Hydraulics Research
Wallingford

AMENDMENTS TO THE HYDROLOGICAL SUB-MODELS OF THE WALLINGFORD PROCEDURE

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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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The DoE nominated officer is Dr R P Thorogood. This report is published with the permission of the Department of the Environment, but any opinions expressed are not necessarily those of the Department.

ABSTRACT

This report provides details of planned amendments to the hydrological models incorporated within the Wallingford Procedure for the Design and Analysis of Urban Drainage Systems. Part 1 provides a detailed design specification for a new sewered sub-area model to represent the hydrological behaviour of large urban subcatchments. This amendment is necessary for the practical implementation of the water quality model MOSQITO currently being developed at HRL under contract from the Department of the Environment. The requirements for this model and its development have been fully discussed within the remit of River Basin Management Programme coordinated by the Water Research Centre. Part 2 summarises a new surface hydrology model incorporating improved calculation of rainfall losses and flow storage and diversion on urban catchment surfaces. Discussions concerning the form of this model have already been held with the Water Research Centre, and this proposal, in part, is a reply to the requirements voiced by WRc. Future discussions concerning the form and development of the model should be formalised within the River Basin Management Programme.

Part 1

Design Specification for New Sewered Sub-Area Model

SEWERED SUB-AREA MODEL: Design specification

1 INTRODUCTION

Urban drainage systems consist typically of a collection of contributing areas, open-channel conduits, pipe conduits and various ancillary devices such as overflows, storage tanks and pumping stations, often arranged in a complex manner. Complete representation of such a system for the purposes of computational modelling is either inappropriate or impossible given the constraints of computational and manpower resources available for the routine application of a particular model. In the application of the Wallingford Procedure for the simulation of the behaviour of urban drainage systems a number of problems there are with completely representing a complex system.

First, data describing the layout and nature of the drainage system is often not readily available. This problem may be distinguished at two levels:-

(i) data may exist on maps and charts but this is time-consuming to extract;

(ii) data has to be collected direct from the field.

In both cases technological advancements, such as the use of digital mapping/geographic information systems, do offer solutions to some of the common problems. However, in many instances it will still be necessary to spend considerable amounts of time and money in collecting and collating such data sets; any method which allows certain portions of the data set to be simplified would obviously reduce this expense.

Second, on the hardware available to many current users and to further potential users, eg IBM-AT (or compatibles) operating within the MS-DOS environment, it is impossible to completely represent a large and complex urban drainage system in terms of all its pipes and individual contributing areas. It is also computationally uneconomic to input a long rainfall time-series - needed for accurately determining the frequency of damage resultant from urban runoff.

Third, it is unncessary to completely describe the features of an urban drainage system in order to adequately simulate its behaviour - nor is it necessary to always represent the operative processes such as infiltration, surface runoff and sewer flow in a complete manner. In this context it must be recognised that the models constituting the Wallingford Procedure are not exact either in their ability to consider all the structural elements of a sewer system (eg WASSP-SIM ignores the storage influence of gully-pots) or in their ability to represent the full range of flow processes operating within an urban catchment. The key to applying the Wallingford Procedure, especially the simulation model, is to identify the appropriate level of system representation required when modelling all but the smallest of systems. A major problem with current implementations of the Wallingford Procedure (eg WASSP-SIM) is that the current simplifying procedure ('The Sewered Sub-Area Model') is both difficult to use and incurrs high overheads in calculation and storage. As a result it has been little used by practitioners; model simplification has therefore developed as an art practiced successfully only by a few of the most knowledgeable and experienced WASSP users. In fact the methods of simplifying system representation when using the Wallingford Procedure have become so involved that artificial intelligence methodologies (eg expert system) are being developed to aid inexperienced users. The aim of a new sewered sub-area model must be to 'redress the balance between science and art' by formalising model simplification rather than allowing users to develop their own individual methods.

Finally, another problem often encountered, particularly when applying a range of urban and non-urban models for considering the behaviour of mixed or urbanising catchments, is the discrepancy and nonsensical results that may arise when deriving percentage runoff for the rural portions of the catchment using the methods embodied within the Flood Studies Report as compared against their urban equivalents derived using the Wallingford Procedure. A desirable feature of the new sewered sub-area model would be an ability to represent the behaviour of both large urban and rural sub-catchments.

Distillation of the above comments indicate that the new sewered sub-area model is required to fulfil three major aims (although the last of these aims may not be entirely possible to achieve):

(i) Represent in a simplified manner systems for which complete system description is readily available or already possesses a verified WASSP SSD file;

(ii) Represent portions of systems for which little or no data exists or is readily available;

(iii) Attempt to represent large urban and rural sub-catchments in a similar manner.

The following paragraphs detail the design specification of a set of models which are to be developed and examined in order to fulfil these requirements.

2 MODEL DEFINITION

The new hydrology model for the Wallingford Procedure has been defined so that both rainfall excess and surface runoff routing are modelled separately for each surface type within an urban subcatchment. Surface runoff is modelled using parallel 'quasi-linear' reservoirs, although other alternatives such as non-linear reservoirs and Muskingum routing may be investigated. The sewered sub-area model must preserve the basic structure of the new hydrological model and extend this structure to be applicable both to larger areas and situations where surcharging and flooding are taking place.

As identified in the original work conducted on the sewered sub-area model by Price et al (1980) there are a number of alternative approaches that may be adopted in developing a model which represents the discharge from a sewered sub-area. One method could be to develop a new model for the above ground phase which could also include the influence of attenuation associated with the below-ground phase. Such a model consisting of two linear reservoirs in series has been previously defined by Sarginson and Nussey (1982). An obvious problem with this approach is in the calibration of the storage coefficients for each reservoir.

The approach adopted within the original version of the sewered sub-area model was to retain the structure of the above and below ground phases of the model but to simplify the representation of the urban drainage system. The pipe network within the sewered sub-area was replaced by an 'equivalent pipe system' defined in terms of four parameters:-

(i) slope - Taylor-Schwartz slope;

(ii) diameter - pipe full discharge of last pipe in equivalent system similar to that of prototype system;

(iii) tapering constant - descriptive of the degree of tapering in pipe diameter downstream from head of system;

(iv) length - length of main branch of the prototype system.

Surface runoff was assumed to be equally distributed along the length of the equivalent pipe system and was simulated by means of the same non-linear reservoir system used in the original above-ground phase of the model.

The above approach suffers from two major deficiencies. First, inadequate account was taken of the storage available during surcharged conditions. Second, the model does not really simplify enough the representation of a sewered sub-area. The first problem would be relatively easy to remedy by increasing the amount of storage associated with manholes allotted to the equivalent pipe system. However, the second problem indicates that it might be better model the below-ground phase differently while still retaining the basic structure of the above-ground model.

The following model definition outlines such a procedure, which although allowing some scope for alternative model testing in terms of the form of the representation of the above ground phase, is a different approach from that adopted in the original sewered sub-area model.

(b) <u>Definition of a new sewered sub-area model</u>

The new sewered sub-area model will be designed so as to model in first instance systems with pre-existing WASSP models; only in later stages of development will the procedure be extended to consider systems for which no SSD data has been created or is difficult or impossible to collect. In the former context the sewered sub-area model can be seen to be 'a model of a model'. Given the current uncertainty in the form of the surface hydrology of the WALLRUS model it is therefore essential that the various sub-models used for representing the behaviour of a sewered sub-area will fit around and complement both the current surface runoff model and any future model to be developed.

(i) Surface hydrology

Representation of the surface hydrology within the sewered sub-area model will be similar to that within the new Wallingford Urban Runoff Model (O'Loughlin, 1987). That is, both rainfall losses and surface runoff routing will be modelled on individual surface types within a subcatchment, with three surface types being allotted to each subcatchment.

Rainfall excess on each surface type is to be calculated by means of an initial loss model together with a continuing losses model. Both of these models will have varying initial conditions dependent on the antecedent history of rainfall events. In the case of the initial losses model standard maximum values of initial loss are to be allocated to each surface type; the amount of this store that is filled prior to the onset of an event will be controlled by a balance of rainfall and the potential evaporation.

In the continuing losses model either a continuous 'PR-type' model or a physically based infiltration equation is to be used (eg Green-Ampt model). The parameters of each of these models will be controlled by the nature of the surface type (largely permeability) and the relative degree of saturation of the soil moisture storage zone. Soil moisture storage is to be represented by a three layer model; the lower two layers will utilise the soil-moisture extraction model incorporated within the MORECS procedure; the upper layer will represent the extra soil moisture storage available between the saturation capacity and the field capacity of the soil. Whereas parameters of the MORECS model will be related primarily to crude notions of vegetation cover, parameters of both the infiltration model and the saturation zone layer will have to be related to such variables as surface type and soil index.

Runoff routing on each surface type is likely to be simulated by means of a 'quasi-linear' reservoir system represented by two equations:

$$S = k \cdot q \qquad (1)$$

$$k = C \cdot i^{(-.4)} \qquad (2)$$

where S = storage;

q = discharge per unit area;

i = rainfall intensity;

C = coefficient dependent on slope and surface type.

This model is currently implemented within WALLRUS with the coefficient C given by:-

$$C = .393\, S^{-.264}\, A^{.333} \qquad (3)$$

However other models that may be investigated are certain non-linear models such as the non-linear reservoir (with and without a time-lag) and the Muskingum model.

(ii) Extension to larger areas

In extending the quasi-linear reservoir model to larger areas both pipes and manholes will be removed from the model. In order to account for this particular influence two possible approaches can be envisaged:-

1. Extend normal runoff model. This may be done in two ways. First, introduce a time lag, T, into the linear reservoir model, that is

$$S(t-T) = k \cdot q(t) \qquad (4)$$

where T is a function of catchment area. This method has the major disadvantage of increasing computer storage dramatically and is therefore not to be investigated.

Second, introduce an increased dependency of the coefficient C in Equation 2 on area or alter the total storage coefficient by a separate factor (k^*) itself dependent on area; both of these methods would have the effect of increasing storage as area increases above a threshold value although the latter approach would probably be easier to implement and would have the important attribute of being independent of the normal storage coefficient. Hence, the preferred model using this approach would be to represent the total storage coefficient of each linear reservoir as

$$St = (k + k^*)\ q \qquad (5)$$

where $k^* = f(A-At)$

At = threshold value of area at which a normal area is considered to be a sewered sub-area.

2. Introduce another linear reservoir to account for pipe storage. This could be applied to each surface separately to form a dual linear reservoir system similar to that put forward by Sarginson and Nussey (1982) or more logically applied to the combined outflow from the three normal linear reservoirs; however, as the system is linear these two alternatives are equivalent. The storage coefficient of this reservoir would again vary with subcatchment area above a threshold value, that is

$$k2 = f(A-At) \qquad (6)$$

Of these two alternatives the latter is thought to represent the most logical and easiest approach to follow as the pipe storage can be represented by an individual sub-model. It may also be necessary to include an extra effect of area on the overland runoff model. The difference between the two approaches may be appreciated by comparing the storage coefficient associated with each. In the first approach the storage coefficient for representing discharge from a particular surface type can be represented as:-

$$St = K'.q$$

where K'=f(rainfall int., slope, area).

In the second approach it can be shown that the total storage coefficient may be represented by:

$$St = (K1 + K2).q - k2.d(d1.q)/dt \qquad (7)$$

Assuming

$$K' = k1 + k^*$$

then for the two approaches to be equivalent either

$$k^* = k2 - (2/q).d(k1.q)/dt$$

or the differential term in Equation 7 is negligible. If in applying the second approach it is found that either of these conditions is approximately true then the former method can be used; this has the distinct advantage of both quickening the simulation time and reducing the amount of computational storage when applying the approach.

(iii) Extension to include surcharging and flooding effects

A major deficiency with the original sewered sub-area model was its inability to take account of the effects of surcharging and flooding on the discharge hydrograph from a sewered sub-area. Figure 1 illustrates a typical discharge frequency curve from a sewered sub-catchment as modelled by WASSP-SIM. Two major effects may be observed. First, on passage from free-surface flow to surcharge flow, there is a rise in discharge as the speed of the flood wave increases dramatically; however, this effect may well be obscured by the non-uniform nature of the onset of surcharge within subcatchments.

Second, at higher levels external storage within the system will be mobilised counteracting the former effect causing a flattening off of the flood-frequency curve.

In order to account for both of these effects it is clear that adjustments will be required to the pipe storage element described above. The variations in the flood-frequency curve can be described in storage terms by the removal and addition of discrete storage elements.

The amount of external storage mobilised during surcharge can be calculated using an adaptation of the Chapman/Osborne method (as detailed in Chapman, 1987). Steps involved in this method are described below:-

1. Assume the subcatchment is rectangular and situated equally either side of the pipe;

2. Assume that contributing areas are spread uniformly throughout the area;

3. An average connection length can then be obtained by either

$$X = A/4L$$

or

$$X = (A^{**}.5)/2$$

where X = connection length

A = catchment area

L = Pipe length

The two options are for calculating connection length are designed to represent connection length for an area associated with a specific pipe (ie unmodelled storage) and connection lengths associated with a simplified sub-area.

Furthermore, X is constrained so as not to be less than 5m and not to be greater than .5(depth to soffit/pipe slope) which takes into account the influence of ground topography on connection length.

4. Calculate number of connections for connected paved, connected roof and for foul only connections. Assume one paved connection per 300 m^2 of paved and one per 80 m^2 of roof; assume one connection per .01 l/s and and 35 properties per hectare and divide the baseflow or foul-flow to obtain number of foul connections.

5. Put in the equivalent volume as extra storage - this will include both manhole and pipe storages removed from the system as well as that added using the above method.

This method was primarily designed to account for the unmodelled storage associated with small diameter pipes not included within a WASSP SSD file. In adapting the method to account for, first, pipes removed from a system and, thereafter, for unmodelled pipes, the method described below can be seen as an alternative to the full MADD method defined above.

First, account for the small unmodelled pipes as described above. Second, for the large pipes removed from the system as part of the simplification process derive a connection density for each pipe diameter. Assuming that unmodelled pipes are represented by 100mm pipes produce a connection density vs. pipe diameter graph for each sewered subcatchment. From this the total amount of extra storage required to represent the storage associated with the pipes mobilised during surcharge and flooding can be derived and expressed in units of area; the amount of the storage associated with removed manholes is also incorporated within this figure. The additional storage volume can then be added to the downstream receiving pipe by dividing the area derived above the area of the downstream manhole.

Via either of the above methods it will be possible to derive curves of additional storage vs. sewered sub-area area. In adapting the procedure so as to be applicable to instances in which no current SSD exists it will be necessary to produce a standard set of these curves differentiated on the basis of the nature and density of the development.

(c) <u>Derivation of model parameters</u>

From the above definition it is clear that two aspects of the new sewered sub-area model will require calibration. First, the parameters of the surface runoff model will need to relate to an index of the total flow path (both above-ground and below-ground phases) together with the parameters of the pipe storage model (although this element may be made redundant as described in section 2.b ii). Second, the coefficients related to the extra-storage model will require investigation. Further aspects that will require examination will be the passage of pipes within the sewered sub-area into surcharge and flooding, particularly the influence of localised effects on sewered sub-area model parameters. A formalised procedure for conducting parameter calibration is listed below.

(i) Derive WALLRUS models for a number of systems and establish discharge and level frequency curves for each catchment;

(ii) Simplify the full models at different levels;

(iii) Relate model parameters to catchment characteristics;

(iv) Verify results.

Details involved in each step are explauined in full below.

(i) <u>Derivation of WALLRUS models</u>

Two collections of WALLRUS SSD models are to be used in the derivation of the sewered sub area model. First, a set of hypothetical catchments. These hypothetical catchments are to be designed using WALLRUS-HYD. Each catchment will reflect a particular set of characteristics:

(a) Distribution of surcharge return period within catchment. Four distribution types are to be designed:

1. Constant return period of surcharge within each pipe in catchment;

2. Return period of surcharge increasing with decreasing distance to catchment outlet - this represents a situation in which peripheral areas within a catchment may be designed in order to retain water to prevent flooding further downstream;

3. Return period of surcharge decreasing with decreasing distance to catchment outlet - this may be synonymous with a system in which new peripheral areas designed to a certain return period are added to a pre-existing system and increasing the frequency of pipe full discharge events.

4. Distribution of return period within catchment is defined on a purely random basis.

WASSP-HYD will be used to design the pipe system. The average return period for design will be 5 years with the range of return periods from 2 to 10 years. In order to ensure a simultaneous transfer of pipes into surcharge within the catchment the range of commercially available pipe diameters (PDIA(25)) in WASSP-HYD will require alternation. The simplest method will be to change the dimension of PDIA to 2000 and define contents of the array to run from 1 to 2000mm. The designed pipe will then be the size of pipe required to convey the desired return period to the next highest mm as opposed to the next highest commercially available pipe diameters. Systems designed using commercially available pipe diameters will also be included within the data set and will be used to investigate the influence of non-uniform passage into surcharge. The critical storm duration for each pipe will be selected from a series of 50 events ranging from approximately 10 to 60 minutes with a 1 minute difference in storm duration.

(b) Distribution of catchment characteristics. Derive a set of catchments with a range of average slopes; for each average slope class derive a collection of catchments with a varying distribution of catchment slopes in different levels of catchment discretisation. A similar procedure may be used for catchment shape. Design pipe network for equal surcharge with variable catchment characteristics using both the 'smooth' range of pipe diameters and the 'stepped' range.

Secondly, collect a set of 'real-world' SSD models some of which are to possess observed discharges and levels. It is suggested that these catchments should consist of the catchments used in the original development of the Wallingford Procedure and the catchments being currently used in the development of the water quality model MOSQITO, that is

1. Shephall - separately sewered;
2. Clifton Grove - separately sewered;
3. Colne - possibly partially separate;
4. Higham Ferrers - combined sewers;
5. Great Harwood - combined sewers;

These will be used to validate the calibrated sewered sub-area model.

(ii) Simplify models

Reduce each SSD file to a variety of levels of simplification by pruning upstream pipes. A fortran program has been created which will add the removed pipe's contributing area to the downstream pipe and calculate the amount of storage associated with each removed pipe and manhole thus facilitating the development of simplified SSD models. The upper limit on subcatchment area for use with the sewered sub-area model will need to be derived as part of the analysis; however, it is probable that areas of the order of 50 hectares represent an upper limit. Derivation of the upper limit can be achieved by conducting statistical tests to establish a critical threshold at which the degree of explanation afforded by the sewered sub-area model becomes unacceptable (a level of acceptance of +-10% for 95% of all events would appear to represent a reasonable criteria).

(iii) Optimise model parameters

Model parameters to be optimised will consist of

(a) k* in the surface runoff model; this may be optimised assuming first a single contributing area type and then adapting for multiple contributing area types. A dependence of k on intensity raised to the power of -.4 is assumed;

(b) k in the pipe-storage linear reservoir.

These two parameters are to be optimised separately with results of goodness-of-fit being used to decide on the appropriate form of the sub-model to account for hydrograph lag associated with the influence of pipe storage. The optimising algorithm used will be a modified version of the Rosenbrock optimisation function. Goodness-of-fit indices will reflect the ability to represent peak discharge, time-to-peak and runoff volume of the outlet hydrograph from a sewered sub-area. Accurate predictions of surcharge and flooding within a sewered sub-area are not required. Four goodness-of-fit indices would appear appropriate.

(a) ($\sum$ abs(Ts - To)/To)/n - time-to-peak
(b) ($\sum$ abs(Qs - Qo)/Qo)/n - peak discharge
(c) ($\sum$ abs(Vs - Vo)/Vo)/n - volume
(d) ($\sum$ ln(Vs-Vo)**2))/n - volume normalised for storm size

Given that the systems upon which model calibration takes place will be hypothetical systems designed to surcharge at a return period of 5 years rainfall inputs will consist of design storms ranging from 1 to 30 years; a constant value of UCWI will be used which is selected to be that appropriate to the location of the hypothetical catchment, ie, the design UCWI ties in with the M60-M2 day ratio and other rainfall parameters.

The procedure adopted in optimisation will be, for a particular system run a series of design storms through the system and optimise the calibration parameters and the removed storage volume to fit the observed flood-frequency curve using the four goodness-of-fit indices indicated above. This will be done for a wide range of hypothetical sewered sub-areas. An appropriate set of parameter estimates for each sewered sub-area will be selected on the basis of the overall values of the goodness-of-fit indices expressed in terms of error maps.

(iv) Regionalise model parameters

The calibrated model parameters are to be regionalised using multiple linear regression included within the GLIM statistical software package. Independent variables will be subcatchment slope and area. A criteria for acceptance of the regression equations will be a total explanatory power of 75% as expressed by the square of Pearson's correlation coefficient. Standard criteria in establishing Best Linear Unbiassed Estimators (BLUE) for the regression equations will be followed.

(v) Validate model

The sewered sub-area model is to be validated using data from the real catchments defined above. A two stage procedure is to be adopted. First, an appropriate range of design storms will be used with the aim to represent the full model behaviour by a model consisting of sewered sub-areas; second, observed rainfall-runoff events will be used to assess the overall accuracy of the sewered sub-area model. Each catchment will be divided up into different arrangements of sewered sub-areas in order to assess appropriate levels of subdivision.

3 PROGRAM STRUCTURE AND INTEGRATION WITH WALLRUS

The sewered sub-area model is to be integrated within WALLRUS as a series of subroutines which are called into operation when the area of a particular subcatchment becomes greater than a threshold level and the ancillary parameter equals 6 on the WALLRUS pipe data record. Subroutines will be required to set up the parameters of the sewered sub-area model in SIMPART1 and to carry out the operation of the model in SIMPART2. Subroutines required are listed below.

(a) SUBROUTINE SSAMST

Purpose: Set up parameters for sewered sub-area model

Call: From SEWER2 in SIMPART1.

Operation: Given an ancillary index of 6 on the pipe record this subroutine will

1. Check total area of subcatchment falls within SSAM range (both lower and upper limits).

2. If greater than upper limit an error will be returned and the user will be advised to change the SSD file accordingly.

3. If less than SSAM range the user will be given a warning but SSAM will still be implemented. This will allow the user to implement the extra storage model.

4. Read in parameters associated with SSAM from ancillary record.

5. Calculate extra number of manholes required on the downstream pipe to accommodate the extra storage mobilised as a result of surcharge and add to the parameter STORE passed to SIMPART2.

(b) <u>SUBROUTINE SSAMIT</u>

Purpose: Initialise parameters of sewered sub-area model for a specific pipe/manhole.

Call: From RUNPAR in SIMPART2

Operation: Set up either parameter k* of surface linear reservoirs or k of pipe linear reservoirs, dependent on final choice of SSAM options.

Commons: Requires data particular to SSAM (see below) and block BL8

Data transferred: pipe/manhole number

(c) <u>SUBROUTINE SSAMOP</u>

Purpose: Operation of sewered sub-area model.

Call: From RUNPUT in SIMPART2

Operation: Implements extra linear reservoir for pipe storage (if required)

Commons: Data particular to SSAM (see below)

Data transferred: Inflow into pipe linear reservoir; returns outflow from pipe linear reservoir

4 DATA SPECIFIC TO SSAM

Data particular to SSAM will consist of

(a) Input data on ancillary record

Input data required to set up SSAM will consist of

1. Development intensity (integer, I1) - to select a particular form of storage-area curve hard-coded within SIMPART1

2. Type of system connections (integer, I1) to pipe, e.g.

   0 = combined
   1 = separate
   2 = partially separate
   3 = ...

3. Density of system connections (real, F5.0) for roofs, paved surfaces and foul sewers (if default values/global values not used)

(b) Global input data

Global input data will be similar to 1., 2., and 3. but will be entered on header records of SSD.

(c) Data transferred from SIMPART1 to SIMPART2

Consists of two types:-

1. Flag signifying a particular subcatchment is to be modelled as a sewered sub-area

2. Extra storage term added to storage term already passed between two programs

(d) Data held in common in SIMPART2

1. Parameters of surface runoff model/pipe linear reservoir (e.g. KSTAR (300))

2. Storage term for pipe linear reservoir (e.g. PSTORE (300))

(e) Data held in common in SIMPART1

Consists of

1. Look-up tables of storage area graphs

5 ERROR HANDLING AND HELP SYSTEM

Errors and help messages associated with the use of SSAM are to be integrated within the two files WALLERR.SYS and WALLHELP.SYS. Particular error messages will be associated with the area to which SSAM can be applied (as indicated above).

6 HARDWARE REQUIREMENTS

SAM is to be written in ANSI-STANDARD FORTRAN-77 and should be compiled and linked with WALLRUS on three types of machine:-

(a) IBM-PC compatible

(b) Appollo Workstation (Unix OS)

(c) Micro-Vax (VMS OS)

7 IMPLEMENTATION

SSAM is to be developed in order to work together with WALLRUS and MOSQITO. A completion date of March, 1988 of the development of the model is envisioned. Staff associated with the project will be:

1 Research Engineer
2 Project Engineer
3 Technical Assistant

It will be the task of the former to supervise the development of the model and aid in technical matters where appropriate. The latter two staff will be required to develop the model and produce documentation.

An approximate time-table of development is

Dec. 87 - Jan. 88	Set up models and data sets; conduct major runs of model
Feb. 88	Write report on SSAM
Mar. 88	Produce documentation for operating model

The model is to be developed on an Appollo Domain Workstation.

Part 2

Summary of new hydrology model

Hydraulics Research Limited

PROPOSED SURFACE HYDROLOGY MODEL FOR **THE WALLINGFORD PROCEDURE**

by Geoffrey O'Loughlin

January 1988

SUMMARY

A new surface hydrology model for the Wallingford Procedure is outlined. This permits continuous simulation for water quality modelling and flexible description of catchment surfaces, flow storage and diversion devices.

1. INTRODUCTION

The **WALLRUS** program is being developed as a replacement for **WASSP-SIM**, the simulation program within the Wallingford Storm Sewer Package.

WASSP-SIM is used widely in the U.K. for analysis of stormwater and combined sewer systems. However, its hydrological model was developed as an event model for design purposes, and is unsuitable for continuous modelling. Since WALLRUS is to be used with the continuous water quality model **MOSQITO**, a revised hydrological model is required.

This should have the following features :

- continuous modelling capabilities for real-time simulation and water quality modelling,

- a flexible description of catchment surfaces, to model soil erosion, natural and artificial infiltration, storage and diversion effects,

- the ability to reproduce recorded runoff data at least as well as the WASSP-SIM model,

- parameters which can be related to readily-measurable quantities, making WALLRUS useable throughout the U.K. and overseas,

- computational efficiency.

Considerable development work has been undertaken, and a working version of WALLRUS has been used with MOSQITO. The hydrological model employed in this interim program allows for three surface types on each sub-area of a drainage network. The "percentage runoff" factor in the WASSP-SIM model has been adapted to operate continuously, and its non-linear reservoir routing procedure has been replaced by a variable-parameter, linear reservoir procedure.

This is being altered and refined, with a different hydrological model and additional capability to model various surface processes.

The new model described here has been implemented as computer code, but has not yet been calibrated and tested against recorded data. A testing programme will be conducted in 1988. There are likely to be some changes to the model outlined, to enable better fits to data and to improve ease-of-use.

2. MODEL STRUCTURE

The new surface hydrology model consists of three sub-models, as shown in Figure 1. This forms a module which can be used repetitively.

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  FLOW                    *  LOSS  MODEL                  *
DIVERTED                  *                               *
ONTO THIS                 *   - depression storage        *
 SURFACE     ....>        *   - Green-Ampt infiltration   *
                          *   - MORECS soil moisture      *
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                          *  ROUTING MODEL                *
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                          *   - linear storages           *
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                          *      10 minute mean rainfall  *
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                          * * * * * * * * * * * * * * * * *
POSSIBLE                  *                               *
  FLOW                    *  STORAGE - DIVERSION MODEL    *
DIVERTED                  *                               *
 TO THIS                  *   - entry capacities related  *
  POINT    ......>        *      to inflow or ponding     *
                          *   - diverted flows passed to  *
                          *      other surfaces or sub-   *
                          *      areas, or out of system  *
                          *                               *
                          * * * * * * * * * * * * * * * * *
                                 |               :
                                 |               :
                                 |               V
                                 V
                                             DIVERTED
                            RUNOFF TO          FLOW
                           PIPE SYSTEM
```

Figure 1 Surface Hydrological Module

The **loss model** converts rainfall to rainfall excess, allowing for depression storage and infiltration. It incorporates a soil mositure accounting model for long-term continuous simulation. The **routing model** describes the changes made to runoff as it passes over catchment surfaces. The **storage-diversion** model calculates the effects of concentrated storages at the outlet to the surface, and splits runoff into flows entering the pipe system and flows diverted elsewhere.

Modules can be linked to describe the surfaces and flow regulation facilities within a sub-area to a high degree of complexity. At present, three modules are provided, with the linkages shown in Figure 2. On most sub-areas, only a few of these options will be used.

It is not necessary to divide each sub-area into three surfaces - one or two may be used, with the remainder considered as null surfaces. As a later development, it may be possible to specify a variable number of surfaces, say from one to ten.

3. MODEL DETAILS

3.1 LOSS MODEL

In its current state, this model itself consists of several parts, and has been formulated to provide flexibility and relative simplicity. It is illustrated in Figure 3.

Calculations on depression storage and infiltration are carried out separately for each surface (three are shown in the figure, but the number can be varied). Infiltrated water passes to a common soil moisture store represented by a two-layer soil moisture model (based on the soil moisture extraction algorithm in the MORECS model (Institute of Hydrology, 1981)). The depth of water stored influences the parameters in the infiltration calculations, by updating the soil moisture tension term in the Green-Ampt Equation.

Rainfalls and possible diversions from upstream surfaces or sub-areas are directed to a top moisture store, representing the top layer of a soil. **Infiltration** to this storage is calculated by the Green-Ampt equation, which is used in models such as the U.S. EPA SWMM Model (Huber et al., 1981) and the U.S. Geological Survey Distributed Area Runoff Model (Alley and Smith, 1982), though not in the same form as in the proposed model. The parameters required are :

(i) saturated hydraulic conductivity,

(ii) ratio of soil moisture tension at the wetting front for a soil at wilting point to that at field capacity, and

(iii) tension at the wetting front when soil is at field capacity.

These values may be related to known values of the U.K. SOIL index or to soil types within a catchment.

Any water which does not infiltrate is directed to a **depression storage** described for each surface as a maximum and a current depth. The maximum depth D (m) is set by the relation :

$$D = k / s^{0.5}$$

where s is the surface slope in m/m and k is a factor dependent on surface type. Currently, k values of 0.000071 to 0.000088 are used for impervious surfaces, 0.000050 for roofs and 0.000280 to 0.000620 for pervious surfaces. These are derived from research by Pratt and co-workers (e.g. Harrison, 1983).

Depression storage is depleted by evaporation, and can "dry out" after storms. **Surface runoff** is modelled by overflows from the depression storage.

Infiltrated water is assumed to drain from the surface store to two deeper stores. **Soil moisture accounting** is carried out by MORECS model procedures. Although this has been developed specifically for the U.K., it is a relatively simple soil moisture model and can be applied elsewhere. The major parameter required for implementation of the soil moisture extraction model is the available water capacity of the soil, AWC, (mm/m). Values of the two stores can be derived from this and the surface cover.

The depth of water held in these deeper stores is linked to the Green-Ampt model parameters, and so influences the infiltration rate into the upper soil layer.

(Later provision may be made for some passage of water from the depression storage to the deeper soil moisture stores.)

These procedures have been chosen to provide an easily-understood and physically-realistic model structure. Iterative calculations have been avoided, so the model is computationally efficient.

The soil moisture model thus enables continuous modelling of hydrological events, with wetting and drying of soils. It may also allow the modelling of infiltration of water into pipes from the surrounding soil.

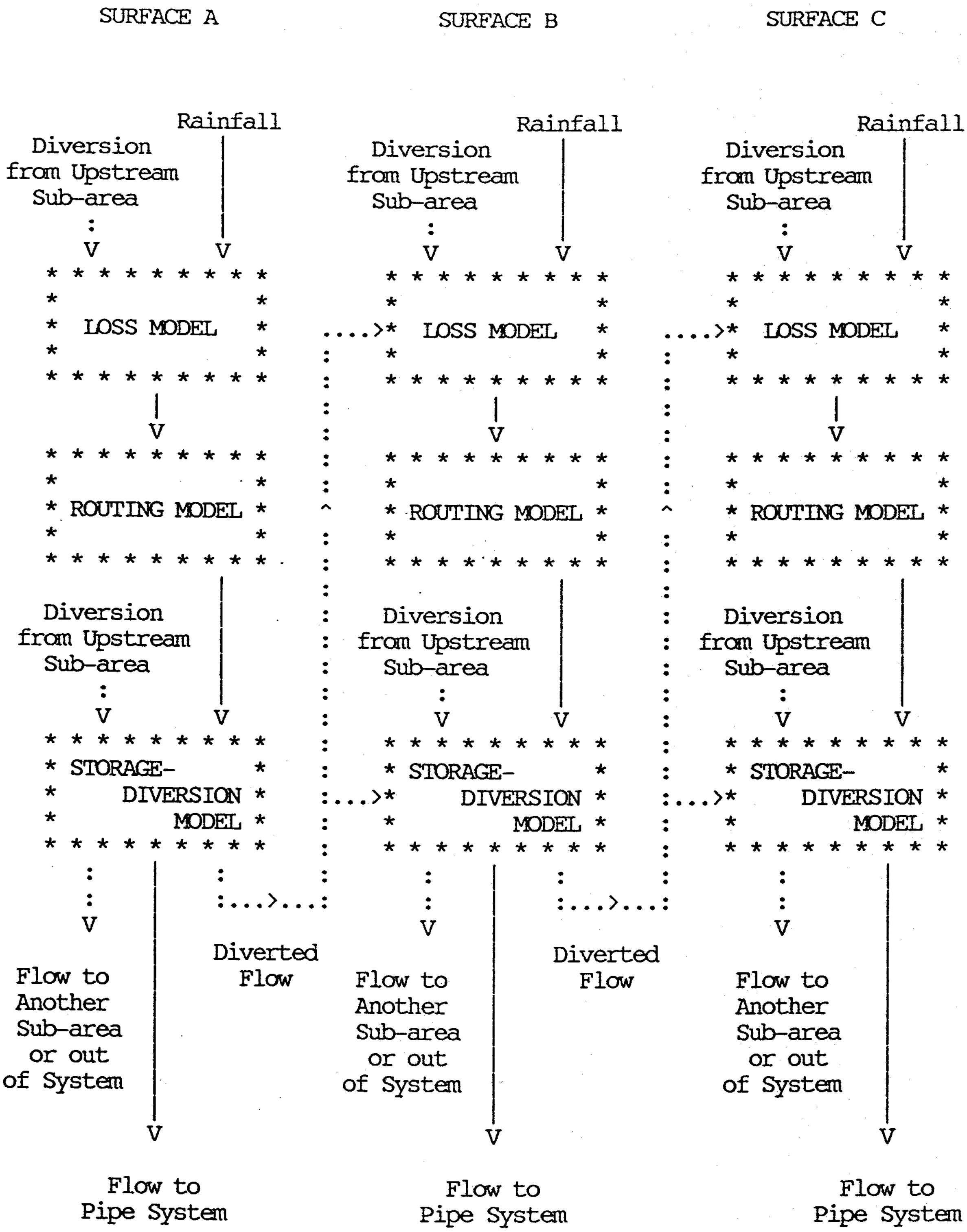

Figure 2 Connections between Surfaces within a Sub-area

```
        SURFACE A                    SURFACE B                SURFACE C


                  Evaporation                 Evaporation                 Evaporation
                            ^                           ^                           ^
                            :                           :                           :
                 Rainfall   :                Rainfall   :                Rainfall   :
    Diversion        |      :     Diversion      |      :     Diversion      |      :
        :            |      :         :          |      :         :          |      :
        V            V      :         V          V      :         V          V      :
    * * * * * * * * *       :     * * * * * * * * *     :     * * * * * * * * *     :
    *               *       :     *               *     :     *               *     :
    * SURFACE STORE *       :     * SURFACE STORE *     :     * SURFACE STORE *     :
    *    FED BY     *       :     *    FED BY     *     :     *    FED BY     *     :
    *  GREEN-AMPT   *..>.:        *  GREEN-AMPT   *..>.:      *  GREEN-AMPT   *....>...:
    * INFILTRATION  *       :     * INFILTRATION  *     :     * INFILTRATION  *     :
    *               *       :     *               *     :     *               *     :
    * * * * * * * * *       :     * * * * * * * * *     :     * * * * * * * * *     :
      |            |        :       |            |      :       |            |      :
      |            V        :       |            V      :       |            V      :
      |      * * * * * * * *        |      * * * * * * * *      |      * * * * * * * *  :
      |      *             *        |      *             *      |      *             *  :
      |      * DEPRESSION  *        |      * DEPRESSION  *      |      * DEPRESSION  *  :
      |      *   STORAGE   *        |      *   STORAGE   *      |      *   STORAGE   *.>.:
      |      *             *        |      *             *      |      *             *  :
      |      * * * * * * * *        |      * * * * * * * *      |      * * * * * * * *  :
      |             |               |             |             |             |         :
      |             V               |             V             |             V         :
      |         Runoff to           |         Runoff to         |         Runoff to     :
      |         Surface A           |         Surface B         |         Surface C     :
      |                             |                           |                       :
      V                             V                           V                       :
    * * * * * * * * * * * * * * * * * * * * * * * * * * * * *                           :
    *                                                        *                          :
    *                    Upper Storage                       *.........>........:
    *                                                        *                          :
    *------ M O R E C S  SOIL MOISTURE MODEL ------          *                          :
    *                                                        *                          :
    *                    Lower Storage                       *.........>........:
    *                                                        *
    * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
                             :
                             :
                             V
                         Drainage
```

Figure 3 Loss Model

3.2 ROUTING MODEL

After rainfall excess is produced by the loss model, it is routed through a linear storage to simulate the attenuation and delay effects occurring on catchment surfaces.

Storage S (m^3) is related to outflow q (m^3/s) by a routing factor k,

$$S = k . q$$

and k is related to the rainfall intensity over the previous 10 minutes, I_{10}, by the relation :

$$k = c . I_{10}^{-0.39}$$

with c being a factor dependent on the type of surface. Normally this is derived from a regression equation on surface slope s (m/m) and contributing area A (m^2) :

$$c = f . s^{-0.278} . A^{0.374}$$

derived from analysis of 27 U.K. catchments (as described in the WASSPOS Overseas Model Manual). For paved surfaces and roofs, f is currently set at 0.37 and for pervious areas, it is 1.48. Other values can be supplied by the model-user.

Routing is performed by a simple, non-iterative procedure which replaces the non-linear reservoir calculations in WASSP-SIM. This has been tested in the WASSPOS model and the first version of WALLRUS, giving reasonable fits to recorded data.

3.3 STORAGE-DIVERSION MODEL

This has been added to allow close modelling of surface features or facilities for storing or diverting water, such as :

- gully pots (on-grade or in sags) and other entrances to a pipe system,
- throttling devices, and
- on-site detention storages.

Used in conjunction with various definitions of surface types and their interconnections, it is possible to model infiltration devices such as soakaways, and to describe overflows between surfaces within a sub-area. Overflows or diverted flows may also be directed to downstream sub-areas, or be lost from the system. Thus "major system" flows resulting from rare rainfall events (say 10 to 100 years return period) can be described.

This type of facility is provided in only a few of the available stormwater runoff models, e.g. in the IPSWM model (Wisner, 1983) and ILSAX (O'Loughlin, 1986). The procedure used in WALLRUS is based on that in ILSAX, and is explained in some detail below.

For each surface to be modelled, the user must specify a value for the following indicator, ISTDIV :

- a value of 0 indicates that there is no storage-diversion effect; flows are passed directly into the pipe system,

- a value of 1 indicates that there is no storage, but that entry to the pipe system is controlled by a relation between entry rate and arrival rate of surface flows, with excess flows being diverted. The relation is of the form :

$$q_{in} = CAP1 + CAP2 \cdot q_{app} + CAP3 \cdot q_{app}^{CAP4} \quad .... (1)$$

  with CAP1 to CAP4 being factors defined by the user.

- a value of 2 indicates that a storage effect is to be defined by a relation between entry rate to the pipe system and ponded volume, with an upper limit of storage specified. Any ponding in excess of this is converted to diverted flows. The relation is :

$$q_{in} = CAP1 + CAP2 \cdot S^{CAP3} \quad .... (2)$$

  where CAP1 to CAP3 are user-supplied factors, and S is the ponded volume.

In the two latter cases, a blocking factor between 0.0 and 1.0 can be applied to entry capacities, to allow for effects of debris or throttling devices. Setting this to 0.0 completely blocks the "entrance" and diverts all runoff onto the next surface.

Diverted flows can be directed to the following destinations, controlled by the indicator IDEST :

- for IDEST = 0, they are directed out of the system and lost,

- for IDEST = 1, they are directed to the next surface of the same sub-area and added to the rainfalls being fed into the loss model,

- for IDEST = -1, diverted flows are directed to the next surface, but avoid the loss and routing models and go directly to its storage-diversion model,

- for IDEST = 2, the diverted flows pass to another sub-area. The user must specify the branch and pipe numbers of this receiving sub-area and a factor IDSURF (+ or - 1, 2 or 3), indicating the number of the surface of the receiving sub-area onto which the diverted flow is directed. If this is positive, the flow is added to the rainfall entering the loss model, while if it is negative, it goes directly to the storage-diversion model.

(Within the WALLRUS program, whenever a flow is diverted to another sub-area, the number of the destination sub-area, the value of the diverted flow, and the IDSURF factor are recorded in a directory. As calculations proceed, checks are made through this directory, and if the current sub-area number and surface number coincide with a stored set, the diverted flow is added. The directory entry is then removed, so that it only contains diverted flows "in transit".)

This system is rather complicated, but it does allow great flexibility in modelling. Special data entry menus can make it easier to use.

Some examples of possible uses of this system are :

To model **entries to pipe systems**, Equation (1) above can be applied to on-grade gully pots or pits, in sloping gutters, while Equation (2) can be applied to sag pits. Figure 4 shows relationships for Australian pits on-grade (from the ILSAX Manual) with entry capacities which can be described by a power function relation. Depending on the parameters specified, Equation (1) can specify a constant value, a linear relation, a power function or a polynomial. (Studies on entry capacity relationships for U.K. gully pots are discussed in Hydraulics Research Summary 128, "Road Drainage".)

Small **on-site detention storages** can be described by Equation (2) with the entry capacity being constant, or related to ponded volume by a linear or power function relationship. Any overflows can be treated as diverted flows. Underground storages could also be described in this way.

Other devices may be modelled by combinations of surface types and storage-diversion devices :

Soakaways can be modelled as a surface with a high infiltration capacity and a storage-diversion device.

Roofs can be modelled as an impervious surface, with gutter or "rain barrel" storage being described by the storage-diversion model.

Roadways receiving bypass flows from gully pots or other diverted flows can be described as a surface, with the routing model being used to model the passage of these flows along the roadway and gutters.

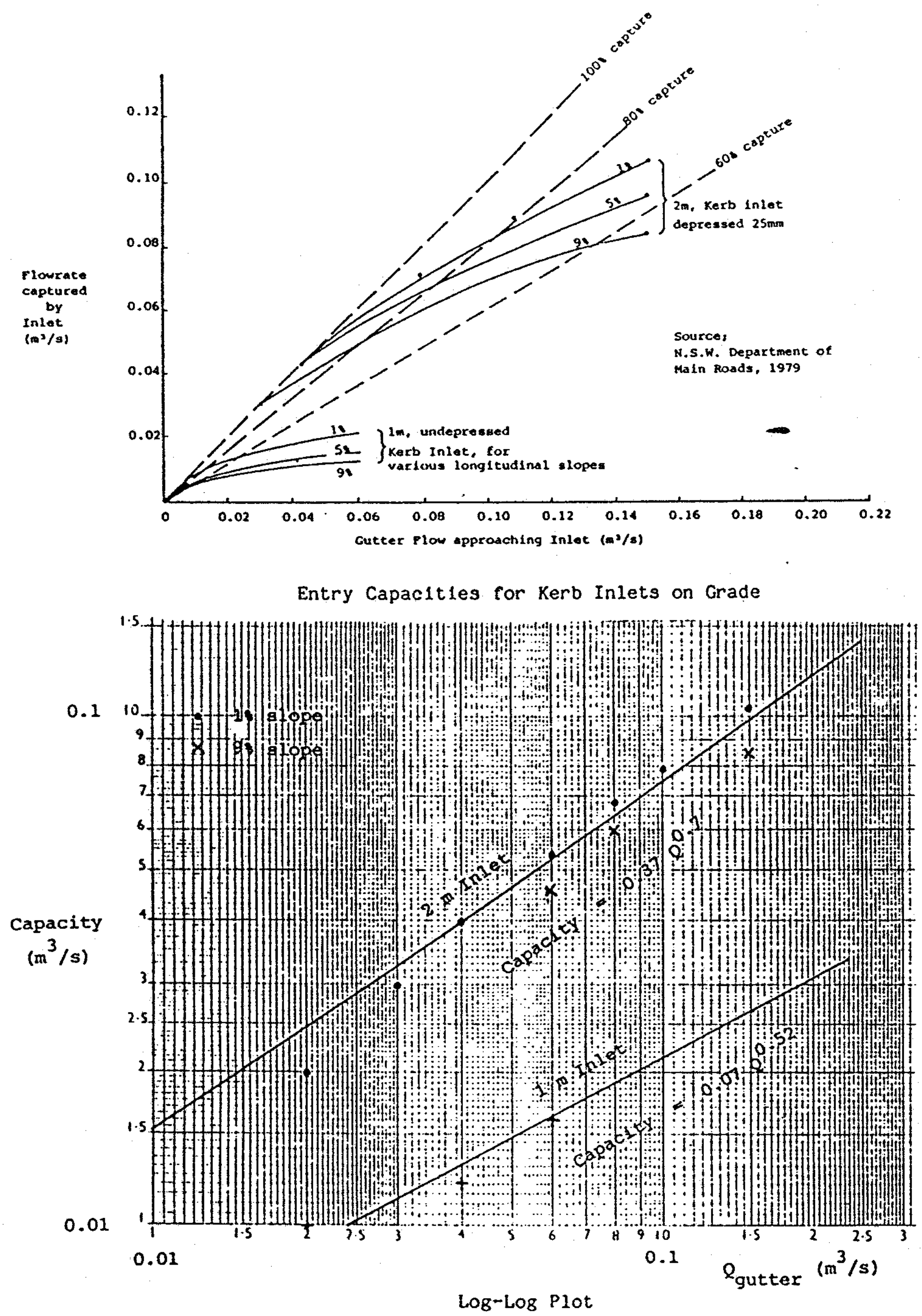

Figure 4 Sample Entry Relationships for Pits on Grade

4. FURTHER DEVELOPMENT

The model described has been implemented as a test version of WALLRUS, and testing and calibration will be carried out in 1988. The specific procedures outlined above will be refined and perhaps altered in order to ;

- give better fits to recorded data,
- work harmoniously with other components of WALLRUS (e.g. the sewered sub-area model), and related programs such as MOSQITO,
- be reasonably easy-to-use, and efficient as a computer program.

With the departure of Geoffrey O'Loughlin, Gary Moys will take over responsibility for the further development of the aspects of WALLRUS described in this report.

He will be coordinating the assembly of suitable test data, with the assistance of Water Research Centre, Institute of Hydrology and other organisations and individuals.

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