$$

where D_g = a diffusion coefficient

4. Change in volume of water

$$V_c = \bar{C}_\ell . \frac{dVg}{dt} \tag{4.25}$$

where V_g = volume of water in gully pot

However, WALLRUS-SIM does not generally consider the behaviour of individual gully-pots. Hence, in application of MOSQITO a gully density is used to obtain the number of gullies per subcatchment. Equation 4.19 is then applied to a conceptual storage area equal in volume to the sum of all the gullies in the subcatchment.

Dissolved oxygen in the gully-pot at the start of a storm is assumed to be zero, that is, fully anoxic. During the event this level changes in relation to the incoming water and the oxidation of BOD within the gully-pot.

Again similar to catchment surfaces potency factors are applied to both the dissolved and suspended solids in order to represent BOD and NH_4-N behaviour. Although H_2S may be generated in gully-pots by anaerobic digestion of organic matter, it is assumed that no such effect occurs; H_2S is only generated within the below-ground sub-system.

4.3 Sub-surface sub-system

Within this sub-system contaminants originating from surface runoff or from the dry-weather flow become mixed and transported through the drainage system. Also, contaminants will be derived from material which is deposited from both dry- and wet-weather flows. Again, it would appear that the use of a continuous mass balance is the best approach to simulate the various sources of sub-surface contaminant material. This section will detail the method of dealing with foul-water flows and the sediment, associated contaminant material deposited within sewers, and the transport of these materials within the drainage system.

(i) Foul flow simulation

Foul-water flows input into the drainage system are represented in one of two ways

1. As prescribed input hydrographs and associated input pollutographs applied at various nodes within the drainage system.

2. As synthetic hydrographs and pollutographs generated from known trends and periodicities of the foul-water component.

In the latter approach seasonal and diurnal periodicities are represented by sine waves with amplitudes derived from the difference between minimum and maximum values of foul-water flows. Average values, to which these periodicities are applied, are related to subcatchment land-use.

(ii) Sediments in sewers

Sediments accumulated within sewers have been classified into four major types.

Type A - largely inorganic, large particulate matter;

Type B - similar to above but concreted;

Type C - organic, highly mobile fine particulate load;

Type D - cohesive sediments and slime absorbed to sewer walls.

The distribution of these four sediment types within a pipe have been hypothesized to occur as shown in Figure 4.5. It is assumed that Type A deposits behave as non-cohesive sediments, while Types C and D exhibit cohesive behaviour. Within MOSQITO each of these sediment types occupies its own separate store. Removal and emplacement within each store is discussed in Section (iii) below. Type D deposits are fixed to the bed and are not moved during a storm event.

Within each store the total amount of solids is divided as before into dissolved and suspended fractions. Again potency factors are ascribed to each fraction to represent the presence of pollutants. In the case of H_2S although this is generated through time within the sewer it is assumed that the potency factor remains constant. Instead the generation of H_2S is related to the growth of slimes which are assumed to grow linearly until a threshold value is reached and related to flow shear stress. Thus the amount of H_2S present within slimes will also grow linearly.

(iii) Transport sub-system

The transport of the aforementioned determinands is simulated by numerical solution of the one-dimensional advection-dispersion equation, that is

$$\frac{\partial c_i}{\partial t} + U_x \frac{\partial c_i}{\partial x} - \frac{1}{A} \frac{\partial EA}{\partial x} \frac{\partial c_i}{\partial x} = S_i \qquad (4.26)$$

where c_i = concentration of determinant;

x = longitudinal dimension

t = time

U_x = mean flow velocity along dimension x

S_i = summation of source and sink terms for determinand i

E = longitudinal dispersion coefficient.

A = flow cross-sectional area

Within MOSQITO this equation is solved for each determinand in three stages, using a split-operator technique. First, the advection portion of the equation is solved using a method of characteristics developed by Holly and Preissman (1977). Secondly, the dispersion term is solved using either an explicit four-point finite difference scheme, or an implicit Crank-Nicholson finite difference technique. Finally, the transfer terms are solved using a four step Runge-Kulta solution technique. Details of each stage of the solution are provided below.

(a) Solution of advection term

One dimensional advection can be represented by

$$\frac{\partial c_i}{\partial t} + U_x \frac{\partial c_i}{\partial x} = 0 \qquad (4.27)$$

Numerical solutions of this equation have in the past proven problematic due to numerical diffusion associated with standard finite difference techniques (Abbott, 1975). Methods in which the numerical diffusion is controlled to represent actual dispersion of the solids within the flow have been proposed (Koussis, 1983) and relate to the methods developed primarily for flood routing by Cunge (1969) and Price (1986). However, an alternative method based on the representation of Eq 4.27 by two ordinary differential equations (hence, a method of characteristics) has been adopted within MOSQITO. Equation 4.27 can be represented by

$$\frac{dc_i}{dt} = 0 \qquad (4.28)$$

Implying that the concentration of determinand i associated with a parcel of water is invariant along its course. The course of each parcel is defined by the characteristic of Eq 4.27

$$\frac{dx}{dt} = u\ (x,t) \qquad (4.29)$$

Solution of the two ODE's is carried out on a grid (x,t) as shown in Figure 4.11. Within MOSQITO the computational grid is derived from that previously set-up by the flow model, WALLRUS-SIM. Thus it is important to ensure that the solution technique is stable for any given grid. The method described below possesses this attribute.

For a given time-step, three operations are performed at each computational point: first the position of point A is calculated by integration of Eq 4.29; second, the concentration at point A is calculated by interpolation of known values at other computational points; third, the concentration at point A is assigned directly to point N (that is, Eq 4.28 is integrated). These steps are detailed below and are based on the outline provided by Sauvegat (1985).

Integration of Eq 4.29 requires, first, that the velocities are known at each point of the grid (x,t). Within MOSQITO these are derived from discharge values at each computational point (obtained from the flow model, WALLRUS-SIM). In the present version of the model these values are calculated explicitly by calculating a flow area for a certain depth, which is then used with discharge to calculate a mean velocity of flow. However, in later versions it is envisaged that a functional relationship between proportional depth, proportional discharge and proportional flow area will be used, enabling computational speed to be increased. Nevertheless, having established the velocities at each point, it is then possible to calculate the position of point A by use of the following iteratire procedure

$$U_A^{(0)} = U_N$$

$$x_A = x_i - \frac{U_A^{(k-1)} + U_N}{2} \Delta t \quad (4.30)$$

$$U_A^{(k)} = \left[(x_A^{(k)} - x_{i-1}) U_i + (x_i - x_A^{(k)}) U_{i-1} \right]$$

$$/(x_i - x_{i-1})$$

The procedure is repeated k times until the precision of the non-dimensional number $(U^{(k)} \Delta t)/(x_i - x_A^{(k)})$ is sufficient.

The second step involves the calculation of the concentration at point A. This is conventially achieved by interpolation of known values around point A involving three or more known points. However, interpolation using points remote from A introduces numerical oscillations into the solution. Holly and Priessmen (1977) proposed an interpolation scheme using only values at point Q and R to calculate the value at point A. The method uses both the concentration and the derivatives of concentration at each of the two points to form a third-degree interpolating polynomial of the form

$$Y(\alpha) = A\,\alpha^3 + B\,\alpha^2 + D\alpha + E \quad (4.31)$$

in which α is the Courant number defined as

$$\alpha = \frac{U_x \Delta t}{x_{i+1} - x_i} \quad (4.32)$$

The four coefficients A, B, D and E can be evaluated such that the following conditions are satisfied:

$$Y(1) = C_i^j$$

$$Y(0) = C^j_{i+1}$$

$$\dot{Y}(1) = \partial C^j_i / \partial x = (CS)^j_i$$

$$\dot{Y}(0) = \partial C^j_{i+1} / \partial x = (CS)^j_{i+1}$$

where $\overset{\circ}{Y}(\alpha) = dY/dx$

Having evaluated A, B, D and E these may be substituted back into Eq 4.31 to obtain

$$Y(\alpha) = C_A = a_1 C^j_i + a_2 C^j_{i+1} + a_3 CS^j_i + a_4 CS^j_{i+1} \quad (4.34)$$

where $a_1 = \alpha^2 (3 - 2\alpha)$

$a_2 = 1 - a_1$

$a_3 = \alpha^2 (1 - \alpha) (x_{i+1} - x_i)$

$a_4 = -\alpha (1 - \alpha)^2 (x_{i+1} - x_i)$

However, in order for the calculations to proceed beyond the first time step it is necessary to calculate the values CS^j_i and CS^j_{i+1}; at the first time step they are obtained as initial and boundary conditions. The advection of the concentration derivature is accomplished in the same manner as the concentration itself. Differentiation of Eq 4.29 with respect to x gives

$$\frac{d(CS)}{dt} + U_x \frac{d(CS)}{dt} = - CS \frac{du}{dx} \quad (4.35)$$

which may be solved as before by calculating the value of CS at the foot of the characteristic by interpolation, and integration along the characteristic of

$$\frac{d(CS)}{dt} = - CS \frac{du}{dx} \qquad (4.36)$$

The interpolating function for CS may be shown to take the following form (Holly and Preissman, 1977).

$$\dot{Y}(\alpha) = CS_A = b_1 C_i^j + b_2 C_{i+1}^j + b_3 CS_i^j + b_4 CS_{i+1}^j \qquad (4.37)$$

where $b_1 = \alpha (\alpha - 1)/(x_{i+1} - x_i)$

$b_2 = - b_1$

$b_3 = \alpha (\alpha - 1) (3 \alpha - 2)$

$b_4 = (\alpha - 1) (3\alpha - 1)$

Integration of Eq (4.36) can be achieved by use of the trapezium method

$$CS_{i+1}^{j+1} = CS_A \left[1 - \frac{\Delta t}{2} \frac{du}{dx} \Big|_A\right] / \left[1 + \frac{\Delta t}{2} \frac{du}{dx} \Big|_N\right] \qquad (4.38)$$

Since u is assumed to vary linearly over the interval (i, i+1) then du/dx is constant over this interval.

The above scheme is only operative if $\alpha \leqslant 1$ for a given grid. If, however, $\alpha \geqslant 1$ then point A on the characteristic will be situated along segment PQ of the computational grid (Figure 4.11). In this use the values C_{i+1}^{j+1} and CS_{i+1}^{j+1} are calculated from values of C_A

and CT_A, where CT_A is the derivative of concentration with respect to time at point A'. The latter two values are calculated from interpolation of C_i^j and C_i^{j+i}, CT_i^j and CT_i^{j+1}. The calculation proceeds as before. CS_A is determined by using Eq 4.35, that is

$$CT_A + U_A \cdot CS_A = 0 \tag{4.39}$$

This interpolation gives

$$C_A = a_i^1 \; C_i^j + a_2^1 \; C_i^{j+1} + a_3^1 \; CS_i^j + a_4^1 \; CS_i^{j+1} \tag{4.40}$$

and

$$CS_A = \frac{1}{U_A} \left[b_i^1 \; C_i^j + b_2^1 \; C_i^{j+1} + b_3^1 \; CS_i^j + b_4^1 \; C_i^{j+1} \right] \tag{4.41}$$

Point A on the segment PQ is identified by

$$\beta = \frac{t^{j+1} - t_A}{t^{j+1} - t^j} - \frac{1}{\alpha} \leqslant 1 \tag{4.42}$$

As before C_{i+1}^{j+1} and CS_{i+1}^{j+1} are obtained by integration of equations 4.28 and 4.36.

In order to conduct the above solution initial conditions and upstream boundary conditions are required. In MOSQITO it is assumed that the solutions commence from a period of steady flow or slowly varying flow in which it can be assumed that the spatial derivatives of concentration are minimal.

Hence, the model is initialised with concentrations set to those of the dry-weather flow prior to the storm and concentration derivatives set to zero.

For normal flow conditions (that is cases in which surcharging or reversed flows are not present) the solutions presented above for all values of α are operative. When α is less than 1, the calculations for reversed flow conditions can be simply solved with minor alterations to the above procedure. However, the interpolation procedure used when $\alpha \geqslant 1$ requires known values of C_i^{j+1} and CS_i^{j+1} before calculating C_{i+1}^{j+1} and CS_{i+1}^{j+1}. This is only possible to achieve explicitly if the calculation is conducted following the direction of flow from upstream to downstream. Hence, in order to conduct the solutions in reversed or surcharging flows in which the characteristic curves may be reversed, it is possible either to process the characteristic curves by a implicit procedure over the whole network, or to use a grid ensuring that α is always $\leqslant 1$ for these conditions. Within MOSQITO this latter option has been adopted and relates to the grid used by WALLRUS-SIM in these conditions.

In the case of free-surface flow conditions the values of C_i^{j+1} and CS_i^{j+1} constitute the required boundary conditions for $\alpha \geqslant 1$. C_i^{j+1} is obtained from the relationship

$$CS_i^{j+1} = \frac{-1}{U_i^{j+1}} CT_i^{j+1} \qquad (4.43)$$

assuming that

$$CT_i^{j+1} \sim \frac{(C^{j+1} - C_i^j)}{\Delta t}$$

(b) Solution of the dispersion and transfer-terms

If advection were the only operative process of affecting the transport equation (Eq 4.26) then the concentration at point A on Figure 4.11 can be taken as the new concentration at point N, that is C_{i+1}^{j+1}. However, in large combined sewers it is likely, first that processes causing dispersion (mixing) of the determinand are operative, and second processes of transfer (erosion, deposition, diffusion and degradation) are active both within the flow, and between the flow and the sediment bed (where present). Little at present is known of the fundamental behaviour of sediments in sewers, so the specification of this part of the model must be seen as only a preliminary step until results from associated research projects becomes available. The model has been written in a modular fashion to enable these results to be incorporated with little changes at a later stage of model development.

For a system in which dispersion and the various source and sink terms of Eq 4.26 are important, the model solves numerically the following equation

$$\frac{C_{i+1}^{j+1} - C_A}{X_A} - \frac{I}{A}\frac{\partial c}{\partial x}\frac{EA\ \partial c}{\partial x} \tag{4.44}$$

where X_A = distance along characteristic curve from point A to N.

Two alternative methods are used in MOSQITO for solving Eq 4.44. First, when values of E are large (greater than $5m^2s^{-1}$) an implicit solution technique is used. For each computational point along a sewer reach, a linear equation is set-up with appropriate definitions of all the transfers incorporated in S (see below). These equations are then solved by use of matrix methods to obtain the new concentratins at each computational point C_{i+1}^{j+1}.

However, this method is computationally inefficient. An alternative method has also been incorporated within MOSQITO and is generally used. This method is based on an approximation of the dispersion term, that is

$$\frac{\partial}{\partial x}\left(EA\,\frac{\partial c}{\partial x}\right) \sim -\frac{\partial}{\partial x}\left(\frac{EA}{u}\,\frac{\partial c}{\partial t}\right) \qquad (4.45)$$

This allows Eq 4.44 to be solved explicitly thus reducing dramatically the speed of solution. However, the method is only accurate for small values of dispersion ($\leq 5m^2s^{-1}$).

The source and sink term, S, incorporates all the transfers of material both within the flow, within the sediment-bed, and between the flow and the bed. For the three different clases of routed determinands different methods are used to represent term S. These methods are described below under the headings suspended solids transfers, dissolved solids transfers and dissolved oxygen transfers.

1. Suspended solids transfer

Suspended solids within the sewer exhibit a range of behaviours ranging from cohesive to non-cohesive. Within MOSQITO it is assumed that Type A deposits are wholly non-cohesive whereas Type C and D deposits exhibit cohesive behaviour. The source and sink terms associated with each deposit type are described below.

The transfer of Type A deposits to and from the sewer bed is represented by use of the Ackers-White sediment transport equation (Ackers, 1984). The model uses this relationship to obtain the maximum transporting capacity of the flow. If the amount already present in the flow is greater than this value, deposition occurs, if the amount is less than this value and there is sediment on the bed available for entrainment, erosion takes place.

The transfer of types C and D deposits are more complex. First, erosion of both deposits is represented by an uplift velocity. This velocity, ν_u, is derived by calibration. Second, accumulation of type C deposits is represented by a settling velocity, ν_d, which is related to the quiescent still-water settling velicity ν_s (adjusted for hindered settling)

$$\nu_d = \frac{A}{Q} \nu_s \qquad (4.46)$$

where A = flow cross-sectional area

Q = discharge

$$\nu_s = \left(\frac{4gD(SPG-1)}{3C_D}\right)^{\frac{1}{2}} / \left(1 + \frac{1.56C_s}{3}\right)$$

where SPG = specific gravity of solid

C_D = drag coefficient (=1)

C_s = concentration of solid flow

g = acceleration due to gravity

D = diameter of particles

Third, the accumulation of Type D deposits is assumed to be linear through time until a threshold value related to flow shear stress is reached.

2. Dissolved solids transfers

Dissolved solids transfers to and from the sediment bed are represented by a 'diffusion-like' relationship.

$$S = k_d (C_b - C_f) \qquad (4.47)$$

where k_d = a diffusion coefficient

C_b = concentration of dissolved solids in bed

C_f = concentration of dissolved solids in flow

3 Dissolved oxygen transfers

Dissolved oxygen transfers are represented in a similar fashion to those of dissolved solids, except extra terms are required to represent oxygen depletion by reaction with organic matter and reaeration from the sewer atmosphere. In this instance the transfer term is represented by

$$S = k_d(C_f - C_b) + k_a(C_s - C_f) - k_b \cdot C_{BOD} \qquad (4.48)$$

where k_a = reaeration coefficient

$= \left(\frac{D_L U}{d^{3/2}}\right)^{\frac{1}{2}}$

D_L = oxygen diffusivity at 20°C

U = flow velocity

d = flow depth

k_b = rate of oxidation of BOD

C_{BOD} = concentration of BOD in flow

C_s = concentration of oxygen in atmosphere

As stated above the three pollutants linked to solids ($+NH_4$-N, BOD and H_2S) are related by means of potency factors. In this way it is possible within the model to represent the range of transfers depicted in Figs 4.7 to 4.10

4.4 Model Initialisation

The prescription of initial conditions for a model run when using the WALLRUS model is achieved using simple input variables such as the Urban Catchment Wetness Index (UCWI) and a dry weather flow value. In the use of the model outlined above, it will be particularly difficult, if not impossible, to define an analogous index to describe the prior catchment conditions for pollution generation. Hence, as stated within Chapter 3, the model will run continuously over a predefined period of simulation to establish appropriate initial conditions for each particular rainfall event. However, the problem remains of defining the initial conditions prior to the continuous simulation run.

On the catchment surface, it is assumed (Section 4.2) that sediment supply is unimportant in defining runoff pollutant loads, although this still does remain to be proved for catchments within the UK. However, within gully-pots the stored liquor will degrade over a dry period from an initial constituent level similar to that within surface runoff. There is an obvious problem in defining the level of accumulated pollutants prior to a model run. For this reason a single model run should incorporate at least one event, inconsequential in terms of its effect upon the receiving water, prior to the event or set of events of major interest. This will enable the surface sub-system to be initialised.

Two aspects of the below-surface sub-system require initialisation. Firstly, the foul-water flow; this is accomplished utilising the model described in ouline in Section 4.3. Secondly, defining the depths of sediment and associated pollution accumulations within pipe sections, ancillaries and various 'dead-zones' (sites of preferential deposition within the sewer system). Limited research suggests that of the sediment types within sewers (see classification within Section 4.3), types C and D are relatively impermanent and accumulate between events from an initially low level. This would suggest that initialisation of these sediment types can be achieved by the use of the 'prior minor-event' methodology introduced above. However, in the case of sediment types A, B and E accumulation will reflect the prior history of a multiple succession of events.

Type B deposits will be assumed to be permanent during any particular model run. Depths of these sediments can be based upon a measurement exercise. This could involve, for example, the classification of pipe-lengths upon the basis of shear-stress/shear velocity using a WASSP model; selection of a number of accessible pipe-lengths within each classification category; and the visual identification of sediments within manholes and near manhole pipe-lengths.

The initialisation of Type A deposits is however more problematic. These sediments are capable of motion but will accumulate over a time-period encompassing a number of runoff events. Hence, the depth of Type A deposits during a particular monitoring exercise will reflect the history of events prior to this period, which will not be generally indicative of depths prior to the events of interest in simulation unless it is assumed that the depth of these sediments oscillates around some mean value. Nevertheless, occasional monitoring of these sediments during the flow survey stage of a rehabilitaion scheme will aid in the verification of the model for a particular application. Two alternative hypotheses may be put forward for initialising these sediment types within a model run.

First, it is assumed that sewer sediments build up to an equilibrium level; this level is obviously dependent upon the hydraulic characteristics of the pipe. Simple surveys as described above will also aid in the definition of this level. Initialisation then simply consists of starting the simulation run with these values associated with particular pipe-classes.

Second, within a time-series of rainfall events input into the model there will be a small number of larger events which remove virtually all mobile sediments.

This may be described as the n-year event. If it is assumed that such an event occurs before a simulation run, then the system can be assumed to be bereft of sediment types A, C and D. The continuous simulation run would then operate over a period of n-years extent utilising a simplified model of the catchment's behaviour.

Accumulation within tanks (Type E sediments) and dead-zones will again reflect the prior sequence of events. In these circumstances it is less easy to visualise the occurrence of a critical flushing event. It may be more appropriate, therefore, to consider that these sediments build-up over a period to an equilibrium level. This level could be determined by using the maximum level observed over the period of a short-term flow survey within relatively accessible regions within the sewer system.

However, these are only hypotheses at present and require testing during the course of model development and as part of the research projects under the aegis of the River Basin Management programme (Clifforde et al., 1986)

4.5 Model simplification

In order to generate a long time-series of pollutant discharges from an urban drainage system, the model will be capable of simulation using a simplified geometric representation of the system. For this purpose a complementary hydrological model is being developed (an updated version of the 'Sewered Sub-Area' model currently within WASSP) to simulate flow discharge from such areas; pollutant discharge is simulated similarly in each case whether the system is simplified or not.

However, in the use of a simplified system associated with a long continuous time-series run, spatial steps and time-steps will be generally larger than those required to ensure stability of the explicit finite difference techniques used for solution of the pollutant transport equations. Two alternative solution techniques are available for overcoming this problem. Firstly, instead of using an Eulerion approach in solution, a Lagrangian approach can be employed (known as a 'plug-flow' approach within chemical engineering) as is used in such models as QQS; or, secondly, the advection-diffusion wave equation can be integrated if it is assumed over the duration of the solutional time-step that certain coefficients remain constant (Medina et al., 1981). Of the two approaches, the latter would appear the most useful as it is similar in concept to the finite-difference technique in application. The accuracy of this scheme will need to be assessed.

Yet it must be noted that neither of these approaches are as accurate as the finite-difference solution, which itself is not a perfect solution of the pollutant transport processes. Consequently, it is useful to consider the potential model errors that may arise in order to provide a confidence level to output predictions.

4.6 Representation of model prediction uncertainty

Uncertainty associated with an output prediction is a general problem associated with the use of all forms of simulation model. These uncertainties may arise from a number of causes generally classified into model uncertainties and input-data uncertainties (Burges and Lettanmaier, 1975). Methods of representing uncertainty within simulation models have been developed based on the recasting of deterministic differential equations into their stochastic counterparts. The solution of these equations involve the use of Monte-Carlo Analysis or direct solution by numerical procedures. Both of these techniques have disadvantages for use with this particular modelling exercise: whereas the former approach is too uneconomic in terms of computational expense for routine operation, the latter, solution of stochastic differential equations by numerical techniques, appears intractable for the complex system representing the behaviour of urban drainage systems.

An alternative technique, therefore, is the use of First Order Error Analysis. Although this approach is relatively straightforward to implement and use it does suffer from a number of quite serious drawbacks (Gardner and O'Neill, 1983). Nevertheless, the procedure will be used within the model to allow the user to allocate confidence limits to predictions made by the model.

4.7 Input data associated with model use

Input data associated with model use can be divided into two major types: first, time-varying input data, such as dry-weather flow quantity and quality; secondly, input parameters associated with specific subcatchments, surfaces, pipe elements or sewer ancillaries, which control the behaviour of particular sub-models within the overall model. This latter type of data will, in general, be time-invariant.

(a) Time-varying input data

As indicated above the major form of time-varying input data, other than those already used by WASSP, within the model will be the variation of dry-weather flow quality. The structure of the input data records will broadly mirror those already utilised within such models as WASSP and SPIDA. It will also be possible, similar to WASSP, to utilise input hydrographs and pollutographs in order to facilitate the modelling of exceptionally large and complex drainage systems, although this practice will be advised against for water quality simulation.

This input data may be used in two ways within the overrall modelling procedure. Either as a direct input of dry-weather flow or alternatively it can be used to calibrate a model of dry weather flow variation. This model, as described previously, will utilise 'end-of'pipe' foul-water flow values together with the distribution of land-uses within the catchment in order to derive inputs of dry-weather flow at specific node-points within the drainage system.

Finally with regard to rainfall data, it must be re-emphasised that design storms will not be used with this procedure. A rainfall time-series following the outline of the series defined by WRc will be the primary source of input rainfall data for prediction purposes; for verfication of model behaviour on individual catchments observed hyetographs will be required, as is the case with the use of WASSP.

(b) Time-invariant input data.

Specific input parameters will be associated with each of the program modules described in Sections 4.2 and 4.3. Although a full description of the parameters necessary as input for utilising the model is not yet possible, it is possible to list certain values following the format of the modules defined above.

(i) Surface module

The major set of input parameters for use within the surface module consist of the potency factors for different sediment fractions. Default values will be supplied within the program, but the user will have the option to override these values in order to aid verification of a particular application model. Other input parameters, defining the behaviour of the surface module may become necessary to define the mass of material available for removal by surface runoff.

(ii) Below-surface module

Parameter inputs for this module may be divided into those used within the foul-flow simulation model and those used within the in-sewer flow model.

In the use of the foul-flow model input parameters will be required to describe catchment population and land-use, and potency factors associated with foul-flow sediments. These latter values and the variations in dry-weather flow values will generally, however, be obtained by the use of input dry-weather flow data.

In the use of the in-sewer flow model parameters will be required to describe the amount of sediments present within the sewer before a simulation run, as described in section 4.4. Other input parameters will be the potency factors for these sediments, the degradation rates of certain pollutants within a sewer, and certain parameters associated with the use of sediment transport equations.

5 PROGRAM DEVELOPMENT SCHEDULE

Figure 5.1 illustrates the development of MOSQITO during the period Autumn 1986 to Spring 1988. The model has been developed in two major phases.

First, a suspended solids model for separately sewered surface water systems has been developed. This has undergone calibration on data obtained from three urban catchments within the UK:-

(i) Clifton Grove, Nottingham

(ii) Shephall, Stevenage

(iii) Chelmsley Wood, Birmingham

Secondly, a prototype combined systems model has been produced and preliminary testing has been conducted on two urban catchments with combined urban drainage systems:-

(i) Great Harwood, Accrington

(ii) Higham Ferrers, Northampton

Calibration and testing of the first version of MOSQITO is to proceed during the coming year with a provisional release date of the software to the engineering community of April 1989. The work involved has been divided into three major areas.

First, continued calibration of the above ground phase of the model. Data relating to washoff from individual catchment surfaces has recently become available, as well as data from another separately sewered catchment. This data will allow more refined calibration studies of the above-ground elements of the model to be conducted and will help in the extension of the model to other determinands such as heavy metals.

Secondly, the below-ground aspects of the model are to be tested and improved. A number of individual research projects coordinated by the 'Sediments in Sewers' Subcommittee of the River Basin Management Programme are contributing both physical insights into the behaviour of sediments and pollutants within this environment, and data with which to calibrate particular aspects of the model. These projects will also aid the in the further development of the Wallingford Procedure[4] to consider more explicitly the influence of sewer-sediments on hydraulic behaviour.

Finally, the Water Research Centre together with staff from Manchester University and the North West Water Authority, will be shortly instigating an investigation to assess the sensitivity of predictions derived from MOSQITO to input data requirements. This will help to define an operational procedure for the use of MOSQITO in sewer rehabilitation studies and in river basin management and planning.

Future developments of the model are related to its extension to consider other determinands such as bacterial and toxics such as heavy metals, and a better consideration of both the pollutants and hydraulic consequences of sediments in sewers. These two major elements of research will contribute to an enhanced version of the model which is to be released prior to 1991. Furthermore, the model is also to be adapted so as to be applicable to both looped urban drainage systems (thus making it suitable for use overseas) and riverine environments in order to act as a river-impact model.

6 REFERENCES

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FIGURES.

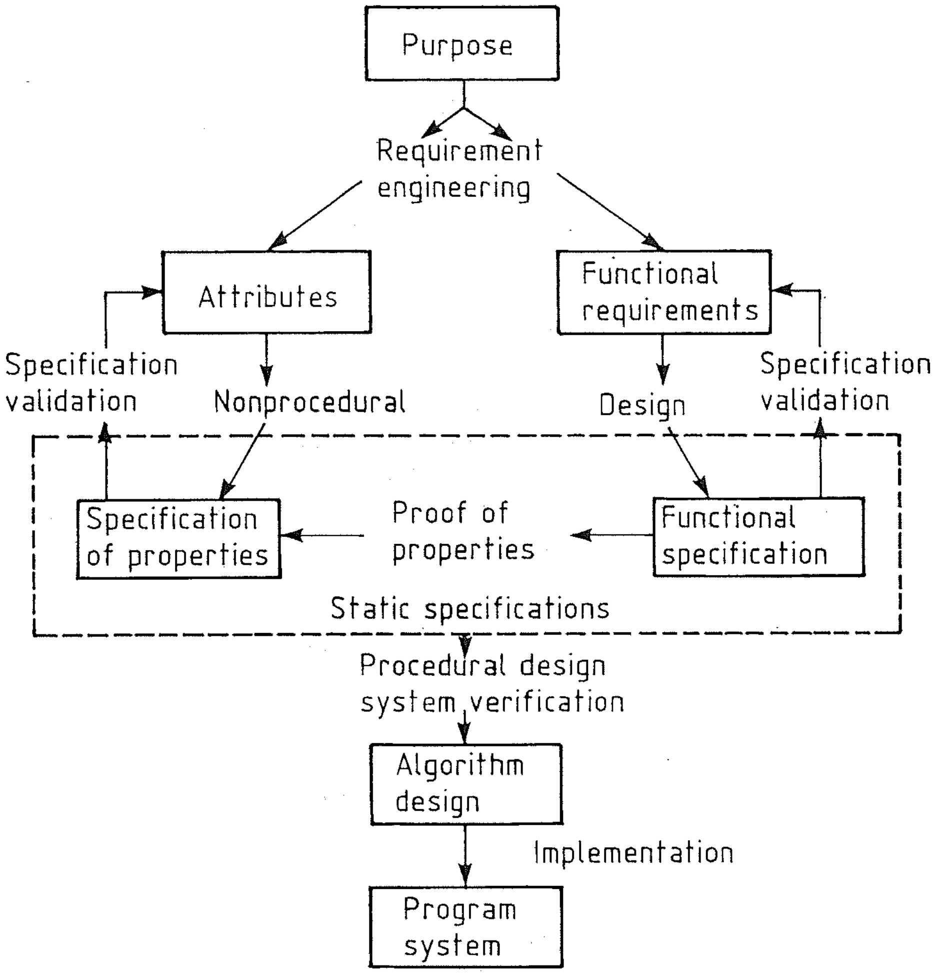


Fig 1 Hierarchical software design methodology
(from Spriet & Vansteenkiste, 1982)

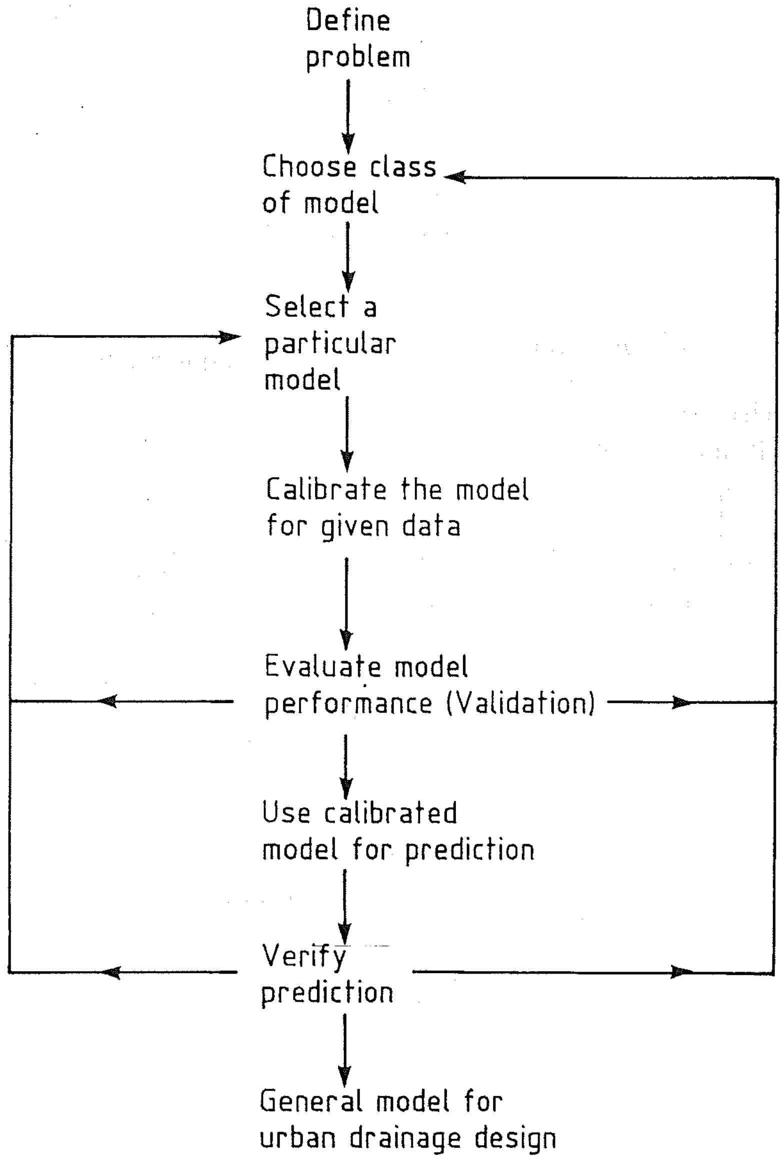


Fig 3.1 The modelling process (adapted from Box & Jenkins 1970)

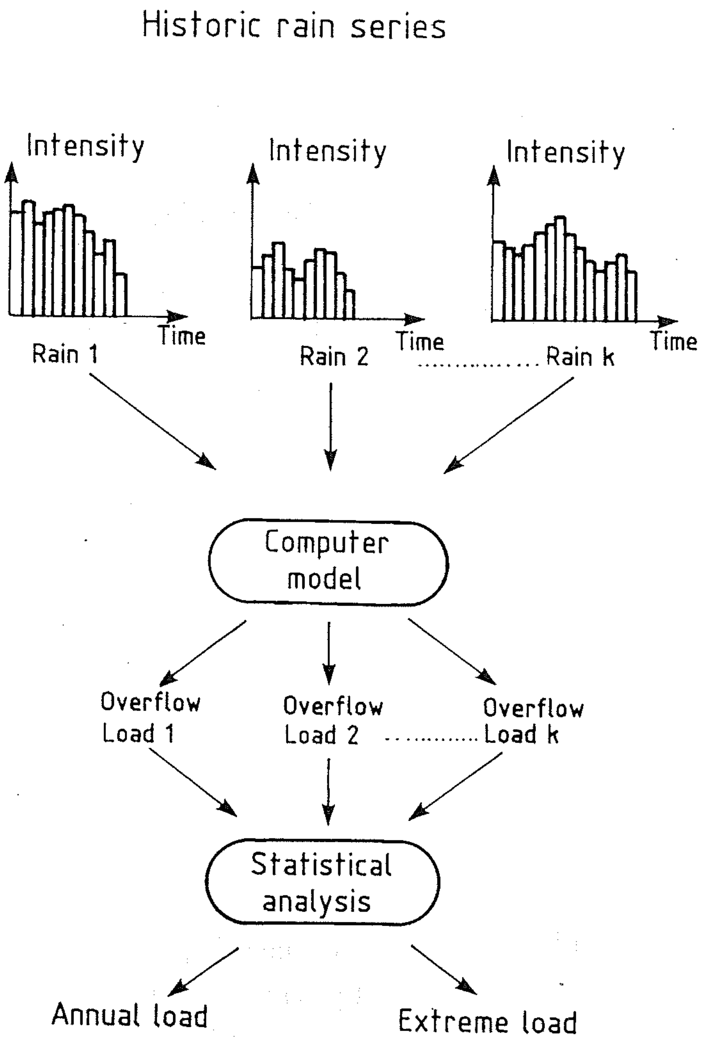
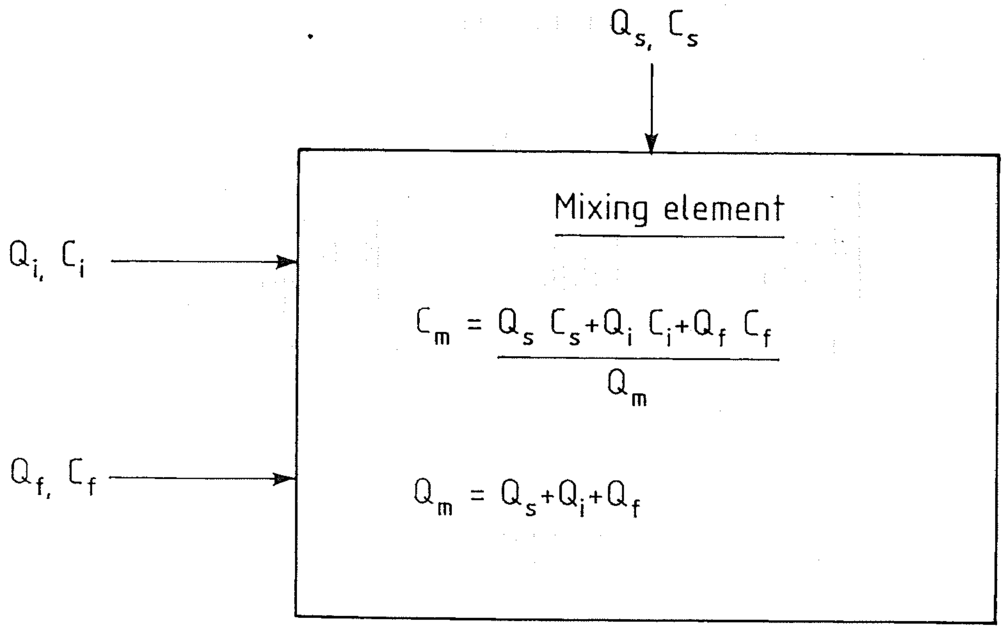


Fig 3.2 Principles of the historical rain-series approach (from Harremces et al 1984)



Subscript s = stormwater
i = upstream inflow
f = foul-water

Q = discharge, C = contaminant concentration

Fig 4.1 Mixing element applied at network nodes

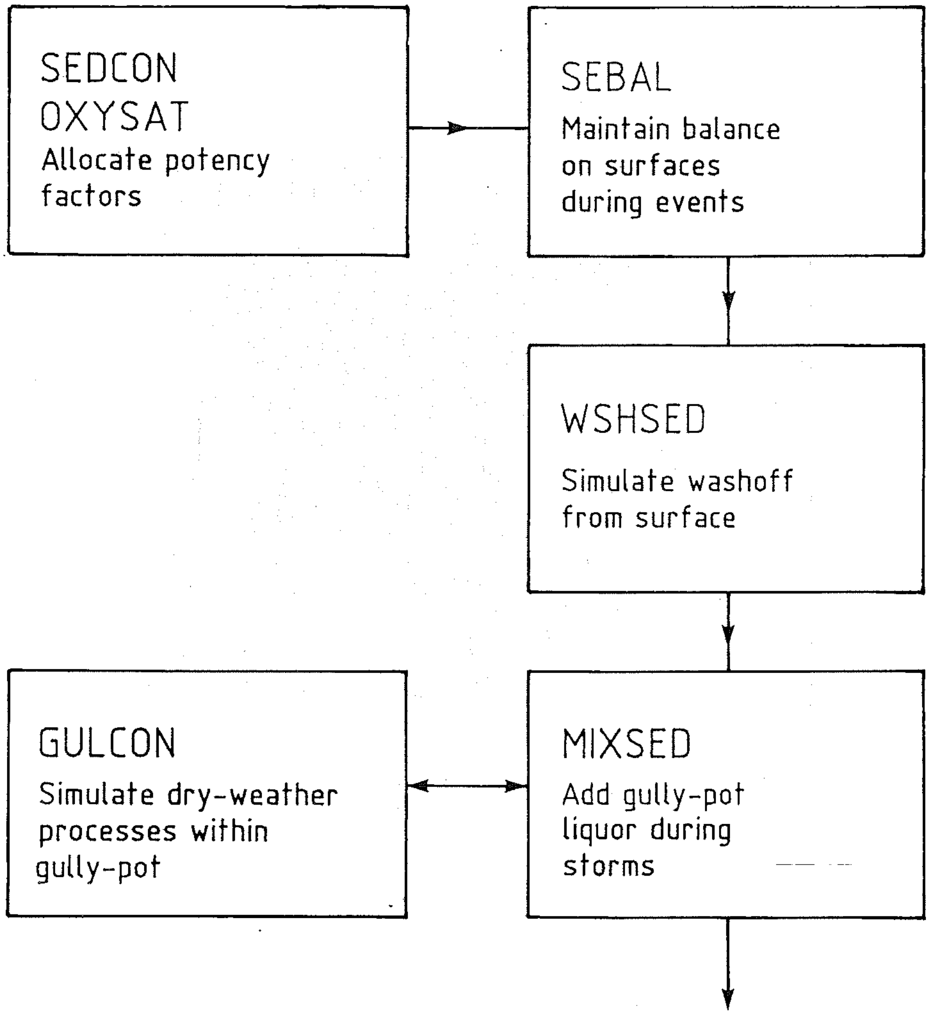


Fig 4.2 Surface-system contaminant model

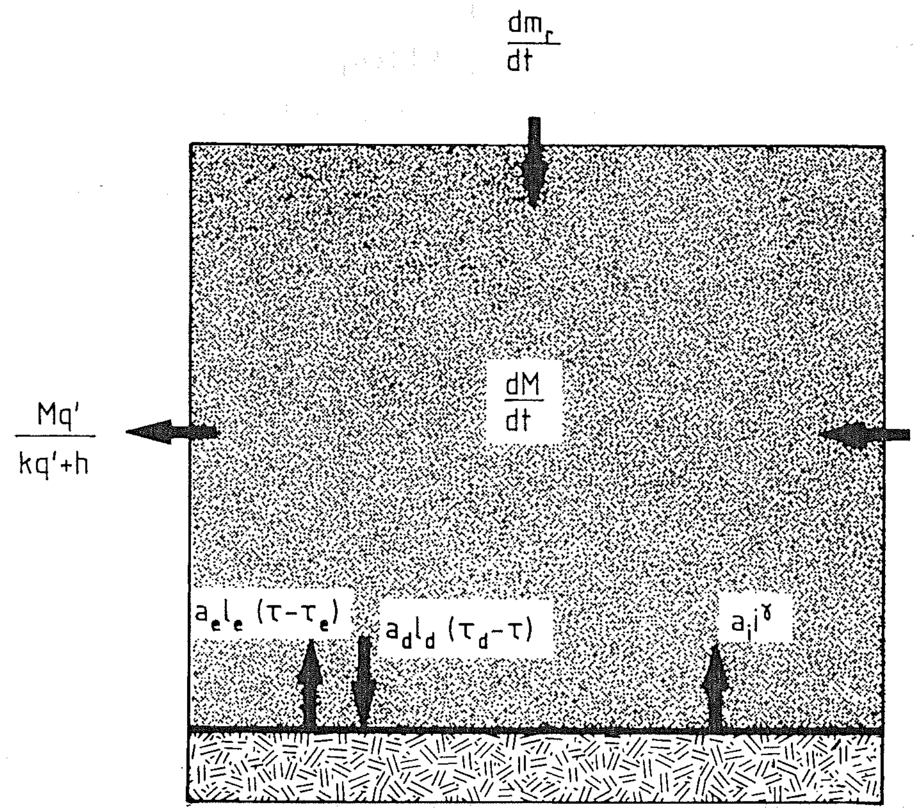


Fig 4.3 Overview of Price and Mance model

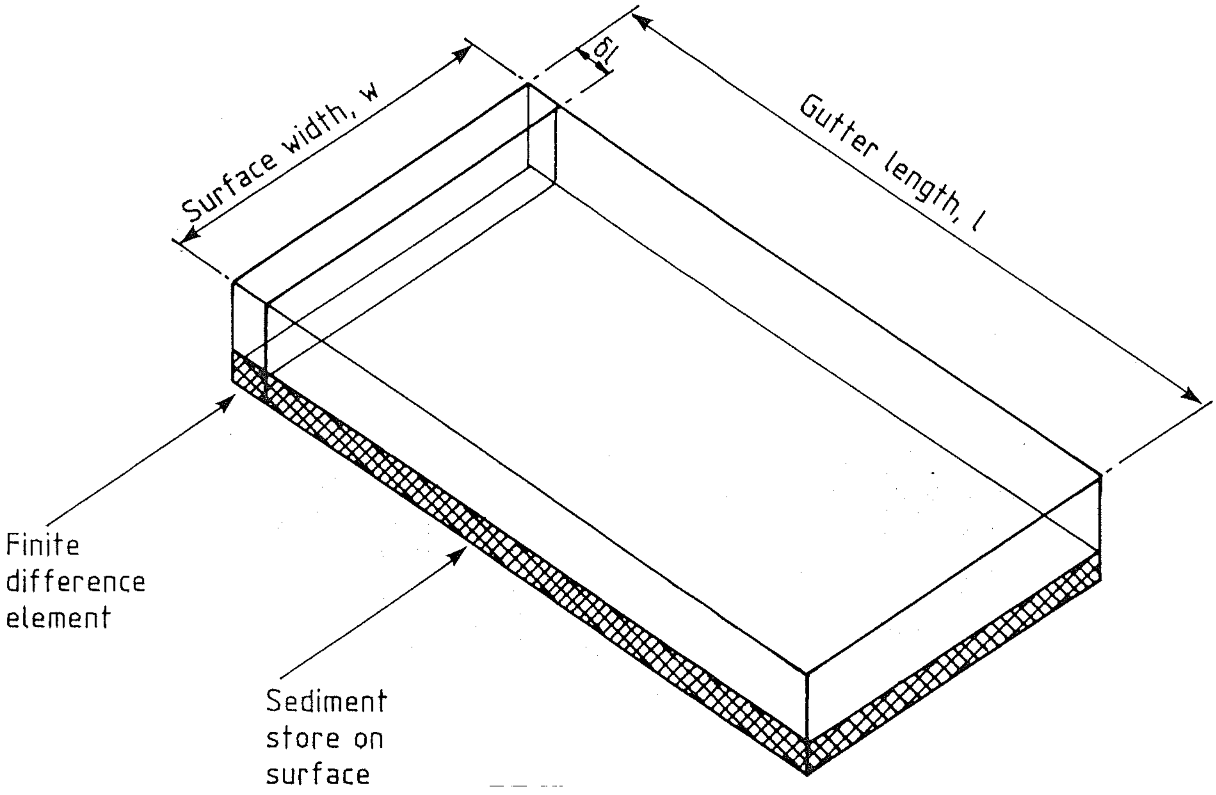


Fig 4.4 A hypothetical catchment element

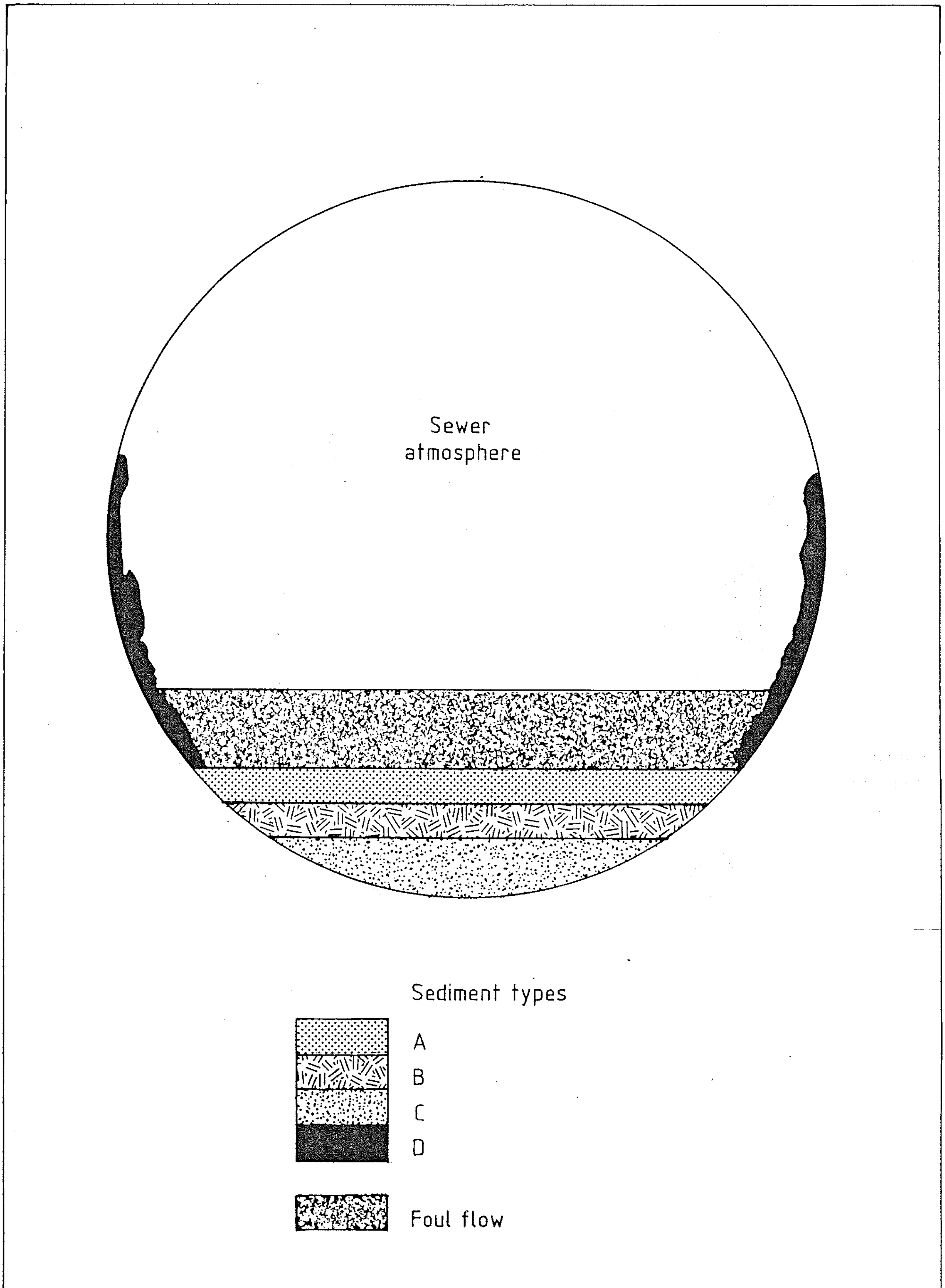


Fig 4.5 Location of sediment types

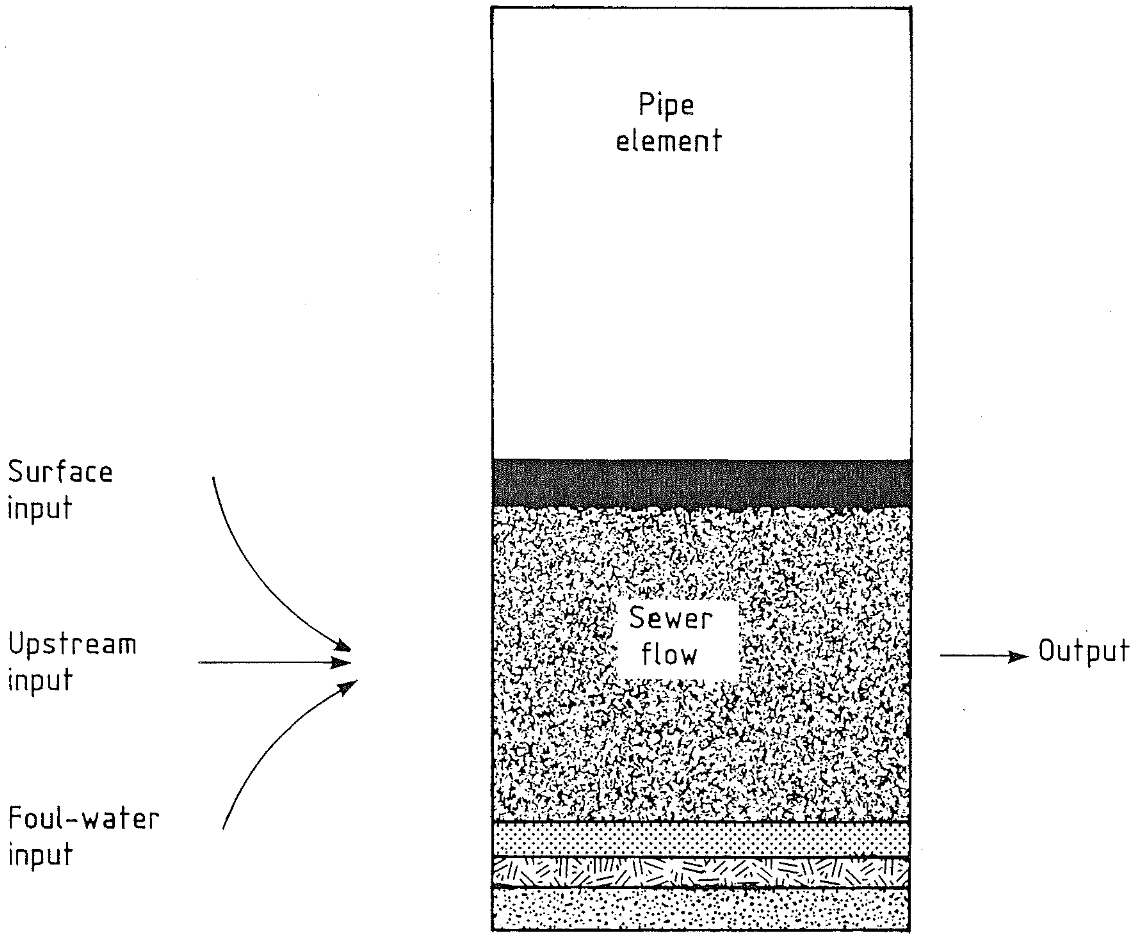


Fig 4.6 Basic 'pipe element' (Key as in Fig 4.5)

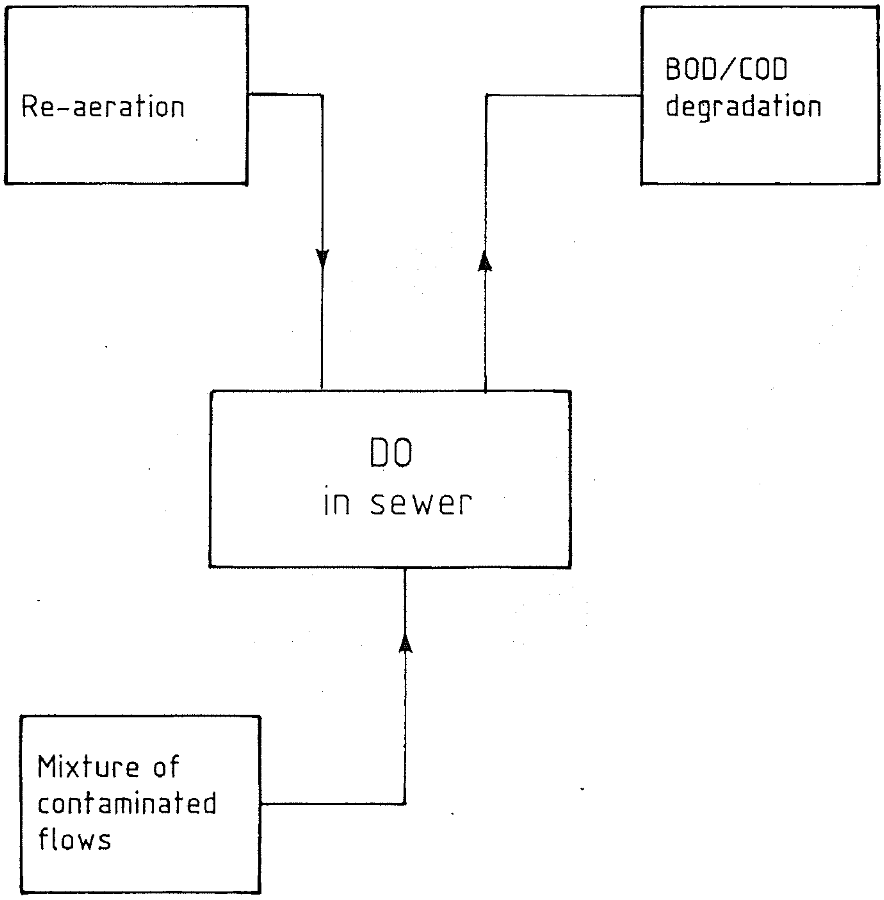


Fig 4.7 Simulation of DO in sewer

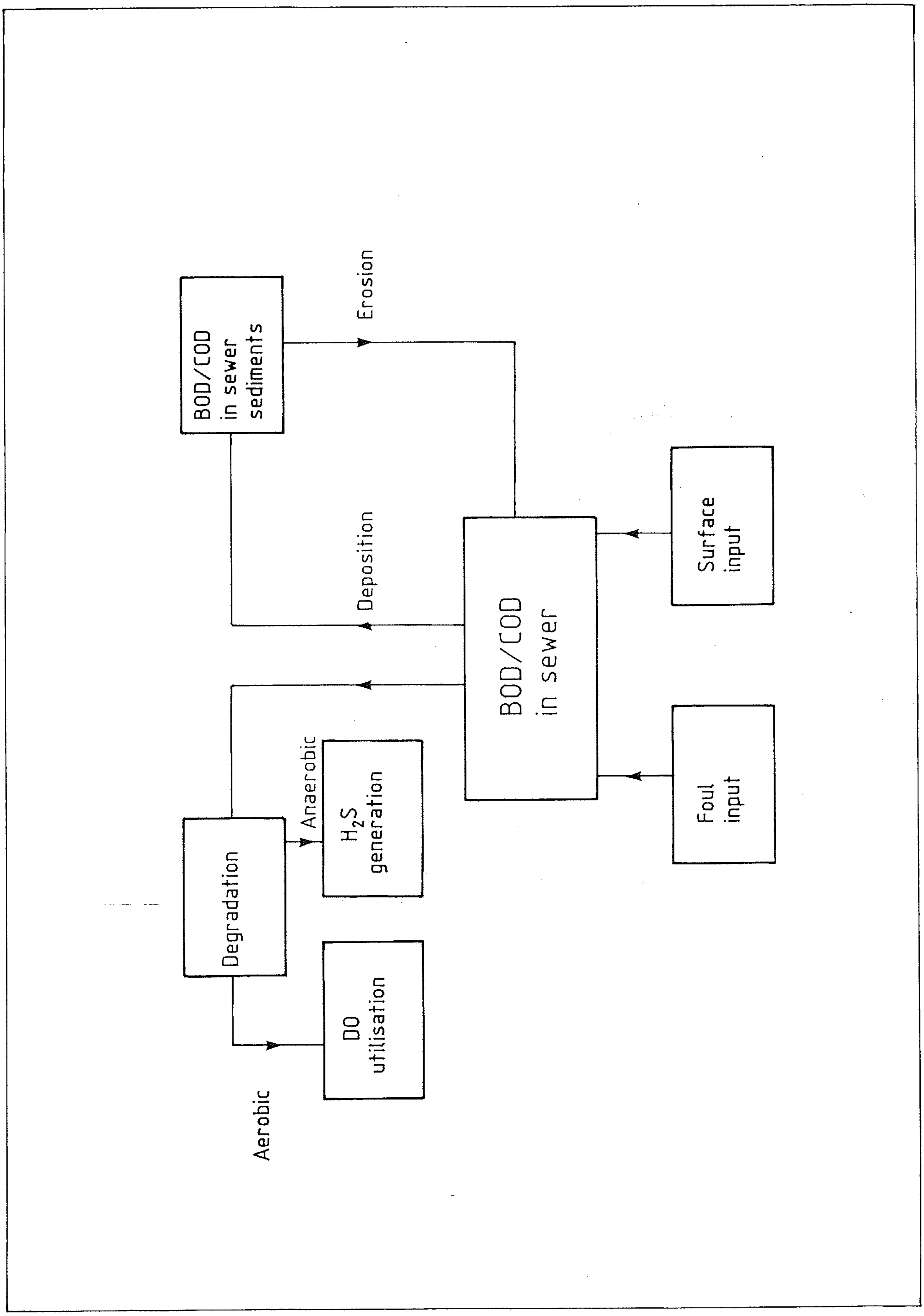


Fig 4.8 Simulation of BOD/COD in sewer

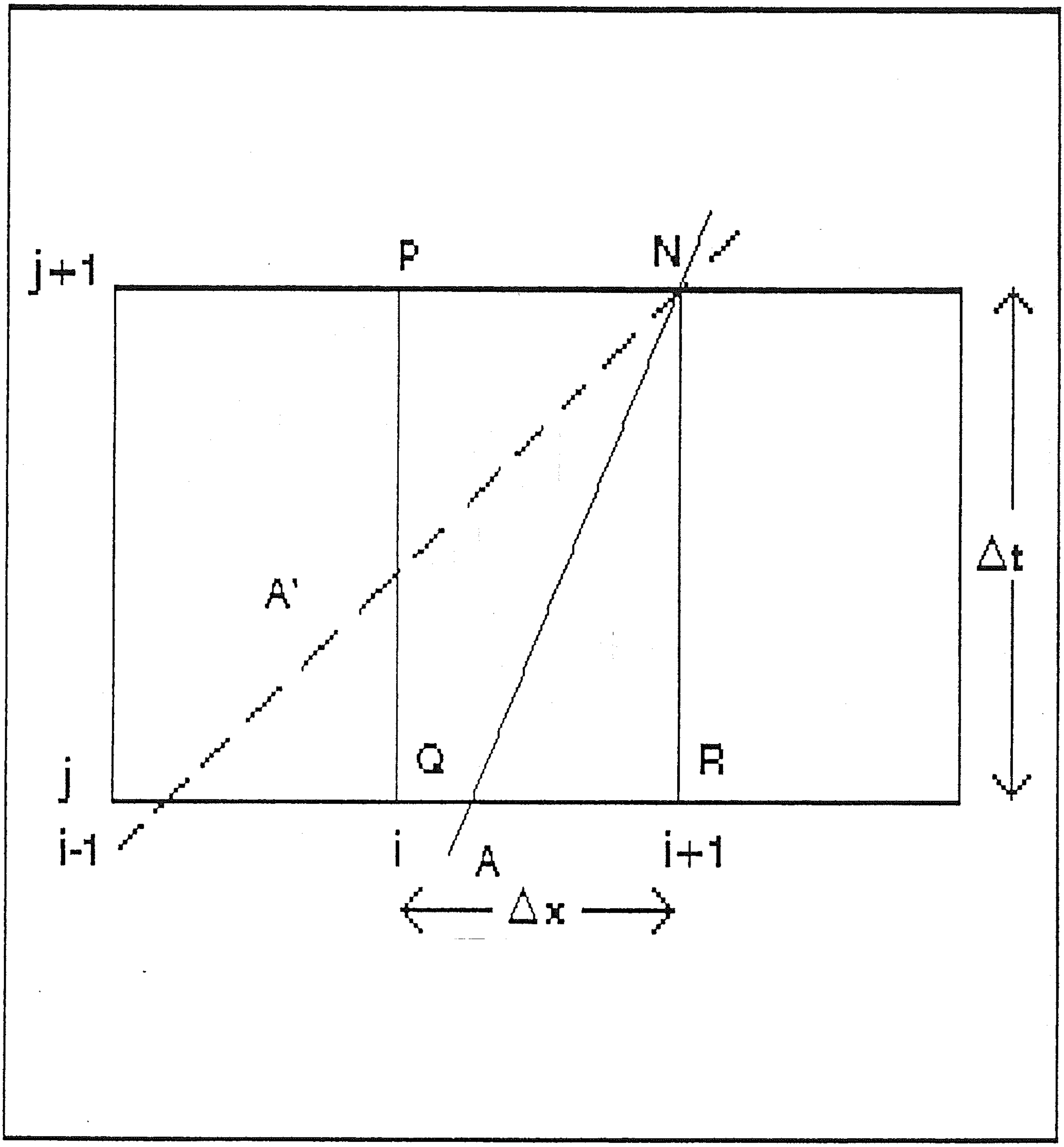


Fig 4.11 Computational grid for the Holly-Preissman method

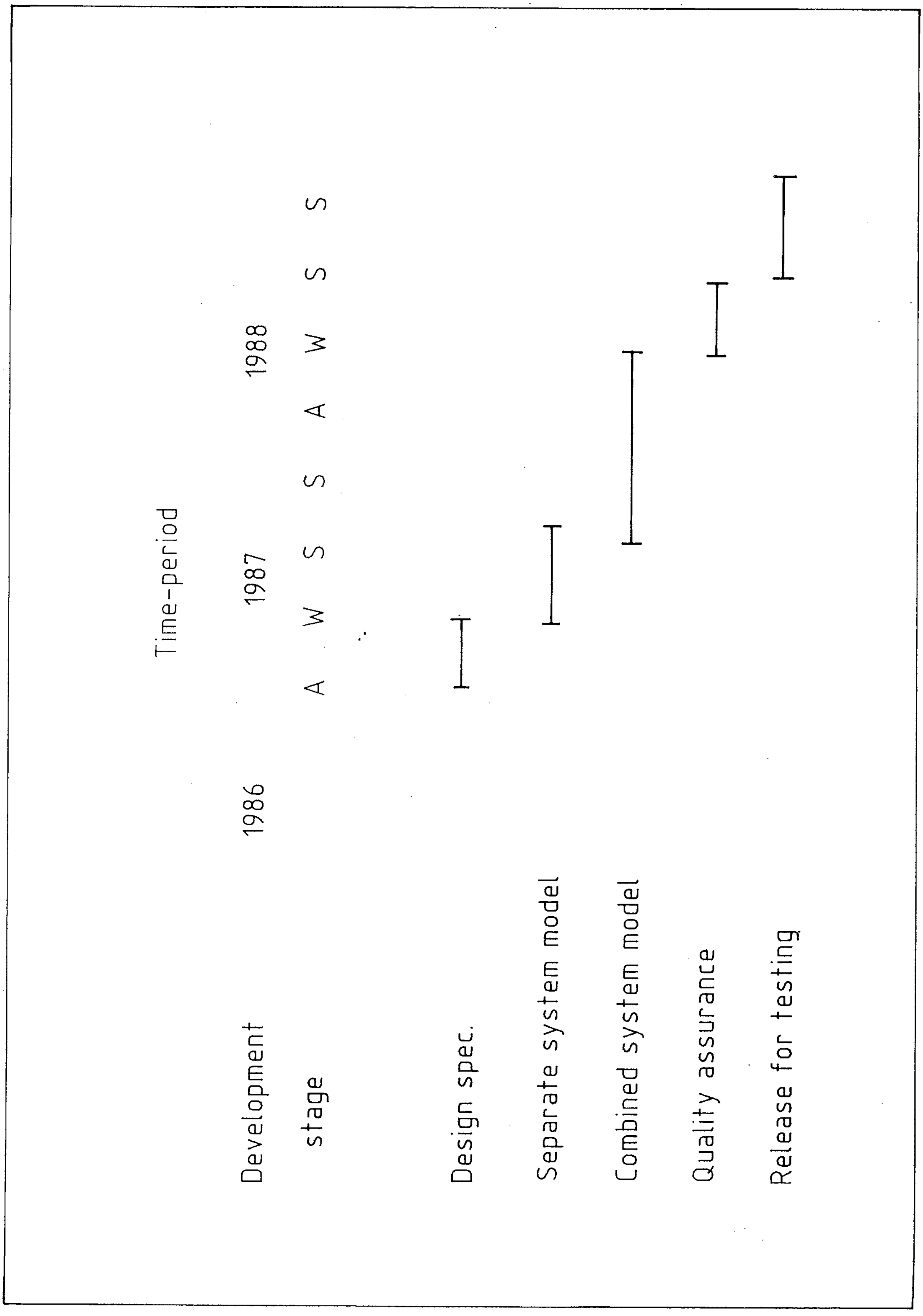


Fig 5.1 Overview of development strategy

APPENDICES.

APPENDIX A

Subroutine: SEDBAL

Purpose

To simulate the transfer to and from sewer discharge of sediments during its passage through a pipe segment.

Method

The method will vary dependent upon the transport phase by which the sediments are carried within the flow, and the cohesive/non-cohesive nature of the sediments.

For the non-cohesive load, a variant of the Ackers-White model can be used (Ackers, 1984)

For the cohesive load, processes are less well researched. Possible methods include equations for deposition developed by Krone (1962) and scour developed by Partheniades (1962).

The results of sediment transport studies within pipes conducted by HRL and Newcastle University should provide the necessary information to select a particular suite of sediment transport routines within this procedure.

Subroutine: DOXBOD

Purpose

To simulate the consumption of dissolved oxygen by BOD/COD during transport through a pipe-segment.

Method

Assumes validity of first-order kinetics for the consumption of dissolved oxygen by BOD/COD, i.e.

$$d\,(CC_{do})/dt = -k\,.CC_{BOD}$$

where CC_{do} = concentration of dissolved oxygen in sewage flow,

CC_{BOD} = concentration of BOD/COD in sewage flow,

k = rate coefficient.

There is an obvious lack of knowledge concerning the magnitude of the rate coefficient in pipe-flow. USWQM in general do not simulate dissolved oxygen, hence, this process is ignored, as the consumption of BOD is marginal compared to the absolute magnitude of BOD within the sewage; however, it may not be marginal compared to the dissolved oxygen level and the rate of reaeration within the sewer length.

Module: CATCON

Purpose

To simulate the time-varying behaviour of contaminant discharges from urban catchment surfaces and gully-pots, and to simulate the continuous dry-weather processes pertinent to contaminant generation within such a system.

Method

Contaminants are specified either as input, or internally, to be associated with particular sediment size classes. The distribution of sediment sizes themselves can also be specified externally. This is handled by input-output routines and SEDCON. The dissolved oxygen concentration within surface water is obtained by use of OXYSAT; dissolved oxygen within gully-pots are obtained by use of GULCON; mixture of gully-pot liquor and runoff concentrations to obtain surface system outflow is obtained by use of MIXCON.

Flows generated by the use of INFLOW within the WASSP-SIM module are used together with WSHSED and TAUCAL to derive the amount of sediment, and, thence, the amount of contaminants washed off a catchment surface. ERRCON is then applied to each contaminant in order to simulate likely errors associated with simulation. ADVECT can then be used to simulate the routing of contaminants. The above collection of subroutines when added to WASSP-SIM form a surface-water system contaminant model.

Subroutine: WSHSED

Purpose

Removal of solid material from catchment surfaces.

Method

Sediment removal from different surface types within a subcatchment is simulated by use of the Price and Mance (1978) sediment transport model. The rate of change of suspended sediment within overland runoff, dM/dt, is given by

$$\frac{dM}{dt} = a_i i^g + a_e 1_e(\tau - \tau_e) - a_d 1_d(\tau - \tau_d) - \frac{dm}{dt} - \frac{Mq'}{kq'+h}$$

where i = rainfall intensity (mm/hr),

τ = flow shear stress,

τ_e, τ_d = critical shear stress for erosion and deposition,

1_e = 0 when $\tau \leqslant \rho_{cr}$ = 1 when, $\tau \geqslant \tau_{cr}$

1_d = 0 when $\tau \geqslant \tau_{cr}$ = 1 when, $\tau \leqslant \tau_{cr}$

dm/dt = input of particulate solids by rain,

q' = surface runoff,

h = depression storage depth,

K = storage constant of linear reservoir,

a_i, a_e, a_e, g = constants.

This equation is first solved in integral form to obtain the mass M; this is then used to evaluate the discharge of sediment mass. This equation is applied to either a conceptual strip representing the lumped behaviour of all surfaces within the subcatchment, or individually to different surface types within the subcatchment. In the latter case, surfaces are represented as conceptual strips; in the case of road surfaces, this strip has the dimensions of gutter length and a fraction of the road width to reflect the unequal distribution of sediment accumulation upon road surfaces.

Subroutine: MIXSED

Purpose

To calculate resultant sediment concentration upon mixing of two or more input flows.

Method

Uses simple mixing model approach, that is,

$$CS_j = \sum_{k=1}^{n} \frac{CS_{j,k} \, Q_k}{\sum_{r=1}^{n} Q_k}$$

where CS_j = sediment concentration within outflow from mixing element,

$CS_{j,k}$ = sediment concentration within influent flow k,

Q_k = discharge of flow k,

i = fraction size class.

This model is applied whenever flows of different concentrations become mixed. The mixing is assumed to occur instantaneously and occurs within a hypothetical 'mixing segment'.

Subroutine: SEDCON

Purpose

Associates contaminants with a particular sediment size class.

Method

The particle size distribution upon catchment surfaces is divided in to n fractions. Within each fraction, contaminants are associated by the use of 'potency factors'. For example, for contaminant j within sediment size class i, the relationship between contaminant mass, MC , and sediment mass, M, is given by

$$MC_{i,j} = k_{i,j} \; MS_i$$

where $k_{i,j}$ = potency factor for contaminant j and fraction i.

The total sediment mass upon each catchment surface is assumed to be limitless. The particle size distribution is divided into four major classes synonymous with solids transported in the following phases:

1. Dissolved/soluble phase (less than 43 microns);
2. Cohesive suspended phase;
3. Non-cohesive suspended phase;
4. Non-cohesive bed-load.

Total contaminant load is then given by

$$MC_j = \sum_{i=1}^{n} MC_{i,j} = \sum_{i=1}^{n} k_{i,j} \; MS_i$$

Subroutine: OXYSAT

Purpose

To simulate the DO saturation level contained within surface runoff water at a certain temperature.

Method

DO saturation levels vary as a function of atmospheric pressure, temperature and chlorinity. Sensitivity to pressure, however, is very small thus DO saturation levels are given by

$$\ln C_{do,s} = -139.34411 + (1.575701 \times 10^5/T) - (6.642308 \times 10^7/T^2) + (1.2438 \times 10^{10}/T^3) - (8.621949 \times 10^{11}/T^4) - Chl[(3.1929 \times 10^{-2}) - (1.9428 \times 10/T) + (3.8673 \times 10^3/T^2)]$$

where $C_{do,s}$ = saturation level of DO,

T = temperature, kelvin,

Chl = chlorinity, parts per thousand.

Chlorinity is defined in terms of salinity which can itself be defined in terms of specific conductance. It is well known that a relationship exists between this latter variable and dissolved solids. Hence, it is possible to define the saturation content in terms of absolute concentrations given a knowledge of temperature and a simulated dissolved solids content.

Subroutine: GULCON

Purpose

To simulate the degradation of the water (liquor) stored within gully-pots during dry-weather flow periods.

Method

Gully-pot storage is assumed to be fully occupied following the cessation of a wet-weather period. This water will contain BOD/COD which utilises the DO within the stored water following a first-order reaction,

$$d(CC_{do})/dt = -k\ CC_{BOD}$$

where CC_{do} = DO level within gully pot liquor,
CC_{bod} = BOD within gully-pot liquor,
k = rate coefficient of the DO-BOD degradation process.

Similar rate-equations are used to describe the degradation of organic matter to BOD/COD and the denitrification of nitrates into ammoniacal nitrogen. In all cases rate-coefficients can be adjusted for temperature dependency.

Subroutine: SUMCON

Purpose

Summate contaminants occurring within each size class to derive total contaminant concentration.

Method

Addition of contaminants occurring within each fraction class, that is,

$$C_j = \sum_{i=1}^{n} CC_{i,j}$$

where C_j = contaminant, j, concentration within flow,

CC_{ij} = contaminant, i, concentration associated with sediment concentration, j.

Module: SEWCON

Purpose

To simulate the accumulation and transport of contaminants within the sub-surface drainage system, assuming contaminants behave in a non-conservative manner. This module operates continuously so as to calculate the sediment/contaminants available for entrainment during wet-weather/increased flow periods.

Method

The basic element within this module is the concept of a 'pipe segment'. Contaminant inputs to a pipe segment consist of inputs derived from CATCON, FOULIN and from upstream application of SEWCON. These inflows are combined by use of MIXSED to provide input concentrations to a pipe segment. Within the pipe-segment suspended sediments are transported by use of ADVECT; sources and sinks of sediment and contaminants are described by DOXBOD, SEDBAL, DOXAIR, and TAUCAL, and in association with routines within WASSP-SIM.

However, elements must also be included to describe the behaviour of sewer ancillaries, especially storage tanks and overflows, in relation to contaminant discharges. These will be included in updates of this draft proposal. However, to derive contaminants associated with overflow discharge SUMCON is used to summate the contaminant load associated with each phase of transport/sediment fraction.

Subroutine: ADVECT

Purpose

Simulate the transport of sediment within the dissolved and suspended phase.

Method

Uses a one-dimensional advection-diffusion equation assuming negligible dispersive effects (apart from contaminant exchange with dead-zones),

$$\partial(CS_j)/\partial t + u.\partial(CS_j)/\partial x - e.\partial^2(CS_j)/x^2 = +-\sum_{j=1}^{n} MS$$

where CS_j = sediment concentration of fraction j,

t = time,

x = longitudinal dimension,

u = stream velocity in direction x,

MS_j = concentration of sediment in fraction j (sink/source).

e = longitudinal dispersion coefficient.

Subroutine: H2SGEN

Purpose

To simulate the growth of sewage slimes (Type D sediments) and generation of hydrogen sulphide within sediments and released to sewer atmosphere.

Method

Sewage slimes following an event are assumed to grow during periods when flow shear-stress is less than a critical shear stress; a limit to growth is also applied by a critical shear stress (Perkins and Gardiner, 1982).

The definition of the mass of hydrogen sulphide generated and stored within slimes is at present difficult to achieve by simulation, largely because no equation has yet been developed. Equations available for the simulation of hydrogen sulphide within sewers are only pertinent to the simulation of gaseous hydrogen sulphide. Such equations can be incorporated within the model to provide an assessment of those sewer lengths likely to suffer from corrosion problems.

Subroutine: FOULIN

Purpose

To simulate the input of foul-water into a sewer segment from a specific contributing catchment area.

Method

The input of foul-water to a specific 'pipe segment' may be treated as an input hydrograph and associated pollutographs, or simulated in terms of factors describing the diurnal and seasonal trends in foul-water flow and constituents. In the latter case the mean level of foul-water flow may be either input itself or simulated on the basis of demographic factors.

(i) Simulation of mean concentration and mean flow

Mean concentration of foul-water flow can be simulated in terms of both land-use and demographic factors, such as:

$$\langle CC \rangle = b0 + b1\ (\text{land-use factors}) + b2\ (\text{population})$$

where b0, b1 and b2 are parameters obtained by regression analysis.

Similarly, mean foul-water flow may be related to these parameterisations of these variables, that is,

$$\langle Qf \rangle = a0 + a1\ (\text{land-use factors}) + a2\ (\text{population})$$

where $\langle Qf \rangle$ = foul-water flow,

a0, a1, a2 = constants derived by regression analysis.

(ii) Simulation of deviations about the mean concentration

The concentration of contaminants within the foul-water can be assumed to be either constant, with variations in contaminant loadings accounted for by the variation of the foul-water flow, or variable dependent upon the time-of-day and the day-number of the year. For example, the variation in foul water discharge could be described by

$$\frac{Qf}{\langle Qf \rangle} = c0 + c1(\text{time-of-day}) + c2(\text{day-of-year})$$

where Qf = foul-water discharge at a specific hour on a specific day.

Subroutine: DOXAIR

Purpose

To simulate the reaeration of sewage during its passage through a pipe-segment.

Method

For reaeration during free-surface flow through a pipe-segment a formula developed by Parkhurst and Pomeroy (1972) can be used.

For reaeration due to passage over weirs equations developed by Gameson et al. (1958) may be used, although their applicability to highly contaminated sewer flow must be questioned.

Subroutine: ERRCON

Purpose

Assign an error term to a specific deterministic simulation of a contaminant concentration or accumulation.

Method

Error terms are drawn from a probabilistic distribution on the basis of random-number generation. A First-Order Error Analysis is then performed to provide a sample estimate of the mean and variance of the simulated output.

Subroutine: ERRORS

Purpose

Define distribution of error terms associated with the three elements of the mixing-model.

Method

Errors associated with the specification of inflows into the mixing-model applied at each node are described by a probabilistic model. This subroutine specifies the form of these distributions for a particular catchment.

Subroutine: TAUCAL

Purpose

Calculate bed/wall shear stress of fluid flow in both catchment and pipe segments.

Method

In surface flow (IFLAG=1) shear stress can be calculated by
(Price and Mance, 1978)

$$tau = \frac{k\ q'}{(Kq' + h)}$$

where variables are as in WSHSED.

In pipe flow (IFLAG=0) by

$$tau = S.gamma.R$$

where S = slope of energy gradient,
gamma = unit weight of water,
R = hydraulic radius of flow.

APPENDIX B

DESIGN SPECIFICATION FOR ESQS (EMISSIVE SEWER QUALITY SIMULATION) MODEL
THE SEWAGE FLOW AND QUALITY SIMULATION VERSION OF WASSP

ABSTRACT

The proposed model (ESQS) will be required to model the processes leading to the production of first foul flush effects within sewerage systems and to produce results which show these effects in terms of short term variations in SSO discharge pollution concentration and load.

The design specification outlines the major processes and parameters to be modelled, both on the urban surface and within the sewerage system.

1. Purpose

The proposed model (ESQS version of WASSP) is to be capable of simulating the build-up and wash off of specified pollutants in an urbanised catchment or sub-catchment. These pollutants will then be routed through a combined or storm water sewer system. The model should simulate both the total pollutant load passing through the sewer system and the short term variations in pollutant concentrations during a storm event.

The role of the model is to produce storm period discharge pollutographs. These are required to evaluate the short term impact of sewage discharges on receiving water courses. Ultimately these pollutographs will provide input to a receiving river quality model. This larger scale model will permit the evaluation of the overflow performance and its impact on downstream river quality in terms of transient, acute effects and long term chronic effects on river quality and ecology.

While the model is primarily concerned with sewer behaviour during storm periods, the inter-storm dry weather flow periods are recognised as being of great significance in terms of duration and frequency. The model must also be capable of simulating the accumulation and generation of pollutants in a sewer during baseflow conditions. Therefore the simulation of the behaviour of the foul sewage flow during dry weather is essential.

A time series rainfall/dry weather period simulation methodology linked to probabilistic criteria for pollutant generation and removal is more appropriate than a fully deterministic design event criteria approach. The output from the stochastic/ deterministic process modelling would also be expressed in probabilistic terms for the long and short term assessment of overflow performance.

2. Determinands

The short term impacts, on the environment, from sewer discharges are due to oxygen depletion in the receiving water and the discharge of toxic substances. In the longer term, many other determinands may be significant, but it is possible to relate these to the behaviour of suspended solids. The generation of Hydrogen Sulphide in sewers is also considered to be important.

ESQS should therefore be able to model:

Oxygen demanding load - (BOD and or COD)

Ammonia (NH_4 - N)

Suspended Solids - organic and inorganic fractions

Hydrogen Sulphide

Dissolved Oxygen - transport and re-aeration within the sewer

Sediments - large size bedload fraction i.e. affecting hydraulic performance of the sewer system.

Other determinands of less immediate interest, which may be appropriate for long term or overseas applications include:

- Heavy Metals
- Bacteria
- Phosphates
- Nitrates
- Specific pollutants of industrial origin

3. Model processes and mechanisms

The model must simulate the following basic processes:

(a) The build-up of pollutants on catchment surfaces:

Pollutants will build up from atmospheric dry deposition on all contributing surfaces within the catchment. Dry weather loading rates may be assumed to be uniform over a catchment and may represent a linear build up of a substantial portion of the total pollutant load of many determinands, notably ammonia and nitrates but also fine particulates, chlorides and heavy metals. Roof areas contribute significant pollution, particularly to surface water systems. Roads and other paved areas provide the majority of pollutants in urban storm runoff and in particular the organic solids component with an associated oxygen demand. The rate of build up of pollutants on road surfaces is a function both of time and traffic loading.

(b) The wash-off of accumulated surface pollutants during rainfall events:

Wash out of aerial pollutants (wet deposition) is rapid and complete and therefore relatively independent of the nature of the rainfall event. The rate of surface wash-off is a function of the quantity of accumulated pollutants; the intensity of rainfall and the physical hydraulic characteristics of the catchment.

Runoff from permeable surfaces may also provide a significant contribution of suspended solids and other pollutants. Soil leachate may contribute to pollutants in infiltration.

(c) Gulley Pot Performance

Gulley pots are believed to influence the quality of sewer flows in two ways:

(i) they may add to the polluting load in terms of ammonia, BOD and organic solids by degradation of the stored water, and

(ii) they may modify the characteristics of the wash off of a particular storm, since the gulley pot liquor will tend to be washed into the sewer system in advance of the new storm's run off from road areas.

The volume of water retained in gulley-pots is significant, typically equating to = mm of rainfall over the contributing catchment.

Temperature and dry weather period duration will be important factors in assessing the generation and storage of pollutants within gulley-pots.

(d) Foul sewage in combined sewers

The daily variations in the quantity and quality of domestic foul sewage are well understood. Cycles of daily and seasonal loads can be established for a catchment incorporating periodic industrial discharges.

For longer term events and assessing annual pollutant loads, a variability factor will be required to compensate for the random time of day at which rainfall events occur.

The settling out of a proportion of the foul sewage flow at various locations within pipe networks during dry weather flow will need to be simulated.

(e) Sedimentation in sewers

Two effects are suspected to be significant with regard to pollutant generation within this aspect:

(i) High density inorgnic particulates tend to deposit in slow flowing sewer lengths during recession limbs of major storm events and minor rainfall inputs. The presence of these deposits encourages the deposition of organic solids during base flow periods. Organic solids will also tend to accumulate at other types of physical obstruction or imperfection. Low density organic solids will be rapidly resuspended and flushed out by storm flows adding to the suspended solids and oxygen demand loads. Hydrogen sulphides is generated within anaerobic sediments. This may be released when the sediments are disturbed by storm flows.

(ii) Sewage slimes tend to build up on pipe surfaces over the range of diurnal flow variations. These slimes will tend to slough-off during turbulent storm flow conditions adding a further suspended solid and oxygen demand load to the storm flow. Hydrogen sulphide is generated within these slimes.

The accumulation of inorganic sediments within sewers, while not exerting a major pollutant load may seriously influence the hydraulic performance of the system. The model should therefore be able to predict where sedimentation may take place within a system.

(f) Transport of pollutants through the sewer system:

The in-sewer behaviour of pollutants can be sub-divided into:

1. the hydraulic performance criteria - e.g. the movement of a flood wave through the system,

2. the deposition and re-entrainment of sediments and the release of oxygen demanding and toxic pollutants,

3. the generation of pollutant loads associated with the accumulation of organic sediments and the growth of slimes.

   For simplicity, sedimentation must be reduced to a relationship whereby the rate of deposition in a sewer length is proportional to the suspended sediment load carried in the flow and inversely proportional to the average daily velocity of flow during dry periods. The build-up must be considered to be uniform with time. The generation of oxygen demanding and toxic pollutants can then be related to volume and or mass of sediment or interstitial water and time since deposition.

4. Calibration and verification

The model should be capable of calibration and verification on the basis of flow survey and sewer inspection procedures employed in drainage area planning studies. Additional quality data requirements should be restricted to dry weather flow sampling where appropriate.

REQUIREMENT SPECIFICATION FOR SEWER FLOW QUALITY SIMULATION MODEL

Discharges from sewer systems have been identified as a major source of river pollution (Ref 1). In severe cases the effect of these discharges may be identified by routine chemical monitoring and result in the river being given an appropriately low quality designation; e.g. Class 3 or 4 of the NWC River Classification System (Ref 2). More frequently the intermittent nature of these discharges is such that routine chemical monitoring does not detect the full impact. In these circumstances the chemical data may indicate an acceptable river quality (e.g. NWC Class 2) but the ecology, which is restricted as a result of the intermittent discharges, will prevent the desired use (e.g. a coarse fishery) being fully established.

Biological damage caused by short term oxygen depletion or the transient presence of acutely toxic substances is therefore a key issue in controlling intermittent pollution. Hence biological assessment should be the criterion by which the effects of sewerage discharges are evaluated. The link between biological effects and transient chemical concentrations is being made through short term toxicity testing with fish and other aquatic organisms. An initial attempt at establishing short term river quality standards (Ref 4) has shown that very short term changes in concentration can have deleterious effects on biological populations. It follows from this that both the total load of pollutants passed to the river during a discharge event and the short duration peak concentrations within the event need to be understood and controlled to limit the damaging effects.

The present and future requirement for river quality management will be to maintain an acceptable balance between sewerage costs and river pollution (Ref 5). This will call for objective planning for discharges from both combined and surface water sewer systems. Past practice has tended to assume that surface water runoff is "clean" and hence can be discharged anywhere without harm. Research into the nature and effect of such discharges has demonstrated that this is not the case (Ref 6). On combined sewer systems, past practice for the setting of overflows has been largely concerned with the control of flows within the sewer system to levels which avoid flooding. Little consideration has been given to the consequences of spilling storm sewage to a river. Future procedures must seek to limit both types of discharge to quantities and locations such that the assimilative capacity of the receiving water, compatible with the desired use, will not be exceeded.

In the foreseeable future, the majority of sewerage capital schemes in the UK will be directed towards the rehabilitation of existing combined sewerage systems. In accordance with the basic tenets of the Sewerage Rehabilitation Manual (Ref 7), the favoured solutions will often incorporate detention tanks. Where such tanks are provided to control pollution, it is important that the requisite polluting load is retained concomitant with the minimum storage volume to optimise construction costs. This is another major reason why it is necessary to have an understanding of the temporal variations of spill quality within a storm event.

From the foregoing, it can be concluded that a sewer flow and quality simulation model is required to aid in the design and rehabilitation of sewerage systems. The model will be used in conjunction with river impact models to provide an objective methodology for the control of sewerage discharges to allow desired receiving water uses to be attained. The WASSP-SIM hydraulic analysis model is already in common use to define the quantitative response of sewer systems. A complementary quality modelling capability is required to produce discharge (pollutographs) to complete the methodology.

Previous attempts at producing sewer flow and quality models (for example SWMM and SAMBA) have aimed to produce an assessment of total pollution load discharged per event. This approach is appropriate under circumstances where:

(i) the total pollution loading is important over long time periods, i.e. chronic pollution and eutrophication;

(ii) delayed oxygen depletion in the vicinity of the overflow after the event is more important than the immediate impact during the event;

(iii) acute pollution from the discharge of toxic substances is not considered to be important;

(iv) first foul flush effects are not significant.

It is recognised that there are difficulties in adopting a requirement to produce discharge pollutographs by a simulation model. However, only this approach will satisfy the two objectives for pollution control which have been described. In the UK the occurrence of the first foul flush effect has been widely reported (Ref 8). This effect must be modelled to:

1. achieve short term river quality criteria in relation to oxygen depletion and acutely toxic substances, such as ammonia and hydrogen sulphide, and hence allow desired uses to be established;

2. optimise design of engineering structures for pollution control.

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