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A METHODOLOGY TO PREDICT THE POLLUTANT LOADS IN COMBINED SEWER FLOW

by

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SUMMARY

In the design of urban drainage systems, synthetic design storms are commonly used to predict the peak flow rate in sewer systems and such storms are usually based on local intensity-duration frequency curves or design storm profiles. To estimate the quality of storm flow, the UPM Manual (1994) has highlighted the development of detailed and sophisticated simulation models to estimate the pollutographs, that is, the temporal variation in the concentration of pollutants in urban drainage systems. The data requirements of these models are quite onerous, and as a consequence simplified models like SIMPOL have been developed. This model predicts the BOD at 1 hour time intervals and is based on the representation of the sewer system by a series of tanks. This approach may be considered satisfactory for the prediction of accumulative pollution over an annual series of events but for the prediction of acute effects, for example, the first foul flush, the temporal variation in the concentration pollutants in sewer flow is required. There is a need therefore to describe the change in pollution over a much smaller time interval than that proposed in SIMPOL and this is particularly so when consideration is given to the comparison of the design and control options which may be proposed, for example, the real time control of storage tanks to retain the first flush of pollutants.

The work outlined in this thesis presents an alternate simple methodology to estimate the pollutographs corresponding to a particular storm event. The work is based on the results of the measured pollutographs recorded on the WRc sewer quality archive (1987) from two catchments at Great Harwood and Clayton-le-Moors in the North West of England. The relationships for the shape of the pollutograph were obtained by the direct comparison of the observed pollutographs. The peak TSS concentrations were obtained by a detailed regression analysis of the observed peak TSS concentrations, the antecedent dry weather period and the hydrological parameters of maximum rainfall intensity, average rainfall intensity and storm duration. These parameters were then related to the shape of the pollutograph and the results of this methodology were shown to satisfactorily reproduce results for the catchments considered. For practical applications, the suggested procedure provides a methodology to calibrate the design pollutographs for any catchment from a limited number of monitored storm events and to utilise these together with time series storms to assist in the performance assessment and selection of alternative design options. The work has the limitation that it is catchment specific but as more information for different catchments becomes available, it may be possible to establish standard pollutographs for application to a wide range of catchment conditions.

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Contents

Chapter 1

Chapter 2

Chapter 5

Chapter 6

APPENDICES

List of Figures

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Chapter 6

List of Tables

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Chapter 6

List of Plates

List of Notations and Abbreviations

Δt	Time interval between occurrence of RFINT_{max} and TSS_{max}
AAR	Average Annual Rainfall (mm)
ADWP	Antecedent Dry Weather Period (hr)
API5	5-day Antecedent Precipitation Index
BOD_5	5-day, 20° C. Biochemical Oxygen Demand (mg/l)
CIRIA	Construction Industry Research and Information Association
COD	Chemical Oxygen Demand (mg/l)
CSO	Combined Sewer Overflow
DO	Dissolved Oxygen (mg/l)
DURN_{ff}	Duration of the first flush (min)
DWF	Dry Weather Flow (m^3/s)
EMC_f	Flow weighted Event Mean Concentration over the entire storm duration (mg/l)
EMC_{ff}	Event Mean Concentration in the first flush (mg/l)
EMF	Event Mean Flow over the entire storm duration (m^3/s)
EMF_{ff}	Event Mean Flow in first flush (m^3/s)
EPA	Environmental Protection Agency (USA)
FLOW_{tot}	Total inflow (m^3)
FSR	Flood Studies Report (NERC, 1975)
LOAD_{ff}	Cumulative Load of TSS in the first flush (kg)
LOAD_{tot}	Total Load of suspended solids (kg)

MOSQITO	Modelling of Stormwater Quality Including Tanks and Overflows
MOUSETRAP	MOdelling of Urban SEwers including TRAnsport of Pollutants
NERC	National Environment Research Council
NH_4N	Ammoniacal Nitrogen (mg/l)
NURP	Nation-wide Urban Runoff Programme (USA)
NWC/DoE	National Water Council/Department of Environment
PEAKEDNESS	$=RFINT_{max}/RFINT_{avg}$
PIMP	Percentage IMPervious area
PR	Percentage Runoff
PROFPK	Percentile of profile peakedness
QIN	Inflow rate (m^3/s)
QIN_{max}	Maximum inflow rate (m^3/s)
Q_{out}	Throughflow (m^3/s)
Q_{over}	Overflow (m^3/s)
Q_t	Threshold flow to cause TSS_p (m^3/s)
R^2	Square of the multiple correlation coefficient
$RAIN_{tot}$	Total Rainfall depth (mm)
RFINT	Rainfall intensity (mm/hr)
$RFINT_{avg}$	Average rainfall intensity (mm/hr)
$RFINT_{max}$	Maximum rainfall intensity (mm/hr)

SOIL	SOIL index
SPIDA	Simulation Program for Interactive Drainage Analysis
SQA	Sewer Quality Archive (WRc)
SRM2	Sewerage Rehabilitation Manual (2/e)
SSD	Sewer System Data
SSO	Storm Sewage Overflow
STDURN	Total storm duration (min)
SWMM	Storm Water Management Model
t	t of Student's t distribution
t_p	time to peak TSS concentration
TDS	Total Dissolved Solids (mg/l)
TKN	Total Kjeldahl Nitrogen (mg/l)
TRRL	Transport and Road Research Laboratory
TSR	Time Series Rainfall
TSS	Total Suspended Solids (mg/l)
TSS_p	Peak TSS concentration (mg/l)
UCWI	Urban Catchment Wetness Index
UPM	Urban Pollution Management Manual
VSS	Volatile Suspended Solids (mg/l)
WALLRUS	WALLingford RUnoff and Simulation
WASSP	WAllingford Storm Sewer Package
WRc	Water Research centre, Swindon, UK

Chapter 1

INTRODUCTION

1.1. Background

Intermittent storm discharges from collection systems have come to be recognised as a major pollution source in urban receiving waters. Urban runoff discharges from both separate sewers and storm sewer overflows are characterised by highly variable spatial and temporal pollutant loads (Ellis, 1989). These temporal variations depend not only on the type and volume of sediment available for transport, but also on the hydrological, catchment and sewer characteristics and the deposition, re-entrainment and transport processes which control the sediment movement (Verbanck *et al.*, 1994). These transient inputs can exert both acute (short term) and accumulative (long term) impacts upon receiving water quality (Harremoes, 1988).

In the UK, 96% of the population is connected to sewers (this is the highest percentage in Europe) and 70% of the drainage system consists of combined sewers (Ellis, 1989). Furthermore, it has been estimated that there are more than 22,000 combined sewer overflows (Morris, 1994) and these overflows contribute about one third of the pollution load to urban streams and watercourses (Andoh, 1994). The consequent flood and pollution alleviation works were estimated at £100 m/year and £40 m/year respectively (Ellis, 1989). Lack of hydraulic capacity and transporting efficiency in the existing urban drainage system has been identified as the main cause of surcharging, local flooding, in-pipe and in-stream pollution.

1.2. First Flush in Combined Sewer Systems

A characteristic often reported in the literature as a catchment response to a precipitation event is the "first flush". This is a phenomenon in which high pollutant concentrations are observed during the initial stages of a runoff event, the concentrations decreasing as the event progresses (discussed in detail in Chapter 2). In some catchments, the effect has not been observed at all, in others it had a strong significance. This variation in the quality of flow has been explained by relating it to the transport capacity of the runoff flow. The potential capacity to transport pollutants is high during the initial phases of an event, which would correspond to the rising limb of the runoff hydrograph. However, transport capacity is reduced considerably once the hydrograph peak is reached. The result is that a significant fraction of the mass load of an insoluble pollutant can be removed by a relatively small fraction of the total runoff volume. Such a situation results in high pollutant concentrations which are potentially damaging to water quality.

To retain the first flush to meet the water quality objectives for the receiving waters, it is frequently recommended that storage tanks be incorporated into the design of combined sewer systems. The concept is one of including an additional "storage" volume for the retention of both flow and pollutant load and these are often located at the site of a combined sewer overflow. The purpose of such tanks may be defined as follows (Saul and Ellis, 1992):

(i) to attenuate the flow and alleviate downstream flooding,

(ii) to control the flow to the downstream sewerage system to within its hydraulic capacity and to return an acceptable continuation flow from the storage tank to the treatment works, and

(iii) to retain the pollutants within the system, and in particular the first flush of pollutants thereby resulting in a corresponding reduction in the concentration and load of pollutants discharged from the system into the receiving watercourse.

If the overall aim is therefore to minimise the pollutants discharged to the receiving watercourse, then for such tanks to be effective in controlling the level of pollutants discharged to the environment, it is important that the optimum pollution load is retained within the system for a minimum storage volume and at an economic construction cost. Simulation of short time increment change in concentrations and loads is necessary for analysis of control options, such as storage and high rate treatment, whose efficiency may depend on the transient behaviour of the quality constituents where first flush mechanisms are influential. Hence, both the total pollutant loads discharged and the temporal variations in pollutant concentrations within an event need to be predicted to enable control measures to be taken.

Various techniques have been proposed to estimate the size (volume) of tank and Ackers *et al.* (1968) presented a design methodology for an on-line tank based on the volume of the dry weather flow which was overtaken by the toe of the advancing storm wave. Other methods, for example, Hedley and King (1971) proposed the retention volume as a proportion of the design storm. This was identified as the volume of flow upto the peak flow minus the volume of the continuation flow; with the selection of the storm return frequency reflecting the size and quality of the receiving stream which ranged from six months for a small stream to an overflow frequency of ten times per annum for large rivers. Common practice in Europe (ATV (Germany) Guideline A128, 1992) is to base the size of the tank on the retention of a specified rainfall amount falling on the impervious catchment area and a volume of storage equivalent to the retention of 1.5 mm - 4.0 mm of rainfall (15 m^3 - 40 m^3) per hectare of impervious area was recommended.

Presently, the preferred approach is to base the size and location of the storage volume on environmental quality standards to meet agreed environmental quality objectives of receiving waters. Mathematical simulation models to predict the quality of sewer flows, for example, HYDROWORKS-QSIM and MOUSETRAP have been developed for this purpose. The models have been shown to be capable of producing acceptable results and to aid the decision process. However, the data collection requirements of these and other detailed quality models are quite onerous. This limits the application of these models to major investigations (Clifforde and Tyson, 1993). A simpler approach is to base the design methodology to estimate the required size of a storage tank on empirically derived relationships between the pollutants (concentration and load) in the sewer flow and the hydrological and catchment characteristics which influence the sewer flow quality. In this respect, attention is often focused on providing a storage tank of sufficient size to retain the pollutants in what is commonly termed the first flush, that is, an increase in the concentration or load of pollution in the early part of the storm flow.

National programmes of research, for example, the US Environmental Protection Agency's (EPA) National Urban Runoff Programme, the Urban Pollution Management Programme in the UK and the French National Program on Runoff Pollution have been carried out to address these issues and these programmes have highlighted the need for an integrated catchment wide approach to pollution control. However, the urban runoff data banks and their subsequent analysis reflected specific urbanisation conditions or data collection program aims in the respective countries.

Nevertheless, a highly lumped parameter catchment schematisation has been identified as being sufficient for predicting receiving water quality and thereby satisfying the immediate engineering needs for sewer design and appraisal (Ellis, 1986).

1.3. Present Study

The aim of the study described in this thesis is to predict the pollutant loads in combined sewer flow utilising available UK water industry software and the WRc sewer quality archive data. The aims may be subdivided as follows:

(i) To develop a simplified model to estimate the total pollutant loads (based on a definition of the first foul flush appropriate to tank design) discharged in the first flush of pollutants resulting from a storm event,

(ii) To develop a simple methodology to define the pollutograph profile in combined sewer flow utilising the WRc sewer quality archive data, and

(iii) To subsequently apply the developed methodology to observed storms and time series rainfall utilising available UK water industry software and to identify an appropriate storage volume.

A highly lumped parameter model based on multiple linear regression analysis was attempted. Therefore, the intricate processes associated with the introduction of pollutants by other mechanisms, for example, from the catchment surface, gully pots or erosion and resuspension from the in-pipe sewer deposits, are not included in this study. However, the factors identified in causing their movement and build-up (for example, rainfall and the antecedent dry weather period) are examined in the lumped parameter formulation.

The above aims have been carried out using multiple regression analysis of the WRc sewer quality archive data set from two catchments - Great Harwood and Clayton-le-Moors in the North West of England. Pollutographs have been examined for trends in shape using curve fitting regression techniques. The methodology developed in this study has been applied to observed storms and time series rainfall to generate pollutographs. In this respect, the WALLRUS software has been used to simulate flows in the combined sewer system and subsequently to compute the optimum storage volume to retain a predetermined fraction of pollutant load.

1.4. Arrangement of the Thesis

A brief review of previous work considered relevant to the present study is presented in Chapter 2.

Using TSS as an indicator of pollution, a suitable definition of the first flush appropriate to storage tank design is formulated in Chapter 3. This definition is then used to develop a simple regression model to relate the total load of suspended solids in the first flush and the hydrological parameters most likely to influence sewer flow quality by reference to data collected at two sites - Great Harwood and Clayton-le-Moors in the North West of England. A multiple stepwise linear regression technique has been utilised for this purpose.

The prediction of total loads may be considered satisfactory for accumulative effects but for the prediction of acute effects, for example, the first foul flush, the temporal variation of the concentration and load of the pollution in sewer flow is required. Therefore, there is a need to describe the change in pollution over a much smaller time interval, for example, 5 minutes, and the development of a methodology to describe the design pollutograph corresponding to rainfall inputs from the various storm parameters is described in Chapter 4.

In Chapter 5, application of the methodology developed in Chapter 4 is made to describe the pollutograph together with the WALLRUS hydraulic modelling software to describe a methodology for the design of stormwater detention tanks. This methodology is oriented towards sizing a tank to retain a specific fraction of the pollutant load from an observed storm or Time Series Rainfall event.

Chapter 6 summarises the salient results of this study and identifies the scope for further work.

Chapter 2

REVIEW OF LITERATURE

2.1. Introduction

This chapter describes briefly the urban stormwater pollution process in relation to the first flush, then reviews some of the studies undertaken to examine pollution characteristics and the first flush phenomenon and also the various models available to predict water quality in urban sewers.

2.2. Background - The Urban Stormwater Pollution Process

Rainwater falling over the urban area scavenges various chemicals from the atmosphere, which reach the catchment surface and come in contact with other pollutants already accumulated on the surface from the abrasion of road surfaces and pollutants from commercial, industrial and residential activities, and occasionally from illegally disposed materials. The pollutants associated with the dust and dirt are then washed off by erosive mechanisms of both the rainfall and the runoff during the storm and transported to the sewer inlets as dissolved loads, suspended loads, or bed loads. Within the sewers, there are also contributions from foul sewage inflows and re-suspension of in-sewer sediment deposits before the flows are finally discharged to the treatment plant/overflows and eventually discharged to the receiving waters. The urban runoff pollution process can therefore be viewed as a four step process:

(i) build-up of pollutants over the catchment surface,

(ii) surface washoff due to rainfall runoff,

(iii) transfer through gully pots, and

(iv) transport, deposition and erosion in sewer pipes,

before the pollutants are discharged to the treatment plant/receiving waters.

As most of the water quality simulation models include build-up and washoff formulations, these processes have been discussed in the section on models (Section 2.5).

2.3. Pollution Studies

Over the past 40 years, many researchers have documented the pollution effects of urban sewer flows both in the UK and abroad. These are reviewed in the following sections.

2.3.1. Studies in the UK

Perhaps the earliest published work in the UK, an investigation of the quality of runoff waters (Wilkinson, 1956) at the London County Council housing estate at Oxhey, Hertfordshire draining on a separate system to the River Hartsbourne identified that in most of the storms, a first flush of stormwater occurred which was more polluting than the rest of the storm. For comparison between storms, fixed measures on a time and volume basis were used as measures of the first flush. On a time basis, a period of thirty minutes was chosen since the time of concentration for the sewage system was about 20 minutes, and it was observed that the concentration of polluting matter passed its peak between 20 and 30 minutes from the start of most storms before beginning to fall. On a volume basis, "the first flush was related to the time basis by taking a rounded value for the volume which was exceeded by the volume of storm flow during the first thirty minutes of one half of the storms sampled and which exceeded this volume for the other half of the storms". This volume was 55000 gallons - arrived at by arranging in ascending order the volumes which were discharged in 30 minutes from all the storms and selecting the median value. It was observed that the first flush contained concentrations of polluting matter roughly twice as great as subsequent flows. Between 43-50% of the polluting matter and 29% of the total volume of water sampled was discharged in the first 30 minutes flow and between 32-38% of the polluting matter and 20% of water was discharged in the first 55000 gallons of each storm. It was also observed that although in many storms the peak flow and peak strength of pollutants occurred at about the same time, there seemed to be no general correlation between strength and flow. Another aspect that was highlighted was that samples collected during 10 storms contained an average of 376 mg/l suspended matter and had an average BOD and permanganate values of 20 mg/l and 25 mg/l respectively which after filtration through paper reduced to 11 mg/l and 13 mg/l respectively. Thus, if a substantial proportion of the suspended matter in the runoff waters could be removed, a considerable reduction in the polluting load would result. It was therefore concluded that the provision of settling tanks for a major part of the runoff water would serve a useful purpose in reducing the solids discharged. It was also emphasised that one could not get rid of the pollution of surface water until after the end of the time of concentration.

Davidson and Gameson (1967) described the studies between 1958 and 1964 of the quantity and quality of storm sewage conveyed by combined sewers in three drainage systems as detailed in Table 2.1. The collection of the experimental data

Table 2.1. Catchment details (Davidson and Gameson, 1967)

Location	Monitoring period	Total catchment area	% roofed or paved	Median slope of sewers	Average CSA of sewers	Average yearly rainfall
	(years)	(ha)	%		(m^2)	(mm)
North-hampton	2	93	50	1:78	1.188	655
Bradford	3	68	28	1:49	0.222	721
Brighouse	3	240	11	1:23	0.317	787

lasted two or three years at each drainage area. The resident populations ranged from 5000 to 10000 and the times of concentration from 12 to 23 min. It was found that an empirical equation could be used to relate the duration of flows in excess of particular values to the annual rainfall, the size of the impermeable area, and the dry weather flow. This equation fitted the recorded flows at all three drainage areas with combined sewer systems - and at a fourth site in Luton where flows from a partially separate system were recorded with a reasonable degree of accuracy. A similar equation was used to define the volume which would have been discharged by an overflow at any given setting on each system. Less consistent results were obtained from measurements of the composition of storm sewage. Although the strength of storm sewage was found to depend to a certain extent on the time of the day, the time since the start of storm, and the flow, it was concluded that the influence of local conditions, such as the presence of deposition in sewers, could be of even greater importance. The approximate average maximum values of suspended solids are shown in Table 2.2. At Northampton, it was shown that scouring of material deposited in dry weather was responsible for the strong first flush during storms and the high average contents of storm sewage. There was no overflow at Northampton while at each of the other sites, there was an overflow. At Northampton and Brighouse, the composition of storm sewage was influenced by the length of the antecedent dry weather period, although this was found to have little effect at Bradford and it was identified that the concentration of solids was greatly affected by local conditions such as the presence of deposits within the sewer.

Table 2.2. Approximate average maximum values of suspended solids (Davidson and Gameson, 1967)

Time interval between successive storms	Suspended solids (mg/l)		
	Northampton	Bradford	Brighouse
1 hour	400	300	400
12 hours	700	260	700
5 days	1800	330	1000

Investigations of a combined and partially separate system of water drainage in the Haunch Valley area of Birmingham highlighted the heavy polluted loading discharged from a conventional storm sewage overflow (Hedley and King, 1971). It was found that there was no degree of quality separation between the flows in the main and overflow sewers. This work also identified the occurrence of a first flush as during storm periods the quality of water in combined or partially separate systems suffered from an initial high concentration of pollutants. Once the sewers had been flushed out, any further rainfall merely created a state of simple dilution within the sewerage system. Therefore it could be discharged to the nearest watercourse where it would be further diluted and have little aesthetic or environmental effect. It was also noted that this first flush had generally passed before the peak flow in the sewer was reached, which in turn, due to the attenuation in the system, usually occurred prior to the time of concentration. A subsequent five year assessment (Hedley and Lockley, 1978) of the provision and performance of retention tanks indicated that they afforded an effective, quick and cheap answer to the problem of undersized sewers receiving storm sewage and were therefore a cheap and simple remedy for the reduction of storm overflow pollution.

Ellis (1977) identified that the pollution loads resulting from storm water discharges to receiving streams in urban areas were primarily exerted by high concentrations of particulate materials. Chemographs for a separately sewered development in the North West suburbs of Greater London showed a double peaking of suspended solids concentration with a strong first flush phenomenon and the subsidiary peak occurring on the back of the recession limb of the flood. However, in most storms, runoff remained highly turbid, often for a considerable time after the peak discharge as indicated by the level of suspended solids concentration. This implied that the catchment area could not be rapidly cleaned by the first flush of storm water to the sewer system. The first flush of particulate materials varied in concentration between 85 and 4500 mg/l with the relation of the solids peak to discharge peaks being quite variable. Occasional lags of the flood wave behind the sediment wave were explained in terms of flow characteristics and the growth of mats of Sphaerotilus fungus in the sewer system. This leading prime sediment peak was explained by the relatively poor flow characteristics of the stormwater sewer system, particularly in the concreted culvert sections. Solids settled and lodged within the system as lag deposits during antecedent storm recessions, but were rapidly and efficiently flushed out on the rising limb of the storm wave and thus entrainment preceded the sewer routing event. The subsidiary peak, representing fresh sediment introduced to the street surface from roofs, pathways and driveways, could be delayed behind the prime peak by upto 3 h, depending on the intensity and duration of the storm event. However, it was shown that the quality of storm water, in terms of particulate concentrations, normally improved after a time period equal to the time of concentration of the sewer system. An apparent linear trend was observed between turbidity and suspended solids. From the analysis of pollutants in terms of the characteristics, components and sizes of particulates discharged, it was noted that the major characteristics of storm water solids which affected receiving water quality were particle size and composition, with the solids fraction below 0.06 mm and percentage organic contents being of prime importance.

A study of two separately sewered suburban catchments (undertaken in 1973-74) in Nottingham, England (Tucker and Mortimer, 1978), demonstrated that the major factors determining the load of total suspended solids discharged in runoff were the catchment impervious area and the volume of runoff. Pollutographs for individual storms revealed that the duration of the preceding dry weather spell and the rainfall intensities occurring in each storm were the influencing factors. Two phases or patterns of solids concentrations were identified - a first flush phase and a subsequent intensity related phase. It was suggested that the mechanisms of generation and removal of solids were different in the two phases, and this was supported by the differences in the nature of the materials observed in each phase. First flush solids were identified as being primarily composed of fine low density material having a high organic content - which was considered to be derived from solids accumulating on catchment surfaces during the preceding dry weather spell, and also from the solids deposited or produced by anaerobic degradation in road gullies. Solids obtained in subsequent runoff were identified as being primarily inert and inorganic, and were considered to be derived from scouring and erosion of surfaces under rainfall forces. There was little evidence of washoff, and the generation of these solids was attributed to the rainfall intensity. Comparisons of all storms showed that the first flush phase was normally confined to the initial runoff (from impervious area) of 0.4 - 0.9 mm. The mass of first flush solids produced in the storm was shown to be proportional to the duration of the preceding dry spell.

Thornton and Saul (1986) described the results of the fieldwork program of research in which the quality of storm sewage flows were monitored at the downstream end of the combined sewer system at Great Harwood, Lancashire. During a ten-month study period 41 separate storm events were monitored and the samples extracted were analysed for Total Suspended Solids (TSS), Chemical Oxygen Demand (COD), Total Dissolved Solids (TDS) and Ammonia (NH_4N). The pollutant concentration in the dry weather flow were observed to follow a diurnal pattern. For over 75% of sampled storm events a distinct foul flush of suspended solids and chemical oxygen demand was observed. Total dissolved solids and ammonia almost always demonstrated a dilution pattern during storm flow that was inversely related to sewer flow rate but a first flush of these determinands was observed in some winter storms. This suggested that the levels of these dissolved pollutants was dependent upon the degree of dry weather flow dilution. Two types of SS and COD first flush were identified and were related to the length of the antecedent dry weather period, the quality of the prevailing dry weather sewage, the maximum rainfall intensity and the sewer discharge. They concluded that both concentration and load criteria should be considered in any assessment of combined sewer quality performance.

In a related study, Pearson *et al.* (1986) presented further confirmation of the results of this study. During a two year period (February 1984 to February 1986), 113 separate storm events were monitored. For approximately 90% of the storm events sampled, a distinctive first flush of suspended solids and COD was observed while ammonia and conductivity almost always followed a dilution pattern inversely related to sewer flow. Using step-wise multiple regression analysis (SPSS), the maximum recorded SS and COD concentrations in the first flush was related to the length of the antecedent dry weather period, the pollutant concentration in the dry weather flow and the maximum rainfall intensity. However, the degree of correlation between the variables (maximum 44%) showed that further work was required to achieve a fuller understanding. A description of the instrumentation used at a typical field site and the monitored temporal variation of pollutants for a number of storm events was described by Saul and Thornton (1989). Their results showed the complexity of the monitored pollutographs and highlighted the large number of variables influencing combined sewer flow quality. They identified that the rainfall intensity and duration and the rate of increase and the volume of sewer flows were the important parameters in the prediction of sewer flow quality.

Ashley *et al.* (1992a) reported a first and second flush of suspended solids for the main Dundee interceptor sewer during storm conditions. The bedload Type C mobile fine-grained deposits which overlay the Type A coarse loose material (Crabtree, 1989) in the Dundee interceptor sewer were found to be relatively weakly resistant to erosion due to their dilute nature and were considered to comprise material which could be readily eroded as a first flush (Ashley *et al.*, 1992a) in conjunction with solids washed-in rapidly by roof runoff.

2.4. The First Flush

From the above studies, it is clear that the first flush may be identified as the relatively high proportion of the total storm pollution load that occurs in the initial part of the combined sewer runoff. There is much evidence to support the view that the first flush regularly occurs in many combined sewer systems (Amandes and Bedient, 1980; Mance, 1982; Pearson *et al.*, 1986; Thornton and Saul, 1986, 1987; Ashley *et al.*, 1992a) but in large catchments its distinctive shape may be lost (Stotz and Krauth, 1984; Geiger, 1986). Hence the concentration of pollutants associated with the first flush has been shown in literature to vary considerably in both magnitude and duration.

2.4.1. Importance of the Flushing Phenomenon

A need for a better understanding and modelling of the first flush phenomenon in combined sewer systems has been identified in order to reduce the high level of pollution caused by combined sewer overflow (CSO) discharges upon receiving watercourses (Thornton and Saul, 1987). The knowledge of the characteristics of the flushing processes in combined sewer systems during the occurrence of stormwater runoff from catchment subareas is advantageous because storage basins can then be located at sites in the sewer network where significant first flush effects can be expected. In systems without storage, this first flush of pollutants would heavily pollute the watercourse. However, by the inclusion of a storage tank, this first flush could be retained and the effluent be discharged in a controlled manner, thus reducing the concentration of pollutants in the spilled flow. Thus the control of the release of sediments and associated pollutants from eroding sediment deposits in sewer systems then becomes very important in order to minimise pollution.

2.4.2. Definitions of the First Flush

Several definitions of the first flush have been proposed. These generally relate to the observation of high concentrations of suspended sediments (and other pollutants) within the first part (not precisely specified) of the storm or combined sewer flow. To define a first flush much use has been made of the relationship between the percentage of total load of pollutants and the percentage of cumulative event flow. A dimensionless ratio is plotted on the ordinate, representing the fraction of total pollutant load which has been removed from the catchment. Corresponding to this on the abscissa is a similar ratio, representing the fraction of runoff volume which has left the catchment. For example, with reference to Figure 2.1, Geiger (1984, 1987) and Stotz and Krauth (1984) suggested that a first flush was observed when this curve had an initial slope greater than 45°, that is, the fraction of pollutant load removed is larger than the corresponding fraction of runoff volume. The 45° degree line shown on the graph represents a condition of uniform pollutant removal from the catchment. Conversely, dilution was assumed to occur when the slope of this line was less than 45°. The percentage deviation of the cumulative load curve from the diagonal was used as a measure of the strength of the first flush or dilution; less than 5% was considered indifferent, 5-20% was termed a moderate flush, and greater than 20% was a strong flush (positive) or dilution (negative). In each case the volume and load in the first flush was defined by the point of maximum divergence from the equilibrium line as highlighted in Figure 2.1. While the load flow relationships of different pollutants sometimes differed substantially for individual events, the average over all events yielded similar relationships for all pollutants.

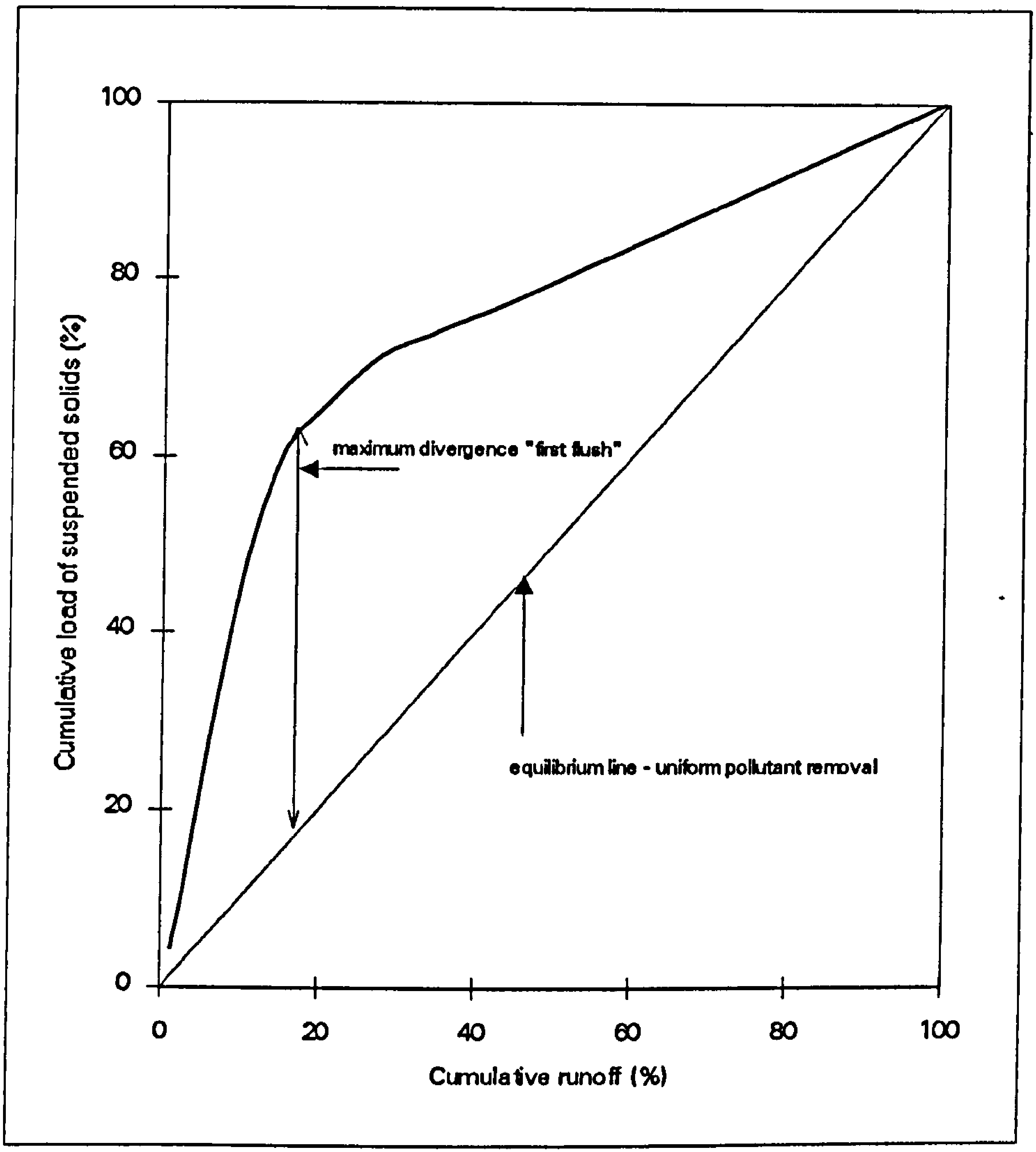

Figure 2.1. First flush as defined by Geiger (1984).

Thornton and Saul (1986) and Pearson *et al.* (1986) defined the first flush as the initial period of storm flow during which the concentration of pollutants was significantly higher than those observed during the latter stages of the storm event. In respect of total suspended solids and chemical oxygen demand, two types of first flush were defined and they were termed Type A and Type B. In a first flush of Type A, the concentrations of TSS and COD were less than, or equal to the concentration in the prevailing dry weather flow and the highest recorded pollutant concentration preceded that of the peak storm flow. Also, there was a continued sharp decline of SS and COD concentration following the initial inflow of storm water to the system. It was hypothesised by the authors that the first flush of Type A resulted from the mixing of dry weather sewage and storm water at the front of the advancing flood wave in the combined sewer system and the SS and COD within the first flush were derived entirely from the pollutants in the dry weather flow. In the Type B flush, concentrations of TSS and COD were greater than the corresponding concentrations in the prevailing dry weather flow. There was an initial increase of TSS and COD concentration to a peak which almost coincided with the peak of storm flow. The pollutant concentrations/loads in the first flush of Type B were attributed to the scouring of in-pipe sediment deposits or from the erosion and washoff from the catchment surfaces. It was further hypothesised that the Type B flushes were strongly related to the antecedent dry weather period (ADWP) and rainfall intensity.

Other definitions include that by Nichols and Short (1992) who suggested that the first flush could be expressed (somewhat arbitrarily) as the amount of rainfall occurring during the 5 year average recurrence interval critical duration storm over a period equal to the time of concentration plus t minutes. This volume would include therefore at least the first t minutes of runoff from all parts of the catchment. For their Illawara catchment in Australia, t was taken equal to 10 minutes. Similarly, Ichiki *et al.* (1993) defined the runoff load during the first flush as the integrated load from the beginning of the storm flow upto the point of the first flow peak.

Using these definitions, several attempts have been made to quantify the first flush phenomenon and these studies highlighted that the time of the day, the antecedent dry weather conditions, the length of the antecedent dry weather period, the magnitude and pollutant characteristics of the dry weather and the storm flows, together with the characteristics of the sewer system and the layout and size of the catchment area, all influenced the temporal variability in the concentration and the load of the pollutants. Also, the deposited sediment in sewers during the dry weather period could be scoured and re-entrained and transported downstream as a first flush in the concentration and load of pollutants. The effects of these factors on the first flush are discussed in the following section.

2.4.3. Occurrence of Foul Flushes

Foul flushes are not observed universally, and are not always observed within the same sewer for different events. However defined, and when observed, the occurrence of foul flushes is invariably attributed to the washout of previously deposited sediments. The deposition of these sediments, in turn, is governed by various above ground factors - for example, surface washoff and effect of gully pots. The principal factors influencing the occurrence of foul flushes may be identified as:

(i) in-sewer sediments,

(ii) surface washoff,

(iii) gully pots,

(iv) antecedent dry weather period (ADWP),

(v) the pollutant concentrations in the preceding dry weather flow,

(vi) the contributing catchment area,

(vii) time of the day,

(viii) rainfall, and

(ix) sewer system characteristics.

2.4.3.1. First Flush and In-Sewer Sediments

The origin of first flush of pollutants observed at the onset of storm flow in many combined sewer systems have been attributed to the scouring/reentrainment of in-pipe sediments deposited during extended periods of dry weather (Saul and Thornton, 1989; Krejci *et al.*, 1987; Lindholm, 1984; Lindholm and Aaby, 1989; Geiger, 1987; Verbanck *et al.*, 1994; Crabtree, 1989; Fletcher *et al.*, 1978; Mance, 1982; Lindholm, 1984). Dry weather pipe deposits sedimented out from the recession limb of previous storms become readily lodged in the sewer system (Mance and Harman, 1978). Such solids can have a low critical erosion velocity and become easily entrained and transported during the onset of the next storm event, their supply being depleted as peak flow and the time of concentration for the system is reached (Ellis *et al.*, 1981). Accumulated sediment deposits inhibit the satisfactory performance of a sewer system in two ways: firstly, they restrict the hydraulic capacity and conveyance efficiency causing surcharging and premature CSO spillage, and secondly, sediments act as a store of pollutants which may have an acute, shock-loading effect upon the receiving water resulting from the first-foul flush of contaminated solids. Field investigations indicated that about 10% of all sewers have permanent sediment deposits (Goodison and Ashley, 1990) and upto 20% of suspended solids may be deposited during dry-weather flows (Geiger, 1987). The CIRIA report (1986) indicated that the nature of sediment tended to vary both from catchment to catchment and within any particular system. Further, it was also identified that in the UK, upto 25000 km of sewers and drains, particularly older combined sewers, were affected by significant accumulation of in-pipe deposits.

2.4.3.1.1. Sediment Classification

Crabtree (1989) suggested five categories of sediment deposit based on observations of the nature and location of the deposits within the sewer system and these are shown in Table 2.3 and Figure 2.2.

Table 2.3. Sewer sediment type classification (Crabtree, 1989)

Type	Description
A	Coarse, loose, granular, predominantly mineral, material found in the inverts of pipes;
B	As A, but concreted by the addition of fat, bitumen, cement, etc. into a solid mass;
C	Mobile, fine grained deposits found in slack flow zones, either in isolation or above A material;
D	Organic pipe wall slimes and zoogloeal biofilms around the mean flow level;
E	Fine-grained mineral and organic deposits found in SSO storage tanks.

Type C and Type A deposits were considered to be the most significant sources of pollutants. The resuspension of Type A deposits was identified as the cause of the high pollution loads associated with extreme rainfall events. Further, it was suggested that Type C deposits which are the mobile fine grained deposits are the source of material discharged during the frequently observed first flush in many sewerage systems in response to average storm events. Types A, B and E deposits were the most significant in terms of restricting sewer flows. Hence, their removal has been identified a common operational requirement.

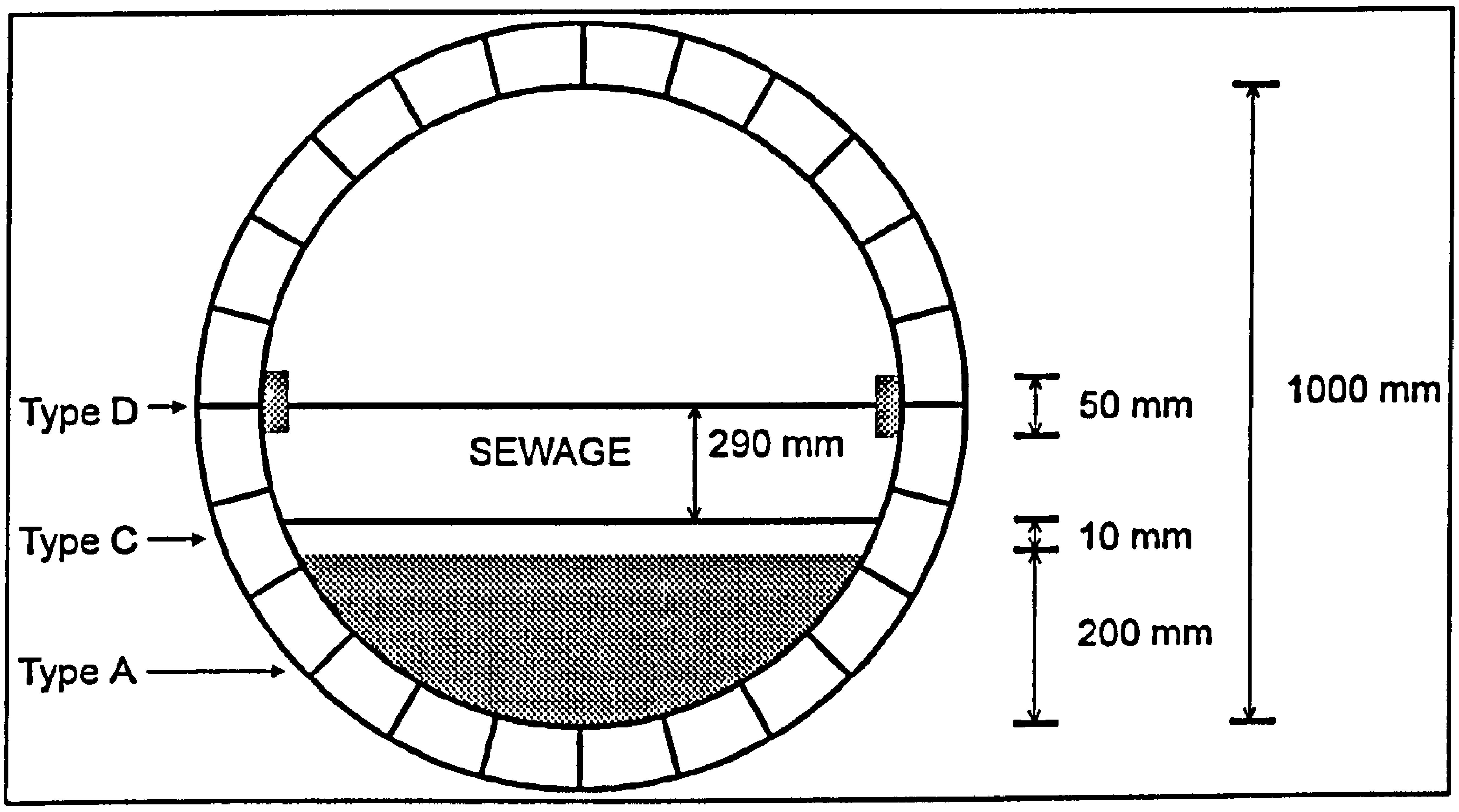

Figure 2.2. A typical sequence of sediment deposits in a combined sewer pipe.

A recent review by Verbanck *et al.* (1994) on the nature, occurrence and erosion/deposition of sewer sediments and their associated pollutants described solids found in sewers as:

(i) Fine material - always present in suspension and found in the bed in tranquil zones;

(ii) Grit - a major bed constituent, and a part of the bed load in combined sewers; and

(iii) Sanitary solids - found in suspension in combined sewers.

Differences between the solids transported in the fluid sediment mode during dry and wet weather as well as differences between the particulates conveyed in the trunk and interceptor sewers were reported.

Under dry weather flow conditions, flows in sewers were observed to be stratified and pollutants and sediments were identified as being transported in three phases described as suspended, wash and bed loads (Ashley and Crabtree, 1992), corresponding to the classical definitions of the sediment movement in natural channels (Verbanck *et al.*, 1994). Investigations in Dundee demonstrated the importance of the bedload phase of transport from a study carried out to investigate the rate and nature of the material so conveyed during dry weather in an interceptor sewer (Ashley *et al.*, 1992a). The weak yield strength of the bed load layer (Ashley *et al.*, 1992b) together with the high pollutant strength suggested that its erosion was rapid and a primary contributor to first flushes in combined sewers. Observed values of erosive stresses in Dundee for deposited foul flow sediments in the range 1.5-2.0 N/m^2 were generally similar to those observed elsewhere (Ashley *et al.*, 1993). The only other reported studies of bed-load transport are for the No. 13 trunk sewer in Marseilles (Laplace *et al.*, 1992).

Difficulties of investigating sanitary sewers due to storm induced effects implied that most data so far only relate to combined sewers during DWF periods. These results are of limited value for characterising sanitary inputs because of the a priori effects of storm flows on the sediments in the system. Other factors complicate the prediction of sediment transport rates such as the cohesive nature of sediment deposits, the effect of concretion and the change with age of the physical, chemical and biological properties of the deposited sediments within the sewers.

2.4.3.2. Surface Washoff

It was hypothesised by Thornton and Saul (1986) that the secondary flush was related to the erosion and washoff of pollutants from catchment surfaces and the scouring of upper pipe sediment deposits. It was also suggested that the subsidiary peak on the recession limb of the flow hydrograph represented fresh sediment introduced to the below ground system from erosion and entrainment of material lying on roofs, paths and driveways which was often delayed behind the first peak (Ellis, 1976). The surface washoff of solids and associated pollutants into the sewers was identified as being dependent upon landuse and rainfall intensity (Ashley *et al.*, 1992a). Impermeable surfaces, particularly roads, tend to be implicated as a source of sediment. In the UK, it has been reported that 11.5 tonnes/km/annum of rock salt, sand and grit are spread on major roads to ameliorate the effects of winter ice and snow (CIRIA, 1986). Other constituents of runoff from urban impermeable areas were identified as fine particulate matter, fallen leaves and litter which contribute to the high polluting load built up within sewer sediments.

2.4.3.2.1. Build-up of Particles on the Catchment - Atmospheric Deposits and Roof Runoff

Aerial deposition can contribute on an average 40-45% of nutrients and heavy metals associated with the total mass discharged from urban catchments (Ellis, 1986). Dempsey *et al.* (1993) showed that most contaminants were associated with particles even during the storm and runoff events, especially if the pH remains above 7. Roof surface runoff also contributes to the total solids, nutrients, metals and bacterial loads. Significant zinc loads from roof runoff in the commercial and industrial landuses were also reported (Bannerman *et al.*, 1993; Good, 1993). Samples from the first flush of roof runoff from five sawmill roofs in coastal Washington during a storm that followed eight days of dry weather indicated that roof runoff could not be used as a source of clean water to dilute stormwater discharges (Good, 1993). The short times of concentration (3-5 minutes) in roof runoff flows represent significant components of the early and peak discharges recorded in storm drains. Whilst disconnection of roof down pipes can attenuate and reduce storm sewer peak flows by 10-30% and total runoff volume by upto 50%, the potential toxicity of roof discharges may make the on-site disposal unacceptable at many locations.

2.4.3.2.2. Street Runoff

Streets were identified as the critical source areas for most contaminants in all the land uses (Bannerman *et al.*, 1993). Parking lots were also identified as being critical in the commercial and industrial landuses while lawns and driveways contributed large phosphorous loads in the residential land use. The earlier studies of Sartor *et al.* (1974) on the effects of urban runoff on water quality centred on the classification of street surface deposition, the contribution of this contamination compared to other pollution sources, and the efficiency of street cleaning and other contaminant removal practices. Runoff from street surfaces was identified as being highly contaminated containing high concentrations of polluting material. Calculations based on a typical city indicated that the runoff from the first hour of a moderate to heavy storm (at least 1.27 cm/hr) contributed considerably more pollution load than the city's sanitary waste during the same period of time - for a situation in which streets were cleaned on the average of about once every five days. A great portion of the overall pollution potential was associated with the fine solids fraction of the street surface contaminants. The major constituent of street surface contaminants was consistently found to be inorganic, mineral-like matter, similar to common salt and sand. Significant amounts of heavy metals were also detected - zinc and lead were the most prevalent. Also, street surface runoff collected additional waste loading from animal wastes, leaves, grass clippings, engine oils and detergents, combustion by-products, vehicle wear and tyre shredding, soil erosion, etc. The quantity of contaminant material existing at a given test site was found to depend upon the length of time that had elapsed since the site was last cleaned, either by sweeping or flushing or by rainfall. The principal factors affecting the loading intensity at any site include the land use, the elapsed time since streets were last cleaned, local traffic volume and character, street surface type and condition, public works practices, and seasons of the year.

Runoff from impermeable highway surfaces were found to be highly contaminated with accumulated mass rate of pollutants being a function of aerial deposition rate, average daily traffic density and the intensity and frequency of the rainfall event (Ellis, 1989). Modelling studies suggested that impermeable urban surfaces virtually provided an unlimited sediment store for washoff such that surface accumulation could be adequately represented by a simple linear function. In another study, metal loadings from a residential street surface carrying low traffic densities were shown to be primarily controlled by stormflow and duration factors (Ellis *et al.*, 1986). This was explained in terms of threshold requirements relating to sediment storage, retention and entrainment on the asphaltic surface and the water losses on the impermeable surface. Antecedent dry period did not appear to be an important factor in explaining variations in pollutant loadings. Analysis of input and removal rates suggested that aerial deposition provided the major source of most metals entering the road drainage system. However, this study was concerned only with the above ground phase of rainfall runoff and concluded that, contrary to previous urban rainfall - runoff assumptions, highway surfaces could not be considered to be completely watertight and that further modelling studies would require more flexible time based storage and infiltration coefficients for the highway surface.

Apart from peak concentrations of suspended solids during short intense street runoff from rain, concentrations of suspended solids in snow melt runoff were reported to be two to fivefold higher than in rain runoff (Daub *et al.*, 1994).

Although dirt which accumulated on the road during a long drought would be washed off with the first storm, its amount would depend on many factors such as wind and sunshine, and not merely the rainfall (Wilkinson, 1956). In foggy weather, the surface of the road might be wet and coated with slimy mud, motor traffic would throw this on the grass verge and clean the road quite considerably. In an average housing estate there would probably always be some building material on the roads, and the building operations were therefore taken as being part of the normal activities in an estate.

2.4.3.3. Role of Gully Pots

The dissolved pollutants in catch basins were identified as making significant contributions to the first flush phenomena and to stormwater pollutant loadings (Butler *et al.*, 1995; Morrison *et al.*, 1995). Between storm events the gullypot sediment and liquor underwent changes in composition as a result of biochemical reactions thereby increasing BOD, COD and total heavy metal concentrations of pot liquor. Concurrently, some material previously held in suspension in the inflow, settled to the base of the pot to form a bed of inorganic, organic and non-particulate matter, similar in nature to sewer sediment while significant amounts of smaller or lighter material remained in suspension.

During storm events, incoming runoff rapidly displaces the standing liquor including its dissolved and suspended polluted load. Although low return period events may not flush all the liquor from the pot, the displaced volume represents a significant fraction of the total flow volume and pollutant load, contributing notably to any first flush. While the quantity of liquor in each pot is under 100 litres, over the whole catchment, the volume is significant. The displacement of the liquors is typically 50-70% of the total and liquors are estimated to be responsible for an average of 11% SS, 21% Dissolved solids, 14% BOD, 21% COD, 32% NH_4N and 16% NO_3N. Ashley and Crabtree (1992) identified that solids washed into gullypots contained organic fractions of upto 40% and possessed a size composition in which 75% of the particles were less than 250 μm in diameter.

However, such inlet chambers were identified as extremely poor sedimentation basins and could retain little of the finest, heavily contaminated particulate fractions. It was demonstrated that overall trap efficiency was a direct function of inflow rates and inflow rates in excess of 3-4 l/s were shown to lead to significant disturbance, mixing and mobilisation of the inlet chamber contents. The solids trapping efficiency was high for particles in excess of 300 µm, but poor for the smaller particles which carried proportionately more of the pollutant load. It was further indicated that flushing/cleaning of a gullypot was ideally required at 4-7 days intervals to provide maximum control of pollutant outflows to the sewer system. In the absence of such regular maintenance, gullypots could only act as effective grit chambers with limited contributions to the removal of persistent toxic pollutants which were washed off from highway surfaces. Gullypots were likely to accentuate stormwater pollution problems through biochemical transformation and release of pollutants from the sediment to the dissolved phase.

2.4.3.4. Length of ADWP

Storms characterised by a long Antecedent Dry Weather Period (ADWP) were observed to have first flush concentrations of SS and COD that were at least 2 or 3 times higher than storms of short ADWP (Thornton and Saul, 1987). This was related to the build-up of sediments and sediment related pollutants during long periods of dry weather which were subsequently flushed from the combined sewer system by stormflow. In the UK, numerous storms with time intervals of upto five days were recorded, but storms with longer intervals were somewhat rarer (Hedley and King, 1971).

However, Ellis *et al.* (1986) reported that there was considerable contradiction in the literature regarding the importance of antecedent conditions in controlling pollutant runoff levels. Both Reinertsen (1982) and Pratt and Adams (1981) considered that runoff loadings were availability limited functions with initial rainfall intensity being important for particle and pollutant removal. Urbonas and Tucker (1980), whilst relating total loads to total runoff volume and antecedent precipitation, also noted a decreasing effect with increasing runoff. Storm rainfall depths over the road surfaces need to be high to produce any effective runoff and this would imply the existence of considerable depression storage and infiltration capacities. Therefore, both total rainfall volume and overland flow velocities will need to be high to overcome the initial resistance provided by both the amplitude and scale of surface roughness as well as by the particle size characteristics. The state of road surface wetness might therefore also be important in overcoming the initial high infiltration losses and lead to a rapid "drowning" of the surface roughness, reducing local bed shear stress and throttling small surface apertures. Ellis *et al.* (1986) reported the results of their study of an evaluation of hydrological controls on pollutant removal rates for a well defined highway catchment of little surface variation, carrying relatively low traffic densities and possessing minimal alternative landuse interferences. This study was concerned only with the above ground phase of rainfall runoff and suggested that antecedent dry weather period (ADWP) length was insignificant in explaining any variation in pollutant loadings. This agreed with the work of Jewell *et al.* (1980) who found that ADWP correlated weakly with both metal and solid concentrations in highway runoff. Similar results were reported by Mance and Harman (1978) for their Stevenage (UK) catchment. A number of studies (Pearson *et al.*, 1986; Stotz and Krauth, 1984) where suspended loads were measured, showed correlation between the type of first flush and the antecedent dry weather period. In other studies, particularly on larger systems (Geiger, 1986), the first flush was found to be dependent on the dry weather flow levels. The analysis of the first flush effects indicated no dependency of the first flush amount on preceding dry periods (Geiger, 1984).

2.4.3.5. The Quality of the Dry Weather Flow

The importance of dry weather flow (DWF) regimes with regard to sediment deposition and availability for subsequent foul flushes were extensively reported (Ashley *et al.*, 1992b). Important differences were reported between summer and winter flows and transport rates of solids, generally with winter flow being higher than in summer. Overall, the depth of the sediment in the main sewer remains fairly constant and shows no tendency to change significantly between summer, winter or due to storm flows. A rating curve based on a regressional analysis of flowrate versus total suspended solids for dry weather flow was formulated (Coghlan *et al.*, 1993), no such relation could be suggested for storm weather flows.

2.4.3.6. Contributing Catchment Area

Large catchments may not experience a distinctive first flush (Geiger, 1984). Some attempts were made to relate the occurrence of first flushes entirely to catchment size (Stotz and Krauth, 1986) and results from Munich-Harlaching for a large catchment were compared with other reported instances and it was concluded that flushes were less likely to occur for catchments which exceeded 100 ha of impermeable contributing area, independent of average bed slope. It was demonstrated that flushing effects taking place in sewer sections of the catchment subareas did not necessarily result in a first flush effect in the main sewer for the catchment area as a whole (Stotz and Krauth, 1984). This was the case when the flow time for the storm water runoff is equal for all catchment subareas. Under such cases, more storage capacity was required for containing that portion of the runoff carrying 70% of the suspended solids.

2.4.3.7. Time of the Day

First flush depended on the time of the day when runoff started (Geiger, 1984). On the basis of extensive measurements of flow and different pollutants over a period of five years in Munich-Harlaching, the diurnal variation of depositions due to dry weather flow velocities was found to be the driving factor for flushing rather than antecedent dry spells (Geiger, 1987).

2.4.3.8. Rainfall

First flushes were found to correlate with rainfall rather than the antecedent dry weather periods (Lindholm and Aaby, 1989).

2.4.3.9. Sewer System Characteristics

The suspended solids discharged into the sewers during storms depend on the geometric and hydraulic characteristics of the sewer system. The characteristics of the flushing processes in sewer sections are largely dependent on the individual bed slopes (Stotz and Krauth, 1984). Other features such as the extent of the sewer system, the geometry (change in pipe direction and non-uniformity of pipeline construction) of the sewers and the loading density of the sewer inflows may also create ideal conditions for the build-up of sediment and these effects are likely to be distributed randomly throughout the sewer system. The variation in dry weather velocities alone may substantially determine the amount of material available when storm runoff starts. The reported variations in occurrence of foul flushes may therefore be attributable entirely to differences in the sewer networks studied.

2.5. Modelling Tools

2.5.1. Introduction

Sewer system planning and design are generally conducted using computer modelling tools and procedures. Huber (1992) identified that a reasonable approach to the simulation of urban runoff quality was to use the simplest approach that would address the project objectives at the time. This implied starting with a simple screening tool such as constant concentration or regression or statistical approach. If these methods indicate that more detailed study is necessary or if they are unable to address all the aspects of the problem, for example, the effectiveness of control options, then one of the more complex models must be run. No method currently available can predict absolute values of concentrations and loads without local calibration data, including complex build-up and washoff models. Thus, if a study objective is to provide input loads to a receiving water quality model, local site-specific data will probably be required. However, several methods and models might be able to compare the relative contributions from different source areas, or to determine the relative effectiveness of control options (if the controls can be characterised by simple removal fractions). When used for purposes such as these, the methods including build-up and washoff models, can usually be initiated on the basis of best currently available source of quality data. When properly applied and their assumptions respected, models can be tremendously useful tools in analysis of urban runoff quality problems.

Empirical models (for example, Hogland *et al.*, 1984; Stotz and Krauth, 1986) are usually site specific or apply only to collector sewers of small diameter, although their application for developing overall planning tools in the absence of more refined techniques, has been reasonably successful.

2.5.2. The Probabilistic Approach

This is based on the premises that rainfall, hence runoff and pollutant events in urban catchments are inherently random and fluctuating phenomenon. It would therefore seem statistically appropriate to analyse water quality impacts within the probabilistic framework. Probabilistic methods have the advantage of being able to consider long or short time periods, monitoring constraints are much less restrictive than those requiring matched sequential data sets. The classical derived distribution approach calculates the probability distribution of receiving water quality concentrations and loading rates given the probability distribution of model inputs such as rainfall volumes/intensity, washoff and flow rates, pollutant loadings and inter-event times. It is significant in this respect that both the Danish Water Pollution Control Committee and the US EPA have recommended that overflow impacts, in terms of DO depletion and heavy metals respectively, should be evaluated on the basis of annual exceedence statistics. However, the most important drawback of these methods is that specific probability density functions (for example, exponential, lognormal or gamma) of input and output variables have been assumed and are forced upon the data (Benoist and Lijklema, 1989). Another drawback that was identified was the restriction that only simple linear models could be considered for the transformation techniques which were applied, thus leading to a loss of detail compared to continuous simulation.

2.5.3. Statistical Regression Models

Many research studies have identified, for example, Lindholm and Aaby (1989), that multiple regression techniques may be used to better understand the importance of each of the relevant factors which influence the quality of storm water flow.

Colston (1974) developed regression equations relating pollutant total loads or concentrations to the watershed or hydrologic conditions. However, the relationships developed were highly site specific, and needed to be re-evaluated before application to other sites.

Haith (1976), using statistical correlation and regression analysis examined landuse and water quality, found impact of forest, cropland, and transportation land used on nitrogen concentrations, and a correlation between densely populated urban residential areas and high suspended solids concentrations.

Marsalek (1976) analysed 19 storms which were monitored on a Canadian test watershed and found that the antecedent dry weather period was the most important variable to influence the total pollutant load of chemical oxygen demand, nitrogen, phosphorus, and suspended solids. It was concluded however that the relationship between total load, rainfall intensity, and antecedent storm rainfall was not statistically significant in the 19 storms monitored.

Jewell and Adrian (1982) pointed out that the derivation of functional relationships between stormwater pollutant loadings and various independent variables was made difficult by two main factors. Firstly, the inherent variability of stormwater data caused by the random nature of storm events and associated sampling and analysis errors. Secondly, by the large number of independent variables and parameters that may influence stormwater pollution washoff. These parameters are identified in Table 2.4. In addition, it was identified that outliers, that is, unrepresentative values resulting from unusual phenomenological events may distort the model. A multiple stepwise linear regression technique was applied to the data of 261 storm events from 26 basins in 12 geographical areas to evaluate several linear, semi-log transform, and log-log transform models with the average intensity of runoff and total volume of runoff as the primary variables. It was reported that a log-log model provided the greatest number of best fits and that the number of antecedent dry days was poorly correlated with suspended solids. It was concluded that no one model was consistently better than others in predicting stormwater pollutant runoff for several basins from different geographic areas. It was recommended therefore that local data should be gathered for each basin to be modelled with a representative model derived using statistical techniques. Regression models although easier to implement enable only the prediction of total loads carried by the runoff and are not suitable for a detailed prediction of the pollutographs.

Table 2.4. Independent variables and parameters influencing stormwater pollution washoff (Jewell and Adrian, 1982)

	Dynamic variables		Parameters
S. No.	Storm event totals	Instantaneous flux	Land use
1	time since last storm event(days)	runoff intensity (cm/hr)	area (hectares)
2	street cleaning practices	cumulative volume of runoff (cm)	percent impervious area
3	total volume of runoff (cm)	time from start of storm (min)	length of overland flow (m)
4	storm duration (min)	rainfall intensity (cm/hr)	percent street and parking areas
5	total volume of rainfall (cm)	cumulative volume of rainfall (cm)	length of streets /hectare (m/ha)
6	average rainfall (cm/hr)		population density (pop/ha)
7	average runoff (cm/hr)		particulate fallout rate (kg/ha/day)
8			number of catch basins/hectare
9			climatological data
			a. temperature
			b. rainfall

Desbordes and Servat (1984) analysed the mean total suspended solids data of the French national runoff quality program in an attempt to establish the main variables which influenced the value of TSS. They showed that 50% of the total variance of the mean suspended solids concentrations could be explained by two variables - the mean maximum 5-minute rainfall intensity and the antecedent dry weather period. No predictive equations were formulated but they concluded that the antecedent climatic conditions preceding a given rainfall event had great influence on the TSS values. They further concluded that the whole solids transformation process could not be precisely modelled by linear models between TSS and hydrological or classical parameters, even in the case of small well defined urban catchments with self cleansing sewers. The Principal Components Analysis (PCA) indicated similar relationships (PCA can be used from a qualitative point of view in order to reduce dimensionality of a p dimensional space described by p more or less linearly correlated variables). The Kalman Filtering Procedure

(KFP) was performed on the TSS time series and TSS ordered in increasing values (the KFP is a a well-known adaptive process, optimising the regression parameters of linear regression in order to take into account systematic errors or random changes that could occur between two successive events). The general trends indicated that TSS modelling was dependent on antecedent weather conditions and on the magnitude of the hydrological variables. All three procedures lead to the same conclusions mentioned above.

In the USA, the data collected through the Environmental Protection Agency (EPA) as part of the Nation-wide Urban Runoff Programme (NURP), which monitored over 100 catchments in 30 US cities, were used to develop predictive equations relating stormwater runoff pollutant concentrations and loadings to storm and catchment characteristics utilising multiple stepwise regression techniques (Tasker and Driver, 1988; Driver and Troutman, 1989; Driver, 1990). This work outlined the application of linear regression models to estimate mean loads for chemical oxygen demand, total suspended solids, dissolved solids, nutrients and heavy metals at unmonitored sites in urban areas in the US. Models for dissolved solids, total nitrogen, and total ammonia plus organic nitrogen as nitrogen were the most accurate models for most areas, whereas models for suspended solids were the least accurate. The most accurate models were for the more arid western United States, and the least accurate models were for areas that had large quantities of mean annual rainfall. The regressional relationships which were established between the loads and/or concentrations or runoff volume and flow rate with varying degrees of success, and it was concluded that concentration was poorly related to the flow rate.

Pearson *et al.* (1986) presented the results of a two year period of study in which 113 separate storm events were monitored in two catchments in the UK. For approximately 90% of the storm events sampled, a distinctive first flush of suspended solids and COD was observed. Ammonia and conductivity almost always followed a dilution pattern inversely related to sewer flow. Using step-wise multiple regression analysis (SPSS), the maximum concentrations of TSS and COD recorded in the first flush of each event was related to the length of the antecedent dry weather period, the pollutant concentration in the dry weather flow at the time of the storm and the maximum rainfall intensity. The results showed that the maximum value of the accumulated correlation coefficient for the derived relationship between the three variables were 44% and it was concluded that further work was required to better describe the results.

Sieker and Durchschlag (1990) applied the method of simulating pollution load using a selection of natural rainfall (a minimum period of 10 years) events as inputs (instead of design storms) to find the appropriate volume of CSO tanks. Their study identified that the storage volume mainly depends on the density of total population, local rainfall characteristics, pollutant concentration of dry weather flow, and the capacity of the treatment plant. Dimensioning criterion of the tank volume was a "permissible" overflow load in kg/ha/year. A sufficient volume is proved if the computed overflow load is equal to or lower than the given permissible overflow load. Functional relationships between simulated overflow load (kg/ha/year) and specific tank volume (m^3/ha of impervious catchment area) indicated that the specific efficiency of the tanks to reduce overflow loads decreases as the volume increases which suggests that it might be of no use to increase the tank volume beyond a certain volume. The authors recommended 30 m^3 per impervious ha.

However, Marsalek *et al.* (1993) stated that no method for urban runoff quality prediction could predict accurate loads and/or concentrations without local, site-specific data for calibration. Calibrated continuous simulation models could then be used to provide input to receiving water quality models.

2.5.4. Advanced Simulation Models

The degree of sophistication of the representations in the various urban drainage models under development was determined by their objectives (Huber, 1992). Build-up and washoff have been used widely in most mathematical models to simulate and predict the intrastorm variations of concentration and load. As all models used build-up and washoff, the build-up and washoff are discussed in the following section and the major modelling packages are described in Section 2.5.7.

2.5.5. Build-Up Parameters

The pollutants were assumed to build-up on urban surfaces from a variety of real but difficult to quantify processes such as erosion, deposition, traffic residue and decaying vegetation. Wind, traffic and street cleaning act to reduce the amount of dust and dirt present at the beginning of a storm; the net amount was usually assumed to build-up as some function of interevent time. Three models (Table 2.5) have been used to describe the accumulation of pollutants on the urban surface.

Table 2.5. Build-up models (after Baffaut and Delleur, 1990)

S.No.	Type of build-up model	Build-up load	Explanation of the symbols
1.	Linear	$= a.t$	a= linear deposition rate in weight per day t= the number of dry days preceding the event.
2.	Exponential	$= \lim (1 - e^{-decay.t})$	lim = maximum amount of pollutant that can be deposited on the watershed. decay = the removal rate of pollutant
3.	Michaelis-Menton	$= \dfrac{\lim t}{c+t}$	c= the number of days after which half of the maximum load has been deposited.

It is now widely accepted that the accumulation of solids on the surface is best described by an exponential build-up (Alley, 1981; Baffaut and Delleur, 1990). This formulation has been incorporated in the SWMM and in a modified form in the MOSQITO and other models - FLUPOL, THALIA (Germany), STORM, etc. while MOUSETRAP used both linear and exponential build-up formulations.

2.5.6. Washoff by Rainfall

Empirical first-order washoff equations still provide an appropriate basis for many modelling approaches and the exponential functions developed in the US (Alley, 1981) have been adopted by European workers. The washoff parameters have an impact on the washoff rate and therefore on the shape of the pollutographs. The washoff loads are directly proportional to the loads of pollutant deposited on the catchment surface. Jewell and Adrian (1982) identified the independent variables and parameters influencing stormwater pollution washoff (Table 2.4).

In a subsequent study the mean TSS was hypothesised as being related to 9 variables (Desbordes and Servat, 1984) which are identified in Table 2.6.

Table 2.6. Variables related to TSS (Desbordes and Servat, 1984)

S.No.	Variables
1.	peak discharge (l/s)
2.	mean maximum intensity during the time of concentration (mm/hr)
3.	mean maximum intensity during a 5 min time interval (mm/hr)
4.	total rainfall depth during the event to be considered (mm)
5.	rainfall event duration (days)
6.	runoff duration (days)
7.	duration (days) of the dry weather period preceding the event
8.	rainfall depth during the seven days preceding the event (mm)
9.	rainfall depth since the last event for which runoff was observed.

The rate at which rainfall washes loose particulate matter from street surfaces was identified as being primarily dependent on three factors: rainfall intensity, street surface characteristics, and particle size (Sartor *et al.*, 1974; Segarra-Garcia and Loganathan, 1992). Their data analysis revealed that the washoff phenomenon was described by a first-order load model as follows:

$$dP/dt = -P_o(t) \qquad (2.1)$$

The integrated form was

$$L_t = P_o\,(1\text{-exp.}^{-KR}) \qquad (2.2)$$

where

L_t = total amount of pollutant washed off during the event,

P_o= available pollutant at the start of the runoff event,

K = washoff decay rate, and

R = the event total runoff volume (cm).

Equation (2.2) has been used to simulate the washoff in many of the advanced models.

Equation (2.2) was then reformulated as

$$P_o - P(t) = P_o [1 - \exp.^{(-KV_t)}] \qquad (2.3)$$

where

V_t = runoff volume at time t, and

K = washoff decay rate.

The left hand side of equation (2.2) represented the amount of pollutant washed off upto time t,

$$L(t) = P_o - P(t) = P_o (1 - \exp.^{-KV_t}) \qquad (2.4)$$

which was said to express the first flush effect (Segarra-Garcia and Loganathan, 1992). To determine K, they assumed that a uniform runoff rate of 1.27 cm/hr washed away 90% of the initial pollutant load in 1 hr. The value of K thus obtained was 1.81 cm^{-1}. Some verification of this rate was obtained by Sartor *et al.* (1974). In the UK, Wilkinson (1956) calculated the removal rate for suspended solids to be 31.5 mg m^{-2} day^{-1}; this (lower) value was obtained because only the fine suspended solid fractions reaching the outfall were considered. Mance (1982) reported the range of removal rates for suspended solids from 17 European catchments (10.7 - 641 mg m^{-2} (impervious area) day^{-1}) and from six UK catchments (23.6 - 251 mg m^{-2} day^{-1}). American studies found considerably higher levels of suspended solids in urban storm drainage with values ranging from 224 to 1094 mg m^{-2} day^{-1} (Whipple *et al.*, 1978) and for total solids upto 4887 mg m^{-2} day^{-1}. However, Alley (1981) showed that K needed to be calibrated for each catchment. The exponential decay model was also used by Tucker and Mortimer (1978) in their study of the generation of suspended solid loads from two separately sewered catchments in Nottingham, England. However, the application of this model was limited because of the need to identify the initial mass of pollutants available for washoff.

Methods to estimate separately build-up and washoff parameters were suggested (Alley, 1981; Alley and Smith, 1981). In the first paper, they presented a method to estimate washoff parameters while the second paper presented a method to estimate build-up parameters once washoff parameters had been estimated. The method assumed an exponential build-up model that seemed to be more realistic of the deposition process. By estimating washoff and build-up parameters separately, Alley and Smith eliminated the problems of unrealistic values. Although the added complexity of the use of build-up and washoff formulations in a model have the advantage of prediction of intrastorm variations which are important for the evaluation of pollutant control options, they are physically based, and must be calibrated with local data. Moreover, when end of pipe concentration and load data are all that are available, all build-up and washoff coefficients end up being calibration parameters (Huber, 1992).

2.5.7. Major Modelling Packages

In almost every country in Europe and in America mathematical models have been developed for the hydraulic simulation of sewer system performance in that particular country. More recently, pollution simulation modules have also been incorporated into these models.

While SWMM is widely used in the US , in the UK and Europe, the currently available software tools for analysis and design of urban drainage systems include WASSP, WALLRUS, SPIDA (these now form part of the integrated HYDROWORKS), micro-DRAINAGE and MOUSE for sewer flow quantity modelling, and FLUPOL, HYPOCRAS, MOSQITO (now QSIM) and MOUSETRAP for sewer flow quality modelling. Selected model attributes were described by Marsalek *et al.* (1993) and these are shown in Table 2.7 and summarised as follows:

HSPF (US): The Hydrological Simulation Program FORTRAN was developed from hydrologic routines that originated with the Stanford Watershed Model in 1966 and eventually incorporated many non point source modelling efforts of the EPA Athens Laboratory (Johanson *et al.*, 1984). This model has been widely used for non-urban non point source modelling in the USA.

Table 2.7. Comparison of selected model attributes (after Marsalek *et al.*, 1993)

	Model					
Attribute	HSPF	ILLUDAS/ AUTOQI	STORM	SWMM	MOUSE TRAP	HYDRO-WORKS
Sponsoring agency[a]	EPA	ILL. State Water Survey	HEC	EPA	DHI	HRL, Wallingford
Simulation Type[b]	C,SE	SE	C	C,SE	C,SE	C,SE
No. of pollutants	10	Generic[c]	6	10	?	?
Rainfall/ Runoff analysis	Y	Y	Y	Y	Y	Y
Sewer system flow routing	Y	Y	N	Y	Y	Y
Dynamic flow routing equations	N	N	N	Y[d]	Y	Y
Surcharge	N	Y[e]	N	Y[d]	Y	Y
Regulators over structures, e.g., weirs, orifices	N	N	Y	Y	Y	Y
Solid routines	Y	Y	N	Y	Y	Y
Storage analysis	Y	Y	Y	Y	Y	Y
Treatment analysis	Y	Y	Y	Y	?	?
Suitable for planning(P) Design (D)	P,D	D	D	P,D	P,D	P,D
Available on micro-computer	Y	Y	N	Y	Y	Y
Data and personnel requirements[f]	High	Low	Low	High	High	High
Overall model[g]	High	Low	Med	High	High	High

Notes:

a EPA = US Environmental Protection Agency, HEC = Hydrologic Engineering Centre, DHI = Danish Hydrologic Institute, HRL = Hydraulic Research Ltd.

b C= Continuous simulation, SE = Single event simulation.

c Generic build-up/washoff formulation included.

d Full dynamic equations and surcharge calculations only in EXTRAN block of SWMM.

e Surcharge simulated by storing excess inflow at upstream end of pipe. Pressure flow not simulated.

f General requirements for model installation, familiarisation, data requirements, etc. To be interpreted only very generally.

g Reflection of general size and overall model capabilities. Note that complex models may still be used to simulate very simple systems with attendant minimal data requirements.

ILLUDAS: The Illinois Urban Drainage Area Simulator (Terstriep and Stall, 1974) evolved from the British Road Research Laboratory Model. The model used time area methods for generation of runoff coupled with Horton or SCS infiltration on pervious areas. A design routine was included to resize pipes of insufficient hydraulic capacity. Its simplicity and early metric option resulted in ILLUDAS being widely used. Quality has been included in the revised version of the model called AUTO-QI (Terstriep *et al.*, 1990).

STORM: The Storage, Treatment, Overflow, Runoff Model was developed by HEC (1977) for application to the San Francisco master plan for CSO pollution abatement. STORM utilised simple runoff coefficient, SCS and unit hydrograph methods for generation of hourly runoff depths from hourly rainfall inputs. Statistics of long-term runoff and quality time series permitted optimisation of control measures. The build-up and washoff formulations were used for simulation of six pre-specified pollutants. However, the model could be manipulated to provide loads for arbitrary conservative pollutants. A microcomputer version is commercially available. The current version includes dry-weather flow input for combined sewer simulation.

SWMM (Storm Water Management Model): This model was originally developed for the US Environmental Protection Agency. SWMM is segmented into various blocks and these are called Rainfall, Transport, Extran, Storage/Treatment and Statistics. Version 4 of the model (Huber and Dickinson, 1988), may be used with a single event or continuous rainfall, and is appropriate for use with dendritic (treelike) or looped systems (EXTRAN block). SWMM can simulate backwater, surcharging, pressure flow and looped connections (by solving the complete dynamic wave equations) in its EXTRAN block, and has a variety of options for quality simulation, including traditional build-up and washoff formulations by Alley (1981) and Jewell (1982) as well as rating curves and regression techniques. Subsurface flow routing (constant quality) may be performed in the RUNOFF block in addition to surface quantity and quality routing, and both CSO and storage tank performance may be simulated in the Storage/Treatment Block using removal functions and sedimentation theory. A hydraulic design routine is included for sizing of pipes, and a variety of regulator devices may be simulated, including orifices (fixed and variable), weirs, pumps, and storage.

However, the water quality portions of both SWMM and STORM models are very similar and require an extensive calibration procedure for each new application (Bedient *et al.*, 1978; Jewell and Adrian, 1978; Amandes and Bedient, 1980; Baffaut and Delleur, 1990; Liong *et al.*, 1991). A subsequent method presented by Baffaut and Delleur (1990) used expert systems to automate the calibration of the water quality parameters of the runoff block of SWMM. The expert system was shown to perform the calibration, but a shortcoming existed in the SWMM model that could not be alleviated through calibration. The application of the expert system to the Denver experiment showed that the same set of parameters was not valid for low and high intensity events. Further evidence supporting this finding was put forth by Srinanthkumar and Codner (1993) while calibrating the SWMM for their Australian catchment, and they also highlighted the need to analyse high and low intensity events separately.

Since the model is non-proprietary, portions have been adapted for various specific purposes and locations by individual consultants and other governmental agencies both in the USA and abroad, for example, in Australia and Singapore. Although SWMM is available in the UK, it is expensive in terms of computer time and amount of data required and it has been identified that the UK model WALLRUS (now HYDROWORKS) requires less data (SRM2; WRc/WAA, 1986) and has shorter run times and is more widely used in the UK.

THALIA (Iossifidis, 1987): Developed in Germany, this model simulated the transfer, deposition and scouring of solids in combined collection systems during dry weather flow. It modelled these physical processes with the aid of the critical shear stress for a deposit free flow and the critical shear stress for a scouring of deposited solids. The results revealed that the mean slope of the sewer pipe, length of the pipes per area served, the area of the collection system and the discharge per capita played a major role in the build-up, transfer, deposition and scouring of solids in combined collection systems.

FLUPOL (Bujon *et al.*, 1992): Developed in France, the primary objective of the model was to forecast the response of an urban catchment and its sewerage system to a given rainfall event, by evaluating the order of magnitude of the discharges, flow and pollution and their evolution during the course of the event. It was coupled with hydrological and hydraulic models using linear reservoirs and Muskingum schemes for flow calculations. The model calculated the flow rates and discharges of suspended solids, BOD_5, COD, and Kjeldahl Nitrogen downstream from an urban catchment and its drainage system for a given rainfall, without needing detailed data which may be expensive to gather. The phenomena simulated included accumulation of polluting matter on urban surfaces during dry weather, runoff during rainy weather and washoff of deposits present on surfaces, propagation into the system of polluting fluxes and loads, and build-up of deposits within the system and the transport of solids through it. It assumed that the pollutants produced by human activity accumulated in linear proportion to the time elapsed on the surfaces, but that they also tended to disappear more rapidly the higher the quantities present. Runoff flow rates were calculated from the rainfall and the characteristics of the catchment using the linear reservoir rainfall flow rate transformation model which considers that at any given moment, the rate of flow drained off from the outlet of the collection area is proportional to the volume of water present on it. For surface washoff, it was assumed that the rate of erosion was proportional to the mass present on the surfaces. However, bed loads were not addressed and also only a single type of sediment was considered. Calibration was accomplished using two rainfall events on two catchments in the Paris region and verification was accomplished on one catchment previously used for calibration and two new sites. The authors' reported differences between calculated results and the measurements less than 20%.

Another outcome of this study was the finding that, although the highest rainfall intensity often occurred during the first storm, the maximal polluting discharge generally occurs simultaneously with the maximum flow rate.

HYPOCRAS (Bertrand-Krajewski, 1992) (HYdrogrammes et POllutogrammes Calculés en Réseau d'ASsainissement): Also developed in France, this was a conceptual model for solid production and transfer in sewer systems for small urban catchments less than 100 ha and imperviousness greater than 20%. The objectives were the calculation of suspended and bed loads and the evaluation of the deposits. Hydrologic and hydraulic phenomena were represented with a cascade of two linear reservoirs. The first part of the solid transfer model was established to reproduce daily and hourly suspended solids loads during dry weather periods. The second part of the model dealt with solid transfer during storm events, including sediment build-up over the catchment, washoff, erosion, deposition and transport. Two classes of particles were introduced to represent the particles which are essentially transported in the bed load and the particles which are essentially transported in the suspended load.

For the dry weather aspect, the sediment deposition was described with an exponential asymptotic relation until an equilibrium limit was reached and the deposition was assumed to be directly proportional to the residual storage capacity of the sewer system. The erosion of deposits was assumed to depend directly on the available mass of solids and on the flow rate. However, the time step used was one hour. Agreement between calculated and observed values were reported satisfactory; the overall accuracy was 20%, except for the first peak where it was 50%.

For wet weather discharges, the HYPOCRAS model was divided into two parts: the hydrological part which calculated the flow rate due to rainfall and the solid transfer part which calculated the solid concentration at the outlet. The net rainfall was introduced into a cascade of two linear reservoirs. The calculated flow was then added to the DWF to determine the total flow. Both the build-up of solids over the catchment and the washoff of the accumulated sediments were calculated using the relations proposed for SWMM (Alley and Smith, 1981; Alley, 1981).

The HYPOCRAS model was applied to data collected for three catchments - Mantes-la-Ville (72 ha), Entzheim (40 ha) and Dundee (81 ha) - all less than 100 ha (Bertrand-Krajewski *et al.*, 1993). The authors identified that a calibration with field data was essential for each catchment. The authors admitted that the model represented principally the surface derived sediment transport, with only limited application to the in-sewer sediment erosion/deposition processes.

2.5.7.1. Wallingford Software

The majority of work pertaining to the design and simulation of urban drainage systems in the UK is undertaken using packages from Wallingford Software (Hydraulics Research Ltd., Wallingford) and the most recent release is HYDROWORKS.

2.5.7.1.1. WALLRUS and SPIDA (now HYDROWORKS)

Historically, the Wallingford Software consisted of clusters of modules, including runoff generation from rainfall, simple and fully dynamic sewer flow routing (WASSP - WAllingford Storm Sewer Package, WALLRUS - WALLingford RUnoff Simulation and SPIDA - Simulation Program for Interactive Drainage Analysis) respectively and a quality routine (MOSQITO - Modelling of Stormwater Quality Including Tanks and Overflows) featuring processes similar to those in SWMM (Henderson and Moys, 1987). The appropriate models to use are WALLRUS for dendritic systems and the SPIDA model for looped systems or systems which involve an interaction between the various drainage components. The hydraulic performance of flow controls, pumping stations and all other forms of ancillary structures such an on- and off-line storage control structures, and pumping stations can also be simulated. Microcomputer versions of each model are available and all the models are capable of simulating a large complex network. As a result, the input data requirements are large and skilled personnel are therefore required to operate the models and to interpret and understand the resulting output.

The data requirement includes: pipe sizes, lengths, levels and roughness; impermeable area contributing to runoff; foul flow; ground wetness; soil permeability and details of ancillary structures such as tanks, overflows and pumping stations. The software was capable of handling networks of upto 2000 pipe lengths, which implied that larger networks would need to be modified in a simpler form. Output from the program includes prediction of peak flows in pipelines, peak surcharge levels in manholes, flood volumes from manholes and spill volumes from overflows. In addition, time-based hydrographs could be produced for water level or flow for any part of the system.

The two principal shortcomings of the WALLRUS software were its inability to calculate full backwater curves or to allow reverse flow in un-surcharged pipes. The lack of full backwater curve calculation limits the effective use of the software for designing tank sewers. However, these shortcomings were overcome in SPIDA - a software package for the analysis of flows in complex, looped storm drainage systems with reversing free surface flows, which has similar input requirements to the WALLRUS. Further details of WALLRUS are discussed in Chapter 5.

2.5.7.1.2. MOSQITO - A Sewer Flow Quality Model

MOSQITO (Payne *et. al*, 1990) was a detailed deterministic model aimed at representing the pollution processes occurring in an urban drainage system. The main objective of this package was to simulate the behaviour of pollutants and sediments in sewer systems for different rainfall and flow inputs and to produce outputs in the form of pollutographs. Determinants modelled included BOD, COD, ammonia and suspended solids. The host hydraulic model for MOSQITO was WALLRUS which comprised of four sub-models:

(i) Rainfall runoff model;

(ii) Dry weather inflow model;

(iii) Pipe and channel flow routing model; and

(iv) Overflow and storage structure model.

The MOSQITO model added water quality calculations to each of these sub-models to simulate the pollutant inflows from surface washoff and from dry weather flow (while industrial inputs are user specified) as follows:

(i) washoff of pollutants from the catchment surface;

(ii) dry weather flow (or foul sewage inflow) pollutant concentrations;

(iii) pollutant and sediment transport and sediment erosion and deposition in pipes and channels; and

(iv) settlement of sediment at ancillary structures.

The behaviour of sediments and pollutants in the sewer was simulated by three sub models. Dissolved and suspended pollutants were routed by advection whilst sediment transport, deposition and erosion was based on the Ackers-White equation. At manholes, complete mixing was assumed to occur whilst at CSOs and tanks, sediment settlement was modelled. Full details have been described by Moys (1987).

A more empirical approach was applied to the development of MOSQITO, as this model was intended to produce more sensitive and detailed information about instantaneous concentration and discharge into rivers during rainfall events. This gain in sensitivity, which was based on a very detailed description of the elementary processes, could only be attained via the collection of a larger set of input data, which are consequently much more expensive to collect.

2.5.7.1.3. HYDROWORKS QM: Sewer Quality Model

QM is the result of an international development project between Wallingford Software and the French water quality specialists, Anjou Recherché, incorporating expertise from the two companies earlier models: MOSQITO and FLUPOL, respectively. QM models the main dry weather flow processes in dendritic and looped networks, and a wide range of water quality parameters. It is based on the Hydro Works PM simulation engine and is suitable for continuous simulation.

2.5.7.2. SIMPOL

It has been identified (UPM Manual; FWR, 1994) that the setting up and verification of an advanced quality model involves a great deal of time and effort and hence, as part of the UPM Procedure, an alternative simplified model of the urban sewer system termed SIMPOL has been developed. In SIMPOL, the elements of the sewer system are represented by a series of tanks. Four tank types have been defined, namely, surface tank (no storage), sewer tank (attenuation of flows), CSO tank (simple on-line storage) and storm tank (off-line tank). SIMPOL accepts any number of rainfall events in the format produced by STORMPAC (described in Section 5.2.1.2), and the event duration is limited to 12 hours. The sewer tanks in SIMPOL are calibrated hydraulically against storm spill results from a detailed sewer flow model such as WALLRUS and it is recommended that to preserve the accuracy of the model, 10-15 events are used. Similarly, the model considers only biochemical oxygen demand (BOD) and this is assumed to originate from three sources: DWF, surface runoff and sewer sediments. Predictions of quality proceed only at hourly time steps from the upstream tank to the downstream tanks and hence the accurate prediction of the temporal variation in pollutant concentration over short intervals of time is not possible using this model. This may be considered a shortcoming when the acute impacts of pollutants; i.e. first flush effects may need be considered. It is recommended that the calibration of the BOD predictions are made against the results of a sewer flow quality model, for example, MOSQITO and hence a detailed simulation model needs to be first prepared in order to calibrate SIMPOL. This may also be considered a deficiency in the application of such a simplified model although, once calibrated, this model may easily be used to assess the performance of a series of different design options.

2.5.7.3. MOUSETRAP (MOdelling of Urban Sewers including TRAnsport of Pollutants)

Developed concurrently with HYDROWORKS, the water quality model from WRc/DHI is MOUSETRAP (Crabtree *et al.*, 1994) which incorporated the results of recent research for sewer sediments and pollutant behaviour into the MOUSE (Modelling of Urban Sewers) sewer system hydraulic analysis package (Lindberg and Jørgensen, 1986). In MOUSETRAP, time varying sewer flow and pollutant concentrations could be simulated under wet and dry weather flow conditions. Pollutants associated with dissolved phase liquid transport (including colloidal, non-settleable solids) and pollutants associated with sediments (including bed deposits, bed load and settleable suspended solids) could be represented.

MOUSETRAP consisted of 4 modules linked to MOUSE to represent the quality of surface runoff, sediment and pollutant transport within the pipe network and the biological and chemical processes which took place within the sewer system. These modules were the Surface Runoff Quality Module (SRQ), Sediment Transport Module (ST), Advection-Dispersion Module(AD) and the Water Quality Module (WQ). These modules could be used individually or in combination, except for the WQ module which was coupled to the AD module. The ST, AD and WQ modules could all be run in parallel with the main hydrodynamic module of the MOUSE system.

2.5.7.3.1. Surface Runoff Quality Module

The SRQ module consisted of two sub-modules, one describing the accumulation of sediments on the catchment surface which was modelled as either a linear or an exponential build-up, and the other describing the build-up and wash-out of dissolved pollutants in the catch basins. The model assumed a linear build up of dissolved pollutants during dry weather and required initial and maximum concentrations and build-up rates.

2.5.7.3.2. Sediment Transport Module

The ST module described the erosion and deposition of graded sediments. The bed load material was considered explicitly as the Type C foul flow deposit. The removal of sediments in tanks was described as a function of settling velocity, inflow discharge and surface area while the removal of sediments in CSOs was described by a removal efficiency concept.

Under dry weather flow conditions, in-pipe sediments had a fixed pollution load and their physical characteristics included a degree of cohesion. Depending on hydraulic conditions, suspended sediments in the foul flow may deposit to form a layer on top of the in-pipe deposit. Any post-depositional changes to sediment deposits were not represented.

During storm flow conditions, surface sediments enter the system. Depending on hydraulic conditions, the deposited foul flow sediments were assumed to be eroded and resuspended, as well as in-pipe sediments, when the relevant erosion thresholds were reached. Transport and any subsequent deposition was as for non-cohesive sediments. If redeposition occurred, deposits would assume the original characteristics of sediments in the system. That is, deposited sediment characteristics and pollutant concentrations remain fixed, but sediment deposit volumes are updated.

2.5.7.3.3. Advection-Dispersion Module

The AD module calculated the transport of dissolved substances based on a one dimensional advection-dispersion equation to describe two different transport mechanisms. These were the advective transport with the mean flow, and the dispersive transport due to concentration gradients.

2.5.7.3.4. Water Quality Module

The WQ module comprised of a suite of sub modules to describe the reaction processes of multi-compound systems, including the degradation of organic matter, exchange of oxygen with the atmosphere, and oxygen demand as represented by BOD, COD or DO from the eroded sewer sediments. The WQ module was directly coupled to the AD and ST modules enabling the transport of dissolved and suspended components within the flow to be carried out simultaneously with the calculation of the effects of the biological processes. The WQ module included diurnal variation of foul flow discharges and concentrations of foul flow components. At present the model only operates under aerobic conditions.

The software "tools" developed to date do not, however, provide a framework which includes methodologies for assessing source control, in-system control and end-of-system control measures in an integrated system fashion incorporating systems reliability and maintenance and operational issues in the assessment process (Andoh, 1994).

All the deterministic models (for example, FLUPOL, MOSQITO, MOUSETRAP) require the collection of a large amount of calibration data, including information regarding average particle size and grading, specific gravity and settling velocity. This is not justifiable if the requirement is to develop a planning, rather than a detailed event-based tool. Further, these models require trained personnel and a need for carefully calibrated simplified models has been identified (House *et. al.*, 1993) to enable easier application by the practitioner.

For all these models, the prediction of accurate values of pollutant concentrations and loads relies on adequate calibration, and no model can yet be used on unguaged basins. Several other models have been proposed; all of them need to be calibrated for each catchment before they can be used.

2.6. Design Storms and Rainfall

Over the last decade, a range of types of rainfall data have been made available to the engineer for a variety of different uses.

DESIGN RAINFALL: The original data provided by the Wallingford Procedure was a series of events covering a wide range of duration and return period. These events, although based on observed data, were synthetically generated. Their use is primarily aimed at pipeline design where peak flow is important, but total volume of runoff is of less significance. The main limitation was that the series of storms was limited to return periods of one year or greater.

ANNUAL DESIGN STORMS FOR SPILL PREDICTION: The most recent developments has been the addition to the rainfall generator within WALLRUS and SPIDA of storm periods of return periods less than one year.

ANNUAL TIME SERIES: For analysis of overflow frequency of more than once a year, the design storms cannot be used. Where storage is proposed as a means of limiting overflow frequency, such that total volume of surface runoff is significant they are regarded as unreliable. To overcome these limitations, the annual time series was developed. This is a series of observed events (99 in total) considered to represent a typical year's rainfall. In use, either all the events, or more typically a sample of events, is run with the model, to provide a prediction of overflow volume and frequency. This series is however limited to a single typical year and is very generalised, covering three regions in England - the South East, the South West and Yorkshire.

STOCHASTIC RAINFALL GENERATOR: To overcome these problems, WRc have developed a further facility which is capable of generating a realistic rainfall series for any location in the UK, for any period of time, and for any range of return periods. This method is considered to give good results, but because so many events have to be run, it is generally restricted to the later stages of a scheme design where specific proposals are being checked for compliance.

The differences obtained in recurrence intervals for different properties of the same event suggest reconsidering the standard procedure for sewer design, which try to conclude from rainfall on all runoff properties (Geiger, 1986). Any strategy, however, must consider its overall effect on receiving waters including sewage treatment plant efficiencies as the sewage treatment plant efficiency may well be influenced by the pollutant retention strategy. One possibility is continuous simulation with statistical analysis of the computed figures. Recurrence frequencies of different runoff properties were investigated and no connection was found between rainfall frequencies and runoff frequencies (Geiger, 1984).

It was suggested that the design storms for pollution control of urban runoff should be based on a desired return period and a minimum dry weather period duration between successive events and that this dry period should be selected on the basis of the time required to minimise cumulative effects of pollutants discharged to receiving streams and to control exposure and recovery time for aquatic organisms (Hvitved-Jacobsen and Yousef, 1988). Based on an analysis of 33 years of rainfall record for the city of Odense, Denmark, it was recommended that a rainfall volume with a recurrence interval of 6 months or 1 year and a 72 hour interevent dry weather period be used for the design of urban runoff detention basins. However, the proposed rainfall analysis did not allow consideration of physico-chemical reactions or hydraulic factors in regulating detention pond efficiency and hence design criteria.

2.7. Detention Storage Design

The methods of designing detention ponds generally fall into three categories (Loganathan *et al.*, 1994): design storm approach; continuous simulation modelling; and statistical methods that incorporate interevent times. The design storm event uses a single extreme event to size the basin either to meet a peak reduction or to satisfy a drawdown time (that is, time to drain the entire pond) requirement. Each of these approaches have been criticised. Goforth *et al.* (1983) pointed out that, due to the sequential occurrence of runoff events, the available volume (empty space) for capturing an event is random, and single storm approaches do not account for it in the design. The second approach involving continuous simulation essentially duplicates the natural occurrence of runoff events, and is very useful for analysing the long-term performance of a given basin configuration. By considering alternative configurations, the engineer can select an appropriate design. However, continuous simulation can be time consuming and data-intensive, and for planning-stage calculations a simplified procedure may be sufficient. The third approach involving statistical methods also considers interevent times and accounts for the net empty space between events. Because they are aimed toward developing simplified probability-based equations, statistical methods often incorporate certain assumptions. As a result, statistical methods are considered to be planning level tools. Previous statistical planning methodologies by Howard (1976), DiToro and Small (1979) and Loganathan *et al.* (1985) concentrated on the fraction of untreated runoff volumes leaving a detention basin. EPA ("Methodology", 1986) and Driscoll (1989) interpreted the results of DiToro and Small (1979) for pollutant settling within a detention pond. The fraction of untreated overflow was interpreted as the fraction of pollutant that had not settled. Goforth *et al.* (1983) did an extensive performance analysis of a detention basin using the EPA SWMM computer program and they considered the aforementioned goals of capturing and detaining the pollutant. Loganathan *et al.* (1994) provided an explicit, closed form solution for the expected detention time under a random sequence of runoff events and provided a relationship between the pollutant settling efficiency and detention time. From a design point of view, the methodology accounted for the pollutant load captured by the detention pond and the reduction of that load due to settling.

However, the most important drawback of the stochastic methods is that specific probability density functions (exponential, lognormal and gamma) of input and output variables have been assumed and forced upon the data (Benoist and Lijklema, 1989).

2.8. Summary

Studies have been reviewed which examined various processes of the urban stormwater pollution process. The processes included build-up and washoff over the catchment; transfer through gully pots; and transfer, deposition and erosion in sewer pipes. Most of the studies to monitor pollution in sewer systems identified the occurrence of a first flush, although its influence may be lost in larger sewer systems. The factors likely to influence the occurrence of the first flush were identified and discussed in detail. Both simple and advanced attempts to quantify the first flush were reviewed and in the latter respect, the advanced simulation models developed have been summarised. The main shortcoming of the advanced simulation models is that the data requirements are onerous, and therefore need for a simplified model has been identified and this forms the subject of the study of this thesis.

Chapter 3

ESTIMATION OF THE FIRST FLUSH LOAD

3.1. Summary

This chapter describes the development of a simple model to predict the first flush load of suspended solids in combined sewer flow using the data from two sites at Great Harwood and Clayton-le-Moors in the North West of England. It has been argued that TSS is the most important indicator of pollution in combined sewer flows for the purpose of storage tank design and a definition of the first flush appropriate to storage tank design is proposed. Using this definition a number of predictive equations have been formulated which relate the first flush load of suspended solids in combined sewer flow to the hydrological parameters which are thought to be most likely to influence the quality of the sewer flow. A multiple stepwise linear regression technique has been utilised for this purpose and it has been shown that the maximum rainfall intensity (or the maximum inflow), storm duration and the antecedent dry weather period are the most important variables to influence the total load of pollutants in the first flush. Site-specific relationships to predict first flush load have been established. The results of the models have been verified using an independent set of data and it is concluded that, with an accuracy consistent with the methodology adopted, the equations developed give reasonable predictions of the first flush load.

3.2. Background

As part of the UK Urban Pollution Management (UPM) programme of research, a comprehensive water quality sampling and monitoring program was carried out at several locations in the UK in an attempt to characterise the pollution in both stormwater and combined sewer flow. This resulted in an extensive data base which is held on the WRc Sewer Quality Archive (1987) and a summary of the database is shown in Table 3.1. The parameters that were measured included the time and date of the storm, the rainfall intensity, sewer flow rate and concentration of pollutants over the duration of the storm event. The samples were usually analysed for TSS, COD, BOD, NH_4N and VSS. An example of the data held on the archive is shown in Table 3.2 and a typical distribution of the rainfall and the corresponding sewer flow and the sewer flow quality are shown in Figure 3.1. The details of a typical site and instrumentation were outlined by Thornton and Saul (1986) and Saul and Thornton (1989) and these are detailed in Appendix A.

Table 3.1. Summary of sewer quality data (after Osborne and Hutchings, 1990)

S. No.	Site Name	Start	End	No. of data sets	GOOD	BEST	Type
1.	Astley Bridge, Bolton	26.01.86	23.11.87	128	24	33	C
2.	Basils Rd, Stevenage	02.08.78	09.03.79	34	-	-	C
3.	Chelmsley Wood	07.12.78	25.10.79	40	30	-	S
4.	Clayton-le-Moors	11.06.85	29.07.87	210	71	52	C
5.	Dundee	03.06.88	27.06.88	13	unprocessed		
6.	Garndifaith, Gwent	15.03.88	02.08.88	15	unprocessed		
7.	Great Harwood	29.03.86	19.04.87	230	79	57	C
8.	Higham Ferrers	14.05.85	05.12.85	68	57	-	C
9.	Preston	23.05.87	18.10.87	47	13	21	C
10.	Shephall	07.01.75	30.01.76	131	12	1	S
11.	Tippings Rd, Bolton	26.01.86	16.12.87	95	62	21	C

Notes:	(a)	C= combined sewer,	S = surface water sewer,
	(b)	"GOOD" data -	storms with full rainfall records and at least three flow and quality samples,
	(c)	"BEST" data -	storms with full rainfall records and at least four flow and quality records in the first hour of the event.

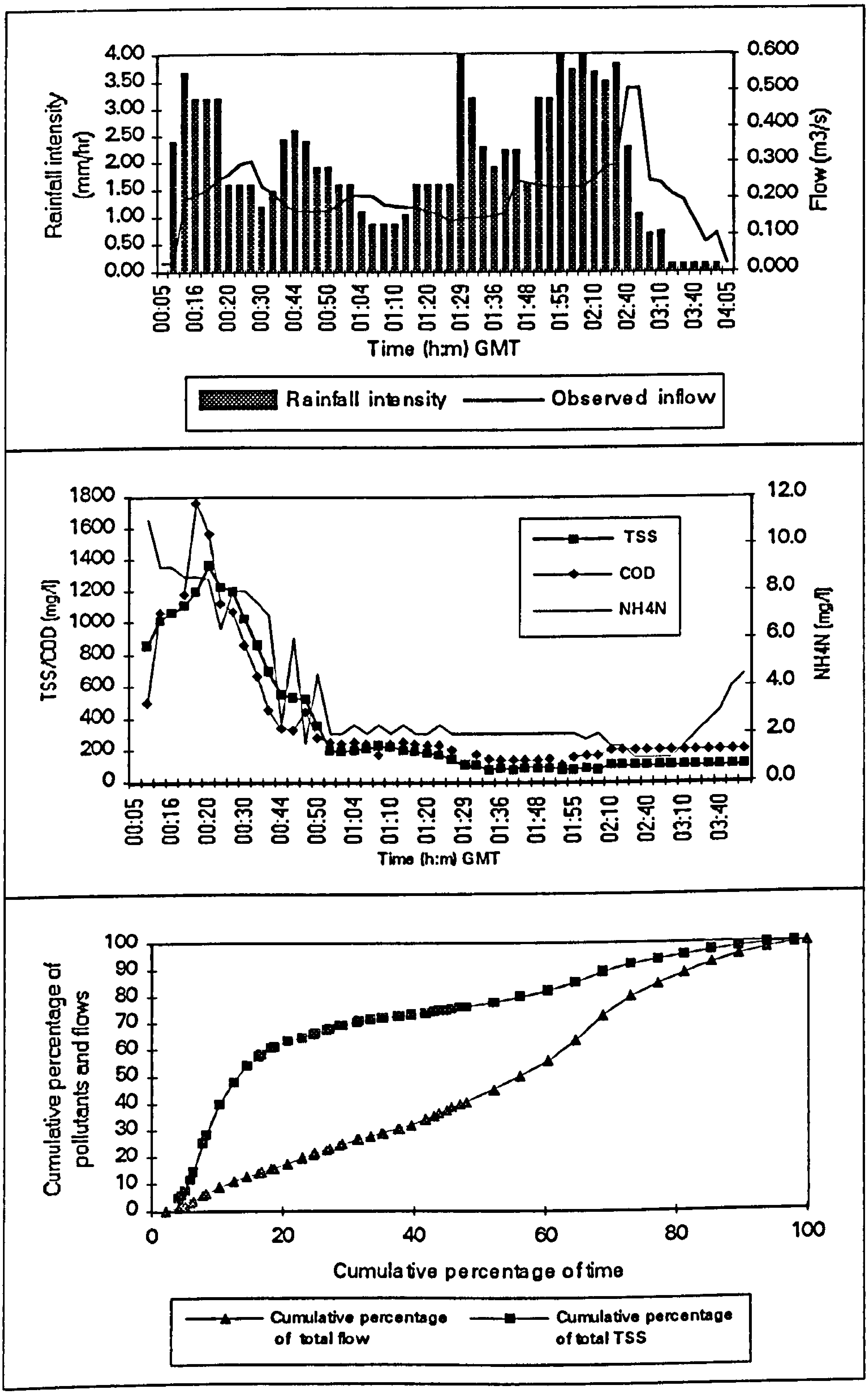

Figure 3.1. A typical plot of Rainfall runoff pollutograph for the Great Harwood site
(a) rainfall vs. flowrate,
(b) temporal variation of pollutants, and
(c) percentage of cumulative flow and pollution vs. cumulative percentage of time.

Table 3.2. Format of the SQA data (Sewer Quality Archive, 1987)

Time		RF INT	QIN	Q_{out}	Q over	Depth	TSS	COD	TDS	NH_4	BOD	VSS	Site name	Storm date
hr	min	mm/hr	m^3/s			mm	mg/l							yr/mth/date
0	5	0	0.025	0	0	0	-9	-9	-9	-0.9	-9	-9	GH BEST	840622
0	10	2.4	0.025	0	0	100	860	500	200	11	-9	-9	GH BEST	840622
0	15	3.68	0.197	0.16	0	500	1060	1060	175	9	-9	-9	GH BEST	840622
0	16	3.2	-0.9	-0.9	-0.9	-9	1060	1060	163	9	-9	-9	GH BEST	840622
0	17	3.2	-0.9	-0.9	-0.9	-9	1018	1175	165	8.6	-9	-9	GH BEST	840622
0	19	3.2	-0.9	-0.9	-0.9	-9	1108	1760	156	8.6	-9	-9	GH BEST	840622
0	20	1.6	0.268	0.19	0	790	1360	1570	155	8.5	-9	-9	GH BEST	840622
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	....	.....
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.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	....	.....
4	0	0.14	0.104	0.11	0	100	100	200	140	4.5	-9	-9	GH BEST	840622
4	5	0	0.022	0	0	0	-9	-9	-9	-9	-9	-9	GH BEST	840622

Note: A value of "-9" in the data set highlights a missing data point and in our study, these missing values have been computed using linear interpolation between the two nearest data points.

The limitations in the SQA database were identified by Osborne and Hutchings (1990) to include:

(i) a limited coverage of different land-use types,

(ii) there was no data on the limiting sources of sediments on the catchments,

(iii) the changes in the washoff of pollutants with antecedent conditions was unknown,

(iv) the data was influenced to an unknown extent by the deposition and erosion of sediments in the upper parts of the system,

(v) there was poor information on the settling velocity grading of the sediments and of the distribution of pollutants between sediment fractions,

(vi) the relationships between the sediment found in sewers and the sources and mechanisms by which it got there was unknown,

(vii) there was only limited information on the shear strength of the sewer sediment, and

(viii) for most sites, there was no record of the nature, type and distribution of the surface or in-sewer sediments or of the pollutants in the surface washoff.

3.3. Present Study

The emphasis of this study was on the data that was obtained from two sites- Great Harwood and Clayton-le-Moors in the North West of England. From Table 3.1 it can be seen that at Great Harwood a total of 230 storms were monitored and of these 79 were deemed "GOOD", with a "GOOD" storm being one which had a full rainfall record and at least three flow and quality samples; whilst 57 storms were defined as "BEST" where a BEST storm was defined as one for which the data included a full rainfall record, a complete flow record for at least an hour, and at least four flow and quality data points in the first hour of the event. At Clayton-le-Moors, the total number of storms recorded was 210 and of these 71 and 52 were classified in the GOOD and BEST categories respectively. In the present study, only the storms labelled "BEST" have been used to characterise the relationships between the pollutant load and the sewer flow. At each site the data was recorded in the format shown in Table 3.2 at the entrance to an on-line storage tank located at the downstream end of each sewer system. The catchment and storage tank characteristics are highlighted in Table 3.3. Both the storage chambers were designed in accordance with the recommendation outlined by Ackers *et al.* (1968).

Table 3.3. Catchment details

	Great Harwood	Clayton-le-Moors
Population	12 500	6500
Impervious area (ha)	56	29
Total area (ha)	121	40.7
Percent impervious	46	70
Pipe density (m/ha)	191.6	-
Length of main sewer run (km)	1.931	1.8
Average pipe gradient	0.0289	0.0270
Mean dry weather flow (cumecs)	0.30	0.20
Maximum flow to treatment (cumecs)	0.27	0.33
Storage volume(m^3)	138	126
Average annual rainfall (mm)	1100	1100

3.4. Total Suspended Solids

Researchers have used a large number of parameters or indicators, for example, BOD, COD and TSS to estimate urban stormwater runoff quality but due to the high costs involved in water quality data collection and analysis programmes there is a need to limit the number of these indicators. There is much evidence in the literature to support the use of suspended solids as an indicator of pollution for urban drainage design; for example, Hogland *et al.* (1984) reported that a large portion of other pollutants such as nutrients, heavy metals, COD and organic compounds may be associated with sewer solids via adsorption/absorption processes and that upto 90% of the total phosphorus and the organic matter (COD) discharging via stormflows may originate from resuspended pipe deposits. Other authors (Albertson, 1995; Lijklema *et al.*, 1993) have recommended the use of COD as a measure of pollution in preference to BOD as it is a more useful and reliable way to obtain the oxygen balance. Moreover, Lessard *et al.* (1982) and Geiger (1984) showed that the variation of suspended solids, chemical oxygen demand and orthophosphates followed a similar pattern. Another study by Chebbo *et al.* (1990) reported that TSS was well correlated with COD and the details are shown in Table 3.4(a). Further studies (Chebbo and Bachoc, 1992) showed that a majority of the pollution load was associated with the solid particulate phase and the average proportion of the pollution associated with this phase, in relation to the total pollution, is shown in Table 3.4(b).

Table 3.4(a) The percentage of total particulate pollution load associated with the different particle size fractions (after Chebbo *et al.*, 1990)

Particle size fractions (μm)	COD (%)	BOD_5 (%)	TKN (%)	Hydrocarbon (%)	Pb (%)
>250	28	28	26	69	13
50-250	4	20	58	4	34
<50	68	52	16	27	53

Table 3.4(b) Pollution load associated to solid particles (as percentage of total pollution) (Chebbo *et al.*, 1992)

Site	Number of Rainfall events	Pollution parameters				
		COD	BOD_5	TKN	Hydro-carbon	Pb
Bequigneaux (storm sewer, Bordeaux)	4	84-89	77-95	57-82	86	79-96
La Molette (CSO, Seine-Saint-Denis)	1	88	83	48	-	99
Trunk Sewer no. 13 (Combined sewer, Marseilles)	1 to 3	83-92	91	70-80	82-99	99-100

From Tables 3.4(a) and 3.4(b), it is clear that for COD, BOD_5, TKN, hydrocarbon, and lead, over 80% of the pollution load (as a percentage of the total pollution) was attached to the solid particles. Further, it was observed that the fine particles (<100 μm) predominated in the solids which were in suspension in the downstream networks of the combined sewer systems (in France) and that the mean specific mass of particles was 2.09. These particles represented between 66 and 85% of the total mass with a median diameter (D_{50}) varying between 25 and 44μm. They further observed that the particle size characteristics of solids transferred in suspension depended, to some extent, on the characteristics of the rainfall event. These studies confirmed earlier investigations (Sartor *et al.*, 1974) who showed that some 80% of COD and 57% of BOD loads were associated with the smaller sediments (<0.246 mm). Subsequently Verbanck *et al.* (1994) confirmed that heavy metals and organic pollutants are primarily associated with the finest particulates.

Bedient *et al.* (1978) observed that suspended solids were much higher from the urban and developing sites while Das (1977) reported that both the peak concentrations and peak mass emission rates for both BOD and TSS usually occurred simultaneously following the commencement of rainfall. Amandes and Bedient (1980) reported that TSS was an easy parameter to model as the solids were not affected by chemical processes although physical processes like erosion, sedimentation, bottom scouring, etc. were involved.

Another advantage of predicting suspended solids in combined sewer flows is in respect of the operation and performance of storage tanks. The deposition of suspended sediments may create significant maintenance problems. For example, it may result in an increase in the hydraulic roughness of the bed of the tank, a reduction in the flow capacity of the system, and hence in an increase in the number of spilled flows from the system. The overall result is an increase in the number of pollution incidents in the receiving watercourses.

Thus, the control of TSS should, in general, result in an improvement of the retention of pollutants within the system and in a reduced impact on the receiving waters. Hence TSS was the parameter considered in this study.

3.5. Methodology

The following methodology was adopted in this study:

(i) A definition of the first flush for the retention of pollutants within the sewer system was selected;

(ii) The variables to be used in the analysis were chosen; and

(iii) Multiple linear and log transformed linear regressional analysis was used to establish relationships between the variables.

3.5.1. The First Flush

The first flush of pollutants has been identified as the relatively high proportion of the total storm pollution load that occurs in the initial part of the combined sewer runoff as detailed in Section 2.3.2.

This study defines the foul flush as that part of the storm upto the maximum divergence between the dimensionless cumulative percentage of pollutants and the cumulative percentage of flows plotted against the cumulative percentage of time as detailed in Figure 3.2.

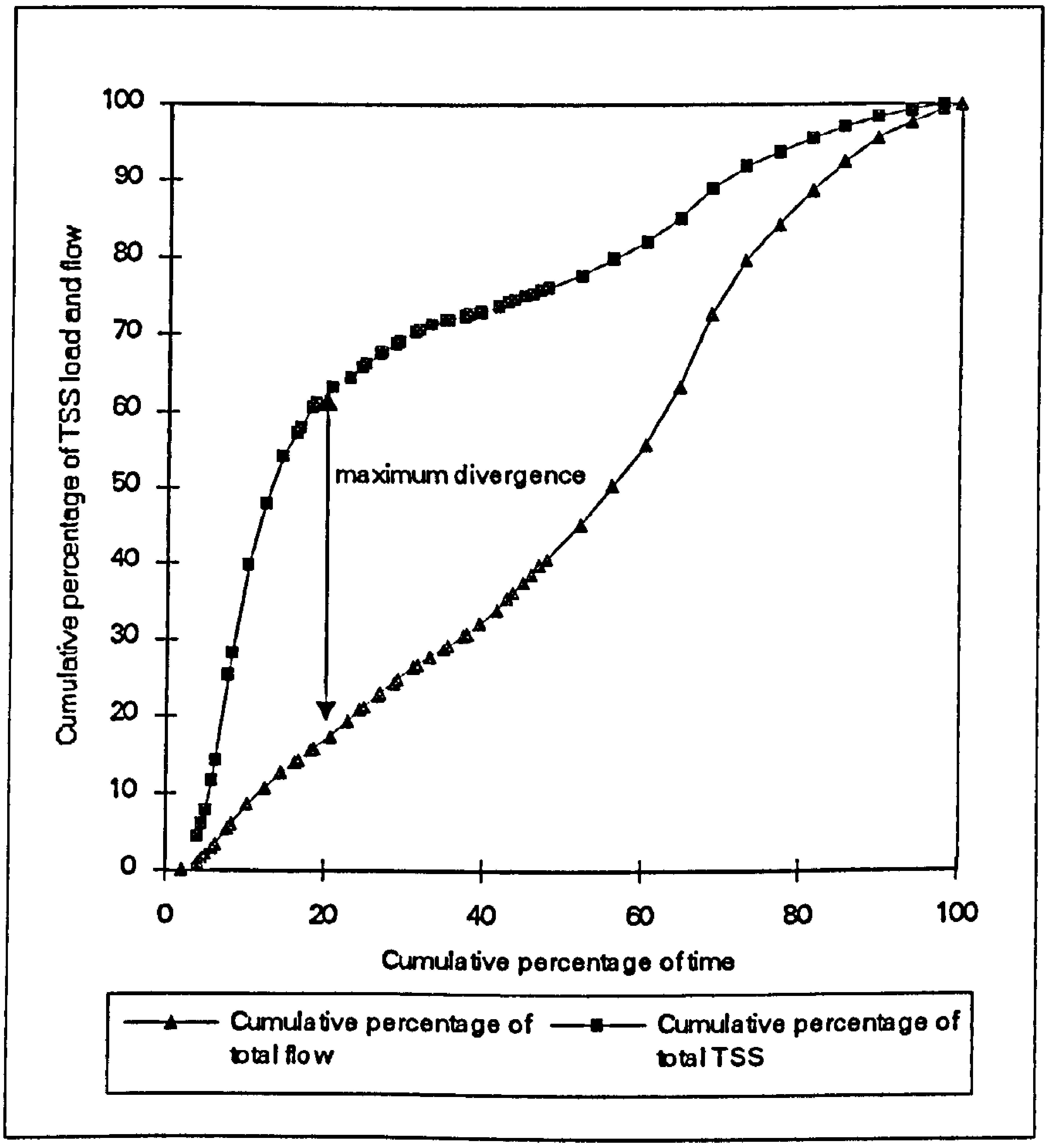


Figure 3.2. Definition of the foul flush as maximum divergence.

The advantages with this approach are, firstly, from a control standpoint, the dimensionless cumulative relation for a particular site allows the engineer to design the detention storage capacity necessary to capture a given percent of suspended solids, for example, collection of 30% of the initial runoff volume may result in a 60-70% capture of suspended load and this percentage would of course depend on the storm and catchment characteristics. Secondly, it would be possible to estimate the time of occurrence of the first flush which would be of considerable importance when strategies for the control and management of stormwater are formulated.

3.5.2. Selection of Appropriate Variables

It was hypothesised that the first flush load of pollutants (the dependent variable) could be expressed as a function of one or more of the following independent variables:

$$\mathrm{LOAD_{ff}} = f\,(\mathrm{EMC_{f},\ EMF,\ RFINT_{avr},\ QIN_{max},\ RFINT_{max},\ STDURN,\ ADWP,\ FLOW_{tot}}).$$

The variables and notation used are shown in Table 3.5. These parameters were determined by writing a computer program using the MACRO instruction facility in EXCEL (ver 4.0) to compute the various parameters relevant to this study for each of the storms at Great Harwood and Clayton-le-Moors from the raw data [time, rainfall intensity (RFINT), the inflow (QIN), and the concentration of total suspended solids (TSS) shown in Table 3.2]. The loadograph was determined as the product of the corresponding ordinates of the hydrograph and the pollutograph. The total load of suspended solids was then computed as the area under the graph while the first flush load was the area under the curve upto the point of maximum divergence and Tables 3.6 and Table 3.7 show the storm summary and the computed variables for Great Harwood and Clayton-le-Moors respectively.

Table 3.5. Variables computed from the SQA data for further regression analysis

(1)	(2)	(3)
Type of parameter	Variables	Notation
Event mean	Flow weighted event mean concentration (mg/l)	EMC_f
	Event mean flow (m^3/s)	EMF
	Event mean concentration in the first flush (mg/l)	EMC_{ff}
	Average rainfall intensity(mm/hr)	$RFINT_{avr}$
Event maximum	Maximum inflow (m^3/s)	QIN_{max}
	Maximum rainfall intensity (mm/hr)	$RFINT_{max}$
Event total	Storm duration (min)	STDURN
	Antecedent dry weather period (hr)	ADWP
	Total load of suspended solids(kg)	$LOAD_{tot}$
	Total inflow (m^3/s)	$FLOW_{tot}$
	Total rainfall depth (mm)	$RAIN_{tot}$
	Cumulative load of suspended solids in the first foul flush (kg)	$LOAD_{ff}$

Table 3.6. Computed variables for the Great Harwood catchment

S. No.	Storm date		S/W	LOAD $_{tot}$ (kg)	ADWP (hr)	ST DURN (min)	RAIN $_{tot}$ (mm)	RFINT $_{avr}$ (mm/hr)	RFINT $_{max}$ (mm/hr)	QIN $_{max}$ (m^3/s)
1	840524	a	S	365	30	55	6.94	6.36	28.80	0.347
2	840622		S	493	0.5	240	1.76	7.03	3.68	0.304
3	840711	a	S	578	42	80	0.35	0.46	3.20	0.567
4	840803		S	686	3	205	2.66	9.08	24.00	1.375
5	841018	b	S	973	10	70	3.57	4.16	67.20	1.618
6	841018	a	S	160	8	210	2.04	7.15	4.80	0.311
7	841029	a	S	38	9	50	1.32	1.10	2.77	0.230
8	841029	b	S	211	0.5	88	2.24	3.29	14.40	0.877
9	850607		S	129	15	54	3.37	3.03	9.60	0.554
10	850713		S	929	1	124	2.45	5.06	28.80	0.567
11	850717		S	145	32	65	2.49	2.70	9.60	0.936
12	850804		S	1431	14	15	20.48	5.12	67.20	1.740
13	850820		S	783	22	260	3.23	13.98	9.60	0.792
14	850824		S	1271	2	125	4.05	8.43	57.60	1.601
15	850828		S	324	53	55	4.15	3.80	9.60	0.340
16	850902		S	117	16	135	1.20	2.71	2.11	0.219
17	860511	a	S	89	3	78	3.12	4.05	3.04	0.324
18	860520	a	S	1571	58	152	2.21	5.60	12.80	1.020
19	860804		S	710	32	170	3.79	10.74	19.20	1.162
20	841102	a	W	214	34	115	2.21	4.23	4.80	0.274
21	841102	b	W	284	0.5	275	2.04	9.34	4.16	0.307
22	841109	a	W	166	16	130	1.72	3.72	3.20	0.330
23	841109	b	W	150	2	165	1.92	5.29	5.28	0.383
24	841122	a	W	262	5	140	2.88	6.72	14.40	0.965
25	841123		W	125	1	105	0.91	1.59	9.60	0.326
26	841127		W	377	36	285	1.54	7.32	7.68	0.426
27	841201		W	394	36	215	1.88	6.73	7.20	0.337
28	841218	b	W	394	10	135	1.16	2.62	11.20	0.469
29	850301		W	426	67	150	0.96	2.40	2.40	0.303
30	850314		W	289	2	90	1.03	1.55	2.40	0.738
31	850315	b	W	266	25	105	0.87	1.52	4.80	0.339
32	850329		W	325	0	265	1.29	5.68	3.33	0.274
33	850403		W	2520	33	395	2.15	14.18	9.60	0.703
34	851105	a	W	984	75	140	1.78	4.16	9.60	0.865
35	851116		W	267	31	185	3.05	9.40	4.80	0.277
36	851210		W	49	27	80	1.20	1.60	2.52	0.284
37	851217		W	228	86	58	2.44	2.36	3.20	0.270
38	860416		W	305	17	178	1.60	4.76	4.80	0.342

Notes: (a) S= summer event (May-October); a => first event on that particular day
(b) W= winter event (November-April); b => second event on that particular day

Table 3.7 Computed variables for the Clayton-le-Moors catchment

S. No.	Storm date		S/W	LOAD $_{tot}$ (kg)	ADWP (hr)	ST DURN (min)	RAIN $_{tot}$ (mm)	RFINT $_{avr}$ (mm/hr)	RFINT $_{max}$ (mm/hr)	QIN $_{max}$ (m^3/s)
1	850824	a	S	421	0	90	1.59	2.38	18.00	0.331
2	850903	b	S	1728	0	187	2.85	8.89	48.00	1.310
3	851003		S	597	8	124	1.95	4.03	24.00	0.339
4	860511		S	52	3	134	1.74	3.88	4.00	0.113
5	860514		S	43	0	107	1.39	2.48	12.00	0.099
6	860517		S	58	28	161	1.04	2.78	2.40	0.075
7	860520		S	538	58	125	3.21	6.68	48.00	0.385
8	860610		S	2803	13	250	3.16	13.17	36.00	0.468
9	860724		S	149	12	156	2.20	5.71	6.00	0.206
10	860804		S	417	9	151	3.15	7.93	12.00	0.445
11	860806		S	61	21	178	1.34	3.98	3.00	0.153
12	860821		S	158	24	85	1.79	2.54	6.00	0.165
13	860825		S	952	23	238	2.52	10.01	6.00	0.347
14	861030		S	1248	21	146	3.48	8.47	72.00	0.757
15	870511	b	S	162	111	181	1.19	3.60	2.40	0.193
16	870512		S	567	0	124	1.34	2.77	12.00	0.355
17	870711		S	764	9	40	3.19	2.13	24.00	0.642
18	860110		W	185	14	304	1.51	7.63	2.40	0.160
19	860128		W	245	26	237	1.26	4.97	3.00	0.173
20	860413	a	W	54	25	77	2.05	2.63	6.00	0.106
21	860416		W	327	17	146	2.11	5.13	12.00	0.395
22	861113		W	728	14	153	1.65	4.20	12.00	0.425
23	861114		W	424	8	92	2.64	4.05	12.00	0.445
24	861123		W	748	7	367	2.06	12.57	12.00	0.464
25	861124		W	446	9	181	1.93	5.81	12.00	0.359
26	861125		W	450	13	339	1.89	10.66	12.00	0.366
27	861217		W	753	0	296	1.46	7.21	12.00	0.525
28	861229		W	325	24	285	2.07	9.84	6.00	0.307
29	870104		W	76	46	274	2.56	11.71	3.00	0.194
30	870301	b	W	718	23	147	1.26	3.09	6.00	0.355
31	870401	a	W	335	3	177	1.34	3.95	3.00	0.368
32	870410	a	W	782	16	158	2.48	6.54	6.00	0.393
33	870419		W	129	10	201	1.35	4.52	4.00	0.850

Notes: (a) S= summer event (May-October); a => first event on that particular day
(b) W= winter event (November-April); b => second event on that particular day

3.5.3. Regression Studies

Many research studies have identified, for example, Lindholm and Aaby (1989), that multiple regression techniques may be used to better understand the importance of each of the relevant factors which influence the quality of storm water flow and the magnitude of the first flush. The regression techniques have been applied in many countries and these have been reviewed in Section 2.5.3 from which it is clear that in many of these studies, attempts have been made to predict the total load of pollutants from the various hydrological parameters or have attempted to characterise the pattern and load of the first flush of pollutants. However, no evidence has been found in literature which attempts to combine these two approaches, that is, a first flush definition appropriate to storage tank design combined with a regression approach to derive the first flush load related to the hydrologic and catchment parameters. This study attempts such an approach.

It has been recommended in literature that linear and log-log transform models be used in stormwater management models (Jewell and Adrian, 1981) whilst Reckhow *et al.* (1990) suggested that environmental contaminant data may be described with a lognormal distribution and therefore, "it is generally recommended to log transform water quality predictions and observations prior to analysis". Hence, the data was subject to multiple linear regression analysis (both linear and logarithmic transform) to establish possible relationships for the cumulative amount of TSS (in kg) (LOAD$_{ff}$) within the sewer flow upto the first flush, as defined above, and the various hydrologic parameters. The linear and logarithmic transform models for this study were formulated as follows:

$$Y \quad = A_0 + A_1X_1 + A_2X_2 + A_3X_3 + \ldots\ldots\ldots\ldots + A_nX_n \qquad (3.1)$$

$$\log Y \;= B_0 + B_1 \log X_1 + B_2 \log X_2 + B_3 \log X_3 + .. + B_n \log X_n \qquad (3.2)$$

where Y = total suspended solids load (kgs),

and A_0, A_1, A_2,......,A_n; B_0, B_1, B_2,.....,B_n = the estimated regression coefficients,

and X_n refers to the variables in column (2) of Table 3.5,

the detransformed equation is then

$$Y = K X_1^{B_1} X_2^{B_2} X_3^{B_3} \ldots\ldots X_n^{B_n} \quad (3.3)$$

where $K = 10^{B_0}$

Two statistical indicators were used to examine the regression relationships and these were the coefficient of determination (R^2) and the Student's t-test. R^2 quantifies the proportion of the data variance explained by the model and a R^2 value of 1 indicates an excellent correlation between the estimated and actual data whereas if the R^2 value is 0, the regression relationship shows no correlation, and the hypothesis is invalidated. In the case of the log-log transformed model, the value of R^2 indicates the proportion of the total variation of logs of the dependent variable explained by the explanatory variables, and is used as a summary measure to judge the fitness of the regression model to the data. The standard error of estimate is an estimate of the standard deviation of the log of the dependent variable about the regression. According to the t-test, the coefficients of these variables have been tested for significance at the 5% level for all models.

3.6. Results and Discussion

As it was hypothesised that the ADWP was an important parameter affecting the build-up of sediments in sewers, the regression analysis was limited to the events for which the ADWP was known. Consequently, a total of 36 storm events at the Great Harwood catchment and 31 events at the Clayton-le-Moors catchment were analysed. Initially, all the data were analysed together but later the data were categorised into summer (May to October) and winter (November to April) events in line with the recommended procedures in the Flood Studies Report (NERC, 1975) as it was thought that the pollution characteristics would be different for summer and winter events. That this is indeed the case can be seen from the storms at Great Harwood for which the computed values of the mean total load of suspended solids, total inflow, flow weighted event mean concentration (EMC_f) and the event mean flow (EMF) are given in Table 3.8. It can be seen that there were significant differences between the data for summer and winter storms but no statistically significant relationship was found between the flow weighted event mean concentration and the event mean flow as shown in Table 3.9.

Table 3.8. Mean values of pollution loads and flow for the Great Harwood data

Storm type	$LOAD_{tot}$ (kg)	$FLOW_{tot}$ (m^3)	EMC (mg/l)	EMF (m^3/s)
all	696	2266	342	0.288
summer	758	2233	406	0.347
winter	635	2299	279	0.228

Table 3.9. R^2 values for EMC_f and the EMF for the Great Harwood data

	All storms	Summer storms	Winter storms
1. (a) $\log EMC_f = a \log EMF + b$	0.00	0.00	0.02
1. (b) $EMC_f = a\ EMF + b$	0.01	0.00	0.03

The various models that were examined are given in Table 3.10 and the results are summarised as follows:

(i) No correlation was found between the flow weighted event mean concentration (EMC_f), event mean flow (EMF) and the ADWP.

(ii) It was also hypothesised that the event mean concentration of the load of suspended solids in the first flush (EMC_{ff}) was related to the input variables of maximum rainfall intensity ($RFINT_{max}$), average rainfall intensity ($RFINT_{avr}$), maximum inflow (QIN_{max}), event mean flow upto first flush (EMF_{ff}), duration upto the foul flush ($DURN_{ff}$), and the total storm duration (STDURN). Again, no correlation between the variables was observed.

(iii) Similarly, the relationship between the cumulative load of suspended solids in the first flush ($LOAD_{ff}$) and the input parameters QIN_{max}, EMF and ADWP, was examined as shown in Table 3.11 and the results confirmed that there was again little correlation between the parameters.

Table 3.10. Regression models

S.No.	Model
1.	EMC_f=a EMF +b
2.	log EMC_f= a log EMF +b
3.	EMC_f=a EMF +b ADWP+c
4.	log EMC_f=a log EMF +b log ADWP+c
5.	EMC_f=a ADWP+b
6.	log EMC_f= a log ADWP +b
7.	EMC_{ff}=a $RFINT_{max}$ +b
8.	log EMC_{ff}= a log $RFINT_{max}$ +b
9.	EMC_{ff}=a $RFINT_{avr}$ +b
10.	log EMC_{ff}= a log $RFINT_{avr}$ +b
11.	EMC_{ff}=a QIN_{max} +b
12.	log EMC_{ff}= a log QIN_{max}+b
13.	EMC_{ff}=a EMF_{ff}+b
14.	log EMC_{ff}= a log EMF_{ff}+b
15.	EMC_{ff}=a $DURN_{ff}$+b
16.	log EMC_{ff}= a log $DURN_{ff}$+b
17.	EMC_{ff}=a STDURN +b
18.	log EMC_{ff}= a log STDURN +b
19.	EMC_{ff}=a $RFINT_{max}$ +b STDURN+c
20.	log EMC_f= a log $RFINT_{max}$ +b log STDURN + c
21.	$LOAD_{tot}$=a ($FLOW_{tot}$)+b
22.	log $LOAD_{tot}$= a log ($FLOW_{tot}$)+b
23.	$LOAD_{ff}$= a (QIN_{max})+b (ADWP)+c
24	log $LOAD_{ff}$= a log (QIN_{max})+b log(ADWP)+c
25	$LOAD_{ff}$= a ($RFINT_{max}$)+b (ADWP)+c
26	log $LOAD_{ff}$= a log ($RFINT_{max}$)+b log(ADWP)+c
27	$LOAD_{ff}$= a (QIN_{max})+b (STDURN)+c
28	log $LOAD_{ff}$= a log (QIN_{max})+b log(STDURN)+c
29	$LOAD_{ff}$= a ($RFINT_{max}$)+b (STDURN)+c
30	log $LOAD_{ff}$= a log ($RFINT_{max}$)+b log(STDURN)+c
31	$LOAD_{ff}$= a (QIN_{max})+b (STDURN)+c ADWP+d
32	log $LOAD_{ff}$= a log (QIN_{max})+b log(STDURN)+c log (ADWP)+d
33	$LOAD_{ff}$= a ($RFINT_{max}$)+b (STDURN)+c ADWP+d
34	log $LOAD_{ff}$= a log ($RFINT_{max}$)+b log(STDURN)+c log (ADWP)+d

(iv) As a next step, the relationship between the cumulative TSS upto the foul flush ($LOAD_{ff}$) (kg), the maximum rainfall intensity ($RFINT_{max}$) (mm/hr), the maximum inflow (QIN_{max})(m^3/s), the ADWP (hr) and the storm duration (STDURN) (min) was determined as $LOAD_{ff}$ = f (STDURN, $RFINT_{max}$ or QIN_{max}, and ADWP). The results of this analysis are shown in Table 3.12 and the following predictive equations were concluded:

Table 3.11. R^2 values for the first flush load of pollutants as a function of ADWP and flow for the Great Harwood data

	All storms	Summer storms	Winter storms
$LOAD_{ff}=k\,(QIN_{max})^a\,(ADWP)^b$	0.28	0.18	0.43
$LOAD_{ff}=a\,(QIN_{max})+b\,(ADWP)+c$	0.13	0.22	0.27
$LOAD_{ff}=k\,(EMF)^a\,(ADWP)^b$	0.30	0.31	0.23
$LOAD_{ff}=a\,(EMF)+b\,(ADWP)+c$	0.16	0.27	0.20

Table 3.12. R^2 values for the first flush load of pollutants as a function of maximum rainfall intensity/flow, storm duration and ADWP for the Great Harwood data

$LOAD_{ff}$ as function of the following variables	Form of equation	All storms	Summer storms	Winter storms
$RFINT_{max}$, STDURN, ADWP	(linear)	0.52	0.55	0.62
$RFINT_{max}$, STDURN, ADWP	**(log transform)**	**0.59**	**0.65**	**0.54**
QIN_{max}, STDURN, ADWP	(linear)	0.54	0.49	0.71
QIN_{max}, STDURN, ADWP	**(log transform)**	**0.59**	**0.54**	**0.71**

ALL STORMS:

$$LOAD_{ff}=1.58\,(STDURN)^{0.61}\,(RFINT_{max})^{0.71}\,(ADWP)^{0.23} \qquad (R^2=0.59) \qquad (3.4)$$

$$LOAD_{ff}=16.98\,(STDURN)^{0.94}\,(QIN_{max})^{0.63}\,(ADWP)^{0.21} \qquad (R^2=0.59) \qquad (3.5)$$

SUMMER STORMS:

$$LOAD_{ff}=1.35\,(STDURN)^{0.68}\,(RFINT_{max})^{0.68}\,(ADWP)^{0.28} \qquad (R^2=0.65) \qquad (3.6)$$

$$LOAD_{ff}=33.88\,(STDURN)^{0.92}\,(QIN_{max})^{0.47}\,(ADWP)^{0.21} \qquad (R^2=0.54) \qquad (3.7)$$

WINTER STORMS:

$$LOAD_{ff} = 3.72\ (STDURN)^{0.94}\ (QIN_{max})^{0.93}\ (ADWP)^{0.21} \qquad (R^2 = 0.71) \qquad (3.8)$$

$$LOAD_{ff} = 0.95\ (STDURN)^{0.92}\ (RFINT_{max})^{0.36}\ (ADWP)^{0.20} \qquad (R^2 = 0.54) \qquad (3.9)$$

By examination of equations (3.4) to (3.9), it can be seen that the ADWP has the same influence on the first flush pollutant load over the entire year. This contradicts the works of others and hence the regression analysis was repeated without taking ADWP into consideration. This resulted in a noticeable reduction in the R^2 values ranging from 0.29 to 0.45 for the summer storms confirming the importance of ADWP at this site and the results are shown in Table 3.13

Table 3.13. **R^2 values for the first flush load of pollutants as a function of maximum rainfall intensity/flow and storm duration for the Great Harwood data (Without ADWP)**

$LOAD_{ff}$ as f(⇓)	Form of equation	All storms	Summer storms	Winter storms
$RFINT_{max}$, STDURN	(linear)	0.31	0.18	0.48
$RFINT_{max}$, STDURN	(log transform)	0.27	0.20	0.40
QIN_{max}, STDURN	(linear)	0.35	0.20	0.59
QIN_{max}, STDURN	(log transform)	0.31	0.22	0.56

It was concluded therefore, that equations of the form (3.6) and (3.7) are considered to be the most appropriate to predict the pollutant load in the first flush at this site.

To further verify the above equations, the analysis was repeated for the Clayton-le-Moors site. It was found that the winter storms did not show any meaningful correlation, possibly due to the extra gritting and salting associated with a severe snowfall. Hence only the results for the summer storms have been reported.

SUMMER STORMS:

$$LOAD_{ff} = 0.92\,(STDURN)^{0.73}\,(RFINT_{max})^{0.93}\,(ADWP)^{0.14} \qquad (R^2 = 0.71) \qquad (3.10)$$

$$LOAD_{ff} = 103.43\,(STDURN)^{0.68}\,(QIN_{max})^{1.74}\,(ADWP)^{0.12} \qquad (R^2 = 0.85) \qquad (3.11)$$

The results of the analysis at both the catchments indicates the importance of the ADWP as a factor determining the build-up of pollutants in the catchment and sewer system. Similar results were reported, for example, by Haster and James (1994) who showed that the rate at which sediments were washed off an impervious area was correlated with the length of the time since the rainfall last occurred and other studies by Marsalek (1976), Pearson *et al.* (1986), and Stotz and Krauth (1984) have also identified a correlation between the pollutants in the first flush and the antecedent dry weather period.

3.7. Validation and Application of the Regression Equations

The usefulness of the regression models was assessed by comparing model results with observed first flush loads for several independent storms not used in the model calibration. As all available data for the Great Harwood catchment was used to develop the model, to illustrate the validity of the derived relationships, equations (3.10) and (3.11) were applied to 12 storms at the Clayton-le-Moors site which had not been included in the model formulation. The predicted and observed values are shown in Figure 3.3 and reasonable agreement was observed for values of loads less than 1000 kg. However, the regression model over predicted the loads greater than 1000 kg and this is identified as a shortcoming of the model.

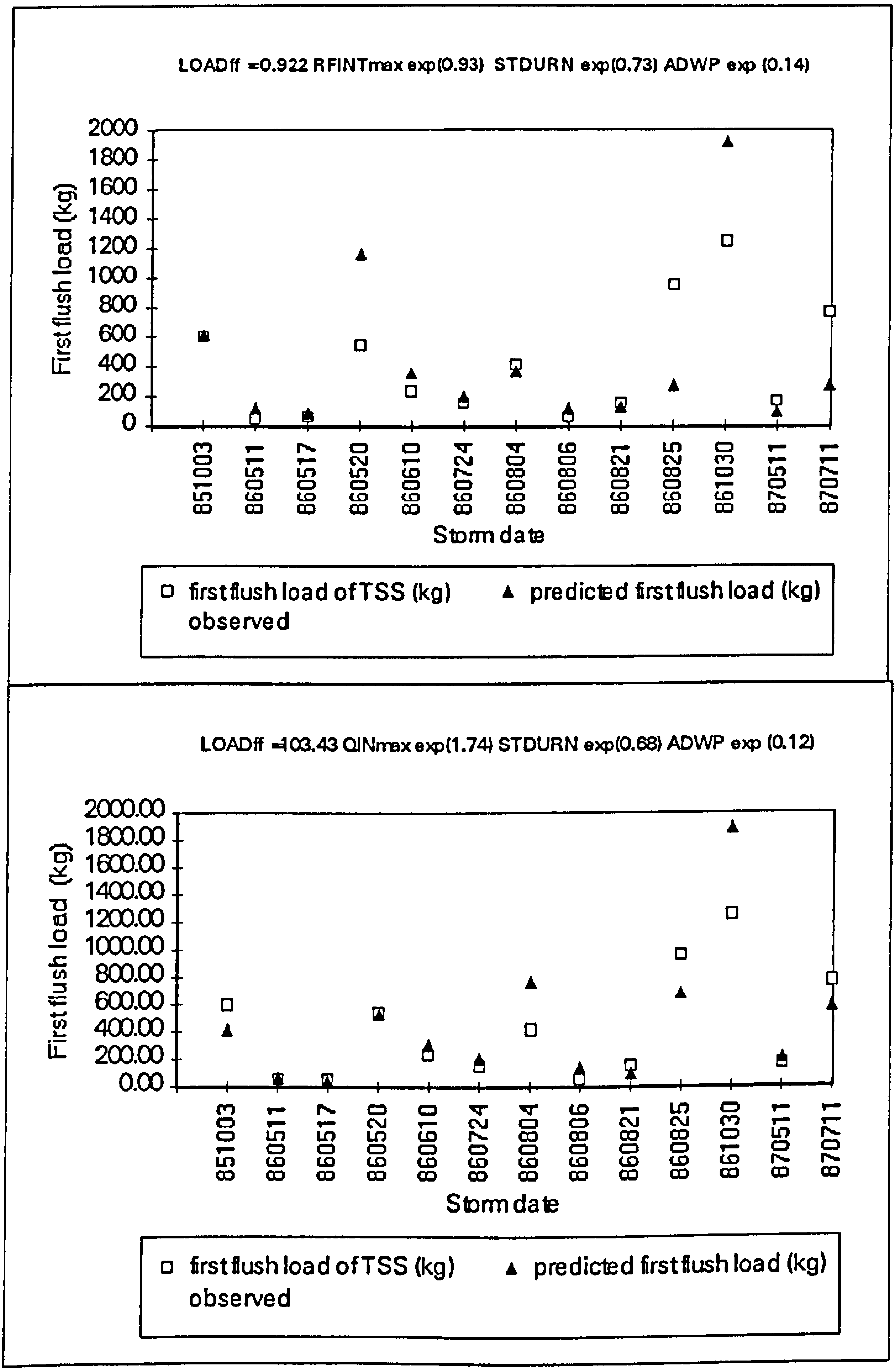


Figure 3.3. Equations applied to Clayton-le-Moors site data.

It was concluded therefore, that within the limitations of the regressional approach adopted, the derived equations may be used to establish a quick estimate of the pollutant load in the first flush of a combined sewer flow for a given storm duration, peak rainfall intensity or flowrate and the antecedent dry weather period. It is stressed however, that while this methodology eliminates the need to estimate pollutant washoff coefficients, the relationships derived are catchment specific.

The storm event total loadings are useful only for estimating the accumulative effects, but for the estimation of acute effects, for example, a detailed storm event pollutograph, the regression models are not suitable because of the large intra-event variations. For simulation of detailed pollutographs, the development of an empirical methodology based on the detailed analysis of the pollutographs is discussed in the following Chapter.

3.8. Conclusions

A suitable methodology to define the pollutant load in the first flush of pollutants in combined sewer flows has been suggested.

It was concluded that TSS was the most important single variable to describe the pollutant load within a combined sewer flow.

Linear and logarithmic transformed regression models for estimating first flush loads were developed and the first flush load was shown to correlate well with the peak rainfall intensity (or the peak flowrate), the storm duration and the antecedent dry weather period. Site specific regressional relationships have been established to predict the first flush load of TSS for the sewer system catchments at Great Harwood and Clayton-le-Moors. These site specific relationships may be used with reasonable confidence to estimate the first flush load within each catchment. However, this method is inadequate to estimate the detailed pollutograph and the development of an empirical methodology based on the detailed analysis of the pollutographs is described in the following Chapter.

Chapter 4

DEVELOPMENT OF THE POLLUTOGRAPH METHODOLOGY

4.1. Summary

The primary objective of this study was to develop a methodology to describe the design pollutograph corresponding to rainfall inputs which are commonly used as the basic parameters of design. In this study, it was hypothesised that the pollutographs could be related to one or more of the following storm parameters: total rainfall depth, storm duration, maximum rainfall intensity, average rainfall intensity, and the antecedent dry weather period. The first four of these storm parameters may be expressed in the form of a non-dimensional storm profile peakedness, defined as the ratio of the peak rainfall intensity to the average rainfall intensity. It has subsequently been shown that the non-dimensional storm profile peakedness can be used to characterise all the parameters of the storm as, by definition, it is a function of four storm parameters: the maximum rainfall intensity, the average rainfall intensity, the total rainfall depth and the storm duration. The results presented in this chapter highlight that it is possible to formulate pollutographs corresponding to storms of different profile peakedness and that the subsequent verification of the model confirms that the proposed methodology is able to predict the pollutographs satisfactorily for the two catchments considered in this study.

4.2. Introduction

An early attempt to develop a model to describe the temporal pattern of pollution in separate sewer systems has been made by several researchers as detailed in Section 2.2 of the thesis, for example, Price and Mance (1978) and Tucker and Mortimer (1978). However, these models are limited in their use in that they require the mass of material available for transport to be specified at the start of each rainfall event and that the definition of this parameter is somewhat subjective. Interim measures have seen the application of an approach based on the use of an average concentration of pollutants which is used in conjunction with the flow predicted from an urban sewer flow quality model, for example, WALLRUS, to compute the pollutant load in the sewer flow. Recently, however, detailed simulation models like MOUSETRAP and QSIM have been made available and these compute the temporal variation in the quality of the sewer flow, but the data requirements for the models are onerous. As a consequence, it has been recommended in the Urban Pollution Management (UPM) Manual (FWR, 1994) that a simplified urban pollution model should be developed for most planning studies. The UPM manual incorporates a simple model, termed SIMPOL to predict the BOD at 1 hour time intervals. This approach may be considered satisfactory for accumulative effects, but for the prediction of acute effects, for example, the first foul flush, the temporal variation of the concentration and load of the pollution in sewer flow is required at a much smaller time interval (say 5 minutes) than that proposed in SIMPOL. Such a pollutograph may then be used to assess the impact of design and control options to be compared, for example, the real time control of storage tanks to retain the first flush of pollutants. There is, therefore, a need to develop a relatively simple model which may be used to describe the temporal variation of pollutants within combined sewer flow at small time increments. It was, therefore, hypothesised that there is the potential to examine the relationship between the observed storms and the corresponding temporal variation in the quality of the sewer flow with a view to developing a methodology to predict sewer flow quality from design rainfall inputs. Such an approach has the advantage that, if successful, the methodology should provide a simple procedure to examine the relationship between pollution and flow from a given catchment prior to the application of more sophisticated modelling approaches. The work outlined in this chapter summarises the methodology that has been adopted in an attempt to establish if such a relationship exists.

4.3. Background to Storm Inputs

Historically, design storms have been applied to catchments, the runoff from which is used to compute the hydrograph and peak sewer flows which are subsequently used for the design of urban drainage structures. It has been identified in the literature (for example, The Wallingford Procedure, NWC/DoE, 1983) that design discharges for new systems should be estimated from a knowledge of the rainfall and the physical characteristics of the urban catchment which drain to the system. Essentially, therefore, design methods consist of procedures which transform the design storm rainfall into a rate of sewer flow. Earlier studies based their designs on the concept of a design storm which was an average rate of rainfall corresponding to a given storm duration and specified return period derived from historical rainfall intensity-duration-frequency relationships, for example, Bilham (1936) and the first edition of Road Note 35 (TRRL, 1963). These were subsequently superseded by the recommendations of the Flood Studies Report (FSR; NERC, 1975) based upon the analysis of a substantial data set of long term rainfall records. The FSR provides information on the variation of storm rainfall over areas of different sizes, and on the construction of storm profiles corresponding to different percentile peakedness; peakedness was defined as the ratio of peak rainfall intensity to the mean intensity of a particular storm event, while percentile peakedness was defined as the percentage of storm events with a peakedness less than or equal to that of a given profile. The second edition of Road Note 35 (1976) recommended the application of design storms based upon the 50 percent summer profile which has also been adopted in the current UK water industry software - HYDROWORKS and QSIM (HR Wallingford, 1994). These suites of programmes utilise the FSR profiles to describe the variation of rainfall intensity with time throughout the duration of the event to estimate the hydrograph shape and peak rate of flow within a sewer system corresponding to a particular catchment.

An analysis of a considerable number of recorded storm profiles by Holland (1967) showed that the maximum rainfall intensity occurred before the midpoint of the storm duration, and that the rise to the maximum rainfall rate was steeper than the subsequent recession. Subsequently, the use of synthetic design storms in HYDROWORKS has been criticised (UPM, 1994) in that a major limitation in their use is that the shape of a synthetic design storm profile is symmetrical about a single central peak and hence does not bear a close relationship to observed rainfall profiles. This problem has only recently been addressed to a large extent in the development of a rainfall time series from both records of historic rainfall and by the use of stochastic rainfall generation techniques (Cowperwait *et al.*, 1991; Cowperwait and Threlfall, 1994). Such rainfall inputs are now incorporated into the STORMPAC rainfall processing package (WRc, 1994). This model disaggregates the hourly values for selected events into five-minute intensity values for direct input into sewer flow or sewer quality models.

While the procedures outlined in the Flood Studies Report provided a methodology for predicting the peak flows from design storms based on storm profiles; a literature review has revealed that, although many studies have been made to predict the peak flows from design storms, no attempts have been reported to relate the peak concentration of pollutant occurring due to the first flush of pollutants in combined sewer flows and the shape of the pollutograph to the observed or simulated storm profiles. The work presented in the next sections of the thesis describes a methodology to relate these parameters.

4.4. Development of the Proposed Methodology

The steps involved in the development of the proposed methodology were:

(i) To examine the measured pollutographs corresponding to individual storm events for any trends or patterns, which could be related to the storm characteristics of maximum rainfall intensity, storm duration and the antecedent dry weather period (ADWP);

(ii) To establish relationships which described the shape of each individual or group of pollutographs corresponding to storm events with characteristics within a specified range;

(iii) To determine equations to estimate the peak pollutant concentration in the first flush; and

(iv) To determine the time to peak of the pollutograph in relation to the rainfall hyetograph and/or the flow hydrograph.

4.5. Data Used

Summer storms (May-October) have been identified as being relevant for urban storm drainage design (The Wallingford Procedure; DoE/NWC, 1983) and hence, in this study the analysis was carried out using only summer storms. In addition, it was shown in Chapter 3 that the ADWP was an important factor contributing to the first flush of pollutants in the sewer system, and hence only those storms for which the ADWP was known have been used in the analysis. This resulted in 16 "BEST" (Section 3.3) storms at the Great Harwood catchment and 11 BEST storms at the Clayton-le-Moors catchment being considered for further study.

However, a subsequent visual examination of the storms highlighted that, for a few events having a peak rainfall intensity of < 10 mm/hr, uncharacteristically high peaks in pollutant concentration were observed that did not correspond to peaks in rainfall or flowrate. For these storms it was hypothesised that the peaks of pollution were derived from sources other than the rainfall runoff or in-sewer sediment processes, for example, industrial discharges. Considering the fact that a large number of industries were located in the catchment, it was highly likely that these large values of pollutant concentrations were caused by such inputs. Hence, the events which exhibited such high concentrations in pollution were subsequently omitted from the data set. This resulted in 13 "BEST" events at Great Harwood and 7 "BEST" events at Clayton-le-Moors being available for subsequent analysis.

4.6. Pollutograph Comparisons

From the results obtained in Chapter 3, the first flush load was shown to be a function of the maximum rainfall intensity, the ADWP and the storm duration. The maximum rainfall intensity has been identified to be an important variable, because it is the impact of the falling rainfall that contributes to the rate of the washoff of surface pollutants and sediments and subsequently, the corresponding peak magnitude of the sewer flow influences the movement of the in-sewer sediments within the sewer system. The ADWP has also been identified as important, because it determines the length of the period for which pollutants are allowed to build-up over the catchment surface and in the sewer system. The storm duration was considered important because this has an influence on the exhaustion of the sources of pollution and due to the fact that in flowing full or surcharged systems which take a long time to empty, the pollutants may be deposited in the sewers during the recession limb of the sewer flow hydrograph. It was therefore hypothesised that some relationship might be obtained if the pollutographs (expressed as concentrations in mg/l) of each storm were classified by these three variables, namely, the maximum rainfall intensity, ADWP and storm duration. Therefore, for both the Great Harwood and Clayton-le-Moors catchment, the analysis was carried out by classifying the pollutographs of the observed storms as follows:

(a) By storm duration: All the pollutographs having durations in the range of 1-2 hours were plotted together. Storms of duration less than 1 hour were not considered because by definition, the BEST events were those with a minimum record duration of 1 hour. These were then examined visually in an attempt to observe any patterns or trends in the peak value and shape of the pollutograph as a function of the storm duration. This analysis was repeated for the pollutographs of storms with durations in the range 2-3 hr and > 3 hr. A plot of the results is shown in Figures 4.1 and 4.2 from which it can be seen that no significant trends were observed.

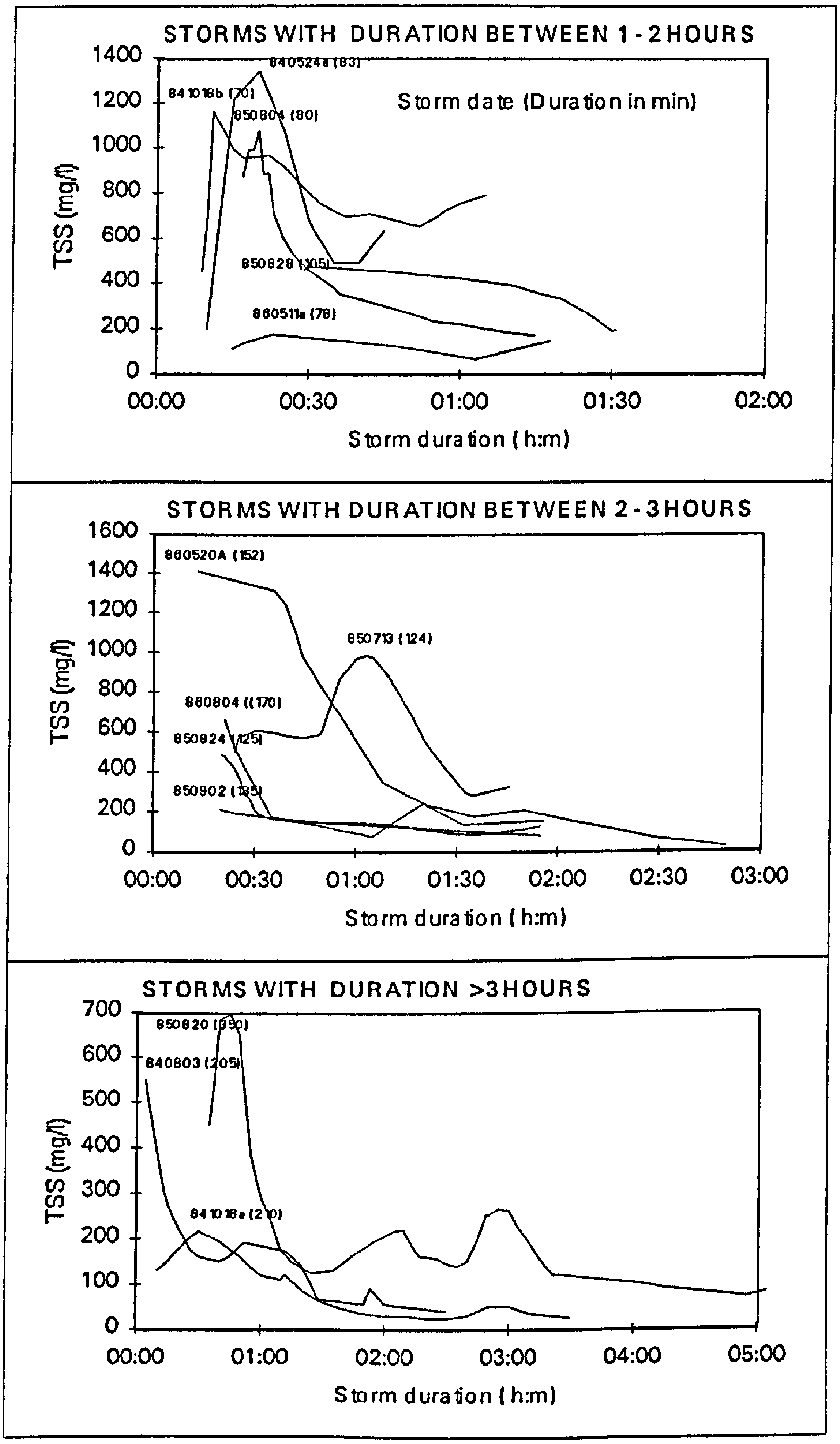


Figure 4.1. Pollutographs compared by storm duration at Great Harwood.

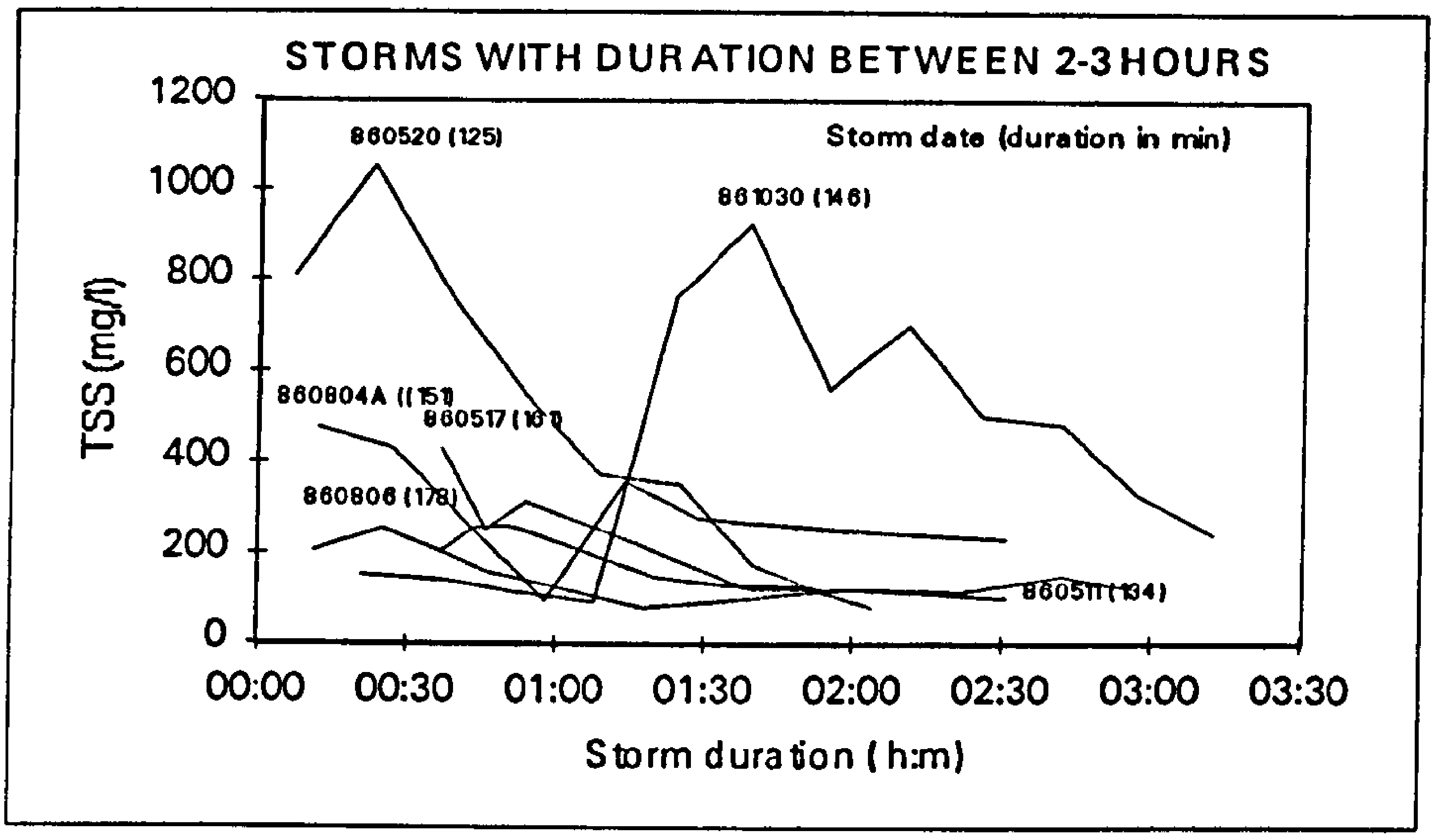


Figure 4.2. Pollutographs compared by storm duration at Clayton-le-Moors.

(b) By ADWP: The pollutographs were classified in the following arbitrary range of ADWP, that is, less than 12 hr, 12-24 hr, and greater than 24 hr as detailed in Figures 4.3 and 4.4. Observations of the storms within each category revealed that there was no discernible relationship between the peak and shape of the pollutograph to the ADWP.

(c) By maximum rainfall intensity: The pollutographs were also classified into various categories based on the maximum rainfall intensity observed within each storm event: < 5 mm/hr, 5-10 mm/hr, 10-15 mm/hr and > 15 mm/hr and these are shown in Figures 4.5 and 4.6. For the pollutographs classified on this basis, it was possible to assign a maximum peak concentration of total suspended solids that was associated with each category of peak rainfall intensity and these are shown in Table 4.1. In addition, at both the Great Harwood and Clayton-le-Moors sites, it was observed from an analysis of the return period for each storm event (Section 5.3.4) that all storms with a maximum rainfall intensity greater than 15 mm/hr (7 at Great Harwood and 3 at Clayton-le-Moors) had return periods of more than 4 months. Such storms have been identified as being appropriate for urban drainage design (Roesner, 1992; Hvitved-Jacobsen, 1988) and hence, this observation suggests that, in addition to the design of urban drainage systems for control of flows, the summer storms also provide a good basis for the design of urban drainage systems for pollution control.

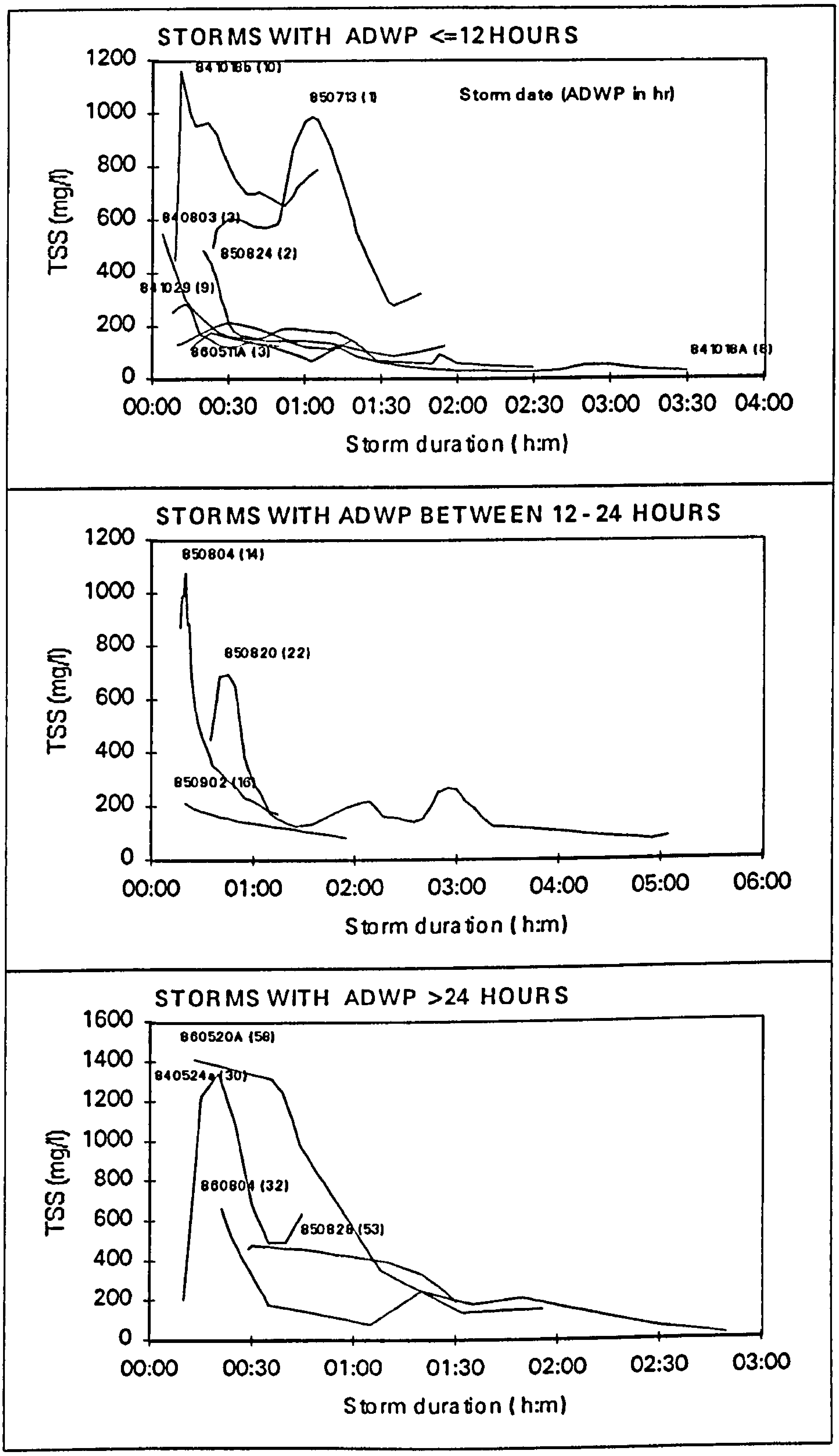


Figure 4.3. Pollutographs compared by ADWP at Great Harwood.

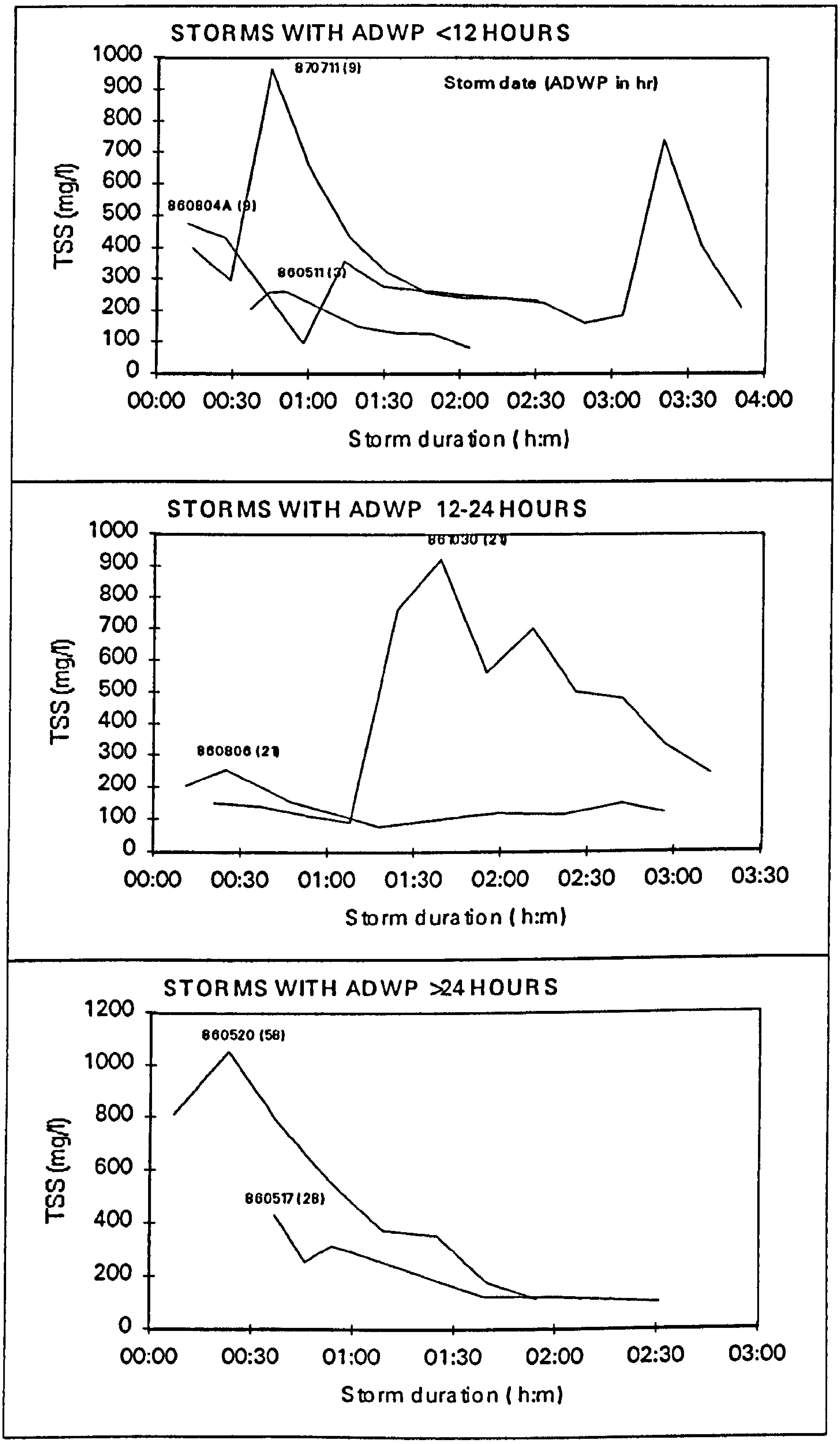


Figure 4.4. Pollutographs compared by ADWP at Clayton-le-Moors.

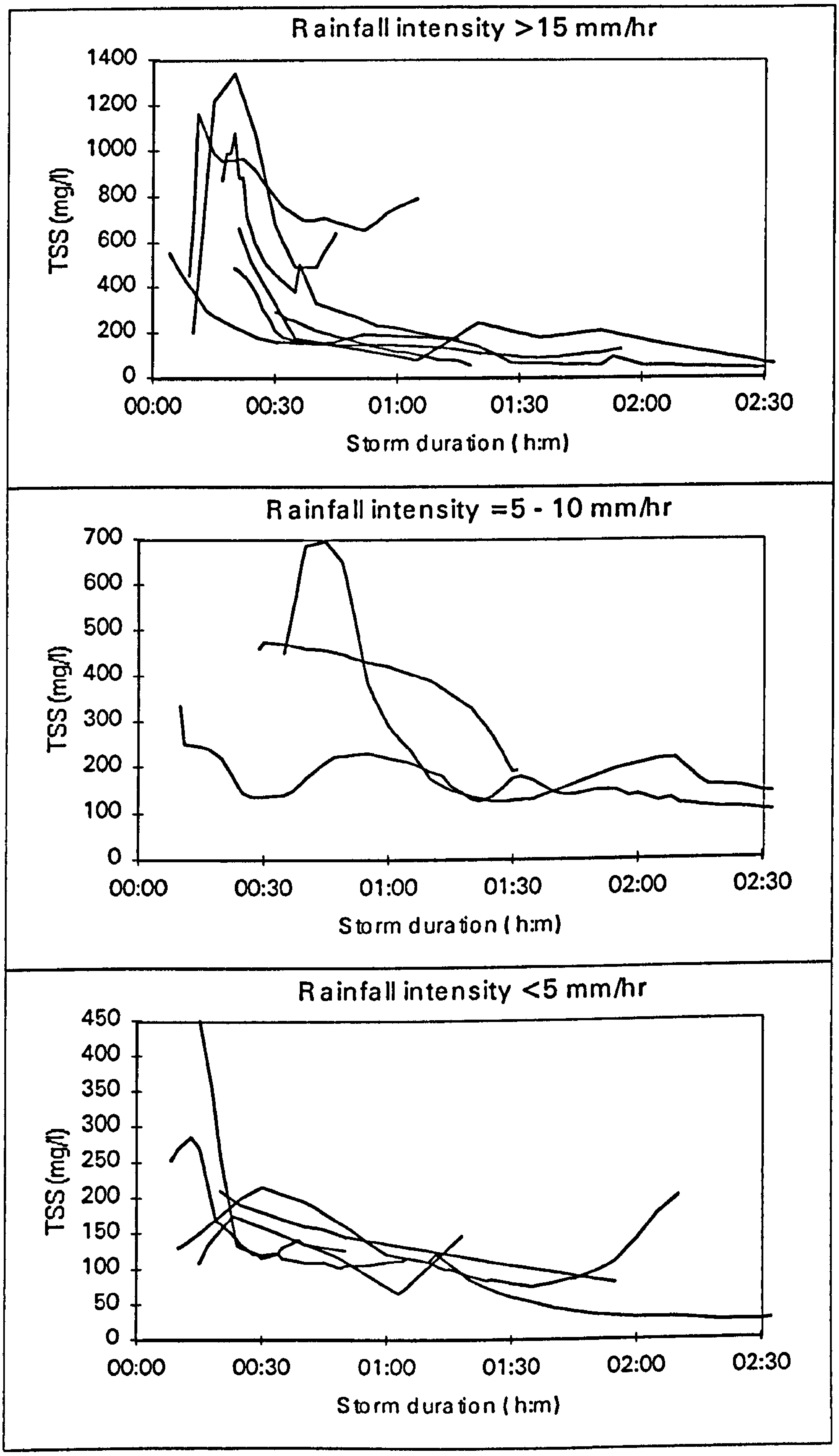


Figure 4.5. Pollutographs compared by rainfall intensity at Great Harwood.

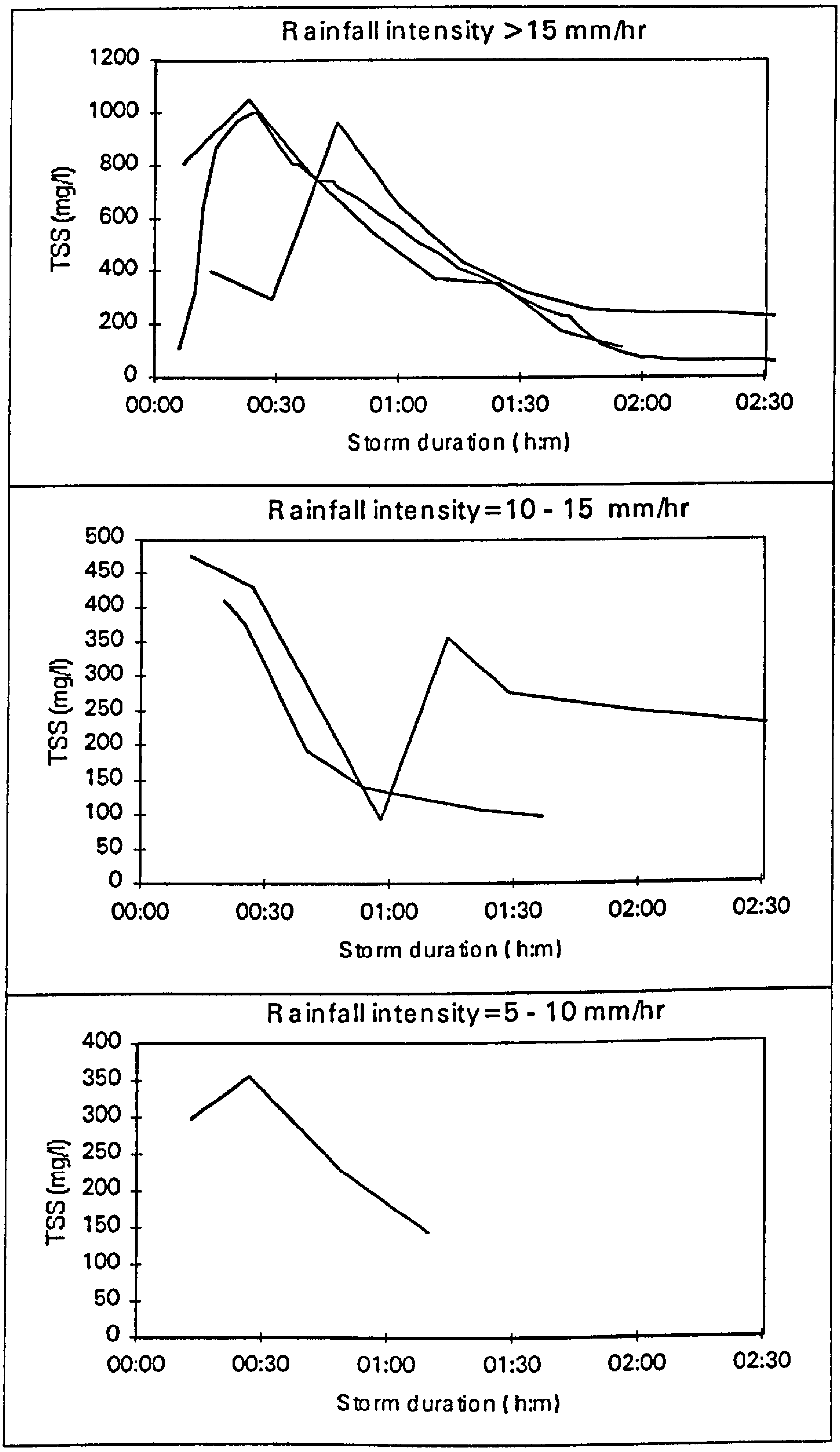


Figure 4.6. Pollutographs compared by rainfall intensity at Clayton-le-Moors.

Table 4.1. Observed peak pollutant concentrations and loading rates associated with various categories of maximum rainfall intensity (SUMMER storms)

(a) AT GREAT HARWOOD

Maximum Rainfall intensity (mm/hr)	Peak TSS concentration (mg/l)	Peak load rates (g/s)	No. of events
> 15	1340	550	7
10-15	-	-	-
5-10	1400	475	3
<5	1360	365	3

(b) AT CLAYTON-LE-MOORS

Maximum Rainfall intensity (mm/hr)	Peak TSS concentration (mg/l)	Peak load rates (g/s)	No. of events
> 15	1000	575	3
10-15	600	250	2
5-10	400	115	1
<5	200	30	1

A similar study was carried out using the pollutographs expressed in terms of a loading rate (g/s). The results of this analysis also showed poor results when the storms were classified on the basis of the antecedent dry weather period and the storm duration. However, on the basis of the classification by the maximum rainfall intensity as shown in Figures 4.7 and 4.8, it was again possible to assign maximum values of the peak load rates (g/s) that may be associated with a particular range of rainfall intensity and these are also shown in Table 4.1. These results give an indication of the maximum TSS loading rate that could be expected from a storm associated with the particular rainfall intensity. As identified by Hedley and King (1971), these may be useful for assessing the impact on receiving water quality, as the strength of the sewage alone is an insufficient measure of the impact and that it is the rate of pollutants which enter the system that is a better indicator of the impact.

To examine whether the pollutant concentrations in mg/l or pollutant loading rates in g/s should be considered for further analysis, the pollutant concentrations (mg/l) and the loading rates (g/s) for each storm were plotted together and a typical plot is shown in Figure 4.9. By visual observation, it was concluded that for each storm, the shapes of the concentration curves were very similar to the corresponding loading rate curves and hence, it was hypothesised that provided such a pollutograph profile could be obtained from observed storm characteristics, the corresponding loading rate graph (g/s) may be determined by multiplying the corresponding ordinates of the pollutograph and the flow hydrograph obtained from a measured or simulated flow. In this latter respect, it is possible to utilise a design storm rainfall hyetograph or an observed hyetograph to compute the simulated flow hydrograph using standard UK stormwater simulation software (for example, WALLRUS/ HYDROWORKS) and subsequently to utilise these flow rates with the derived concentration to generate the time varying load of pollutants. Therefore, further analysis was carried out using the observed pollutographs in the form of pollutant concentrations expressed as mg/l.

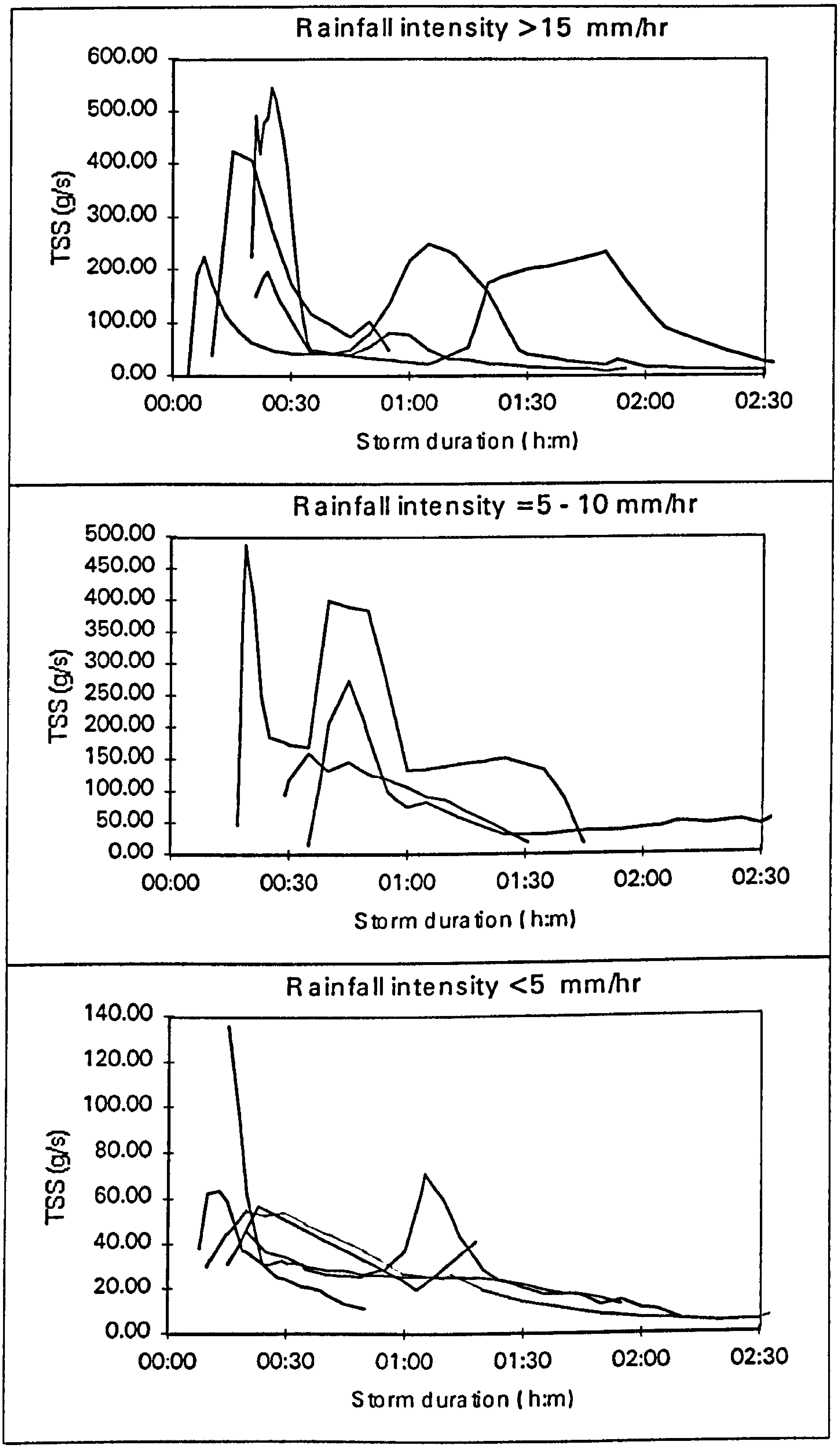


Figure 4.7. Loading rate (g/s) graphs compared by rainfall intensity at Great Harwood.

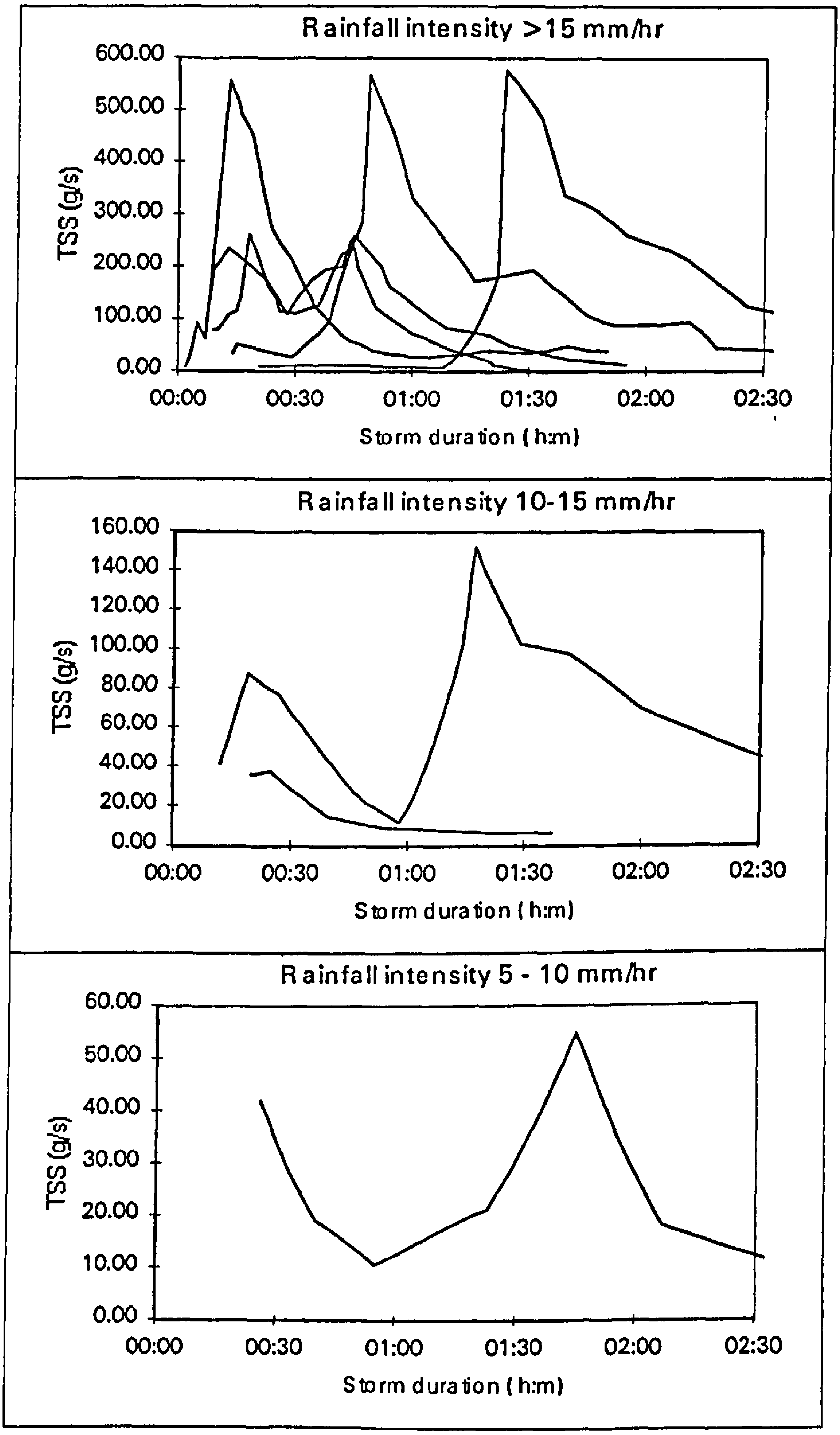


Figure 4.8. Loading rate (g/s) graphs compared by rainfall intensity at Clayton-le-Moors

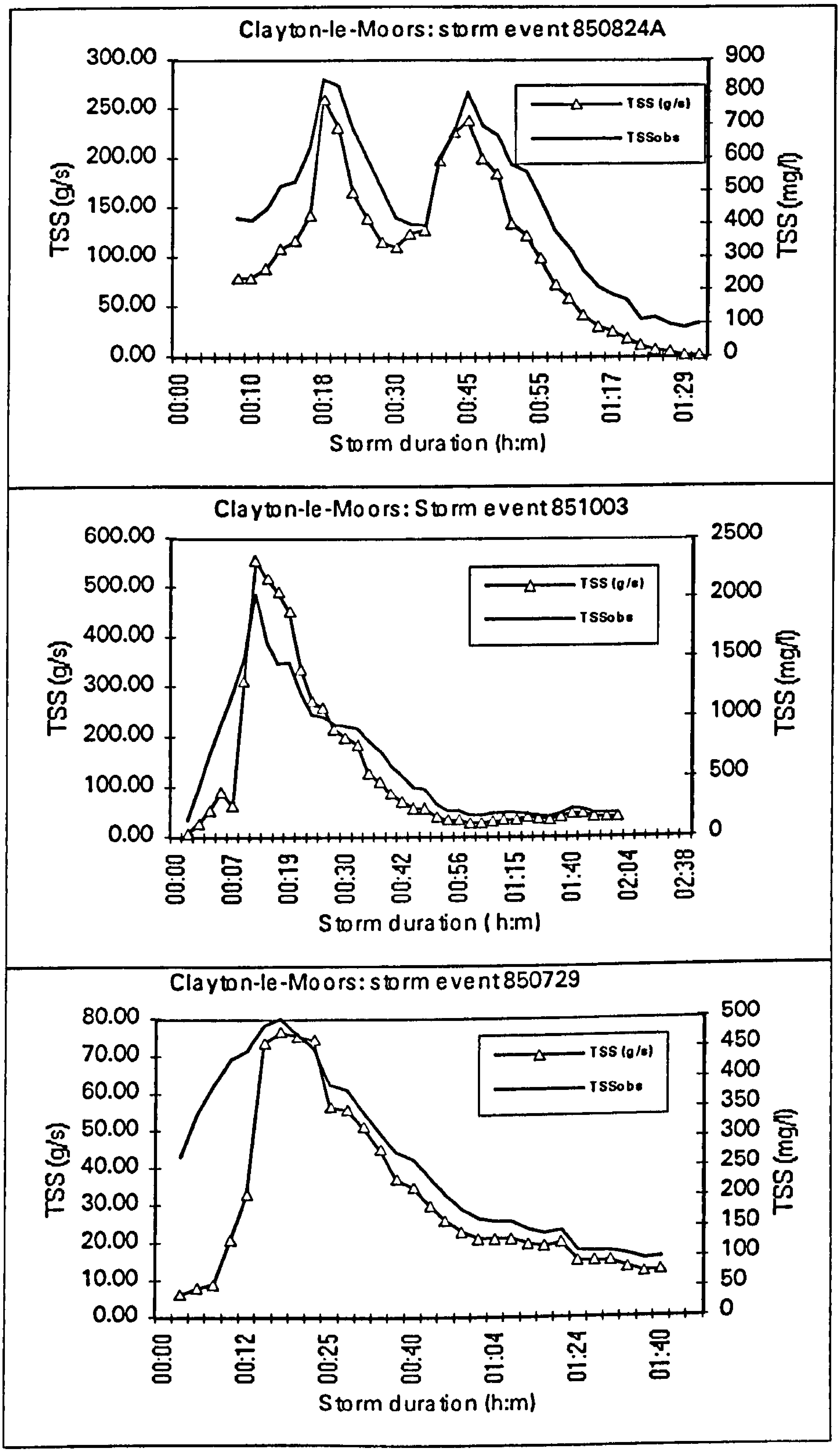


Figure 4.9. Pollutographs (mg/l) and loading rate (g/s) plots compared.

Observation of Figures 4.5 and 4.6 highlights that, following the peak value in the pollutant concentration, the recession limb of each of the pollutographs followed a similar pattern. By overlaying each individual pollutograph so that the recession limbs coincide, as shown subsequently in Section 4.8 and in Figure 4.10, it can be seen that this is certainly the case. This leads to the hypothesis that the shape of the storm may have some influence on the measured pollutograph and, in this respect, the storm profile peakedness (The Flood Studies Report, 1975; The Wallingford Procedure, 1983) may be used to describe the characteristics of each individual storm. This hypothesis follows from a subsequent literature survey which indicated that for simulating the flows in urban sewer systems in the UK, extensive use has been made of storm profiles based on the storm profile peakedness to predict the flows in urban sewer systems. It was therefore hypothesised that it might be possible to classify the pollutographs of observed storms into similar categories based on the storm profile peakedness and subsequently relate the shape of the pollutograph in some way to the hydrologic parameters by non-dimensionalising the parameters considered important for urban storm sewer design. For this purpose, use was made of the way in which the Flood Studies Report (NERC, 1975) described, for summer storm profiles, the relationship between the percentile of profile peakedness and the proportion of mean intensity of rainfall as shown in Table 4.2.

Table 4.2. Summer storm profiles for point rainfall (from FSR, 1975)

Percentile of profile peakedness	10	25	50	75	90	95
Peakedness = Peak intensity as a proportion of mean intensity of rainfall	1.5	2.2	3.75	6.0	9.0	11.0

Therefore, in this study, the storm profile peakedness was computed for each individual storm, and this value was used to classify the storm within a particular range of percentile profile peakedness, for example, an event with a value of the peakedness equal to 4.10 was assumed to have a percentile of profile peakedness of between 50% and 75%. Initial studies were carried out by classifying the storms belonging to a particular category of the maximum rainfall intensity (as defined in Section 4.6) and the groups defined by the storm profile peakedness were then subdivided into subgroups. All the storms belonging to a particular category of rainfall intensity were then further subdivided into storms of profile peakedness of less than 10%, 10-25%, 25-50%, 50-75%, 75-90%, 90-95% and greater than 95%. However, it was subsequently perceived that the classification of the storms by the maximum rainfall intensity and the storm profile peakedness taken together was duplicative because the parameter of maximum rainfall intensity forms part of the definition of the storm profile peakedness and hence may not be considered as an independent variable. As a consequence, storms were subsequently classified on the basis of storm profile peakedness only. However, this classification meant that only a very limited number of events could be assigned to each category of storm profile peakedness and in some cases there were no events belonging to a certain category of storm percentile profile peakedness. It was therefore decided to reduce the number of classifications to four, namely, less than 25%, 25-50%, 50-75% and greater than 75%. This enabled the apportionment of the maximum pollutant concentration that could be expected from storms belonging to a particular storm profile and these are shown in Table 4.3.

Table 4.3. Classification of the "BEST" summer storms into various storm profile categories

	Great Harwood		Clayton-le-Moors	
Storm profile peakedness (%)	Number of storms	Maximum observed TSS conc. (mg/l)	Number of storms	Maximum observed TSS conc. (mg/l)
> 75	5	1410	3	1050
50-75	4	1350	1	640
25-50	1	1050	2	450
<25	3	650	1	300

An inspection of the pollutographs classified in this manner highlighted that the pollutographs, for which the rising limb was known, had a very steep ascent to the peak followed by a recession limb, the shape of which was observed to be similar for the majority of the storm events within each particular classification. This led to the hypothesis that the shapes of the observed pollutograph within each particular classification of storm profile peakedness could be represented by a linear rise to the peak followed by a recession limb which could be represented by a simple mathematical function. The use of polynomial, exponential, linear and power functions were examined in this study and this aspect of the analysis is described in Section 4.8.

4.7. Estimation of the Peak Concentration

The results presented in Table 4.3 were arrived at by a visual examination of the pollutographs and indicated a need for further analysis of the data. It was therefore hypothesised that the peak concentration of total suspended solids (TSS_p) could in some way be related to the storm profile and other hydrological characteristics of the catchment and could be expressed as a function of one or more of the following explanatory variables:

$$TSS_p = f\,(ADWP, PEAKEDNESS, RFINT_{max}, RFINT_{avg}, QIN_{max}, STDURN, RF_{tot}) \quad (4.1)$$

where

$ADWP$ = Antecedent dry weather period

$PEAKEDNESS$ = $RFINT_{max}/RFINT_{avg}$

$RFINT_{max}$ = Peak rainfall intensity (mm/hr)

$RFINT_{avg}$ = Average rainfall intensity (mm/hr)

QIN_{max} = Peak inflow (m^3/s)

$STDURN$ = Storm duration (min)

RF_{tot} = Total rainfall (mm)

It has been identified in literature that the peak flow is not a truly independent variable, being a function of the rainfall intensity, volume and duration (Pearson *et al.*, 1986). Therefore, the flows were not considered in the subsequent analysis and attention was focused on the characteristics of the design or observed storm events. This is in line with current methodology which uses rainfall as input to the simulation models. The data of the 13 summer storms at Great Harwood was subjected to both multiple linear and log transformed linear regression analysis (as described in Section 3.5.3). The multiple linear regression analysis did not yield any significant relationships (R^2=0.55), however the multiple linear regression analysis of the log transformed variables showed significant results and the correlation matrix for the log transformed variables is shown in Table 4.4.

Table 4.4. Correlation matrix for the log transformed variables at Great Harwood

	$LTSS_{max}$	LADWP	LRFINT max	LRFINT avg	LRF_{Tot}	LDURN	LPEAKED-NESS
$LTSS_{max}$	1.00						
LADWP	0.33	1.00					
$LRFINT_{max}$	0.66	-0.16	1.00				
$LRFINT_{avg}$	0.34	-0.13	0.75	1.00			
LRF_{Tot}	0.17	-0.06	0.47	0.63	1.00		
LDURN	-0.07	0.03	-0.03	-0.02	0.76	1.00	
LPEAKED-NESS	0.70	-0.14	0.95	0.51	0.31	-0.02	1.00

Note: An L before the variable indicates that the figures are for the log transformed variable.

From Table 4.4 it can be seen that the maximum rainfall intensity appeared to be the most significant parameter to influence the peak TSS concentration followed by, in order of importance, the storm profile peakedness, the average rainfall intensity, the total depth of rainfall and the ADWP. By definition, the storm profile peakedness is the ratio of the peak rainfall intensity to the average rainfall intensity while the average rainfall intensity is computed from the total rainfall depth and the storm duration. Consequently the four variables - the maximum rainfall intensity, the average rainfall intensity, the storm duration and the total rainfall depth were considered to be adequately described by the single parameter of the storm profile peakedness and were therefore not considered as separate variables. Thus it is argued that the storm profile peakedness is a non-dimensional parameter which may alone be used to describe the temporal nature of the storm in addition to the shape of the rainfall profile. In addition, it is argued that the ADWP is also an important variable as this parameter represents the time available for the sediments and associated pollutants to build up in the sewer system and the catchment. A forward stepwise regression approach was adopted and the corresponding R^2 values and relevant statistical parameters are shown in Table 4.5.

Table 4.5. Introduction of variables and results for the log transformed variables at Great Harwood

S. No.	Log-transformed parameter (⇓)	R^2	F	t-statistic	$t_{cr0.95}$
1.	LPEAKEDNESS	0.49	13.56	3.68	1.75
2.	LPEAKEDNESS +LRFINT_{max}	0.49	6.31	1.23,-0.11	1.76
3.	LPEAKEDNESS+ LRFINT_{max}+ LADWP	0.68	8.53	1.45, [0.04],2.66	1.77
4.	LPEAKEDNESS +LADWP	0.77	16.28	5.25,2.24	1.76

Note: An L before the variable indicates that the figures are for the log transformed variable.

Based on the detailed regression analysis, it was observed that the storm profile peakedness and the ADWP were the explanatory variables in determining the peak TSS concentration and the resulting equation for the TSS concentration was of the following form:

$$TSS_p = 123.02\,(\text{PEAKEDNESS})^{0.64}\,(\text{ADWP})^{0.17} \qquad R^2=0.77 \qquad (4.2)$$

where

TSS_p = the maximum peak concentration of total suspended solids (mg/l),

PEAKEDNESS = the storm profile peakedness expressed as the ratio (maximum rainfall intensity/average rainfall intensity), and

ADWP = the antecedent dry weather period preceding the storm (hr).

This equation suggests that the storm profile peakedness strongly influences the peak concentration of total suspended solids. This confirms the intuitive expectation that it is the intensity of the rainfall which determines the instantaneous energy for the removal of sediment and associated pollutants from the surface as well as the resuspension of the in-sewer sediments.

The regression analysis was repeated for the 7 storm events occurring in summer at Clayton-le-Moors with known ADWP and this enabled a relationship of the following form to be concluded for the catchment at Clayton-le-Moors:

Multiple linear regression analysis:

$$TSS_p = 17.38\,(PEAKEDNESS) + 8.94\,(ADWP) + 220.11 \qquad (R^2 = 0.87) \qquad (4.3)$$

Multiple linear regression analysis of the log transformed variables:

$$TSS_p = 147.9\,(PEAKEDNESS)^{0.42}\,(ADWP)^{0.18} \qquad (R^2 = 0.91) \qquad (4.4)$$

A comparison was made between the predicted and observed values for both the sites at Great Harwood and Clayton-le-Moors and is shown in Tables 4.6 and 4.7, and, as expected, due to the limitation of having to use all available data to formulate the equations, it can be seen that there is also a good agreement between the observed and predicted peak concentration values of TSS. Hence, it was concluded that the peak TSS concentration of pollutants could be represented by an equation of the form:

$$TSS_p = K\,(PEAKEDNESS)^a\,(ADWP)^b. \qquad (4.5)$$

An equation of the form (4.5) may therefore be used to provide estimates of the peak TSS concentration for a range of storm profile peakedness corresponding to storms of return period less than one year.

Table 4.6. Details of storms and the various variables used in the regression analysis at Great Harwood

S.No.	Storm date	TSS_{peak} (observed)	ADWP	PEAKED-NESS	$RFINT_{max}$	$RFINT_{avg}$	RF_{tot}	STDURN	QIN_{max}	PROFPK	TSS (predicted)	Return Period (FSR notation)
	(yr-mt-day)	(mg/l)	(hr)	-	(mm/hr)	(mm/hr)	(mm)	(min)	(cumecs)	(%)	(mg/l)	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(13)	(14)
1	841018B	1160	10	18.83	67.20	3.57	4.16	70	1.618	95+	1191	M5
2	850804	1074	14	17.50	67.20	3.84	5.12	80	1.740	95+	1203	M5
3	850824	485	2	14.81	57.60	3.89	8.43	130	1.601	95+	777	M2
4	850713	984	13	11.87	28.80	2.43	5.06	125	0.567	95+	926	2M
5	840803	550	3	9.03	24.00	2.66	9.08	205	1.375	90-95	606	3M
6	840524A	1340	30	11.88	28.80	2.48	3.32	83	0.347	50-75	1068	2M
7	860520A	1410	58	5.79	12.80	2.21	5.60	152	1.020	50-75	755	6M
8	860804	662	32	5.07	19.20	3.79	10.74	170	1.162	50-75	626	3M
9	850828	475	53	4.42	9.60	2.17	3.80	105	0.340	50-75	625	6M
10	850820	695	22	4.01	9.60	2.40	13.98	350	0.792	50-75	634	6M
11	841018A	215	8	2.35	4.80	2.04	7.15	210	0.311	25-50	303	12M
12	841029	286	9	2.11	2.77	1.31	1.10	50	0.230	10-25	288	<12M
13	850902	210	16	1.75	2.11	1.21	2.71	135	0.219	10-25	282	<12M

Table 4.7. Details of storms and the various variables used in the regression analysis at Clayton-le-Moors

S.No.	Storm date	TSS_{peak}	ADWP	PEAKED-NESS	$RFINT_{max}$	$RFINT_{avg}$	RF_{tot}	STDURN	QIN_{max}	PROFPK	TSS (predicted)	
		(observed)									Linear R^2 0.87	Log-transform R^2 0.91
	(yr-mt-day)	(mg/l)	(hr)	-	(mm/hr)	(mm/hr)	(mm)	(min)	(cumecs)	(%)		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
1	860520	1050	58	14.96	48	3.21	6.68	125	0.385	95+	999	957
2	860517	430	28	2.32	2.4	1.04	2.78	161	0.075	25-50	511	384
3	861030	920	21	20.67	72	3.48	8.47	146	0.760	95+	767	913
4	860806	255	21	2.24	3	1.34	3.98	178	0.153	25-50	447	359
5	870711	962	9	43.57	24	0.55	2.13	232	0.640	95+	1058	1072
6	860804A	476	9	3.81	12	3.15	7.93	151	0.450	50-75	367	385
7	860511	260	3	2.30	4	1.74	3.88	134	0.113	25-50	287	256

4.8. Estimation of the Recession Limb of the Pollutograph

It was hypothesised that the observed pollutographs could be defined to fall within a range of storm profile peakedness. Therefore the recession limbs of the observed pollutographs of all the storms belonging to a particular storm profile peakedness category were plotted together (Figures 4.10a to 4.13a). By visual examination, there appeared to be similarities in the shapes of the recession limb of each pollutograph. It was therefore, hypothesised that the behaviour of the sewer system on the recession limb of the flow hydrograph, i.e. as it empties, is the same. To explore the hypothesis that the shape of the recession limb of the pollutograph corresponding to storms of similar profile peakedness was the same, the position of the recession limb of each pollutograph was arbitrarily adjusted in time so as to bring together, onto one curve, all the recession limbs of each pollutograph (Figures 4.10b to 4.13b). These were subsequently smoothed out by utilising a three minute moving mean applied to the data. For each range of storms, the maximum recorded pollutant concentration was used to define the start point for the recession limb of the pollutograph (Figures 4.10c to 4.13c) and care was taken to ensure that the duration of the moving mean curve was sufficiently long to adequately represent the "tail" of the pollutograph. Subsequently, for each particular profile peakedness category various curve-fits - polynomial, exponential, logarithmic, power function were fitted to the corresponding moving mean curve. This analysis was carried out using spreadsheet software, (Microsoft Excel version 5.0a) and the results of the analysis are also shown in Figures 4.10c to 4.13c respectively. In all cases, it can be seen that the power function gave the best fit for the recession limb of the pollutograph followed by the exponential curve while the polynomial and logarithmic functions gave relatively poor fits. The values of the coefficients A and k in the power function ($y = At^{-k}$) and B and k' in the exponential function ($y = Be^{-k't}$) and the respective R^2 values for each of the storm profile category are summarised in Table 4.8. From the R^2 values, it can be seen that the power function shows the best fit to the recession limbs of the pollutographs.

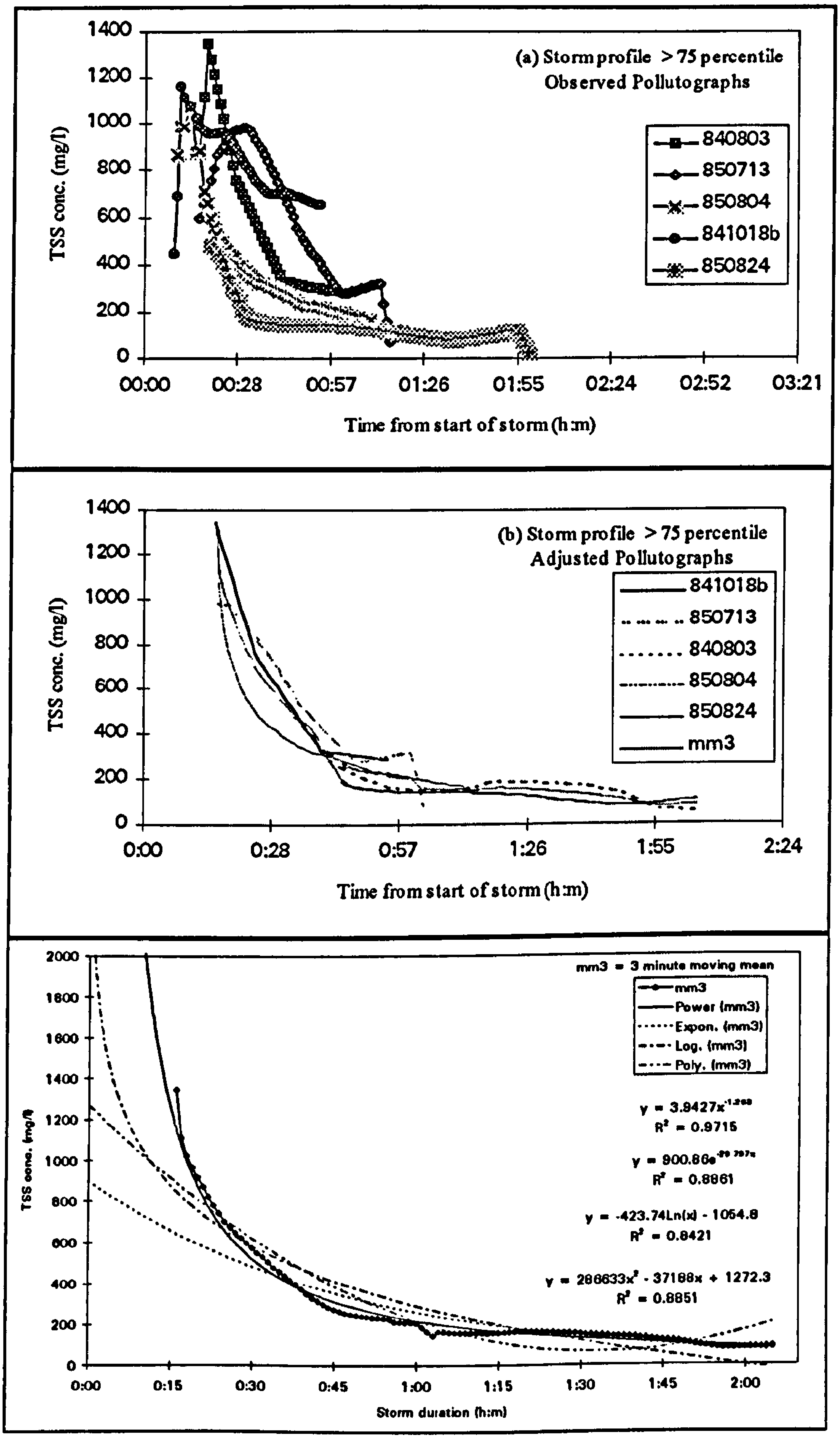


Figure 4.10. Events with storm profiles > 75 percentile at Great Harwood
(a) Observed pollutographs,
(b) Adjusted pollutographs= > to common time base,
(c) Recession equations.

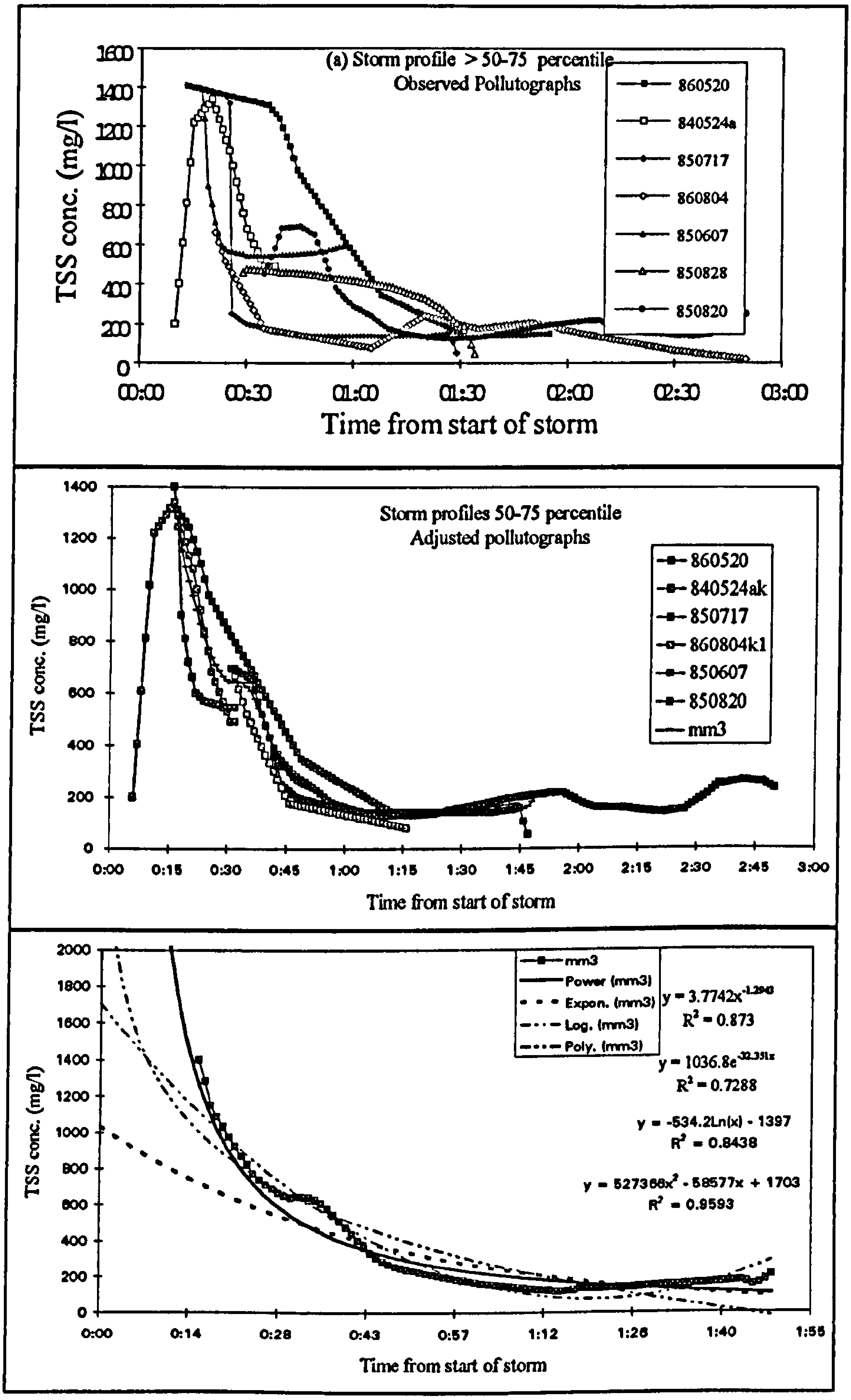


Figure 4.11. Events with storm profiles > 50-75 percentile at Great Harwood
(a) Observed pollutographs,
(b) Adjusted pollutographs => to common time base,
(c) Recession equations.

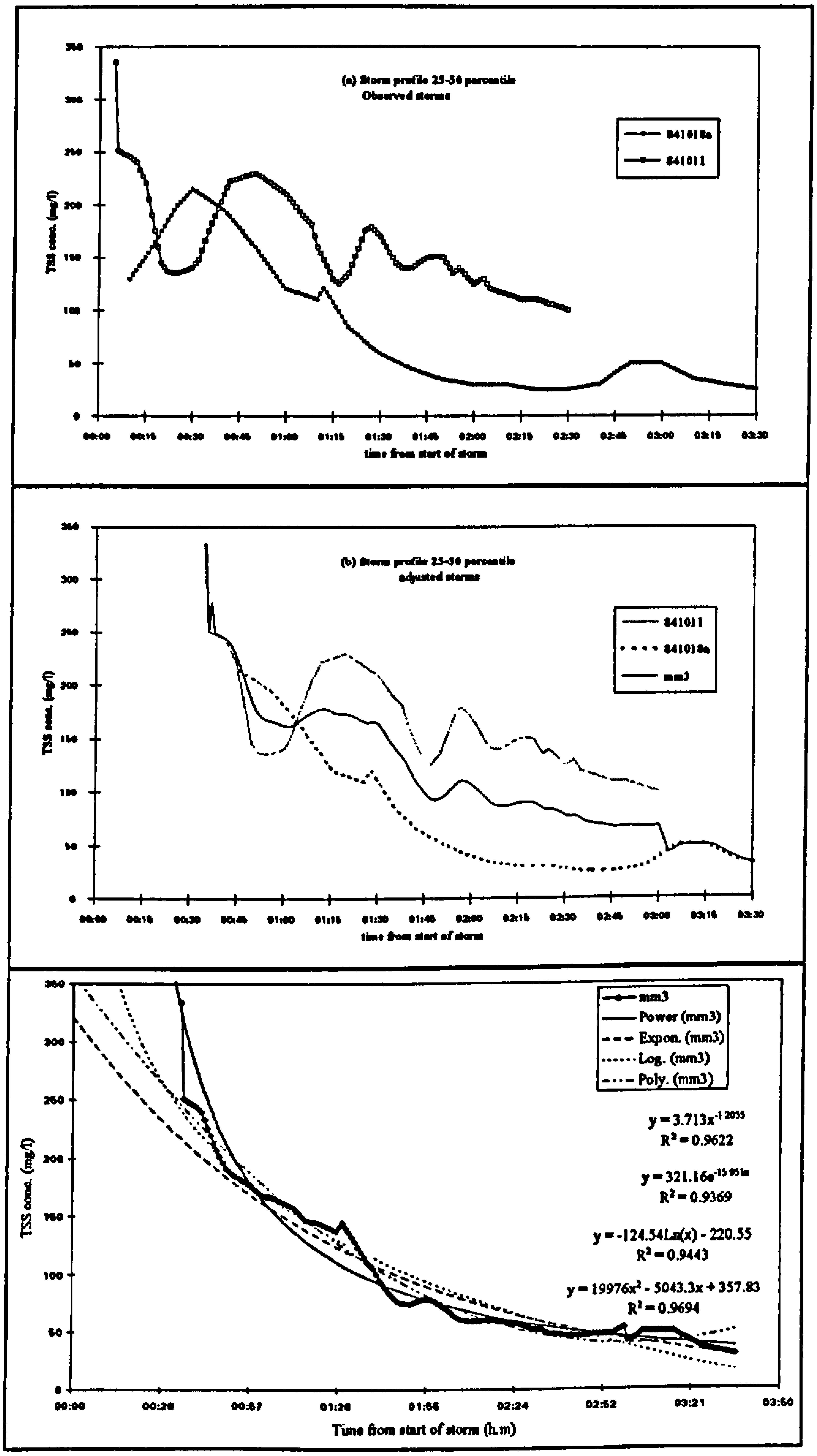


Figure 4.12. Events with storm profiles > 25-50 percentile at Great Harwood
(a) Observed pollutographs,
(b) Adjusted pollutographs => to common time base,
(c) Recession equations.

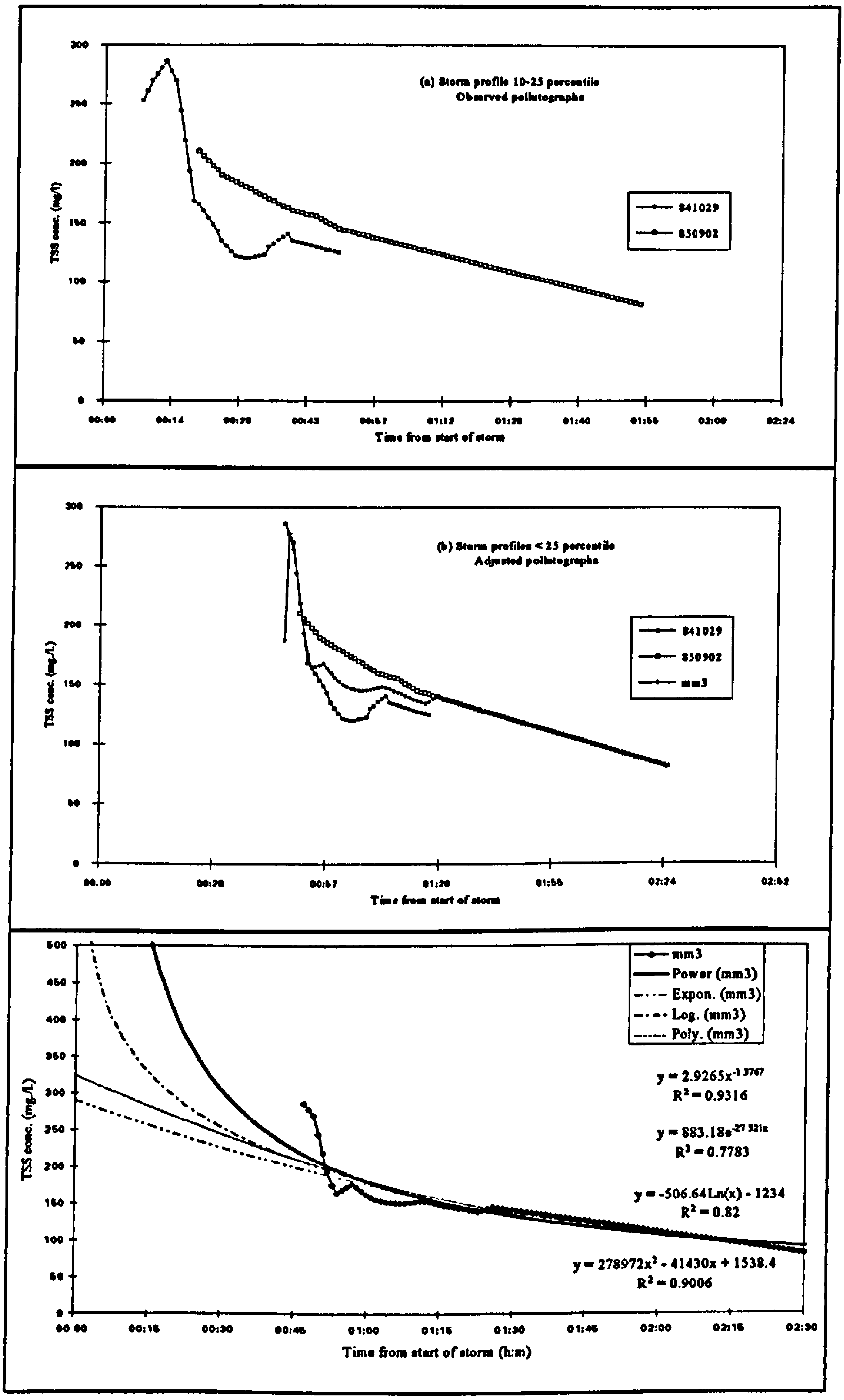


Figure 4.13. Events with storm profiles <25 percentile at Great Harwood
(a) Observed pollutographs,
(b) Adjusted pollutographs => to common time base,
(c) Recession equations.

Table 4.8. Equations for the recession limbs of pollutographs at Great Harwood

Percentile of profile peakedness	$y=At^{-k}$		R^2	$y=Be^{-kt}$		R^2
	A	k		B	k	
75+	3.94	1.26	0.97	900	29.80	0.88
50-75	3.77	1.29	0.87	1036	32.35	0.73
25-50	3.713	1.21	0.96	321	15.95	0.94
10-25	2.93	1.38	0.93	883	27.32	0.78

Many of the earlier studies, for example, Sartor *et al.* (1974) have used an exponential decay function to represent the washoff of pollutants from the urban surface. It is emphasised however that most of the earlier studies used pollutant data monitored at intervals of 30 minutes or more and this may have missed the first flush in the concentration of pollutants which is known to occur in many catchments. Comparing the power function and the exponential decay curve as a means of representing the first flush effect and the associated pollutograph, it can be seen from Table 4.8 that an exponential decay function is seen to provide a good fit only for storms which do not have a significant first flush or for the latter part of the storm when the first flush effects are not prominent. It is concluded therefore that, in general, a power function of the form of $y=At^{-k}$ provides an adequate representation of the recession limb of the pollutograph and, in particular, to describe the first flush effect.

Further examination of the coefficients which describe the recession of the pollutograph for each group of storms showed that all values were similar and this led to the hypothesis that it may be possible to represent all the pollutographs by a single recession curve. To test this hypothesis, the procedure described earlier in this section was repeated whereby the recession limbs of the pollutographs of all the 13 storms were plotted together, to define a single shape of the recession limb, again by using a three minute moving mean technique. Care was again taken to ensure that the maximum observed pollutant concentration was included as part of the recession curve and the final form of the recession curve is shown in Figure 4.14.

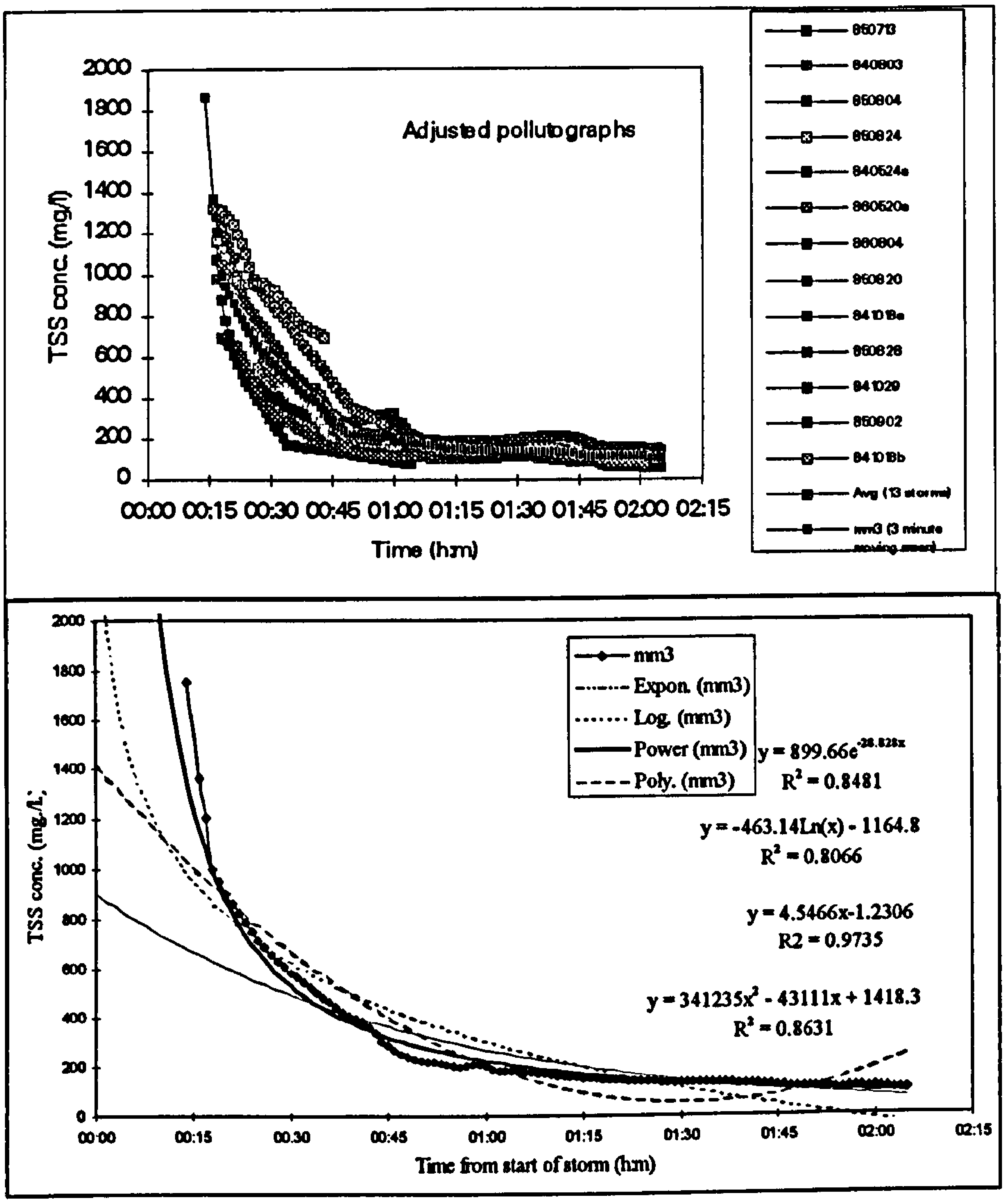


Figure 4.14. (a) Adjusted pollutographs (to common time base) for all SUMMER events plotted together
(b) Recession equations (Great Harwood).

This yielded an equation:

$$TSS(t) = 4.5\ t^{-1.23} \qquad (4.6)$$

where

TSS(t) = the concentration of total suspended solids (mg/l) at any time t;

t = time from start of storm (min).

Having completed this analysis it was considered important to highlight the differences that occurred between the recession limbs of the predicted and measured pollutographs of the 13 storms used in the data set. These figures are shown in Appendix B. In the majority of cases, the recession limbs of the pollutographs were predicted with reasonable accuracy and this confirmed the hypothesis that a single recession curve may be used to adequately describe the shape of the recession limb of the pollutograph. It should also be mentioned that the shape of the recession curve was not very sensitive to the values of the coefficients A and k and this highlights that the procedure is particularly attractive for formulating a pollutograph profile from a few observed storm events. This is because equation (4.6) is only used to describe the shape of the recession limb of the pollutograph. The peak concentration for the pollutograph can be determined from an equation of the form (4.2).

To further validate this observation, equations for the recession limbs were also computed for the storms monitored at Clayton-le-Moors. Observed storms having a rainfall depth of greater than 5 mm at each site were considered (WRc, 1987) (The WRc criteria for typical suitable rainfall for sewer flow surveys are described in further detail in Section 5.3.3), and, as before, the recession limbs of the pollutographs at each site were brought together and a three minute moving mean was computed. Again, at each site, it was observed that the power function gave the best fit for the recession limb of the pollutograph and the appropriate coefficients are summarised in Table 4.9 and plotted in Figure 4.15.

Table 4.9. Coefficients of the equation for the recession limb of the pollutograph (At^{-k})

	A	k	R^2	Maximum observed peak TSS concentration (mg/l)
Great Harwood	4.5	1.2	0.97	1435
Clayton-le-Moors	11.2	1.1	0.96	1035

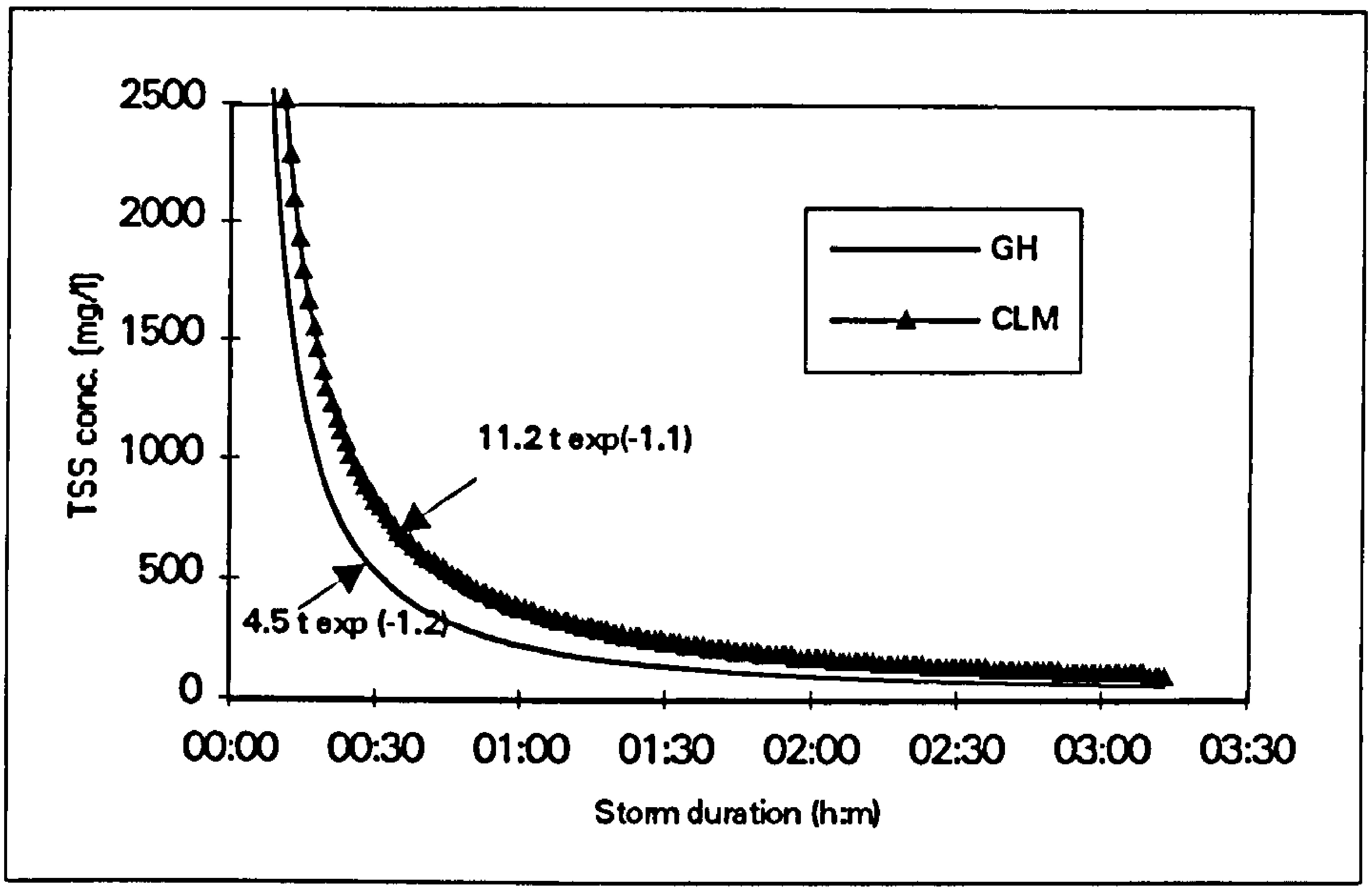


Figure 4.15. Recession limbs of pollutograph at Great Harwood and Clayton-le-Moors.

From an examination of Figure 4.15, it is seen that the shape of the recession limbs are very similar at both the sites and the results of the foregoing analysis suggest that the power decay function provides an adequate representation of the recession limb. Hence it can be concluded that the equation of the recession curve of the form:

$$\mathrm{TSS}(t) = A\, t^{-k} \qquad (4.7)$$

where

TSS(t) = the concentration of total suspended solids (mg/l) at any time t;

t = time from start of storm (min)

provides an adequate representation of the recession limb of a pollutograph.

However, a sensitivity analysis of equation (4.7) revealed that the coefficients were very much a function of the peak TSS concentration (when the time of occurrence of the peak was kept constant). Also, that the coefficients were a function of the time of occurrence of the peak TSS concentration. This indicated that while this equation provided an adequate representation for the shape of the recession limb of the pollutograph, this equation does not provide any indication of the time of occurrence of the peak TSS concentration. Attention was therefore focused on a methodology to determine how this parameter could be defined.

4.9. Time of Occurrence of the Peak Pollutant Concentration

In addition to estimating the peak concentration of TSS, it is also necessary to establish the time at which the peak concentration occurs and preferably to reference this time to some aspect of the storm rainfall. In respect of flow, the methodology outlined in the FSR (NERC, 1975) is that the occurrence of the peak flow may be taken to occur at some time interval from the centre of gravity of the rainfall hyetograph. A similar approach was adopted in this study and it was hypothesised that the peak pollutant concentration could also be taken to occur at some time interval from the centre of gravity of the rainfall hyetograph. However, detailed analysis of the observed storms highlighted that this was not the case.

Therefore, attempts were made to define the time of occurrence of the peak TSS concentration in relation to the rainfall and runoff characteristics, for instance, the start of rainfall, a threshold of rainfall depth, the peak rainfall intensity, and a threshold value of the flow. As a consequence, the BEST summer storm events at Great Harwood and Clayton-le-Moors were examined and the following parameters were determined for each storm event:

(i) Time to peak TSS concentration,

(ii) Rainfall depth to peak concentration,

(iii) Peak rainfall intensity to peak TSS concentration,

(iv) Mean rainfall intensity in the time upto the peak TSS concentration, and

(v) Flow rate corresponding to the peak TSS concentration.

The values of each parameter are shown in Tables 4.10 and 4.11 and the general observations made are now discussed.

Table 4.10. Time to peak TSS concentration - parameters at Great Harwood

Storm date	Maximum TSS	Time to peak TSS	Peak RFINT to TSS	Δt (RFINT max to TSSmax)	RFdepth to TSS_{max}	Flow corresponding to TSS max	$RFINT_{avg}$	ADWP	Total rainfall
	(mg/l)	(min)	(mm/hr)	(min)	(mm)	(m^3/s)	(mm/hr)	(hr)	(mm)
840524A	1340	20	28.80	00	4.56	0.304	13.68	30	6.36
840803	550	04	4.80	00	0.16	0.033	2.40	3	9.08
841018A	215	30	4.80	19	1.32	0.251	2.64	8	7.15
841018B	1160	11	67.20	07	4.06	1.618	22.15	10	4.16
841029	286	13	2.77	00	0.38	0.222	1.75	9	1.10
850713	984	10	28.80	33	4.24	0.544	25.44	1	5.06
850804A	1074	20	67.20	10	5.12	0.770	15.36	14	5.12
850820	695	45	9.60	37	2.64	0.393	3.52	22	13.98
850824	485	20	57.60	10	5.44	0.464	16.32	2	8.43
850828	475	30	9.60	24	2.43	0.249	4.86	53	3.80
850902	210	20	1.60	15	0.43	0.219	1.29	16	2.71

Table 4.11. Time to peak TSS concentration - parameters at Clayton-le-Moors

Storm date	Maximum TSS	Time to peak TSS	Peak RFINT to TSS	Δt (RFINT max to TSSmax)	RFdepth to TSS_{max}	Flow corresponding to TSS max	$RFINT_{avg}$	ADWP	Total rainfall
	(mg/l)	(min)	(mm/hr)	(min)	(mm)	(m^3/s)	(mm/hr)	(hr)	(mm)
860511	260	50	3.2	07	1.38	0.085	1.66	3	6.68
860517	430	37	2.4	01	0.63	0.05	1.02	28	2.78
860520	1050	23	48	19	2.49	0.163	6.50	58	8.47
860804A	476	12	12	06	1.21	0.087	6.05	9	3.98
860806	255	25	3	21	0.73	0.093	1.75	21	2.13
861030	920	99	72	20	7.03	0.366	4.26	21	7.93
870711	962	45	24	05	2.13	0.26	2.84	9	3.88

From an examination of the data, it was observed that the peak TSS concentration usually occurred within the time of concentration of the system and the average time to peak TSS following the onset of rainfall was 20 and 22 minutes for the Great Harwood and Clayton-le-Moors catchments respectively. However, a large scatter in the data was observed for individual storm events and ranged from 4 minutes to 45 minutes at Great Harwood and from 8 minutes to 45 minutes at Clayton-le-Moors. Similarly, the mean time lag from the peak rainfall intensity to the peak TSS concentration was 10 and 7 minutes respectively and again, a range in the magnitude of the values for each storm was observed. Hence it was hypothesised that the peak TSS concentration occurred after a time t minutes following the onset of rainfall or the occurrence of the peak rainfall intensity.

It was also hypothesised that the time to peak concentration coincided with the time of occurrence of a threshold flow Q_t. From a practical viewpoint, this flow may be considered sufficient to transport the pollutants in the washoff from the catchment surfaces and/or in the mobilisation of in-sewer sediments. Examination of the flow data showed that, for a large number of storms, a flow of at least 0.25-0.30 m^3/s at Great Harwood and 0.13-0.15 m^3/s at Clayton-le-Moors was associated with the peak TSS concentration but that in other storms there was a wide variation in the flow magnitude corresponding to the peak TSS concentration. This hypothesis was therefore considered unproved.

A third hypothesis was that occurrence of the peak TSS concentration coincided with the time of occurrence of a minimum rainfall depth which may, as before, be considered sufficient to transport the pollutants in the washoff from the catchment surfaces and/or in the mobilisation of in-sewer sediments. It was also observed that, in a number of events, the peak concentration of TSS occurred 10 minutes after a rainfall depth of 1.3 mm at Great Harwood and 10 minutes after a rainfall depth of 1.0 mm at Clayton-le-Moors but again, a wide difference in the threshold of rainfall depth was observed.

It may be summarised that the definition of the time from the start of storm event to that of the peak TSS concentration has proved to be the most difficult parameter to define and clearly it is a function of the hydrological and catchment and sewer system characteristics.

The above analysis has enabled some general patterns of the time of occurrence of peak concentration to be identified but these are subjective and therefore not amenable to mathematical analysis. Therefore, the design philosophy of this work was reviewed, and an alternative approach to compute the time of peak TSS was attempted and is described in the following section.

4.9.1. Alternative Methodology to Compute the Time of Peak TSS Concentration

An alternative methodology that has been adopted relates to the work outlined in Chapter 3 and utilises the definition of the pollutant load in the first flush of pollutants. The methodology is outlined in Figure 4.16 and it is an iterative process. To illustrate the procedure, reference is made to the observed storm event on the 4th August 1985 (850804) at Great Harwood and this event is detailed in Figure 4.17.

ILLUSTRATIVE EXAMPLE:

The methodology is illustrated by reference to the storm dated 850804 at Great Harwood. The procedure and calculations are described below:

Observed storm data:

Storm date 850804

Antecedent dry weather period (hr) = 14

Maximum rainfall intensity (mm/hr) = 67.2

Storm duration (min) = 80

Total flow (m^3) = 1137

Total TSS load (kg) = 1431

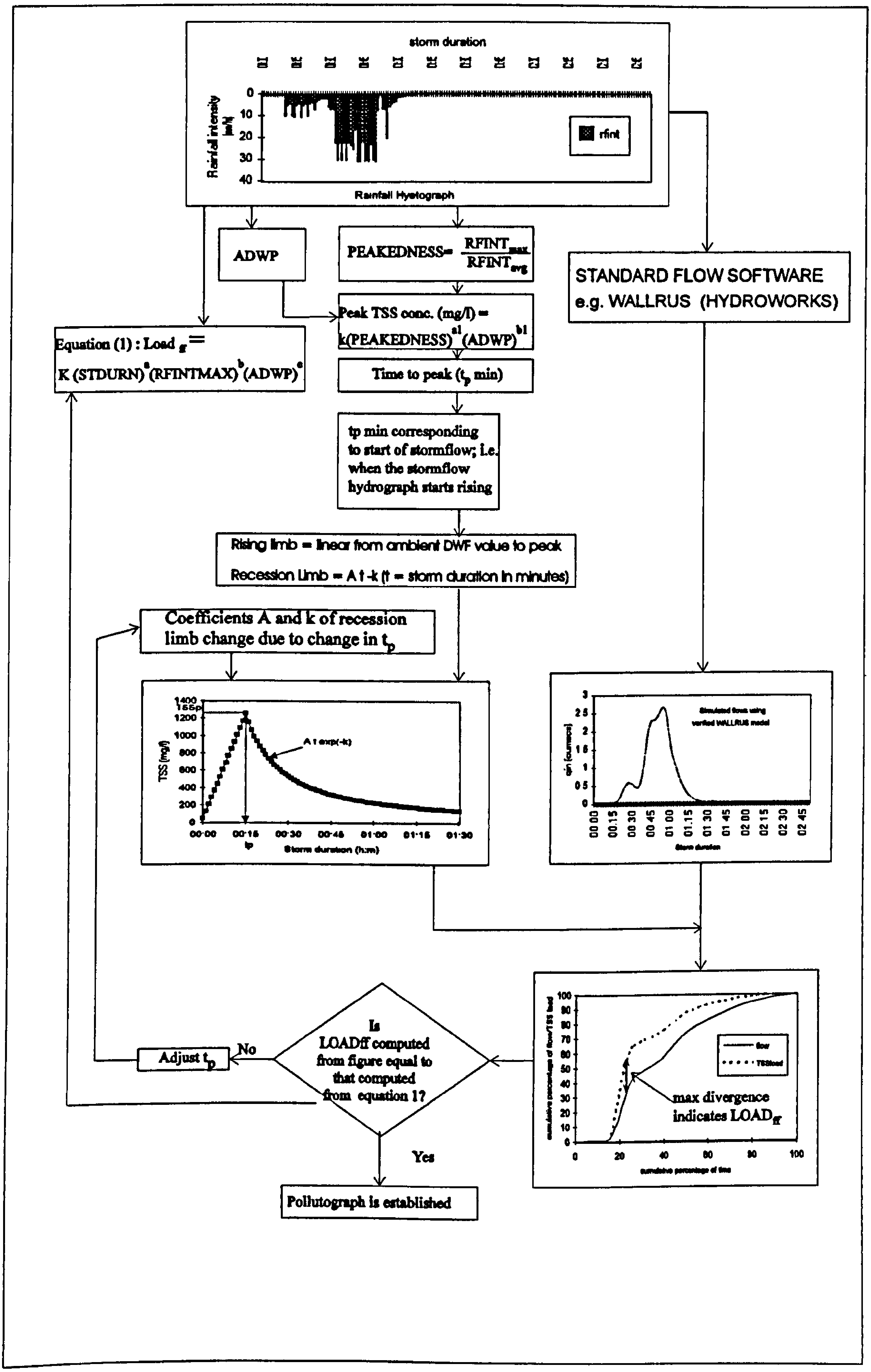


Figure 4.16 Flowchart showing the pollutograph methodology

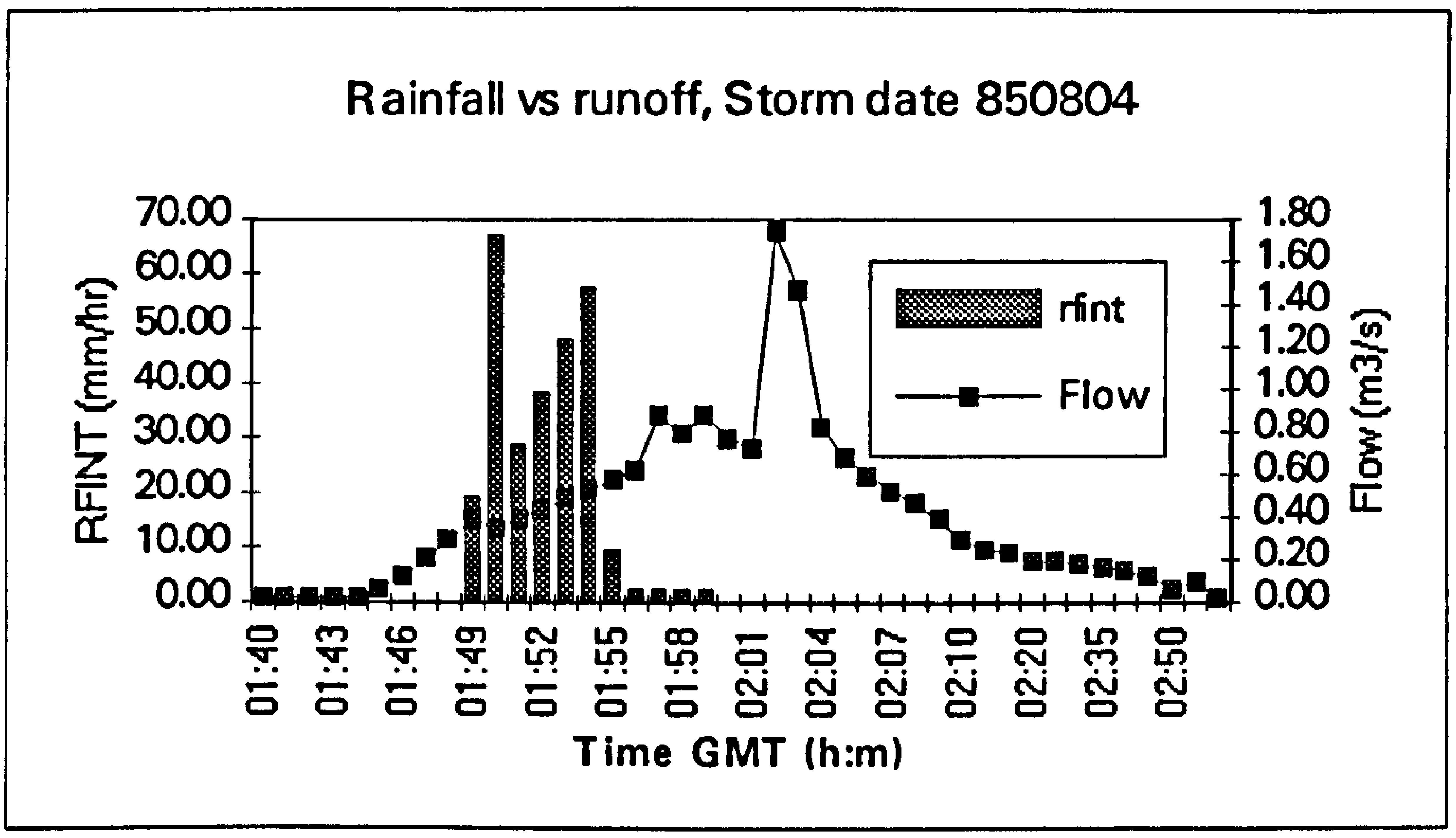


Figure 4.17. Observed Rainfall - runoff for storm date 850804 at Great Harwood.

STEP 1. Compute the first flush load

$$LOAD_{ff} = 1.35\ (STDURN)^{0.68}\ (RFINTMAX)^{0.68}\ (ADWP)^{0.28} \quad (4.8)$$

from which the load of suspended solids in the first flush is obtained as

$$LOAD_{ff} = 972\ (kg)$$

This is equal to 70% of the of the total load of suspended solids.

STEP 2. Compute the peak TSS concentration

$$TSS_p = 123.02\ (PEAKEDNESS)^{0.64}\ (ADWP)^{0.17} \quad (4.9)$$

Total rainfall depth	(mm)	=	5.12
Average rainfall intensity	(mm/hr)	=	3.84
$\text{Peakedness} = \dfrac{\text{(Peak rainfall intensity)}}{\text{(Average rainfall intensity)}}$		=	17.50

from which

$$TSS_p = 1203\ mg/l$$

STEP 3. Compute the profile of the predicted pollutograph:

(a) Recession limb ($t \geq t_p$, where t_p is time to peak TSS concentration):

The equation for the master recession curve at Great Harwood, derived in Section 4.8 and shown in Figure 4.18(a), is given by

$$TSS(t) = 4.5\, t^{-1.23} \qquad (4.10)$$

where

TSS(t) = the concentration of total suspended solids (mg/l) at any time t;

t = time from start of storm (min)

For the storm 850804, the recession limb is the same as the master recession curve with the start of the recession limb defined as TSS_P, as computed in Step 2, as shown in Figure 4.18(b).

(b) Time to peak (t_p):

Computation of the time to peak (t_p) is an iterative process. It is assumed as a first approximation, that this time corresponds to the time of occurrence of the TSS_p on the master recession curve, as shown in Figure 4.18(b), that is, a time of 15 minutes. Thus the shape of the recession limb of the pollutograph is defined.

(c) Rising Limb ($t = 0$ to $t = t_p$):

To compute the form of the predicted pollutograph prior to the time to peak, it is assumed that there is a linear rise in the pollutant concentration from that in the preceding (ambient) dry weather flow to that of the peak TSS concentration (TSS_p, as defined in Step 2). The concentration of pollutants in dry weather are known to follow a typical diurnal variation which follow the pattern of human activity and this has been reported by Butler and Graham (1995) (see Section 4.10). For the Great Harwood catchment, the diurnal variation in dry weather flow was reported by Thornton and Saul (1986) and this data has been used in this study. Hence, in the methodology, the pollutant concentration at the start of the storm is taken as the pollutant concentration in the dry weather flow corresponding to the time of the start of the storm event. Hence the resultant shape of the predicted pollutograph is shown in Figure 4.18(c).

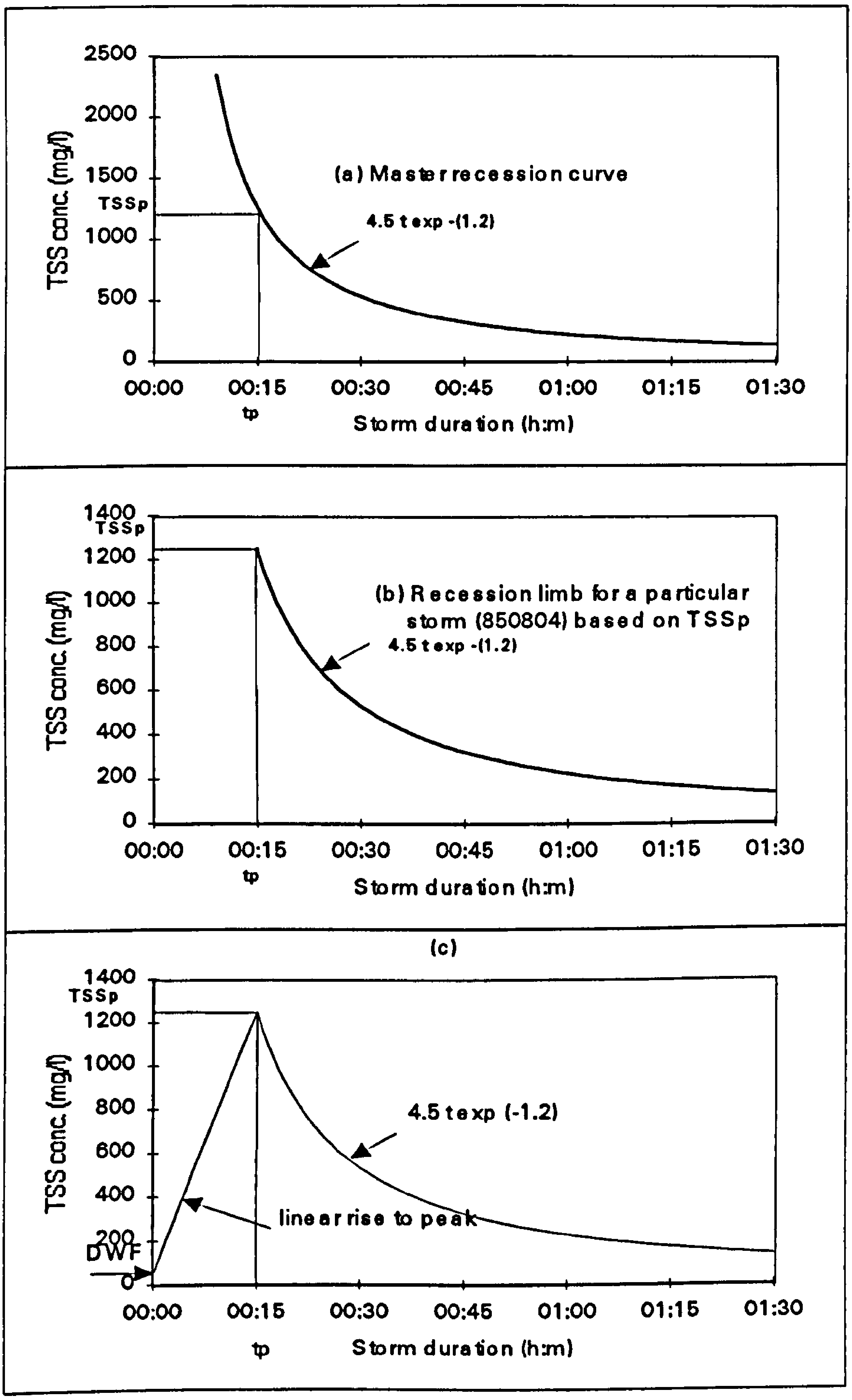


Figure 4.18. (a) Master recession curve,
(b) Section of master recession curve for a particular storm event,
(c) Representation of predicted pollutograph

Using the pollutograph defined in Figure 4.18(c) and replotted as Figure 4.19(a), together with the measured inflow hydrograph corresponding the storm 850804, as shown in Figure 4.19(b), it is possible to compute and plot the cumulative percentage of pollutants and flow against the cumulative percentage of time, as shown in Figure 4.19(c). This latter figure is then used to establish the load in the first flush of pollutants, defined in section 3.5.1, as the maximum divergence between the dimensionless cumulative percentage of pollutants and the cumulative percentage of flows plotted against the cumulative percentage of time. In this case, the first flush load is 64% of the cumulative load, that is,

$$LOAD_{ff} = 0.64 * (1431) = 915 \text{ kg.}$$

This load is smaller than the computed value of 972 kg from equation 4.8 in Step 1. It is necessary therefore to adjust the position of the peak value of the predicted pollutograph such that the first flush load using the derived pollutograph is equal to that calculated from the regressional relationship given in Step 1.

STEP 4 Adjusting the time to peak (t_p)

The next step in the methodology is therefore to adjust the time to peak (t_p) such that the first flush load using the derived pollutograph is equal to that calculated from the regressional relationship given in Step 1. The iterative procedure adopted is illustrated by the following example:

A shift in the position of the peak TSS_p to the left is shown in Figure 4.20(a) whilst a shift in the position of the peak to the right is shown in Figure 4.21(a). The shape of the recession limb remains the same but a change in the time to peak results in a change to the constants A and k in equation 4.7 to define the shape of the recession limb to a common time t. The equations of the recession limb are then defined as $TSS(t) = B\ t^{-m}$ and $TSS(t) = C\ t^{-n}$ respectively. For illustrative purposes, the first flush corresponding to a change in the time to peak TSS of 5 minutes to the left ($t_p = 10$ min) and right ($t_p = 20$ min) are shown in Figures 4.20(c) and 4.21(c) respectively. The corresponding values of the first flush load for these arbitrarily selected positions of the time to peak are 60 % of the total load, that is, 0.6 x 1431 = 859 kg (Figure 4.20c) and 80% of the total load, that is 0.8 x 1431 = 1144 kg (Figure 4.21c). Again, neither of these values match the computed first flush load $LOAD_{ff}$ of 972 kg derived from Step 1.

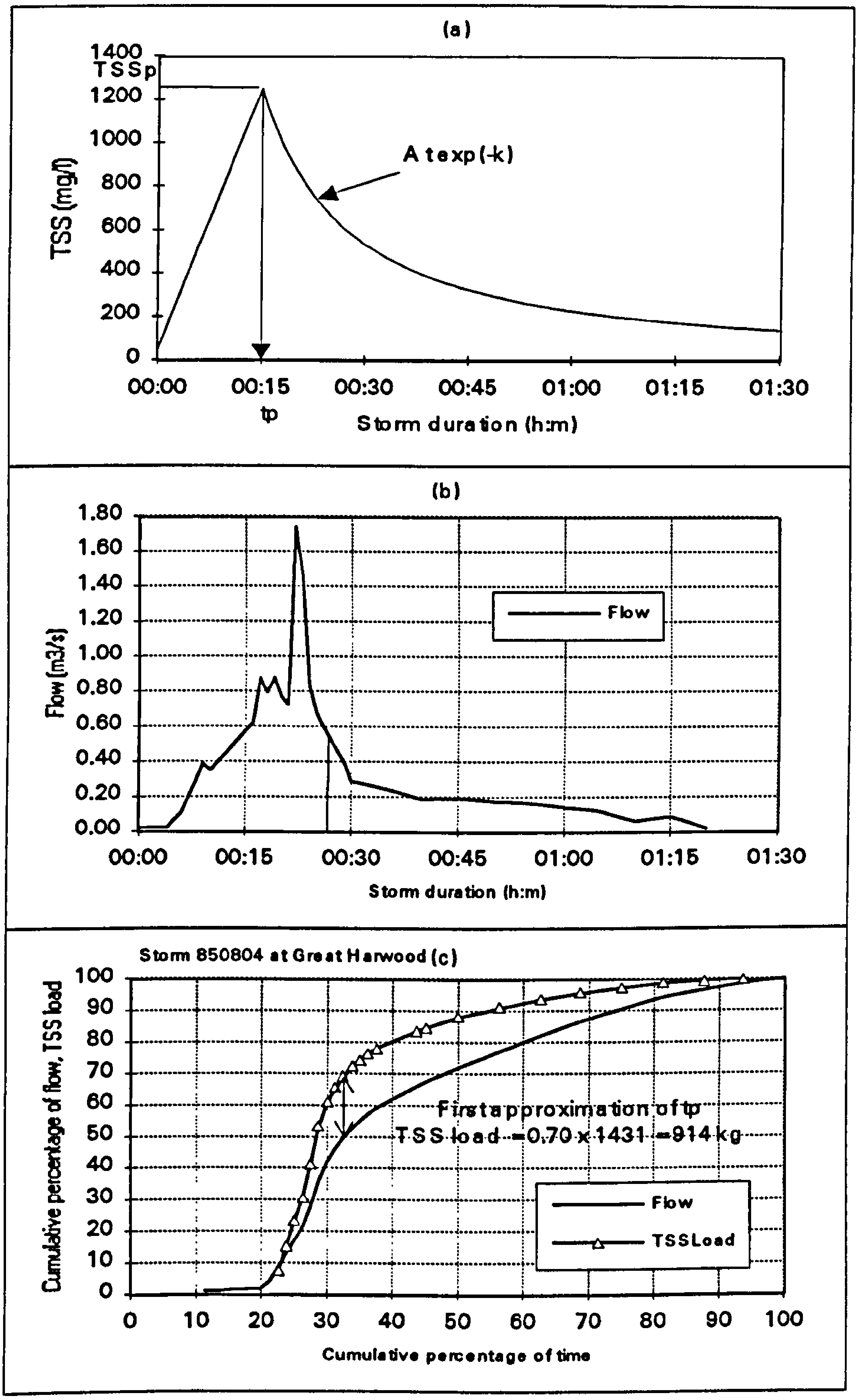


Figure 4.19. (a) Predicted pollutograph, first approximation - t_p,
(b) Observed flow,
(c) Cumulative flow and cumulative load plots for predicted pollutograph.

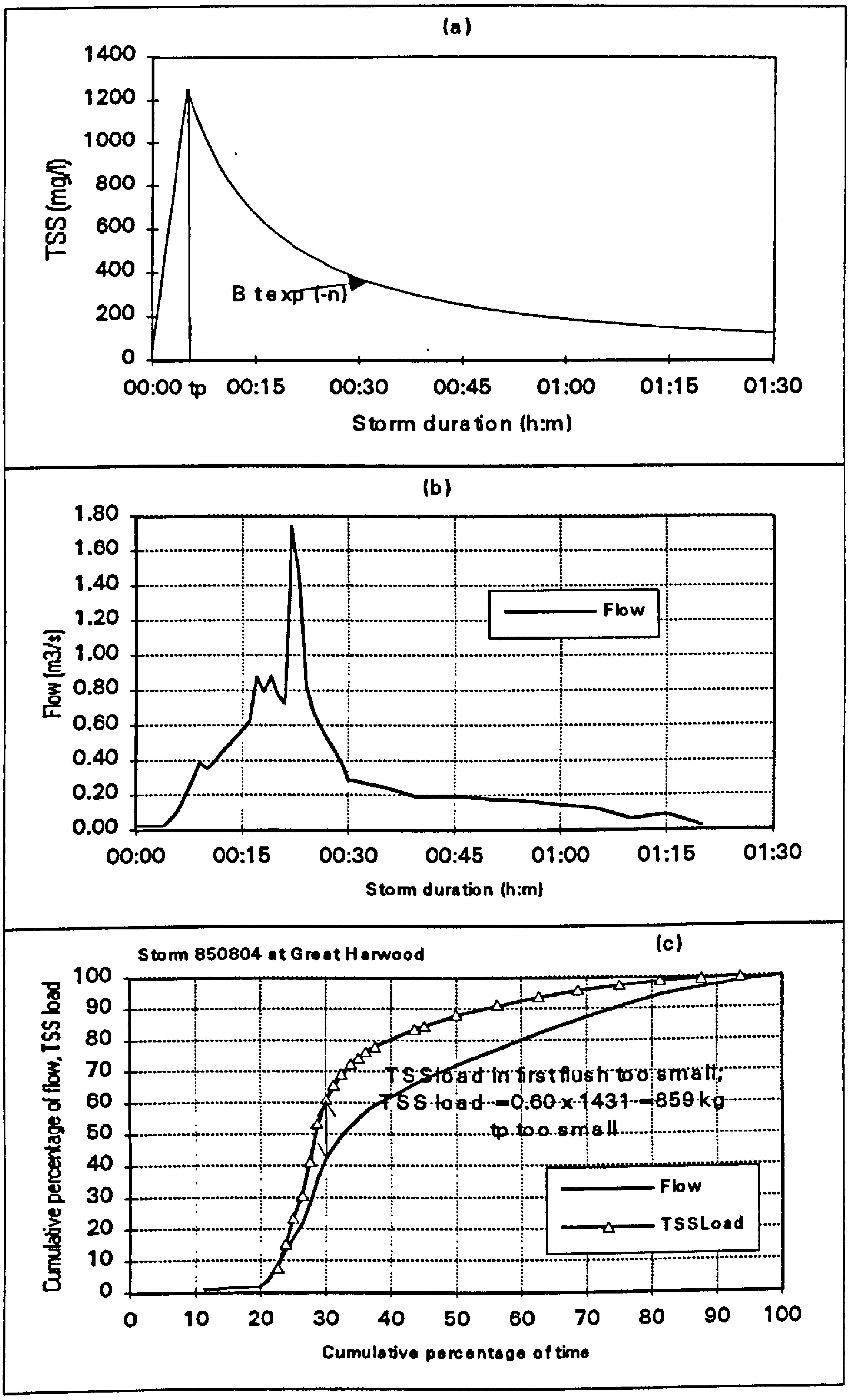


Figure 4.20. (a) Predicted pollutograph - shifted to the left,
(b) Observed flow,
(c) Cumulative flow and cumulative load plots for predicted pollutograph.

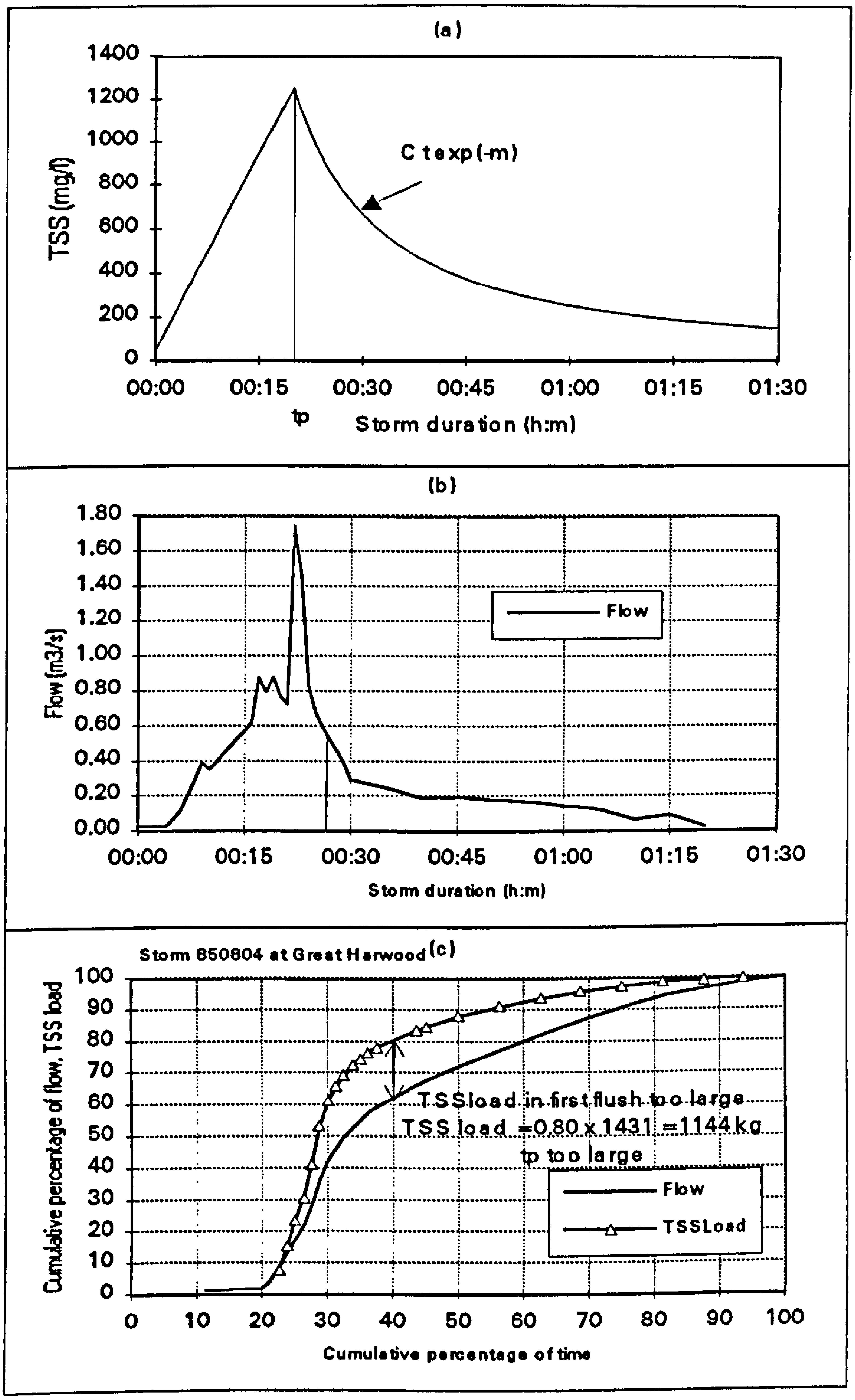


Figure 4.21. (a) Predicted pollutograph - shifted to the right,
(b) Observed flow,
(c) Cumulative flow and cumulative load plots for predicted pollutograph.

Clearly therefore the time to peak at which these values would correspond lies somewhere between 15 minutes ($LOAD_{ff}$ = 914 kg) and 20 minutes ($LOAD_{ff}$ = 1144 kg). By iteration and following the procedure outlined above, the time to peak at which the first flush loads from Step 1 and Step 3 equal to 972 kg was 17 minutes. This time corresponds very closely with the actual measured time of 20 minutes.

To further validate the model, the above methodology has been applied to all the storms in the data set and the corresponding results are shown in Appendix B, Figures B.1 to B.13. In general, there is good/reasonable agreement between the observed and predicted pollutographs. Hence, within the limitations of the methodology, whereby the same data has been used in the development and in the validation of the model, these comparisons are considered sufficiently good for the model to be validated.

Therefore, it is concluded that the above methodology is appropriate to define the time to peak TSS concentration. However, the methodology utilises a definition of the pollutant load in the first flush of pollutants and is therefore only appropriate for storms and catchments which exhibit a first flush. For more general application, the methodology needs to be tested on additional data and such that it may be possible to develop standard pollutographs for different catchments.

4.10. Relationship of Peak Pollution to the Diurnal Variation of Flows

The dry weather flow in sewer systems is known to follow a diurnal pattern which is a function of the pattern of human activity in urban areas. Butler and Graham (1995) carried out a study of the flows and pollution in combined sewers resulting from the use of domestic appliances. They identified that there was "an initial increase in the dry weather appliance use at about 6:00 hrs, which continued to build toward the morning peak between 08:00 and 08:30. Usage then subsided to a low point at 10:00, continuing to a stable level until about 15:30. At this time usage tended to increase to another (lower) peak at about 19:00, followed by a further peak at 23:00. Most activity had fallen off by 02:00". It was therefore hypothesised in this study that the peak storm pollution may be influenced by the temporal variation of pollutants in the dry weather flow. To test this hypothesis, the peak concentration of TSS and the time at which they occurred were plotted for 50 summer events at Great Harwood (Figure 4.18) and 60 summer events at Clayton-le-Moors (Figure 4.19) using both the BEST and GOOD storm data.

These plots suggest that the peak TSS concentration did not exhibit any diurnal variation and consequently it has not been possible to relate the peak TSS concentration to the diurnal pattern in dry weather flow. This can be explained on the basis that the volume of the stormflow was, in general, orders of magnitude greater than that in the dry weather flow. As the pollution characteristics in combined sewer runoff have been shown to be of the same order of magnitude of those found in dry weather flow (Ellis, 1989), it is clear that the storm flow masked the influence of the temporal variation in the dry weather flow at the two sites.

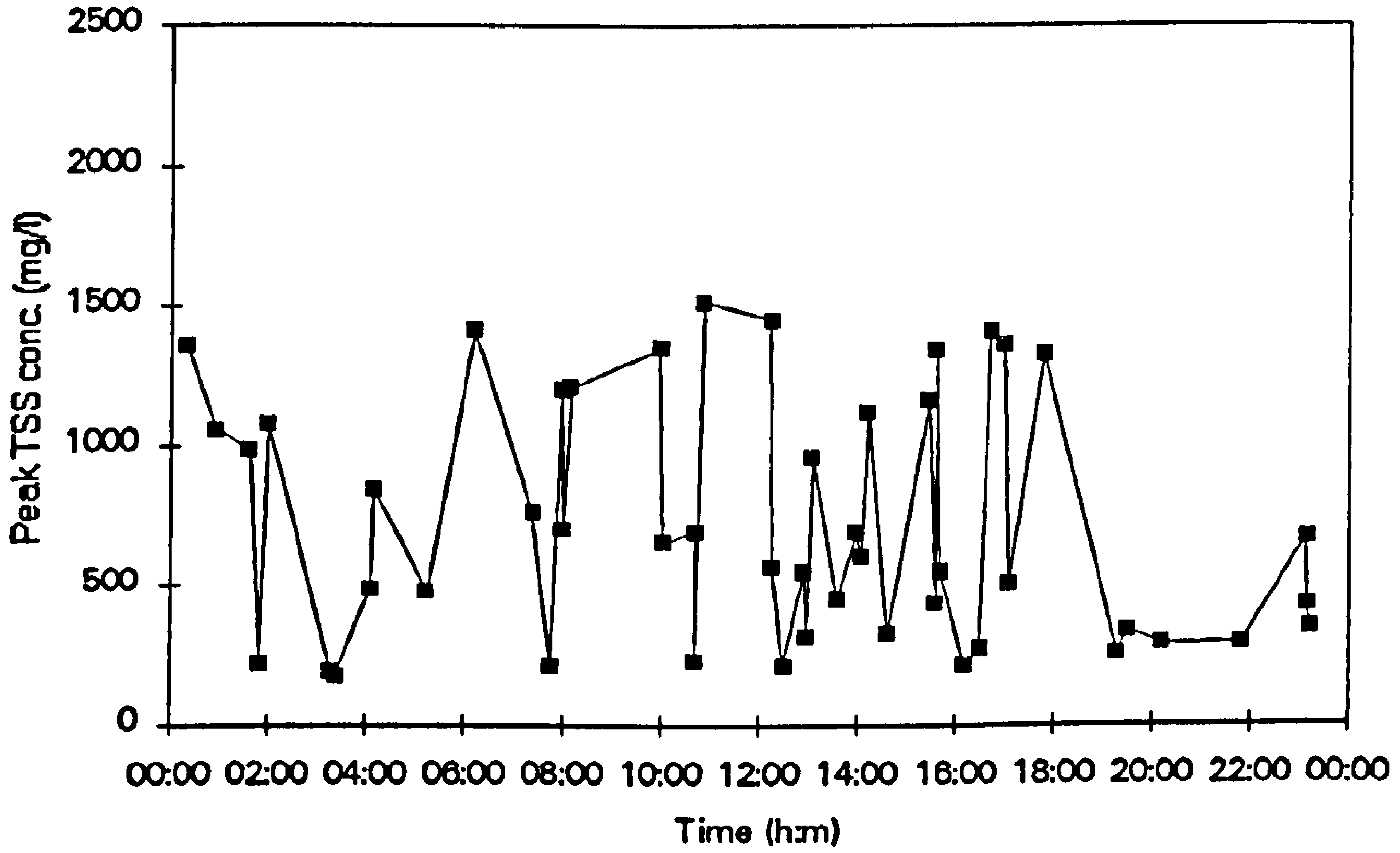


Figure 4.22 Diurnal pattern of peak concentration of TSS (mg/l) at Great Harwood.

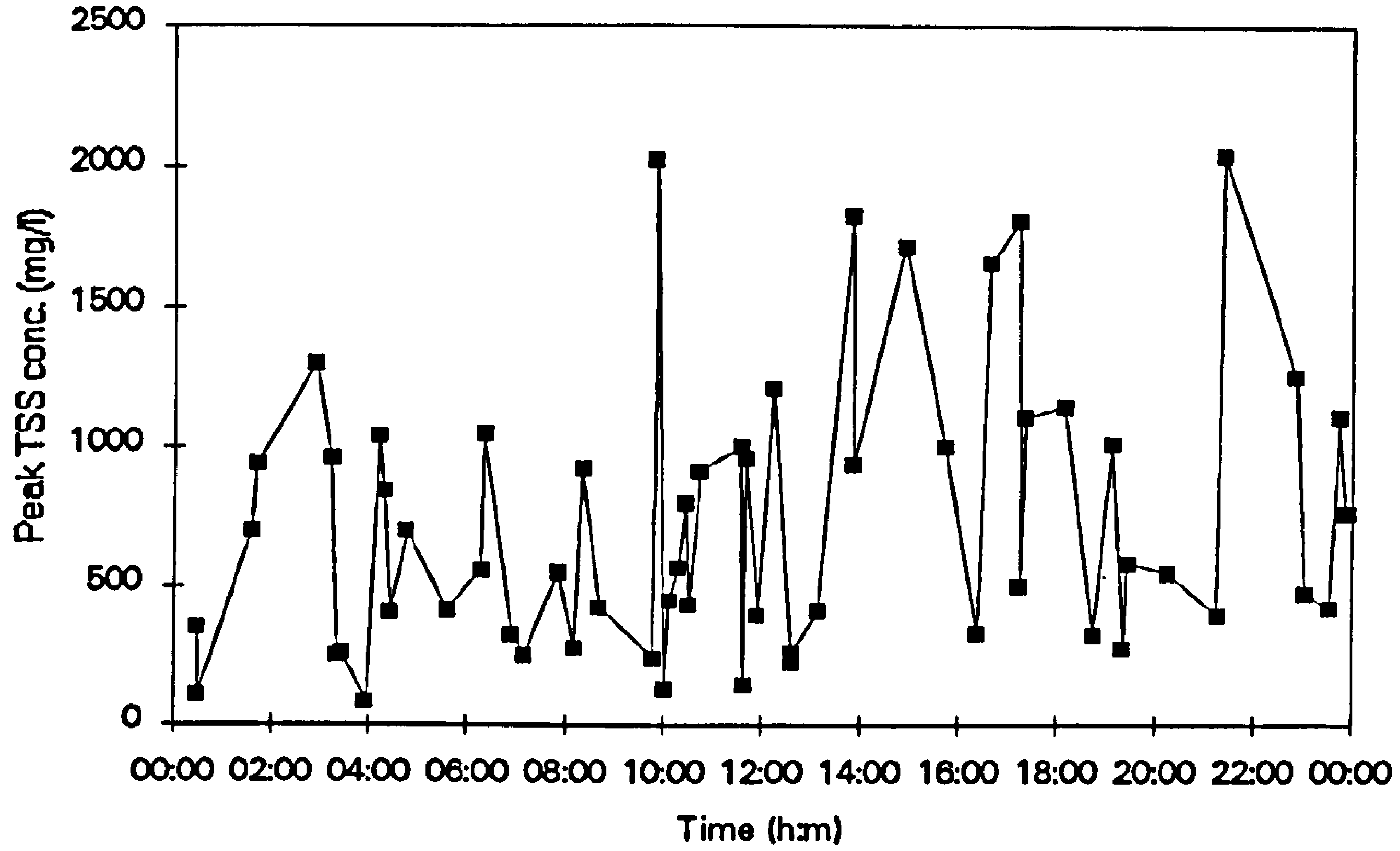


Figure 4.23. Diurnal pattern of peak concentration of TSS (mg/l) at Clayton-le-Moors.

4.11. Results and Discussion

The methodology developed in this chapter has resulted in a simple alternative approach to estimate the shape of the pollutograph corresponding to a given storm profile. It has been shown that the peak value of the pollutant concentration of each pollutograph can be determined from the antecedent dry weather period and the storm profile peakedness while the recession limb of the pollutograph can be represented by a single recession curve. A method to obtain the time to peak TSS has also been illustrated. The time to peak TSS can be obtained by adjusting it's position such that the load over the duration of the first flush corresponds to the total cumulative load in the first flush. When this load is equal to that derived from the cumulative load plot the time to the peak is established.

The simplicity of the model gives rise to various limitations:

1. One of the limitations in the application of the proposed methodology is that it is only appropriate for storms with known ADWP, and for

catchments and sewer systems where a first flush of pollutants is known to occur.

2. Because of the data constraints, the predictions are valid only for the return periods associated with the storms used for the calibration. In this study it was concluded that the methodology was appropriate for storms of return period 1 year or less. It has been shown in literature that for storage tanks/retention basins, a period of 6 months or 1 year is sufficient for storage tank design (Hvitved-Jacobsen and Yousef, 1988) and therefore the results presented in this study may be considered to be of particular value for use in the design of storage tanks.

3. The secondary flush was not modelled by the methodology outlined above. It was observed that the pattern of rainfall could be classified as a series of small individual events and that for each component of rainfall there was an associated pollutograph. In some instances, for successive rainfall events, these were observed to be defined by the merging of the pollutographs for each event. Clearly therefore the importance of any secondary flush was observed to be relatively less when compared to the first flush effect. It is therefore proposed that, where appropriate, storms which contain two distinct blocks of rainfall should be modelled as separate components of rainfall and pollution runoff. In this way, the secondary components of a flush in pollutants with peak flow may be better described.

4. The study was constrained by the non availability of the dry weather flow data. However, it was usual for the volume of the stormflow to greatly exceed the volume of the dry weather flow. Analysis of the data showed that the time of the day, and the magnitude and concentration of the dry weather flow had little influence on the magnitude of the peak concentration and load. It was concluded therefore that an analysis based only on the prediction of pollutants associated with stormflows provided a satisfactory methodology.

Although the proposed methodology is limited by the various assumptions, in the absence of detailed information, it does offer the potential to provide a simple alternative method that can be further developed when additional information on sewer flow quality and its relationships with catchment characteristics becomes available. Once this information is available, the reliance of the methodology on catchment specific details may be reduced.

Once the pollutograph has been determined, it can be used for

(i) determining the size of storage to retain a proportion of the pollutants (as described subsequently in Chapter 5);

(ii) to work out real time control strategies for pollution control.

In Chapter 5, Section 5.6, the procedure has subsequently been modified to allow it's application in design and it is therefore most appropriate for application to an annual time series of storms.

4.12. Conclusions

A methodology has been developed to predict the pollutograph, that is, the temporal change in the concentration of pollution with time, corresponding to a given rainfall event falling on the catchment and this is shown in Figure 4.17.

The pollutograph profile has been defined as a linear rise from the ambient concentration in the dry weather flow to a peak concentration defined in terms of the storm profile peakedness and the ADWP. Analysis has been based on a regression of log transformed data with the peak TSS defined by an equation of the form

$$\text{Peak TSS} = K\,(\text{PEAKEDNESS})^{a}\,(\text{ADWP})^{b} \qquad (4.11)$$

and the recession limb of the pollutograph has been defined by a power function of the form:

$$TSS(t) = A\,t^{-k} \qquad (4.12)$$

The time of occurrence of the peak TSS has been related to a definition of the first flush load and a subsequent regressional relationship to establish the load in the form:

$$LOAD_{ff} = K_1\,(STDURN)^{a1}\,(RFINT_{max})^{b1}\,(ADWP)^{c1} \qquad (4.13)$$

The coefficients K_1, a1, b1, c1, K, A, a, k, and b may be obtained from a limited number of observed storm events. The time to peak TSS can be obtained by a trial and error procedure. The position of the peak TSS concentration is adjusted on the time axis such that the load over the duration of the first flush is computed for each position of the peak TSS concentration. This is repeated until the area under the curve is made to correspond with the total cumulative load in the first flush obtained from equation (4.13). When this load is equal to that derived from the cumulative load plot the time to the peak is established.

The model validation showed good agreement between the observed and predicted pollutographs for 70% of the storm events. It is hypothesised that the values of the coefficients based on the observations from the two catchments outlined in this study can be used as a guide for application to similar catchments.

The results of the analysis presented in this chapter has shown that good estimates of pollutographs can be obtained from limited number of data observations for the two sites considered. Hence, in time, as more good quality data becomes available, it should be possible to develop standard pollutographs for typical catchments thereby achieving a saving in terms of time and cost.

Chapter 5

APPLICATION OF THE POLLUTOGRAPH METHODOLOGY TO STORAGE TANK DESIGN

5.1. Summary

This Chapter describes the application of the methodology developed in Chapter 4 of the thesis to compute the pollutograph profile corresponding to both observed events and Time Series Rainfall events and attention has been focused on the Great Harwood catchment. Subsequently the methodology has been used to carry out a comparative study of the effect of storage tank size (volume) on the flow and pollutant retention efficiencies of the storage tank. In respect of the computation of flows, a verified WALLRUS model for the catchment was first established. Subsequently, this model and the proposed pollutograph model have been used with time series of rainfall events as inputs to compute the pollutograph profile and to study the effect of storage tank size (volume) on the retention of pollutants within the system.

5.2. Background to Urban Drainage Modelling in the UK

Advanced water quantity and quality models for combined sewer flows have been described in Section 2.5.7. The complexity of the problem of modelling stormwater runoff and the subsequent hydraulic performance in the sewer system dictates that no model can reproduce the exact hydraulic conditions experienced within each pipe of the system. However, in the UK, the accuracy of modelling achieved by the WALLRUS model (WALLingford RUnoff Simulation suite of programs developed by Hydraulics Research Ltd, Wallingford) has been identified to be far in excess of that which could previously be expected from traditional methods of unverified analysis (Sewerage Rehabilitation Manual, 1986) and, compared with other simulation models, the WALLRUS model requires less data and has shorter run times. The WALLRUS model has been used widely by the water industry in the UK for the analysis of dendritic systems while for looped systems, a related model SPIDA has been developed and these currently form part of the HYDROWORKS suite of models marketed by HR Wallingford. The hydraulic performance of the flow controls, pumping stations and other ancillary structures, for example, storage tanks, may also be simulated.

The available methods of analysis in the Wallingford Procedure are:

(i) The Rational Method: This traditional design method is only satisfactory for the analysis of isolated lengths of peripheral area sewers ≤ 600 mm diameter. The method gives a value of peak discharge only; no information is obtained on runoff volume or hydrograph shape (NWC/DoE, 1983). This method is recommended for initial design and for use on homogeneous catchments of upto 150 ha in total area.

(ii) Hydrograph Method: This is a computer-based method incorporating separate models of the surface runoff and pipe-flow phases. This is identified as being appropriate for both the analysis of existing systems and the design of new systems. However, it was not able to account for surcharging in pipes.

(iii) Simulation Method: The WALLRUS model is able to simulate both surcharge and flooding and represent ancillary structures, such as overflows and pumping stations, commonly found in existing systems. The hydraulic modelling described in this Chapter employs this method.

5.2.1. Rainfall Inputs

The rainfall generator in the WALLRUS model generates a symmetrical rainfall hydrograph with the peak at the mid-point of the hyetograph. However, it has been recognised that this rarely occurs in practice (UPM Manual; FWR, 1994). Therefore, the use of a design storm approach has been identified as being inappropriate to the consideration of CSO performance because CSOs generally operate for much more frequently occurring storm events. Hence, to effectively simulate the full range of their quantitative performance with a mathematical model, the full spectrum of naturally occurring precipitation must be used (Clifforde *et al.*, 1986). Time Series Rainfall (TSR) (Henderson, 1986) have been identified as being appropriate for sewer system studies and these are described in the following section.

5.2.1.1. Time Series Rainfall

Time series rainfall may be defined as a sequence of historic rainfall events that are statistically representative of the annual or long term pattern of rainfall at a given location. Henderson (1986) reported on the development of a suitable rainfall time series for application in the UK and presently three time series are available to represent the annual rainfall series to the West, the North East and the South East regions. These series were derived from records of rainfall at particular locations. The analysis consisted of selecting a typical month from the data sets available in each region and the selected months were then concatenated to form a complete year for each region. Therefore, there were differences between the number of events, the magnitude of the annual average rainfall and the values of M5-60 minute rainfall depth and r (the ratio of the M5-60 min rainfall to the M5-2 days rainfall) at the location at which the rainfall time series was derived and at the location where the sewerage rehabilitation was to be carried out. To take account of these differences, two multiplicative factors have been identified for use together with the published series to produce an appropriate time series for any particular location in the UK. These multiplicative factors are a function of the M5-60 rainfall and the Average Annual Rainfall (AAR) for the sewer system location and the location at which the time series was derived.

Such a series may then be used in a chronological order to simulate the hydraulic performance of the system in the order that the storms are likely to occur. Alternatively, the series may be ranked with the most severe event as the first storm and the smallest storm at the end of the series. The series may be further split into a ranked series of summer storms (April to September) or winter storms (October to March).

The Annual TSR has been identified as an aid to planning because it is readily available. The application of these series allow investigations of the hydraulic performance and the behaviour of existing and renovated systems under day to day rainfall conditions. The application of the series is particularly appropriate as an effective means of assessing the hydraulic performance, and subsequently the pollution impact of sewer systems as the frequency, rate, volume and duration of the flows within the system may be assessed on an annual basis. Therefore, in this study, the Time Series Rainfall event has been used to examine the pollutant and load retention efficiency of the storage tank at the Great Harwood catchment.

However, limitations in the use of the annual TSR have been identified (UPM, 1994) and these are as follows:

(i) The regionalisation procedure was relatively crude and therefore cannot be expected to accurately represent all locations;

(ii) Return periods cannot be assigned to any of the events and therefore the series were not amenable for checking compliance with the intermittent river standards; and

(iii) The WRc time series represents a typical year of rainfall, and the existing series do not contain any particularly extreme events, that is, those of return period much greater than one year. In sewerage rehabilitation and, in particular, when the planned upgrade of a system includes a review and rationalisation of CSO and storage ancillary structures, the performance of the system for more extreme events that is, 5, 10 or even 50 year return period may be particularly important.

5.2.1.2. Stochastic Rainfall Generator

To overcome the above shortcomings, the stochastic rainfall generator (Cowperwait *et al.*, 1994) has recently been developed. The model is based on five parameters:

(i) Mean waiting time between the beginning of storms events (hr);

(ii) Mean number of rain cells per storm;

(iii) Mean duration of each rain cell (hr);

(iv) Mean intensity of each rain cell (mm/hr); and

(v) Mean waiting time for each rain cell after the beginning of the storm (hr).

These parameters have been derived for each month from historical records of measured rainfall at a number of sites throughout the UK and these may be used to simulate 100 years of hourly time series rainfall. Annual time series rainfall for a typical year may be extracted from the 100 year record and subsequently the 100 most severe events can then extracted from the simulated typical year.

5.2.2. Runoff

For modelling the rainfall-runoff process for urban drainage design in the UK using the Wallingford Procedure, the percentage runoff equation is used which was derived by Kidd and Lowing (1979) using multiple regression analysis techniques using 510 observed events from 17 catchments to predict the runoff volume. The percentage runoff (PR) equation is

$$PR = 0.829\,PIMP + 25.0\,SOIL + 0.078\,UCWI - 20.7 \quad (R^2 = 0.57) \qquad (5.1)$$

where

SOIL = index of soil type (based on the soil map of the UK),

PIMP = percentage impermeable area to the total catchment area,

UCWI = urban catchment wetness index (mm) related to the SAAR (standard average annual rainfall), and

PR = percentage runoff from the total catchment area and is defined as

$$PR = \frac{RUNVOL}{(P * AREAC)} \cdot 100 \qquad (5.2)$$

in which, P = rainfall depth (mm),

AREAC = total catchment area (ha), and

RUNVOL = runoff volume (in mm over the total catchment area).

In the surface runoff model, the net rainfall depth is calculated from the percentage runoff equation (5.2) and allowance made for depression storage. The time distribution of this net rainfall is calculated according to whether it falls on pitched roofs or paved or pervious areas. Historically, the runoff response of these areas was derived by routing the net rainfall through a non-linear reservoir to produce a hydrograph of surface runoff. Nine such standard hydrographs were used for paved or pervious areas (depending on catchment slope and the paved area per gully) and one for pitched roofs. These standard hydrographs were multiplied by the relevant contributing areas and then combined to form the surface runoff hydrograph. In the HYDROWORKS suite of programs, two linear reservoirs in series are used to describe the overland flow process. In the routing model, the surface runoff hydrographs entering each pipe length are then routed through the drainage network using a version of the Muskingum-Cunge method. The effects of surcharging and surface flooding are also incorporated. In this manner, the flood hydrograph at any pipe junction may be calculated using the Wallingford simulation method.

5.3. Verification of the WALLRUS Model

On the basis of the procedure outlined in Figure 5.1 (WaPUG, 1993), the simulation method in the WALLRUS model has been used to simulate the flows in the sewer system considered in this study. It was therefore considered necessary to first verify the WALLRUS model for flows for the sewer system at Great Harwood and such that the verified model could be used, together with the pollutograph prediction methodology outlined in Chapter 4, for further simulation with observed storms and Time Series Rainfall events. Verification has been identified as the process of comparative analysis whereby gross errors in the input data to a model are identified and corrected until simulated and measured performance agrees within acceptable limits. This section describes the calibration and verification of the WALLRUS simulation model (version 1.3) applied to the Great Harwood sewer system drainage area.

5.3.1. Rainfall Event Data

The use of the WALLRUS simulation model with an observed rainfall event required data defining the rainfall in the form of an event hyetograph at a uniform time step throughout the event. It was also necessary to define the wetness of the catchment at the start of the event in order to calculate the rainfall losses and rates of runoff. In this respect, the parameters required were the Urban catchment wetness index (UCWI), the Antecedent condition index, simulation time and the measured rainfall data. API5 (the 5-day antecedent precipitation index) values were also required as input to the rainfall event data (RED) files to enable computation of the UCWI value. The UCWI was then computed for observed rainfall events from:

$$\text{UCWI} = 125 + 8\,\text{API5} - \text{SMD} \qquad (5.3)$$

where

UCWI = the Urban Catchment Wetness Index,

API5 = the 5-day Antecedent Precipitation Index,

SMD = the Soil Moisture Deficit.

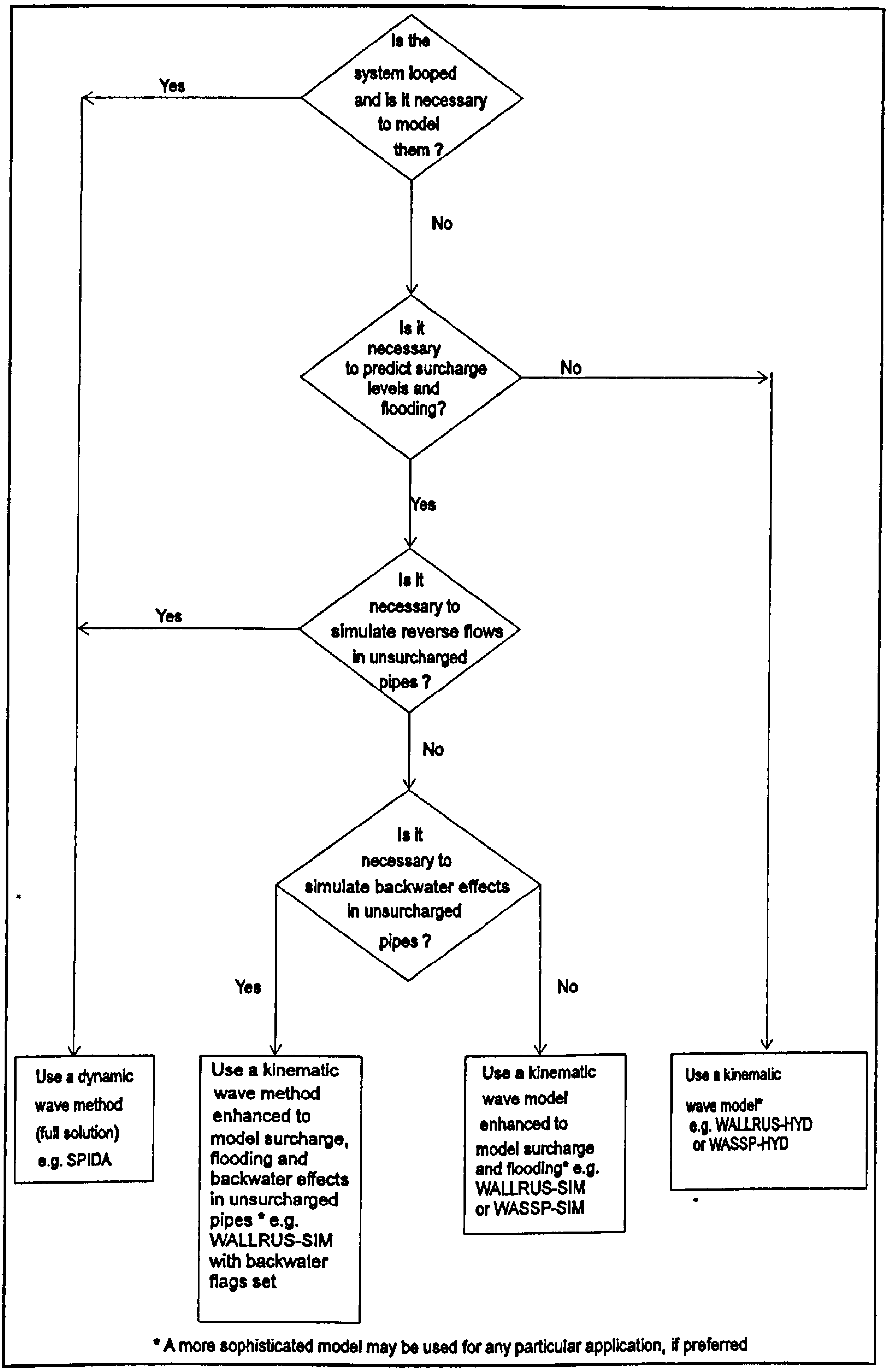


Figure 5.1. Flow diagram for selecting a program for modelling an existing system (WaPUG, 1993).

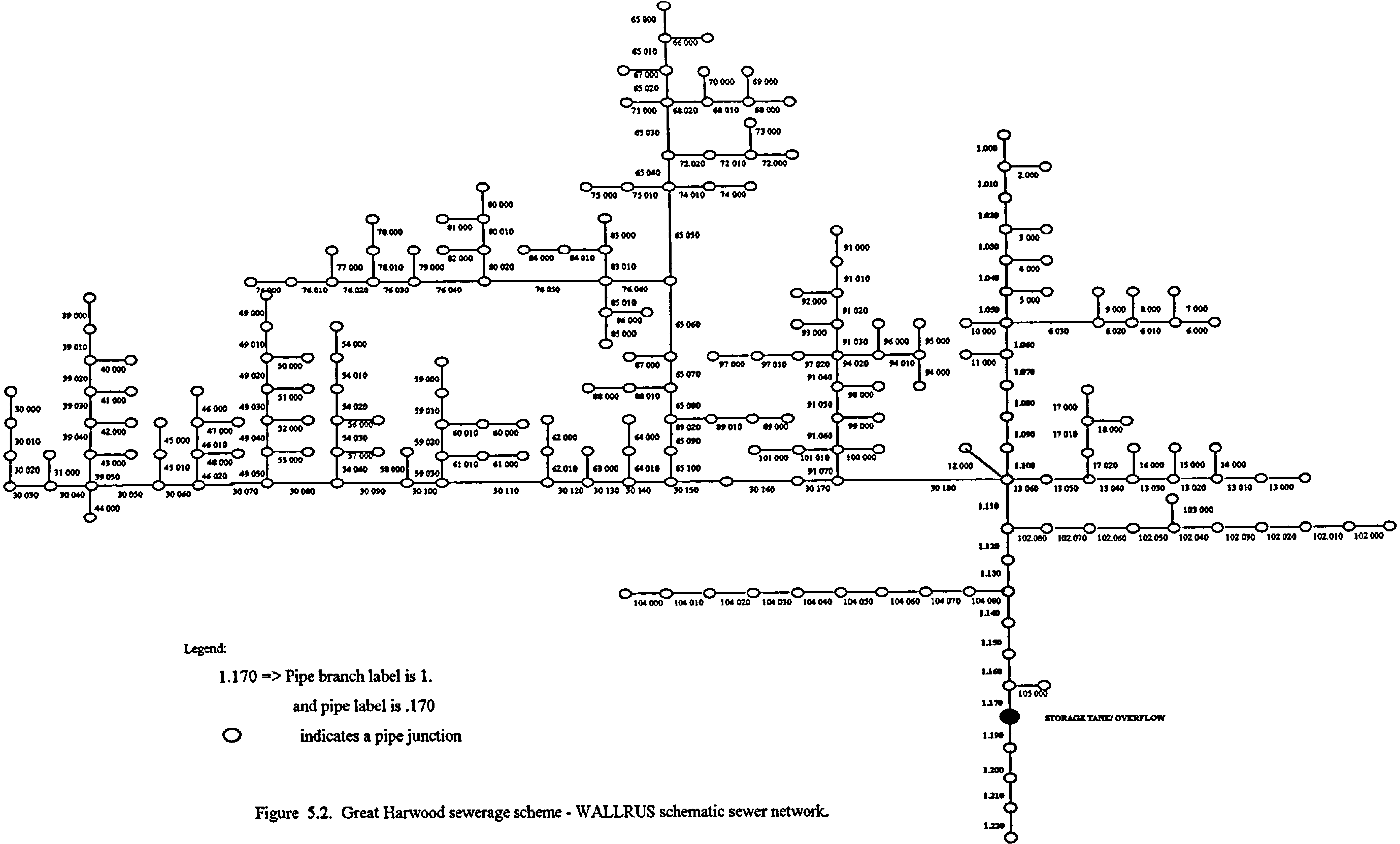
As measured SMD values were not available for each storm event, in this study, the average value of SMD = 5 mm for the Great Harwood location was taken from the Effective Mean Soil Moisture deficit map (Met. Office, 1981).

The observed rainfall hyetograph could then be input as a series of rainfall intensities at predefined time steps. A typical Rainfall Event Data file is described in Appendix C.

5.3.2. Sewer System Data for the WALLRUS Model

The data required as input to the simulation model consisted of a combination of catchment and sewer system data. The schematic diagram of the sewer system layout of the Great Harwood catchment area is shown in Figure 5.2.

The basic sewer system data, for example, pipework dimensions, cover and invert levels were taken from sewer records and the catchment contributing areas, pervious and impervious, were assessed from 1:2500 catchment plans by personnel of Hyndburn Borough Council and these were available to the author in the previous WASSP-SIM format. The WALLRUS suite of programs has an option by which the sewer system data can be input in the old WASSP-SIM format and converted into the WALLRUS SSD (Sewer System Data) format (as specified in the WALLRUS ver. 1.3 User guide) and this data is described in Appendix D. The data in the SSD file consisted of global parameters, for example, soil index, pipe roughness, dry weather flow, and the time step for the simulations. For each pipe, the data consisted of the pipe branch reference number, pipe and manhole characteristics - length, size, shape, invert levels, gradient, hydraulic roughness, and the loss coefficient at manholes. The catchment characteristics for each pipe were the total area drained to each pipe, impervious area (paved and roofed), pervious area, slope, cover level and the paved area per gully. In addition, the SSD file included the information for the storage chamber, for example, the chamber geometry, the discharge coefficients to define the head discharge relationships for the continuation flow outlet and for the overflow weir used to spill the excess flow from the chamber.



Legend:

1.170 => Pipe branch label is 1.
and pipe label is .170

○ indicates a pipe junction

Figure 5.2. Great Harwood sewerage scheme - WALLRUS schematic sewer network.

5.3.3. Selection of Events for Verification

Various criteria were used to select the events for the verification of the WALLRUS model. These included: the guidelines as set out in the WRc/WAA (1987) publication - "A guide to sewer flow surveys" and WaPUG (1993); the return period of the storms; and the use of events which represented the different rainfall groups already identified in Section 4.6.

The guidelines (WRc/WAA, 1987) for identifying storms for verification (the relevant extract is shown in Table 5.1) indicated that storms with a minimum rainfall intensity of 5 mm/hr occurring for at least 4 minutes, a minimum duration of 30 minutes, and total depth of rainfall greater than 5 mm and resulting in a minimum depth of flow 150 mm at the time of peak flow should be considered for verification.

Table 5.1. Typical suitable rainfall (A guide to sewer flow surveys; WRc, 1987)

Catchment	Rainfall			
	Total (mm)	Minimum intensity	Storm duration	Variability
Small urban catchment (under 5000 people) OR Sub-catchment well defined in the sewer network	5	5 mm/hr for a period of at least 4 minutes	at least 30 minutes	Not more than 40 % in rainfall totals, as measured by all gauges

In addition, it has been identified that only the storms with the storm durations in the range of total duration of rainfall corresponding to 1/2 T_c, T_c, and greater than $2T_c$, where T_c is the time of concentration, should be considered (WaPUG, 1993). However, in this study storm events of 1/2 T_c and T_c could not be considered for verification because, as described in Section 5.5.1, the time of concentration for the system was determined to be about 30 minutes and as described in Section 3.2, all storms defined as "BEST" had a minimum storm duration of at least 1 hour. Hence the verification was carried out using storms with a duration greater than 1 hour.

A further factor governing the selection of the storms to be used for verification purposes was that the events adequately represented the pollutographs corresponding to the 4 different rainfall intensity categories defined in Chapter 4, that is, greater than 15 mm/hr, 10-15 mm/hr, 5-10 mm/hr and less than 5 mm/hr. There was only one event in the range 10-15 mm/hr, but this event did not result in a rainfall depth of 5 mm, and was therefore not considered.

It was also considered appropriate to verify the WALLRUS model for a range of return periods. In this respect, it was therefore first considered necessary to determine the return period corresponding to each storm event.

5.3.4. Return Period Analysis

The storm characteristic of peak rainfall intensity (mm/hr) was used to prepare tabular rankings of all the recorded GOOD and BEST storm events at Great Harwood, a total of 113 in all. It may be argued that total volume, depth and duration should also have been taken into account to compute the return period of the storms. However, for pollution studies, it was shown in Chapter 3 that, from a regression analysis of the total pollution load and the hydrologic variables of total rainfall depth, storm duration, maximum rainfall intensity, average rainfall intensity, and the antecedent dry weather period prior to the storm, the total load of suspended solids in the first flush correlated well with the peak rainfall intensity over the catchment or the peak inflow into the sewer system. This finding was also supported by the studies of MacArthur *et al.* (1994) who identified that the most significant parameters in terms of their impacts on a combined sewer system were the precipitation characteristics of peak intensity and total rainfall. While total rainfall may be the primary factor to be considered when determining the total quantity of combined flow requiring treatment or storage, peak intensity is the most likely primary factor to influence the maximum runoff rate and hence the consequent conveyance capacity of the system.

To compute the return periods corresponding to each storm event, the observed series of events were listed in descending order of peak rainfall intensity and they were each accorded a ranking m, starting with m=1 for the highest value, m=2 for the next and so on, in decreasing order. The recurrence interval was then computed using Weibull's Formula

$$T_r = \frac{(n+1)}{m} \qquad (5.4)$$

where m = the event ranking, and

n = number of events.

The return period of each individual storm is shown in Table 5.2 and from which it can be seen that, in a ranked set of events from 36 months of rainfall data, the 3rd ranked storm approximates to a return period (RP) of one year, the 6th ranked event corresponds to a 6 month RP, and the 12th event, a 3 month RP. However, as identified by Wilson (1990), objections to the use of the Weibull's Formula were raised by Cunnane (1978) as it was considered to introduce a bias for the largest event in a short series. Reservations were also made about the Californian Formula $T_r = \frac{(n)}{(m)}$ and Hazen's Formula $T_r = \frac{(2n)}{(2m-1)}$. However, the formula after Gringorton $T_r = \frac{(n+0.12)}{(m-0.44)}$ was suggested as satisfactory whilst Cunnane recommended $T_r = \frac{(n+0.2)}{(m-0.4)}$. The return period was therefore also computed using Gringorton's and Cunnane's Formulations. From Table 5.2, it can be seen that Weibull's method resulted in the storm with rank 1 defined as a storm of 3 year return period whereas the method of Gringorton and Cunnane resulted in the same storm having a 5-year return period. The latter method was therefore adopted and, based on the storm rankings by the peak intensity of rainfall, the return period associated with each of the storm events was computed and these are also shown in Table 5.2.

In the subsequent discussion, to describe the rainfall corresponding to a particular return period and duration, the notation MT-D (FSR, NERC, 1975) was adopted, where T is the return period and D is the rainfall duration. For example, the M1-30 event described an event of return period once in 1 year and a duration of 30 minutes. For return periods less than 1 year, the notation TM-D was used, for example, the 4M-30 event described an event of return period once in 3 months (4 times a year) and a duration of 30 minutes.

Table 5.2. Storm events ranked on the basis of peak rainfall intensity (mm/hr)

S.No.	Storm event	RFINTmax	Qinmax	Ranking	Weibull's (n+1)/m	Gringorten's (n+0.12)/ (m-0.44)	Cunnane (n+0.2)/ (m-0.4)	Return period
		mm/hr	cumecs					
1	850804	67.20	1.740					
2	841018b	67.20	1.618	1	37.00	64.50	60.33	M5
3	850824	57.60	1.601	2	18.50	23.15	22.63	M2
4	850803	38.00	0.381	3	12.33	14.11	13.92	M1
5	841026f	30.00	0.683	4	9.25	10.15	10.06	M1
6	860815	28.80	1.821	5	7.40	7.92	7.87	2M
7	850713	28.80	0.567	6	6.17	6.50	6.46	2M
8	840524a	28.80	0.347	7	5.29	5.51	5.48	2M
9	840803	24.00	1.375	8	4.63	4.78	4.76	3M
10	860730b	19.20	1.391	9	4.11	4.22	4.21	3M
11	860804	19.20	1.162	10	3.70	3.78	3.77	3M
12	860610	19.20	0.869	11	3.36	3.42	3.42	3M
13	850802	19.20	0.453	12	3.08	3.12	3.12	3M
14	841122a	14.40	0.965	13	2.85	2.88	2.87	4M
15	841029	14.40	0.877	14	2.64	2.66	2.66	4M
16	870410	14.38	0.480	15	2.47	2.48	2.48	6M
17	860520a	12.80	1.020	16	2.31	2.32	2.32	6M
18	870207	12.05	0.277	17	2.18	2.18	2.18	6M
19	850401	12.00	0.561	18	2.06	2.06	2.06	6M
20	860515	12.00	0.463	19	1.95	1.95	1.95	6M
21	841218b	11.20	0.469	20	1.85	1.85	1.85	6M
22	860724	10.34	0.559	21	1.76	1.76	1.76	<6M
23	850717	9.60	0.936	22	1.68	1.68	1.68	<6M
24	851105a	9.60	0.865	23	1.61	1.60	1.60	<6M
25	841011	9.60	0.835	24	1.54	1.53	1.53	<6M
26	861005b	9.60	0.795	25	1.48	1.47	1.47	<6M
27	861005e	9.60	0.795	26	1.42	1.41	1.41	<6M
28	850820	9.60	0.792	27	1.37	1.36	1.36	<6M
29	840612a	9.60	0.775	28	1.32	1.31	1.31	<6M
30	850403	9.60	0.703	29	1.28	1.26	1.27	<6M
31	841008	9.60	0.556	30	1.23	1.22	1.22	<6M
32	850607	9.60	0.554	31	1.19	1.18	1.18	<6M
33	860404	9.60	0.450	32	1.16	1.14	1.15	<6M
34	850828	9.60	0.340	33	1.12	1.11	1.11	<6M
35	841003	9.60	0.334	34	1.09	1.08	1.08	<6M
36	841123	9.60	0.326	35	1.06	1.05	1.05	<6M
37	860729	9.60	0.282	36	1.03	1.02	1.02	<6M
38	860813a	9.60	0.236	37	1.00	0.99	0.99	<6M
39	860813b	9.60	0.227	38	0.97	0.96	0.96	<6M
40	860401	9.60	0.212	39	0.95	0.94	0.94	<6M
41	850823	9.60	0.206	40	0.93	0.91	0.91	<6M
42	870317b	9.39	0.939	41	0.90	0.89	0.89	<6M
43	850819x	8.85	0.245	42	0.88	0.87	0.87	<6M
44	860520c	8.56	0.627	43	0.86	0.85	0.85	<6M
45	841127	7.68	0.426	44	0.84	0.83	0.83	<6M
46	860514	7.68	0.413	45	0.82	0.81	0.81	<6M
47	841201	7.20	0.337	46	0.80	0.79	0.79	<6M
48	860402	7.20	0.229	47	0.79	0.78	0.78	<6M
49	870202	7.01	0.631	48	0.77	0.76	0.76	<6M
50	870419	7.00	0.354	49	0.76	0.74	0.74	<6M
51	870419	7.00	0.354	50	0.74	0.73	0.73	<6M
52	850124	6.72	0.370	51	0.73	0.71	0.72	<6M
53	860117	6.11	0.327	52	0.71	0.70	0.70	<6M
54	851108a	6.00	0.302	53	0.70	0.69	0.69	<6M
55	841109b	5.28	0.383	54	0.69	0.67	0.68	<6M
56	870317	4.88	0.246	55	0.67	0.66	0.66	<6M
57	870228	4.84	0.220	56	0.66	0.65	0.65	<6M

.... *(cont'nd)*

S.No.	Storm event	RFINTmax	Qinmax1	Ranking	Weibull's n+1/m	Gringorten's (n+0.12)/ (m-0.44)	Cunnane (n+0.2)/ (m-0.4)	Return period
		mm/hr	cumecs					
58	860416	4.80	0.342	57	0.65	0.64	0.64	<6M
59	850315b	4.80	0.339	58	0.64	0.63	0.63	<6M
60	841018a	4.80	0.311	59	0.63	0.62	0.62	<6M
61	860730a	4.80	0.299	60	0.62	0.61	0.61	<6M
62	851116	4.80	0.277	61	0.61	0.60	0.60	<6M
63	841102a	4.80	0.274	62	0.60	0.59	0.59	<6M
64	860728	4.80	0.248	63	0.59	0.58	0.58	<6M
65	860322b	4.80	0.242	64	0.58	0.57	0.57	<6M
66	861005c	4.80	0.213	65	0.57	0.56	0.56	<6M
67	861005a	4.80	0.199	66	0.56	0.55	0.55	<6M
68	861005d	4.80	0.199	67	0.55	0.54	0.54	<6M
69	860120	4.72	0.319	68	0.54	0.53	0.54	<6M
70	841102b	4.16	0.307	69	0.54	0.53	0.53	<6M
71	860327a	3.84	0.411	70	0.53	0.52	0.52	<6M
72	840622	3.68	0.304	71	0.52	0.51	0.51	<6M
73	870323	3.39	0.281	72	0.51	0.50	0.51	<6M
74	850605	3.36	0.251	73	0.51	0.50	0.50	<6M
75	850329	3.33	0.274	74	0.50	0.49	0.49	<6M
76	840711a	3.20	0.567	75	0.49	0.48	0.49	<6M
77	850315	3.20	0.523	76	0.49	0.48	0.48	<6M
78	841109a	3.20	0.330	77	0.48	0.47	0.47	<6M
79	851217	3.20	0.270	78	0.47	0.47	0.47	<6M
80	860328	3.20	0.235	79	0.47	0.46	0.46	<6M
81	860511a	3.04	0.324	80	0.46	0.45	0.45	<6M
82	841022	2.96	0.301	81	0.46	0.45	0.45	<6M
83	860304b	2.93	0.222	82	0.45	0.44	0.44	<6M
84	860320	2.88	0.242	83	0.45	0.44	0.44	<6M
85	841029	2.77	0.230	84	0.44	0.43	0.43	<6M
86	860110	2.74	0.281	85	0.44	0.43	0.43	<6M
87	851210	2.52	0.284	86	0.43	0.42	0.42	<6M
88	850314	2.40	0.738	87	0.43	0.42	0.42	<6M
89	851202	2.40	0.429	88	0.42	0.41	0.41	<6M
90	850301	2.40	0.303	89	0.42	0.41	0.41	<6M
91	840527	2.40	0.234	90	0.41	0.40	0.40	<6M
92	860326	2.40	0.233	91	0.41	0.40	0.40	<6M
93	870305	2.18	0.200	92	0.40	0.39	0.40	<6M
94	860128	2.16	0.290	93	0.40	0.39	0.39	<6M
95	850902	2.11	0.219	94	0.39	0.39	0.39	<6M
96	860309	2.06	0.460	95	0.39	0.38	0.38	<6M
97	860104	2.04	0.774	96	0.39	0.38	0.38	<6M
98	860704	2.04	0.223	97	0.38	0.37	0.37	<6M
99	860322a	1.77	0.217	98	0.38	0.37	0.37	<6M
100	860505	1.73	0.220	99	0.37	0.37	0.37	<6M
101	860328a	1.61	0.380	100	0.37	0.36	0.36	<6M
102	860511b	1.60	0.198	101	0.37	0.36	0.36	<6M
103	860304a	1.60	0.158	102	0.36	0.36	0.36	<6M
104	860318	1.56	0.202	103	0.36	0.35	0.35	<6M
105	860520b	1.55	1.550	104	0.36	0.35	0.35	<6M
106	851212	1.30	0.244	105	0.35	0.35	0.35	<6M
107	851231	1.20	0.198	106	0.35	0.34	0.34	<6M
108	860327b	0.66	0.660	107	0.35	0.34	0.34	<6M
109	841120	0.33	0.501	108	0.34	0.34	0.34	<6M
110	840806	0.17	0.215	109	0.34	0.33	0.33	<6M
111	851230	0.17	0.000	110	0.34	0.33	0.33	<6M
112	860624c	0.06	0.248	111	0.33	0.33	0.33	<6M
113	851108	0.00	0.000	112	0.33	0.32	0.32	<6M

Based on the screening procedure described above, three events - 850824, 841011 and 840622 were selected for verification purposes and these covered a range of storm types, return periods and antecedent conditions. The details of these storms are shown in Table 5.3.

Table 5.3. Details of storms identified for verification of the WALLRUS model

S.No.	Storm event	Rainfall intensity represented	Duration (min)	Total rainfall depth (mm)	Return period
1.	850824	>15 mm/hr	124	5.06	M2
2.	841011	5-10 mm./hr.	157	9.34	<6M
3.	840622	< 5 mm./hr.	240	7.03	<12M

5.4. Simulation of the Selected Events

Once the storms for verification were selected, these were then used in the WALLRUS simulation program in an attempt to verify the model. A number of simulation runs were made and initial verification results highlighted an overprediction of the flow volumes in pipe labelled 1.170 located immediately upstream of the storage chamber as detailed in Table 5.4. One possible explanation was that the percentage impervious area had been inaccurately represented. The presence of several old mills and other areas with separate

Table 5.4. Simulated and observed flows for actual and modified cases

	From initial data set			After paved areas were reduced by 25 %	
Storm date	Observed volume	Simulated inflow volume	Obsvol/ simvol	Simulated inflow volume	Obsvol/ simvol
	(m^3)	(m^3)		(m^3)	
850824	2357	3232.8	0.73	2656.8	0.89
841011	3833	4579	0.84	3605	1.06
840622	3212	3915	0.82	3164	1.02

drainage systems had been identified as the possible cause and in consultation with the personnel of Hyndburn Borough Council, the percentage paved area was therefore reduced by 25%. Such a reduction in the percentage paved area resulted in the predicted total storm flow volume being comparable with the observed volumes and these are also shown in Table 5.4. The discharge hydrographs for pipe 1.170 predicted using the WALLRUS model together with the actual measured values of the flow and the rainfall hyetographs are shown in Figure 5.3. Good agreement was observed in all three storms and differences between the simulated and observed flows were within acceptable limits (20%) as stated in WaPUG (1993). It was concluded that the WALLRUS model could be considered as verified. This justified its use to predict the rainfall, runoff and sewer flow response in the Great Harwood sewer system. This model was subsequently used in further analysis to examine the pollution response of the catchment for design storms of differing return period. However, the sensitivity of the model was first explored.

5.5. Sensitivity Studies

To get a better insight into the performance of the Great Harwood sewer system to changes in the various input parameters, such as the design storm return period, storm duration, catchment imperviousness, soil index, urban catchment wetness index (UCWI), and pipe roughness, a sensitivity study was carried out using the verified WALLRUS simulation model. The sensitivity of the peak discharge in pipe 1.170 located immediately upstream of the storage chamber to the changes in these parameters was examined and the results of this analysis are described in the following sections.

5.5.1. Sensitivity to the Return Period and the Duration

The traditional approach to the use of sewer flow modelling has embodied the use of design storms of standard profile, return period and duration. In this latter respect, the critical rainfall duration has to be identified because this duration will result in the largest peak flow. As the average rainfall intensity is known to decrease as the rainfall duration is increased, the critical duration usually approximates to the time of concentration of the catchment, that is, the time needed for the entire catchment to contribute to flow at the outlet.

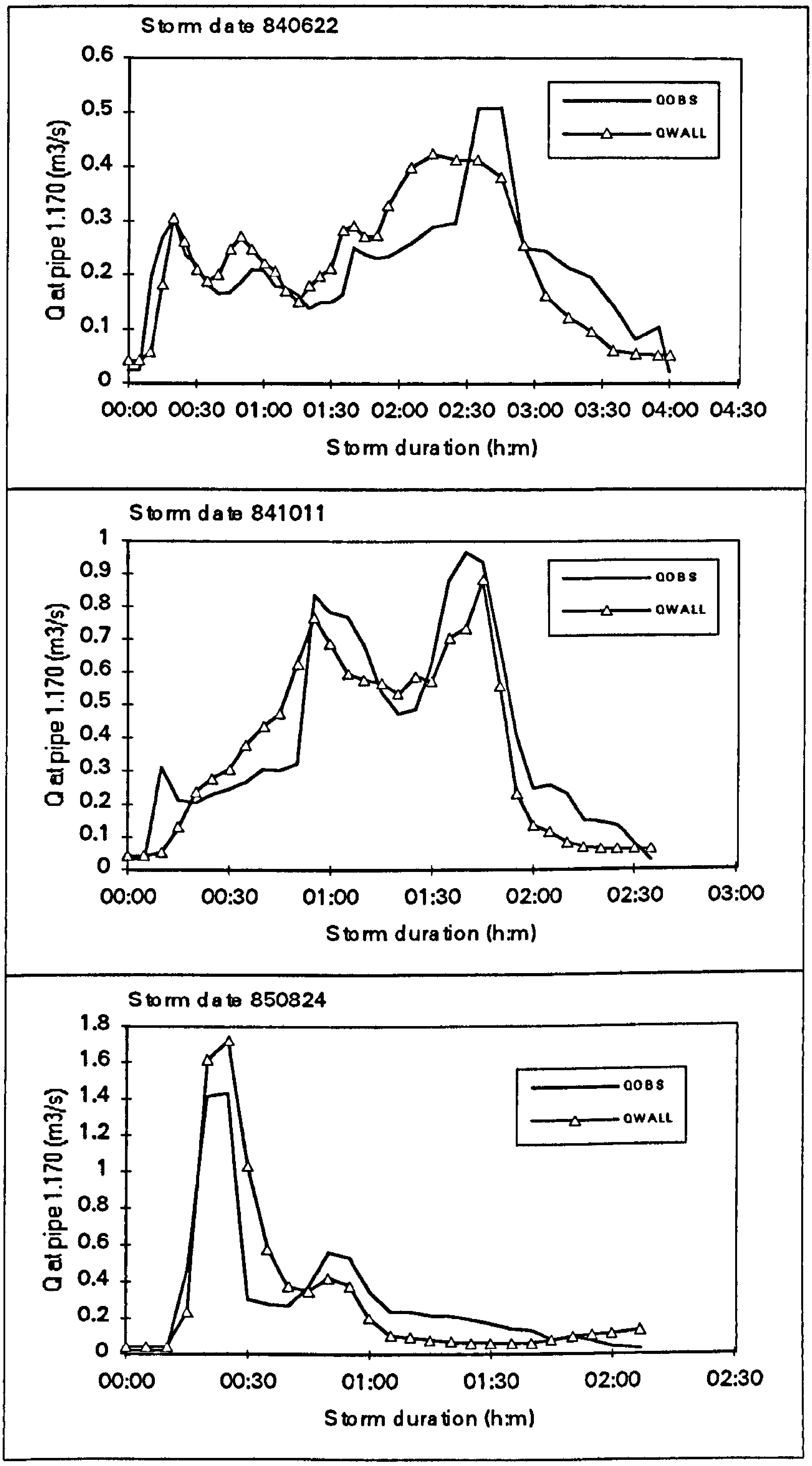


Figure 5.3. Observed and simulated hydrographs in pipe 1.170 for the Great Harwood sewer system.

To determine the time of concentration, the model was run for a series of storms (50% summer profile) of arbitrary return periods (1 in 1 year to 1 in 20 years) and durations 15, 30, 60,120, 180 and 240 minutes respectively, as identified in SRM2 (1986). The results, expressed in non-dimensional form (Q_p/Q_{p130}, where Q_{p130} is the maximum flow corresponding to the storm having a return period of 1 year and 30 minutes duration), are summarised in Table 5.5 and are shown in Figure 5.4.

Table 5.5. Q_p/Q_{p130} at pipe 1.170 as a function of design storm duration and return period

Return period	Q_p/Q_{p130} (m^3/s) at pipe 1.770 (Q_{p130} = 3.292 m^3/s)						
T_r	Storm duration (min)						
(years)	15	30	45	60	120	180	240
1	0.98	1.00	0.98	0.93	0.78	0.67	0.59
2	1.09	1.11	1.11	1.09	0.92	0.80	0.70
3	1.14	1.17	1.16	1.14	0.99	0.86	0.75
5	1.19	1.22	1.21	1.20	1.07	0.93	0.83
10	1.25	1.28	1.27	1.25	1.15	1.03	0.92
20	1.31	1.34	1.33	1.31	1.21	1.12	1.02

The following observations were made:

(i) This analysis enabled the critical storm duration to be established. From the simulations for each of the storms corresponding to different return periods and storm durations, it was observed that the storm duration of 30 minutes gave the maximum peak flows and hence, it was concluded that the time of concentration for the catchment was 30 minutes.

(ii) With respect to the effect of changing the return period, it can be seen that, as expected, as the return period was increased, the peak flow rate also increased. For example, a five-year 30 minutes rainfall resulted in a peak discharge which was 22% higher than that from a one-year summer storm of the same duration.

(iii) An examination of the variation of peak discharge with storm shows that a one-year 60 minutes rainfall produces a peak discharge which is 7% lower than that from a one-year summer storm of the same return period but 30 minutes duration. This is to be expected, as an increase in storm duration is accompanied by a decrease in the peak rainfall intensity.

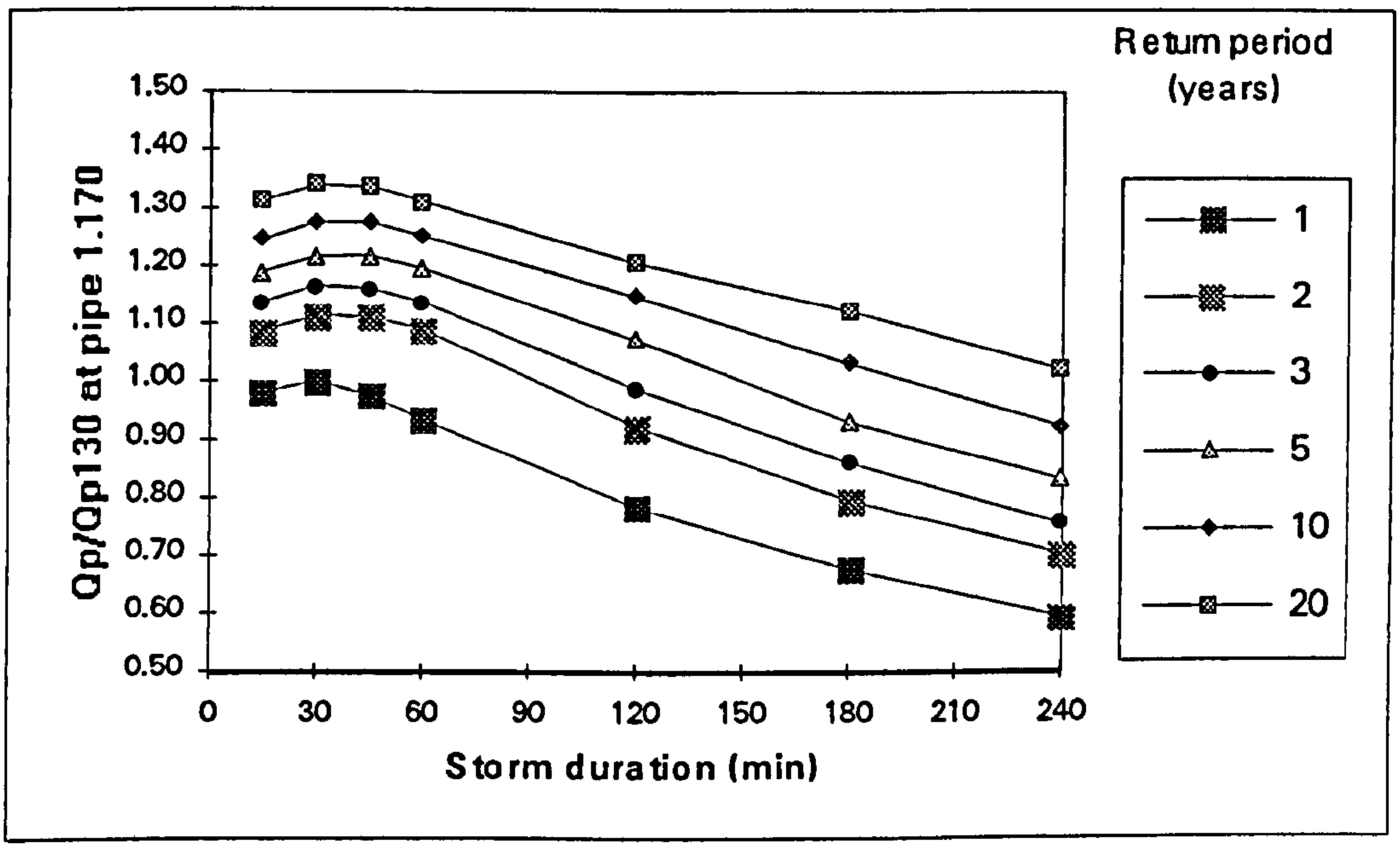


Figure 5.4. Variation of Q_p/Q_{p130} with return period and duration at Great Harwood.

Therefore, the 30 minute storm corresponding a return period of 1 year was selected and used throughout thereafter to examine the effect of varying the urban catchment wetness index (UCWI), catchment imperviousness (PIMP), soil index (SOIL), as these parameters were considered to determine the percentage runoff from a catchment (equation 5.1). The effects of a change in pipe roughness was also examined.

5.5.2. Percentage Impervious Area (PIMP)

Developments in the catchment area may result in substantial changes to the flow characteristics from the catchment surface. For example, the construction of new buildings may result in an increase in the impervious area contributing to the sewer system. Therefore, it was decided to examine the effect of an increase in the percentage impervious area on the peak flow. The percentage impervious areas were adjusted to 50, 60 , 70, 80, 90, and 99% of the area draining to each pipe. Values of PIMP of less than 50% were not used, because it has been identified in the Wallingford Procedure (NWC/DoE, 1983) that negative values of PR would result. The results of this analysis are summarised in Figure 5.5 from which it can be seen that changing this parameter has a significant effect on the magnitude of the peak flow. For example, an increase in imperviousness from 50 to 75% resulted in an increase in the peak runoff by 25%. This indicates that the calculation of runoff and flow is particularly sensitive to the impervious area and hence, in any mathematical simulation of catchment runoff, these areas need to be identified and assessed most accurately.

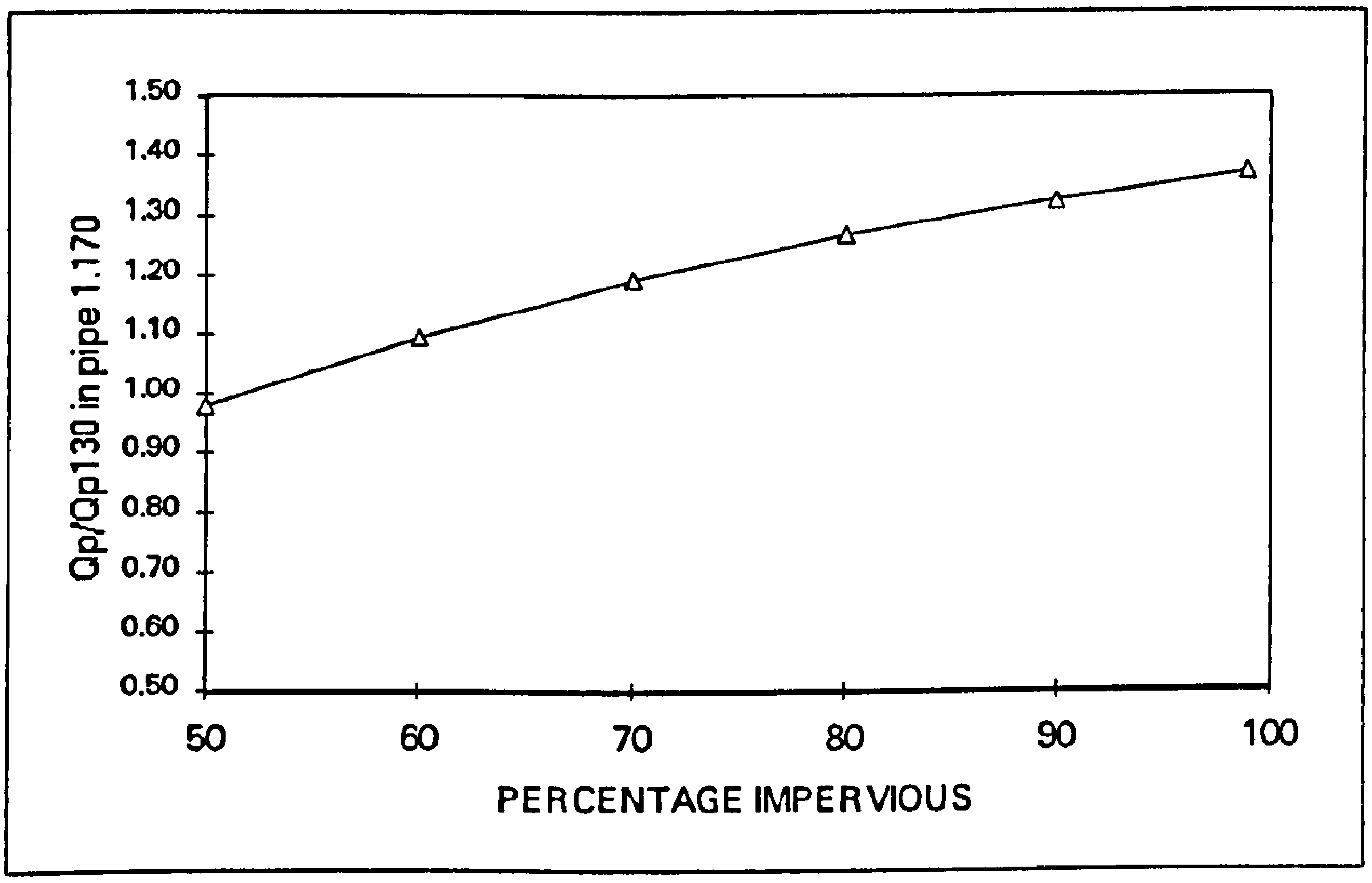


Figure 5.5. Variation of Q_p/Q_{p130} with percentage paved area at Great Harwood.

5.5.3. Soil Index (SOIL)

The SOIL index for a particular catchment can be established by referring to a Soil map of the UK which defines the types of soil in the catchment in terms of a winter rain acceptance. The soil index is defined as

$$SOIL = (0.15A_1 + 0.3A_2 + 0.4A_3 + 0.45\,A_4 + 0.5\,A_5) \,/\, (A_1 + A_2 + A_3 + A_4 + A_5) \qquad (5.5)$$

where A_i = area covered by soil of type i.

and hence, when a catchment includes more than one soil class, a weighted average of the soil index is used. The effect of varying the soil index on the value of the peak flow was examined and the values of the soil index (SOIL) considered were 0.15, 0.30, 0.40, 0.45, and 0.50 corresponding to the five soil types 1 to 5 identified in the Flood Studies Report. The results of this analysis are shown in Figure 5.6 from which it can be seen that the effect of changing the soil index from 0.15 to 0.30 on the peak flow is about 6%.

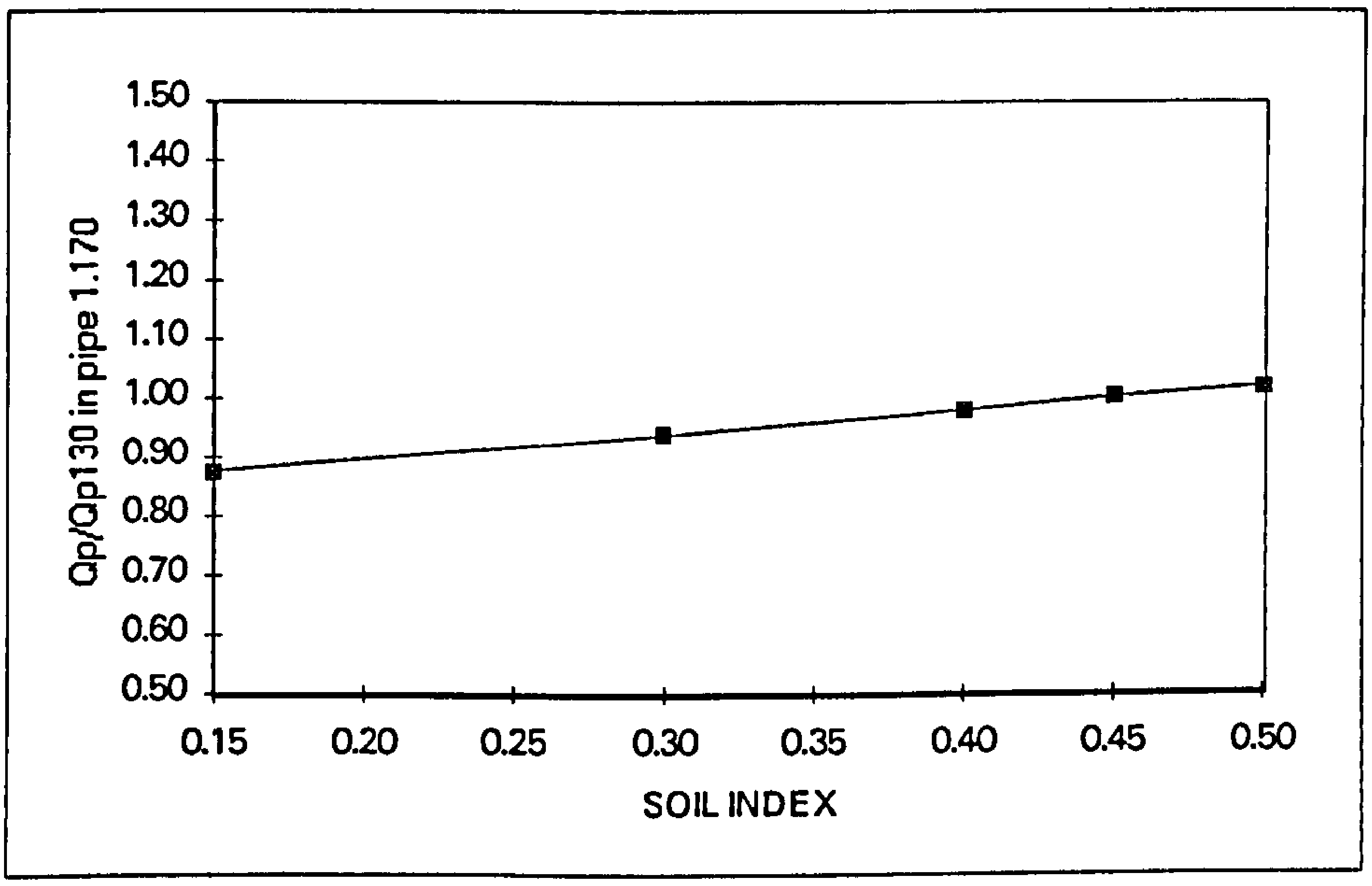


Figure 5.6. Variation of Q_p/Q_{p130} with soil index (SOIL) at Great Harwood.

5.5.4. Urban Catchment Wetness Index (UCWI)

The UCWI is a measure of the initial catchment wetness which governs the infiltration of rainfall into the ground. For a design rainfall event, the recommended value of UCWI was read from the relationship with standard average annual rainfall (WALLRUS User manual, 1991). To examine the sensitivity of the peak flows to a change in the initial catchment wetness conditions, values of UCWI from 0 to 300 were input into the simulation model for the Great Harwood sewer system and the results of this analysis are shown in Figure 5.7. It can be seen that for a change in the UCWI value from 125 to 200, the resultant variation in the peak flowrate was about 6% and hence the selection of the magnitude of UCWI was considered to be of little relative importance. This can be explained in terms of the percentage runoff equation which is reproduced below:

$$PR = 0.829\ PIMP + 25.0\ SOIL + 0.078\ UCWI - 20.7 \qquad (5.6)$$

From equation (5.6), it can be seen that the term involving the UCWI may be anticipated to have only a small influence on the value of the percentage runoff.

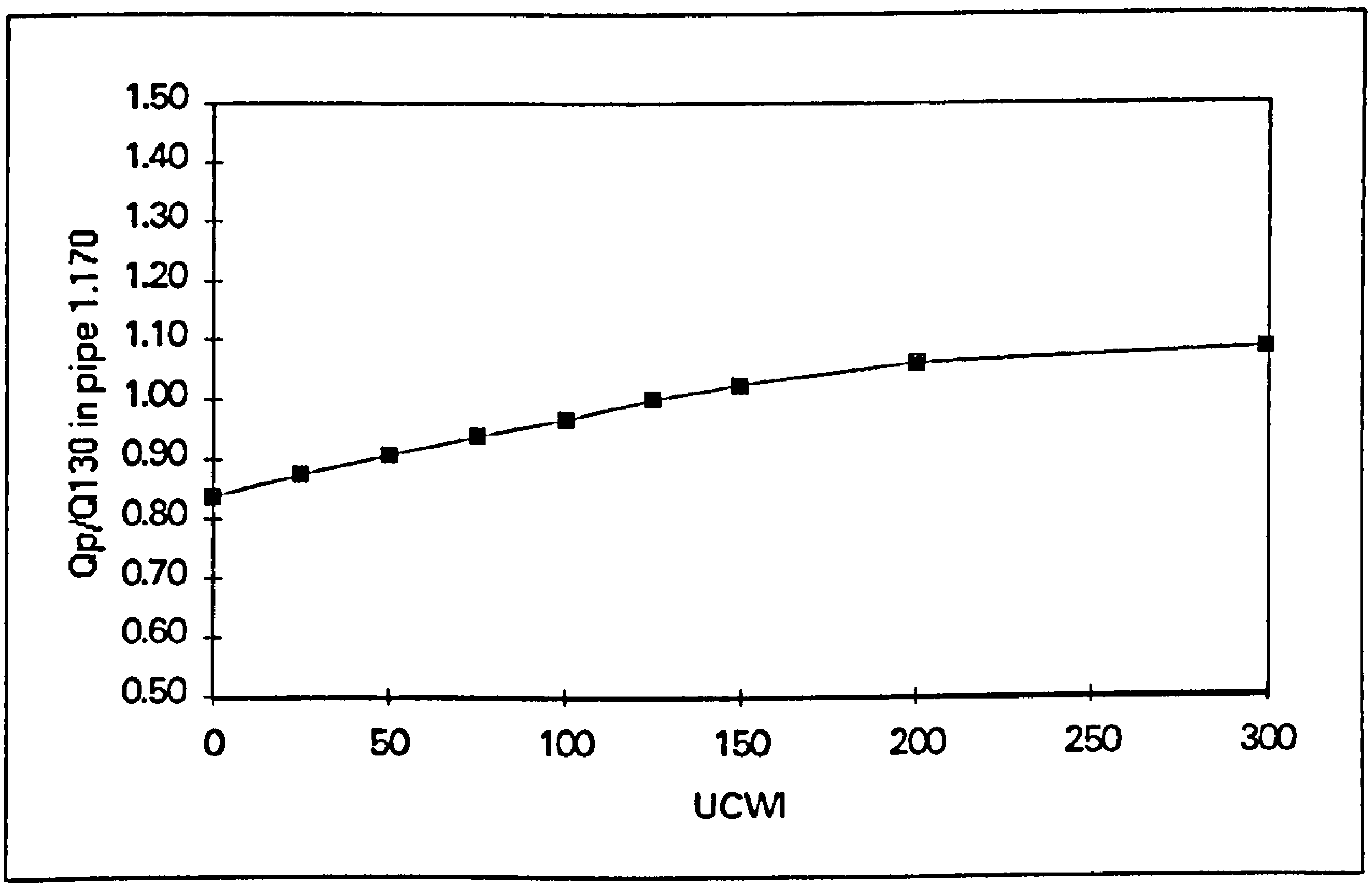


Figure 5.7. Variation of Q_p/Q_{p130} with UCWI at Great Harwood.

5.5.5. Pipe Roughness (k_s)

For existing systems, the value of the pipe roughness (k_s) depends on the condition of the sewers and the presence of sediments and these may therefore, result in significant changes to the flow regime in the pipes. Hence, the effect of changing the values of k_s on the peak flows was examined and the results of this analysis are shown in Figure 5.8. A change in the magnitude of the pipe roughness resulted in an attenuation of the flow, for example, an increase in the pipe roughness from 1.5 mm to 3.0 mm decreased the peak flow rate by about 6-7%.

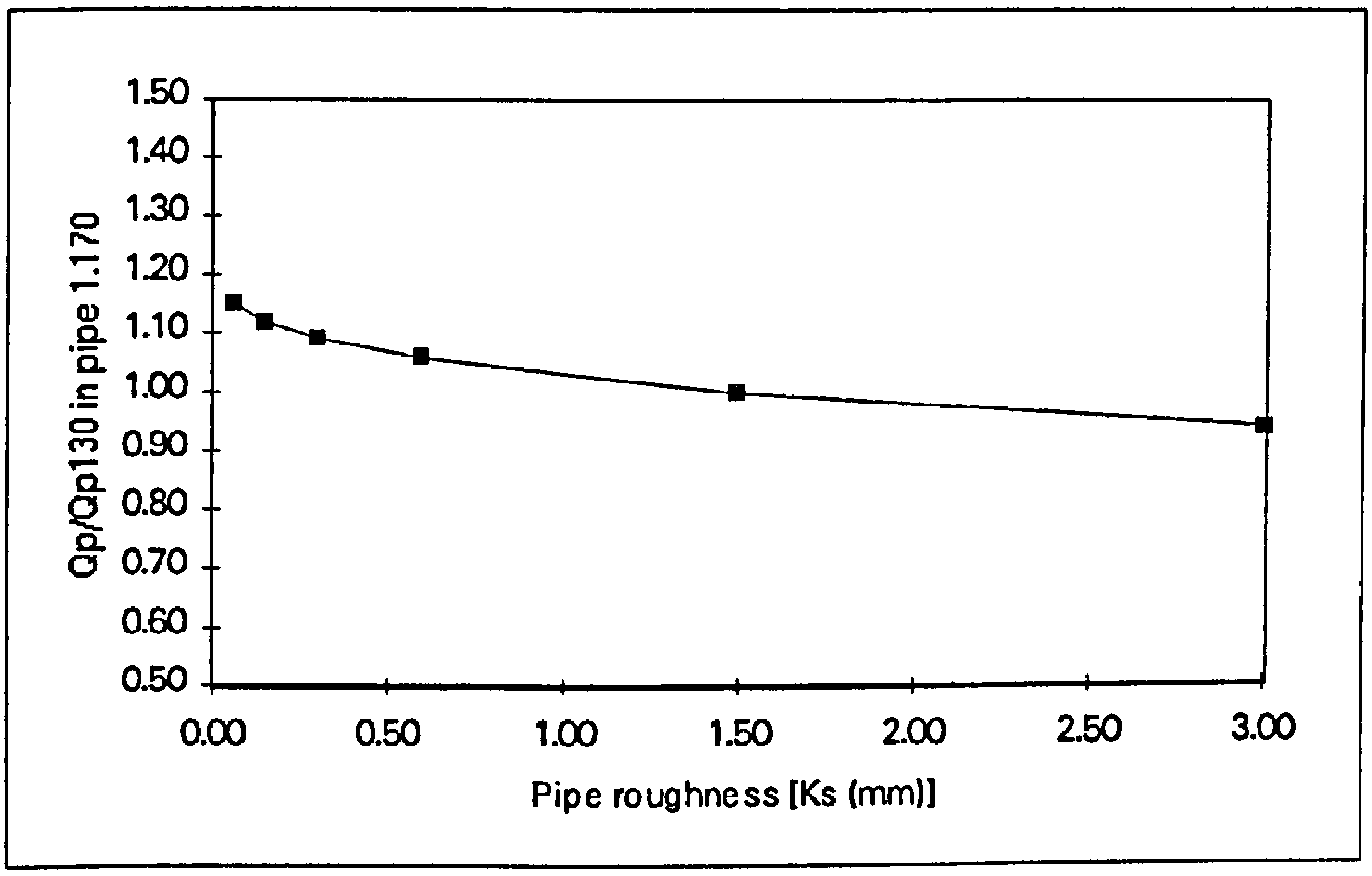


Figure 5.8. Variation of Q_p/Q_{p130} with pipe roughness at Great Harwood.

The WALLRUS model was verified for the Great Harwood catchment and from a subsequent sensitivity analysis, it was observed that the peak flow rate in the system was most sensitive to a change in the value of the percentage of impervious area. It is recommended therefore that in any study the percentage impervious areas need to be assessed most accurately before applying the proposed methodology.

The verified WALLRUS model and the methodology to establish the pollutograph may then be used to predict the pollution load spilled from the storage tanks of different size. The steps involved in the procedure to examine the flow and pollution retention characteristics of the storage tank are outlined in Figure 5.9 and as an example, the procedure is described in the following section using a Time Series Rainfall Event.

5.6. Application of the Proposed Methodology

The procedure outlined in Section 4.9.1 has subsequently been modified to allow it's application in design and is appropriate only for storms for which the ADWP is known and for which there is a first flush of pollutants. It is therefore most appropriate for time series storms. For such events the procedure is illustrated with reference to TSR event no. 5 as follows:

TSR event no. 5 data:

Antecedent dry weather period	(hr)	=	72
Maximum rainfall intensity	(mm/hr)	=	43.80
Storm duration	(min)	=	70

1. The TSS load in the first flush is computed from the relationship

$$LOAD_{ff} = 1.35\,(STDURN)^{0.68}\,(RFINT_{max})^{0.68}\,(ADWP)^{0.28} \qquad (5.7)$$

Substituting the data for TSR event no. 5 results in

$LOAD_{ff}$ =1050 kg

2. The corresponding peak TSS concentration is computed from

$$TSS_p = 123.02\,(PEAKEDNESS)^{0.64}\,(ADWP)^{0.17} \qquad (5.8)$$

from which

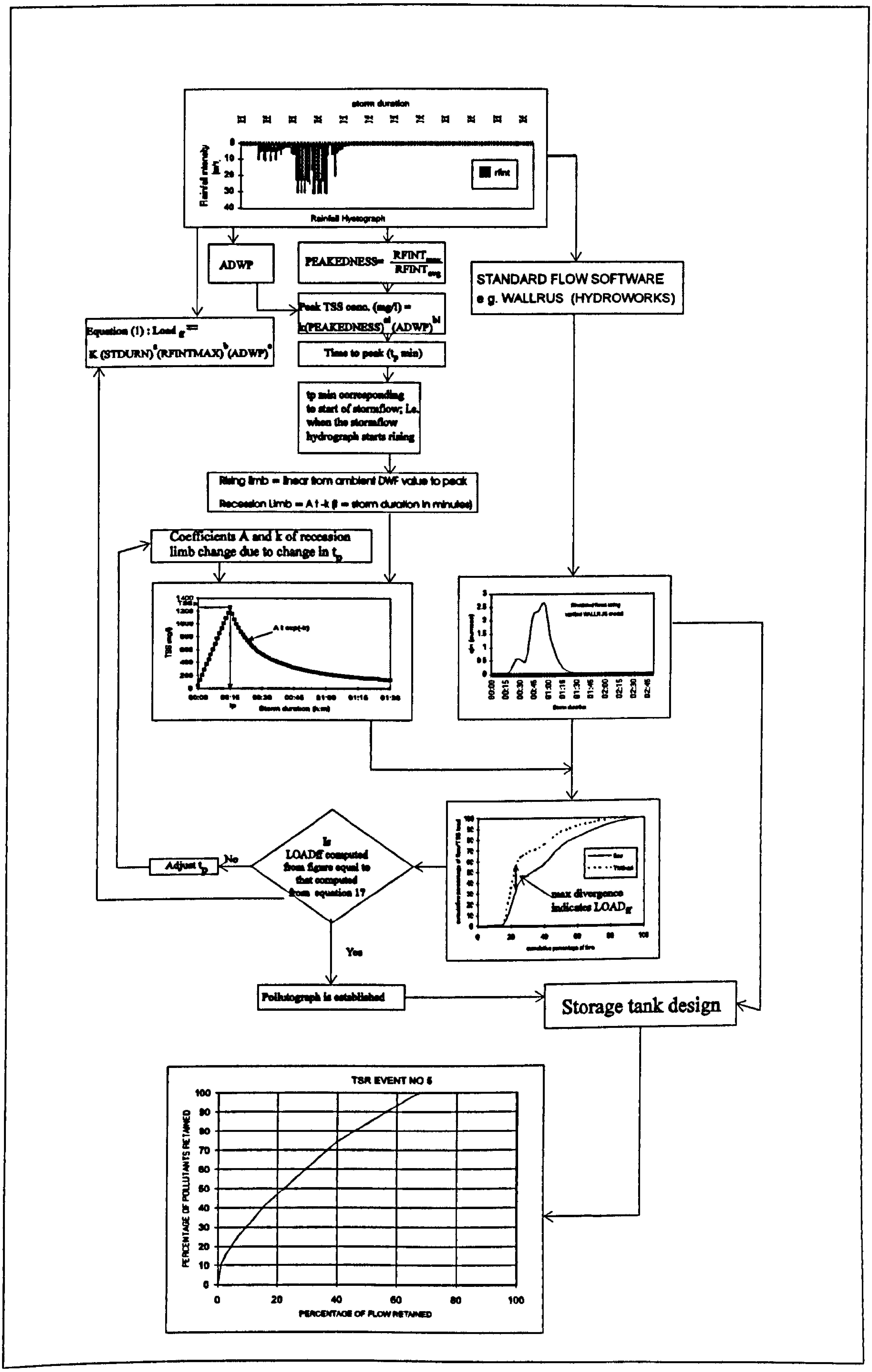


Figure 5.9 Flowchart showing the pollutograph methodology applied to sizing of a storage tank

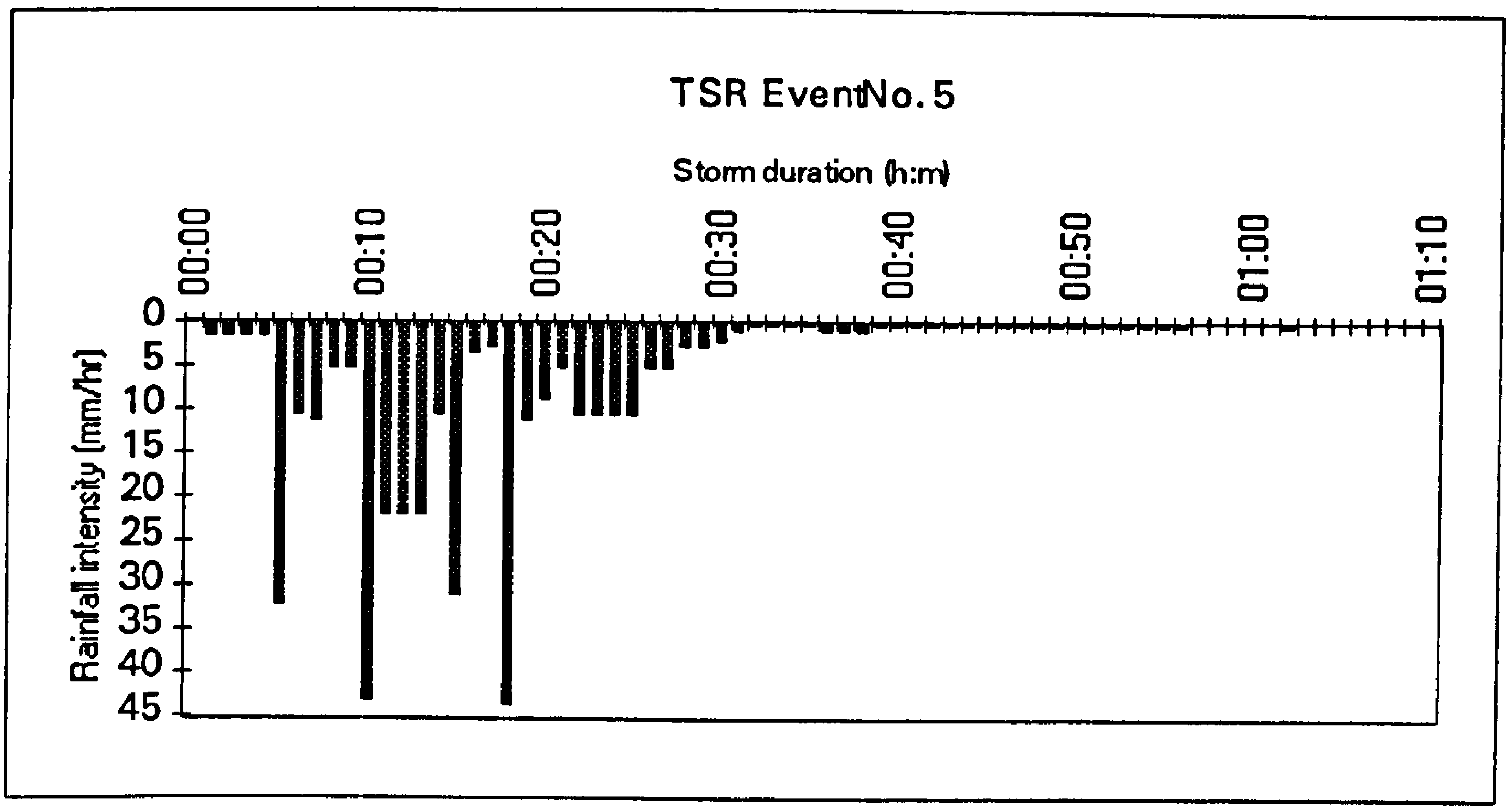


Figure 5.10. Rainfall hyetograph of TSR event no. 5.

$TSS_p = 964$ mg/l

3. The shape of the recession limb of the pollutograph is computed from

$$TSS(t) = 4.5\ t^{-1.23} \qquad (5.9)$$

where TSS(t) = the concentration of total suspended solids (mg/l) at any time t;

t = time from start of storm (min).

4. The flow hydrograph is computed using the verified WALLRUS model.

5. The computed pollutograph is then superimposed on the hydrograph with the time to peak TSS arbitrarily selected. As an initial estimate, it is chosen to occur at a time corresponding to the start of stormflow, that is, when the flow hydrograph starts rising. This parameter is obtained from a simulation of the flows using the verified WALLRUS model.

6. The cumulative load versus the cumulative flow plot is then obtained from which the TSS load in the first flush is computed.

7. If the computed TSS load in the first flush from the above plot and TSS load in the first flush as obtained from equation (5.7) agree, then the position of the pollutograph is correct and the time to peak is established. If they do not, then the step (5) and (6) are repeated. If the calculated TSS load is greater than the actual TSS load in the first flush, the pollutograph peak is adjusted in time to the left and *vice versa*, until the TSS loads balance.

8. Once the pollutograph is obtained, it is then possible to examine the effects of tank size on the pollution load retention characteristics as a function of storage volume. The WALLRUS model is used to compute the inflow, overflow and continuation flow hydrographs for different storage volumes. In this example, storage volumes of 1, 137.7 (actual), 200, 300, 500, 1000, and 2000 m^3 were considered. A mass balance in the tank enables the volume of flow retained to be computed and a typical plot of the inflow, overflow and the continuation flow corresponding to storage volumes of 137.7, 500 and 1000 m^3 is shown in Figure 5.11.

9. The total pollutant loads corresponding to the inflow, overflow and continuation flow for each of the storage volumes were also computed (complete mixing was assumed) and the pollution load retained in the tank for each of the storage volumes was computed from the mass balance. The results of these computations are shown in Table 5.6 and Figure 5.12 from which it can be seen that the proportion of pollutant load retained is greater than the corresponding percentage of the total flow and a retention of 30-40% of the flow volume enables a capture of 40-60% of the pollutant load.

The same methodology may then be applied to all storms of the time series such that an annual spill load may then be predicted for different sizes of the storage chamber. Judgements may then be made to select the appropriate size of the storage chamber to protect the watercourse in respect of long-term accumulative impacts.

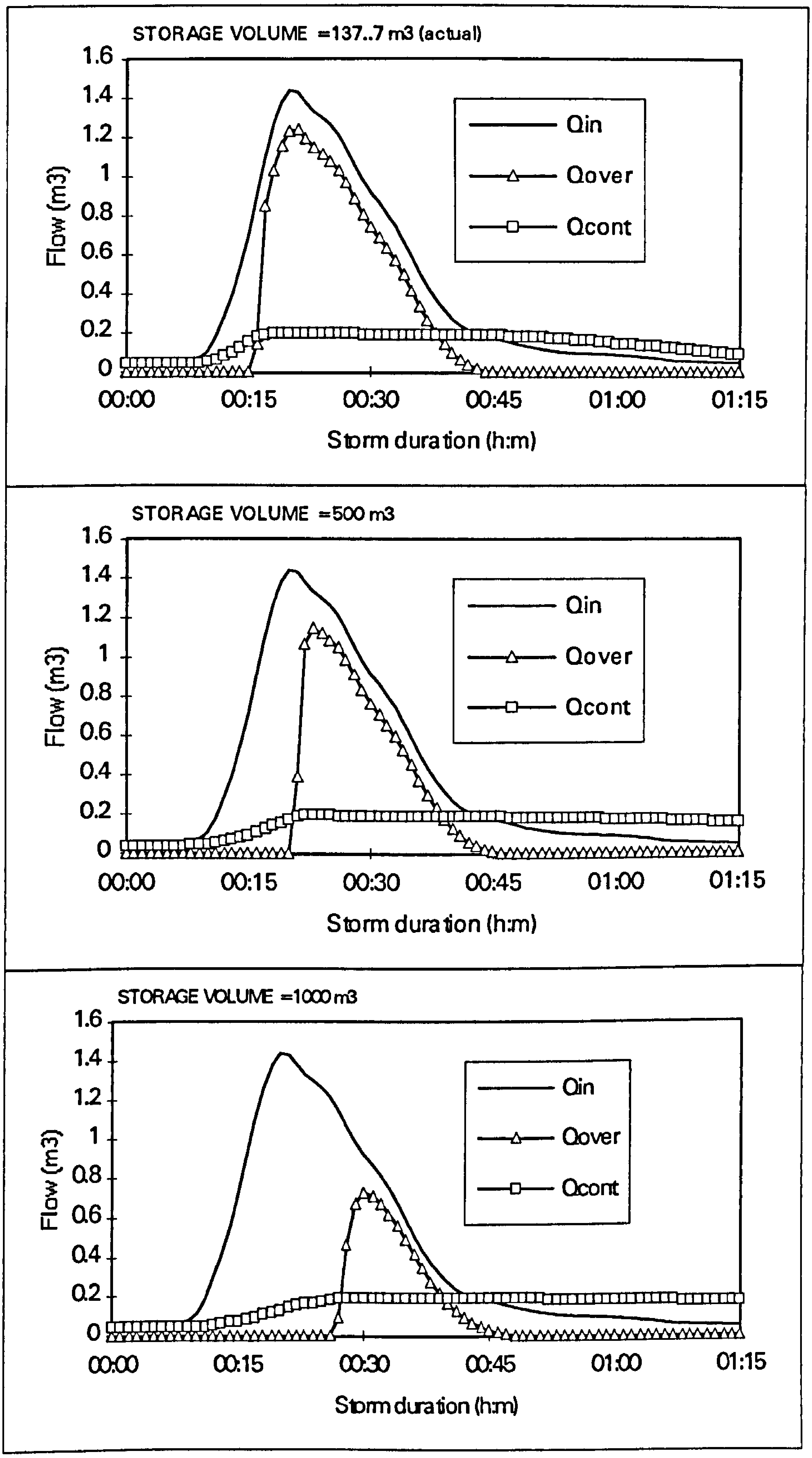


Figure 5.11. Effect of storage volume on spilled and throttle flow for TSR Event No. 5.

Table 5.6. TSR Event No. 5 total inflow volume 1806 m^3; total inflow load 1549 kg

S. No.	Storage volume in tank	Over flow vol.	Cont. vol.	Vol. retained	% flow retained	Over flow load	Cont. load	Load retained	% load retained
	(m^3)	(m^3)	(m^3)	(m^3)		(kg)	(kg)	(kg)	
1	1.7	1207	600	0	0.00	1138	405	6	0.00
2	137.7	1116	669	22	1.20	1004	406	139	11.14
3	200	1067	682	57	3.13	936	404	209	16.78
4	300	987	691	128	7.09	832	398	319	25.56
5	500	824	693	289	16.02	643	386	519	41.62
6	1000	408	680	719	39.80	262	361	926	74.23
7	1500	2	654	1151	63.71	1	336	1211	97.12
8	2000	0	585	1221	67.61	0	301	1247	100.00

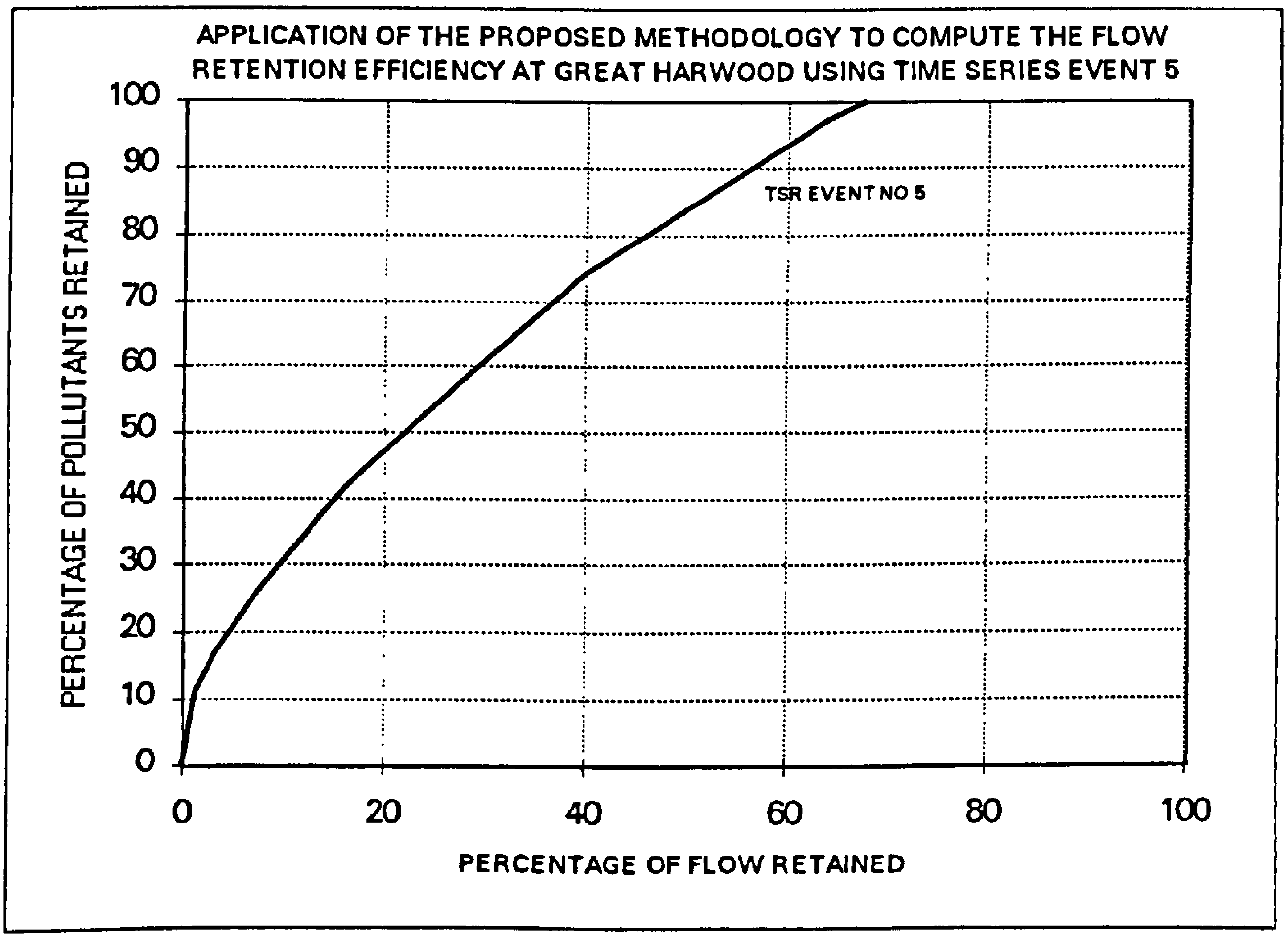


Figure 5.12. Proportion of pollution load retained for a particular proportion of flow volume.

5.7. Conclusions

The WALLRUS model was verified for the Great Harwood catchment and from a subsequent sensitivity analysis, it was observed that the peak flow rate in the system was most sensitive to a change in the value of the percentage of impervious area. It is recommended therefore that in any study the percentage impervious areas need to be assessed most accurately before applying the proposed methodology.

Subsequently, the verified WALLRUS model has been used to highlight the application of the pollutograph methodology and it has been shown that the pollutograph methodology can be quickly applied to a range of storm events to assess the pollutant load retention efficiency of tanks of different size. This work has been directed to a study associated with the effect of storage tank size (volume) on the retention of pollutants within the system corresponding to the design rainfall inputs. By using an annual Time Series Rainfall, it has been shown that the spilled load and frequency of spill may be quickly estimated, and this information may subsequently be used to assess the likely longer term impacts and effects on the receiving watercourse. Judgements may therefore be made to assess the short term acute pollution effects from individual storm events. It is stressed however that, at the moment, the methodology is site specific and further work is required so that the methodology may be applied to a larger range of catchment conditions.

Chapter 6

CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

6.1. Summary

The methodology developed in this study is based on the measured storms and pollutographs at two sites in the North West of England, UK, at Great Harwood and Clayton-le-Moors and all the data is contained in the WRc sewer quality archive (WRc, 1987). It is stressed however, that, at the present time, this analysis is site specific and requires a data base of the flow and TSS pollutant concentration for a small number of storm events. An effective working definition of the first flush has been established and this research work has resulted in the development of regressional equations to predict the load of suspended solids in the first flush of pollutants. The first flush was defined as the maximum divergence between the cumulative load of pollutants (expressed as a percentage of the total load) and the cumulative flows (expressed as a percentage of the total flow) plotted against the cumulative percentage of time. Regressional equations were also established to predict the peak concentration of suspended solids from a small set of parameters, namely, the storm profile peakedness and the antecedent dry weather period. This work formed the basis for the development of a simplified and rapid means for defining the shape of the pollutograph corresponding to an observed event or a time series rainfall event.

For practical applications, the suggested procedure provides a methodology to compute, for the specific catchment studied, the pollutograph corresponding to an observed or design storm event for which the antecedent dry weather period (ADWP) is known. This procedure is shown in Figure 6.1. Moreover, by quantifying the first flush phenomenon in combined sewer systems, the procedure developed allows for the effect of a change in the size of a stormwater detention tank in urban combined sewer systems to be examined. This technique is oriented towards designing a tank to retain a flow volume corresponding to a predetermined fraction of the pollutant load from a runoff event resulting from either a time series rainfall storm or an observed storm event. This procedure makes use of the methodology developed above to establish the shape of the pollutograph together with standard UK water industry software, for example, WALLRUS (now HYDROWORKS). The methodology developed in this study is therefore intended as an aid to planning and the preliminary screening of different options, but subsequently for critical and sensitive projects, it is recommended that the full UPM methodology should be applied.

6.2. Limitations of the Work

The major limitation of the work is that the derived equations are based on a limited data set and are catchment specific. Similarly, the methodology is only appropriate for storms with known ADWP, and for catchments and sewer systems where a first flush of pollutants is known to occur. Because of the data constraints, the predictions are valid only for the return periods 1 year or less which were associated with the storms used for the calibration. The methodology for positioning the occurrence of the peak TSS concentration is dependent on the occurrence of a first flush and requires a data base of the flow and TSS pollutant concentration for a small number of storm events. Ideally, a methodology for predicting the pollutograph shape which is not dependent on the first flush is desirable. However, as more data becomes available in time, the methodology may be applied to a wide range of catchments and eventually, it should be possible to obtain a set of standard pollutographs for differing catchment conditions.

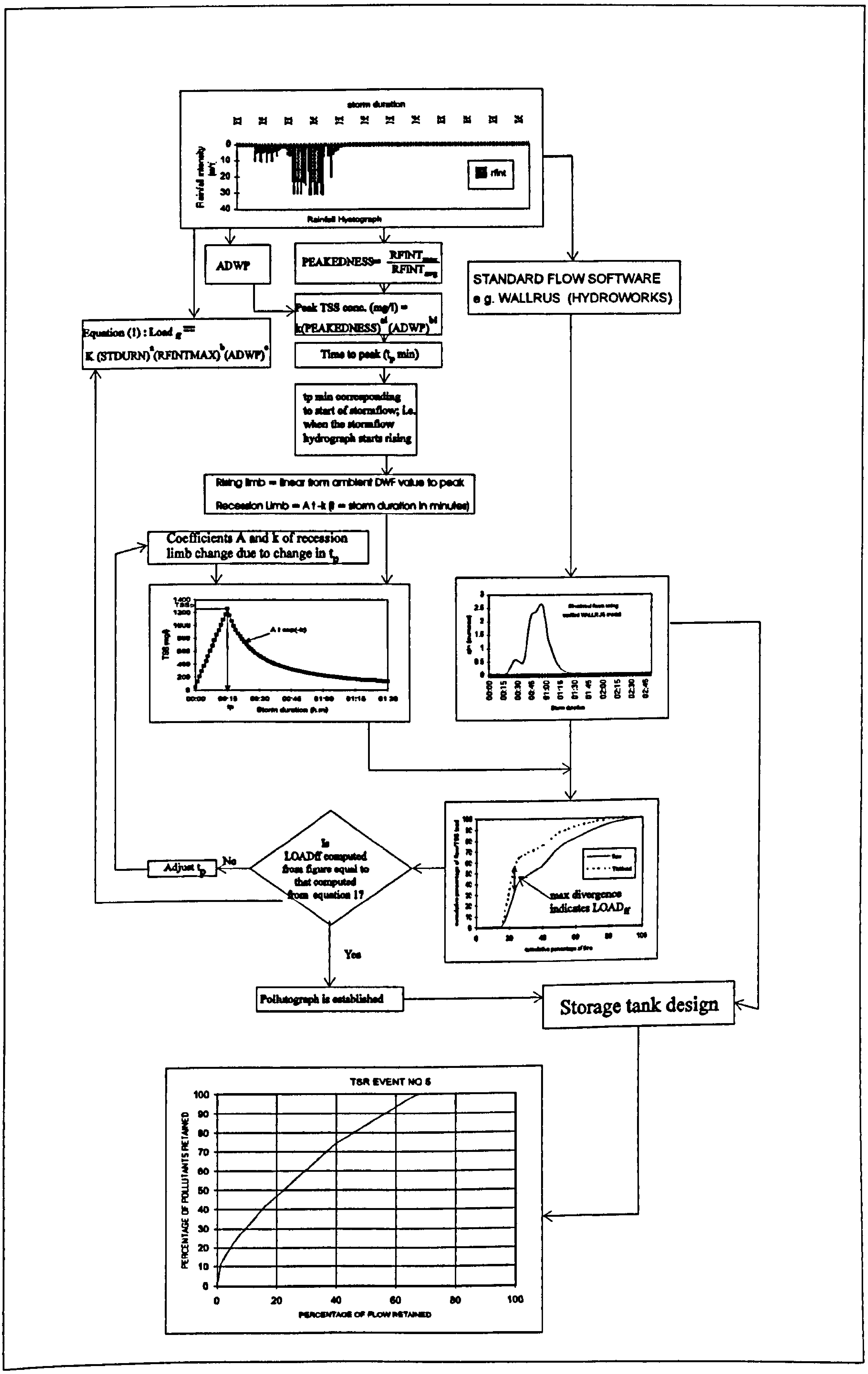


Figure 6.1 Flowchart showing the pollutograph methodology applied to sizing of a storage tank

6.3. Detailed Conclusions

The detailed conclusions of this study were as follows:

1. A suitable methodology to define the pollutant load in the first flush of a combined sewer flow has been suggested and has been defined as that part of the storm upto the maximum divergence between the dimensionless cumulative percentage of pollutants and the cumulative percentage of flows plotted against the cumulative percentage of time as detailed in Figure 6.2.

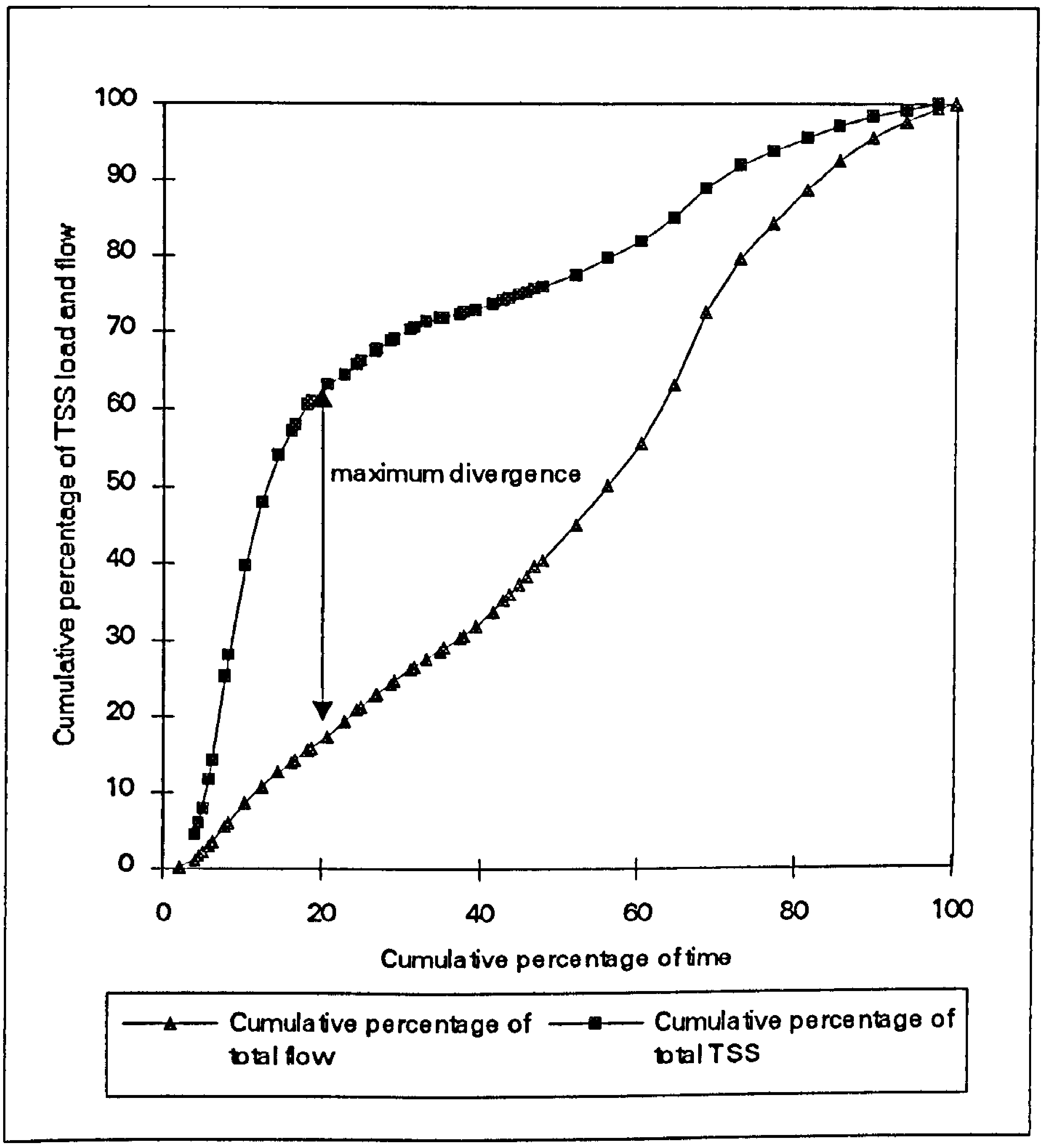


Figure 6.2. Definition of the foul flush as maximum divergence.

The advantages with this approach were identified, for instance, from a control standpoint, the dimensionless cumulative relation for a particular site allows the engineer to design the detention storage capacity necessary to capture a given percentage of pollution, for example, collection of 30% of the initial runoff volume may result in a 60-70% capture of suspended solids load.

2. Based on the above definition, linear and logarithmic transformed regression models were examined to estimate the first flush loads from one or more of the following independent variables:

$$LOAD_{ff} = f(EMCf_, \quad EMF, \quad RFINT_{avg}, \quad QIN_{max}, \quad RFINT_{max}, \quad STDURN, ADWP, FLOW_{tot}) \qquad (6.1)$$

where the variables and notation used are shown in Table 6.1.

Table 6.1. Variables computed from the SQA data for further regression analysis

(1)	(2)	(3)
Type of parameter	Variables	Notation
Event mean	Flow weighted event mean concentration (mg/l)	EMC_f
	Event mean flow (m^3/s)	EMF
	Event mean concentration in the first flush (mg/l)	EMC_{ff}
	Average rainfall intensity(mm/hr)	$RFINT_{avr}$
Event maximum	Maximum inflow (m^3/s)	QIN_{max}
	Maximum rainfall intensity (mm/hr)	$RFINT_{max}$
Event total	Storm duration (min)	STDURN
	Antecedent dry weather period (hr)	ADWP
	Total load of suspended solids(kg)	$LOAD_{tot}$
	Total inflow (m^3/s)	$FLOW_{tot}$
	Total rainfall depth (mm)	$RAIN_{tot}$
	Cumulative load of suspended solids in the first foul flush (kg)	$LOAD_{ff}$

The various models that were examined are given in Table 6.2 and the results are summarised as follows:

Table 6.2. Regression models

S.No.	Model
1.	$EMC_f = a\ EMF + b$
2.	$\log EMC_f = a \log EMF + b$
3.	$EMC_f = a\ EMF + b\ ADWP + c$
4.	$\log EMC_f = a \log EMF + b \log ADWP + c$
5.	$EMC_f = a\ ADWP + b$
6.	$\log EMC_f = a \log ADWP + b$
7.	$EMC_{ff} = a\ RFINT_{max} + b$
8.	$\log EMC_{ff} = a \log RFINT_{max} + b$
9.	$EMC_{ff} = a\ RFINT_{avr} + b$
10.	$\log EMC_{ff} = a \log RFINT_{avr} + b$
11.	$EMC_{ff} = a\ QIN_{max} + b$
12.	$\log EMC_{ff} = a \log QIN_{max} + b$
13.	$EMC_{ff} = a\ EMF_{ff} + b$
14.	$\log EMC_{ff} = a \log EMF_{ff} + b$
15.	$EMC_{ff} = a\ DURN_{ff} + b$
16.	$\log EMC_{ff} = a \log DURN_{ff} + b$
17.	$EMC_{ff} = a\ STDURN + b$
18.	$\log EMC_{ff} = a \log STDURN + b$
19.	$EMC_{ff} = a\ RFINT_{max} + b\ STDURN + c$
20.	$\log EMC_f = a \log RFINT_{max} + b \log STDURN + c$
21.	$LOAD_{tot} = a\ (FLOW_{tot}) + b$
22.	$\log LOAD_{tot} = a \log (FLOW_{tot}) + b$
23.	$LOAD_{ff} = a\ (QIN_{max}) + b\ (ADWP) + c$
24	$\log LOAD_{ff} = a \log (QIN_{max}) + b \log(ADWP) + c$
25	$LOAD_{ff} = a\ (RFINT_{max}) + b\ (ADWP) + c$
26	$\log LOAD_{ff} = a \log (RFINT_{max}) + b \log(ADWP) + c$
27	$LOAD_{ff} = a\ (QIN_{max}) + b\ (STDURN) + c$
28	$\log LOAD_{ff} = a \log (QIN_{max}) + b \log(STDURN) + c$
29	$LOAD_{ff} = a\ (RFINT_{max}) + b\ (STDURN) + c$
30	$\log LOAD_{ff} = a \log (RFINT_{max}) + b \log(STDURN) + c$
31	$LOAD_{ff} = a\ (QIN_{max}) + b\ (STDURN) + c\ ADWP + d$
32	$\log LOAD_{ff} = a \log (QIN_{max}) + b \log(STDURN) + c \log (ADWP) + d$
33	$LOAD_{ff} = a\ (RFINT_{max}) + b\ (STDURN) + c\ ADWP + d$
34	$\log LOAD_{ff} = a \log (RFINT_{max}) + b \log(STDURN) + c \log (ADWP) + d$

3. It was shown from the storms at Great Harwood that there were significant differences between the data for summer and winter storms.

4. The relationship between the cumulative TSS upto the foul flush ($LOAD_{ff}$) (kg), the maximum rainfall intensity ($RFINT_{max}$) (mm/hr), the maximum inflow (QIN_{max}) (m^3/s), the ADWP (hr) and the storm duration (STDURN)

(min) showed a strong correlation and the following predictive equations were concluded:

ALL STORMS:

$$LOAD_{ff} = 1.58\,(STDURN)^{0.61}\,(RFINT_{max})^{0.71}\,(ADWP)^{0.23} \qquad (R^2 = 0.59) \qquad (6.2)$$

$$LOAD_{ff} = 16.98\,(STDURN)^{0.94}\,(QIN_{max})^{0.63}(ADWP)^{0.21} \qquad (R^2 = 0.59). \qquad (6.3)$$

SUMMER STORMS:

$$LOAD_{ff} = 1.35\,(STDURN)^{0.68}\,(RFINT_{max})^{0.68}\,(ADWP)^{0.28} \qquad (R^2 = 0.65) \qquad (6.4)$$

$$LOAD_{ff} = 33.88\,(STDURN)^{0.92}\,(QIN_{max})^{0.47}\,(ADWP)^{0.21} \qquad (R^2 = 0.54) \qquad (6.5)$$

WINTER STORMS:

$$LOAD_{ff} = 3.72\,(STDURN)^{0.94}\,(QIN_{max})^{0.93}\,(ADWP)^{0.21} \qquad (R^2 = 0.71) \qquad (6.6)$$

$$LOAD_{ff} = 3.72\,(STDURN)^{0.92}\,(RFINT_{max})^{0.36}\,(ADWP)^{0.20} \qquad (R^2 = 0.54) \qquad (6.7)$$

5. That the ADWP was found to have a strong influence on the total load of pollutants in the first flush was concluded by repeating the regression analysis but without taking ADWP into consideration resulted in a noticeable reduction in the R^2 values ranging from 0.29 to 0.45 confirming the importance of ADWP at Great Harwood.

It was concluded therefore, that equations of the form (6.2) and (6.3) were the most appropriate to predict the pollutant load in the first flush at Great Harwood. However, from a practical viewpoint, equation (6.2) is more appropriate because it requires a knowledge of only the rainfall characteristics, whereas, the application of equation (6.3) would require a detailed flow survey to estimate the flows.

6. The analysis was repeated for the Clayton-le-Moors site and the following equations were obtained:

SUMMER STORMS:

$$LOAD_{ff} = 0.92\,(STDURN)^{0.73}\,(RFINT_{max})^{0.93}\,(ADWP)^{0.14} \qquad (R^2 = 0.71) \qquad (6.7)$$

$$LOAD_{ff} = 103.43\,(STDURN)^{0.68}\,(QIN_{max})^{1.74}\,(ADWP)^{0.12} \qquad (R^2 = 0.85) \qquad (6.8)$$

Various other relationships, which might reasonably have been expected to reveal correlations were also examined, but no statistically significant relationships could be obtained and these are summarised in points 7-10.

7. No statistically significant relationship was found between the flow weighted event mean concentration and the event mean flow. Also, no relation was found between the mean total load of suspended solids, total inflow, flow weighted event mean concentration (EMC_f) and the event mean flow (EMF).

8. No correlation was found between the first flush event mean concentration (EMC_f), event mean flow (EMF) and the ADWP.

9. The event mean concentration of the load of suspended solids in the first flush (EMC_{ff}) was related to the input variables of maximum rainfall intensity ($RFINT_{max}$), average rainfall intensity ($RFINT_{avr}$), maximum inflow (QIN_{max}), event mean flow upto first flush (EMF_{ff}), duration upto the foul flush ($DURN_{ff}$), and the total storm duration (STDURN) but again no correlation was observed between the variables.

10. Similarly, the relationship between the cumulative load of suspended solids in the first flush ($LOAD_{ff}$) and the input parameters QIN_{max}, EMF and ADWP, was examined. The results confirmed that there was little correlation between these parameters.

11. The usefulness of the regression models was assessed by comparing the results from the model with observed first flush loads for several independent storms not used in the model calibration. Reasonable agreement was observed but differences of upto 20 % were observed.

It was concluded therefore, that within the limitations of the regressional approach adopted, the pollutant load in the first flush may be predicted with reasonable confidence using the derived relationships between the total storm duration, the peak inflow of the storm and the ADWP. Hence, the derived equations, which at this stage are site specific, may be used to establish a quick estimate of the pollutant load in the first flush of a combined sewer flow for a given storm duration, peak rainfall intensity or flowrate and the antecedent dry weather period.

The above methodology may be considered adequate for predicting the total load of pollutants in the first flush, which may be considered adequate for accumulative effects. However, for control options, detailed pollutographs to describe the temporal variation in the concentration of pollutants are required and this formed the subject of the subsequent study.

12. Attempts were made to relate the peak pollutant concentration of suspended solids in combined sewer flows to the various storm characteristics, for example, the maximum rainfall intensity, the average rainfall intensity, the storm duration, the total rainfall depth and the antecedent dry weather period. It was shown that the peak TSS concentration was a function of two storm characteristics, namely the storm profile peakedness (defined as the ratio of the maximum rainfall intensity to the average rainfall intensity), and the antecedent dry weather period (ADWP). Based on a detailed regression analysis, a relationship of the following form was established to predict the peak TSS concentration for the two catchments considered in this study:

Great Harwood $TSS_p = 123\ (\text{PEAKEDNESS})^{0.64}\ (\text{ADWP})^{0.17}\quad (R^2=0.77)\quad (6.9)$

Clayton-le-Moors $TSS_p = 148\ (\text{PEAKEDNESS})^{0.42}\ (\text{ADWP})^{0.18}\quad (R^2=0.91)\quad (6.10)$

However, analysis of the data showed that the time of the day, and the magnitude and concentration of the dry weather flow had little influence on the magnitude of the peak concentration.

13. To evaluate the time to peak TSS (t_p), use was made of the fact that the TSS load in the first flush had been established. The occurrence of the peak concentration was determined from a definition of the first flush, that is, to occur at a point in time defined by the maximum divergence between the cumulative load and cumulative flow plotted against cumulative time as shown in Figure 6.2. The TSS load in the first flush was derived from the known load and flow in the first flush of pollutants (equation 6.1). It was assumed as a first approximation, that t_p corresponded to the occurrence of TSS_p on the master recession curve. The position of the peak was adjusted so that the magnitude of the first flush load within the known cumulative flow was equal to that determined from an equation of the form (6.4). The

initial and final concentrations of the pollutograph were taken at ambient levels that are representative of the dry weather flow. From the initial concentration, the concentration was taken to increase linearly and rapidly to the peak concentration.

14. However, other alternatives to determine the time to the peak concentration of total suspended solids were also explored and was found not to be a function of the following variables:

    (i) time interval between the centre of gravity of the rainfall hyetograph and the peak TSS concentration,

    (ii) time interval between the start of rainfall and the peak TSS concentration,

    (iii) the time interval between the occurrence of the peak rainfall intensity and the peak TSS concentration, and

    (iv) the time of occurrence of a threshold flow or a threshold of rainfall depth.

15. To define the pollutograph profile, it was observed that the recession limbs of each pollutograph were very similar and that these could be represented by a power decay function of the form:

$$TSS(t) = A\,t^{-k} \;((t \geq t_p, \text{ where } t_p \text{ is time to peak TSS concentration}) \qquad (6.11)$$

The specific equations for the two catchments were as follows:

Great Harwood $TSS(t) = 4.5\,t^{-1.2}$ $(R^2=0.97)$ (6.12)

Clayton-le-Moors $TSS(t) = 11.2\,t^{-1.1}$ $(R^2=0.96)$ (6.13)

It was observed that the shape of the recession limb of the pollutographs recorded in the two catchments were similar and the storm profile did not influence the shape of the recession limb of the pollutograph.

16. In catchments which exhibited a first flush, it has been therefore concluded that the design pollutograph could be obtained as a linear rise from the DWF

value of the TSS at the time of start of storm to the peak followed by the recession limb of the pollutograph.

17. Based on the results of the aforementioned analysis, a methodology is proposed to obtain the pollutograph profile from an observed rainfall hyetograph or for a number of events in the form of time series rainfall. The steps in the methodology are shown in Figure 6.1 and described in Section 6.4. The model validation showed good agreement between the observed and predicted pollutographs for 70% of the storm events.
18. It is shown that application of the above methodology to determine the pollutograph profile in conjunction with a flow modelling software, for example, WALLRUS (now HYDROWORKS), can be used to determine the cumulative percentage of flows and loads in individual storms or for a time series of rainfall events. This may be computed for a range of storage options and hence it is possible to establish the required storage volume to retain a specific fraction of the pollutant load.
19. The work has shown that with respect to the design of storage tanks, substantially smaller chambers may be required for water quality protection in urban areas than would be the case if they were designed based strictly on the retention of a volume of runoff. For example, it has been shown that a retention of 30% of storm runoff may result in a retention of 70% of storm pollutant load.

6.4. Methodology

The proposed methodology shown in Figure 6.1 requires data from a few monitored storms and the steps are as follows:

1. From the rainfall hyetograph, compute the storm profile peakedness as the ratio of the maximum rainfall intensity to the mean rainfall intensity.
2. Compute the peak TSS concentration from an equation of the form:

$$TSS_p = K\,(PEAKEDNESS)^{a}\,(ADWP)^{b} \qquad (6.14)$$

3. Obtain the coefficients of the equation ($TSS(t) = At^{-k}$) and compute the shape of the recession limb of the pollutograph from a field survey. Alternately the values derived from the two catchments outlined in this study can be used as a guide for application to similar catchments.

4. The occurrence of the time of peak concentration (t_p) is determined from a definition of the first flush, that is, to occur at a point in time defined by the maximum divergence between the cumulative load and cumulative flow plotted against cumulative time as shown in Figure 6.2. The TSS load in the first flush is derived from the known load and flow in the first flush of pollutants (equation 6.1). It is assumed as a first approximation, that t_p corresponds to the occurrence of TSS_p on the master recession curve. The position of the peak is adjusted so that the magnitude of the first flush load within the known cumulative flow is equal to that determined from equation (6.14). The initial and final concentrations of the pollutograph may be taken at ambient levels that are representative of the dry weather flow. From the initial concentration, the concentration is taken to increase linearly and rapidly to the peak concentration.

5. The design pollutograph can then be obtained as a linear rise from the DWF value of the TSS at the time of start of storm to the peak TSS concentration followed by the recession limb of the pollutograph.

6. Subsequently, the flow may be obtained from a WALLRUS/HYDROWORKS simulation.

7. The cumulative percentage of flows and loads may then be computed and the required volume to retain a specific fraction of the pollutant load may be determined.

6.5. Suggestions for Further Work

The results presented in this thesis reveal the need for further research in several areas:

1. The methodology presented in this thesis is based on the observed pollutographs for two catchments. Therefore, the techniques presented herein need to be further assessed through application to additional data sets from other sites, so that the methodology may be made more general.

2. The methodology for positioning the occurrence of the peak TSS concentration is dependent on the occurrence of a first flush and requires a data base of the flow and TSS pollutant concentration for a small number of storm events. Ideally, a methodology for predicting the pollutograph shape which is not dependent on the occurrence of a first flush is desirable. It is therefore recommended that further research effort may be directed to examine this aspect of the methodology.

3. Moreover, it is suggested that some sort of catchment classification, for example, in terms of their size, slope and contributing catchment areas may be useful in developing a more general model. There is evidence that the nature and propensity for sediment deposition may be related to this classification (Ashley *et al.*, 1992a, 1992b). The relationships proposed in this thesis do not take into account such a classification. Hence it is proposed that a detailed investigation based on the above criteria and further classification of these elements based on the average gradient of the sewer system to attempt to relate the pollutograph to the catchment characteristics, for example, high, medium and low gradients may yield further insights into the phenomenon and may facilitate the application of the methodology developed in this thesis to a wider range of catchments.

4. A related aspect that would also need to be examined would involve taking account of the characteristics of the catchment surface, perhaps in the form of the percentage runoff equation to refine the technique and to allow its general application to catchments and sewer systems defined by their characteristics.

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with a wire wound potentiometer) fastened to the roof of the chamber. Analogue data from both level measurement devices, recorded either continuously or on a storm event basis, and periodical digital data from the raingauges were recorded continuously using a data logger (Type 2 Golden River Dataman logger). Recorded data was retrieved from the Dataman on site by a Golden River retriever with a facility to display or store the data.

At times of storm, the throughflow through the throttle is a function of the area of the penstock opening and the head above the centreline of the control penstock. Also, the weir flow iss governed by the head discharge relationship for the particular geometry of the weir, and was calculated using an iterative routine to solve the full equations representing flow over side weirs. The throughflow and weir flow equations are dependent upon coefficients which are selected by the engineer.

At the field site at Great Harwood, these coefficients were derived using a flow survey package which recorded depth and velocity in both the inflow and throughflow pipes for a selected number of storm events. Subsequently, the relationship between the water level in the chamber and these flowrates was established as a functional relationship between inflow, overflow, throughflow and the rate of change of water surface level within the chamber governed by an equation of the form

$$Q_{in} = Q_{through} + Q_{weir} + dV/dt$$

where

Q_{in} = inflow

$Q_{through}$ = throughflow to treatment

Q_{weir} = overflow

dV = volume retained by the system in time interval dt (positive on rising limb of the hydrograph and negative on the recession limb).

The computed flow was compared and verified using the results obtained by a WRc flow survey package.

Plate A.1 A typical view of the paved surface at the Great Harwood catchment

Plate A.2. A bird's eye view of the Clayton-le-Moors catchment

APPENDIX B

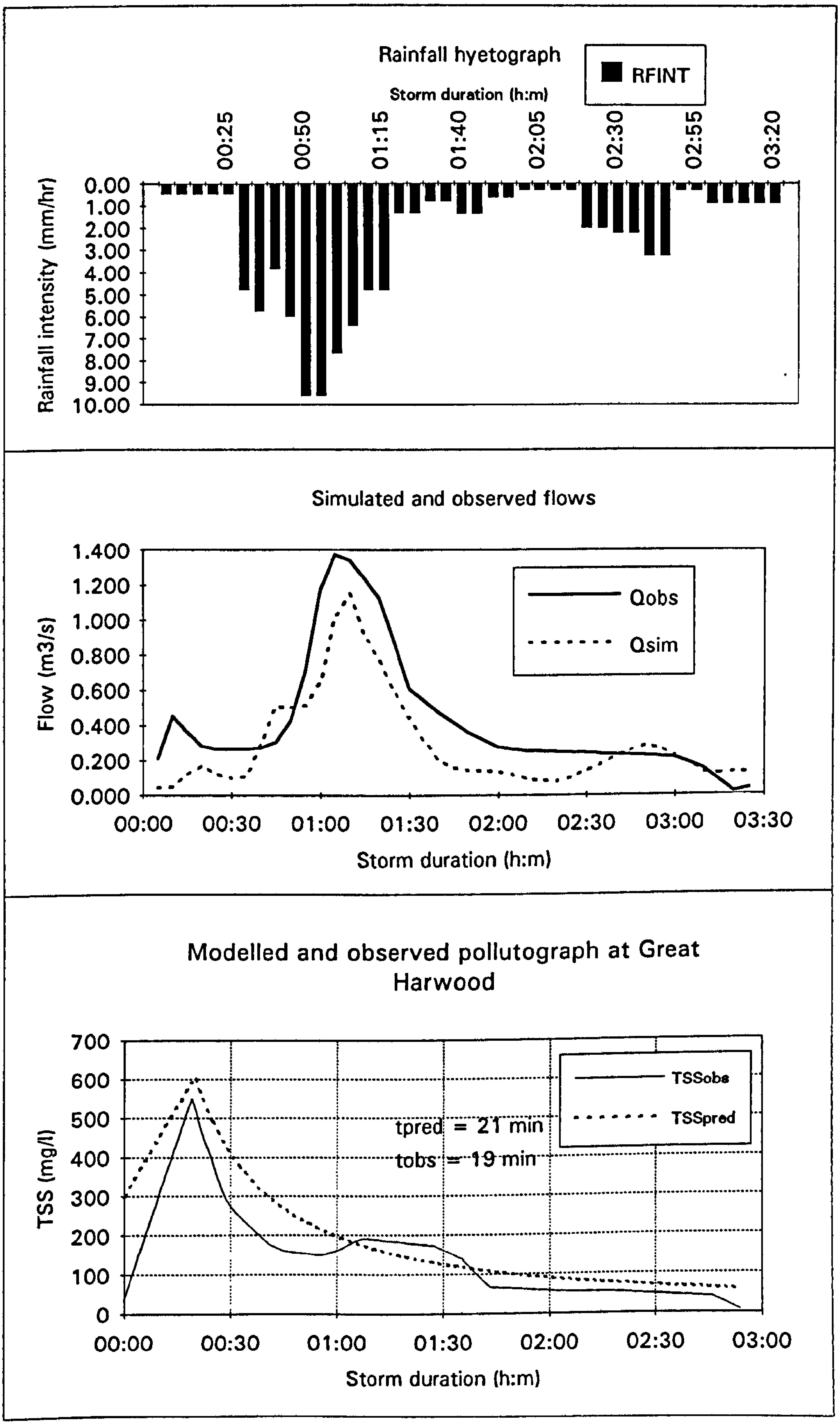


Figure B.1. Storm event 840803A at Great Harwood

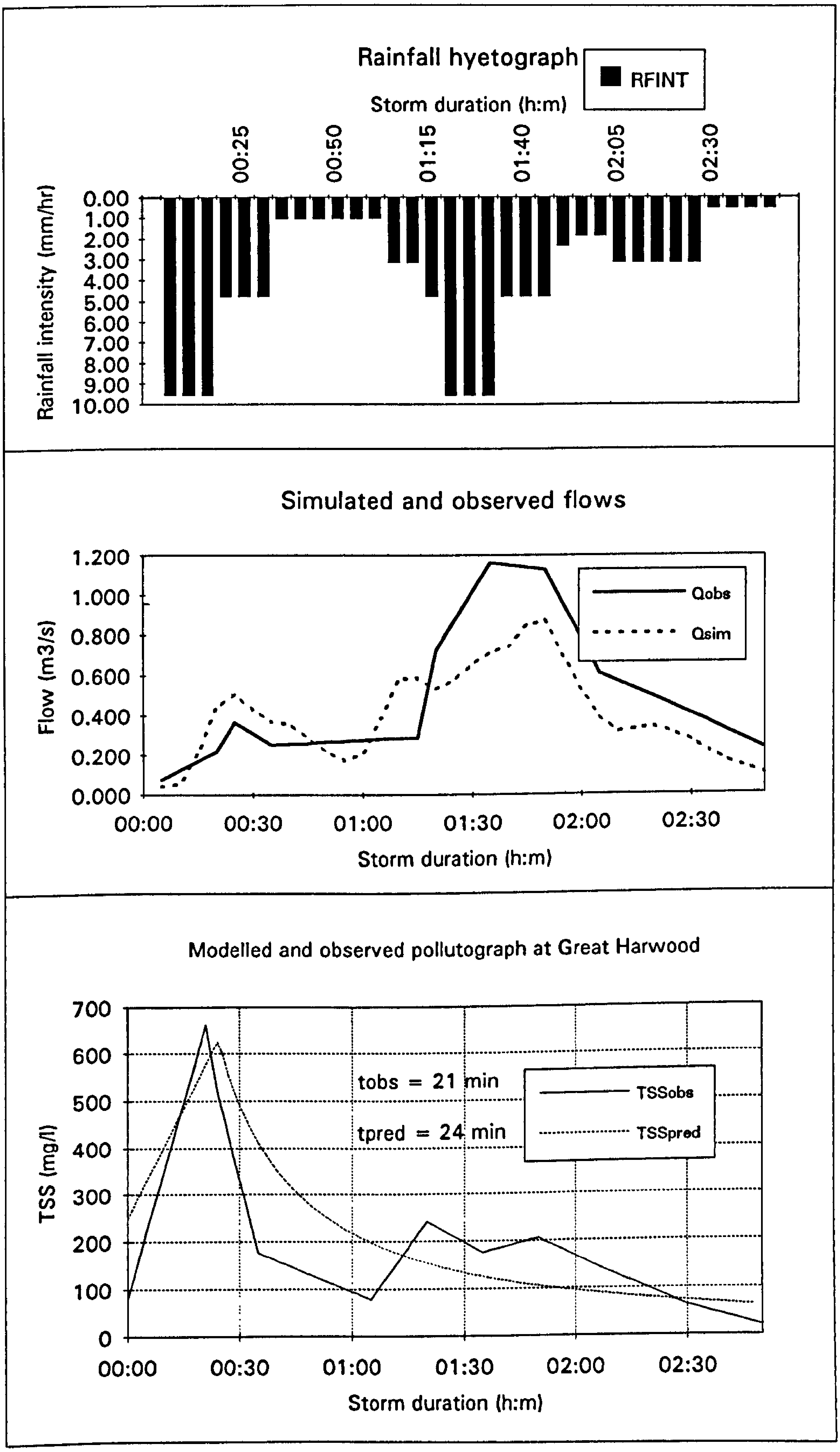
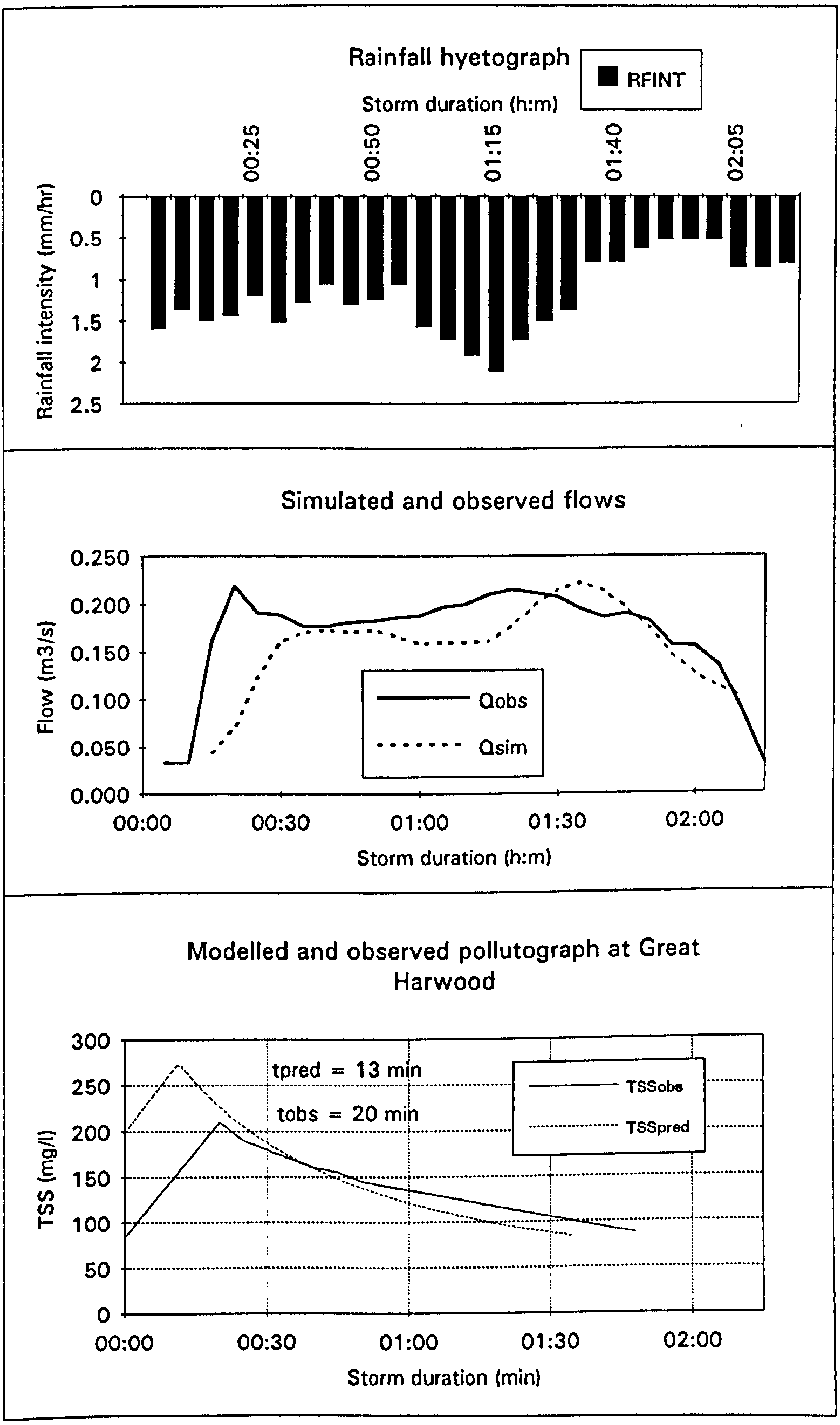


Figure B.2. Storm event 860804 at Great Harwood


Rainfall hyetograph

Simulated and observed flows

Modelled and observed pollutograph at Great Harwood

Figure B.3. Storm event 850902 at Great Harwood

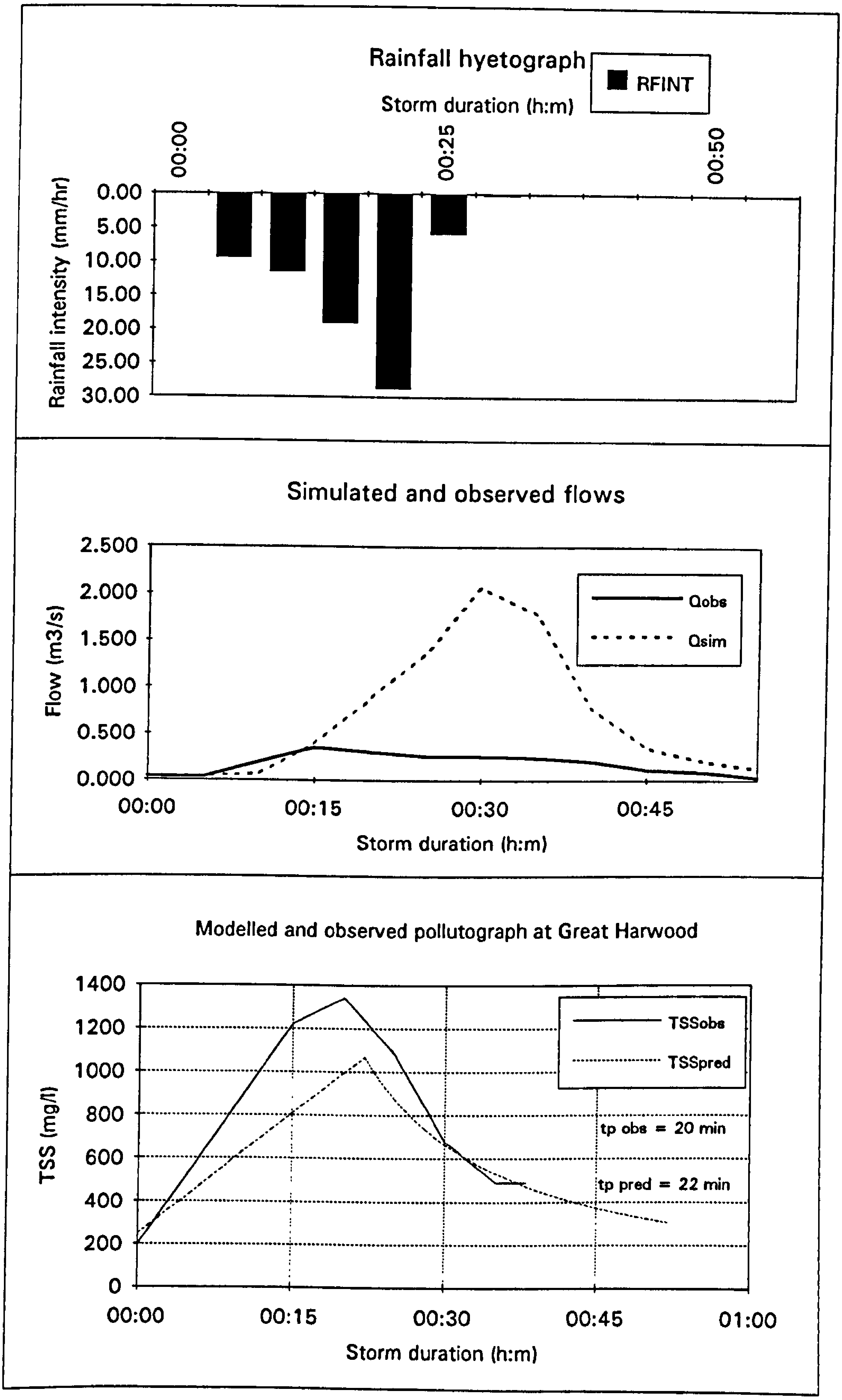


Figure B.4. Storm event 840524a at Great Harwood

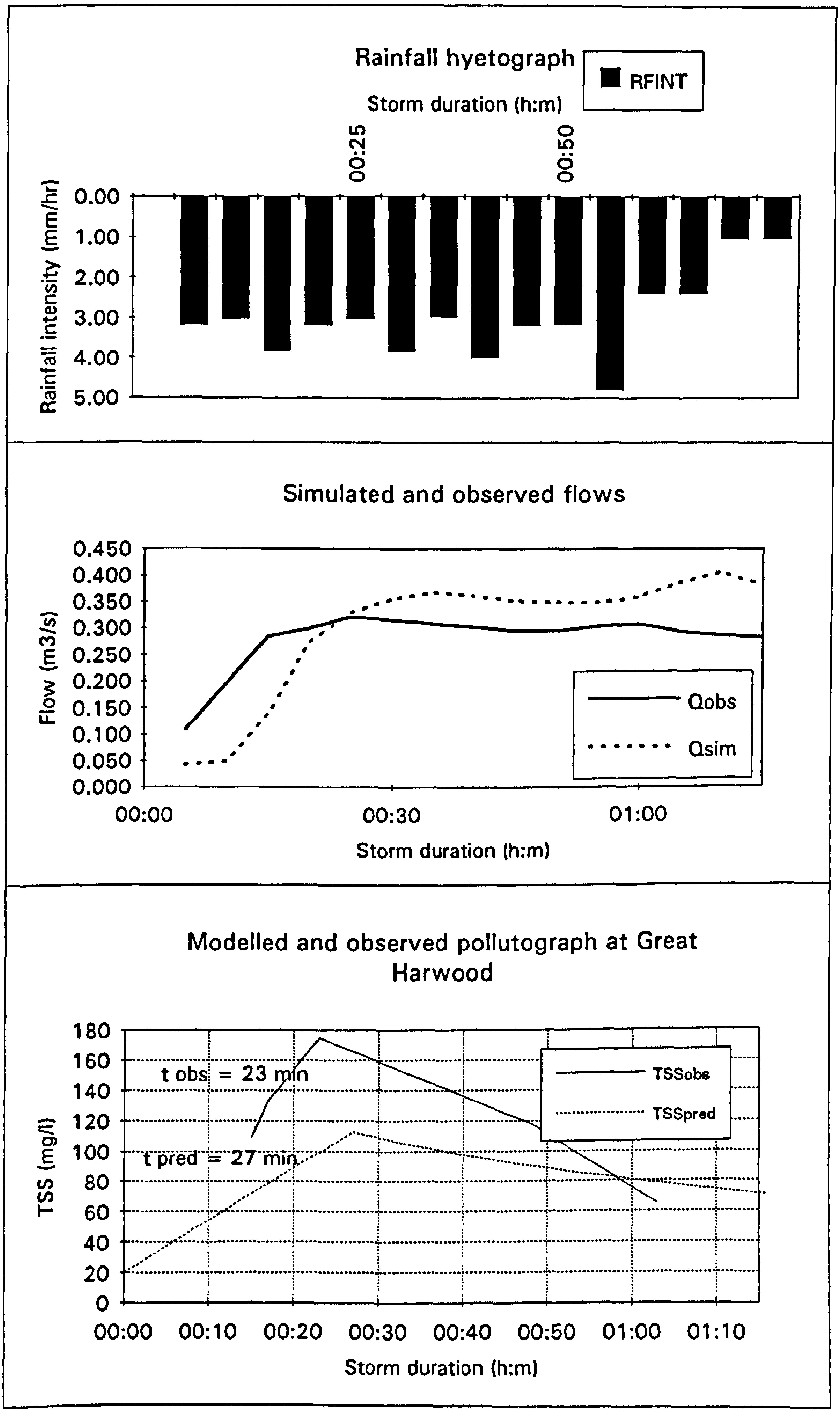
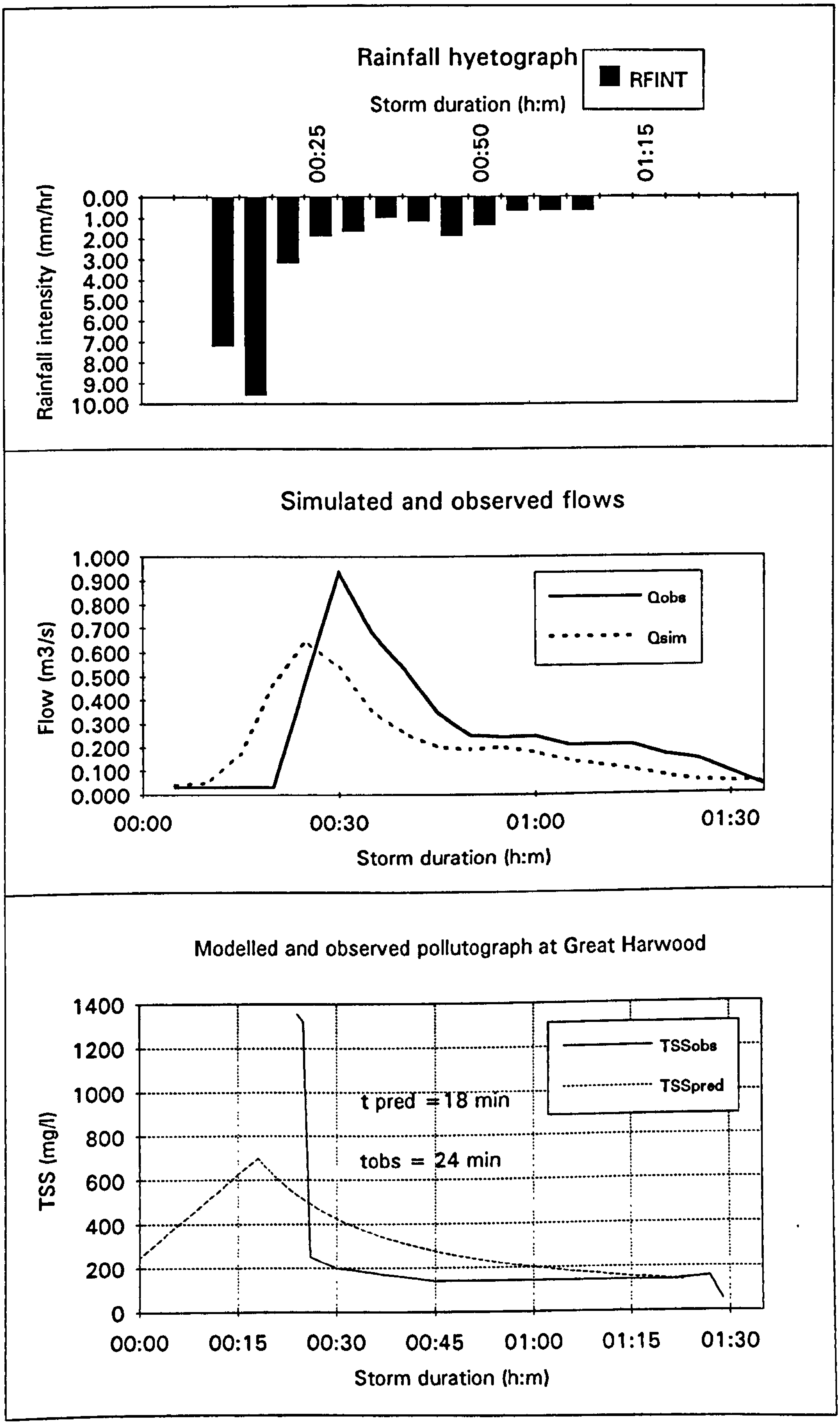


Figure B.5. Storm event 860511a at Great Harwood



Rainfall hyetograph

Simulated and observed flows

Modelled and observed pollutograph at Great Harwood

t pred = 18 min

tobs = 24 min

Figure B.6. Storm event 850717 at Great Harwood

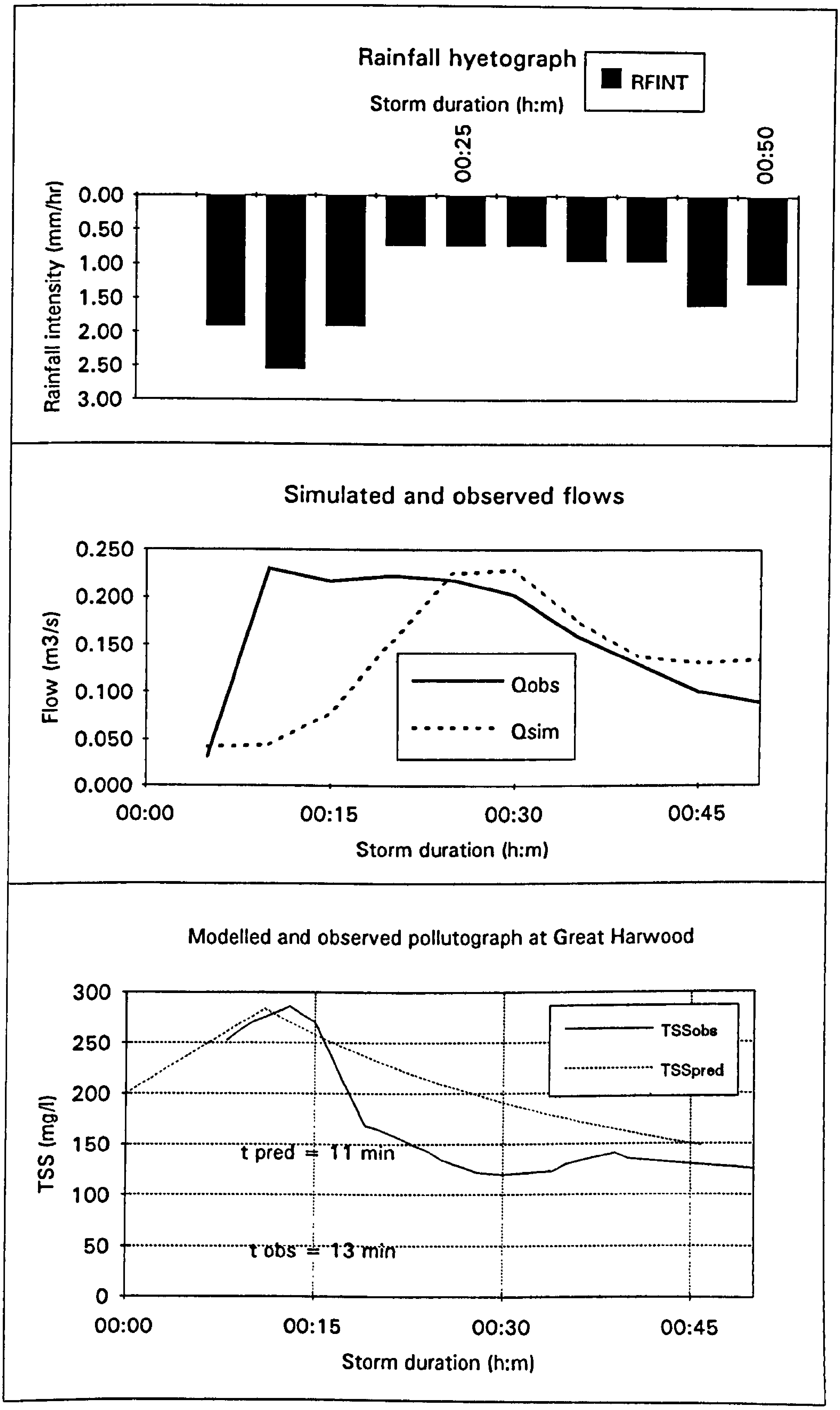


Figure B.7. Storm event 841029 at Great Harwood

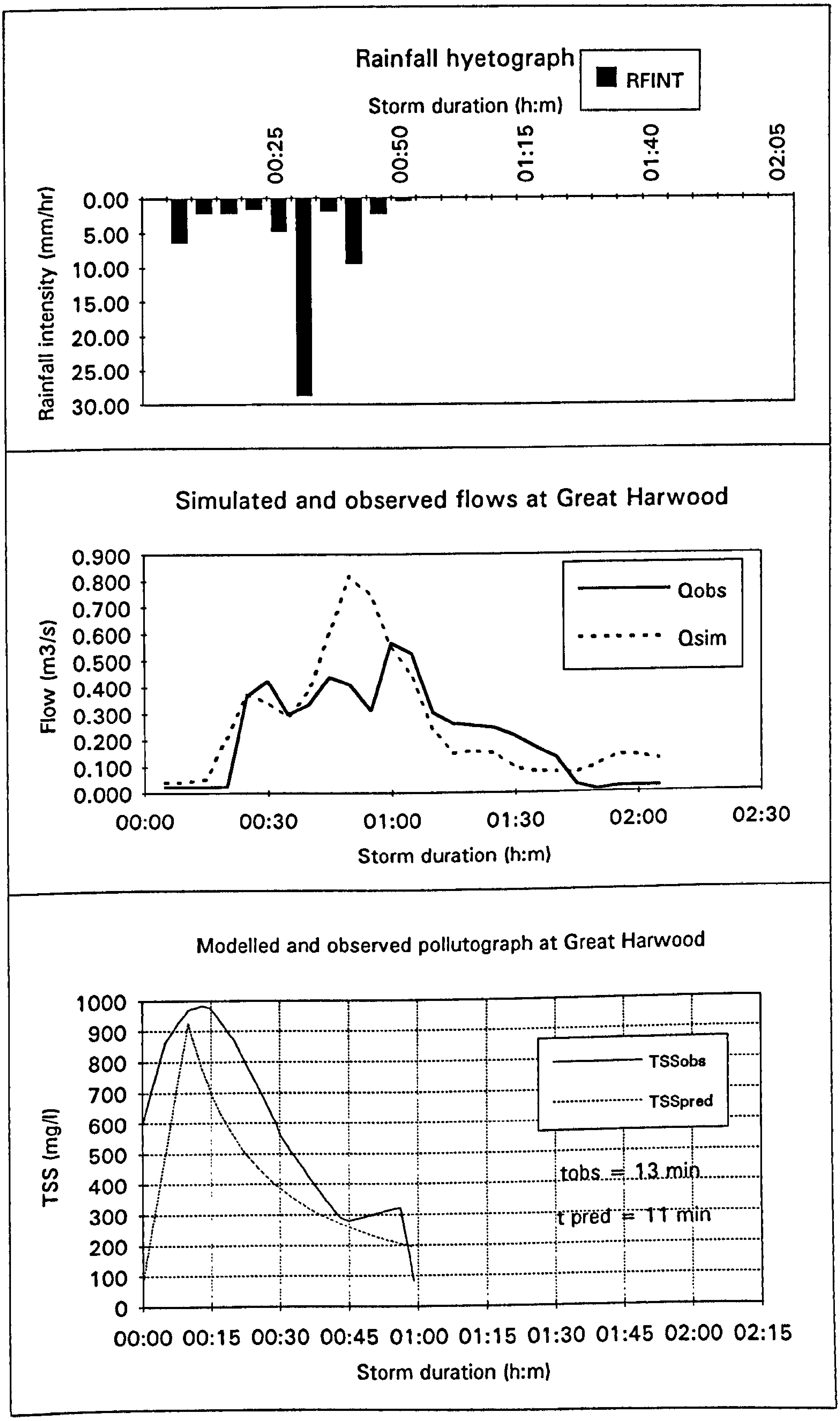


Figure B.8. Storm event 850713 at Great Harwood

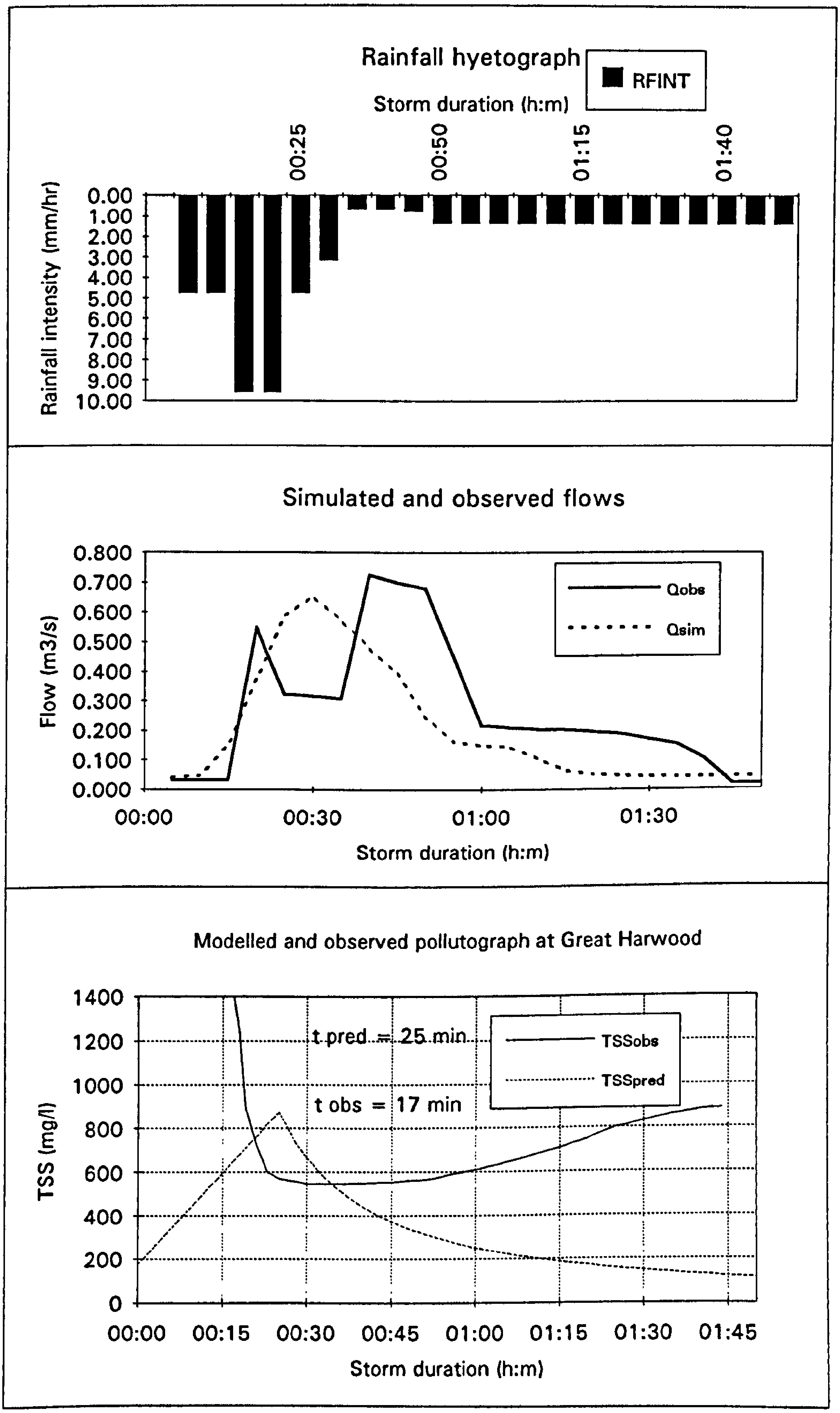


Figure B.9. Storm event 850607 at Great Harwood

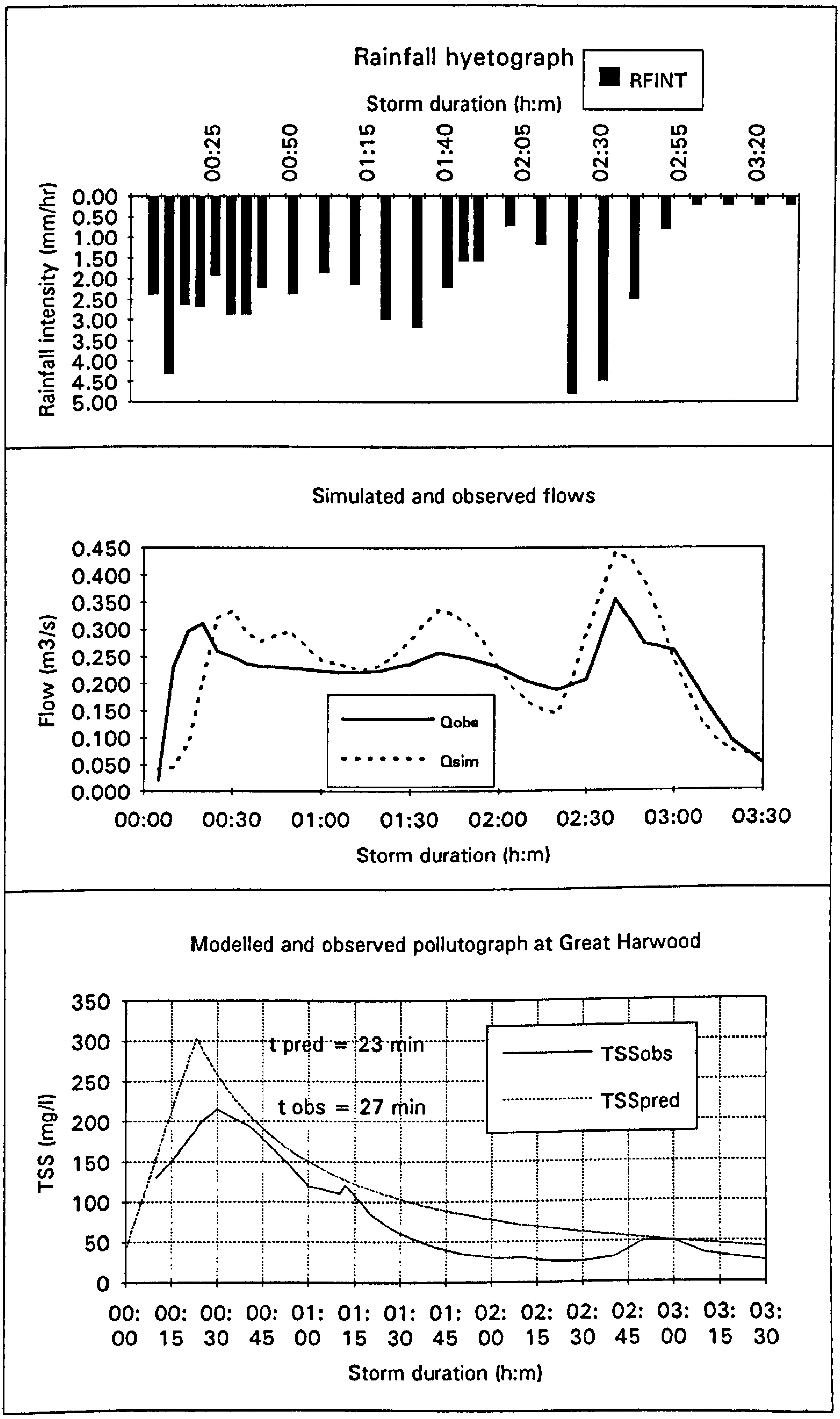


Figure B.10. Storm event 841018a at Great Harwood

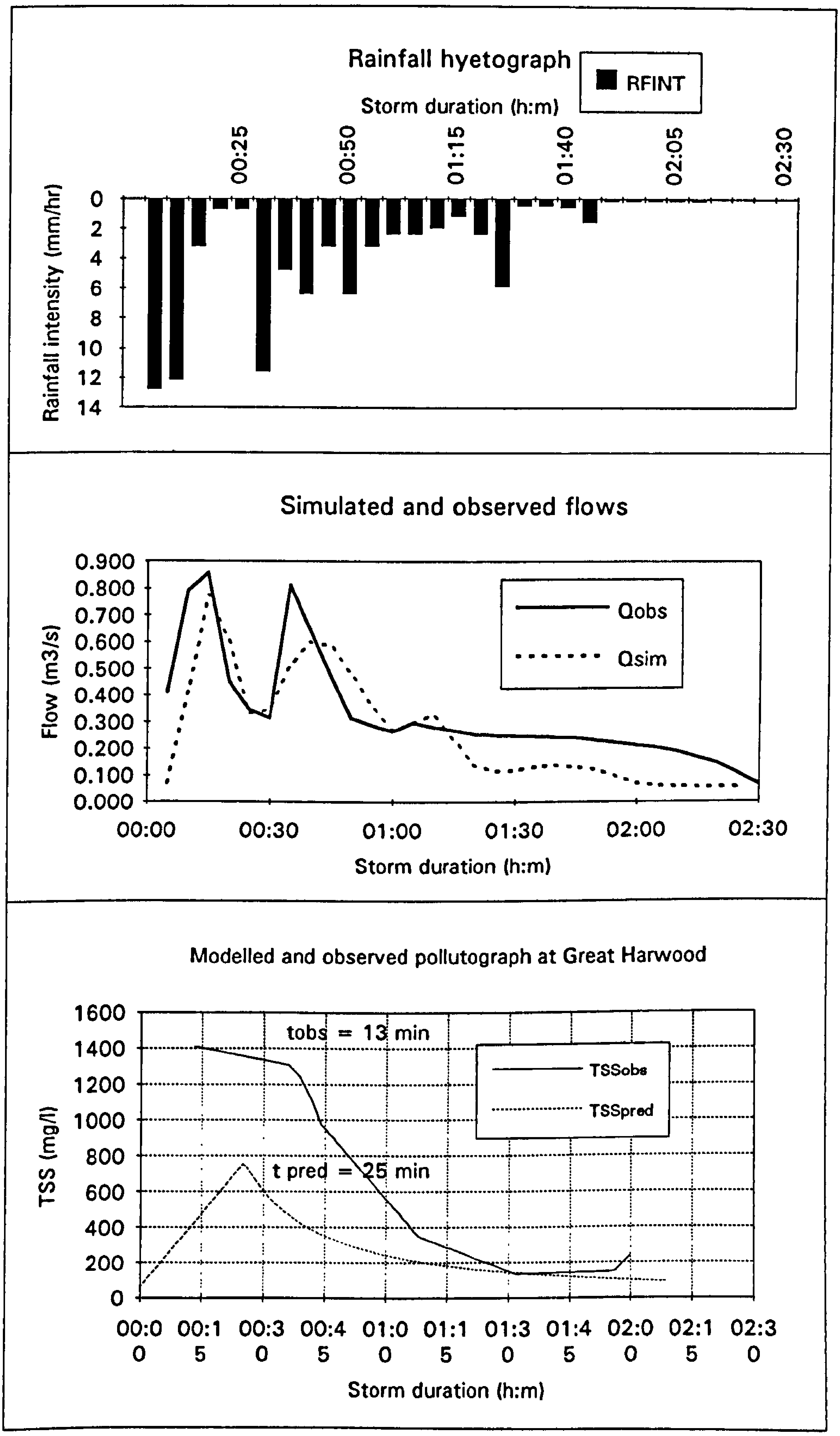
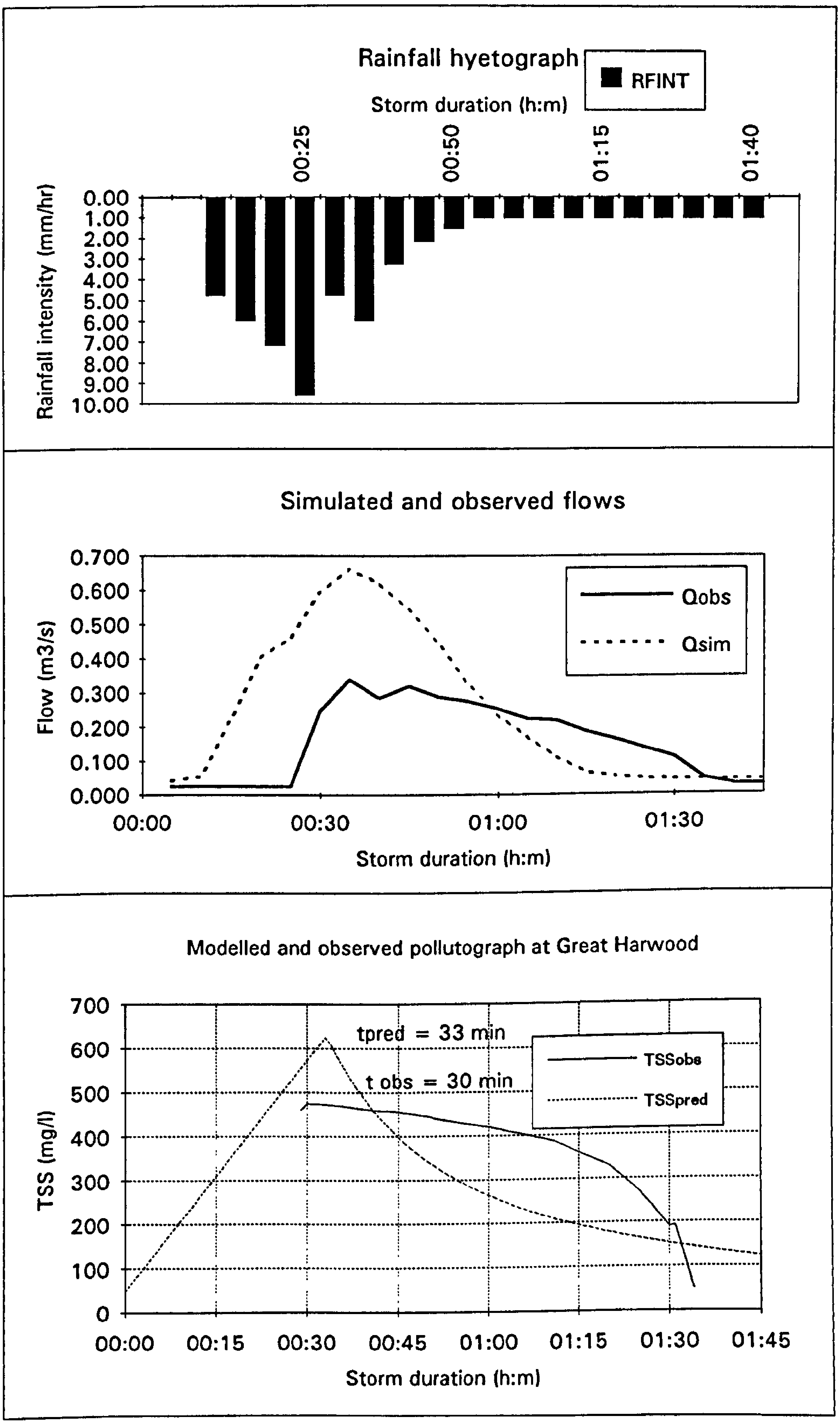


Figure B.11. Storm event 860520a at Great Harwood



Rainfall hyetograph

Simulated and observed flows

Modelled and observed pollutograph at Great Harwood

Figure B.12. Storm event 850828 at Great Harwood

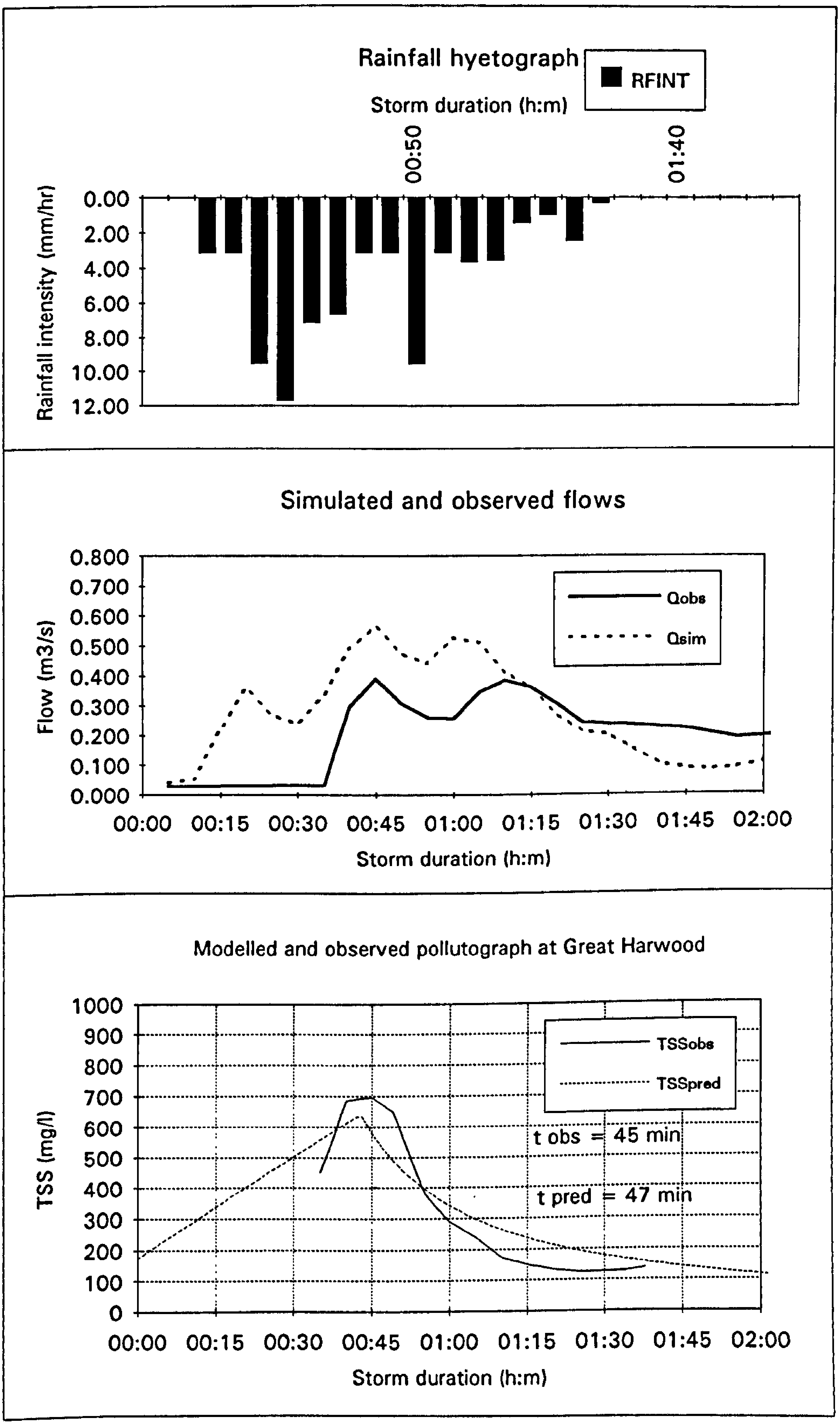


Figure B.13 Storm event 850820 at Great Harwood

APPENDIX C

RAINFALL EVENT DATA

The WALLRUS program requires data defining the rainfall for which the system is to be designed or analysed. For the simulation method, a rainfall hyetograph was input at a uniform time step throughout the event.

The parameters (WALLRUS User Manual, 3/e, 1990) for the rainfall event data file are described.

1st Line of the data file (Record 20 - Title for the rainfall event):

Item No.	Description of Input
1.	Flag indicating the file content blank or 0 => rainfall hyetograph
2.	Descriptive Title

2nd line of the data file (Record 21 - global parameters):

Item No.	Description of Input	Example
1.	Event Reference Number	1
2.	Not used	-
3.	Rainfall time step (s)	300
4.	Number of profiles	1
5.	Not used	-
6.	Urban Catchment Wetness Index(UCWI) for the UK urban runoff model	120

3rd line of the data file (Record 22 - profile parameters):

Item No.	Description of Input	Example
1.	Local value of the urban catchment wetness index (UCWI), if zero or blank, the value from record 21 is used.	341
2.	local value of rainfall depth immediately before the event	70 mm

The WALLRUS program assumes that the surface is saturated at the start of the event. Hence, a large antecedent rainfall depth (say 70 mm) was therefore used.

Subsequent lines of the data file (Record 23 - Hyetograph values):

Item No.	Description of Input	Example
1.	Rainfall intensities (mm/hr) at each time step at each duration step, one per line.	0.0,4.8,0.46,....

Last line (Record 33 - Terminator for data)

Item No.	Description of Input	Example
1.	The word END.	END

An example of a rainfall event data file used in this study is given overleaf.

```
GREAT HARWOOD STORM 840803A BEST  RAINFALL EVENT DATA FILE FOR WALLRUS MODEL   20
   1                 300    1                120.                              21
     341.      70.0                                                            22
     .0                                                                        23
    4.8                                                                        23
    .46                                                                        23
    .46                                                                        23
    .46                                                                        23
    9.6                                                                        23
    4.8                                                                        23
   5.76                                                                        23
    4.8                                                                        23
    6.0                                                                        23
   24.0                                                                        23
    9.6                                                                        23
    9.6                                                                        23
    6.4                                                                        23
    4.8                                                                        23
   3.08                                                                        23
   1.36                                                                        23
    1.1                                                                        23
    .84                                                                        23
   1.11                                                                        23
   1.37                                                                        23
   1.01                                                                        23
    .64                                                                        23
    .48                                                                        23
    .32                                                                        23
    .32                                                                        23
    .32                                                                        23
   1.17                                                                        23
   2.02                                                                        23
```

```
    2.13                                                                                        23
    2.24                                                                                        23
    2.76                                                                                        23
    3.28                                                                                        23
     1.8                                                                                        23
     .32                                                                                        23
     .61                                                                                        23
      .9                                                                                        23
      .9                                                                                        23
      .9                                                                                        23
      .9                                                                                        23
      .9                                                                                        23
     .45                                                                                        23
      .0                                                                                        23
END                                                                                             33
                                                                                                20
```

APPENDIX D

SEWERAGE SYSTEM DATA

In addition to the rainfall event data, the data used to describe the sewerage system and the catchment are described (WALLRUS User Manual, 3/e, 1990).

1st Line of the data file (Record 1 - Title for the rainfall event):

Item No.	Description of Input
1.	Sewer system Title

2nd line of the data file (Record 2 - System control parameters):

Item No.	Description of Input	Example
1.	Number to identify data format used	2
	2 = old WASSP format for UK data	
2.	Pipe/channel index	0
	0 = original shapes (default)	
3.	Major time step used in the model (s)	15
4.	Soil index for the UK runoff model	0.45
5.	Global pipe roughness (k_s in mm)	1.50
6.	Global dry weather flow (m^3/s)	0.042

3rd line of the data file (Record 4 - Pipe data: UK format):

Item No.	Description of Input	Example
1.	Branch Label	1
2.	Pipe label	000
3.	Sewer ancillary index	
	= 0, or blank, no action taken	0
	= 2, on- or off-line storage tank	2 (at pipe 1.170)
4.	Pipe length(m)	128
5.	Ground level at upstream manhole (m AD)	129.00
6.	Invert level upstream (m AD)	127.000
7.	Invert level downstream (m AD)	124.640
8.	Diameter for circular pipe (mm)	300
9.	Pipe index (= 0, circular)	0
10.	Number of additional manholes along sewer excluding upstream and downstream manholes	- (e.g., 1 for pipe 1.010)
11.	Roughness height (mm)	- (e.g., 0.6 for pipe 1.050)
12.	Total surface area contributing directly to the pipe (ha)	0.579
13.	Impervious area as percentage of total area	45
14.	Pitched roof area as percentage of total area	12
15.	Flooded are as percentage of total area	- (45 for pipe 1.010)
16.	Dry weather flow directly to the pipe from the subcatchment (m3/s)	0.000

Record 9 - On-line Tank (First Record)

Item No.	Description of Input	Example
1.	Tank reference label	1
2.	Sewer ancillary index	0
3.	Branch label for the next pipe in the calculations	1
4.	Branch label for the other pipe in the calculations	900
5.	Continuation branch index = 1 if the first of the two branch labels refers to the continuation branch	1
6.	Plan area of tank (m^2)	81.00
7.	Level of bottom of tank referred to system datum (m AD)	77.710

Record 10 - On-line Tank (Second Record)

Item No.	Description of Input	Example
1.	Discharge coefficient for orifice in downstream pipe	0.850
2.	Invert level of orifice (m AD)	77.710
3.	Area of orifice (m^2)	0.0572
4.	Discharge coefficient for overflow weir	0.520
5.	Crest level of overflow weir (m AD)	79.410
6.	Crest length of overflow weir (m)	11.000

Last line: Standard Terminator Record - Negative integer to terminate file (-1).

The Great Harwood sewer system data file is given overleaf.

```
GREAT HARWOOD SEWER SYSTEM DATA                                                   1
2 0      1                       15  .45      1.50     0.042                      2
  1.000 6  128129.00127.000124.640    300     0          .579 45 15          .000 4
  2.000 6  230136.60134.800124.640    257     0         2.048 19  4          .000 4
  1.010     69127.79124.640122.700    300       1        .279 53  8 45            4
  1.020     70125.50122.700119.950    375                .514 30 15               4
  3.000 6  349141.01139.610119.950    417               3.377 34 15               4
  1.030     83122.69119.950117.930    450                .800 53 11 38       .003 4
  4.000 6  355141.70140.290117.930    416               3.400 45 11               4
  1.040     55121.08117.930116.230    450                .210  0  8 45       .001 4
  5.000 6  617151.30149.960116.380    369               3.940  2 11          .001 4
  1.050    232119.34116.000106.850    675       4   0.6 1.990 23 19 30            4
  6.000 6  224135.40134.000121.980    300                .220 38  0          .001 4
  7.000 6  200136.30134.240121.550    368               1.744 23  8               4
  6.010     60124.63121.550115.240    375       1        .630 45  8 30            4
  8.000 6  370130.60129.220115.240    379               3.800 45 11          .001 4
  6.020    148121.28115.240109.440    450       1        .789 45  0 45       .002 4
  9.000 6  244125.50123.560109.440    318               1.460 45  8               4
  6.030    115112.55109.440107.090    450       1        .914 23  8 45            4
 10.000 6  172117.30115.800107.220    322               2.800 38 15          .001 4
  1.060    130110.09106.470104.870   1050       1   0.6 1.120 11  8  8            4
 11.000 6  262117.50114.780105.540    285               2.630 23 23          .001 4
  1.070    129109.16104.870103.090   1050       1   0.6  .441 15  8 30            4
  1.080    123107.54102.940101.250   1200           0.6  .186  0  0  0            4
  1.090     66105.56101.250 99.840   1200           0.6  .081  0  0  0       .002 4
  1.100     44104.40 99.840 98.400   1200           0.6  .060  8  4 15            4
 12.000 6  234110.20106.970 99.500    227                .980 23  8               4
 13.000 6  588147.40145.730113.950    450               3.200 30 15          .001 4
 14.000 6  184128.80127.510113.950    312                .611 45 19               4
 13.010    124115.42113.950108.480    450                .405 38  8 38            4
 15.000 6  210124.10122.790108.480    293               2.003 41 19               4
 13.020     97111.37108.480106.780    450                .389 30 15 30            4
```

```
16.000 6  170118.40116.390106.780   291                1.700 45 11  0       .001 4
13.030    146108.99106.780102.800   450      1          .611 15  8  0       .001 4
17.000 6  432135.50134.040110.280   340                3.930 15  8               4
18.000 6  192118.50116.040110.690   300                4.600  8  2               4
17.010    192112.39110.280103.280   450      2         2.030 23 38 23       .001 4
17.020     17105.62103.280102.800   535                 .000  0  0  0            4
13.040     57105.06100.650100.570   675          0.6    .130 30  8 23            4
13.050     44103.66100.570 99.810   750          0.6    .542 15 30 15            4
13.060    101103.33 99.810 98.780   825      1   0.6    .639 38 15 38            4
30.000     31125.33123.971123.311   225                 .130 45 19 45            4
30.010     39125.05123.311122.481   225                 .110 45 19 45            4
30.020     58124.19122.481119.845   225                 .110 41 19 41            4
30.030     53121.12119.845113.956   225                 .150 41 19 41            4
31.000     35117.94115.810113.720   375                 .000  0  0  0       .001 4
30.040     37118.30113.720113.210   675                 .001  0  0  0       .001 4
39.000     52127.48126.611125.309   225                 .110 41 19 41            4
39.010     24126.47125.309124.386   225                 .050 53  8 53            4
40.000     39126.64125.361124.386   225                 .090 45 11 49            4
39.020     65125.78124.386120.053   225                 .240 34  0 34            4
41.000     59125.28123.003120.053   225                 .110 45 11 49            4
39.030     26122.10119.978118.245   300                 .050 45 15 45            4
42.000     73124.66121.971118.320   225                 .180 45 15 45            4
39.040     27120.62118.245116.445   300                 .040 53  8 53            4
43.000     81124.28120.570116.520   225                 .180 41 19 41            4
39.050     28118.76116.445114.500   300                 .050 38 23 38            4
44.000    101123.63119.180114.130   225                 .260 38 23 45            4
30.050     18116.88113.210112.950   525                 .020 60  0               4
45.000    116126.43123.792121.270   225                 .210 45 15 53            4
45.010    110123.40121.270113.210   225                 .180 45 15 53            4
30.060     54116.62112.950112.094   525                 .080 45 15          .001 4
46.000     74122.25119.548115.653   225                 .090 60  8 60            4
47.000     47119.80116.959115.653   225                 .140 53  8 56            4
```

```
46.010   23118.33115.653114.004   225          .030 60  0 74       4
48.000   47118.04115.179114.004   225          .130 45 15 38       4
46.020   26116.82114.004112.307   225          .030 60  0 74       4
30.070   77115.55112.019111.299   600          .110 53  8          4
49.000   64121.21117.861116.092   225          .140 30 30 41       4
49.010   23119.58116.092115.047   225          .050 60  0 74       4
50.000   65119.76116.853115.047   225          .160 30 30 38       4
49.020   24118.13115.047113.547   225          .050 45 15 49       4
51.000   68118.16115.547113.547   225          .140 38 23 41       4
49.030    9116.55113.547112.855   225          .010 60  0 74       4
52.000   42117.36113.555112.855   225          .105 38 23 38       4
49.040    8116.04112.855112.240   225          .010 60  0 74       4
53.000   67116.62113.580112.240   225          .140 45 19 41       4
49.050   18115.44112.240111.300   225          .010 60  0 74       4
30.080   38114.39111.299110.920   450          .070 49 11     .001 4
54.000   66122.14119.227117.341   225          .178 34 26 41       4
54.010   58120.31117.341115.270   225          .136 38 23 38       4
54.020   25119.00115.270114.556   225          .041 60  0 74       4
56.000   42119.36116.031114.631   150          .080 38 23 45       4
54.030   25118.51114.556113.750   225          .041 60  0 68       4
57.000   40117.98114.601113.750   225          .041 60  0 68       4
54.040   54117.09113.600110.900   375          .091 41 19 49       4
30.090   29114.01110.900110.781   450          .014 60  0          4
58.000   46116.41113.231110.931   225          .078 38 23 41       4
30.100   81113.78110.781110.302   450          .174 53  8     .001 4
59.000   78118.72117.579114.979   225          .211 34 26 41       4
59.010   23116.65114.979113.768   225          .063 49 11 56       4
60.000   50117.86116.375114.589   225          .143 34 26 41       4
60.010   23116.36114.589113.768   225          .044 53  8 60       4
59.020   24115.59113.768112.505   225          .036 45 15 53       4
61.000   68117.10115.720113.291   225          .221 38 23 45       4
61.010   22115.14113.291112.505   225          .058 38 23 53       4
```

```
59.030    39114.42112.505110.452  225            .050 45 15 53        4
30.110    25112.34110.302110.154  525            .011 59  1           4
62.000    39115.95114.854112.904  225            .154 38 23 15        4
62.010    52114.40112.904110.304  225            .218 38 26 11        4
30.120   108111.88110.154109.515  600            .283 60  0       .001 4
63.000    80113.73111.665109.665  225            .460 53  8 38        4
30.130    23111.50109.515109.379  600            .013 59  1           4
64.000    56113.69111.862110.929  225            .141 45 15 38        4
64.010    49112.44110.929109.529  225            .149 45 15 38        4
30.140    28111.57109.379109.322  600            .077 49 19       .001 4
65.000    16127.34125.570124.930  225            .036 53  8 60        4
66.000    75129.24127.930124.930  225            .094 30 30 38        4
65.010    23127.46124.930124.470  225            .012 53  8 60        4
67.000    41126.82125.290124.470  225            .128 45 15 45        4
65.020    56127.49124.320123.200  375            .140 45 15 45        4
68.000    32128.76126.667126.125  225            .060 38  0 38        4
69.000    24128.86126.710126.125  225            .060 53  0 53        4
68.010    30128.22126.125125.427  225            .039 53  0 38        4
70.000    42129.01126.662125.652  225            .101 53  8 38        4
68.020    27127.74125.652123.350  225            .026 60  1 74        4
71.000    40127.66124.947123.350  225            .092 45 15 38        4
65.030    46126.79123.200122.595  375            .145 49 15 45        4
72.000    28128.51126.388125.311  225            .070 45 15 38        4
73.000    16127.50126.252125.311  225            .026 49 26 41        4
72.010    23126.79125.311124.216  225            .029 49 26 41        4
72.020    25126.07124.216122.745  225            .053 53  8 56        4
65.040    49125.70122.595121.950  375            .120 41 19 41        4
74.000    43125.82123.738122.894  225            .055 41 19 41        4
74.010    27125.02122.894122.100  225            .029 60  1 74        4
75.000    86126.14124.411122.411  225            .220 30 30 38        4
75.010    28124.20122.411122.100  225            .038 60  1 74        4
65.050   133124.52121.950118.540  375            .314 53 11 53        4
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76.000    125129.25127.839123.929   225          .329 38 30 38       4
76.010     23126.06123.929123.394   225          .058 53  8 60       4
77.000    133128.77127.547123.394   225          .268 45 19 41       4
76.020     24125.78123.394122.836   225          .043 49 15 56       4
78.000     44128.07126.111124.854   150          .141 38 23 38       4
78.010     68127.13124.854122.911   150          .152 38 23 38       4
76.030     22125.40122.761122.250   300          .043 56 11 56       4
79.000     96126.56124.557122.325   225          .195 49 19 41       4
76.040     47124.95122.250121.588   300          .123 53 15 53       4
80.000     60125.72124.339124.006   225          .164 45 23 38       4
81.000     15125.69124.312124.006   225          .026 45 23 38       4
80.010     24125.38124.006122.506   225          .027 45 23 38       4
82.000     44125.23123.204122.506   225          .094 45 23 38       4
80.020     27124.82122.506121.663   225          .025 68  1 74       4
76.050     59123.94121.588120.035   300          .166 49 19 49       4
83.000     22124.51122.111121.622   225          .044 38 38 38       4
84.000     17124.59122.387121.887   225          .030 49 19 41       4
84.010     22124.10121.887121.622   225          .036 49 19 41       4
83.010     65123.82121.622120.110   225          .144 49 19 41       4
85.000     82124.27121.945120.555   225          .187 38 30 38       4
86.000     50123.19121.349120.555   225          .045 56 11 56       4
85.010     28122.77120.555120.110   225          .046 45 23 45       4
76.060     54122.31120.035118.615   375          .096 56 15          4
65.060     11121.27118.540118.242   375          .021 60 15          4
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65.070     50120.90118.242116.891   450          .123 56 11 56       4
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88.010     30119.38117.458117.041   300          .056 45 23          4
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89.000     66116.62115.475113.637   225          .147 49 11 26       4
89.010     52115.28113.637111.909   225          .119 49 11 34       4
89.020     26113.76111.909111.436   375          .025 68  1          4
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 65.090     50113.84111.286109.970   450                     .125 56 15           4
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 30.160    143108.53107.104103.238   600                     .212 49 23           4
 30.170     57105.34103.238101.697   600                     .096 53 15           4
 91.000     50108.43107.692106.079   225                     .135 45 23 38        4
 91.010     10107.20106.079105.079   225                     .030 68  1 74        4
 92.000     32107.01105.719105.079   225                     .046 45 23 38        4
 91.020     12107.19105.079104.806   225                     .014 45 23 53        4
 93.000    160112.08109.967104.806   225                     .671 53 19 53        4
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 94.000     20107.89106.544105.975   225                     .025 45 23 49        4
 95.000     50106.70106.075105.975   225                     .130 34 26 41        4
 94.010     26107.96105.975105.708   225                     .034 45 23 38        4
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 94.020     65108.27105.708103.738   225                     .129 49 19 41        4
 97.000     41108.32105.852105.032   225                     .128 49 19 41        4
 97.010     42107.00105.032104.208   225                     .098 41 26 41        4
 97.020     24105.70104.133103.663   300                     .039 68  1 74        4
 91.040     22106.44103.663103.296   300                     .028 53 15 53        4
 98.000     52106.77104.238103.371   225                     .118 41 26 41        4
 91.050     23106.07103.296102.913   300                     .039 53 15 53        4
 99.000     67106.82104.105102.988   225                     .116 45 15 45        4
 91.060     22105.57102.913102.546   300                     .031 53 15 53        4
100.000     57106.36103.571102.621   225                     .127 49 23 41        4
101.000     58105.70103.792102.964   225                     .186 45 23 38        4
101.010     24104.60102.964102.621   225                     .013 68  1 74        4
 91.070     24105.22102.546101.772   300                     .036 68  1 74        4
 30.180     32104.80101.697100.832   600                     .001  0  0  0        4
  1.110    334104.42 98.250 94.360  1350                0.6  .880 41  8 30        4
102.000 6  155111.40108.930105.070   300                    2.100 23  4       .001 4
102.010     26106.10105.070105.150   300                     .000  0  0  0        4
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102.040    195106.36103.740 98.300    300               1.505 15  8 68            4
103.000 6  410111.50108.530 98.150    538               4.444 15  8               4
102.050     27 99.81 98.150 97.900    535                .000  0  0  0            4
102.060    183 99.70 97.680 95.760    750       1        .692  8  8  8            4
102.070     64 98.31 95.760 94.960    750                .800 23 23 38            4
102.080     85 98.25 94.960 94.290    750       1        .000  0  0  0            4
  1.120    151103.24 94.360 86.700   1350           0.6  .000  0  0 68            4
  1.130     85 99.20 86.700 83.600   1350           0.6  .000  0  0  0            4
104.000    708131.10129.720115.810    375      30 4    14.000 15  4           .013 4
104.010     30117.94115.810113.460    375         4      .130  0  0  0            4
104.020     80114.60113.460110.940    375       3 4      .279  8  0               4
104.030    130113.98110.940102.530    375       2 4     1.113  4  0               4
104.040    430103.97102.530 98.980    450       3 4 3.0 5.300  2  0               4
104.050     63101.97 98.980 96.090    450         4 3.0 2.310  2  0           .003 4
104.060    317 97.61 92.450 88.790    450       3   3.0  .000  0  0  0            4
104.070    378 92.99 88.790 85.260    450       4 3 3.0 1.000  8  0               4
104.080     87 89.39 85.040 84.350    600         3 3.0  .000  0  0  0            4
  1.140    103 88.16 83.600 80.700   1350           0.6  .000  0  0 00            4
  1.150     38 85.17 80.700 80.000   1350           0.6  .000  0  0  0            4
  1.160     80 84.42 79.250 79.070   2100           0.6  .000  0  0  0            4
105.000 6  205 97.90 96.810 81.480    225               2.113 15 19               4
  1.170 2   11 83.94 79.070 79.040   2100           0.6  .000  0  0  0            4
     1         1  900          1   81.00    77.710                                9
       .850    77.710    0.0572    .520    79.410    11.000                    10
  1.190     27 83.46 77.706 76.648    450           0.6                           4
900.000     20 83.94 77.800 77.700   1900           0.6                           4
201.000 6  200140.00137.985122.60000  600      0 0 0    2.330 23                  4
202.000 6  100133.00130.934122.60000  225      0 0 0     .440 23                  4
201.010 0   57125.00122.600118.21600  600      0 0 0     .040 75                  4
203.000 6  100137.00134.327125.99400  300      0 0 0    1.090  0                  4
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203.010 0   26130.00125.994124.54900  300     0 0 0     .060 75                4
204.000 6   50130.00127.049124.54900  225     0 0 0     .460  0                4
203.020 0   60127.00124.549121.21600  300     0 0 0     .260 75                4
203.030 0   54125.00121.216118.21600  300     0 0 0     .250 75                4
201.020 0  106121.00118.216115.56600  600     0 0 0     .210 75                4
201.030 0   40119.00115.566114.56600  600     0 0 0     .040 75                4
201.040 0   24117.00114.566114.08600  600     0 0 0     .210 75                4
201.050 0   75117.00114.086111.58600  600     0 0 0     .250 75                4
205.000 6  100116.00113.438111.58600  300     0 0 0     .640  0                4
201.060 0  106114.00111.586107.34600  600     0 0 0     .350 75                4
201.070 0   75110.00107.346104.34600  600     0 0 0     .280 75                4
206.000 6  100110.00108.891104.34600  225     0 0 0     .340  0                4
201.080 0   94108.00104.346103.17100  675     0 0 0     .220 75                4
201.090 0   51107.00103.171102.53300  675     0 0 0     .140 75                4
201.100 0  124107.00102.533100.98300  675     0 0 0     .220 75                4
207.000 6   50104.00101.909100.98300  225     0 0 0     .450  0                4
201.110 0  124104.00100.983 99.43300  675     0 0 0     .100 75                4
201.120 0   41103.00 99.433 98.92100  675     0 0 0     .100 75                4
201.130 0   44102.00 98.921 98.43200  675     0 0 0     .170 75                4
201.140 0  140102.00 98.432 96.87600  675     0 0 0     .240 75                4
201.150 0   80100.00 96.876 95.98700  675     0 0 0     .110 75                4
201.160 0   71 99.00 95.987 95.10000  675     0 0 0     .500 75                4
208.000 6  100 99.00 96.638 95.10000  450     0 0 0    2.070 56                4
201.170 0   30100.00 95.100 94.60000  675     0 0 0     .530 75                4
209.000 6  350100.00 98.208 94.60000  300     0 0 0    2.570  0                4
201.180 0   66 98.00 94.600 93.50000  675     0 0 0     .030 75                4
210.000 6   30 97.00 93.962 93.50000  300     0 0 0     .630 38                4
201.190 0   66 97.00 93.500 91.30000  675     0 0 0     .190 75                4
201.200 0   80 95.00 91.300 88.63300  675     0 0 0     .030 75                4
201.210 0  250 92.00 88.633 80.46000  675     0 0 0     .010                   4
900.01010   70 83.94 77.700 70.000    900         6     .001  0   0 75         4
900.02010   70 83.94                                                           4
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 1.200     40 81.17 76.648 75.648    450           0.6                           4
 1.210     34 80.45 75.648 74.798    450           0.6                           4
 1.220     99 77.44 74.798 70.260    450           0.6                           4
-1.000        69.04                                                             15
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APPENDIX E

LIST OF PUBLICATIONS

1. Gupta, K. and Saul, A.J. (1994). Storage tank design for the retention of pollutants. Proceedings, *HYDROTOP'94*, 12-15 April, Marseilles, FRANCE.

2. Gupta, K. and Saul, A.J. (1995). Suspended solids in combined sewer flows, Proceedings, *IAWQ International Conference on Sewer Solids - Characteristics, Movement, Effects and Control, Dundee, 5-8 Sept.*, 312-319. (under consideration for publication in *Wat Sci Tech.).*

3. Gupta, K. and Saul, A.J. (1995). Site-specific relationships for the first flush load in combined sewer flow. **submitted** *to* Water Research.

4. Gupta, K. and Saul, A.J. (1995). A methodology to predict the pollutograph profile in urban sewer flows: theory and applications. **in preparation**