Aesthetic pollutant loadings in upstream combined sewers.

DIGAMN, Christopher James.

Aesthetic Pollutant Loadings in Upstream Combined Sewers

Christopher James Digman

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Notation list

A	Plan area of reservoir
Area_{IMP}	Impermeable Area
b	Breadth
B	Weir width
C	Weir constant
d_c	Critical depth
d_s	Depression storage
g	Gravity
H	Depth of water over weir
H_d	Housing density
H_{OUT}	Water depth leaving the reservoir
I	Inflow
k	Solids stored equation co-efficient
K	Storage constant
k_1	Surface type coefficient
$M_{ENTERING}$	Mass of solids entering during storm
$M_{E\square T}$	Mass entering in the first time step
M_{MOTION}	Mass of solids in motion prior to the storm
M_P	Stored mass per person
M_S	Mass stored
M_{STORM}	Mass measured during storm
$M_{S\square T}$	Mass stored in the first time step
M_T	Mass entering in one day
O	Outflow
P	Total population in each catchment

P_P	Population density
ρ	Density of the fluid
Q	Discharge
Q_c	Critical flow
Q_{IN}	Reservoir inflow
$Qin_{runoff\ \Delta T}$	Flow generated from runoff at each time step
R	Hydraulic Radius
$R_{DEPTH\ \Delta T}$	Rainfall depth at each time step after depression storage
s	Ground slope
S	Storage
S_0	Bed Slope
$S_{C\ at\ time\ zero}$	Solids concentration at start of the event to be modelled
t	Time
T_F	Time of day factor
T_S	Rate of solids entering factor
τ_c	Shear stress
$U_{\%SINK}$	Percentage of panty liners sinking
U_*	Shear velocity
V	Volume of water in reservoir
$V_{I\ \Delta T}$	Volume entering in the first time step
W_C	Water consumption figure
W_s	Settling velocity
x	Dimensionless constant for a sewer network (Muskingham)
X	Quantity of solids in the pipe

Abbreviations

ADWP	Antecedent dry weather period
AMP	Asset Management Planning
BATNEEC	Best Available technology not exceeding excessive costs
BOD	Biological oxygen demand
CCTV	Closed-circuit Television
CFD	Computational fluid dynamics
COD	Chemical oxygen demand
CSO	Combined Sewer Overflow
DS	High income catchment storm
DWF	Dry weather flow
EA	Environment Agency
EC	European Community
EPSRC	Engineering and Physical Research Council
FRF	Faecal related flushes
FWR	Foundation for Water Research
GROSSIM	Gross solids simulator
GS	Low income catchment storm
GSS	Gross solids sampler
LGSS	Gross solids sampled loading
LTSS	Total suspended solids loading
OFWAT	Office of Water Services
OS	Ethnic catchment storm
PIMP	Percentage impermeable area
SANPRO	Sanitary Protection
SC	Sub-catchment

SEED	Socio-economic, ethnic and demographic factor
SET	Sewer Entry Team
SPV	Standard production value
SSAS	Sewer systems analysis software
SSV	Standard solid value
STW	Sewerage Treatment Works
TSS	Total suspended solids
UKWIR	United Kingdom Water Research
UPM	Urban Pollution Management
UWTD	Urban Wastewater Treatment Directive
WaPUG	Wastewater Planning User Group
WC	Water Closet
WITE	
WWTW	Waste Water Treatment Works

Abstract

An improvement to the standard of discharges from combined sewer overflows is necessary to meet the challenges set by the EC Urban Waste Water Treatment Directive (1991). To prevent aesthetic pollutants being discharged from a CSO, it is first necessary to gain an understanding of the quantity and temporal distribution of solids that enter the structure. This knowledge can then be used to predict the quantity of solids that are presented to a CSO under storm conditions.

A field study was undertaken to determine the quantity and temporal distribution of solids entering a combined sewerage system and their transportation through the network in dry and wet weather. Flow monitoring and aesthetic pollutant sampling was undertaken in dry and wet weather at three catchments that contained different population types. The aesthetic pollutants sampled were characterised and tested in a laboratory to determine their settling rate.

Analysis of the sampled data has indicated that aesthetic pollutants are stored in upstream sewers and private drainage connections during the dry weather period prior to a storm occurring. These pollutants and those within the flow in dry weather are transported out of the sewer at the start of the storm as part of a first foul flush. Sampling showed that over 80% of the solids by mass were faeces and toilet tissue, with a comparatively small number of sanitary products in the remaining percentage. Different solids are stored at different rates and this is clearly linked to the antecedent dry weather period and the quantity of solids that enter the system. The quantity of solids entering is also linked to the population type.

A solid input and transportation model has been developed to predict the quantity of solids entering and moving through an upstream sewer system in dry and wet weather. The accuracy of the model is good particularly in the context of the variability of the solids that enter the system. The model predicts the quantity, rate and temporal distribution of six types of solids that could enter an upstream CSO and could aid in the development of more cost effective CSO solutions.

1 Chapter 1 – Introduction

This chapter provides an overview of the sewer system and the problems that commonly occur with regards to aesthetic pollution. Numerous tools developed to reduce the discharge of solids are identified with regards to the consent standards issued by UK Government and the EC. An introduction to the collaborative project that has funded this work is detailed to set it in context, identifying why it was important and how it could help to reduce the discharges of aesthetic pollutants from CSOs.

1.1 The purpose of the sewerage system

Sewerage systems in urban areas are used to convey wastewater and storm water away from its point of entry to suitable discharge points such as rivers, brooks and estuaries. The treatment of these waters prior to discharge is necessary to prevent the water entering a watercourse and polluting the environment. The two types of water contain different pollutants. Wastewater is the result of potable water supplied to homes and industry, which is used for numerous reasons and then discharged when it is of no further use. Domestic wastewater is likely to contain dissolved pollutants, fine solids and larger solids, mainly from the water closet (WC). Wastewater needs to be removed from source and be treated to prevent these pollutants entering directly into receiving waters. Storm water is primarily created by precipitation of any kind falling on impermeable surfaces in urban areas, although runoff can also occur from permeable areas as well. Storm water needs to be removed from its point of entry to prevent flooding, and conveyed to suitable points of discharge that generally can provide temporary storage in the natural environment. Pollution generally occurs at the start of the storm where pollutants (such as oils, grits etc) are washed off and enter as part of the runoff from roofs and pavements. Ideally this water needs to be treated or retained prior to discharge to prevent pollution of the natural environment.

In the UK there are three types of sewerage systems that exist:

- Combined
- Separate
- Partially separate

All three types of systems convey the wastewater to treatment works during dry weather. In wet weather the three types of system operate differently. Combined sewers convey wastewater and storm water together, however the capacity of the system is limited and cannot retain all the water for treatment. Therefore it is necessary to pass a proportion of the storm water mixed with wastewater directly to receiving waters via a combined sewer overflow (CSO). The quantity of water discharged is determined by the CSO setting that limits the rate at which water continues through the network, with the remainder being stored and / or spilt dependent upon chamber type and size. This prevents the sewer system being flooded by releasing a large quantity of the storm water, rather than retaining this water. This is particularly important at wastewater treatment works (WWTW) that are designed to handle a maximum flow. Without the relief upstream, the WWTW would need to discharge a large quantity of water and pollutants directly into a receiving water at one location, that would lead to flooding and pollution in the area if the capacity of the receiving water was not great enough. Approximately 70% of the systems in the UK are combined (Butler and Davies, 2000).

The separate system became common place in the UK after 1945 (Butler and Davies, 2000), although some systems connect into combined sewers before reaching a WWTW. The separate system carries wastewater and storm water in different pipes.

The wastewater is conveyed in foul sewers and transported directly to the WWTW. The storm water is directed to the nearest watercourse and discharged untreated. However the pollutants washed off during the runoff process can contaminate the watercourse. This pollution can also get worse if wastewater connections are incorrectly connected to the surface water system or if illegal connections are made. The cost of the construction of the two systems is more expensive than the combined system due to the need for two pipes and possibly wider or deeper trenches.

The partially separate system uses two pipes to convey waters and originated following the expansion of industrial towns at the turn of the century. A large increase in the population in the towns occurred as the need for factory workers grew and the rapid construction of rows of terraced housing with back yards. The foul sewer conveys the wastewater and a proportion of the storm water, which is drained from the back of the roofs and yards etc. The remaining storm water from the front of the roofs, drives and pavements etc. is conveyed in the surface water pipes. As with the separate system, problems exist with incorrect or illegal connections.

1.2 The development of the Sewerage System

The problem of dealing with human excrement entering natural watercourses is not new, but has occurred for as long as we have been alive. The importance of dealing with bodily functions was noted in the Bible (approximately 1500 BC) where Moses instructed the people to turn the remains of bodily waste into the ground. Prior to and during the reign of King David, a network of main and auxiliary sewers were used to remove sewage from homes and streets (theplumber.com 2000a).

Ancient civilisations such as the Greeks, Egyptians, and Minoans constructed and used sanitation systems to transport waste away from the cities. In ancient Greece, many houses had closets or latrines that drained directly into sewers beneath the street (theplumber.com 2000b). However in many cultures it was common for waste to be passed from the house into a "cesspit" which would be periodically emptied or covered. This practice remained common into the 1800s in the UK. As populations started to congregate together and become large, this practice was unworkable, if good sanitation practices were to be upheld. The Romans constructed a large network of sewers which carried sewage out to the River Tiber, which transported this out to sea (BBC Education 2000). The development and use of sewerage systems declined following the fall of the Roman empire, through the Middle Ages.

During the Middle Ages it was common to empty chamber pots from upstairs windows into the streets below. This activity was often accompanied by the shout 'Garde l'eau' warning passers-by to expect the contents to land on the street. The main drain would run down the centre of the street, and despite it being made illegal to dump out the contents in 1372, the practice remained.

Sewers in the Middle Ages were not constructed to carry human waste but act as natural and artificial drainage systems at ground level. The word sewer in Old English means "seaward", and these were designed with a gentle slope to drain into the local river. The first Act of Parliament regarding the pollution of rivers and waters occurred in 1388 to safeguard the water quality of the Thames (Humphries 1930). In the late 1500s, King Henry VIII made it the responsibility of each house owner to clear the sewer which passed by their dwelling. This was prompted by the sewers overflowing with garbage and human excrement (Gayman 2000).

In the UK in the early 18th Century many residences had a cesspit beneath the floors where all human excrement was passed. These cesspits were periodically cleaned, however it was common for them to overflow into the streets and soak foundation walls leaking into neighbouring buildings.

During the latter part of the 18th Century and early 19th Century, sewers had been constructed to carry rainwater to prevent flooding, however it remained illegal to connect to and drain sewage into sewers. In 1815 the government accepted the practice of connecting houses to the sewers, but it was not until 1847 that the law was changed and became legal (Reed 1982). It was during the years of the Industrial Revolution that the development of the sewerage system primarily occurred and this is where the modern system was first born.

The Industrial Revolution led to a sudden increase in populations in the main cities in the UK, moving away from spacious villages into cramped and confined conditions, a hazard in themselves. Large growth rates also increased the environmental health risk to those living in the squalid conditions. In the early 19th Century 20 per cent of the population resided in towns of over 5000; this increased to 50 per cent by 1851 and by 1901, nearly 80 per cent lived in urban areas (Porter 1999). London had increased in size from 800,000 occupants in 1801 to 1.8 million in 1841, with other towns and cities increasing in size at a similar rate. With this growth in size, the quantities of human excrement grew, and where previously it was possible to collect the waste for farm use from cleaning the cesspits, the quantity of solid waste produced far outgrew the demand.

The conditions of the dwellings were reported in a report in 1841 on the Sanitation Condition of the Labouring Population, by Edwin Chadwick, the Secretary to the Poor Law Commission (Chadwick 1842). This report was commissioned due to the major

Cholera epidemics across the country. Chadwick's reports identified the need to have an arterial system of drainage to ensure that water supplies remained pure and reduce the chance of the supply becoming infected. Chadwick was one of the leading reformers of the time but met resistance through the 'Laissez-faire' attitude, where many politicians at the time believed that the government should not interfere with the public health of the population. However partly from Chadwick's call for reforms the 1848 Public Health Act was passed, and further reinforced in 1854 enforcing the responsibility of the public's health upon the central and local Boards of Health.

In 1847 it became permissive to drain the cesspools into the sewers and within 6 years in London, 30000 cesspools had been abolished (London County Council 1909). This however shifted the problem from the streets to the nearest watercourse where the sewer outfall was located. In London towards the end of the 1850s it was estimated that 250 tons of faecal matter found its way into the Thames daily. This pollution of the Thames caused numerous problems in the provision of clean potable water (Dept.of Scientific & Industrial Research 1964). A considerable part of the water supply was drawn from the Thames and the increasing pollution led to numerous outbreaks of water-borne diseases such as Asiatic cholera. Dr John Snow provided a link between the cholera and the abstraction of drinking water from the Thames and the Metropolis Water Act was passed in 1852 preventing abstraction below Teddington Weir. In 1856 Sir Joseph Bazalgatte was ordered to draw up plans to intercept the sewers and move the outfalls further downstream (London County Council 1909). Interceptor sewers were constructed between 1858 and 1874 to run parallel to the Thames, on the North and South side and carry the sewage to the East of the city to outfalls constructed at Barking and Crossness. The existing points of discharge to the Thames were retained to allow excess storm water to be discharged to the river when the interceptor sewers reached their maximum capacity. These were the first CSOs to be used for the purpose of providing relief to the system. The existing outfalls remained in operation for heavy storm events when the system could not cope with the flows. At the new outfalls, reservoirs were constructed to release the foul flow with the out flowing tide.

By the late 1880s growth in London had caused the interceptor sewers to be overloaded and discharges to the Thames were regularly occurring (Baker and Binnie 1891). New relief sewers were planned and constructed on both sides of the Thames to prevent these discharges. In the 1890s treatment works were constructed at Barking and Crossness where partial separation of solids and chemical treatment occurred. These undertakings substantially improved the water quality and Binnie (1899) noted in a report to the London County Council that *'the effect upon the river has certainly been marvellous and has far exceeded … anticipation'*. Biological treatment was introduced in the 1920s and further improvements followed that gradually improved the Thames' water quality.

The Royal Commission on Sewage Disposal reported in 1915 that the overflows in the system should limit the flow continuing to treatment to being 6 times the estimated dry weather flow (DWF). Although during dry weather the problem of pollutants directly being discharged to watercourses had generally been removed, during wet weather, pollution of the environment still existed. Numerous Acts of Parliament were passed to control the discharges from CSO's. The Rivers (Prevention of Pollution) Act 1951 required that individual consent limits for effluent discharges were required for new CSO's. It was not until the Rivers (Prevention of Pollution) Act 1961 that pre 1951 discharges from CSO's were covered. These Acts were superseded by the Control of Pollution Act (1974) that applied to coastal waters as well as rivers. This however did not resolve the problem of pollutants being discharged in wet weather.

1.3 Aesthetic Pollutants and the CSO problem

The original intention of a CSO was to provide relief to the sewer system, however with the need to restrict the quantity of pollutants being discharged, further considerations of the design were required. Simple CSO's have given way to more complex structures since the 1960s following research into the retention and separation of pollutants at overflow structures. However many of the simpler overflow structures are still in existence today, and are yet to be improved. The Ministry Of Housing and Local Government (1970) estimated from a sample survey that 40% of all storm overflows were unsatisfactory. This was in relation to all pollutants being discharged. These pollutants were of a physical, chemical and biological nature. The types of pollutants varies between catchments but may consist of BOD, COD, ammonia, suspended solids, dissolved solids, pipe sediments, near bed solids, gross solids and many others. These pollutants when discharged can have varying degrees of effect on the receiving water. Many of the pollutants lead to the quality of the water deteriorating which can kill aquatic life or promote other forms that do not ideally exist under normal conditions. The larger more identifiable solids will often not cause the problems that chemical or biological pollutants cause with the loss of aquatic life, but do reduce the amenity value of the area.

A report by the Working Party of Storm Sewage identified that there was a lack of information regarding the composition of storm sewage (Working Party On Storm Sewage 1977). It was noted that the aesthetic pollutants that were discharged from the CSO's caused the public to complain, and this was their main objection to overflows. Yet in 1995 it was estimated that approximately one third of the 25000 CSO's discharging were unsatisfactory with regards to aesthetic pollution (UKWIR 1995). 'Aesthetic pollutants' or 'gross solids' are defined as *'solids that are greater than 6 mm in two dimensions, are clearly of a sewerage origin and are aesthetically unpleasant'.*

Report FR0440 (FWR 1994) observed that sewage derived contaminants had a larger impact on the public's enjoyment of a visit to the river or beach than any other aesthetic pollutant. Of all the aesthetic pollutants, female sanitary protection (SANPRO) products were deemed to be the most offensive. The first sanitary towels were devised by nurses in the First World War, and soon after, the first disposable towels were launched (O'Kelly 1992). However, the use of SANPRO items has been a likely cause in the publics increased disliking to aesthetic pollutants discharged from CSOs. SANPRO items are slow to degrade with some having a plastic shell and are particularly fibrous therefore can easily become entangled on vegetation or deposited on banks, hence they are very visible. Other aesthetic pollutants often observed in the sewer include faeces, toilet tissue, condoms, wet wipes, cotton bud sticks and cotton wool.

The most problematic pollutants, the SANPRO items, can be disposed of in a different format, away from the WC. The solid waste disposal is deemed as a better alternative than the WC and has been considered to be more sustainable Souter et al. (1999). The cost implications of passing them direct to landfill or incineration is cheaper than passing them via the WC to WWTW. A number of campaigns have been trialled to change peoples attitudes such as 'Think before you flush' campaigns. The publics attitudes to these campaigns have been positive although a large change in the disposal habits will take a considerable period of time, however could hold the key in reducing the number of pollutants spilt at CSOs. However until that time, improvements to CSOs is seen as the best alternative in reducing the number of solids discharged.

Current practice for the design of CSO's utilises a number of design guides and management tools. In the UK guidance is provided by the Urban Pollution Management (UPM) manual and the third edition of the Sewerage Rehabilitation Manual (1994). The UPM procedure was developed to provide an integrated approach to wastewater management under wet weather conditions (FWR 1998). It provides details of the best current practice for the management of wet weather discharges. The first UPM manual formalised the procedures laid down in Asset Management Plan (AMP) 2. The water companies produce AMPs every 5 years. The plans detail the work that will be undertaken to refurbish, replace or newly construct various parts of the system such as CSOs, outfalls etc. and lists the benefits that will be seen from this programme of work. The plans last for a period of 5 years and are submitted to the Office of Water Services (OFWAT) for approval. OFWAT also sets the rate of increase or decrease that water companies can charge their consumers. The AMPs have been used to meet the objectives defined in the EC Urban Wastewater Treatment Directive (UWWTD) (EU Directive No.91/271/EEC 1991) and is discussed further in section 1.5.

The UPM procedure considers the wastewater system, comprising of the sewer network, treatment plant and receiving water as one entirety in which the changing of one part has implications on other parts and must be taken into account. The procedure is entirely aimed at meeting the environmental standards. The modelling process is required to demonstrate the compliance of a scheme to the standards set by the regulator. The procedure also encourages the practitioner to use tools that are appropriate to the technical needs of the study, where many studies can use simple tools to estimate whether standards will be met or not. The UPM provides principles that can be followed to assess whether a scheme will satisfactorily meet the standards set by the regulator therefore providing important guidance.

The UPM is not a design guide, and for CSOs, guidance for their design is given in the FR 0488 Design Guide (Balmforth et al. 1994) in conjunction with the consent standards required to be met. This superseded the previous ER 304E design guide by Balmforth and Henderson (1988), where the majority of design recommendations were based upon laboratory studies using discrete particles of plastic and wood to simulate sewage solids (Saul 1998). The FR 0488 design guide introduced a K factor that related the design inflow and flow split to the annual load of pollution retention for the high side weir, end weir stilling pond and vortex chamber with peripheral spill. The dimensions of the chamber continued to be based upon the one year return period of a storm to produce a peak design flow rate, minimum diameter of the inlet pipe and the factor K. Also available for CSO design is the WaPUG design guide. Other publications regarding aesthetic pollutant control are also available for use such as the Design of CSO's to Meet Aesthetic Regulatory Requirements (UKWIR 1995). This identifies the regulatory requirements and how they can be met through a variety of design options. The design procedure is presented in a step by step approach with a design example and the design charts used that was produced in FR 0488. This guide offers a useful example in designing CSOs to meet the regulatory requirements of the EC UWWTD.

1.4 Consent Standards

The EC UWWTD (EU Directive No.91/271/EEC 1991) set clear standards for the quality of water discharged during wet weather events. The directive required member states to produce their own regulations and was incorporated into UK legislation under the Urban Waste Water Treatment (England and Wales) Regulations (UK Government 1994). A requirement is to limit the pollution of the discharges to receiving waters. This was defined under schedule 2 of Regulation 4 that

"The design, construction and maintenance of collecting systems shall be undertaken in accordance with the best technical knowledge not entailing excessive costs, notably regarding: (part c) limitation of pollution of receiving waters due to storm water overflows"

The deadlines to meet various levels of the schedule were defined in Regulation 4 where:

- Discharges to receiving waters in a sensitive area with a population equivalent (p.e.) of more than 10000 to be met by 31st December 1998
- Discharges to all waters with a p.e. of more than 15000 by 31st December 2000
- Discharges to all waters with a p.e of between 2000 and 15000 by 31st December 2005

Exceptions were made to these requirements for where no environmental benefit would occur or that excessive cost was involved. The regulator at the time, the National Rivers Authority now known as the Environment Agency provided guidance for AMP2 to enable operators to meet the requirements (National Rivers Authority 1993). To determine whether a CSO was deemed unsatisfactory was defined within the guidelines and later on in the second UPM manual:

"If the CSO causes significant visual or aesthetic impact due to solids (i.e. sewage derived litter such as sanitary hygiene products, contraceptives and alike) or sewage fungus (cotton-wool like growths of attached micro-organisms associated with heavy organic enrichment) and has a history of justified complaint" (FWR 1998)

The receiving water has an intrinsic amenity value that may be reduced by the discharge of aesthetic pollutants from a CSO. This amenity value must be protected therefore emission standards have been set at the point of discharge to the receiving waters. The factors that are likely to affect the amenity use of the receiving water are described in the second edition of the UPM manual (FWR 1998):

- The amenity use category of the affected receiving waters
- The type and size of gross solids in the sewage flow which are likely to cause aesthetic problems
- The volume and frequency of discharges from the urban wastewater system to the receiving water, since this will affect the risk of aesthetic pollution problems occurring
- The practical limitations of available control measures

Table 1.1 indicates the standards that have been adopted in England and Wales in response to the UWWTD as defined by the NRA in their guidelines. Balmforth (1999) identified six possible options to meet the aesthetic pollutant control requirements defining the type of CSO chamber and whether a screen should be used or other suitable method to control the discharge of aesthetics.

The UK water industry is now working to meet the standards defined by improving the sewer system. One significant part of this work is the upgrading of CSOs. This work is defined in the current AMP3 that was submitted to the regulator and was an agreement of the work to be undertaken during that time period with the aim of meeting the regulations set. The current AMP3 commenced in April 2000 and concludes in March 2005. It draws on the experiences gained from the work completed in meeting AMP2, where 1200 unsatisfactory overflows were improved (Environment Agency 2000).

Table 1.1 Aesthetic control requirements for the discharge to freshwaters, coastal waters and estuaries (after National Rivers Authority 1993)

Amenity Classification	Spill Frequency	Aesthetic Control Requirement
High Amenity i) Receiving water passes through formal public park ii) Formal picnic site iii) Influences area where bathing and water contact sport (immersion) is regularly practised (wind surfing sports canoeing) iv) Shellfish waters	> 1 spill per annum	6mm solids separation(1)
	1 spill per annum	10mm solids separation (2)
Moderate Amenity i) Boating on receiving water ii) Popular footpath adjacent to watercourse iii) Watercourse passes through housing or frequented town centre area (bridge, pedestrian / shopping area) iv) Recreation and contact sport (non-immersion) area	> 30 spills per annum	6mm solids separation (1)
	30 spills per annum	10mm solids separation
Low Amenity i) Basic amenity use only ii) Casual riverside access on a limited/infrequent basis (bridge in rural area, footpath adjacent to watercourse) Non-Amenity i) Seldom or never used for amenity purposes ii) Remote or inaccessible area	Not applicable	Solids separation achieved through "best engineering design" of CSO chamber (high side weir, stilling pond, vortex)

Notes

1 For spill flow rates up to and including the design flow [3], separation from the effluent, of a significant quantity of persistent material and faecal/organic solids greater than 6mm in any two dimensions. Spill flow rates in excess of the design flow [3] shall be subject to 10mm solids separation [2].

2 For spill flow rates up to and including the flow resulting from a 1 in 5 year return period storm, separation, from the effluent, of a significant quantity of persistent materiel and faecal/organic solids giving a performance equivalent to that of a 10mm bar screen.

3 Where Time-Series data is available, the design flow for 6mm separation[1] shall be the flow equivalent to 80% of the flow volume that would be discharged in an annual time series. Where Time-series data is not available, the design flow for 6mm solids separation[1] shall be the flow equivalent to 50% of the volume that would be discharged in a 1 in 1 year return period design storm.

4 Experience has shown that the 6mm design flow based on annual time series will normally be less than that using design rainfall. For this reason, use of locally adjusted time series rainfall should always be considered, despite the additional time taken to determine the design flow.

The AMPs are a compromise based on what is deemed affordable in the context of the minimal scientific understanding of the problem. The work carried out is therefore in accordance with the best available technology not entailing excessive costs (BATNEEC) to limit the pollution of receiving waters from CSOs so to meet the UWWT Regulations. The current technologies to reduce the quantity of aesthetic pollutants spilt at CSOs involve the introduction of screens or produce chambers with the equivalent performance. The options to reduce the quantity of solids spilt are to use hydraulic separation and the use of storage.

However at this moment in time there is a lack of knowledge of the type and quantity of pollutants that enter from different populations and this is important to estimate the efficiency of a CSO. Also little is known about the solids' physical properties or their spatial and temporal distribution within the system. Yet without this knowledge about the solids entering into CSO chambers during a storm, optimal methods for their control cannot be developed. This is important as nearly £7 billion is being spent in AMP3 to improve the water environment with part of this money being focused on over 4800 schemes to deal with the unsatisfactory CSOs (OFWAT 1999).

1.5 Project Aims and Objectives

The current AMP3 undertaking includes the improvement of a large number of unsatisfactory CSOs, however at present there is a lack of knowledge of the nature and composition of aesthetic pollutants entering a sewer system and CSO. The improvements to CSOs are being undertaken within the BATNEEC, however the knowledge gap is evident and a collaborative research project has been undertaken in an attempt to bridge this gap. The work undertaken and presented in this thesis was part of a collaborative project supported by the Engineering and Physical Science

Research Council (EPSRC) and UK Water Industry Research Ltd. (UKWIR) involving Imperial College of Science, Technology and Medicine (IC), University of Sheffield (UofS) and Sheffield Hallam University (SHU).

This project was in response to a specific call for proposals from the Water Infrastructure and Treatment Engineering Programme (WITE) as part of EPSRC. The project 'Predicting Aesthetic Pollutant Loadings from Combined Sewer Overflows' aimed to develop a greater understanding of the correlation of the production and transportation of aesthetic pollutants during storm events. This was to take into account the physical nature of the catchments, the catchment characteristics of the sewer network and the socio-economic groupings of the population. This understanding was also to produce a predictive model of aesthetic pollutant loadings that would be presented to CSOs to provide assistance to sewerage upgrading schemes (Balmforth et al. 1998).

As part of the project the UofS classified the population types residing in each catchment where fieldwork was undertaken by SHU. They also undertook a postal questionnaire to determine the types and quantities of sanitary solids that were flushed by individuals in one month. Work at SHU involved a dedicated programme of field monitoring, sampling pollutants and measuring flows. A mathematical model was then constructed to predict the flushing of solids during storm events. This was connected to a solid tracking model produced by IC that monitored the movement of solids during dry and wet weather. This model then linked into a CSO model built by the UofS that used CFD and separation efficiency cusps of actual pollutants to determine the quantity of solids retained or spilt during a storm.

The output from this collaborative project will provide part of the knowledge gap that exists informing of the type and quantity of solids that could be presented to a CSO chamber and the quantity of solids that could be spilt during different wet weather events.

The main objectives of the work at Sheffield Hallam University and the PhD, that forms the work presented in this thesis, was to:

- To develop an understanding of the physical characteristics of the aesthetic pollutants and their spatial and temporal variability in the sewer system through a programme of field monitoring during dry and wet weather events
- To determine the effects of various social, economic and ethnic population types on the production of aesthetic pollutants
- To determine the effect that the physical properties of the catchment and the characteristics of the sewer network have on the transportation and temporal distribution of aesthetic pollutants
- To build and verify a mathematical model for predicting the composition, quantity and temporal distribution of aesthetic pollutants in combined sewerage system

1.6 Outline of Thesis Chapters

The structure of the thesis highlights the many uncertainties at the start of the project due to a lack of quality information. Field data was initially required to provide an understanding of the processes occurring within the sewer system in dry and wet weather. This work confirmed that solids were stored in the sewerage system and flushed out during a storm creating a first foul flush of aesthetic pollutants. It also confirmed that different populations produce different quantities and types of aesthetic pollutants. This knowledge enabled the subsequent prediction of the quantity of solids deposited in dry weather and a model to predict the temporal distribution, quantity and type of solids exiting the system under storm conditions. The importance of this work as part of the collaborative research project is highlighted in the final chapter.

Chapter 1 introduces the work in the thesis explaining why it has been carried out. The problem of aesthetic pollutant discharges from CSOs is discussed and set against the context of consent standards set by UK Government and the EC. The aims and objectives of the work are described along with an introduction to the collaborative research project that has supported and complimented this work.

Chapter 2 contains a literature review of the three main areas of work related to the project; the quantity and type of solids entering the sewer, aesthetic pollutant sampling and gross solids modelling in CSOs and sewers. A critical review of this previous work is provided that highlights the position of current research with regards to aesthetic pollutant movement in sewers.

Chapter 3 introduces the catchments selected for fieldwork describing the site selection procedure, the sewer network, catchment characteristics and the population residing. The methodologies used for the fieldwork are defined. HydroWorks models constructed for each catchment are discussed and reasons for their use.

Chapter 4 provides the results of the field monitoring conducted at the three catchments in dry and wet weather. A comparison between the total and individual pollutant quantities and types sampled is presented.

Chapter 5 describes the methodology used to predict the quantity of aesthetic pollutants stored in the sewers upstream of the sampling locations. Relationships are developed between the quantity of solids stored and catchment characteristics.

Regression analysis enabled predictive equations to be produced for solids stranded in dry weather in sewers.

Chapter 6 describes the construction of a simple model to predict the temporal distribution of solids leaving the sewer system under storm conditions. Empirical data is used to test the solids' transportation technique used to predict the rate at which solids leave the sewer.

Chapter 7 presents a refinement of the model in Chapter 6 by incorporating a solid input model that predicts the rate that solids enter the transportation model. This enables the solids entering and leaving in dry weather to be predicted and automatically calculates the quantity of solids stored presented in Chapter 5. The overall model is compared with measured dry weather sample data shown in Chapter 4.

Chapter 8 presents the results from the model that was developed in chapters 5, 6 and 7 for individual solid types under storm conditions. The model results are compared with measured data and the accuracy of the model is discussed.

Chapter 9 contains conclusions and recommendations for further work. A brief summary of how the model has been used in the joint project is discussed and its use within industry.

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2 Chapter 2 – Literature Review

This chapter provides a critical review of work completed within the subject area of this project. A number of methods of sampling have been identified as well as methods to model pollutant movement within the sewer system and CSOs.

2.1 Introduction

To combat the discharge of aesthetic pollutants from CSOs, a greater understanding of the source and movement of the pollutants is required. At present there is limited knowledge regarding the quantity of solids that enter the sewer system and how they are transported. Work has been undertaken by various institutions in the UK to monitor and model aesthetic pollutants and the state of this work is considered in this chapter. A summary and critical review of work is undertaken to fully assess the knowledge gap. Five main areas of work have been identified that partially address this gap:

- The quantity and type of solids entering the sewer system
- The methods to measure the solids in the sewer
- The methods to measure the solids in or leaving a CSO
- The attempts to model these solids in a CSO.
- The attempts to model these solids in the sewer

2.2 Source of Aesthetic Pollutants

The type of solid that enters the sewer is largely dependent upon the items flushed via the WC. These solids known as aesthetic pollutants or gross solids are greater than

6 mm in two dimensions, are of a sewerage origin and are aesthetically unpleasant. To understand the movement of these pollutants in the sewer system it is first necessary to know the quantity and rate at which these solids may enter it. This has mainly been undertaken previously by diary surveys and more recently by questionnaires.

Limited research has been conducted relating to studies of wastewater discharges from domestic appliances, in particular the WC. The usage of the WC provides an important insight to the timing of when solids may enter the sewer and forms approximately 35% of the DWF (Ainger et al. 1998). Butler (1991) conducted a diary survey into the frequency of use of the WC and other domestic appliances over a 7 day period. 76 people were involved in the study, pre-dominantly residing in urban and suburban areas of south-east England. The study identified an increase in usage of the WC from 06:00 in the morning to peak between 07:30 and 08:30 before reducing during the middle of the day. A sustained evening peak was observed between 16:00 and 01:00 although the peak was smaller than in the morning. These timings identified when solids would enter the sewer system.

A more detailed study of WC derived sewer solids was conducted by Friedler et al. (1996). A diary survey to determine domestic toilet usage was conducted, with 319 people participating. Evidence was collected relating to faecal related flushes (FRF) toilet tissue and sanitary refuse. Estimates of the quantity of faeces produced were between 100-130 g_{wet}/capita/day. Daily averages for FRF were 0.87 and 1.09 flushes/capita/day for weekdays and weekend days respectively. The high FRF value was surprising as 70% of the population worked away from the home suggesting that most people would pass faeces at home rather than at work. The diurnal profile of FRF flushes is shown in Figure 2.1. This indicates a substantial quantity of faeces is passed during the morning between 06:30 and 09:00, similar to the WC usage observed by Butler (1991).

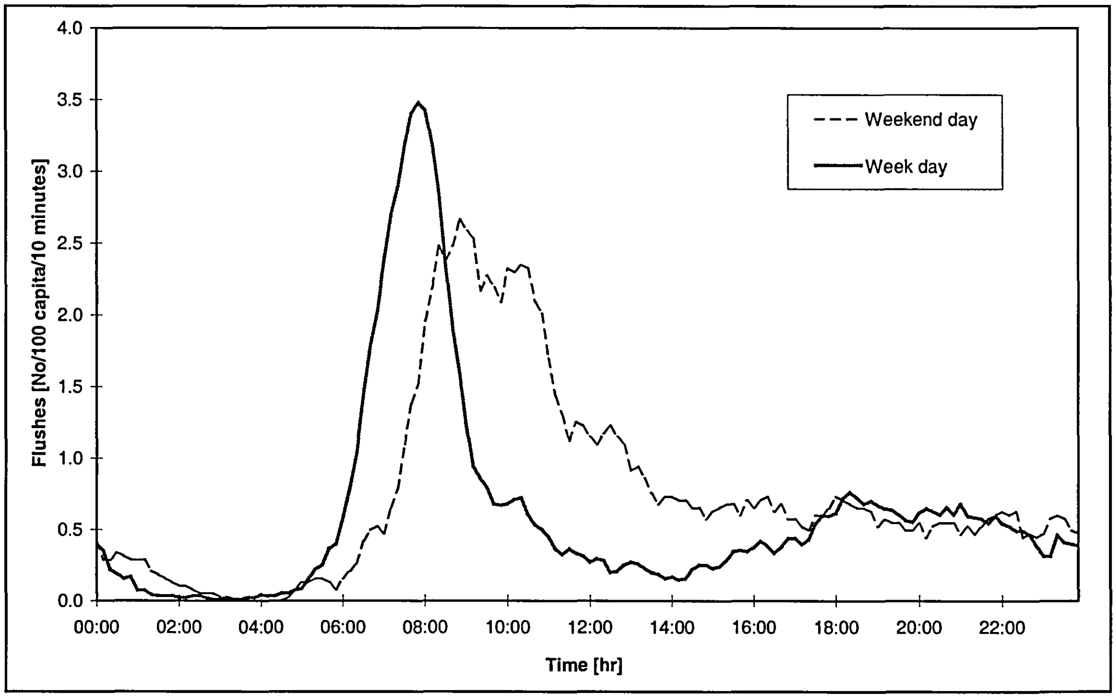


Figure 2.1 Diurnal patterns of faecal related flushes (from Friedler et al. (1996)

An average person in the UK uses 19.4 g of toilet tissue a day (National Bag It and Bin It Campaign 1995). However the quantity used in the Friedler et al. (1996) survey was 8.4 and 4.3 g_{dry}/capita/day for females and males respectively equivalent to 15.3 and 7.8 sheets/capita/day if a sheet has an average dry mass of 0.55 g. These values were substantially lower than the average of 19.4 g equivalent to 35.3 sheets. Meeds (1995) conducted a survey of toilet tissue usage of colleagues and determined that females used 94.5 g_{wet}/person/day and males used 40.6 g_{wet}/person/day. The average value of a sheet of wet toilet tissue measured in the laboratory is 4.7 g therefore the number of sheets used in the survey by Meeds (1995) equates to approximately 20.3 and 8.7 sheets/person/day. These values are greater than that reported by Friedler et al. (1996) but less than from the National Bag it and Bin it campaign highlighting the variability of the surveys undertaken. The number of sheets used is likely to be affected by the number of times faeces are passed to the WC and type of food consumed. Therefore it is reasonable to assume that the quantities of toilet tissue used vary significantly depending upon the individual. The temporal distribution of toilet tissue entering the sewer follows a very similar pattern to the FRF profile in Friedler (2000).

The quantity of faeces and toilet tissue entering the system would be classified as aesthetic pollutants, clearly being of sewerage origin and greater than 6 mm in two dimensions. However these solids readily degrade into smaller particles and a proportion of the solids will have become smaller than 6 mm in two dimensions therefore not being classified as an aesthetic pollutant. The rate of degradation is important and for faeces, a number of factors influence this rate such as the strength and size of the faecal stool. The age, sex and diet of the individual will affect this (Burkitt et al., 1972).

The other main group of items recorded during the Friedler et al. (1996) diary survey was sanitary refuse. This included various items such as tampons (22.9% of all items flushed), wet wipes (14.4%), tissue paper (11.8%), panty liners (3.8%) although no sanitary towels were reported to be flushed. Due to the low number of items flushed, 340 in total, the diurnal profile was found to be rather erratic. This profile included a variety of items disposed including hair, food, finger nails, make up, chewing gum, cigarettes, kitchen towel, soap and bandages. Hence the diurnal disposal profile included items that were not sanitary protection (SANPRO) products (Figure 2.2).

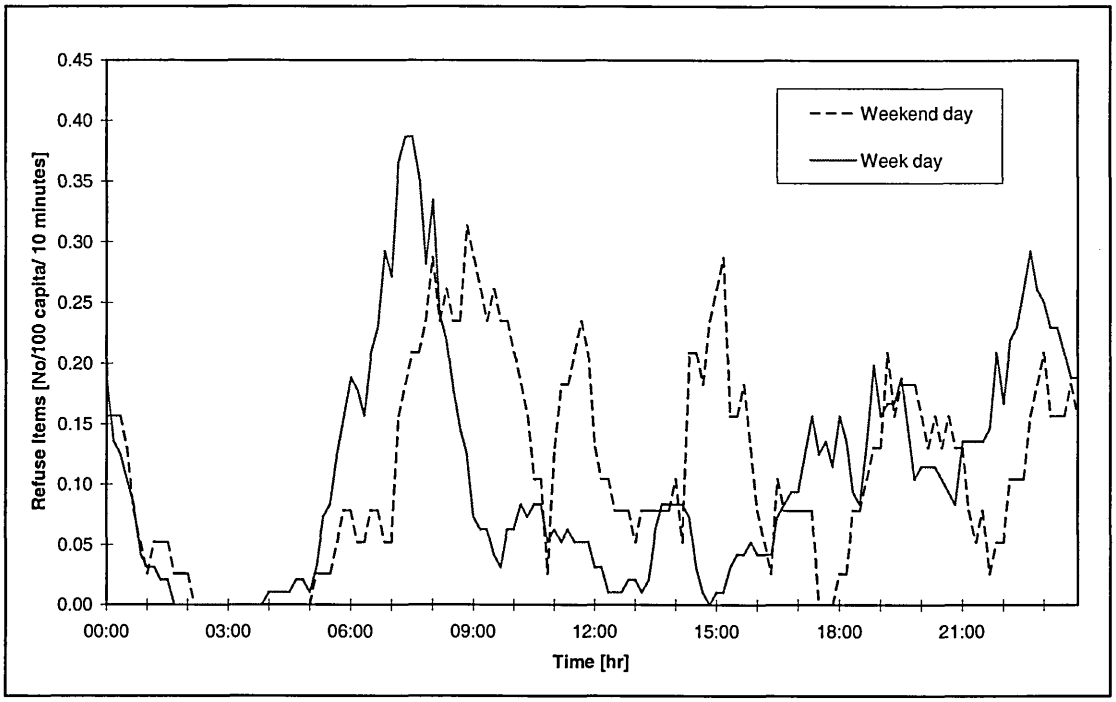


Figure 2.2 Diurnal profile of sanitary refuse disposed of via the WC (after Friedler et al. 1996)

The reliability of the Friedler survey is completely dependent upon the accuracy of the data recorded by the participants. The recording of the diurnal profile of WC usage and types of solids flushed as well as the counting of the number of toilet tissue sheets used requires careful observations. Therefore the data collected was outside of a controlled environment.

Other work to define the disposal of SANPRO products has been undertaken by the Wastewater Technology Centre at the University of Abertay and by the University of Sheffield. In Dundee, Ashley et al. (1999) conducted a questionnaire survey of 927 people who were interviewed regarding their disposal habits before and after a 'Think before you flush' campaign. It was found that 79% of tampons were flushed as were 50% of sanitary towels and 32% of panty liners prior to the campaign. This indicated that the most common pollutant to enter the sewer were tampons prior to the campaign. Following the campaign tampons remained most likely to be flushed although the value was reduced to 54%, while the number of sanitary towels flushed were reduced to 25%. No information was available for panty liners. Unfortunately no values for the quantity of pollutants used were presented making a comparison against other surveys limited.

A second study, recently undertaken by Houldsworth (1999a), posted a questionnaire to residents in the catchments defined in Chapter 3 and was similar to that used by Ashley et al. (1999). This work was part of the collaborative research project defined in section 1.5. The main aim of the Sheffield questionnaire was to obtain data on product disposal habits within the home only Houldsworth (1999b). Encouragement to return the questionnaire was in the form of a £5 gift voucher. A total of 250 surveys were sent out in each catchment and the response rate in every catchment was over 60% (Houldsworth (1999b), Houldsworth (2000) and Houldsworth (2001)). The questionnaire provided information regarding what SANPRO and hygiene products were used in the home, how many, and whether they were disposed via the solids waste route or via the WC. The number of SANPRO items and wipes used in total and those disposed of via the WC are shown in Table 2.1. Three different catchments had been selected that represented different population types, these being Low income, High income and a minority Ethnic area. The number of SANPRO items used was similar across the catchments. The pollutant most likely to be flushed was the tampon, with a percentage flushed in all catchments similar to that observed in the Dundee survey. Panty liners were more likely to be flushed in the Low and High income catchments, whereas sanitary towels were more likely to be flushed in the Low income catchment. Baby wipes were more commonly disposed of in the Ethnic area, although the percentages flushed were all relatively low compared to SANPRO items. The questionnaire survey highlighted the large number of SANPRO items that were disposed of via the WC and that different types were more likely to be flushed than others. The results indicated that different population types were more likely to use and dispose of different SANPRO products.

Table 2.1 Quantities of SANPRO products and wipes disposed of in total in the home and the number flushed via the WC in three catchments per a 1000 population in one day.

Pollutant	(No. or % of Total)	Low Income	High Income	Ethnic
All SANPRO	Total	261	283	270
	Flushed	109	151	73
	% Flushed	42	53	27
Panti Liner	Total	107	92	82
	Flushed	36	33	14
	% Flushed	33	36	17
Sanitary Towel	Total	96	58	121
	Flushed	31	5	13
	% Flushed	33	9	11
Tampon	Total	59	133	67
	Flushed	42	113	45
	% Flushed	72	85	68
Wipes	Total	255	340	532
	Flushed	17	16	73
	% Flushed	7	5	14

The accuracy of the survey by Houldsworth is difficult to ascertain. The questionnaire asks for the number of products disposed at the home only, which may be difficult for people to estimate. The estimation of the number of items used may also be based on what they perceive they should use rather than what they actually do. The number of people responding to this survey was only small with approximately 450 responses, of which 60% were female, equating to responses from people using SANPRO products of 270. Take into account the number of females past menstruating age and not using any type of product and the sample population is rather small.

The diary and questionnaire surveys have provided an important insight into the quantity and number of solids disposed of via the WC. The diary survey provided information regarding when faeces, toilet tissue and SANPRO items were disposed of. The questionnaires provided information on the number of SANPRO pollutants flushed in one day, and an indication that different population types use different products. The combination of these surveys could provide a temporal distribution of the rate and time at which these solids enter a sewer system. However the quality of the data is less reliable because of the low number of participants and that they are outside of a controlled environment. These surveys would also benefit from being on a larger scale with more participants.

2.3 Measurement and Analysis of Aesthetic Pollutants

2.3.1 Measurement of aesthetic pollutants from CSOs and sewers

Once an understanding of the production rates has been established, knowledge of the solid types in the sewer is required to determine whether the quantities perceived to enter, actually do. Some solids that enter are more likely to degrade during transportation than others therefore solids like faeces and toilet tissue are likely to be measured in smaller amounts than what actually entered. Other solids such as SANPRO products are unlikely to degrade due to their plastic nature and are more likely to be measured accurately.

To enable the comparison between solids entering and the quantity at various locations in the system various attempts have been made to collect these solids. Physical, chemical and biological sampling from the sewer system has been commonplace for many years in the form of total suspended solids, BOD, COD etc. However the measurement of the larger pollutants has only been of particular interest to practitioners and researchers alike, over the last three decades.

The first focus in measuring aesthetic pollutants was at a CSO investigating the quantity of solids discharged during a wet weather event. An early attempt by Mutzner (1987) to quantify discharges from CSOs was by counting the number of visible solids per metre on a river bank. This method did not suggest any relationship between the flow discharged and the antecedent dry weather period (ADWP). The ADWP was considered to be important due to the longer the dry weather period prior to a storm event, the more time was available for solids to be deposited on the sewer inverts upstream of the CSO structure. This method was also used in the 'User Guide to Assess the Impact of Gross Solids Discharged from CSOs' (Milne and Clarke (1994)). This guide recommended a procedure for classifying and prioritising CSOs if upgrading of the structure was required in terms of the impact on the receiving water course.

The approach of counting the number and type of solids downstream of a CSO is useful. It provides an indication to the quantity of solids that are likely to cause offence to people using the area, therefore providing an indication of whether the CSO is performing correctly. However, the number of solids that could be deposited at the edge of a watercourse could be very different after an event with some solids being washed downstream with the flow that could vary depending upon the size of the event. If this number were large then the quantity deposited would not indicate the total number of solids being spilt form the CSO. The area where the solids are deposited will be different from site to site therefore it could be difficult to determine how many solids would be visible after a storm at different sites. It is also important to include only items of a sanitary origin rather than all litter. It is not surprising that a link with ADWP could not be determined due to the large number of other factors that contribute to the solids being discharged and deposited.

Three main other methods have been used at CSOs to sample the quantity and type of pollutants entering, or as part of the spill flow providing relief to the system. These were:

- The Gross Solids Sampler (GSS)
- Copa sacks at the spill side of a CSO
- Trash traps at the spill side of a CSO

The GSS attempted to take representative samples from combined sewer overflows and was partly developed by Cootes (1990) at SHU with the Water Research Centre (WRc). One hundred millimetre tubes were used to suck up samples from the inlet or at the spill point and pass the material under a video camera that recorded the shapes of the solids passing. An attempt was made to automatically count the number of solids, however this was abandoned because of difficulties in getting the system to work satisfactorily. Instead each tape was analysed by eye with the number of solids passing being counted. Unfortunately this initial system to count the number of solids could not provide definition of the type of solids passing.

Further work using the GSS as well as a TSS sampler was undertaken by Jefferies (1992) in an attempt to predict the loadings at CSOs. One hundred millimetre diameter pipes were used to suck up samples and pass through COPA mesh sacks. These would retain solids that were greater than 6 mm in two dimensions at the inlet and overflow points to the CSO. This therefore allowed the quantity and type of solids to be determined, unlike previously with Cootes work. Trash traps were also positioned at the overflow point to retain discharged pollutants. The number of items was counted on the trash traps as well as downstream of the overflow discharge point for 25 m. No correlation was found with the numbers of solids for peak flow rate or spill volume, however a correlation was observed between the ADWP and the number of solids counted on the trash trap for a number of storms (Figure 2.3).

A number of sampling problems was experienced with the GSS due to the equipment not working correctly. However where the sampler was working correctly, a relationship was developed between gross solids and TSS (Equation 2-1).

$$LGSS = \mathbf{0.005} \times e^{2\times\ln(LTSS)} \qquad \textbf{(2- 1)}$$

Where:

LGSS = Gross solids sampled loading

LTSS = Total suspended solids loading

However when this equation is plotted with the data recorded for inlet and overflow using the GSS, the data suggests that there is a poor correlation between the predictive equation and the data points (Figure 2.4). A large amount of scatter was observed yet this is not discussed in the text of the paper. It would appear that the relationship between TSS load and the gross solids load is not strong.

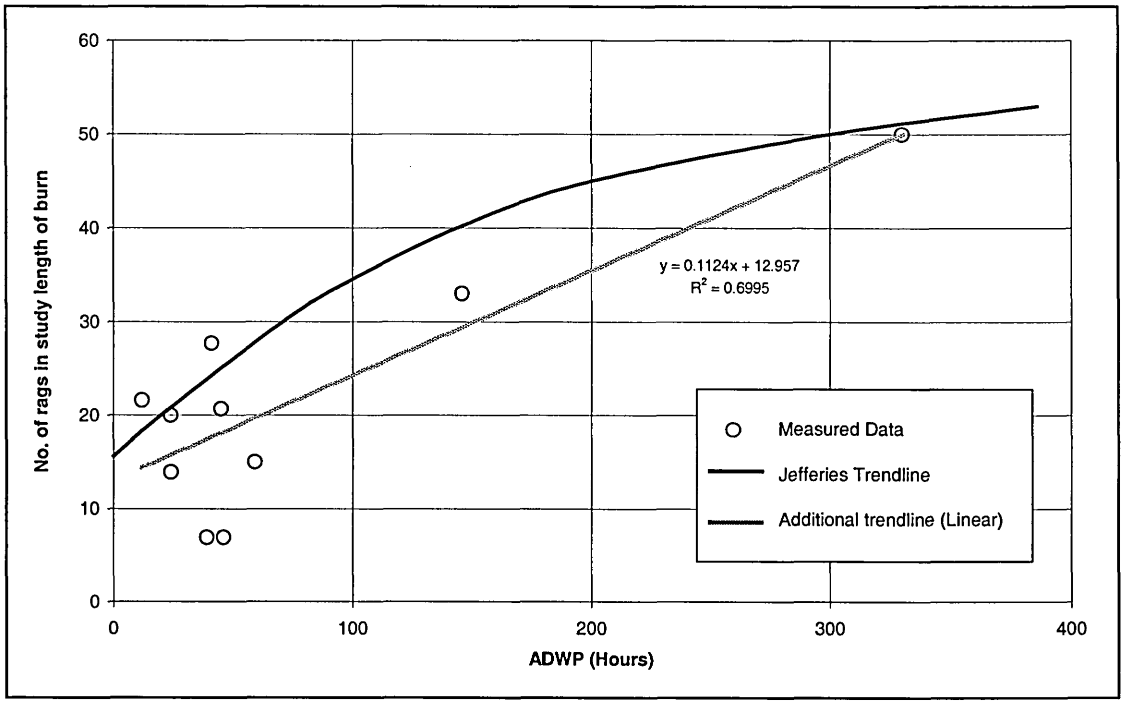


Figure 2.3 Discharge of visual solids against ADWP, adapted from Jefferies (1992)

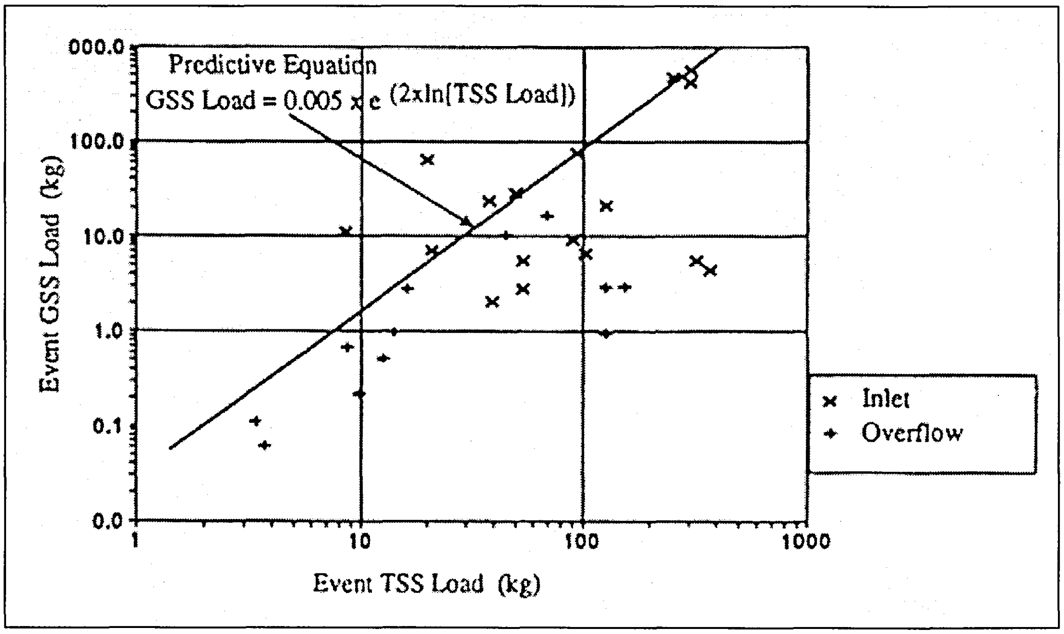


Figure 2.4 Estimation of Gross Solids Loads compared to measured TSS and gross solids, from Jefferies (1992)

The GSS effectiveness in determining the quantity of gross solids was hampered by its design and method of working. The GSS was the size of a caravan and hence could only be used in large accessible areas. In addition samples of gross solids were taken which only allowed a small proportion of the solids in the flow to be sampled. This limited the ability to accurately predict the temporal distribution, quantity and type of aesthetic pollutants entering CSOs or being spilt.

Further work conducted by Jefferies and Ashley (1994) used the GSS to produce some temporal catchment relationships. In dry weather the number of solids observed dropped to almost zero during the night, and they suggested that this was the principal period when solids would be deposited. However the research by Friedler et al. (1996) suggested that number of solids entering the system was low during the night, hence the number of solids sampled would have also been low. This is more likely to be the case as water consumption drops to a minimum at night, suggesting that fewer solids will be flushed via the WC during this period.

Other work by Jefferies and Ashley (1994) identified the rate of solids production being a critical factor in determining loading and differentiating between catchments with collector sewers and trunk sewers. It was also inferred that gross solids were transported under the same hydraulic conditions as the highly mobile Class C sediments (as defined by Crabtree (1989)). This was an important assertion when attempting to understand how gross solids moved through the sewer system. Further work regarding the importance of ADWP was presented that considered that greater than 24 hour periods would allow considerably greater accumulations than shorter dry weather periods. Fieldwork undertaken in France by Bertrand-Krajewski (1992) has identified that the ADWP has an effect on the quantity of solids produced. An increase in the mass of deposits was observed at one catchment as the ADWP increased (Figure 2.5). However these loadings had not been directly measured but were calculated following the interpretation of five suspended solids loadings. The reliability of these results without any direct measurement of solids' loading is questionable as they do suggest that the loadings increase as ADWP increases, but potentially the rate of increase reduces as the ADWP increases.

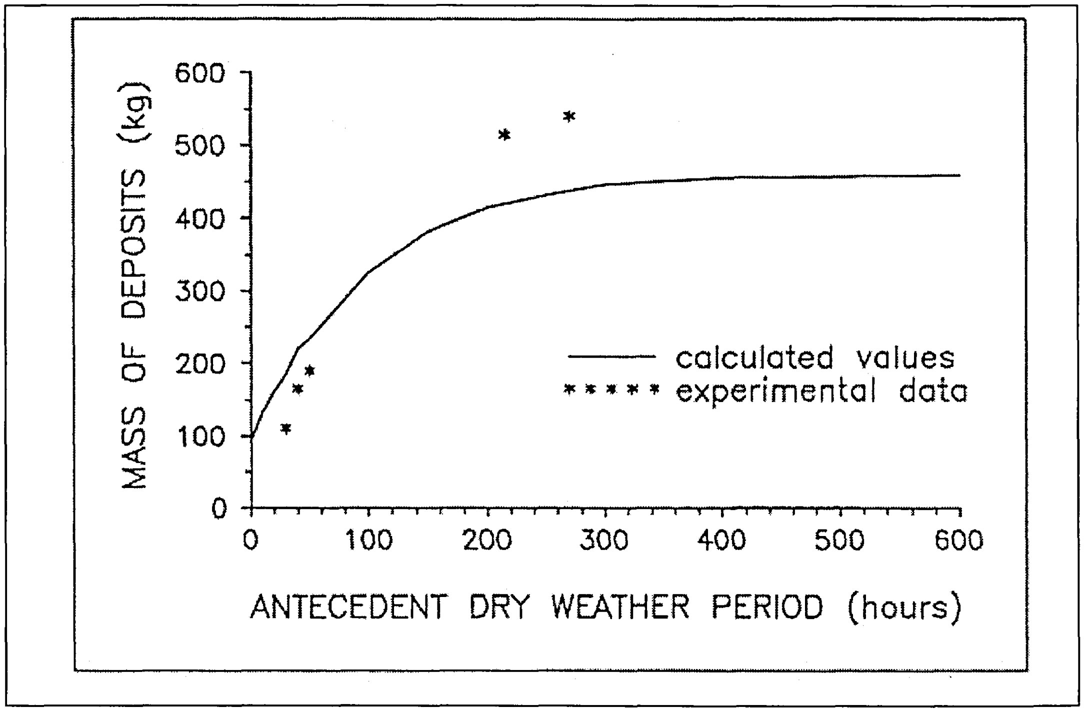


Figure 2.5 Mass of deposits measured and calculated from Bertrand-Krajewski (1992)

Other collection methods at CSOs have been concentrated at the overflow point where COPA mesh sacks were attached to the spill side of a CSO (Balmforth et al. (1995) and Meeds (1995)). This enabled the total mass spilt per a storm event to be known and the typical composition of this mass but not the temporal distribution during a storm. Secondly an error could occur if the sacks became blinded and filled with water. This would provide the potential for solids to continue to the discharge point and not be retained in the sack. This would mean that the results could have under predicted the quantity of solids being spilt. COPA mesh sacks used in these and other applications had an aperture of 6 mm by 4 mm.

Arthur and Ashley (1998) used COPA mesh sacks to sample in the sewer. The sack was attached to a 100 mm diameter pipe and lowered into the flow. The time the sack was in the flow was for short periods of time only and not over a 24 hour period. A number of problems exist with this method of sampling in that only a snapshot of the solids passing at that particular time was obtained and it did not direct all the solids through the sack. Hence only a percentage of the solids were sampled, yet without knowing this percentage, the loadings of the solids within the catchment remains unknown.

In all the previous methods of sampling from combined sewers, none have successfully recorded the temporal variation of aesthetic pollutants. Without this knowledge it is not possible to determine the gross solids' loading presented to a CSO during a storm.

2.3.2 Classification of samples

The methods used to classify the samples taken at the spill side of CSOs are well founded by Balmforth et al. (1995) and Saul et al. (1998). Samples were sorted by hand into specific types of pollutants with the mass and size recorded. A different step was used by Milne et al. (1996) where wet solids were dried in an oven at 105°C and weighed before being placed into a furnace to determine its volatile weight. Classification was then governed by their different weights through the various phases.

Following the classification of pollutants, they are often subjected to further testing to determine their rise or settle velocity. This has been undertaken to help understand their behaviour in CSO chambers in an attempt to reduce the number spilt as part of the discharged flow to a water course. Simplistic methods have been used for gross solids testing by Meeds (1995) and Saul et al. (1998) where a 2 m tall Perspex column, 400-500 mm in diameter, was filled with potable water and pollutants introduced at the top of the column. A large diameter cylinder was used to reduce the chance of solids coming into contact with the sides. The time for the pollutant to sink over a one metre central length was recorded. Where pollutants were found to rise, they were gently lowered to the base of the column using a grab claw and released, with the time taken to travel the central distance recorded. Meeds tested two types of unused products, sanitary towels and panty liners that were dry and soaked with the mean terminal velocity and standard deviation shown in Table 2.2.

Table 2.2 Mean terminal velocity and standard deviation of two types of unused products tested, from Meeds (1995)

	Mean Terminal Velocity (m/s)	Standard Deviation (± m/s)
Regular Sanitary Towel		
Dry	-0.195	0.076
Soaked for 24 hrs	-0.090	0.045
Soaked for 48 hrs	-0.066	0.042
Plastic Shell	-0.035	0.023
Panty Liner		
Dry	-0.282	0.121
Soaked for 24 hrs	-0.147	0.118
Soaked for 48 hrs	-0.053	0.104
Plastic Shell	-0.047	0.032

All the mean terminal velocities of the products dry and after soaking floated. The standard deviation reduced after the pollutants had been soaked for longer, although the standard deviation was larger for the panty liner than the sanitary towel. After soaking the terminal velocities of the pollutants were considerable slower than under dry conditions. It suggests that the solids have terminal velocity closer to zero the longer they are soaked. These raw results are very useful, however the opportunity to tests used products was not taken during fieldwork where samples were collected from CSOs. Used products may well behave differently during tests because of their application.

Saul et al. (1998) tested used products following the collection of samples from the Wigan CSO test facility. The main types of pollutants tested are shown in Table 2.3. The three pollutants of an aesthetic pollutant origin are discrete tissue paper, tampons and toilet roll. All of these solids settled, unfortunately no standard deviations of the pollutants tested were presented. The work by Meeds (1995) and Saul et al. (1998) does highlight that different pollutants will behave differently sinking and floating, however it would have been useful if the same pollutants had been tested to draw a comparison.

More complicated forms of testing have involved a column of water to be rotated and the pollutants released (Pisano 1995 and Tyak et al. 1995). These have been used on sediments, sands and suspended solids, which were smaller than gross solids therefore could be tested using this method. This method is not suitable for the larger solids would come into contact with the other pollutants as well as coming into contact with the side of the equipment. In addition it would be very difficult to measure the rise or settle velocity of each pollutant. Therefore it is more appropriate to use a large Perspex cylinder and test the pollutants individually, rather than all together.

Table 2.3 Characteristic diameters and settling velocities of the main particle types tested from samples taken at the Wigan CSO test facility, from Saul et al. (1998)

	Discrete tissue paper	Stringy matter	Tampons	Toilet roll	Vegetable matter
Number of particles	18	18	12	18	101
Mean characteristic diameter $(l_1 \times l_2 \times l_3)$ (mm)	45.12	40.24	48.11	11.19	13.32
Mean settling velocity (m/s)	0.022	0.040	0.056	0.028	0.026
Total mass of collected solids (g)	1019.8	3214.1	624.4	258.4	5649.5
Overall mean diameter (mm)			25.22		
Overall mean settling velocity (m/s)			0.032		

2.4 Modelling Aesthetic Pollutants

2.4.1 Modelling aesthetic pollutants at CSOs

Advances have been made to model gross solids in sewerage systems and CSOs. A simple model to calculate the quantity of aesthetic pollutants presented to a CSO was developed by Balmforth and Meeds (1997). A simple input model of SANPRO item production and transportation were used to determine the loading in a single pipe, representative of the whole catchment. The model assumed that the solids in the DWF prior to the storm arrived at the CSO before the time to peak of the flow hydrograph. The aesthetic pollutant split at the CSO was assumed to be the same as pollutants in fine suspension. A predictive model then calculated the mass presented to the screen (Figure 2.6 and Equation 2-2). This was a simplistic model but showed a good correlation with measured and predicted results (Figure 2.7). The importance of knowing the quantity of solids within the DWF at a particular time of day was therefore an important component for this model to work.

$$\text{Mass of pollutants presented to a screen} = \text{Total mass} \times \frac{b}{a+b} \qquad \textbf{(2-2)}$$

Where: Area a = continuation volume

Area b = volume to overflow (passed to screen)

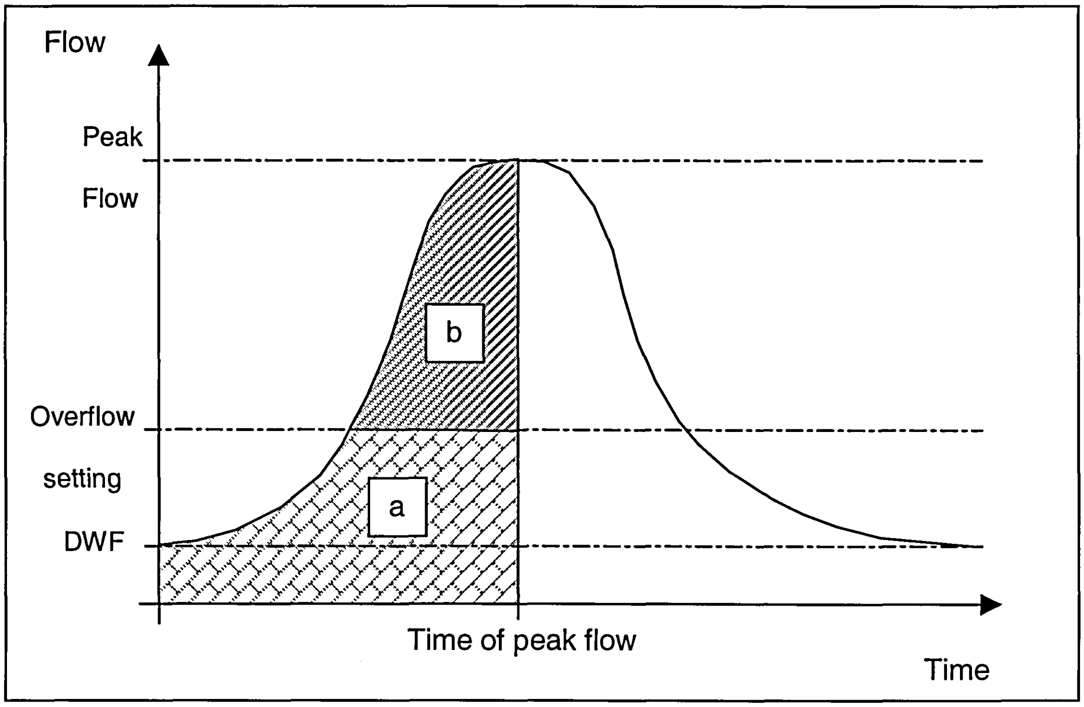


Figure 2.6 Flow and theoretical pollutant split within a CSO after, Balmforth and Meeds (1997)

The previous model was based upon solids in the sewer that would enter and have the potential to be presented to a screen in a CSO. More recently a predictive tool has been developed called 'Aesthetisizer' (UKWIR 1997). This is used as an aid in the design and improvement of CSOs for aesthetic pollution control. 'The software enables design flows for 6 mm screens to be established from storm event data, to calculate CSO dimensions based on design tables and to calculate overall efficiency using both storm event data and design chart tables' (UKWIR 1997). It calculates the division of aesthetics at CSOs based upon empirical data depending upon the type of chamber and whether a screen is used.

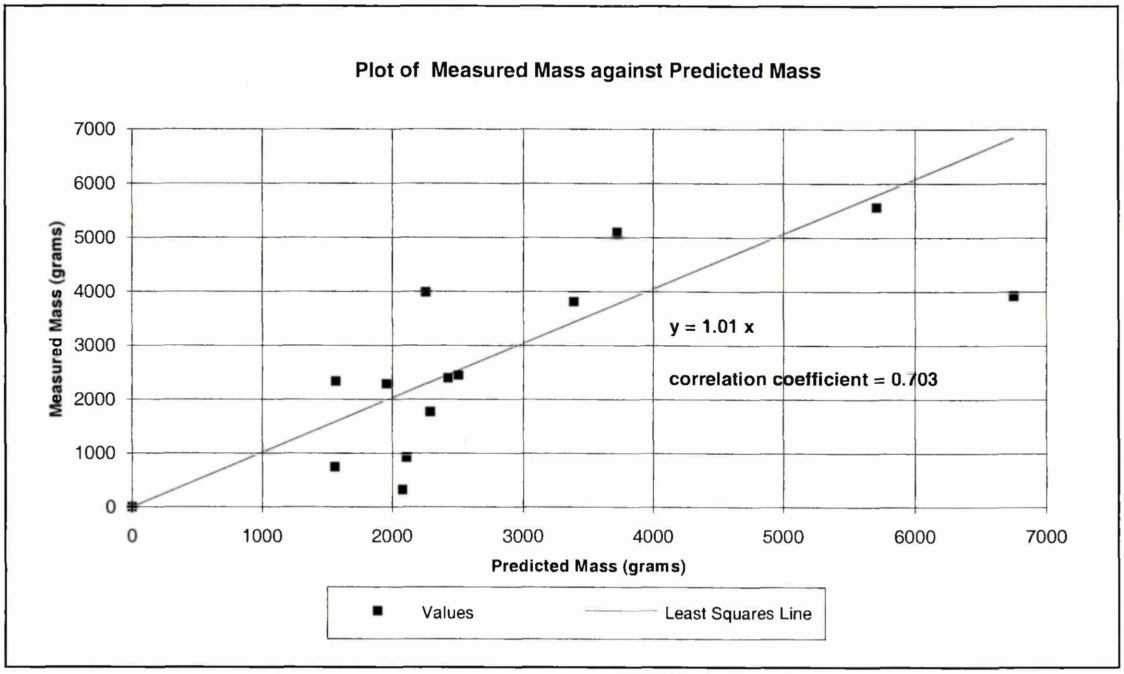


Figure 2.7 Comparison of measured and predicted values for the quantity of aesthetic pollutants passed to a screen at a CSO, after Balmforth and Meeds (1997)

Other models being developed in CSO's relate to the use of computational fluid dynamics (CFD) to predict the movement of the water within CSO chambers (Saul et al. 1998, Stovin et al. 1999). The retention efficiency of each structure can be predicted by tracking individual solids, determining whether they are spilt or pass to continuation. This, as with other models is highly dependent upon the solids that are assumed to enter the chambers. The solids used in these tests were spherical in shape and not sizes observed for SANPRO products. Saul et al. (1998) acknowledges that aesthetic pollutants are rarely spherical therefore the particle tracking is only an approximation. The difference in the behaviour of gross solids to spherical particles is likely to be related to their shape, mass and drag forces that the particles are subject to in the CSO. Until the behaviour of these solids is understood, an accurate model of tracking the movement of solids in a chamber is unlikely to be realised.

2.4.2 Modelling aesthetic pollutants in sewers

A number of computer simulation models that were primarily designed to be hydraulic models such as Hydroworks and the MOUSE suites, have been adapted to include functions that will predict physical, chemical, and biological pollutants. However these models have not so far included aesthetic pollutant transportation. The Aesthetisizer software and other CSO models do not model the quantity, spatial or temporal distribution of aesthetic pollutants that enter a CSO or in the combined sewerage system upstream. This forms an important part of the process to be able to predict the quantity of pollutants that could be spilt from a CSO. The modelling process of solids in sewers has mainly been based upon laboratory work and has identified various important factors relevant to the transportation of solids. Once the solids have entered the system they are then transported immediately, or are deposited and eroded at a later date during higher flows than when they were deposited. The importance of ADWP in the accumulation of pollutants has been identified in section 2.3.1 following observations made in the field. Other factors and associated models are considered in this section.

An early investigation into the movement of pollutants was conducted by Ackers et al. (1967). It was observed that relatively little longitudinal mixing occurred between the existing steady foul flow and the storm water. During a storm an increase in the water depth and discharge would occur in advance of the arrival of storm water and contain undiluted foul flow. It was observed prior to this by the Hydraulics Research Station

(1965) that the volume of the undiluted flow at the front of a storm surge was equal to the original DWF volume. This movement of the undiluted foul flow was classified as a first foul flush. This work identified when the major quantity of solids would arrive at a CSO during a storm event. The DWF volume was therefore the initial volume of water with solids that would require to be treated or retained within the system rather than being discharged to a receiving water.

Davies (1987) investigated the movement of artificial particles in a base flow when a storm wave was introduced. It was observed that floating particles were contained in the volume at the front of the storm wave, whereas sinking particles were spread over a greater volume throughout the wave. This suggested that particles with different specific gravities would move at different velocities within the flow. One particular note referring to further work required, was the inclusion of deposited solids that would be re-entrained during a storm. Further work by Davies (1990) and Davies et al. (1996) identified that the relationship between particle velocity and mean flow velocity was the same for unsteady and steady flow. The relationship between 3 solid types and the mean flow velocity under steady flow conditions is shown in Figure 2.8. This was determined following tests in a 100 mm diameter Perspex pipe with steady and unsteady flow where artificial and actual sewage particles of a floating, suspended and bed load nature were introduced into the flow. A model constructed using the relationship above produced a close agreement between simulated and laboratory observed data. This work identified how different solids could be transported in a sewer although the conditions in a Perspex pipe would be very different to that in a sewer where the roughness of the pipe would be greater. The authors noted that they would expect the behaviour of the pollutants in the sewer to be different because of physical degradation and interaction with other material.

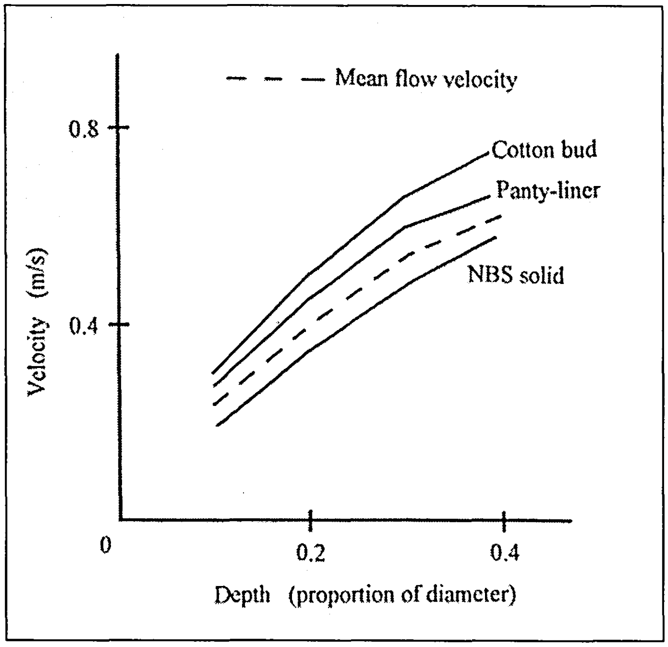


Figure 2.8 Solid velocities and mean flow velocity against depth (as a proportion of the pipe diameter for a gradient of 1:500, after Davies et al. (1996)

Numerous researchers have investigated the advection and deposition of solids. This work has enabled a variety of models to be developed to predict the movement of solids in a single pipe in the laboratory. Studies by Davies et al. (1995) and Davies et al. (1996) observed that the water depth and water velocity at a variety of gradients was critical in determining whether panty liners were deposited. The re-erosion of the solid would not occur until the critical values were exceeded. Different values were observed for different solids and a relationship between the solids velocity and mean water velocity was determined. The third factor, although deemed not as critical as depth or velocity was the shear stress at the wetted perimeter. The shear stress was observed to consistently reduce, as the gradient of the bed slope became shallower. A model to predict the transportation of solids was developed by the above authors and Brown et al. (1995) using the full Saint-Venant equations to produce water depth and velocity at any point. The solids movement was then calculated using the relationships between mean water velocity and solid velocity. The solids movement was then tracked to determine the time taken to travel 9 m in a pipe. A comparison between measured and simulated results is shown in Figure 2.9. This model had only been tested under laboratory conditions in a single pipe, and testing against fieldwork data was proposed. Also the model did not include degradation of solids, nor the influence of other particles affecting the movement of solids.

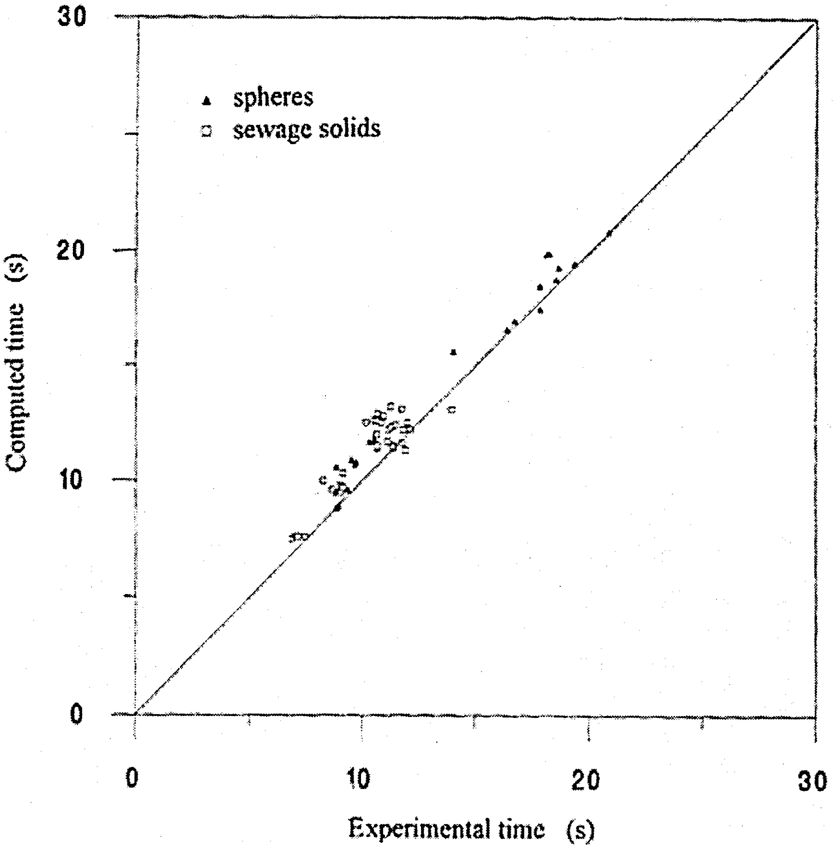


Figure 2.9 Comparison between the simulated and measured time for particles to travel 9 m in unsteady flow conditions, after Davies et al. (1996)

Studies by Davies and Sekuloski (1996) and Davies et al. (1998a) conducted in a smooth and roughened 300 mm diameter pipe identified that solids' deposition was influenced by the size of the particle. Solids of the same density but smaller in size were likely to be deposited at lower values of depth and velocity. This is important, as certain solids such as faeces and toilet tissue are likely to degrade in the sewer because of their physical properties. The NBS (a US National Bureau of standards artificial faecal solid) solid is used to represent a standard faecal stool however as this does not degrade the behaviour of faeces in the sewer could potentially vary significantly from that of the NBS solid. This would therefore change the rate of movement of faeces through a sewer as they are transported further through the system. Currently degradation of particles has not been included in any transportation model however it is an important process that could effect the accuracy of a simulation of particles that are likely to degrade.

Later work by Davies et al. (1998b) suggested that the calculation of the water depth and velocity, essential to predicting the solids' movement, could be determined using Hydraulic computer simulation packages. An example was presented that used the Davies et al. (1996) model to track the solids' movement through a pipe in unsteady flow. Figure 2.10 shows the tracking of particles through a pipe and the distance each particle travelled against time. When the depth or velocity dropped below a critical value (discussed previously) the solids became stranded and only moved once the depth or velocity increased above the critical value. This example was highly simplified and the authors recognised the need for the model to be tested further to determine if the approach could be used to model solids' movement. This approach appears to be logical in tracking the movement of solids and has the potential following further testing to be applied to a number of pipes in a network. However, the model does not account for the interaction with other solids. This is potentially important when considering individual solids movement, particularly in low or intermittent flow regimes. Under these conditions it may be possible for a number of pollutants to collect together at the same location in the system and require an increased depth or velocity to mobilise them. At these points in the system the solids may become stranded and build up with time, only being flushed out under storm conditions.

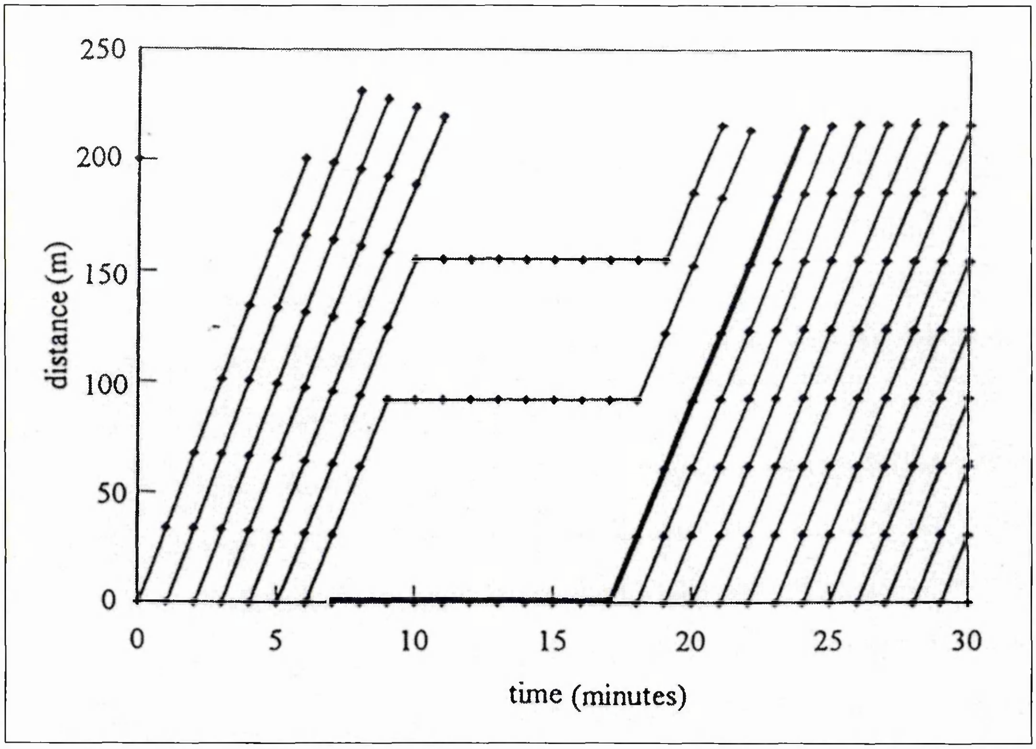


Figure 2.10 Example of the simulation and tracking of particles entering and moving through a pipe, after Davies et al. (1998b)

An adaptation of the model with sensitivity analysis, calibration and verification was reported by Babaeyan-Koopaei et al. (1999). The model was adapted by considering the physical forces acting on the solid; i.e. lift and drag. The governing equations of motion were defined as well as equations for solids motion. Experimental data using artificial particles was utilised in the calibration and verification process of the new model. The experimental results also indicated that the most important parameters to identify the advection behaviour of these solids were water depth and flow shear stresses.

The model by Babaeyan-Koopaei et al. (1999) was furthered by Schütze et al. (2000) where the production, transportation, sedimentation and erosion of gross solids has been accounted for. The production model used data obtained from the survey by Friedler et al. (1996). The transportation model was based upon work by Babaeyan-

Koopaei et al. (1999). Sedimentation and erosion of individual solids was considered following the laboratory studies by Davies et al. (1998a). A simplification of this was to assume that solids' transportation occurred if the water velocity and depth exceeded the critical values, as developed for each solid. The flow was determined using the full solution of the Saint Venant equations. This model formed the fundamental parts of a gross solids simulator (GSS). It was considered not necessary to model the degradation of solids however laboratory work (discussed above) contradicts this opinion by the authors and has the potential to have an effect on the prediction of solids movement. An example of the output from the model is shown in Figure 2.11 where solids entered and were temporarily stranded until the critical values for re-suspension reached therefore a large number of solids were released at the same time. The model was still only based upon the movement of solids in one pipe and not a sewer network. It had not been connected to a Hydraulic computer simulation model or calibrated against measured field data from a real sewer system.

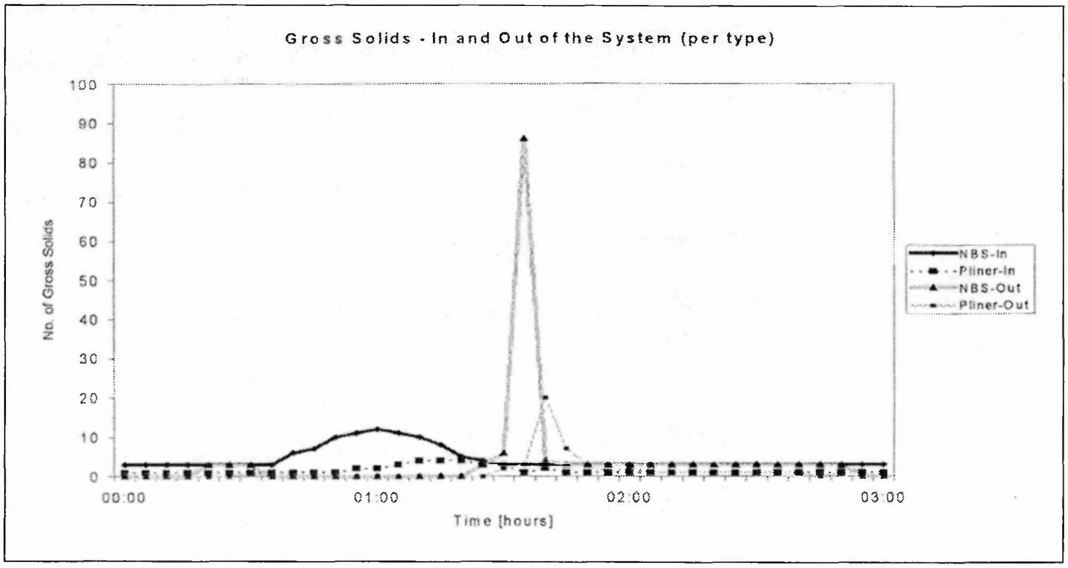


Figure 2.11 Response of to two different solid types entering, being transported and leaving a system, after Schütze et al. (2000)

A number of advances have been achieved in understanding and modelling aesthetic pollutant movement in sewers. However none of the current models presented thus far have been tested against fieldwork therefore further work is required to test against results from real catchments. This could be achieved by linking the transportation model to a hydraulic model as suggested, to enable the prediction of solids movement for the whole network. The development of the latest model by Schütze et al. (2000) built upon the knowledge gained by previous work shows good potential to track the movement of solids. However, it is heavily dependent upon the solids input model being correct. More work is required in this area to confirm Friedler et al. (1996) work as it is vital to predict the quantity of solids that enters the system accurately to ensure the quantity leaving is correct. The modelling of certain solid types is also very important. Faeces and toilet tissue are likely to degrade in the sewer and further investigation into this occurrence is required to enable a model to replicate this.

3 Chapter 3 – Catchment Selection and Field Monitoring Methodologies

This chapter defines the methodologies used to obtain field data from three catchments in the Sheffield area. These catchments and their populations are described. An introduction to the Hydroworks models constructed for each catchment is also provided.

3.1 Objectives of Field Monitoring

Field monitoring was undertaken to investigate the aesthetic pollutant loadings produced by various population types in small upstream combined sewers. This chapter identifies the selection criteria of the catchments, the methodologies employed to obtain field data and descriptions of the sites selected. The site selection and methodologies were designed to enable aesthetic pollutant sampling to be achieved. This data was required to develop an understanding of the production and transportation of aesthetic pollutants in combined sewerage systems.

3.2 Catchment Selection Criteria

3.2.1 Social, Economic and Ethnic Criteria

The initial catchment selection was dependent upon the type of population that resided in the area. Research conducted by Houldsworth (1999) and Houldsworth (2000a) identified locations in which different population types resided. These populations represented different social, economic and ethnic types. Four population types were identified for investigation in the Sheffield area:

- Low-Income
- High-Income
- Ethnic Minority
- Middle Income

The investigation of these different population types would enable an understanding of the quantity, type and temporal distribution of aesthetic pollutants produced. The population types represented a broad cross section of those found in the UK.

The selection of the Low, Middle and High Income catchments utilised a social deprivation map as used by Houldsworth (1999) (Figure 3.1). This map of Sheffield identified 5 different population types based upon socio-economic criteria ranging from low income (marked black) to high income (marked white) based upon data collected from the 1991 Census. The boundaries of the map were based upon political wards that indicated the socio-economic type of the population residing in the area. The map was then adapted to be overlayed on to an OS Landranger map to identify the exact locations. This enabled an investigation of the sewerage system. Similarly the ethnic minority areas were identified by Amin (1996) and this data was transferred to OS maps. A number of areas were then identified for a detailed investigation prior to a suitable catchment being chosen. Following the selection of a site, census data was obtained from the UofS to determine the population size and demographic information.

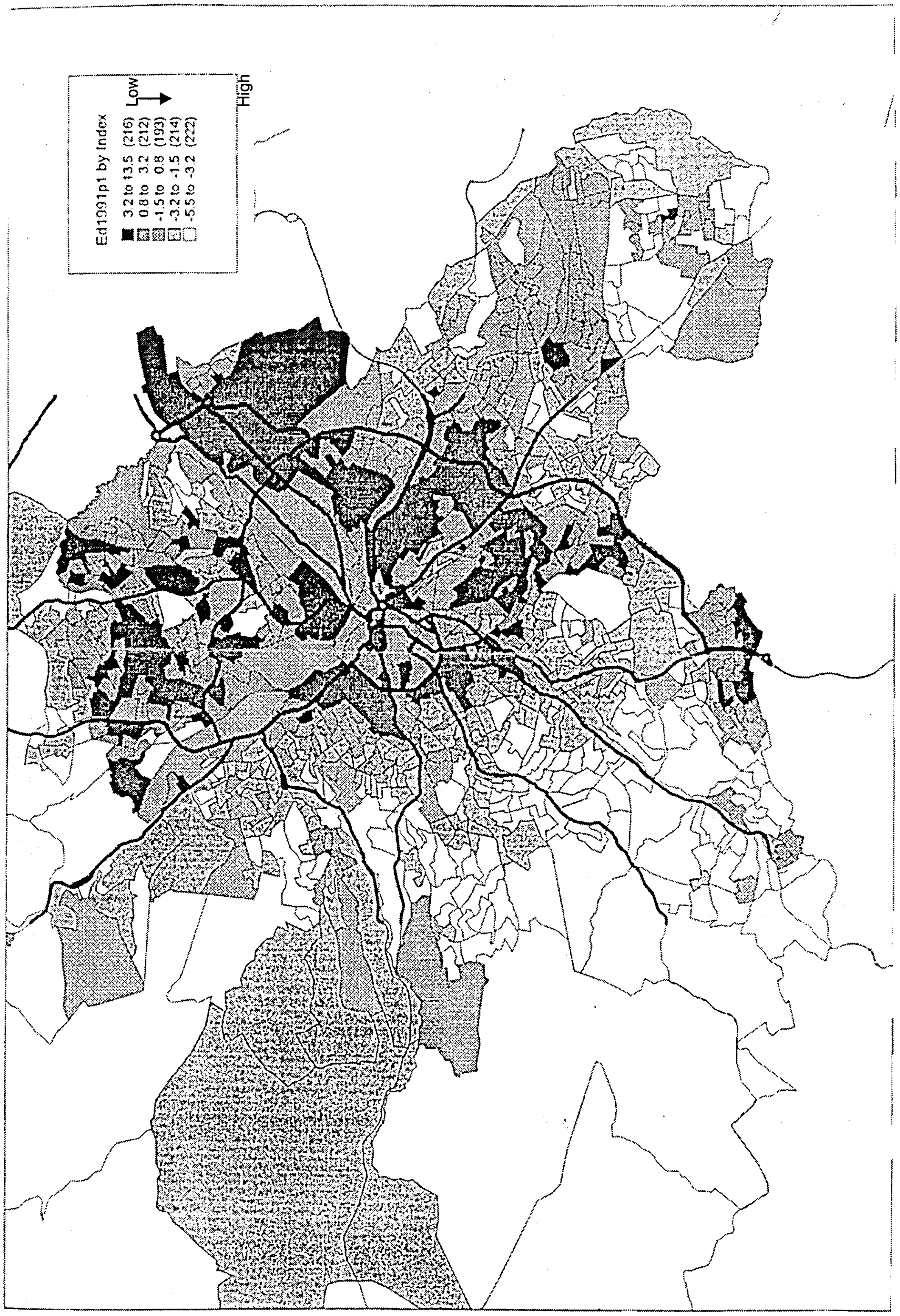


Figure 3.1 - Social Deprivation Map of Sheffield by ED's (from Census Data 1991)

3.2.2 Monitoring Locations Criteria

A number of criteria were considered prior to the selection of catchments and the subsequent fieldwork. A desktop survey for every potential site was undertaken prior to any fieldwork commencing. Three main criteria were considered in the selection of the sites:

1. The sewer network arrangements, pipe sizes and gradients
2. Health and Safety considerations
3. Accessibility

If any one of the criteria could not be satisfied then the site was considered inadequate.

3.2.2.1 Sewer Network Arrangements, Pipe Sizes & Gradients

The desktop survey investigated the sewer network and monitoring locations within the proposed areas. The computer database AD2020 which holds Yorkshire Water (YW) asset data was interrogated to determine the network arrangement, gradient, and size of pipes within the catchment. The drainage boundary of the considered network was investigated to determine if the area was discrete. Systems identified that were not discrete were discarded to prevent water and solids flowing in or out of the survey area without being monitored.

An investigation of the pipes sizes and gradients were undertaken to ensure field monitoring could physically be achieved at the monitoring points. Many sewers in Sheffield have steep gradients because of the general topography of the city. Hence many sewers in upstream areas have small diameters which makes sampling and flow monitoring difficult. The most efficient size of sampling equipment requires the sewer diameter to be at least 450 mm. The flow monitors require a minimum depth to prevent water jumping over the sensor head. A steep gradient produces a low depth and a high velocity which creates this problem preventing accurate measurement.

All potential locations where field monitoring was to be conducted were investigated by lifting the covers and entering the chambers where necessary, to assess the suitability of each site for the type of monitoring proposed. Sampling points were chosen where the shaft was less than 4 m in depth and a straight line of sight from the sewer invert to ground above. This was to enable equipment to be safely raised or lowered.

3.2.2.2 Accessibility

Following the investigation using AD2020, YW were contacted and their offices at Blackburn Meadows Sewerage Treatment Works (STW) visited to obtain the sewer pipe arrangements and locations drawn on to an OS background. This enabled the location of the sewers and manholes in the monitoring locations to be accurately determined. Permission to enter and use selected sites was sought from Yorkshire Water prior to any work being carried out.

An on-site investigation was then conducted to examine the exact location of the manholes in the public highway. Any monitoring locations situated on busy public highways were discarded immediately to avoid dangers to the general public and the Sewer Entry Team (SET), as access to these areas would be necessary during rush hour periods. Ideally, locations were chosen which were away from busy public highways and amenities. The locations required a minimum 6-9 m^2 area to be cordoned off. This was to enable field measurements to be safely and practically conducted without danger to the general public. The on-site investigation included lifting covers and entering the manholes to inspect the suitability of the sewer pipe or benching. The depth to the invert was kept to a minimum to ensure that sampling equipment could be lowered and raised from ground level. All locations were chosen in and around the Sheffield area to minimise the time travelling to and from a site.

3.2.2.3 Health and Safety Considerations

All work was conducted following risk assessments and method statements being undertaken. Three main aspects of Health and Safety were considered explicitly:

1. Safe working in and around confined spaces
2. Safe working in the public highway
3. Safe working with and the disposal of, sewer samples.

All sewers were entered in accordance and with respect to, the Confined Spaces Regulations (Health and Safety Commission 1997). A winch was used for safe access and egress to monitoring locations, with a gas monitor and escape breathing apparatus (BA) in position at all times. All members of the SET who worked on site had attended a 'Full BA' course and were inoculated against various infections by Occupational Health who advised on the types of injections required.

All road signage and protective barriers were used in accordance with RASWA and YW were informed of all work conducted during field monitoring with reflective clothing worn where appropriate.

The handling of sewer samples was carried out in accordance with the method statements and risk and COSHH assessments. All samples were kept away from the general public and disposed of as soon as possible once characterisation and rise / settle velocity tests were complete. All samples were taken to Blackburn Meadows STW for disposal.

3.3 Field Monitoring Methodology

Field monitoring at each site followed a generic methodology designed to satisfy the following objectives:

1. To collect accurate depth and velocity data of the sewer flow
2. To collect aesthetic pollutants from combined sewers continuously within a confined space during dry and wet weather conditions
3. To collect samples by safe means of working for personnel from the university and the general public near the sampling sites
4. To obtain accurate results which represent the aesthetic pollutant loadings produced by a population
5. To cause minimal change to the hydraulic conditions in the sewer during storm sampling

6. To analyse the collected samples to produce useful and valid results, which can be used to verify the mathematical model
7. To verify the methodology to assess the reliability and accuracy of the results obtained
8. To eliminate the requirement to resample catchments due to inadequate data

The methodologies developed have used the experiences of previous research projects at SHU (Balmforth et al. 1995, Meeds 1995) and University of Abertay (Milne et al. 1995, Arthur and Ashley 1998) that involved sampling of CSOs and large sewers.

3.3.1 Sampling Design

A number of ideas to enable the complete collection of aesthetic pollutants from the sewer were considered. These were based on the use of a blanking plate with a central section removed, through which water and solids passed. These pollutants would then be directed into a mesh sack with apertures of 6 mm by 4 mm slotted into the rear of the plate. Thus solids with greater dimensions would be retained. The possibility of adding a chute to the front of the plate was considered. This would reduce the possibility of solids being trapped upstream between the sewer pipe and the lower part of the blanking plate. Field trials in dry weather using the first design (made from hardboard) were very successful, but highlighted the need for the base of the central section to be as close to the invert of the sewer pipe as possible. A second improvement was also required as the profile of the blanking plate did not exactly fit the base of the pipe and enabled water to pass under and potentially trap solids. To eradicate this problem, lagging foam used to insulate pipes was attached to the base of the section to obtain a good seal to prevent leaks.

The blanking plate used for sampling was made of 6 mm steel (Figure 3.2) and individual plates were manufactured for each monitoring point chosen. Guides were attached to the rear of the plate to hold a 'nose box' which held the mesh sack. A number of different sized nose boxes were available, however a common size was chosen for use which provided the greatest cross sectional area for the water and solids to pass through. The nose box was raised and lowered using specially designed frames from ground level. This eradicated the need to enter the chamber during sampling (Figure 3.3). Slotted channel fixings were attached to the benching in the chamber to enable the blanking plates to be held in position. Further development enabled the frames to be lowered and raised from the sewer using ropes.

Figure 3.2 – Blanking plate used to direct all solids and water into a sack

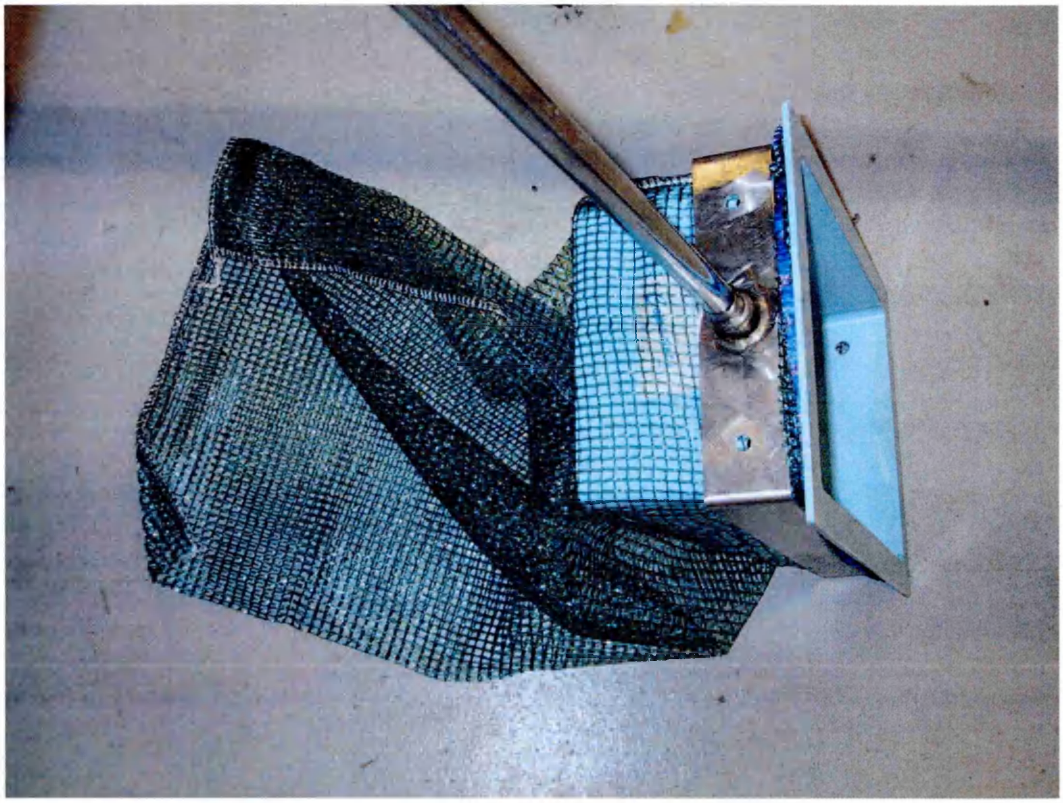
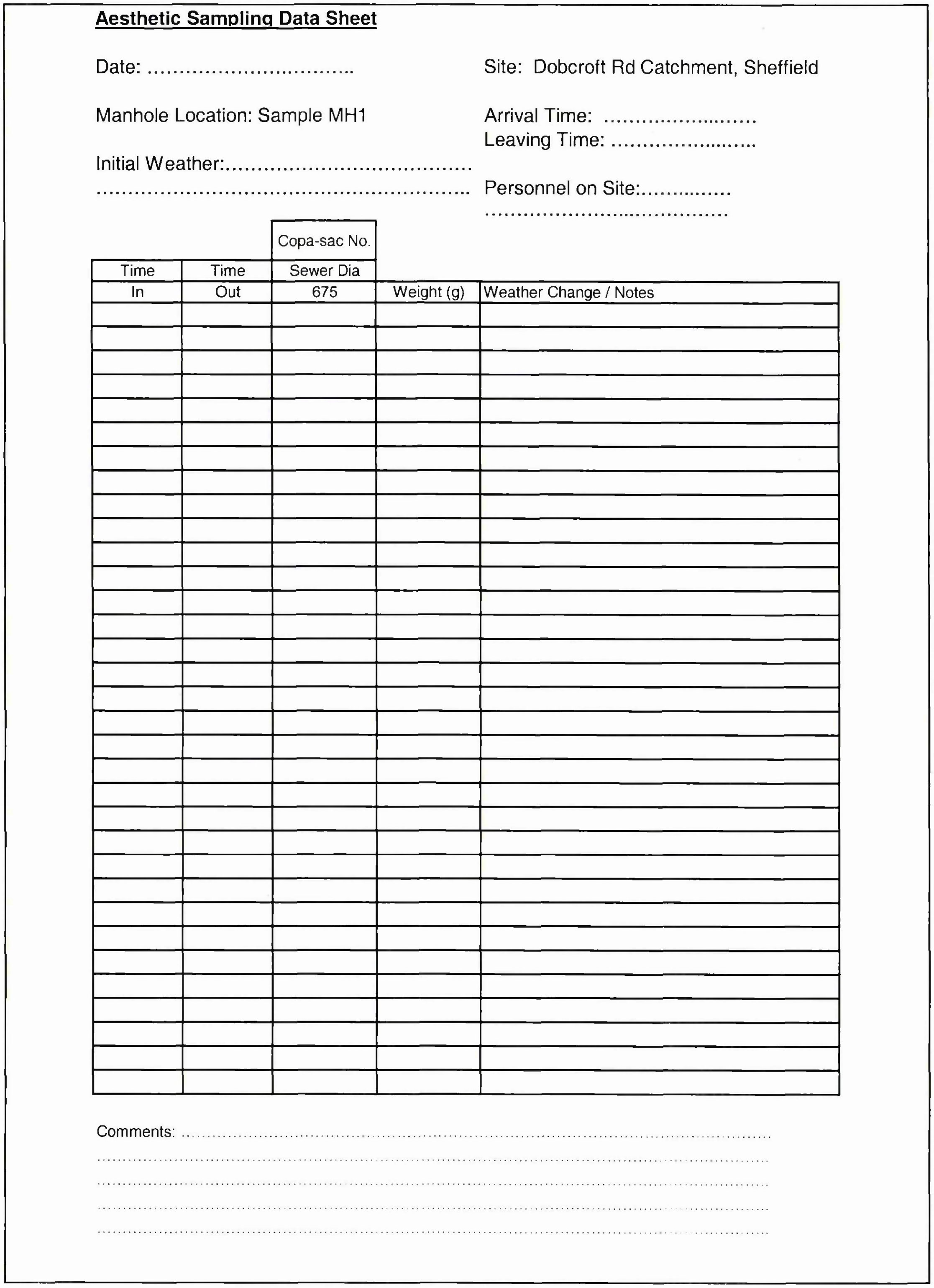


Figure 3.3 – Nose box and mesh sack situated in a sampling frame which can be raised and lowered from above.

3.3.2 Sampling Methodology

The design of the sampling equipment enabled all the pollutants in the flow to be sampled. It also allowed for near continuous sampling to be achieved in dry and wet weather events. As stated nose boxes with sacks were lowered into guides at the rear of the blanking plate. At the end of a pre-determined time period (dependent upon it being dry or wet) the sack and nosebox would be removed and a new sack on a nosebox would be lowered into position. This procedure took approximately 5 to 10 seconds between each change over, with the time for each sack being entered and removed recorded. Once the sacks were removed they were left for 30 minutes to allow excess water to drain. Each sack was then weighed with the mass recorded onto a pro-forma (Figure 3.4). The sacks were then retained or discarded depending on whether they were to be characterised (section 3.3.3).



Aesthetic Sampling Data Sheet

Date: ....

Site: Dobcroft Rd Catchment, Sheffield

Manhole Location: Sample MH1

Arrival Time: ....

Leaving Time: ....

Initial Weather:......................................

....

Personnel on Site:...............

....

		Copa-sac No.		
Time	Time	Sewer Dia		
In	Out	675	Weight (g)	Weather Change / Notes

Comments: ....

....

....

....

....

Figure 3.4 Aesthetic pollutant sampling pro-forma to record wet masses

During dry weather sacks were swapped every 30 minutes. Three 24 hour time periods were to be sampled and split into manageable shifts:

1. 06:00 to 12:00 – Morning
2. 12:00 to 19:00 – Afternoon
3. 19:00 to 01:00 – Evening
4. 01:00 to 06:00 – Night

The night period was to be sampled if the preceding and following hours suggested that a significant quantity of solids were being input into the system and transported to the sample point. The sampled rate of solids at the start of the morning period and at the end of the evening period were very low hence sampling during the night was omitted. One sample was also taken on a Sunday at each catchment. This was initially from 09:00 to 16:00. But following sampling at the low income catchment, the times were changed from 08:00 to 15:00 to ensure the morning peak was captured.

In wet weather sacks were changed every 5 or 10 minutes. Originally it was planned to swap sacks every 4 and 8 minutes respectively, however after trials, 4 minutes to swap over a sack and complete other necessary tasks was insufficient. This time interval was reduced (in an emergency) to prevent water overtopping the blanking plate when the sack became blinded. At the start of a storm event, sacks were changed every 10 minutes to ensure the start of flush was not missed. When the rain intensity visibly increased, sacks were swapped every 5 minutes, to enable the flush of solids to be easily observed over time. After approximately 40 minutes, sacks were then swapped every 10 minutes for a minimum of 40 minutes, to measure the solids loading after the main flush of solids.

The prediction of a wet weather event occurring relied on a number of sources. Primarily, National television weather forecasts were used to determine when and at what time a storm would occur. This method due to the time between the forecast and time of the storm often proved inaccurate. A wet weather tracking radar system was available for purchase called MIST, however the cost of this was too great. Television forecasts remained the main source of information until the BBC weather internet site showed the location and intensity of the rain every hour which was updated approximately 25 minutes past the hour. This improvement to the forecasting of storms occurred in the summer of 2000 and enabled a far more accurate prediction of when a wet weather event was to reach Sheffield. When waiting on site for a wet weather event, colleagues in the office used this system. They were able to help predict when the rain event may occur and prevent time being spent on site if the rain was slow moving, travelling in a different direction or significantly reducing.

3.3.3 Characterisation Methodology

The characterisation of the samples was an important procedure to identify the types of pollutants disposed by each population type. Following initial sampling it was decided to characterise 1 in 4 sacks at the first catchment. This was because the population produced a large quantity of solids. This would have taken approximately 2.5 days to characterise all the samples. At the remaining sites, all the sacks were characterised due to the catchment population and quantity of solids produced being less than the first.

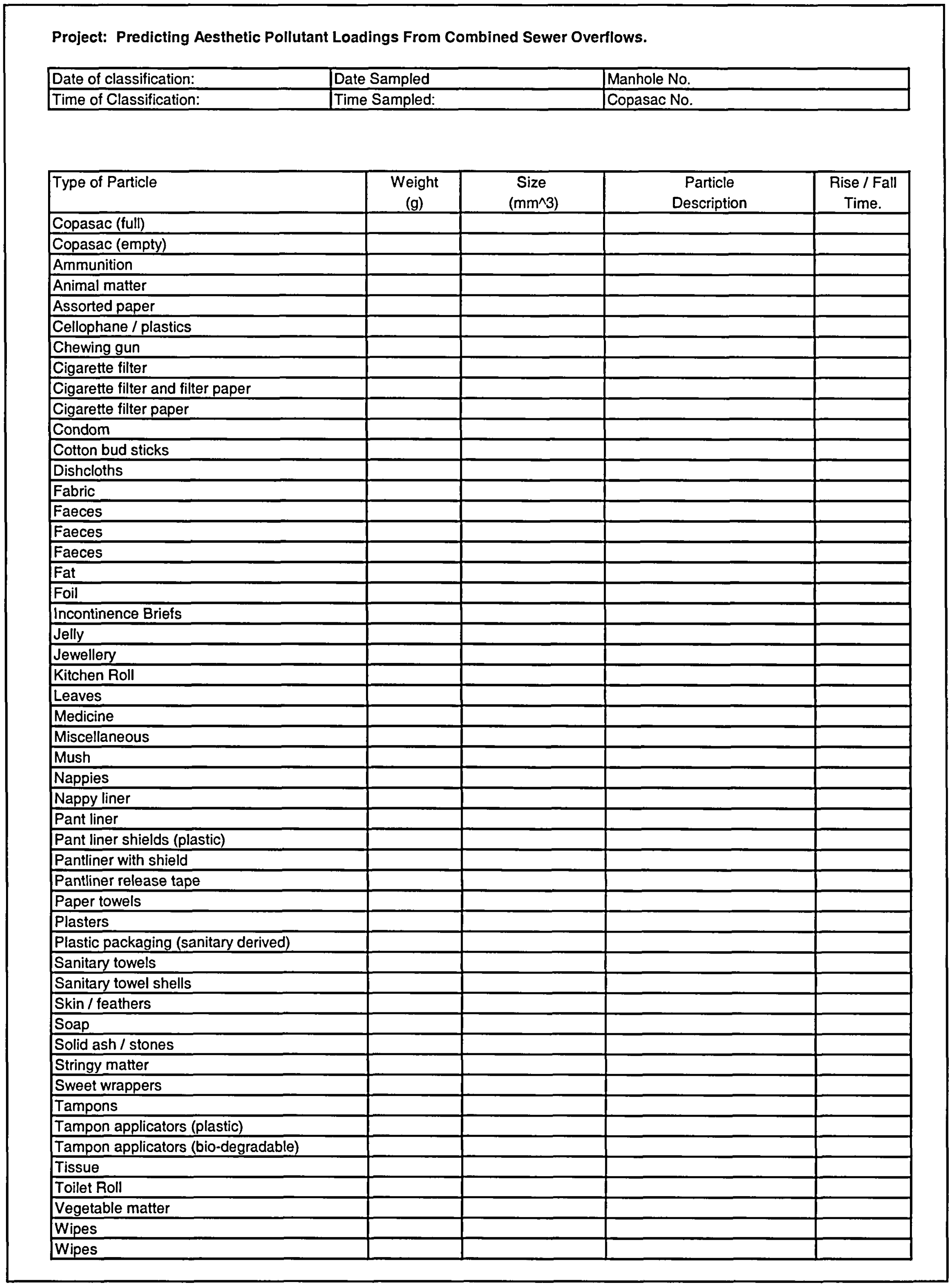
All sacks were weighed full at the start of characterisation. Solids were then sorted into 45 different categories (Figure 3.5), with seven of the main aesthetic pollutants (identified as of sewerage origin) being retained for rise / settle velocity tests. The aesthetic pollutants retained were:

1. Faeces
2. Toilet tissue
3. Tampons
4. Sanitary Towels (including shells)
5. Panty Liners (including shells)
6. Cotton budsticks
7. Baby / nappy wipes (including cloth wipes)

Each solid type was weighed individually, and where possible, the dimensions were also recorded. On the completion of the characterisation and rise / settle velocity tests, samples were disposed of at Blackburn Meadows STW.

3.3.4 Rise and Settle Velocity Test Methodology

Settling velocity tests were conducted in a 2 m tall, 0.5 m diameter clear Perspex tube filled with potable water as used in previous tests by Meeds (1995). Each pollutant was placed into the water and the time was recorded for it to rise or fall over a central one metre section using a stop watch. The pollutants were generally only dropped once, due to the nature of the pollutants. Floaters were lowered to the base of the tube using a 'grab claw' and released.



Project: Predicting Aesthetic Pollutant Loadings From Combined Sewer Overflows.

Date of classification:	Date Sampled	Manhole No.
Time of Classification:	Time Sampled:	Copasac No.

Type of Particle	Weight (g)	Size (mm^3)	Particle Description	Rise / Fall Time.
Copasac (full)				
Copasac (empty)				
Ammunition				
Animal matter				
Assorted paper				
Cellophane / plastics				
Chewing gun				
Cigarette filter				
Cigarette filter and filter paper				
Cigarette filter paper				
Condom				
Cotton bud sticks				
Dishcloths				
Fabric				
Faeces				
Faeces				
Faeces				
Fat				
Foil				
Incontinence Briefs				
Jelly				
Jewellery				
Kitchen Roll				
Leaves				
Medicine				
Miscellaneous				
Mush				
Nappies				
Nappy liner				
Pant liner				
Pant liner shields (plastic)				
Pantliner with shield				
Pantliner release tape				
Paper towels				
Plasters				
Plastic packaging (sanitary derived)				
Sanitary towels				
Sanitary towel shells				
Skin / feathers				
Soap				
Solid ash / stones				
Stringy matter				
Sweet wrappers				
Tampons				
Tampon applicators (plastic)				
Tampon applicators (bio-degradable)				
Tissue				
Toilet Roll				
Vegetable matter				
Wipes				
Wipes				

Figure 3.5 Aesthetic pollutant characterisation pro-forma

3.3.5 Measurement Errors

The methodology defined above has been designed to reduce, as far as possible, the number of systematic and random errors that could occur during the collection of field data. It is possible that measurement errors could occur in the following processes used to sample the pollutants:

1. Time for sacks to be removed and replaced from the sewer. During this period solids could pass through the orifice and not be sampled.
2. Sacks are initially weighed after 30 minutes draining time. If the sacks are measured several minutes before or after this period, then the sacks may have lower or higher moisture content.
3. Measurement error of the scales used to record the mass.
4. The aperture of the sacks used for sampling. This could allow some smaller solids to pass through, or when solids are collected trap solids that are smaller than 6 mm in two dimensions.

The time taken for sacks to be changed is relatively short, approximately five seconds. Table 3-1 shows the sack change over time as a percentage of the total time each sack is positioned in the flow. The percentage is highest during storm sampling when the sacks are within the flow for shorter period due to the higher solids loading, however this is still a relatively small percentage of the total sampled during each time period.

The accuracy of the measurement equipment to weigh the sacks and pollutants was also a potential error point. To reduce this likelihood the electronic weighing scales were regularly tested with a set of known weights. No difference was recorded over the survey period.

Table 3-1 – Percentage error during different modes of sampling when sacks are changed

Sampling Mode	Dry Weather	Storm During Main flush	Storm After Main solids flush
Duration for solids collection (min)	30	5	10
Proportion of the sampling time for solids to not be measured (%)	0.3	1.7	0.8

Sacks were left to drain for 30 minutes before weighing to determine the overall temporal distribution. This was measured on each occasion to ensure that the time between removal from the system and weighing was 30 minutes. Any variation from this time period could result in an under or over measurement of the total quantity at that time period.

The third measurement error could occur with the sacks themselves. It could be possible for fine material such as faeces and toilet tissue to degrade in the sack due to the forces generated within the sack and pass through. Meeds (1995) reported that the retention efficiency of the mesh sacks (used for sampling) was approximately 42% for toilet tissue and an overall efficiency of 56%. However during these tests, material smaller than 6 mm in two dimensions was collected downstream of the trial sack. This material directly affected the efficiency calculations. The efficiency of the sack could also be improved when the apertures became blinded with a mixture of toilet tissue and faeces. The other pollutants sampled such as SANPRO items and wipes were all collected in the mesh. Therefore it is not possible to quantify an overall efficiency of a sack once blinding commences, however it is a potential source of error.

The other possible error is the random nature of pollutants entering the network, which cannot be controlled during the field study. Sampling cannot account for the variation in the type and quantity of solids that enter the system from day to day, and temporally during the day. This is because different populations are in the catchment at different times of day and people habits in the use of the WC are likely to vary. These random errors could occur because:

- Faeces and toilet tissue are dependent upon the quantity and type of food consumed over the previous 24 to 48 hours.
- SANPRO products entering are dependent upon the number of women who are menstruating at that period of time when sampling is undertaken
- Solids may not enter the catchment sewer system but at a different location outside of the area from the working population
- SANPRO products could be disposed by the solid waste disposal route rather than via the WC
- SANRPO products could also be used for other purposes other than menstruation

The methodology has partially addressed this issue by sampling on three separate occasions at the same time of day to enable an average solid content to be determined.

3.3.6 Flow and Rainfall Monitoring Equipment

Detectronic 'Intrinsically Safe Surveyloggers' were used to measure the depth and velocity of the water in the sewer (Figure 3.6). Data loggers were used to record the depth and velocity measured by transducers at programmed intervals. 'Velocity transducers measure the speed of the flow by the Doppler effect. The transmitter emits a beam of ultrasonic sound at a fixed frequency. The sound is reflected by particles and air bubbles in the flow, and it's frequency is changed by an amount dependent on the speed of movement and the receiver detects the signal. A depth transducer produces a pressure signal that is proportional to depth. The survey logger converts the frequency difference into a velocity value, the pressure signal into a depth value and stores the data.' (Detectronics 1992)

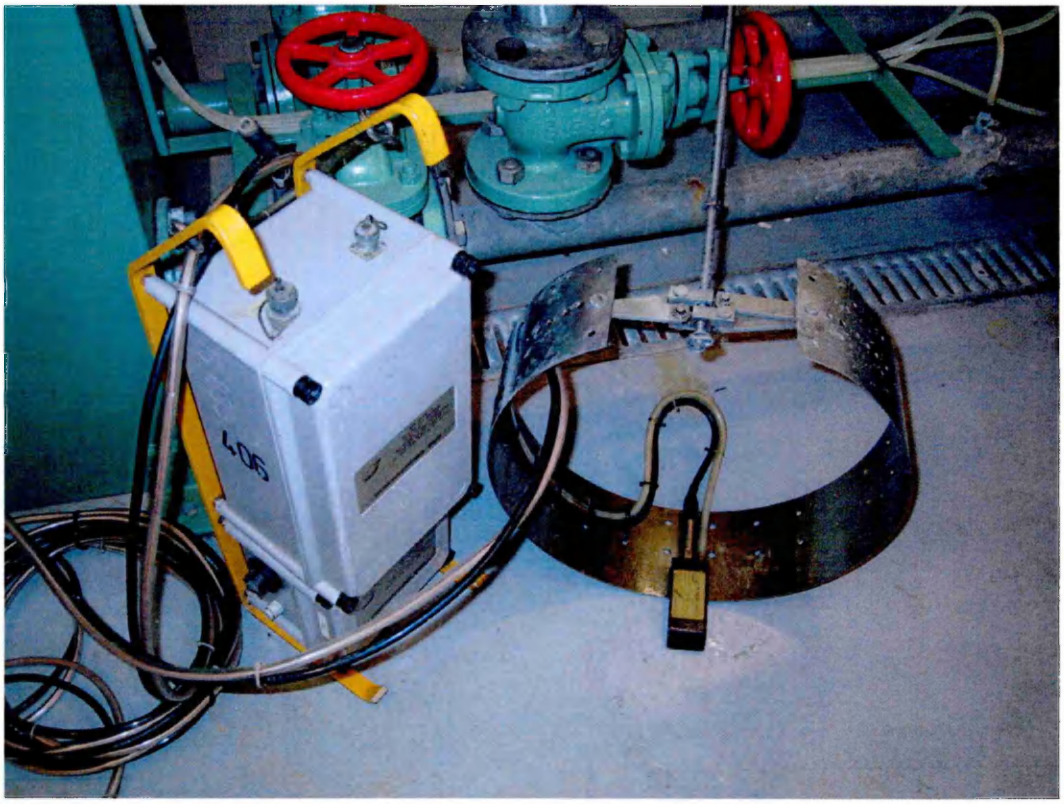


Figure 3.6 – Detectronic IS Surveylogger used to record the water depth and velocity in the sewer

A tipping bucket raingauge was used to measure the rain intensity with time at each catchment (Figure 3.7). A data logger recorded the number of tips per time interval, with one tip equal to 0.2 mm.

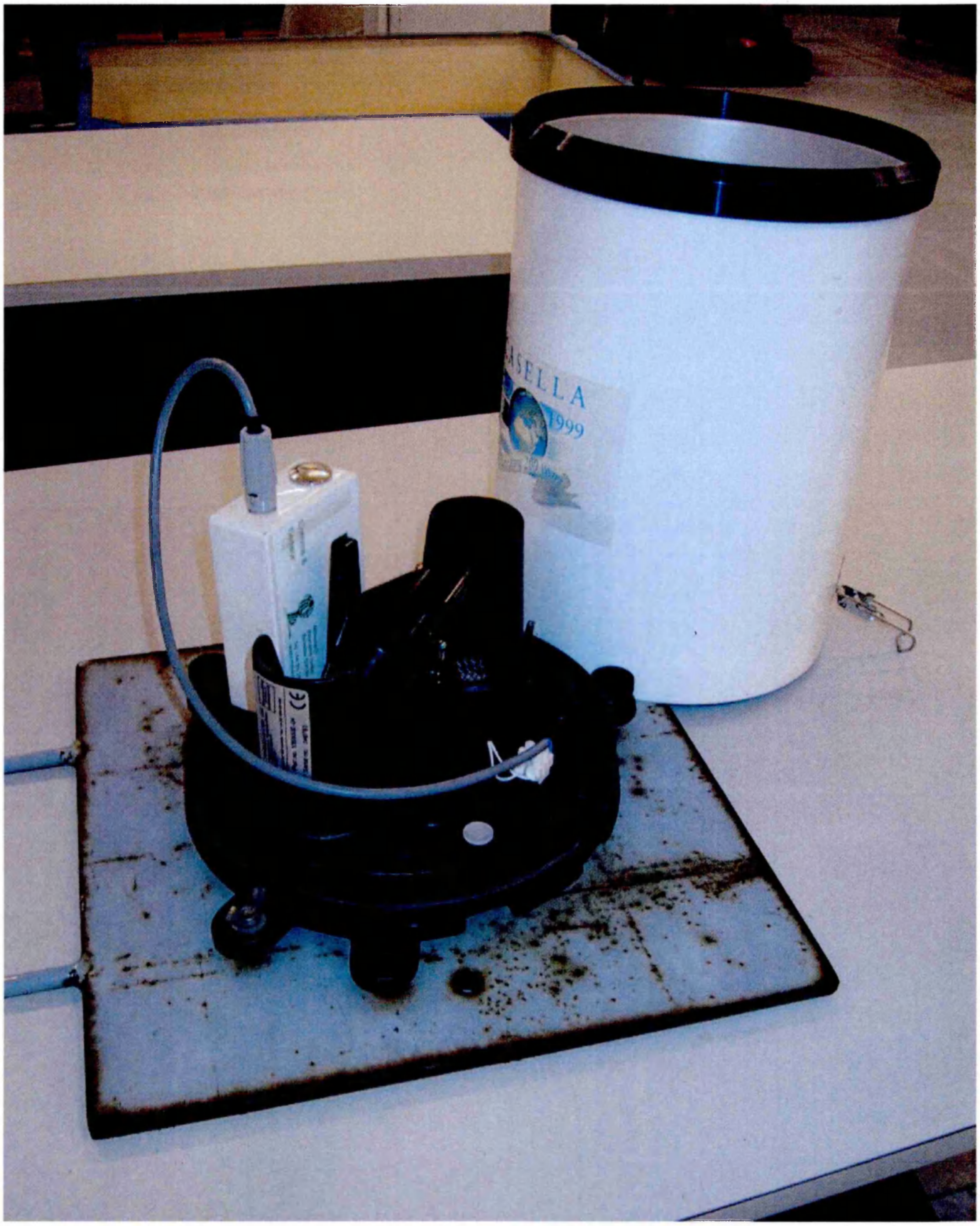


Figure 3.7 – Casella 0.2 mm tipping bucket raingauge with data logger

A Husky hand held computer was used to programme the Surveylogger and raingauge, to retrieve data from the data loggers, and transfer the downloaded data to a PC for analysis.

3.3.7 Flow and Rainfall Monitoring Methodology

Locations for situating the Surveylogger and raingauge were selected as part of the catchment selection process. The selection of these locations was conducted following the guidelines set out in 'A guide to short term flow surveys of sewer systems' (WRc 1987).

The transducer head was fixed to the invert of the sewer pipe using an expandable stainless steel ring that would hold the sensor securely within the pipe (Figure 3.6). Typical positioning of equipment in the sewer is shown in (Figure 3.8). If the location suffered from silting, the transducer head was moved off centre to prevent it being covered with silt and poor quality measurement occurring (Figure 3.9).

Prior to installation, depth calibration and velocity checks were undertaken in the laboratory to ensure the transducers were accurately measuring their respective components of the flow. Any Surveylogger which did not comply for depth and velocity was sent away for re-calibration.

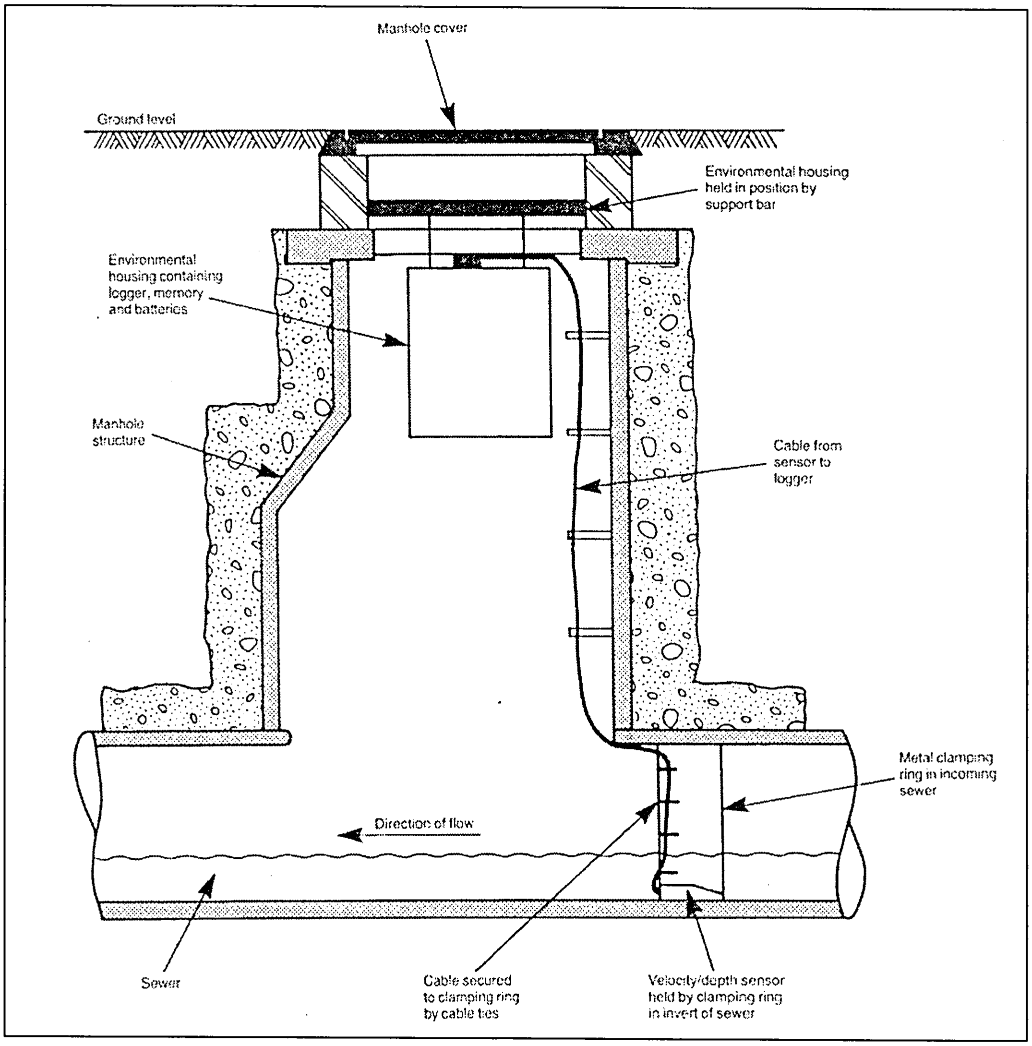


Figure 3.8 – Typical positioning of a Surveylogger and transducer head in a sewer (WRc 1987)

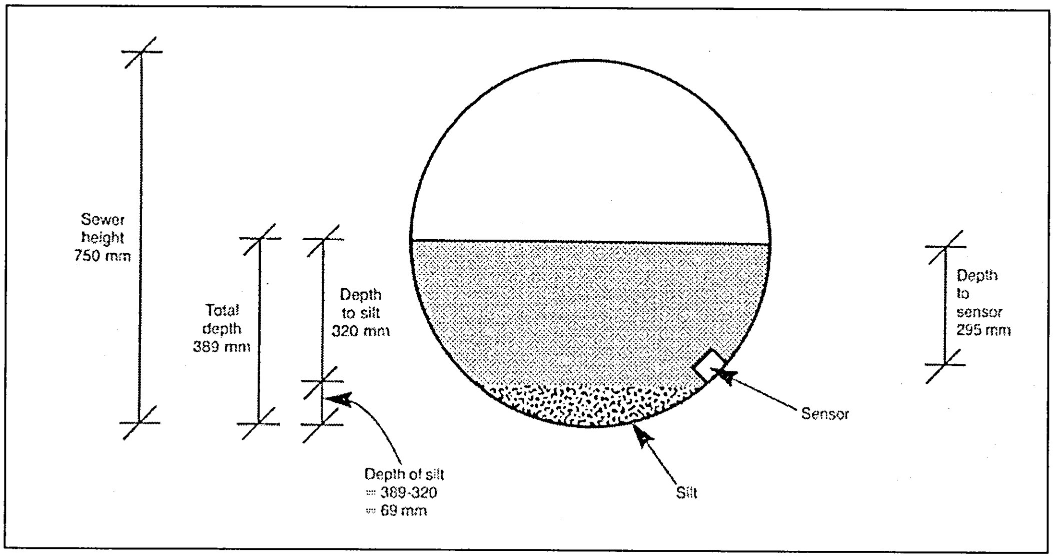
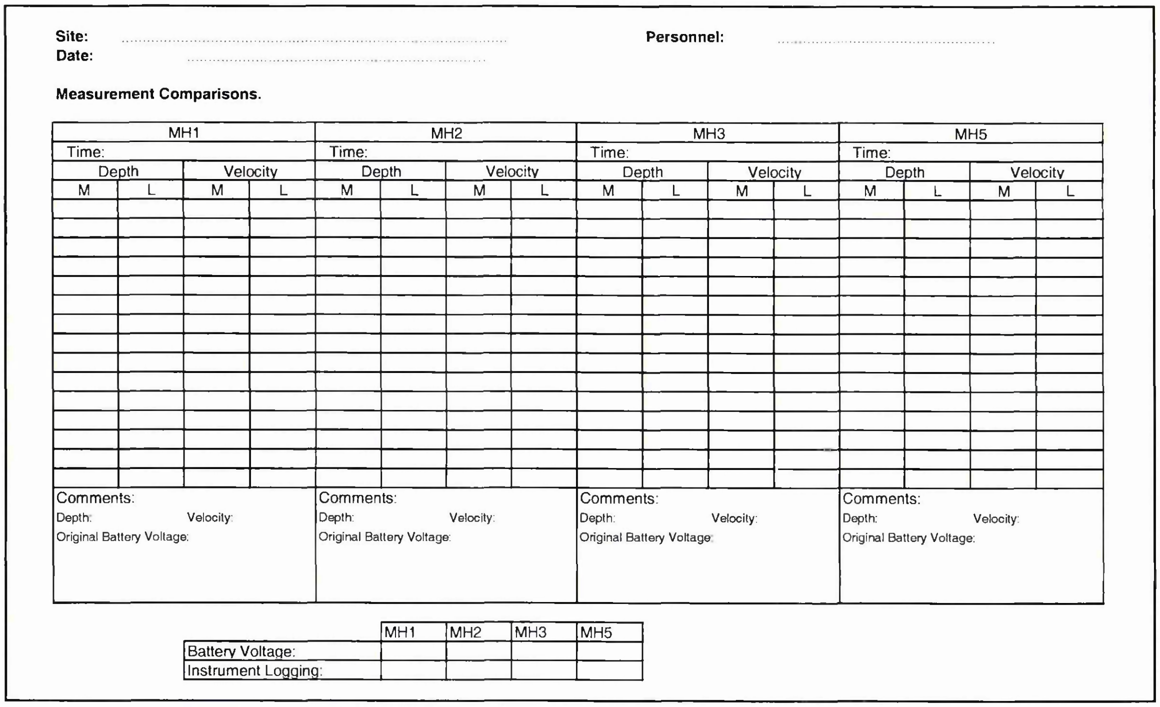


Figure 3.9 – Location of the transducer head if silting occurs (WRc 1987)

Weekly visits to site were taken to inspect the equipment, perform manual checks and download the data. During the inspection procedure, the battery would be changed and recharged, the transducer head would be cleaned to remove any silting or ragging from fibrous solids. Manual checks of the depth and velocity measurement would be undertaken with the results recorded Figure 3.10) and used when the depth and velocities were combined to produce the flow using SASS software.



Site: .... **Personnel:** ....

Date: ....

Measurement Comparisons.

MH1				MH2				MH3				MH5			
Time:				Time:				Time:				Time:			
Depth		Velocity		Depth		Velocity		Depth		Velocity		Depth		Velocity	
M	L	M	L	M	L	M	L	M	L	M	L	M	L	M	L
Comments: Depth: Velocity: Original Battery Voltage:				Comments: Depth: Velocity: Original Battery Voltage:				Comments: Depth: Velocity: Original Battery Voltage:				Comments: Depth: Velocity: Original Battery Voltage:			

	MH1	MH2	MH3	MH5
Battery Voltage:				
Instrument Logging:				

Figure 3.10 Pro-forma to record measured and logger readings for velocity and depth at each flow monitoring site

The introduction of a weir downstream of a Surveylogger was required when the depth was too low and velocity too high. This prevented the flow breaking up at the transducer head that produced in-accurate measurements. The weirs were 50 mm high and inclined at angle of 30° to prevent solids build up and siltation in front of the weir and around the monitor head. The weirs were attached to stainless steel expanding rings to enable them to be located securely.

3.4 Catchment Descriptions

3.4.1 Low Income Catchment

3.4.1.1 Catchment Characteristics

The first catchment selected for use contained a low income population. This was a good site to commence work on, as the site had been previously used for other monitoring work at the CSO at the downstream point of the catchment. The low income catchment was a discrete site with no extra flows in or out of the sewer network. It contained an ageing population totalling 1810 (Figure 3.11), with 76.9 % of the population having a household income of less than £16000 a year (Houldsworth 1999b) as shown in (Figure 3.12). The catchment was split into 4 sub-catchments (Figure 3.13) with each site being slightly different in size, shape, population and slope. A summary of the catchment characteristics is shown in Table 3-2.

Table 3-2 - Summary of the low income catchment characteristics

Sub-catchment	SC 1	SC2	SC3	SC4	Overall
Total Area (Ha)	8.1	6.8	9.1	7.5	31.6
Roof Area (Ha)	1.3	1.0	1.5	1.3	5.1
Pavement Area (Ha)	1.9	1.8	1.6	1.5	6.8
Permeable Area (Ha)	4.9	4.1	6.0	4.7	19.7
Average Gradient of Sewer (1 in)	19.6	21.6	33.4	47.3	30.7
Total Length of Sewer (m)	1301	1286	1648	1643	5878
Population No.	454	359	526	471	1810

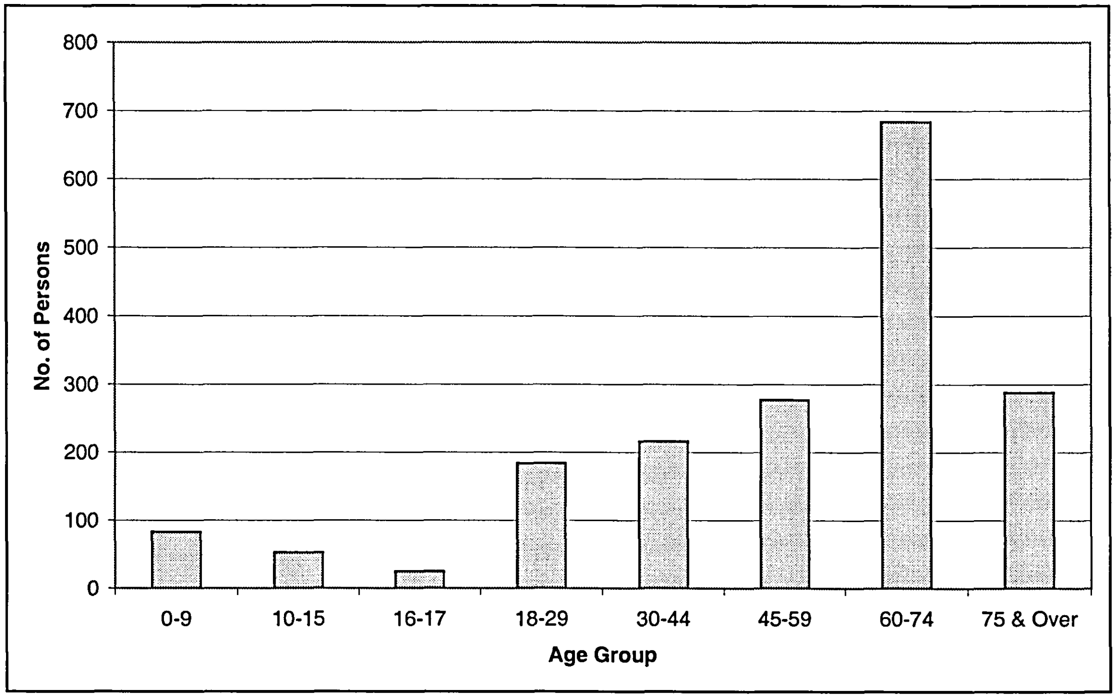


Figure 3.11 – Age distribution of the population in the low income catchment from the 1991 census data

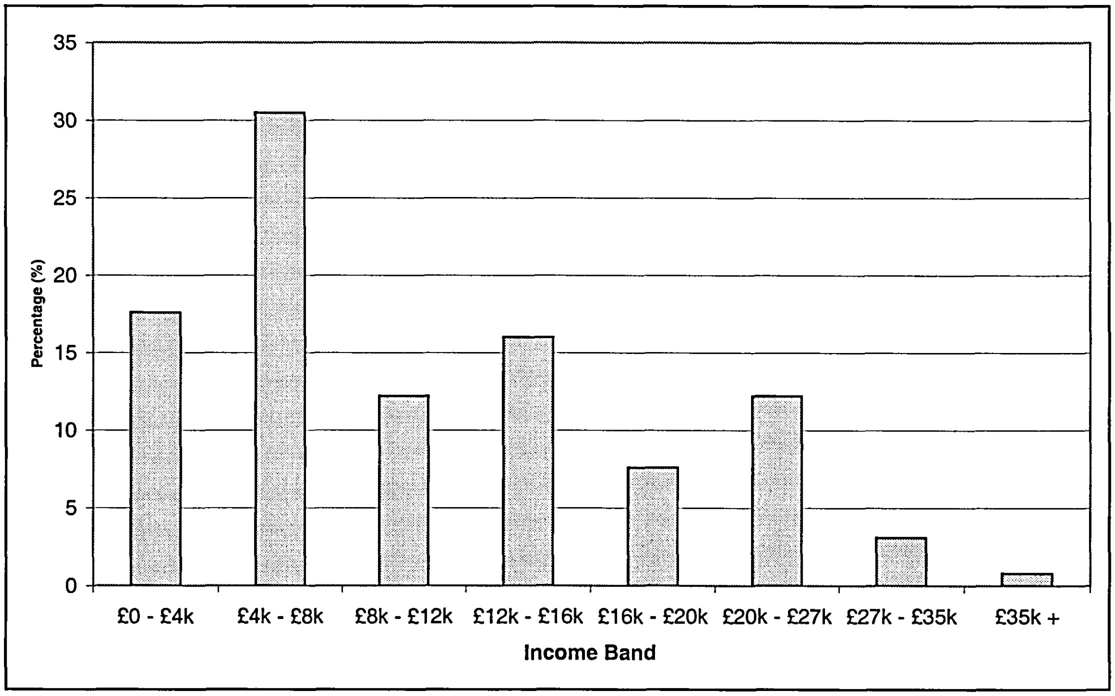


Figure 3.12 – Household income for the population of the low income catchment from the UofS questionnaire survey (after Houldsworth 1999b).

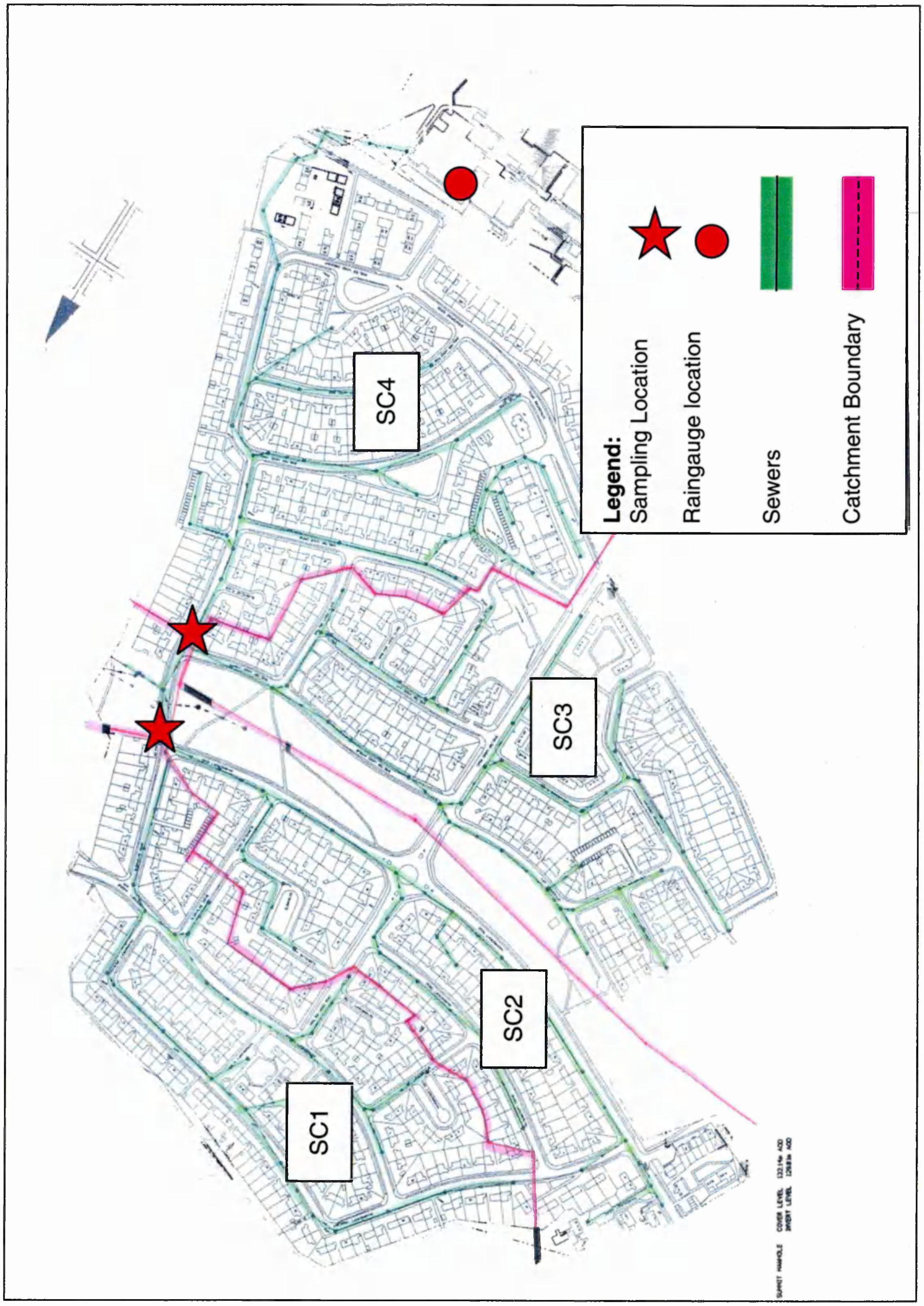


Figure 3.13 - Low Income catchment split into 4 sub-catchments

3.4.1.2 Monitoring Locations

Sampling locations were chosen where two sub-catchments converged enabling the four sites to be sampled from the 2 locations (Figure 3.14).

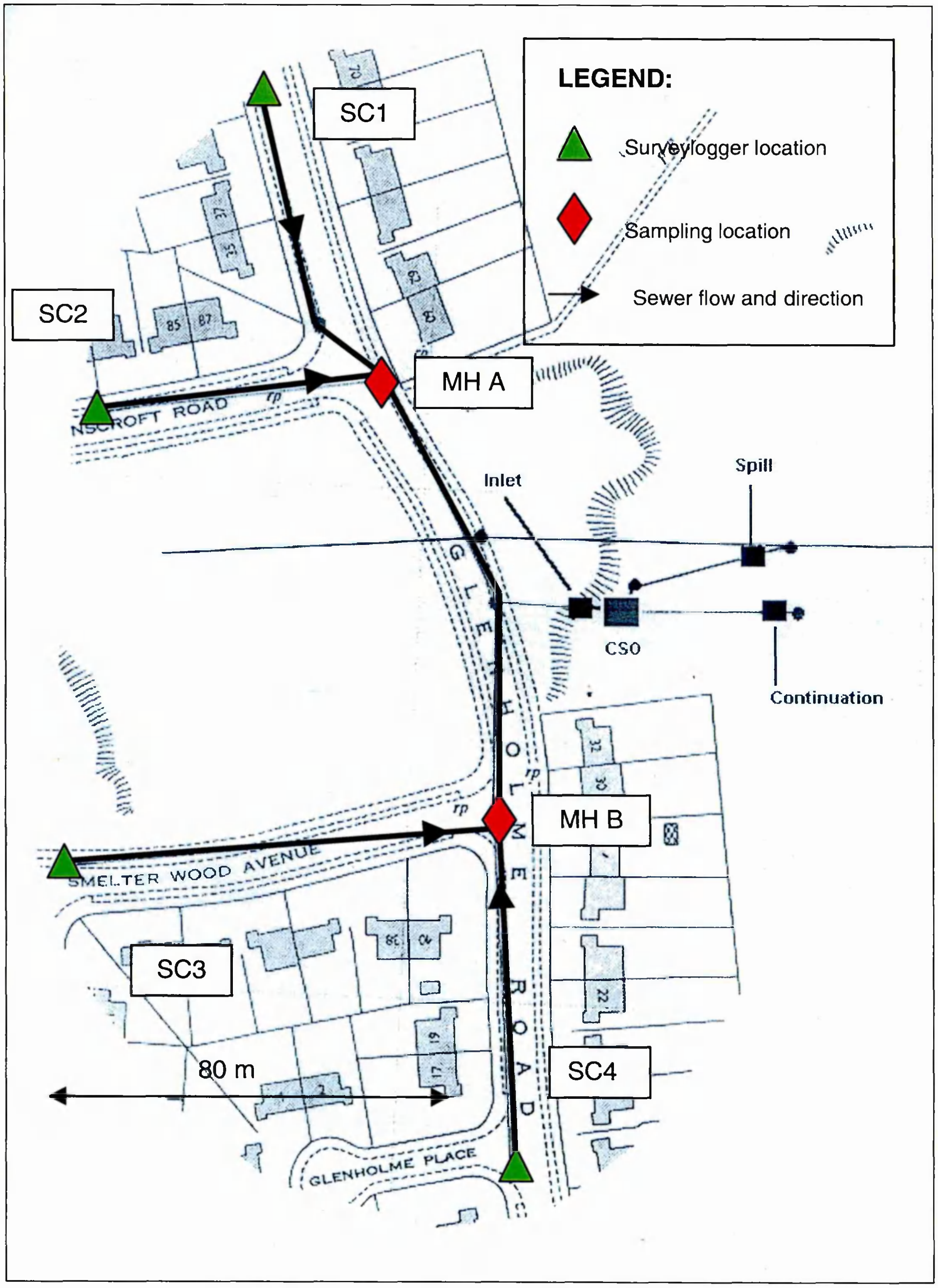


Figure 3.14 – Monitoring locations at the low income catchment

In manhole A for sub-catchments SC1 and SC2, sandbags were introduced to ensure solids were not retained at the base of the blanking plates. Depth and velocity loggers were installed at the next available manhole upstream of the sampling points. Due to the low depths and high velocities, weirs were introduced at all the sites to increase the water depth. One raingauge was situated at the 'City School' on the edge of the catchment (Figure 3.13).

3.4.2 High Income Catchment

The next type of catchment to be sampled was a high income catchment, and the areas containing this population type were selected using the social deprivation map (Houldsworth,J.K. 1999). A number of sites were initially considered but this was reduced to two following a desktop study. An on-site investigation was conducted at the most preferable site in Fulwood. After this initial investigation the catchment was considered to be unsuitable because:

1. The diameter of the sewers were too small, making it hard to sample effectively
2. The location of the manholes for sampling were located in a well used public highway
3. A bifurcation of the sewer pipe at the downstream end could have enabled flow and solids to not miss the monitoring point

The second site was investigated was to contain a population of approximately 2000. Monitoring locations were selected, but only one sampling location was available for use. Following the experience gained at the first catchment this would have potentially produced a very high solid loading rate. Therefore the potential quantity of solids sampled during a storm could have been too large to measure. Hence another location was chosen further upstream in the catchment to sample. This had a population that was approximately 33% smaller than the previous population.

3.4.2.1 Catchment Characteristics

The selected high income catchment contained a point in the system where water could exit the system prior to arriving at the monitoring points. However the invert of this overflow point was 0.86 m above the invert of the main sewer pipe. It was considered that this overflow pipe would not be generally used under storm conditions. The on-site investigation confirmed this by indicating the pipe had not had water passed through it for some considerable time. The arrangement of the network was long and thin without many smaller branches off the main sewers as seen in the low income catchment (Figure 3.15).

The catchment itself contains a population of 1309 with a normalised adult age profile (Figure 3.16) and a high income population (Figure 3.17) (Houldsworth 2000b). A summary of the catchment characteristics is shown in Table 3-3.

Table 3-3 - Summary of catchment characteristics for the high income catchment

Catchment	Overall
Total Area (Ha)	21.5
Roof Area (Ha)	3.6
Pavement Area (Ha)	2.4
Permeable Area (Ha)	15.5
Average Gradient of Sewer (1 in)	33.5
Total Length of Sewer (m)	3578
Population No.	1309

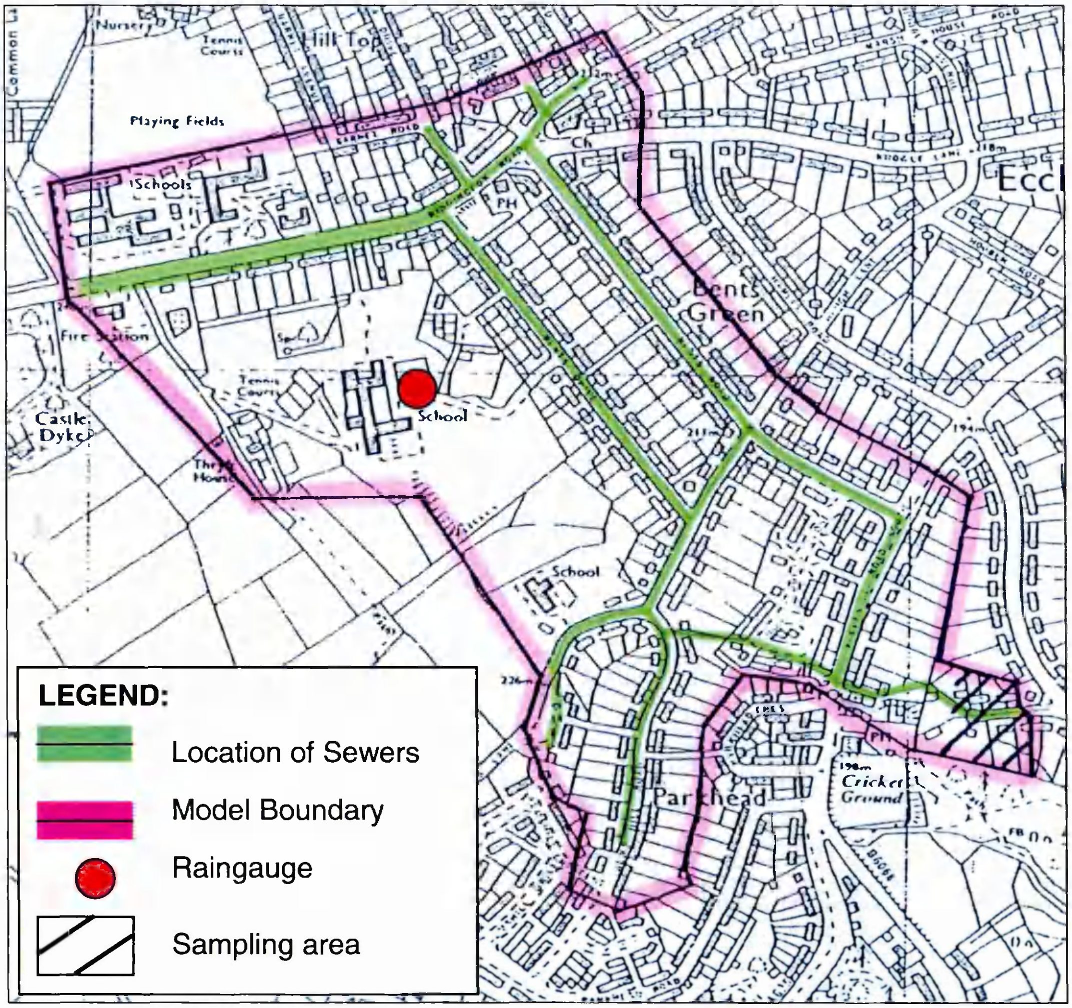


Figure 3.15 – High Income catchment showing the location of the sewers

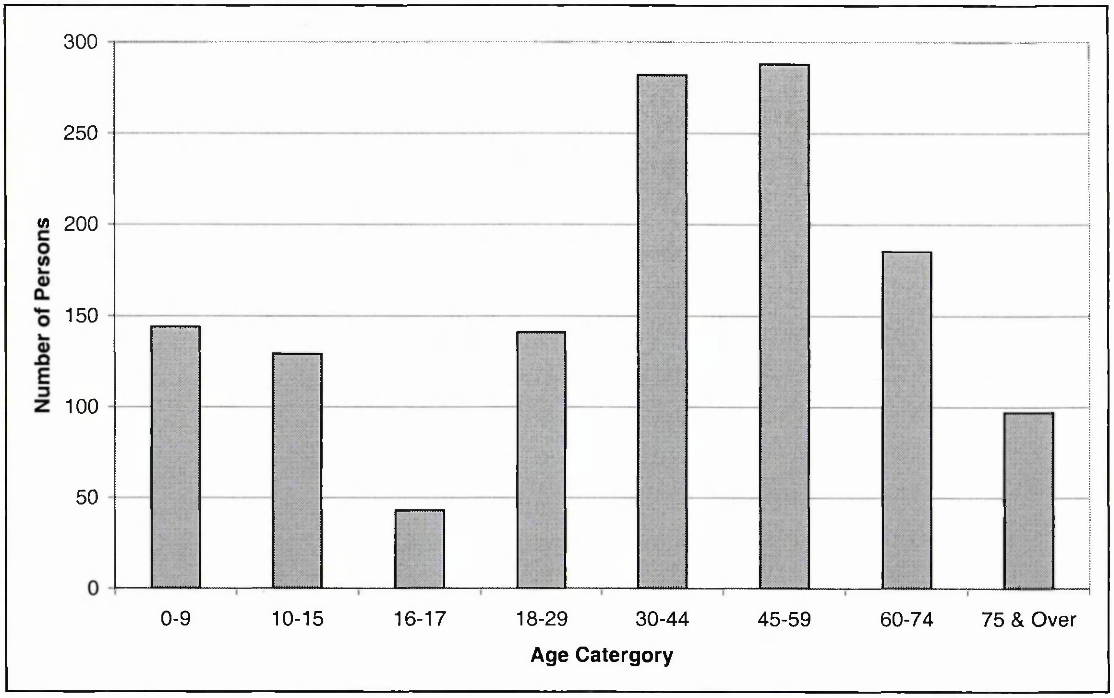


Figure 3.16 – Age distribution of the population of the high income catchment from the 1991 census data

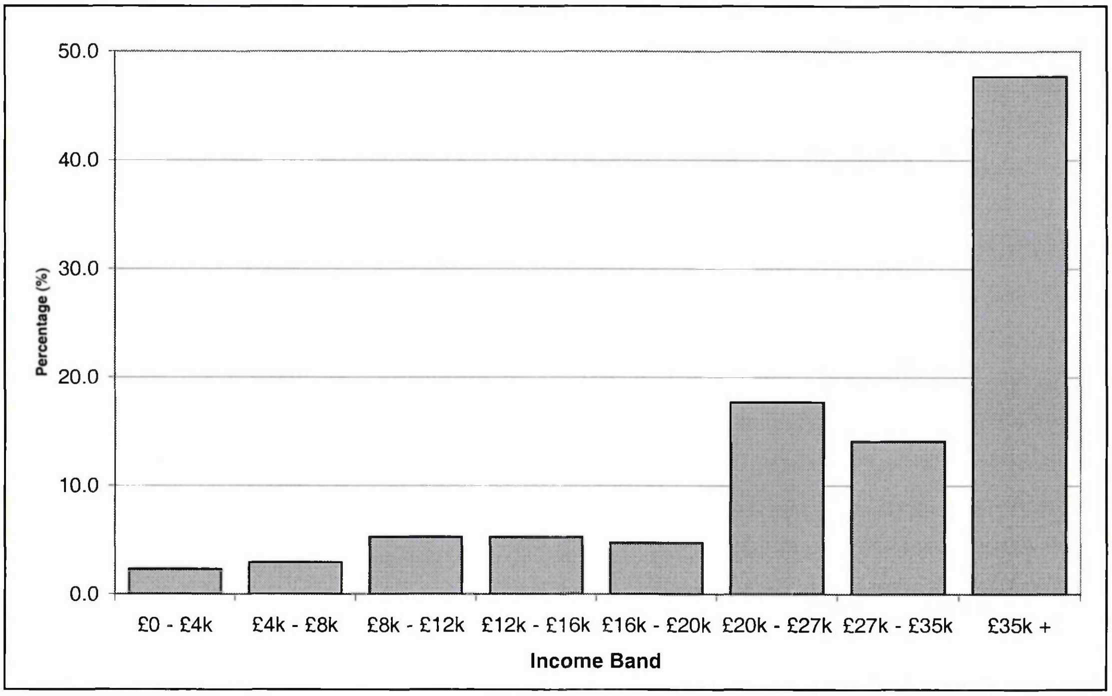


Figure 3.17 – Household income of the population of the high income catchment from the UofS questionnaire survey (after Houldsworth 2000).

3.4.2.2 Monitoring Locations

A single monitoring point was chosen for sampling and three locations for installation of depth and velocity loggers (Figure 3.18). Potentially it was possible to split this catchment into two sub-catchments, however, the location of these manholes were situated on the edge of a busy public highway. One Surveylogger was installed during the first phase of sampling at the site. During the second phase of sampling, three Surveyloggers were installed to provide extra verification of the flows (Figure 3.18). A raingauge was situated at the local high school during both sampling phases (Figure 3.15).

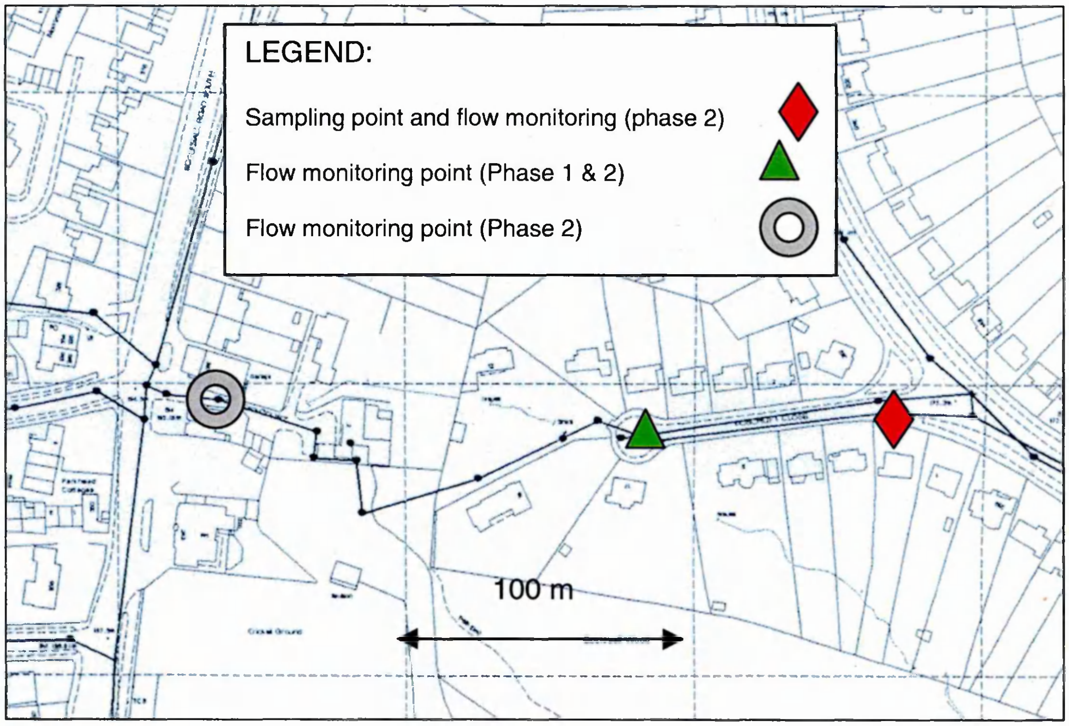


Figure 3.18 – Selected monitoring locations at the high income catchment

Table 3-4 – Summary of catchment characteristics for the minority ethnic catchment

Sub-catchment	SC 1A	SC 2B	Overall
Total Area (Ha)	7.7	3.5	11.1
Roof Area (Ha)	2.4	1.0	3.4
Pavement Area (Ha)	1.1	0.5	1.6
Permeable Area (Ha)	4.1	2.0	6.1
Average Gradient of Sewer (1 in)	18.9	15.1	18.0
Total Length of Sewer (m)	1957	544	2501
Population No.	1259	340	1599

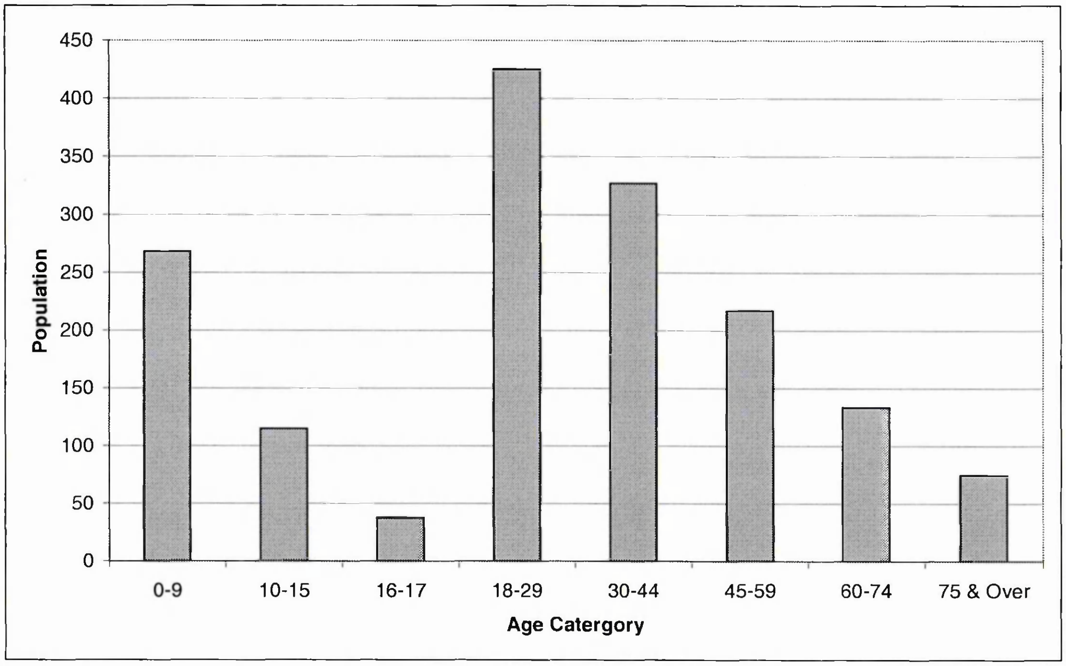


Figure 3.19 – Age distribution of the population in the minority ethnic catchment (after Houldsworth 2000b)

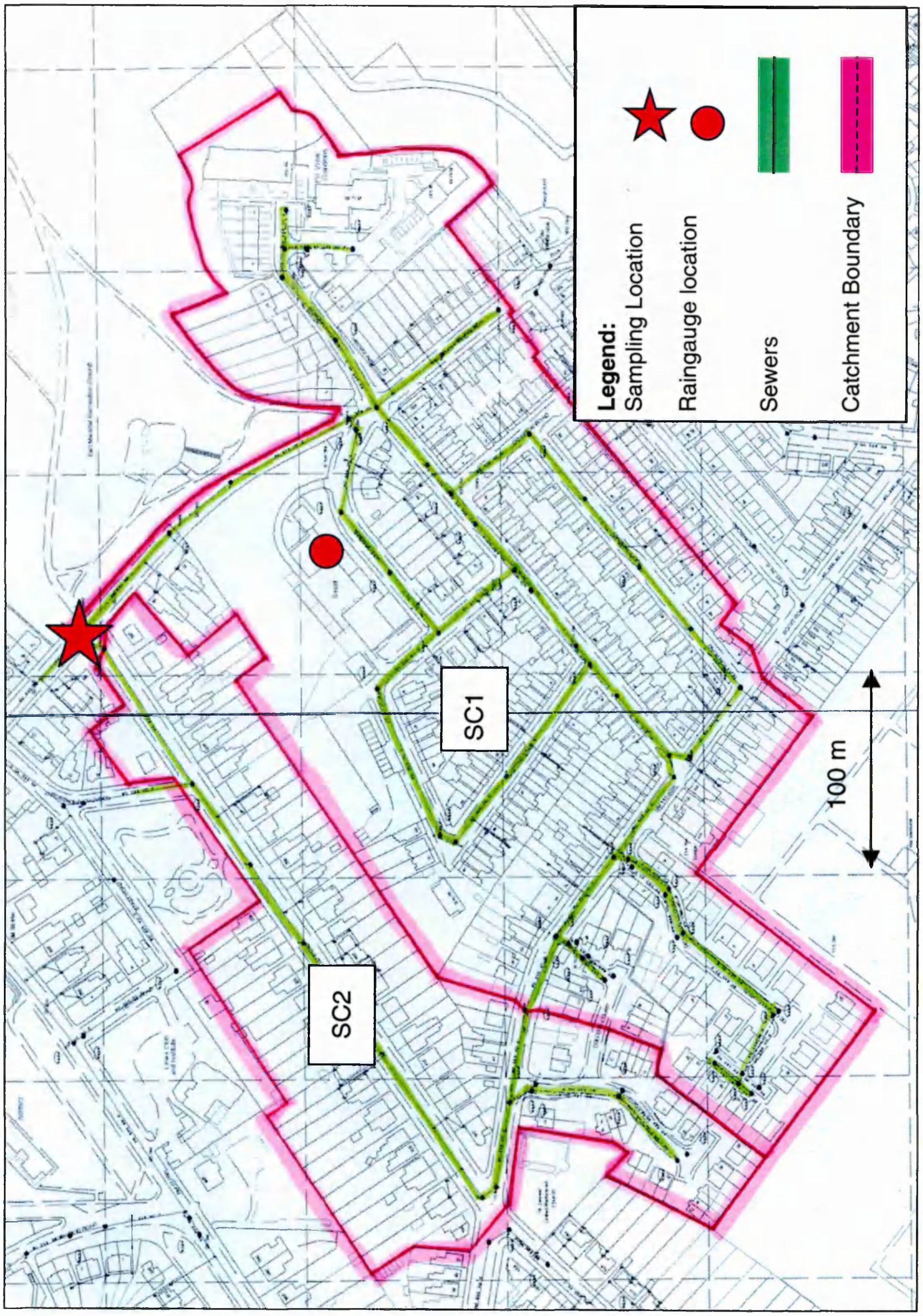


Figure 3.20 – Ethnic population catchment showing the 2 sub-catchments

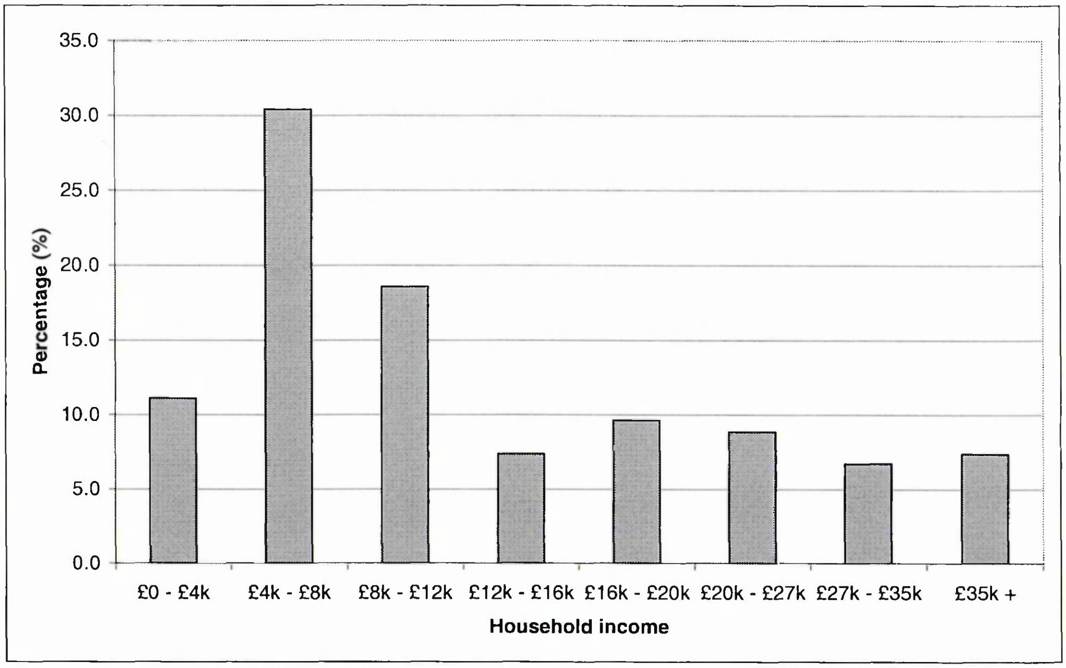


Figure 3.21 – Household income distribution for the minority ethnic population catchment from the UofS questionnaire survey (after Houldsworth 2000b).

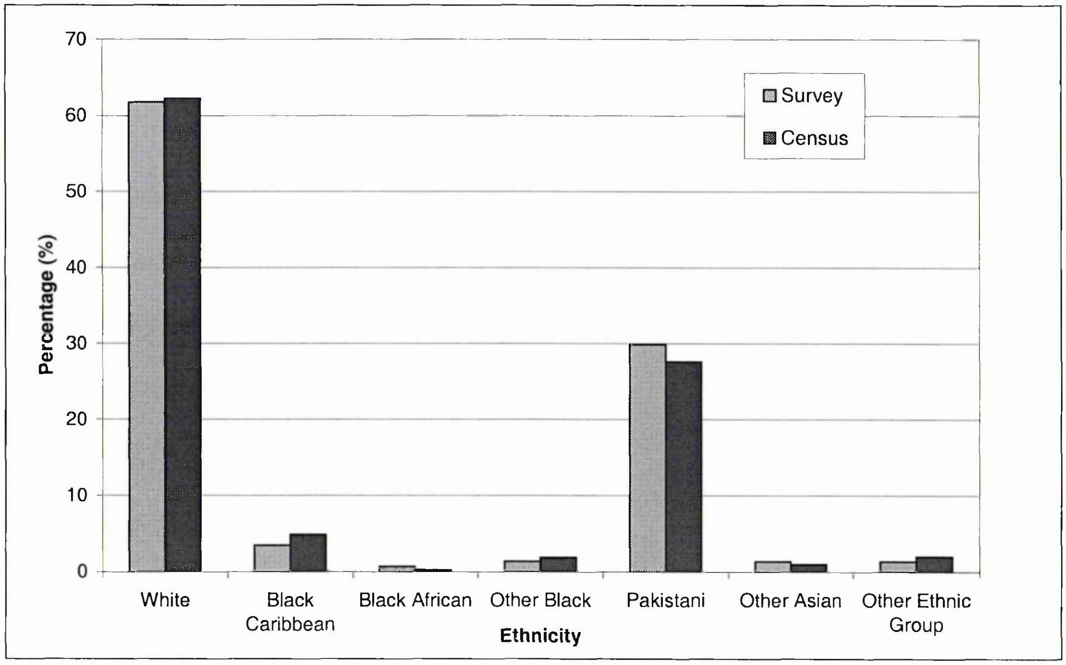


Figure 3.22 – Ethnicity of the population in the ethnic minority catchment from the UofS questionnaire survey (after Houldsworth 2000b).

3.4.3.2 Monitoring Locations

Individual sampling locations were chosen for each sub-catchment (Figure 3.20 and Figure 3.23). The monitoring locations were situated in the public highway, however the volume of traffic was very low. The flow monitoring points were approximately 70 m upstream of the sampling locations. A raingauge was situated in the centre of the catchment at the Environmental Health offices (Figure 3.20).

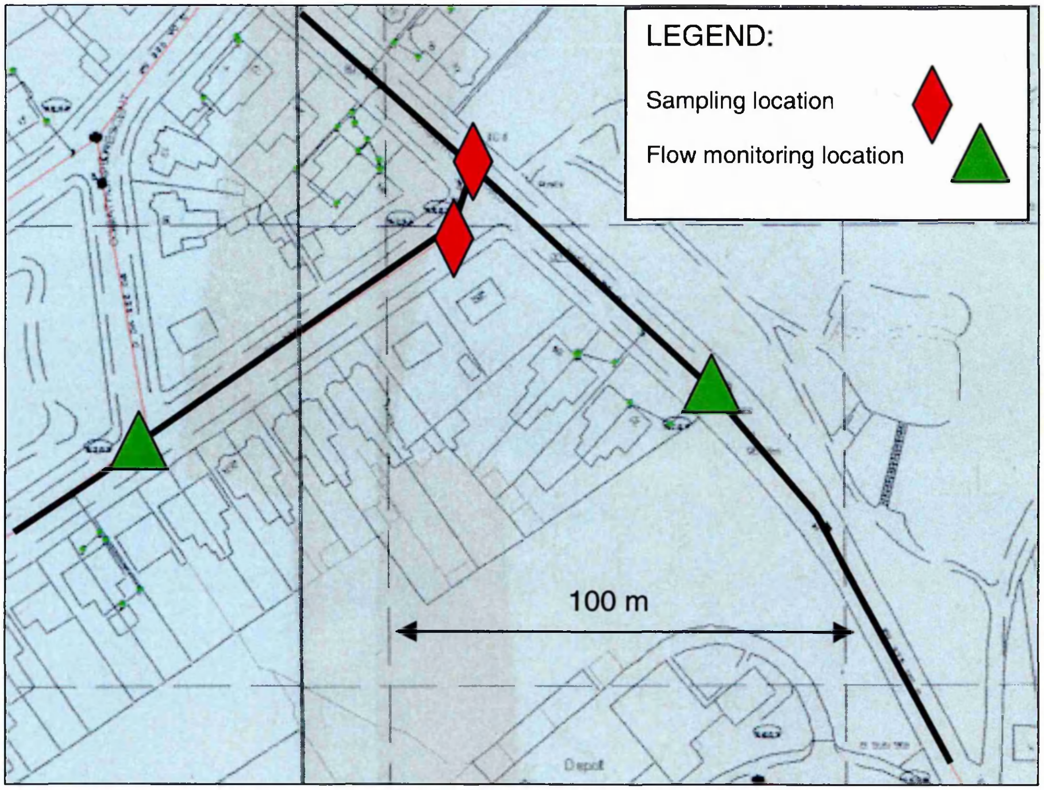


Figure 3.23 – Monitoring locations at the minority ethnic catchment

3.4.3.2 Monitoring Locations

Individual sampling locations were chosen for each sub-catchment (Figure 3.20 and Figure 3.23). The monitoring locations were situated in the public highway, however the volume of traffic was very low. The flow monitoring points were approximately 70 m upstream of the sampling locations. A raingauge was situated in the centre of the catchment at the Environmental Health offices (Figure 3.20).

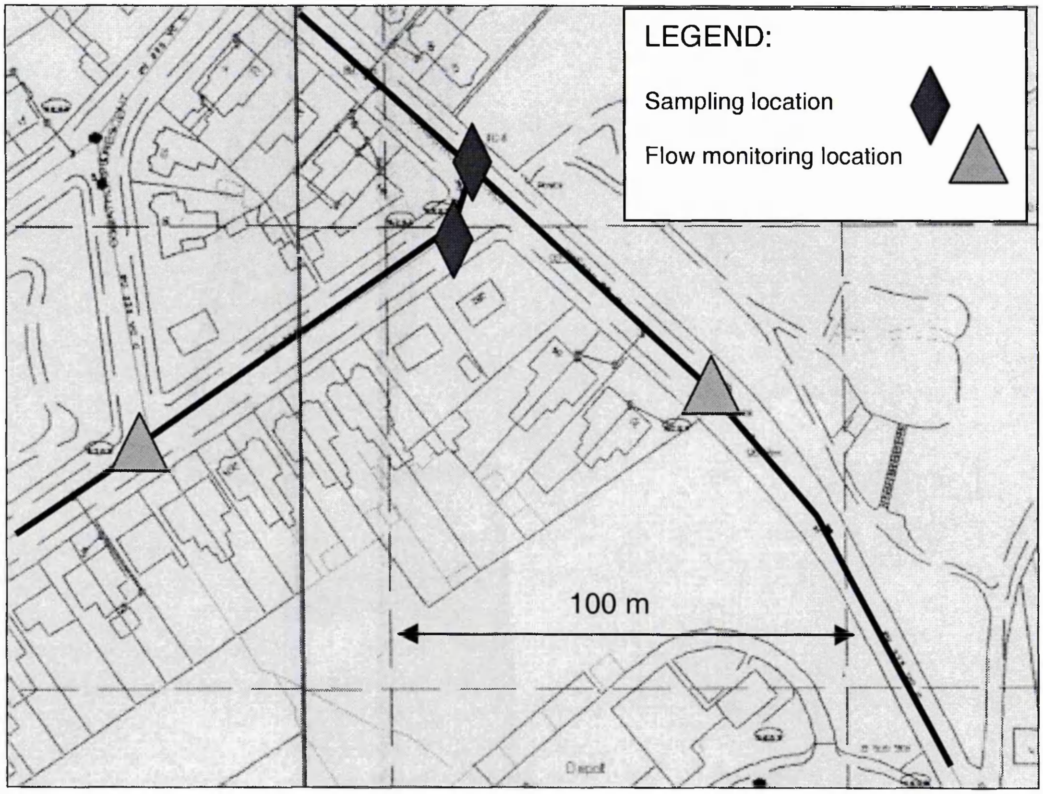


Figure 3.23 – Monitoring locations at the minority ethnic catchment

3.4.4 Middle Income / Flat Catchment

The fourth catchment to be sampled was to contain a middle income population type. The selection of this catchment proved very hard with a total of 8 sites considered during a desktop study. Four of the sites were investigated with an on-site survey, but considered unsuitable. These were:

1. Retford Rd, Woodhouse – Monitoring locations only available for use were opposite a School creating a hazard when sampling.
2. Richmond Park Rd, Handsworth – The monitoring locations were situated away from the public highway and very close to housing. The sampling requires the vehicles used to be adjacent to the monitoring point therefore this was unsuitable.
3. Abbey Lane, Meadow Head – The monitoring locations were situated in the middle of a busy public highway.
4. Thorpe House Avenue, Norton Woodseats – A number of monitoring points could have been selected at this site. However the sampling points were situated either in the centre of the public highway or away from the vehicle.

The selection of a site in Sheffield containing a middle income population was not possible. A second type of catchment was considered which in particular would investigate the catchment characteristics, and this was a flatter catchment. The only location with low gradients in the Sheffield area (typically 1:100) was in and around the Rother Valley area to the East and North of Sheffield.

A suitable site was found during a desktop study in the Canklow area of Rotherham. Further investigation identified suitable monitoring locations for the Surveyloggers and sampling. However the desktop survey did identify outfalls from the system, but it was unclear on how they were connected. An investigation of these points identified un-screened overflow points. The inspection of the chambers suggested the overflow points had a regular spilling frequency. The site therefore could not be used because flow and solids could have spilt from this point and not reached the downstream sampling point.

Following the non-selection of a fourth catchment it was decided to omit this site from the proposed sampling programme and concentrate on extra storm sampling at the existing sites.

3.5 Hydraulic Computer Simulation Model

HydroWorks has been used to construct hydraulic models of the three catchments used in the field work. These have been built and verified in accordance with the Wastewater Planning Users Group (1998) "*Code of practice for the hydraulic modelling of sewer systems,* Version 2". The models have been constructed to enable:

- Other storms to be simulated that were not monitored accurately due to equipment failure
- Model development investigation
- The time of flows and volumes of water in the system to be predicted.

The use of the HydroWorks models is discussed further in Chapters 4,5 and 6.

4 Chapter 4 – Field Monitoring, Results and Analysis

4.1 Introduction

There are many factors that affect the quantity and type of aesthetic pollutants that enter into and are transported through a combined sewerage system. Field monitoring was undertaken to determine some of these factors and observe the loadings produced by different populations in the Sheffield area. Sites were selected for field monitoring in accordance with the methodologies defined in Chapter 3. Different population types were selected to determine if socio-economic or ethnic factors affected the quantity and type of solids produced. The catchment characteristics of each site were used to identify factors that may affect the quantity of solids deposited on the sewer bed.

4.2 Dry Weather Sampling

Sampling in dry weather was undertaken to determine the solids loading produced by a population prior to a storm occurring. This was for the total and individual quantity of solids. This enabled the quantity and type of solids sampled during a storm to be compared to that normally occurring in dry weather.

4.2.1 Low Income Catchment

4.2.1.1 Dry weather total solids

The majority of dry weather sampling at the low income catchment was conducted between June and August 1999. Three morning, three evening and two afternoon samples were completed during this time period. The third afternoon sample was taken during an attempted wet weather sample that remained dry in January 2000. The third afternoon sample was delayed due to a shift in focus from dry to wet weather sampling.

The three sets of sampling data during dry weather enabled an average total and individual quantity of solids to be calculated. The profile of the total wet masses for each sampling period (morning, afternoon and evening) were similar except in SC3. A typical example of this is shown for sub-catchment SC4 in Figure 4.1. An average, maximum and minimum value for each 30 minute sampling time is shown in Figure 4.2. The largest variation in the total solids for each data set occurred during the morning period. The morning peak in the first sample occurred 30 minutes later than in the second and third sample. Sample 2 and sample 3 in the morning period were taken on a Thursday, whereas the first sample was taken on a Tuesday. This variation was not constant in each sub-catchment indicating that the day of the week was not necessarily responsible for the difference in SC4. This was also observed during the three day samples that were taken on the same day, where for example a large variation occurred with the first sample in comparison to the others at SC4 (Figure 4.1). This was generally typical in all sub-catchments sampled except SC3. The average calculated value showed a significant morning peak of solids from 06:30 through to 12:00. This peak was approximately twice the size of the second peak in the evening between 17:30 and 19:30. The size and timing of the morning and evening peaks were similar for each catchment as would be expected for the same population type. In sub-catchment SC3 the diurnal pattern was less prominent than in all other catchments sampled (Figure 4.3). A morning peak occurred from 06:30 to 12:00, with the peak value being only twice that measured during the day from 12:00 to 18:00. This variation was also observed in the dry weather flow monitoring data (Figure 4.4). The average variation of the minimum and maximum values from the mean of the sampled wet masses was 60% and 146% respectively (Table 4-1). The variation from the mean is shown for sub-catchment SC4

(Figure 4.5). It was generally observed that the largest variation from the mean occurred in the afternoon and evening sampling period rather than the morning.

Table 4-1 Average total mass collected from each sub-catchment per day per a 1000 population

Sub-catchment	Gradient (1 in)	Mass Collected per 1000 Population per day (kg)	Average variation of minimum values from the mean measured value (%)	Average variation of maximum values from the mean measured value (%)
SC1	19.6	65167	65	142
SC2	21.6	62097	60	146
SC3	33.4	61720	65	138
SC4	47.3	110652	66	140

Five dry weather days were used to calculate an average dry weather flow profile for each sub-catchment. Flow depths in dry weather were too low. Therefore weirs were introduced to increase the depth at the sensor head. This prevented the water jumping over the monitor head and thus increased the accuracy of measurement. Generally the flows in dry weather at each sub-catchment peaked at 3 to 4 l/s. The depths measured were on the boundary of the acceptable range recommended for monitoring with the survey loggers. Hence the quality of data was dependent upon the conditions on site and monitoring equipment available for use. The profiles of the flows produced per 1000 population were compared with the solids sampled profiles and showed that both were similar for each sub-catchment (Figure 4.4).

Logically, the quantity of solids produced is likely to be proportional to the population. Different population numbers reside in each sub-catchment, therefore the solids produced and sampled should vary. To account for this, the mass was normalised by calculating the mass produced at each sub-catchment by a 1000 population (Figure 4.3).

This comparison identified differences in the total rate of solids sampled at each sub-catchment. It suggested that:

1. The quantity of solids produced per person varies in each sub-catchment even when they have the same classification
2. Certain members of the population remained in the sub-catchment while others left to go to work.
3. Different quantities of solids were potentially stored in the sub-catchments' sewer systems
4. A variation in the quantity of solids entering occurs as discussed in section 3.3.5.

A large difference was observed in sub-catchment SC4, which has an average gradient of 1 in 47.3 (Table 4-1). The mass collected from SC4 was significantly greater than the other masses sampled. This was the shallowest sub-catchment, where Davies et al. (1996) suggests that less solids would be sampled per person in dry weather and more stored in this sub-catchment because of its shallow gradient. However, according to work undertaken by Houldsworth (1999a), the catchment contains a significant number of people over the age of 60. This was particularly prominent at this sub-catchment where a nursing home was situated (containing 10% of the population). Secondly the sub-catchment also contains a number of maisonettes, where an elderly population reside. This suggests that a high quantity of solids enter the catchment from the elderly population. The dry weather sampling suggested that for the total solids, the importance of the gradient of the sub-catchment in retaining pollutants were preceded by the variation in the quantity of solids entering the catchment per person. This variation was highlighted when comparing the concentration of solids in the flow for each sub-catchment (Figure 4.6). The concentration was similar throughout the day in SC3 where as the other sub-catchment indicated an increase in the concentrations in the morning period. This highlights the difference between the quantity of solids entering each sub-catchment throughout the day.

A low mass was sampled at SC1, which had the steepest average gradient of all the sub-catchments. A severe pipe defect was located upstream of the flow monitoring location where a very large quantity of solids was regularly observed during flow survey checks, to be deposited in dry weather. The pipe was rutted across the invert of the pipe and allowed solids to be collected readily, which significantly reduced the loading recorded in dry weather.

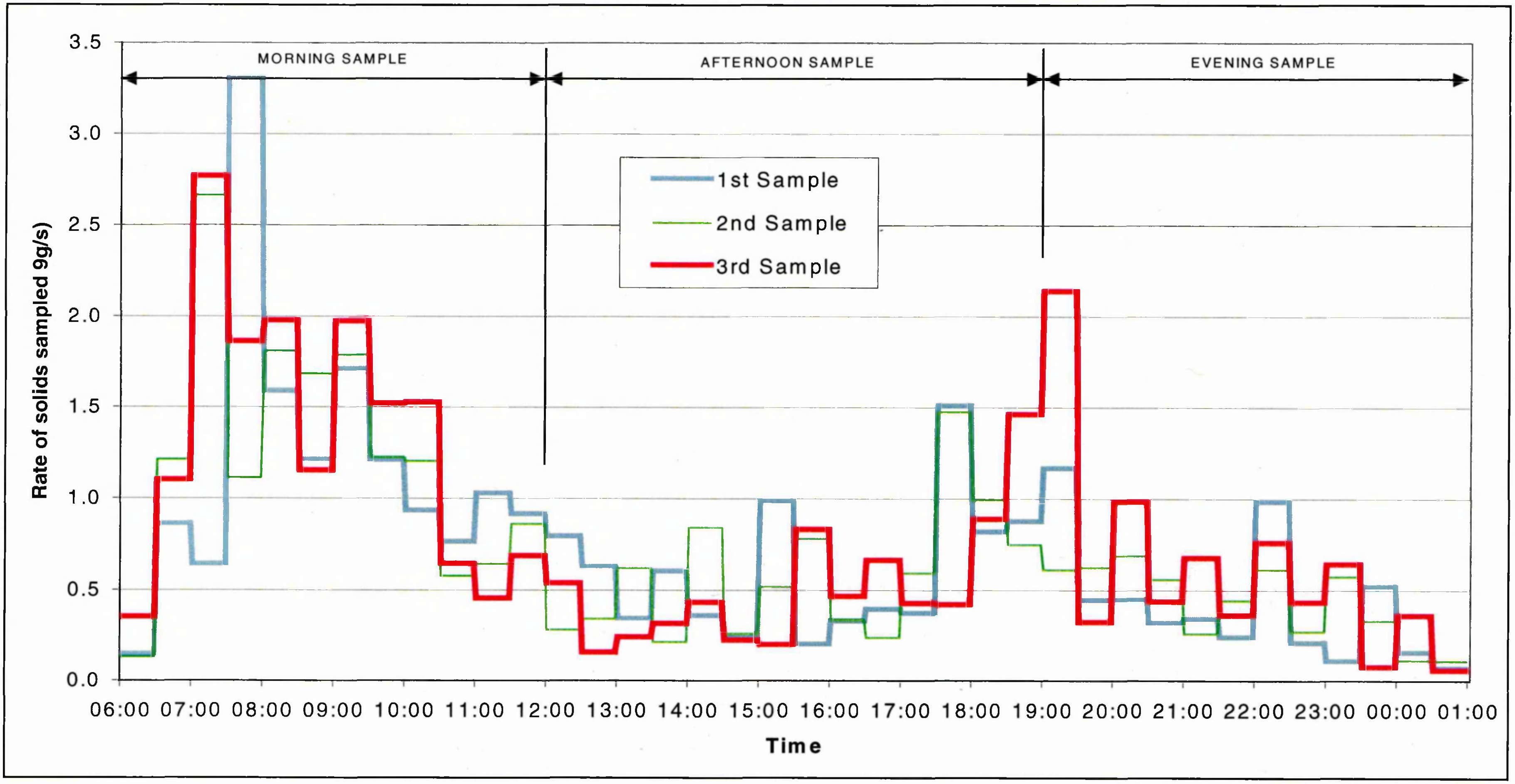


Figure 4.1 Three data sets of total wet masses sampled at sub-catchment SC4 at the low income catchment

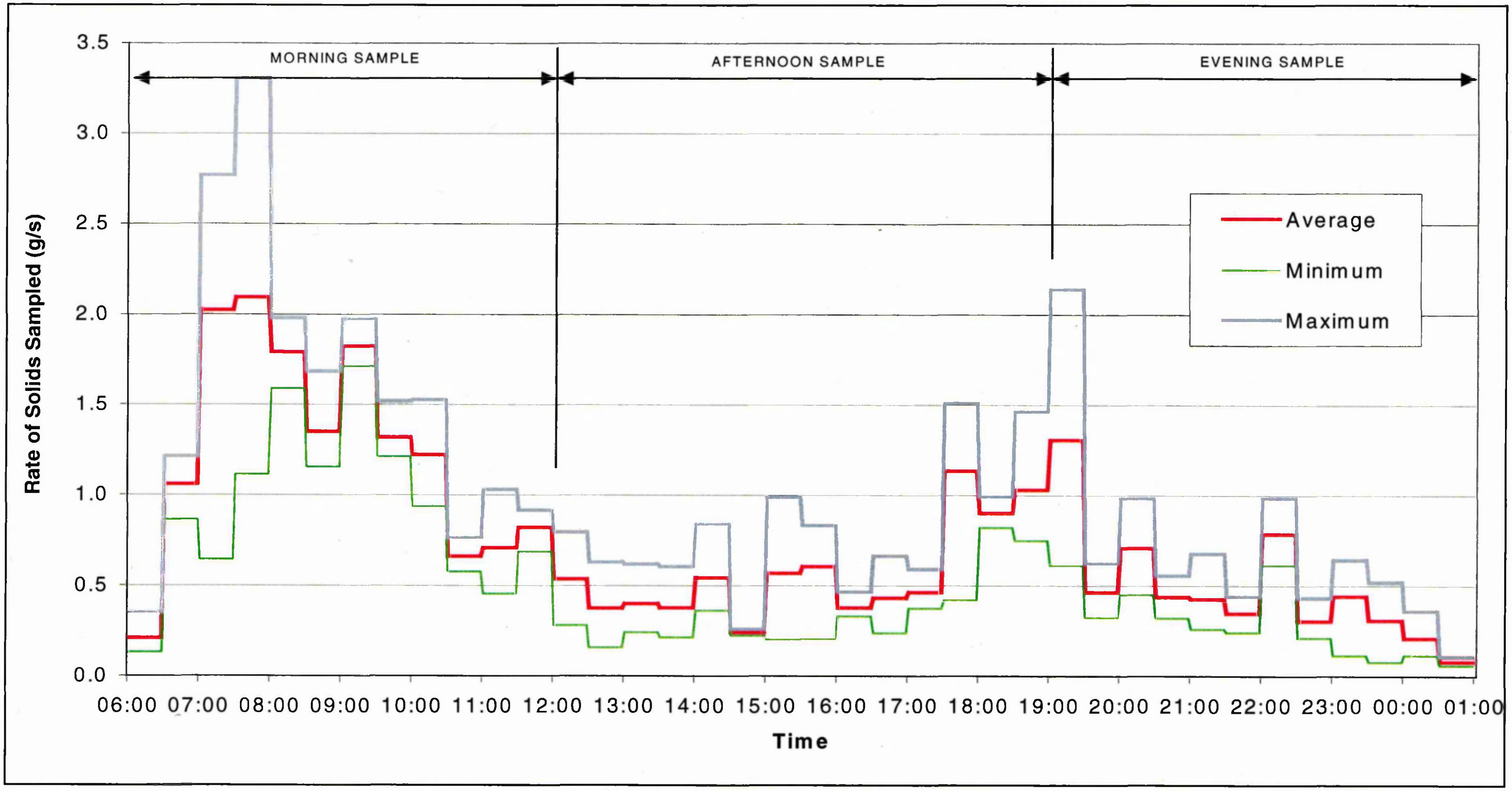


Figure 4.2 Variation of total solids sampled during dry weather for sub-catchment SC4 at the low income catchment

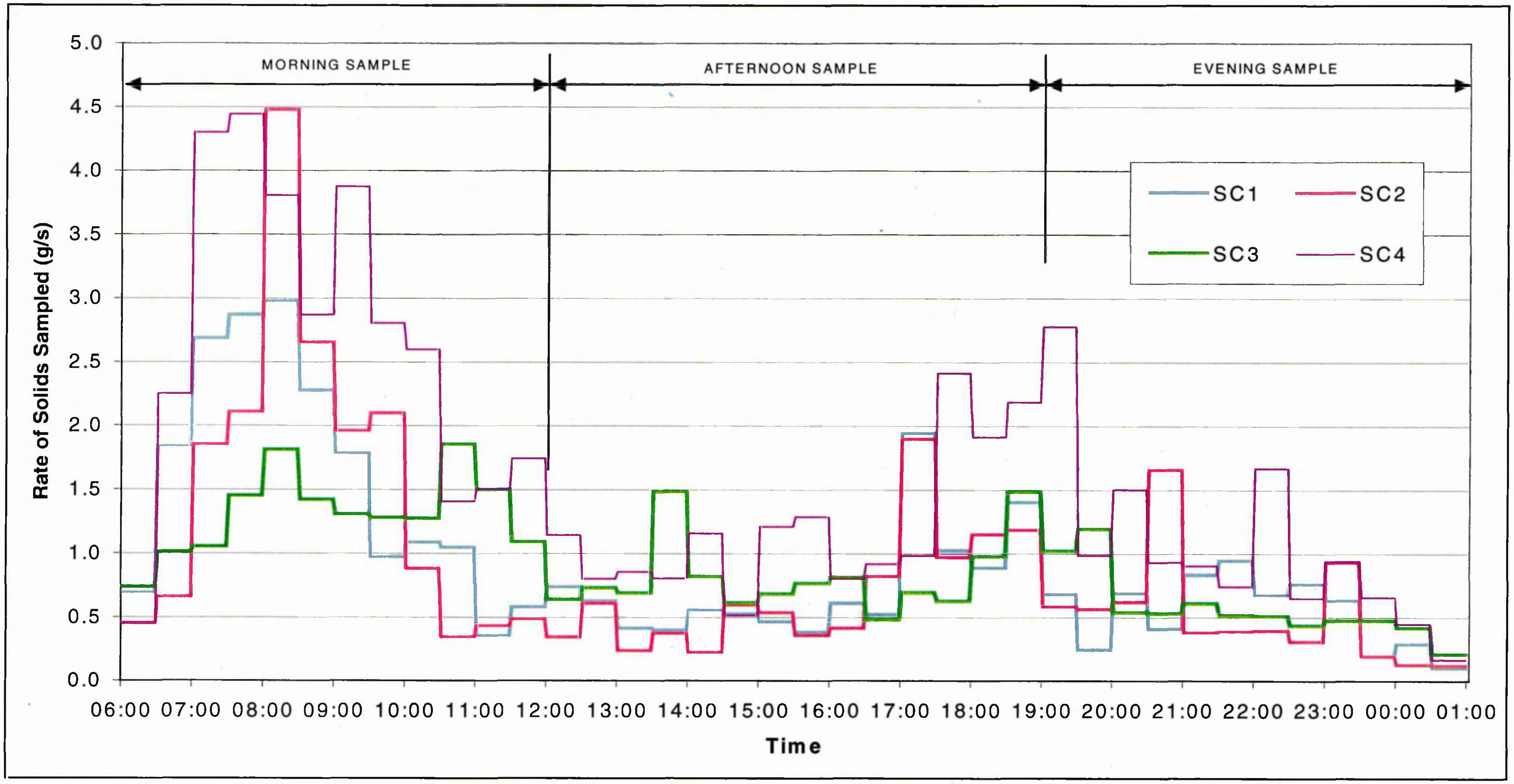


Figure 4.3 Difference in solids sampled in dry weather produced by a 1000 population at each sub-catchment in the low income area

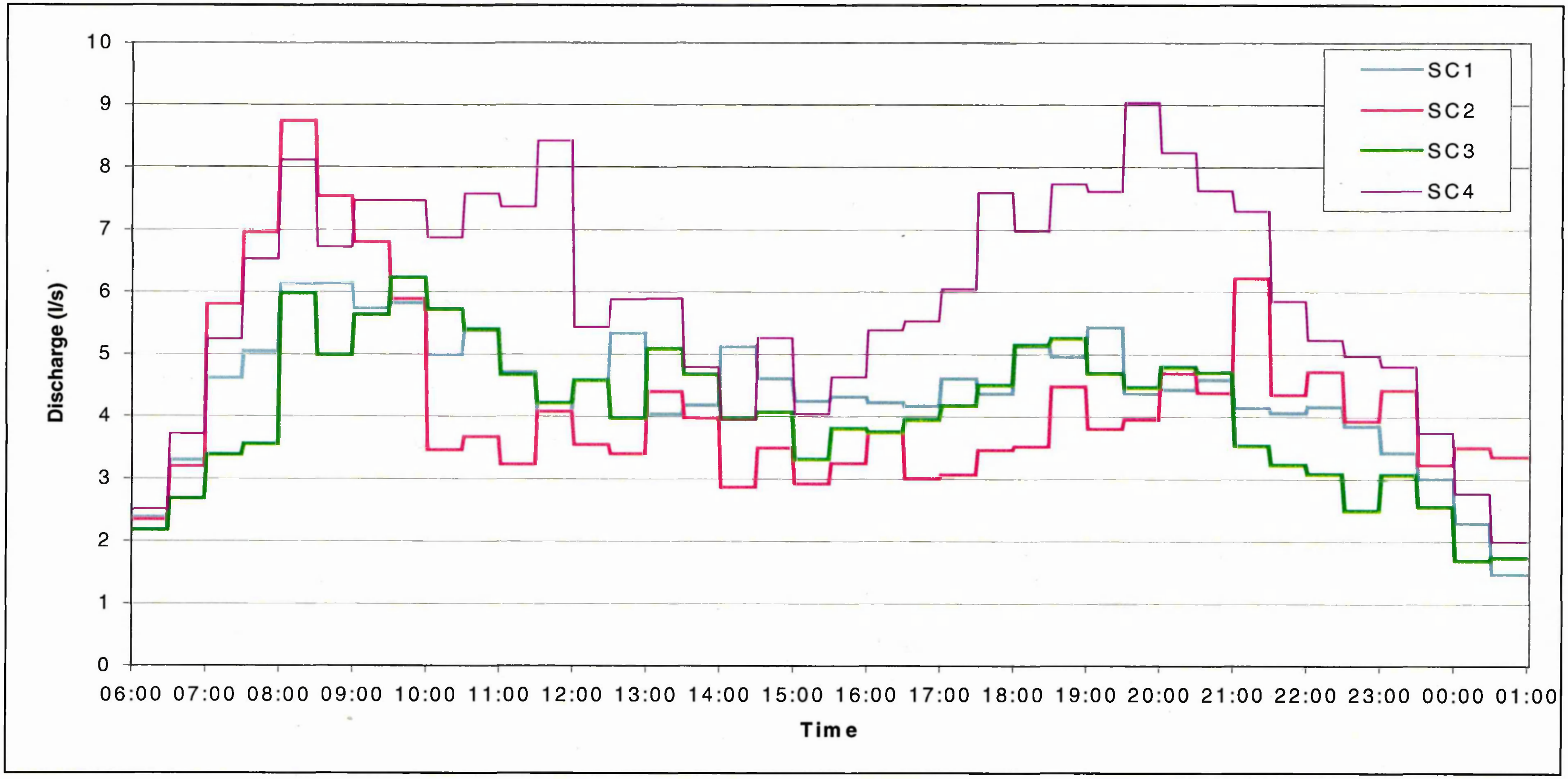


Figure 4.4 Measured flows produced by a theoretical 1000 population in each sub-catchment

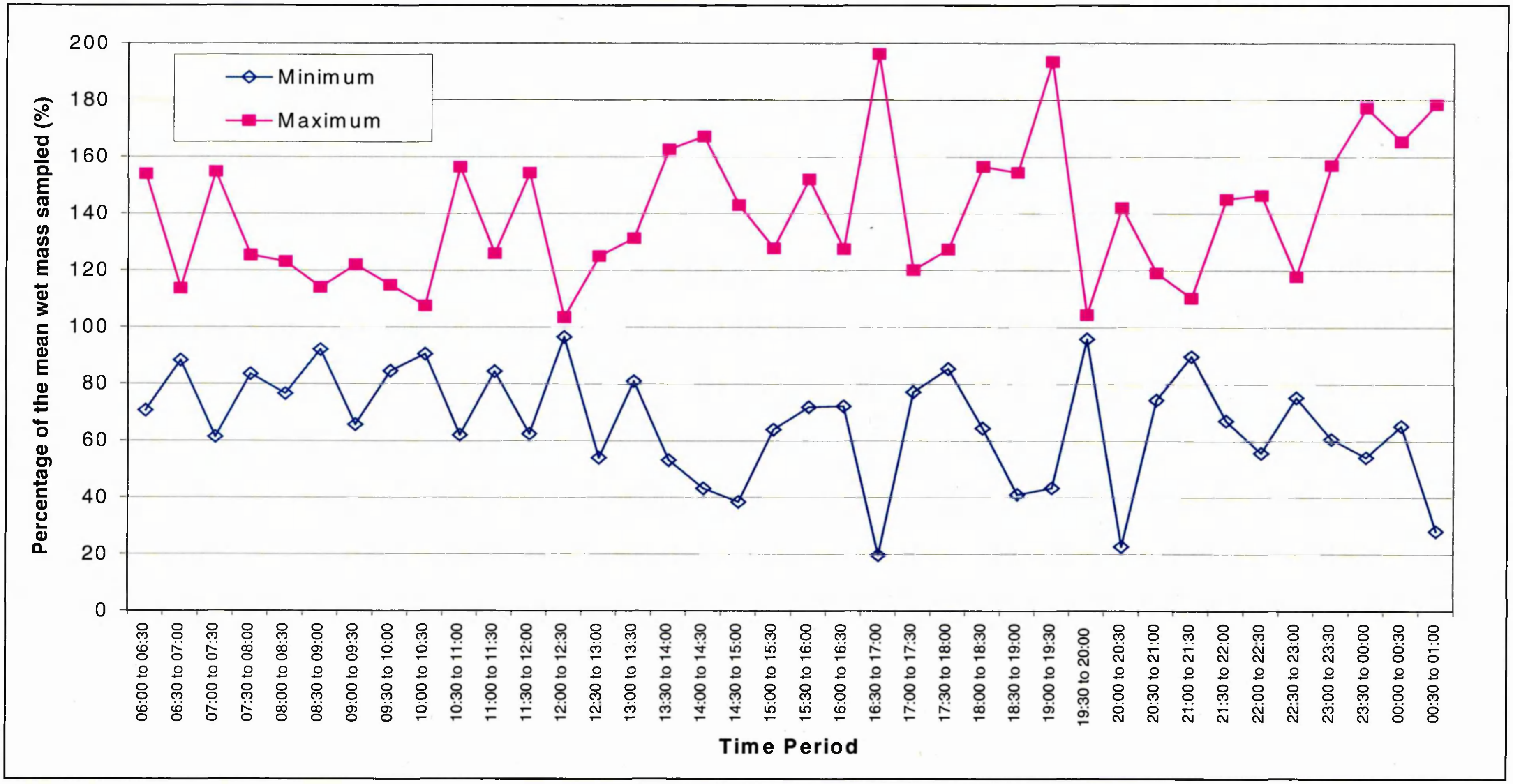


Figure 4.5 The variation of the maximum and minimum measured values from the mean value for three sets of sampling in sub-catchment SC4

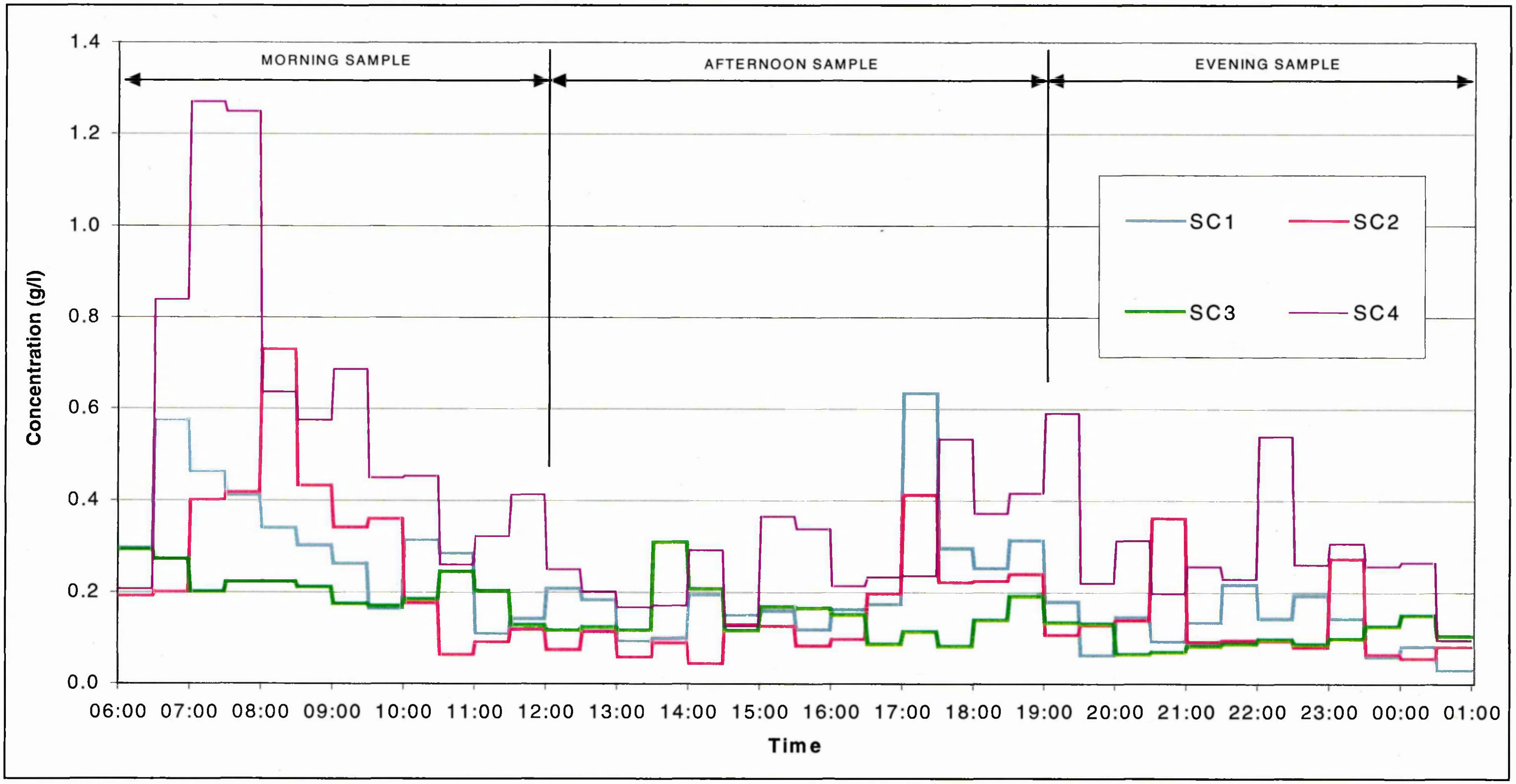


Figure 4.6 Concentration of dry weather solids and flow at the four sub-catchments

4.2.1.2 Dry weather characterised solids

Characterisation of the total solids was undertaken to determine the quantity and type of pollutants that enter into the combined sewerage system by a low income population. One sack from each sub-catchment was characterised in rotation for each time period therefore one in four sacks were characterised from each sub-catchment. The contents of the characterised sack from the single sub-catchment were proportioned for all the sub-catchments by using the total wet masses measured on site.

The three main components of the total mass of solids were faeces (32%), toilet tissue (22%) and mush (33%) which constituted 87% percent of the total mass. The remaining mass mainly constituted of SANPRO items, kitchen roll, wipes, fat, and litter. Mush was created from the sampling procedure, where a mixture of faeces and toilet tissue was degraded in the sack and became attached to the mesh. This material remained attached to the sack when it was emptied. It was estimated from observations of the material that it composed an even distribution of faeces and toilet tissue. This created as a percentage of the total mass, faeces of 49% and toilet tissue of 38%. The diurnal profiles of both pollutants follow similar pattern to flushing profiles (Figure 2.1) of faecal related flushes and toilet tissue flushes (Friedler et al. 1996) with a slight variation during the morning peak (Figure 4.7). The measured toilet tissue peak (with a similar timing to the flushing toilet tissue peak) occurs approximately 1 hour before the faeces and was similar in shape, with a large quantity of toilet tissue measured in all three morning samples. During rise and settle velocity testing, toilet tissue would float on the surface until completely saturated and required pushing below the water surface before it would sink. At the sampling locations, the toilet tissue was observed to travel separate from faeces. Faeces during rise and settle velocity tests were observed to generally fall, with a specific gravity greater than one however only a small number of faeces were tested.

These solids are known to form part of the bed load and hence travel slower than toilet tissue under laboratory testing Brown et al. (1996). Therefore the toilet tissue was likely to be transported through the system at a faster rate.

Of the remaining solids SANPRO items and wipes were most commonly sampled. Due to their relatively low collective mass these products were analysed by mass and number. It was also easier to visualise a number of products rather than just by a mass.

A large number of wipes were sampled during dry weather, particularly in the morning period between 07:00 and 11:00 (Figure 4.8). A number of smaller peaks occurred throughout the rest of the day through to 00:30. Three significant clusters of sampled SANPRO items was observed:

1. The morning from 06:00 to 10:30
2. Early evening from 16:30 to 19:30
3. Late evening from 21:00 to 0:00

The overall SANPRO profiles follows flushing profiles (Figure 2.2) identified by Friedler,E. et al. (1996) with a morning and several evening peaks . A significant large evening peak was observed with the sanitary towels between 17:00 and 18:00.

The number of SANPRO items sampled varied with 16.3 /1000pop./d panty liners, 19.4 /1000pop./d sanitary towels and 10.5 /1000pop./d tampons. This suggested that either tampons were being deposited and retained in the system, or that panty liners and sanitary towels were the most commonly disposed SANPRO product, accounting for 77% of usage. Panty liners were most commonly sampled in the morning, whilst sanitary towels were most commonly sampled in the evening. This may suggest the preference for using a specific type of SANPRO item during a particular part of the day.

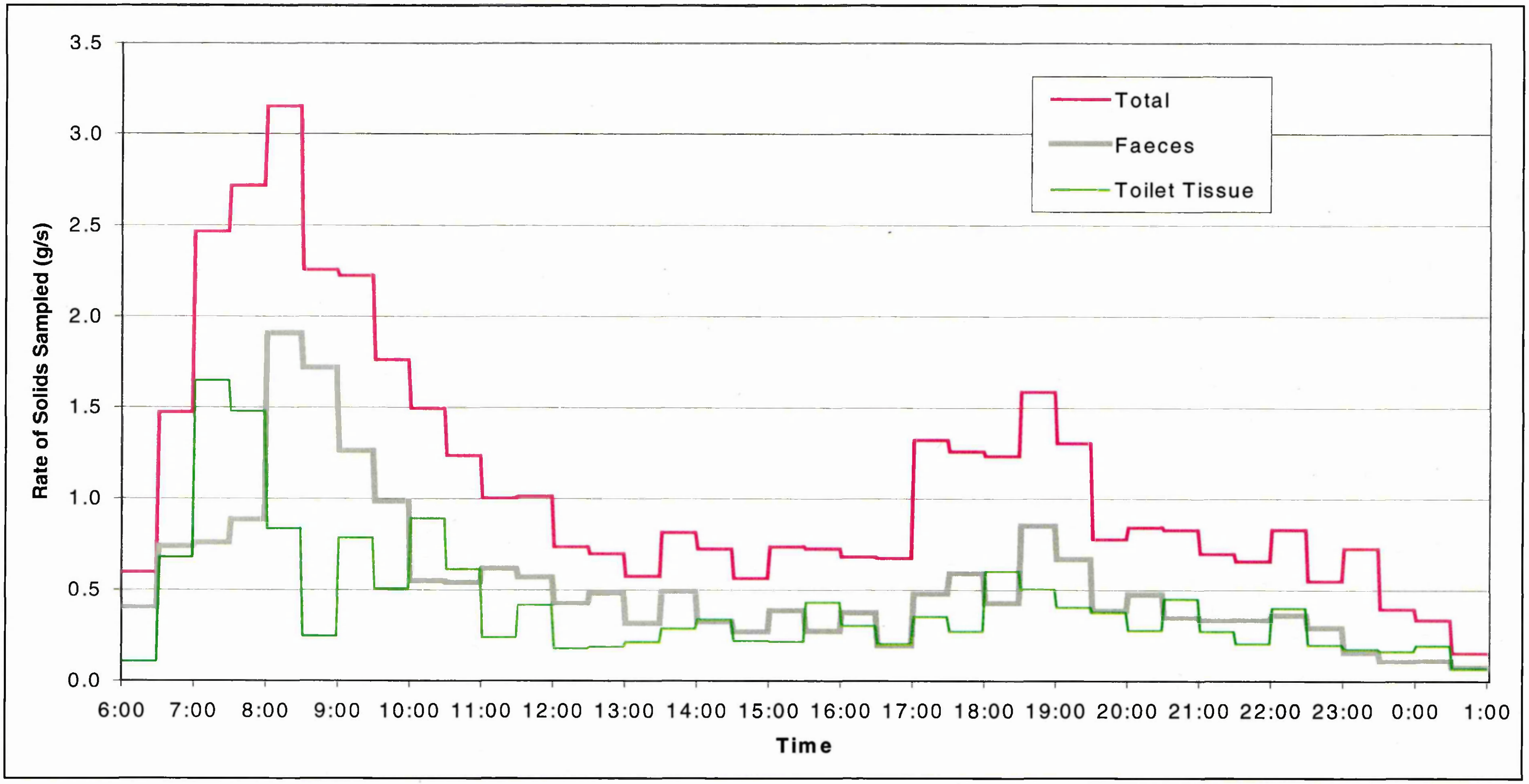


Figure 4.7 Diurnal profile of faeces and toilet tissue produced by a 1000 population in the low income catchment

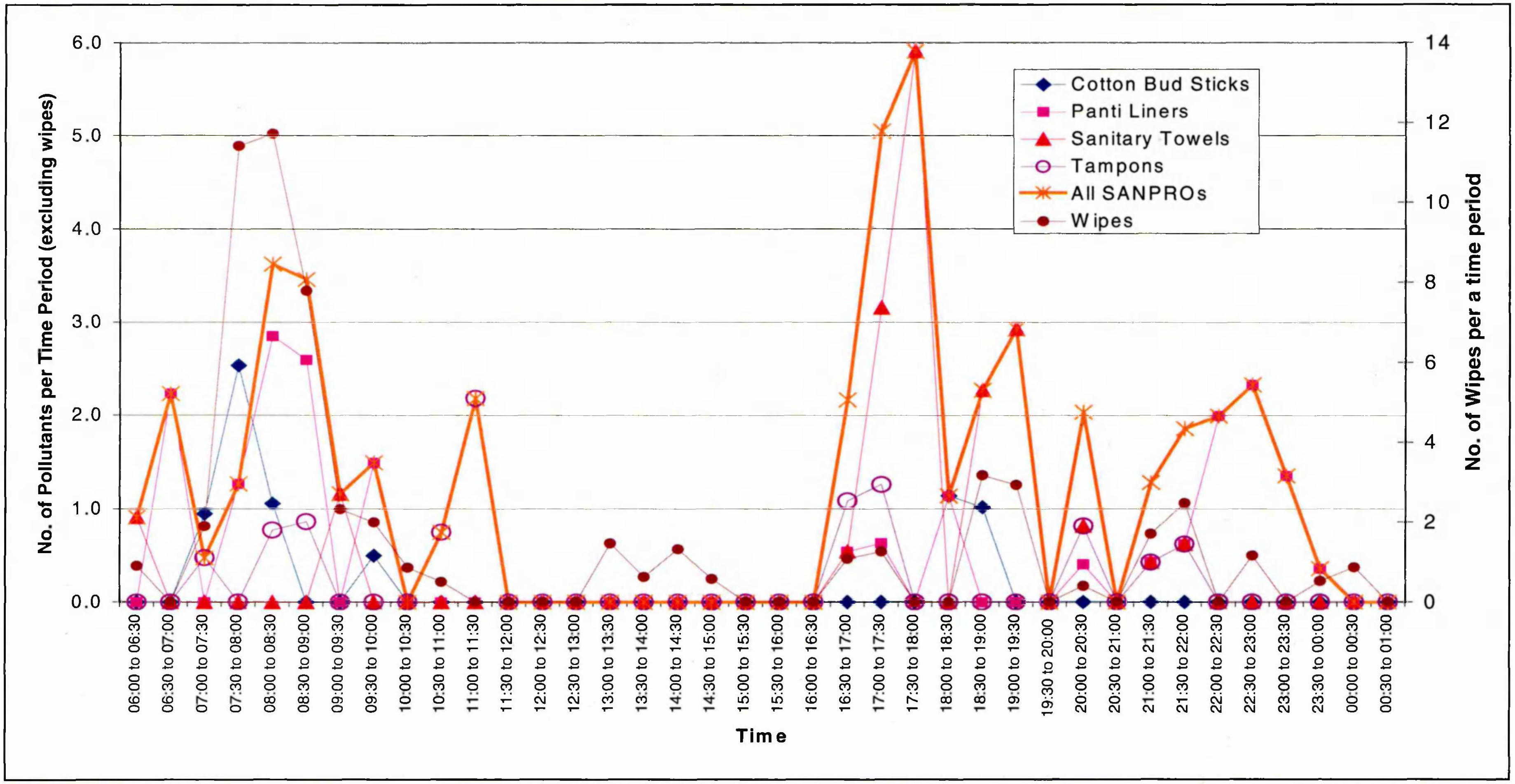


Figure 4.8 Distribution of SANPRO items and wipes per a 1000 population at the low income catchment

4.2.2 High Income catchment

4.2.2.1 Total dry weather solids

Sampling at the high income catchment commenced in March 2000 and concluded in July 2000. An extra morning sample was taken following the large variation between the second and third sample, both of which occurred on a Thursday. Generally the data sets sampled in the morning, afternoon and evening periods compared well (Figure 4.9 and Figure 4.10). However a large difference in loading was observed during the morning period for the third sample showing a large peak (3.8 g/s) and an increased overall loading during the morning sampling period (29.2 kg). The second morning sample showed a delayed single peak (1.9 g/s) in the morning with a low overall loading (17.2 kg). The overall mass of the first and fourth morning sample were very similar 22.4 kg and 23.1 kg respectively with similar size peaks, 1.9 g/s and 2.2 g/s respectively, however the peak of the fourth sample occurred 1 hour earlier. The larger peak of the third sample in the morning could possibly be attributed to infiltration following a large rain event on the preceding day creating larger flows and hence velocities and depths. This would have reduced the number of solids being deposited and aided a greater number to be transported through the system.

The average variation of the minimum and maximum values from the mean of the sampled wet masses was 68% and 135% respectively. The variation from the mean is shown (Figure 4.11). A large variation from the mean occurred in the morning from the third sample. A second large variation occurred between 20:00 and 20:30 where a very low value was recorded.

The average dry weather rate of solids sampled profile follows a similar trend to the dry weather measured flow profile (Figure 4.12). To enable accurate monitoring the depths were increased by locating a weir downstream of the monitor. An average dry weather flow was then calculated from 5 days data.

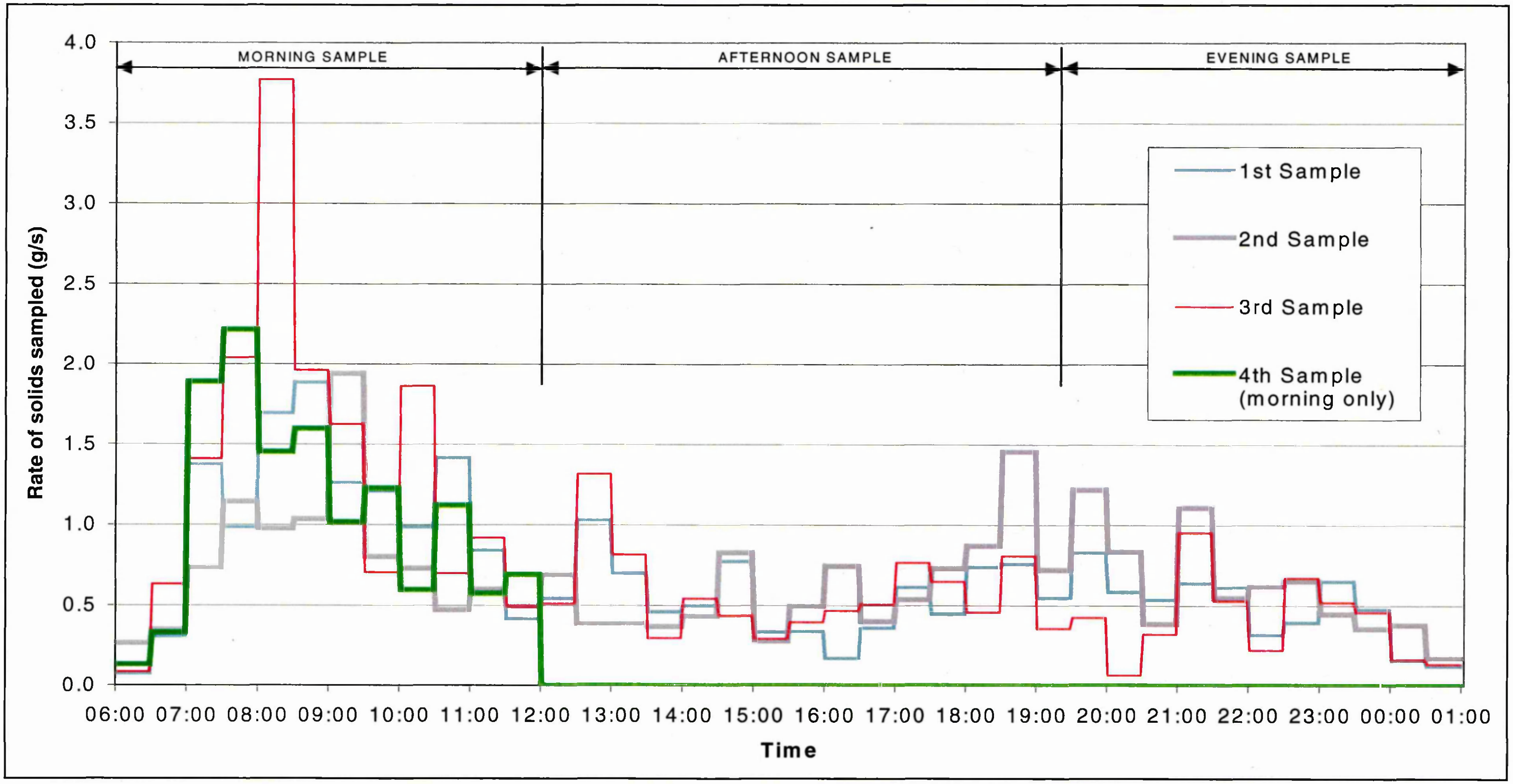


Figure 4.9 Variance of the total solids sampled for the morning, afternoon and evening sample periods at the high income catchment

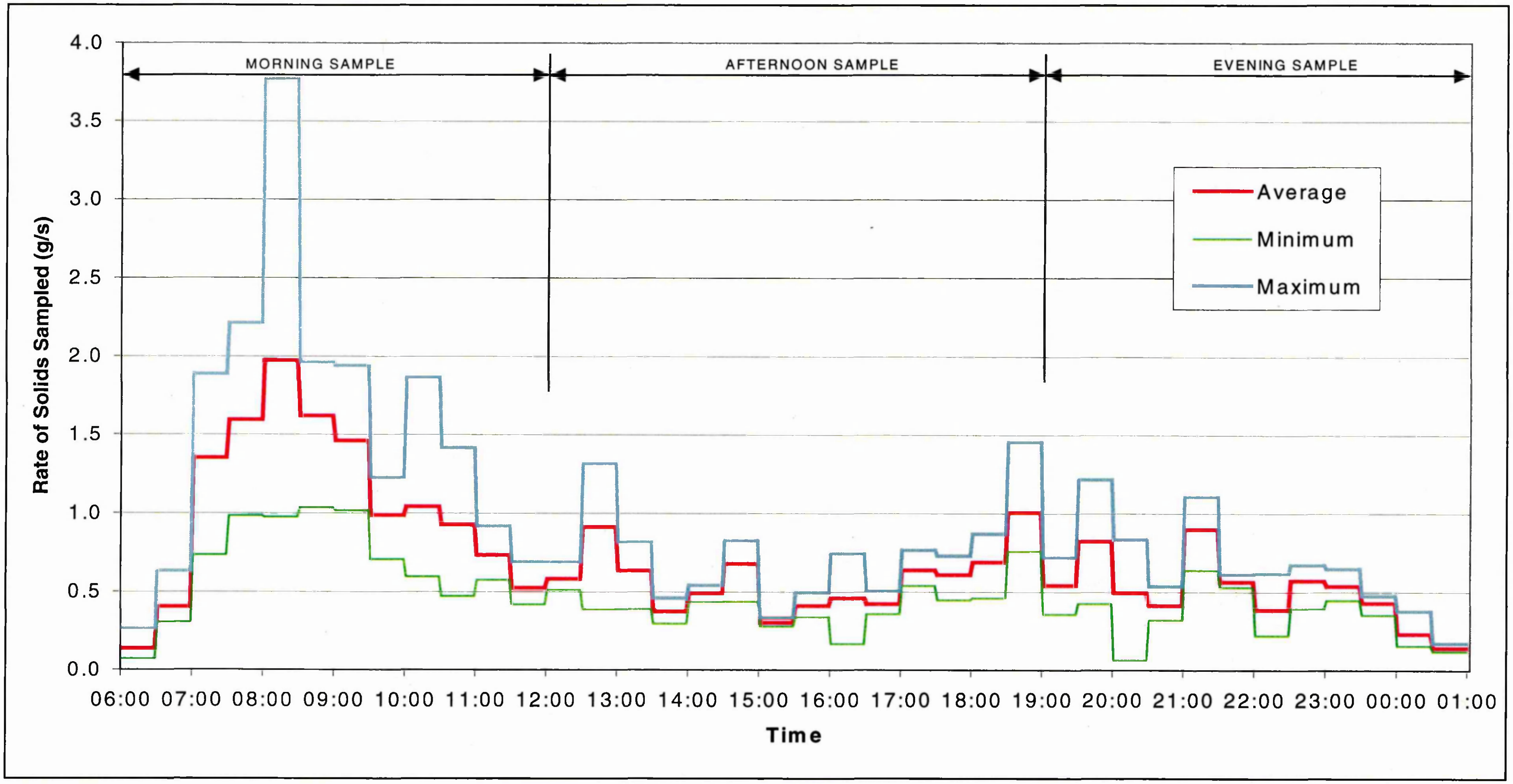


Figure 4.10 Average, maximum and minimum values total wet masses from dry weather sampling at the high income catchment

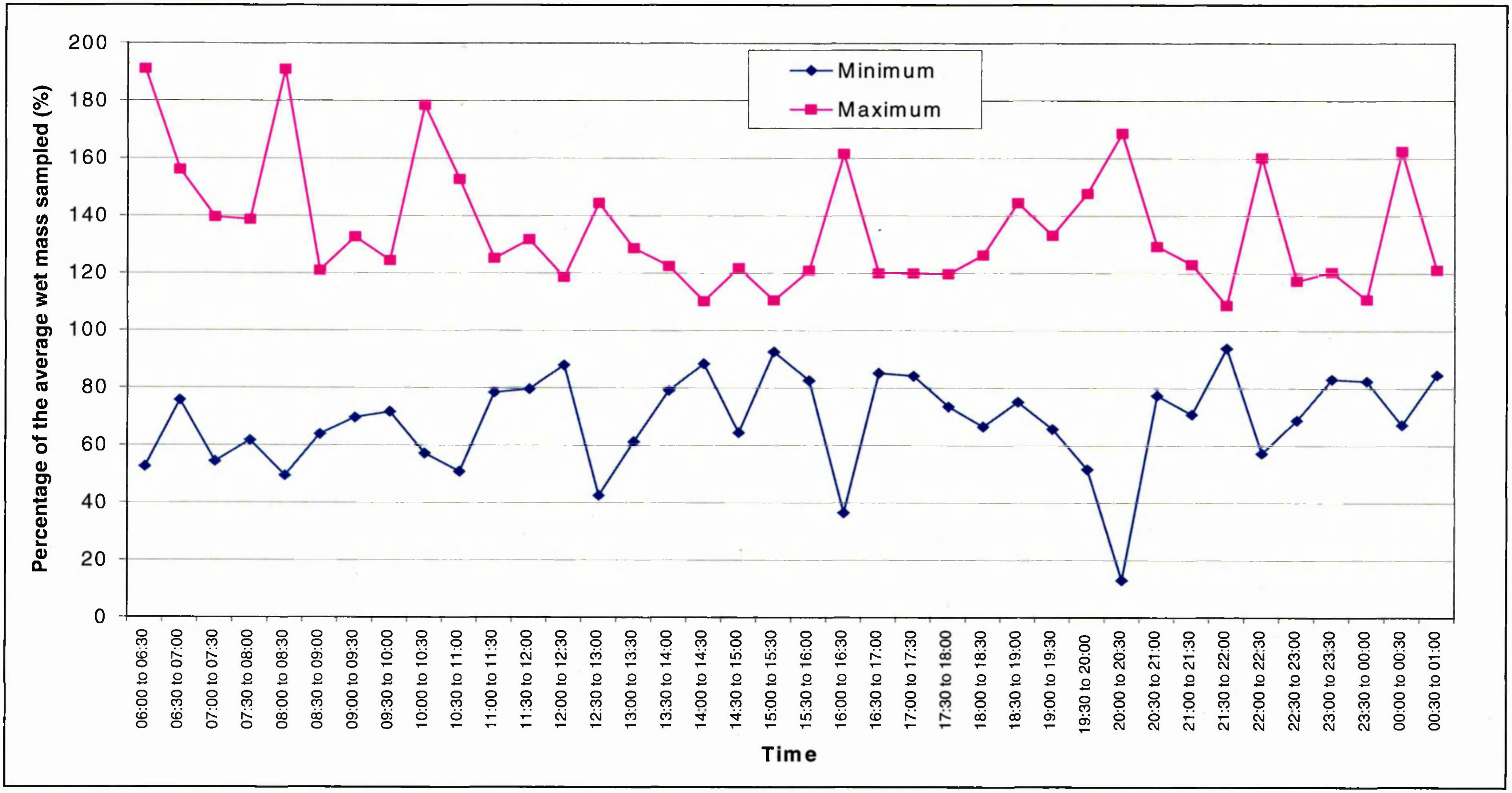


Figure 4.11 Variation of the maximum and minimum values from the measured mean value in the high income catchment

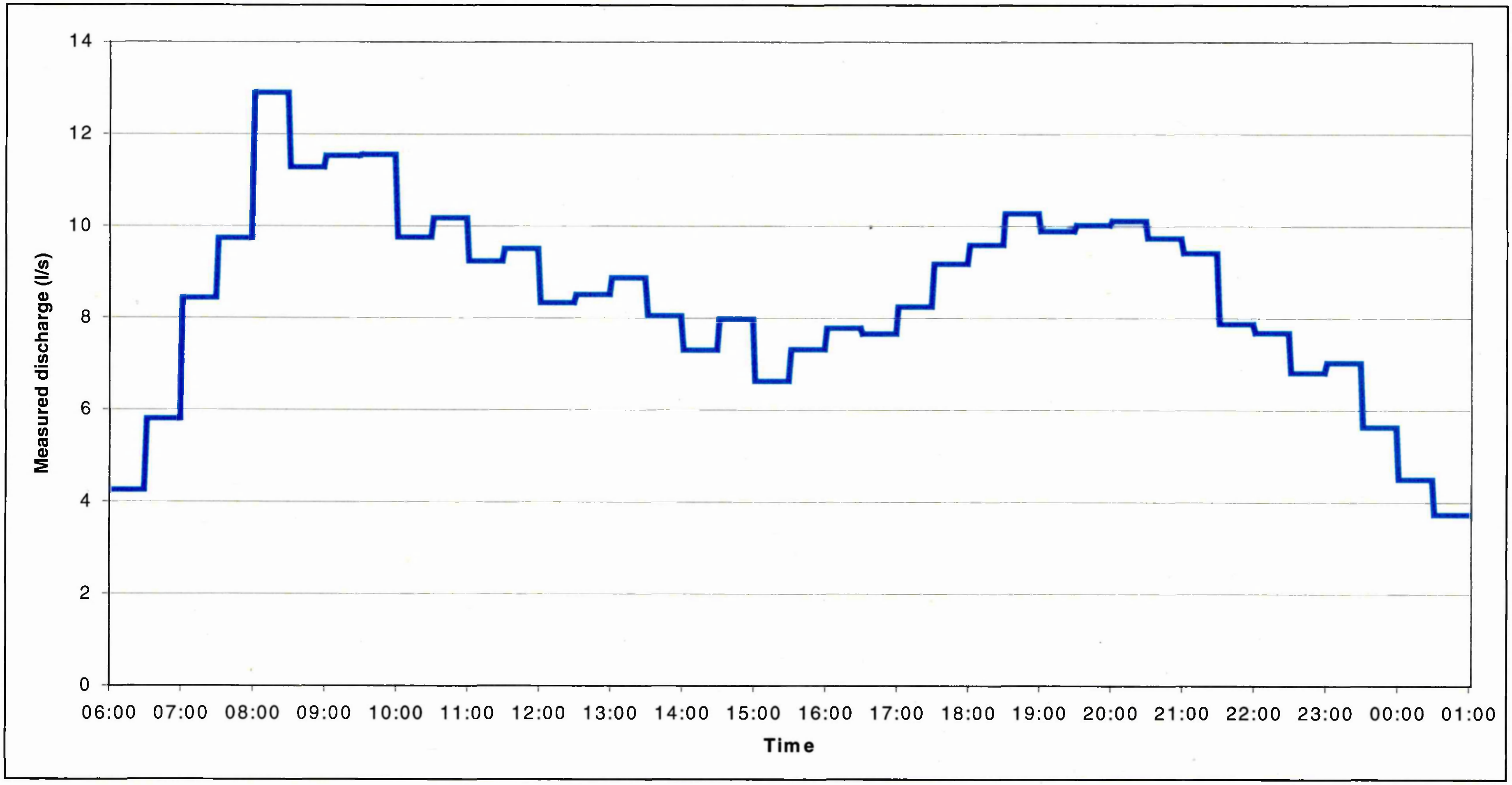


Figure 4.12 Average measured dry weather flow for a 5 day period at the high income catchment

4.2.2.2 Characterised dry weather solids

All sacks were characterised at the high income site, due to less solids being sampled than at the low income catchment. This provided a more accurate indication of the solids being produced by the population and their temporal distribution during dry weather. An average value for the samples was produced for each 30 minute time period. This value was then converted into a mass or number produced by a 1000 population.

A clear peak of faeces was observed during the morning and evening in line with the total solids flush and dry weather flow monitoring (Figure 4.13). The morning peak was positively skewed between 07:00 and 11:00, with a smaller evening peak from 17:00 through to 22:00. Toilet tissue followed a similar profile to the faeces in the morning although it was not sampled 1 hour before the faeces as observed at the low income site. No increase in toilet tissue was observed in the evening. The three main components of the total mass were faeces (44%), toilet tissue (13%) and mush (33%) with the remaining mass comprising of SANPRO items, wipes, kitchen roll and leaves. The mush was observed to contain a mixture of faeces and toilet tissue as seen at the low income catchment, therefore it was divided by two and added to faeces and toilet tissue. This created as a percentage of the total mass, faeces being 60% and toilet tissue of 30%.

The SANPRO products and wipes showed no clear diurnal pattern (Figure 4.14). Although a significant number of SANPRO items were sampled in the morning period, peaks occurred throughout the day. Tampons (34.9 /p/d) dominated the main type of SANPRO item sampled at the high income catchment. Panty liners (10.6 /p/d) were the second largest SANPRO item sampled followed by sanitary towels (3.7 /p/d). Wipes followed a similar diurnal profile to SANPRO items throughout the whole day. This profile was different to the Freidler flushing profile (Friedler et al. 1996) and the measured dry weather flow profile (Figure 4.12). Whether this was caused by the variation in the solids entering the system during the sampling period, or that certain items were disposed of via the solid waste disposal route is unclear.

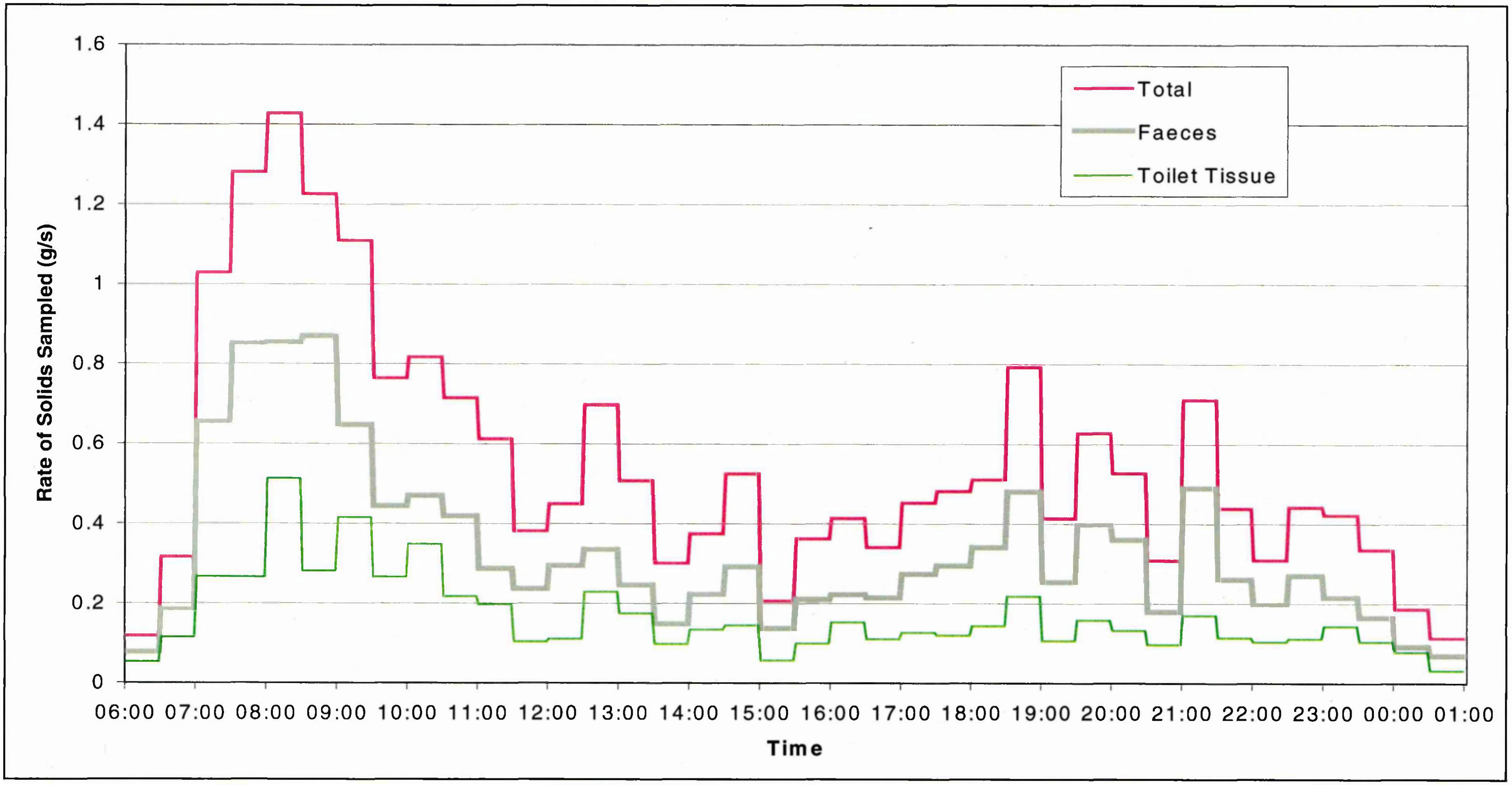


Figure 4.13 Rate of total solids, faeces and toilet tissue per a 1000 population at the high income catchment

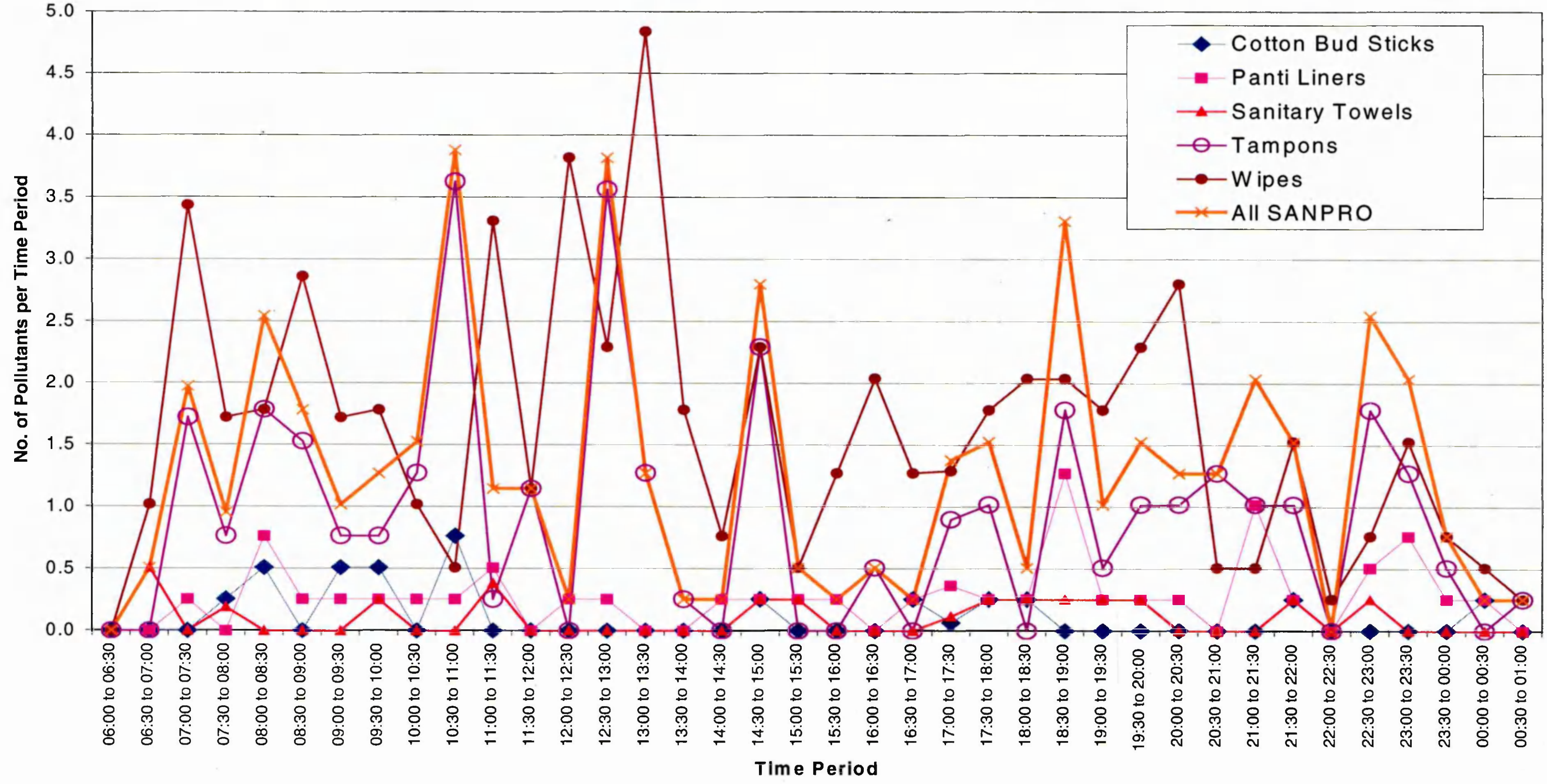


Figure 4.14 Number of SANPRO items and wipes sampled per a 30 minute time period per a 1000 population at the high income catchment

4.2.3 Ethnic Catchment

4.2.3.1 Total dry weather solids

Dry weather sampling at the ethnic catchment was conducted between July 2000 and January 2001. This occurred at both sub-catchments (section 3.4) however following storm sampling at the catchment, it was discovered from Yorkshire Water that the sewer network in sub-catchment SC2 was suffering from severe root intrusion (Birch 2001). Root intrusion is likely to cause other problems such as damaging the structure of the pipe therefore a combination of these pipe defects were likely to cause solids to be stored in locations where solids' deposition would not normally occur. Therefore the quantity of solids sampled in dry weather would be lower than expected and the quantity of solids sampled during a storm would be greater than expected as a result of an increase in storage. This could have also caused an increase in infiltration affecting the discharge. Therefore the results for sub-catchment SC2 are not presented.

Clear morning peaks were observed in the total mass from the three samples taken, with a slight variation in the time of these peaks (Figure 4.15). A second morning peak was observed in the morning sample between 10:00 and 12:00 for the three samples, although a variation in the timing of these peaks was observed. A large variation in the magnitude of the evening peaks (sampled on different days) was observed where the second evening sample had a peak from 21:30 to 22:00 of 1.8 g/s. This was greater than the maximum morning peak (1.7 g/s). The three evening samples were taken on different days of the week. Overall, the collective masses for each sample period were similar varying by ± 10 % from the average value. The average rate of solids sampled shows the diurnal distribution, identifying a positively skewed morning peak (1.5 g/s) from 06:30 to 12:00 and an evening peak (1.2 g/s) from 17:30 to 22:00 (Figure 4.16).

Secondary peaks during the morning flush correlate with the secondary peak observed in the average five day dry weather flow (Figure 4.17). The dry weather flow profile also compares favourably with the less significant morning and evening peaks and the rate of solids sampled.

The average variation of the minimum and maximum values from the mean of the sampled wet masses was 72% and 131% respectively. The variation from the mean is shown (Figure 4.18). This catchment showed the lowest variation from the mean of total masses sampled.

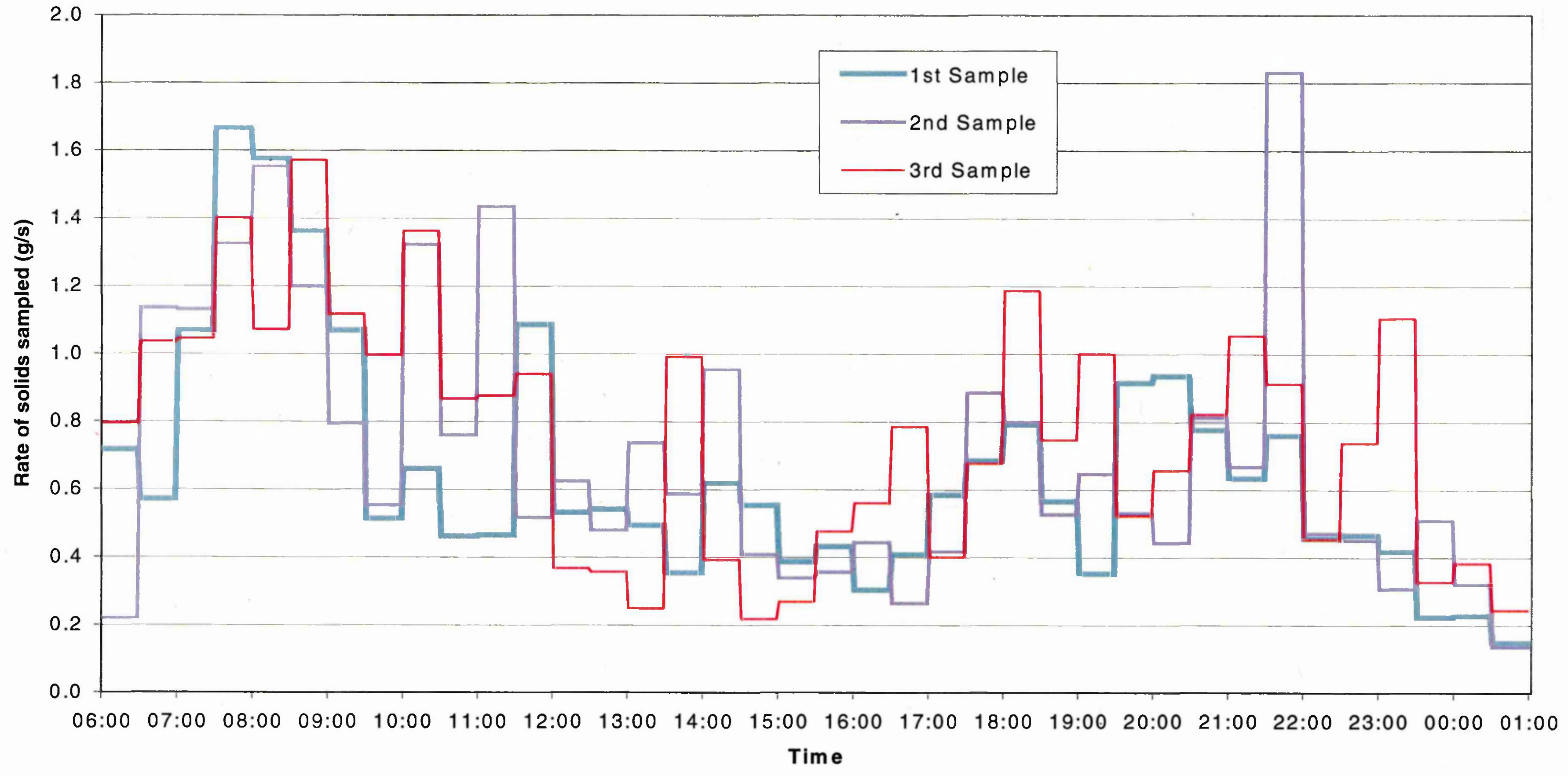


Figure 4.15 Variation of solids sampled for each data set from sub-catchment SC1 at the ethnic site

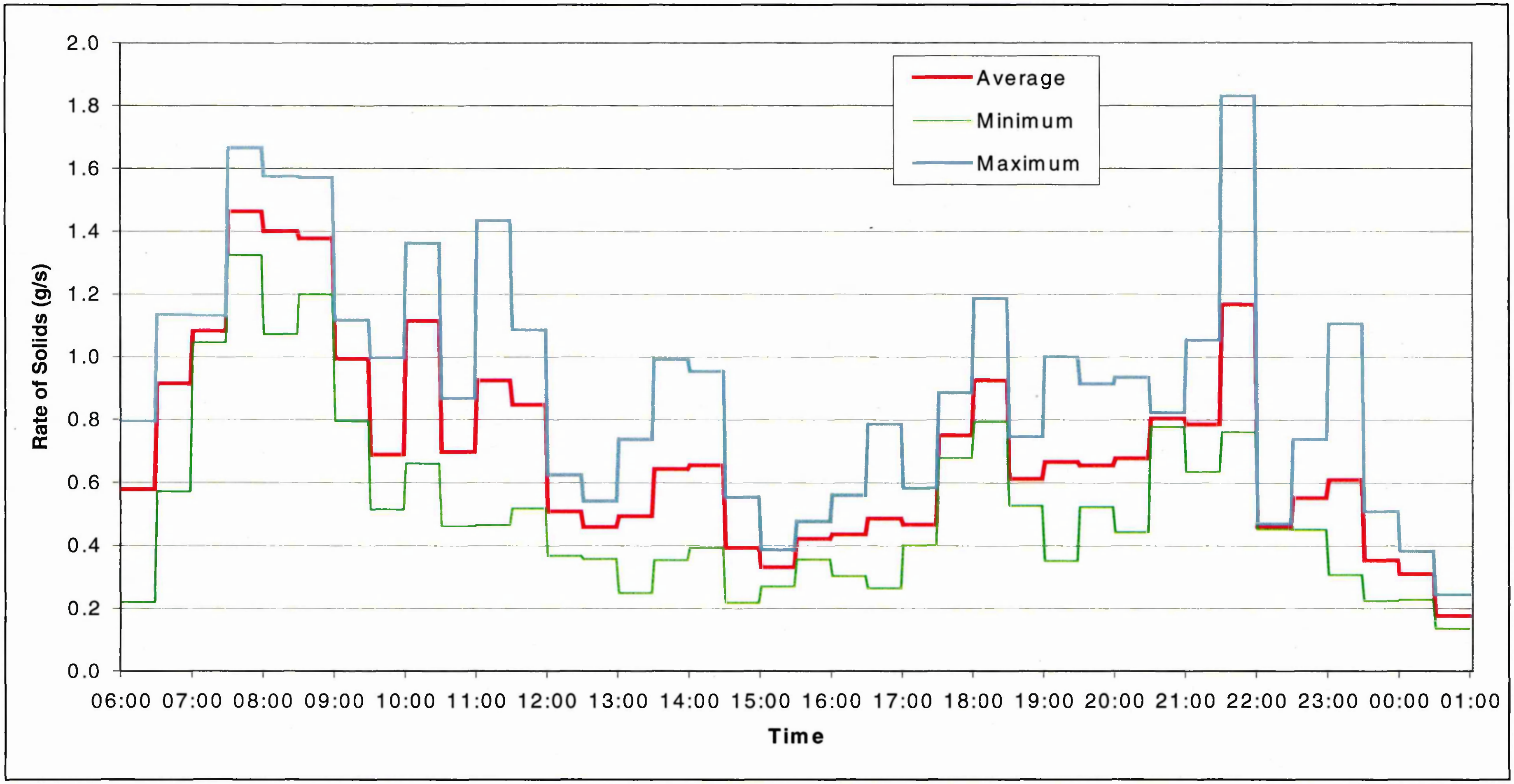


Figure 4.16 Average, maximum and minimum values of total solids sampled of the data sets sampled at the ethnic catchment

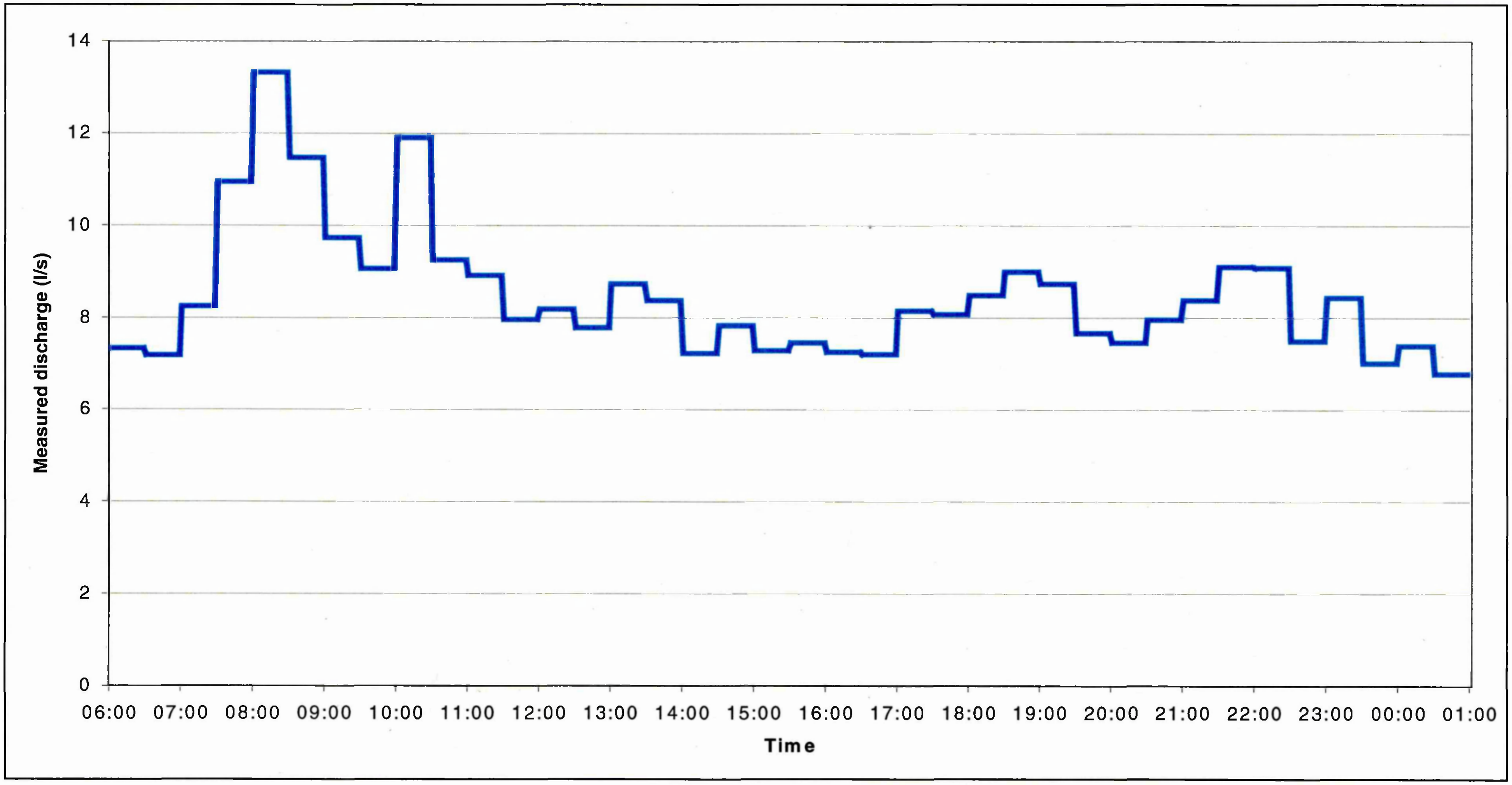


Figure 4.17 Measured dry weather flow produced from sub-catchment SC1 from the ethnic catchment

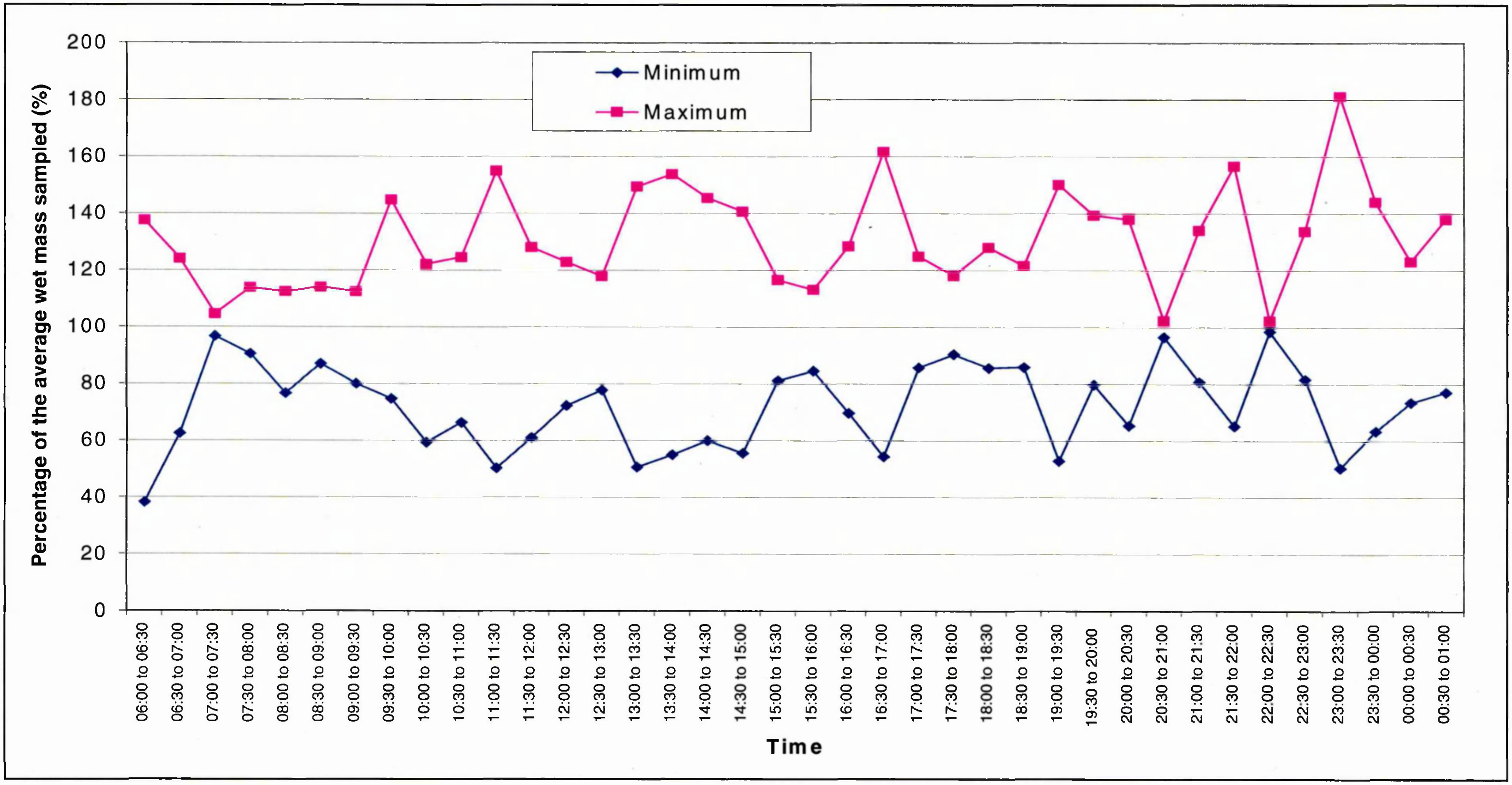


Figure 4.18 Variation of the maximum and minimum values from the measured mean value in the ethnic catchment

4.2.3.2 Characterised dry weather solids

All sacks were characterised at the ethic catchment, enabling the temporal distribution of the individual solids to be accurately calculated. The same procedure as stated in section 4.2.2.2 was employed at the ethnic catchment.

Clear faecal and toilet tissue peaks was observed in the morning and evening diurnal pattern (Figure 4.19). Faeces had a morning peak that was positively skewed (following a similar trend to the total solids sampled) as well as a defined smaller evening peak. Toilet tissue had a morning peak between 06:30 and 09:00 before a secondary peak at 09:30. A significant secondary peak occurs during the evening flush at 21:30. This value of toilet tissue considerably affects the total solids rate at 09:30 and 21:30.

No clear diurnal distribution was observed for any SANPRO items sampled as seen in the high income catchment. Large numbers were sampled in the afternoon and evening rather than as would be expected in the morning following females waking from sleep (Figure 4.20). Tampons (11.9 /1000pop./d) were the most sampled SANPRO item followed by panty liners (2.6 /1000pop./d) and sanitary towels (1.6 /1000pop./d). The low number of pollutants sampled may indicate that the population in the catchment is more likely to dispose of SANPRO items via the solid waste disposal route. Wipes had a more identifiable diurnal profile with a double morning peak at 09:00 and 11:00. Two other main peaks occurred in the evening at 19:00 and 22:00.

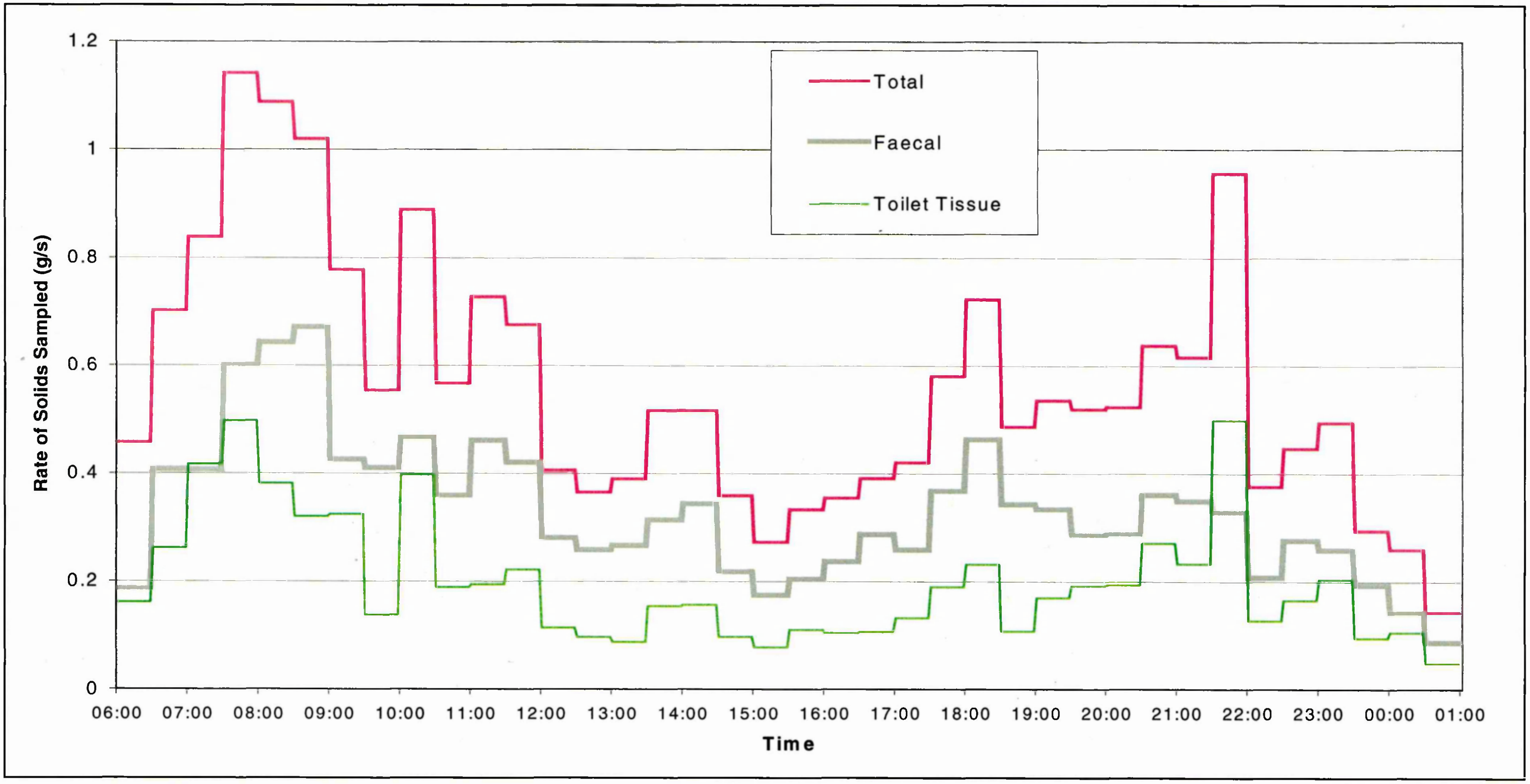


Figure 4.19 Temporal distribution of total solids, faeces and toilet tissue per a 1000 population at sub-catchment SC1 at the ethnic site

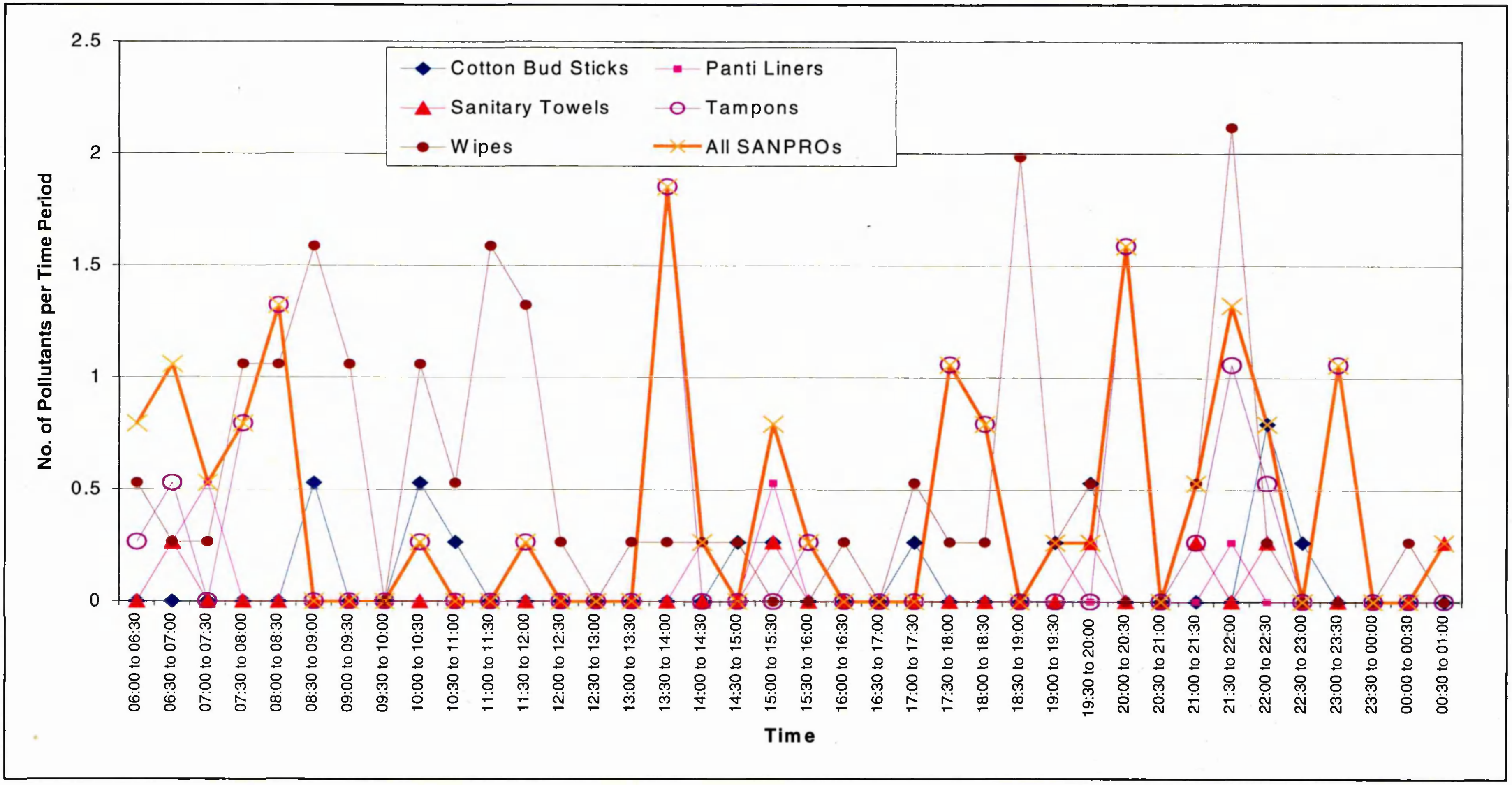


Figure 4.20 Temporal distribution of SANPRO items and wipes per a 1000 population for sub-catchment SC1 in the ethnic site

4.2.4 Comparison of Dry Weather Solids Sampled from the different population types

Primarily, dry weather sampling was required to enable accurate comparisons with the sampled storms. The knowledge of the temporal distribution of measured pollutants is important to facilitate this, as the time of the storm will affect the quantity of solids being flushed out. Secondly the dry weather sampling enables a comparison of the solids produced by different population types identifying the type and quantity of certain solids that were disposed of via the WC. Thirdly this data could be used to aid in the prediction of loadings presented to WWTW identifying the quantity and type of pollutants. The comparison of solids was undertaken using values produced by a 1000 population throughout.

4.2.4.1 Comparison of total dry weather solids sampled

The low income catchment generally had a rate of solids sampled greater than the high income and ethnic catchments, particularly for the morning and evening peaks (Figure 4.21). During these periods, the low income rate was approximately twice that of the high income and ethnic populations. This potentially indicates that the type, number, and age of the population is important. The low income site contained an ageing population. Hence a large number of people may remain in their house during the day, rather than leave the catchment to go to work. The high income and ethnic diurnal plots were similar throughout the day suggesting a similar proportion of people may reside in the catchments or that their working patterns were similar. The quantity of solids per a 1000 population in one day by the low income catchment (75.4 kg) was approximately double that measured in the high income (37.2 kg) and ethnic (38.5 kg) catchment. This large difference was observed with the individual solids (section 4.2.4.2). At all sites one sample was taken on a Sunday, from 09:00 to 16:00 at the low income site and 08:00 to 15:00 at the other sites (Figure 4.22). A change in the sampling times occurred as a result of identifying that the morning peak occurred between 09:00 and 10:00. Although only one sample was taken, the quantity of solids produced by a 1000 population was still greater at the low income catchment (32.5 Kg) for between the hours of 09:00 and 15:00 than at the high income (18.4 Kg) and ethnic (20.0 Kg) catchments. This would indicate that the low income population produces more faeces and uses more toilet tissue than the populations at the other catchments. Therefore the residency factor of people remaining in the catchment during the day in the week would not have a substantial effect.

Dry weather flows form an important part of solids transportation, as it can define when solids will be deposited depending upon the depth or velocity of the water. Generally the total solids loading was related to the dry weather flow diurnal profile for each catchment. This was to be expected when considering that WC usage forms 35% of water consumption (Ainger et al. 1998) and is the main contributory of solids. The timing and use of the WC also coincides with the sink, bath and shower usage, which forms a further 25% of all water consumption. In the morning the measured DWF profile for the high income catchment was greater than the other catchments when the night flow was removed (Figure 4.23). This was to be expected as links exist between water consumption and income, where a high income location uses more water (Russac et al. 1991). The DWF morning peak at the low income and ethnic catchment was the same. However, the evening peak at the ethnic catchment was lower than the low and high income catchments which were similar. The infiltration rates calculated from the night flows can form a large percentage of the measured flow. This was observed at the ethnic catchment, which was not expected due to its inner city location and small total area. This may have been related to a leak in the water distribution system in the area

(Woodward 2000) although the exact location of this leak was unknown. The dry weather flows including the base flow were used to calculate the concentration of solids (Figure 4.24). This shows the higher solids loading sampled in the low income catchment compared to the high income and ethnic catchment. It substantiates the Sunday sample information that indicates that the low income population type pass more solids to the sewer than the other population types.

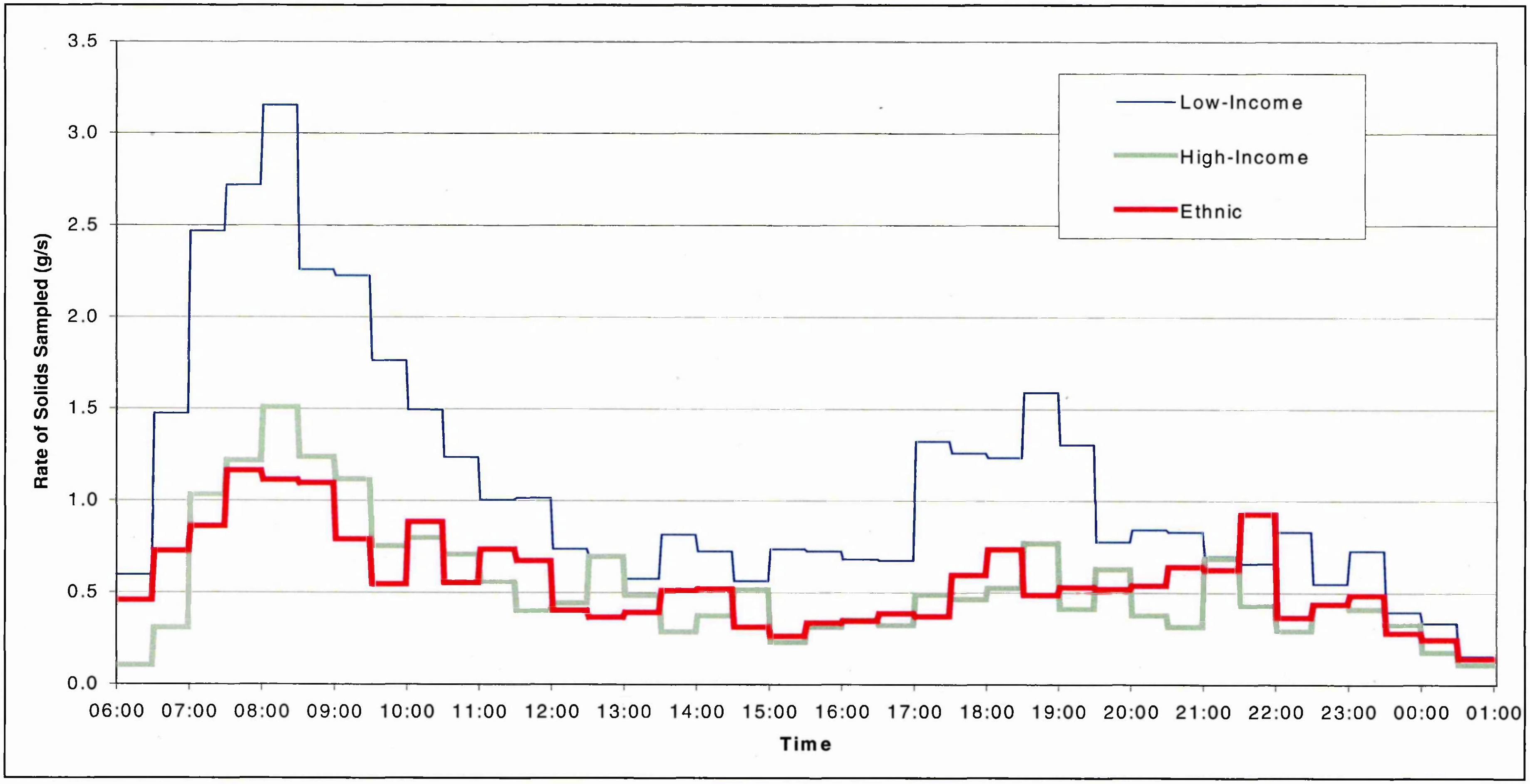


Figure 4.21 Comparison of total solids sampled per a 1000 population at each catchment

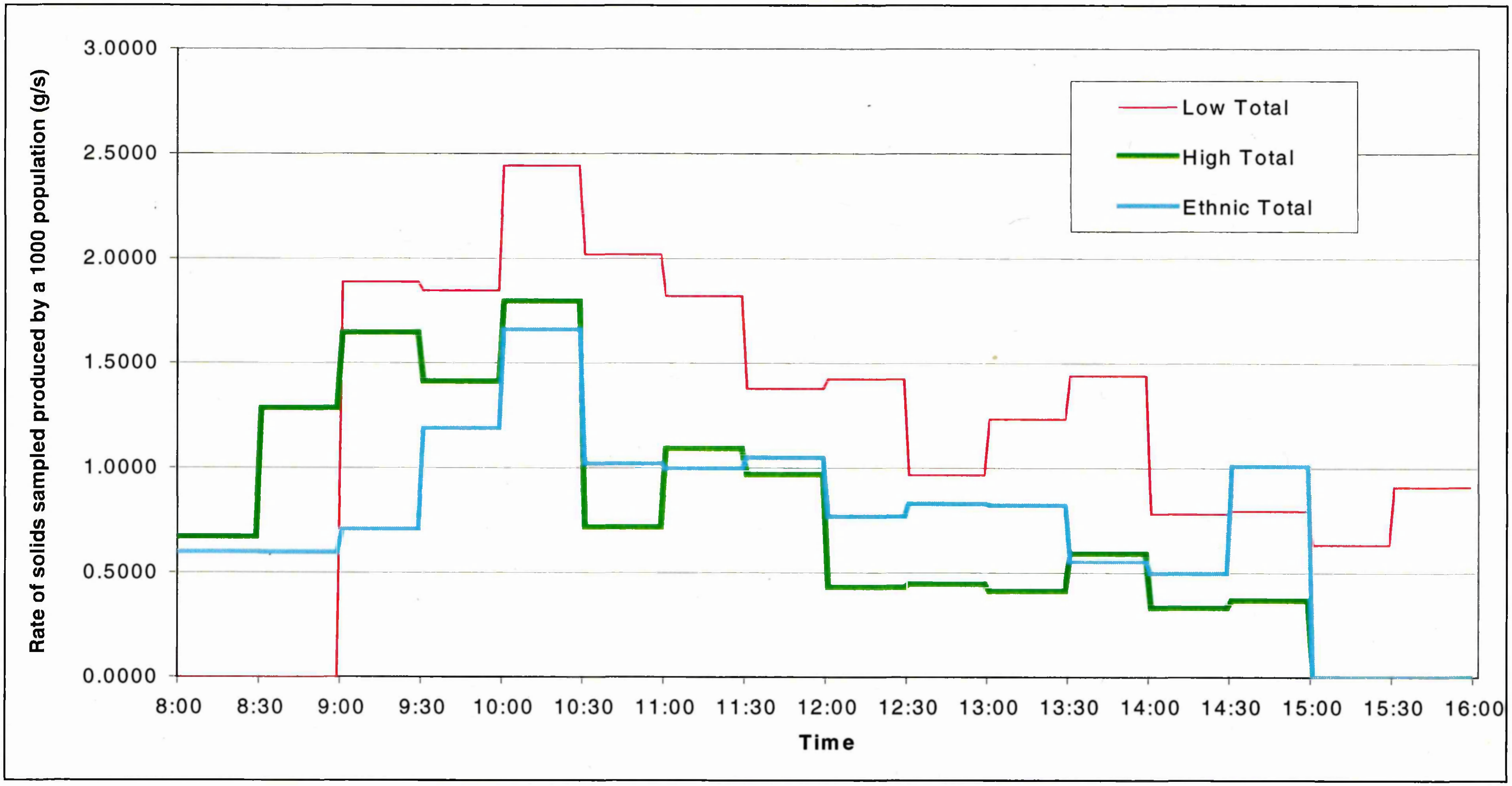


Figure 4.22 Comparison of rate of solids sampled during one Sunday only at each site for a 1000 population

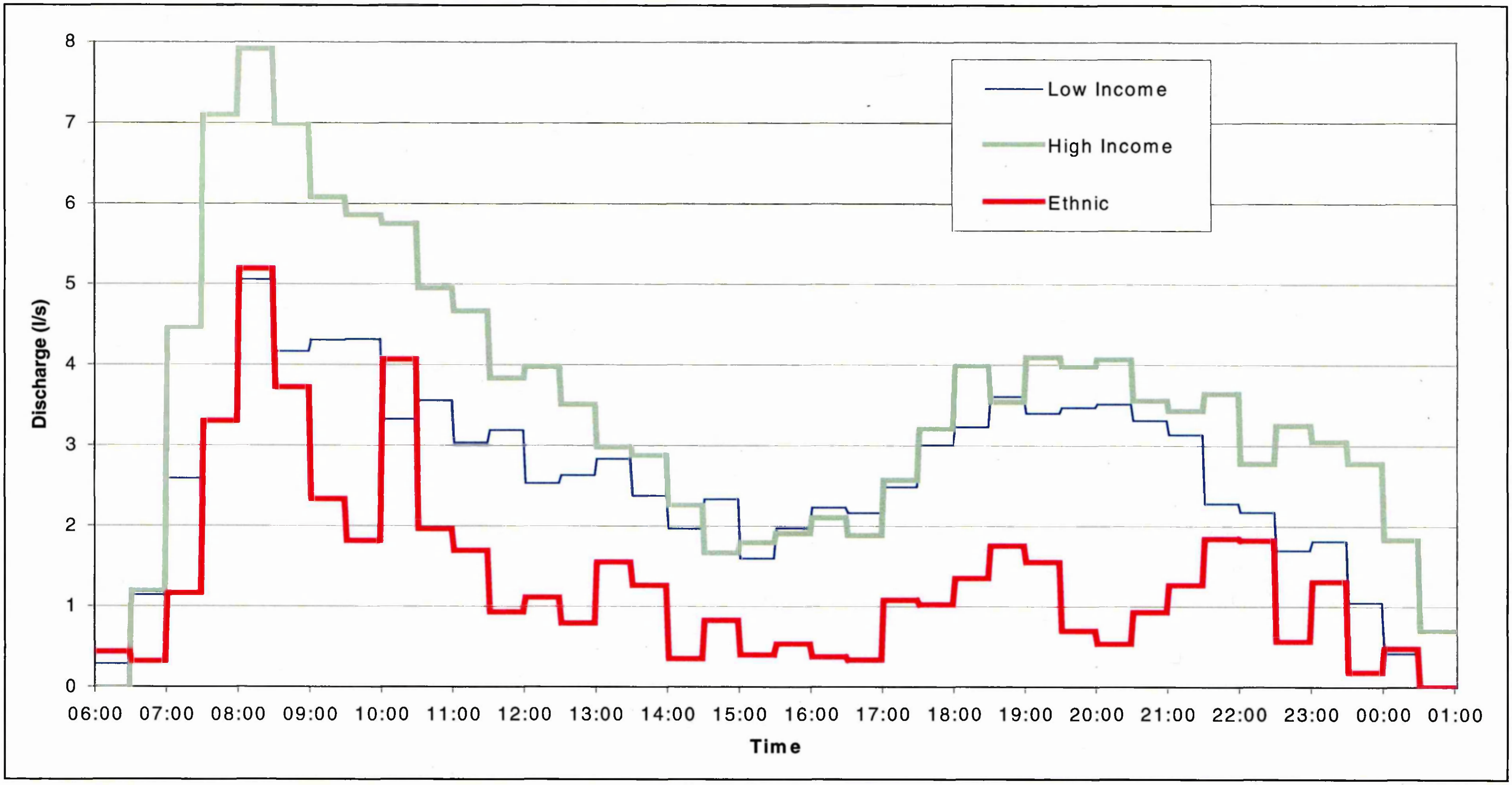


Figure 4.23 Dry weather flow for a 1000 population with the night time base flow removed at each catchment

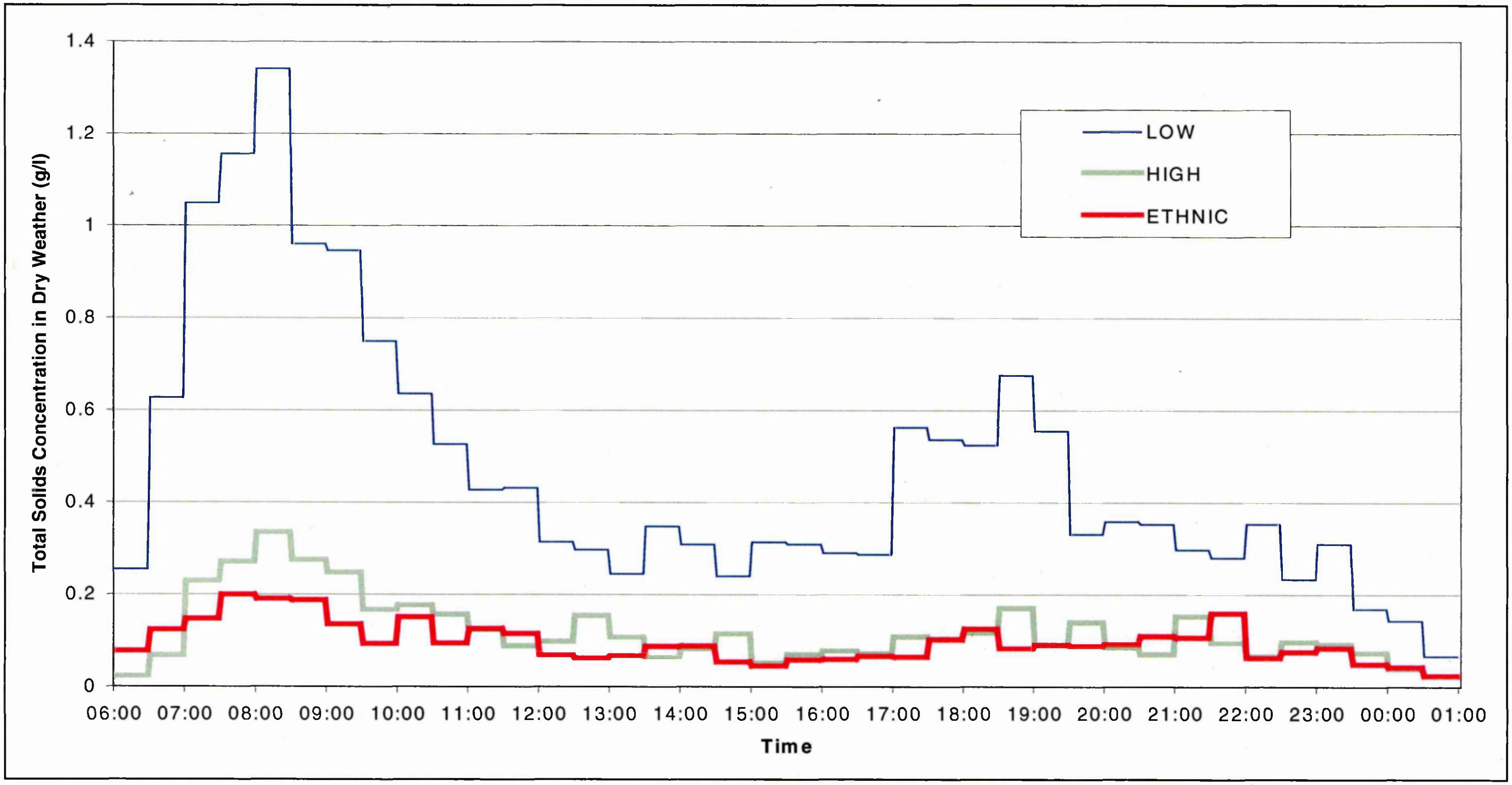


Figure 4.24 Concentration of solids produced at each catchment for total dry weather flows including night time base flow

4.2.4.2 Comparison of individual dry weather solids

The measurement of total solids in dry weather provides a clear indication that the low income population produced twice the quantity of solids compared to the other catchments (Figure 4.25). This was represented by the overall increase of the major pollutants by mass. Faecal material, toilet tissue and wipes were all greater in the low income site. In particular, the toilet tissue sampled was greater than twice the quantity at the other sites. Other notable differences were the low quantity of wipes sampled at the ethnic site. Similar quantities of faecal material were sampled in the high income catchment and the ethnic site. However a slight increase in the quantity of toilet tissue was observed at the ethnic catchment. The quantity of wipes sampled in the low income area was 3 times that of the high income area. In turn the high income catchment produced twice the quantity measured in the ethnic site. These comparisons clearly highlight the difference in solids produced by different population types in this study.

The second set of solids to be compared was those measured by number rather than mass. A clear difference between the types of SANPRO items disposed of was evident between the catchments (Figure 4.26). Tampon disposal via the WC was greatest in the high income catchment, whereas the low-income and ethnic population disposed similar quantities. In the low income catchment, sanitary towels were the highest number of items sampled in dry weather, followed by panty liners. These far exceeded the disposal numbers in the other catchments. The ethnic catchment indicated the least SANPRO products sampled in dry weather. This of course does not indicate that less SANPRO items are used, only that less were disposed of via the WC rather than by binning.

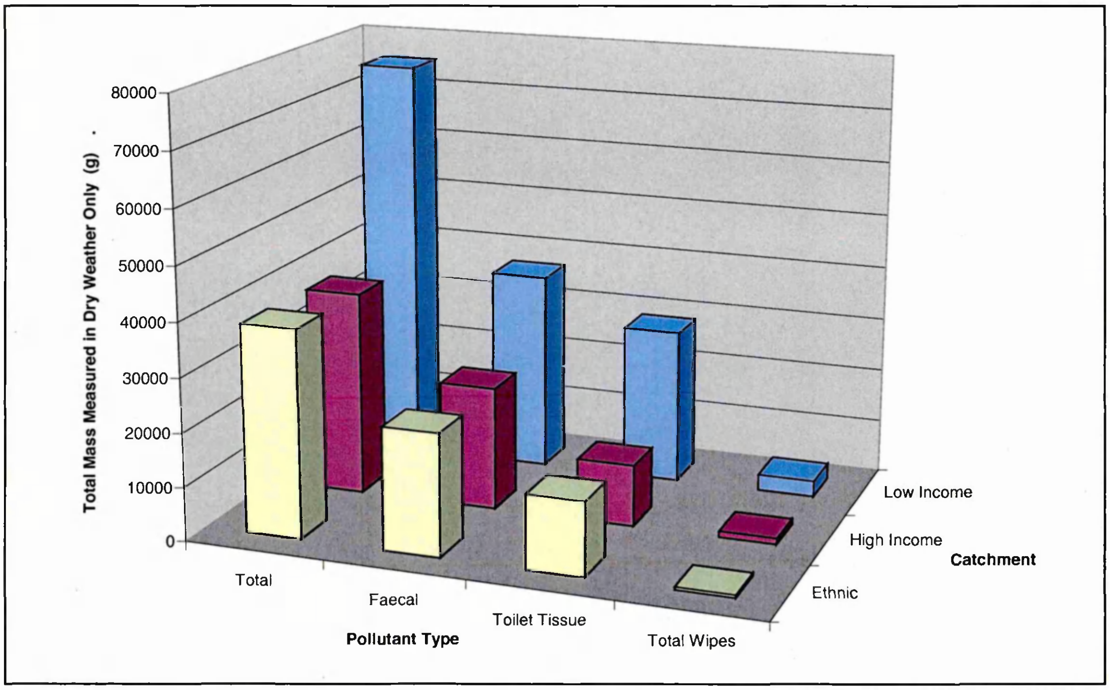


Figure 4.25 Comparison of the main pollutants by mass for each catchment per a 1000 population per day

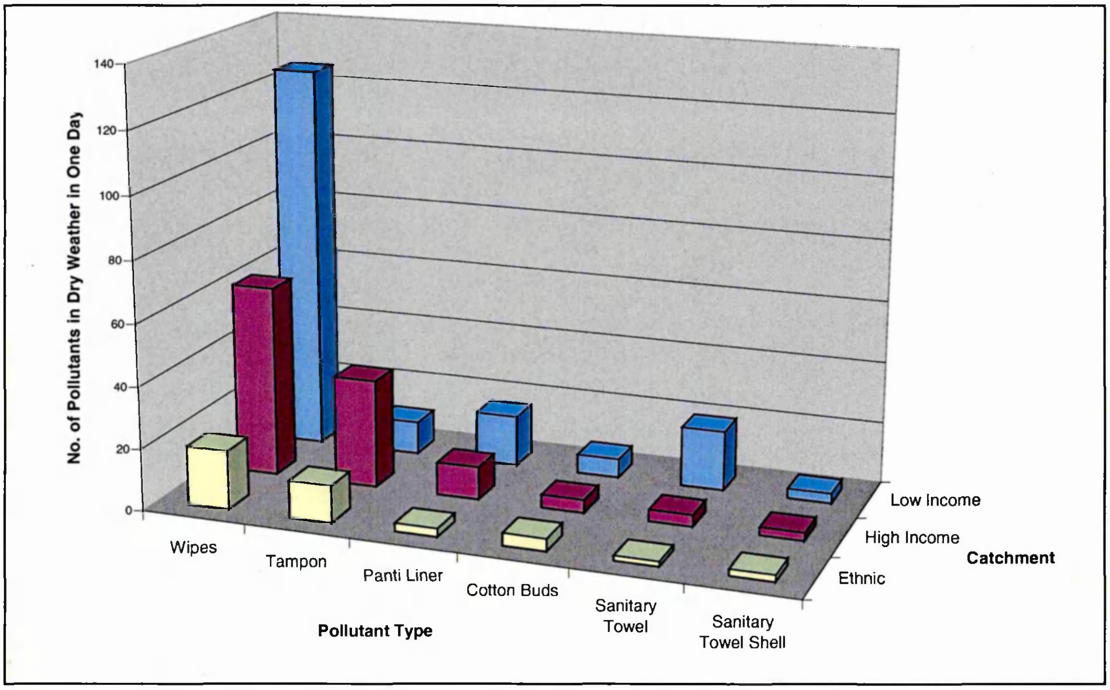


Figure 4.26 Comparison of the SANPRO items and wipes sampled at each catchment per a 1000 population per day

4.3 Wet Weather Sampling

4.3.1 Low Income Catchment

4.3.1.1 Total wet masses

Three storms were sampled at the low income catchment between November 1999 and February 2000. The results clearly showed that during storm events, the solids' loading were significantly greater than that measured in dry weather (Figure 4.27, Figure 4.28 and Figure 4.29). The temporal distribution of solids was evident and showed a first foul flush. This solids' flush occurred on the rising limb of the hydrograph indicating solids were being transported at the front end of the storm. The loading in storms GS2 and GS3 were significantly greater than that in GS1. This was likely to be related to the greater rain intensity and subsequently higher flows, depths and velocities that would enable solids to be mobilised and flushed from the system (Table 4-2). This was confirmed as less solids were flushed out despite the ADWP being greater, as it would be expected that more solids would have the potential to be stored, the longer the ADWP. Therefore it was unlikely that a full flush of solids occurred during storm GS1. A similar quantity of solids was flushed during storm GS2 and GS3. However the time of day when a storm occurs is important when comparing the quantity of solids flushed. In the morning the solids that are travelling in the DWF is at its greatest and would contain more solids than in the afternoon. Hence a larger quantity of solids that would normally be transported were sampled in storm GS3 in comparison to GS2. Therefore more solids were likely to have been stored and flushed out in storm GS2 as this had a longer ADWP than storm GS3.

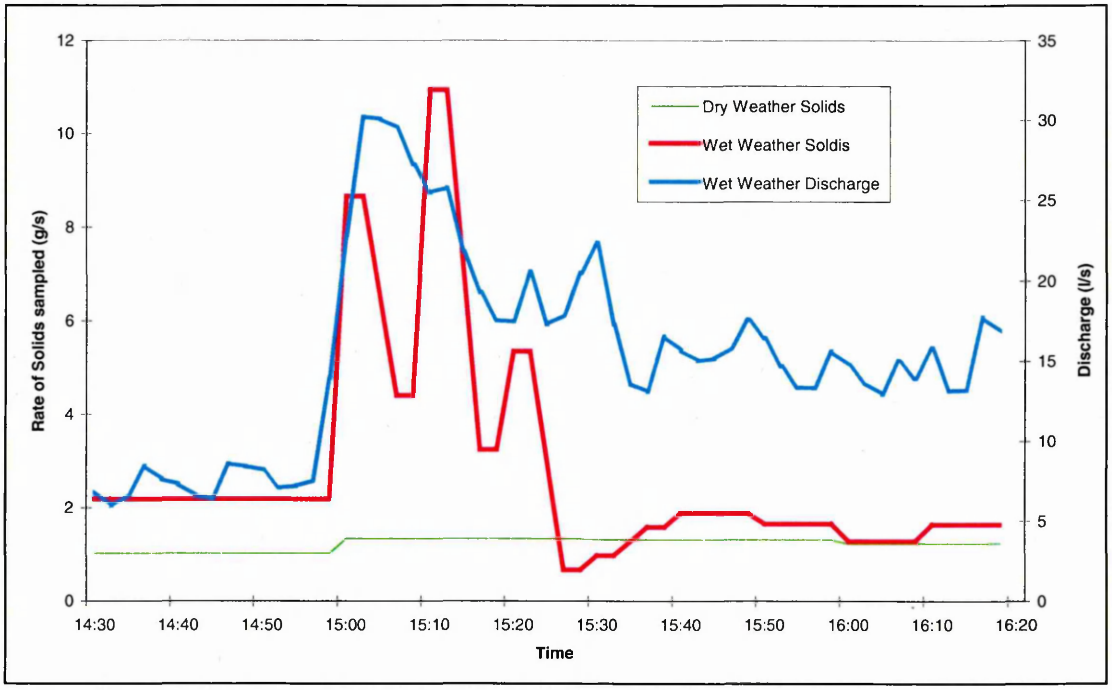


Figure 4.27 Sampled storm GS1 for the whole of the low income catchment

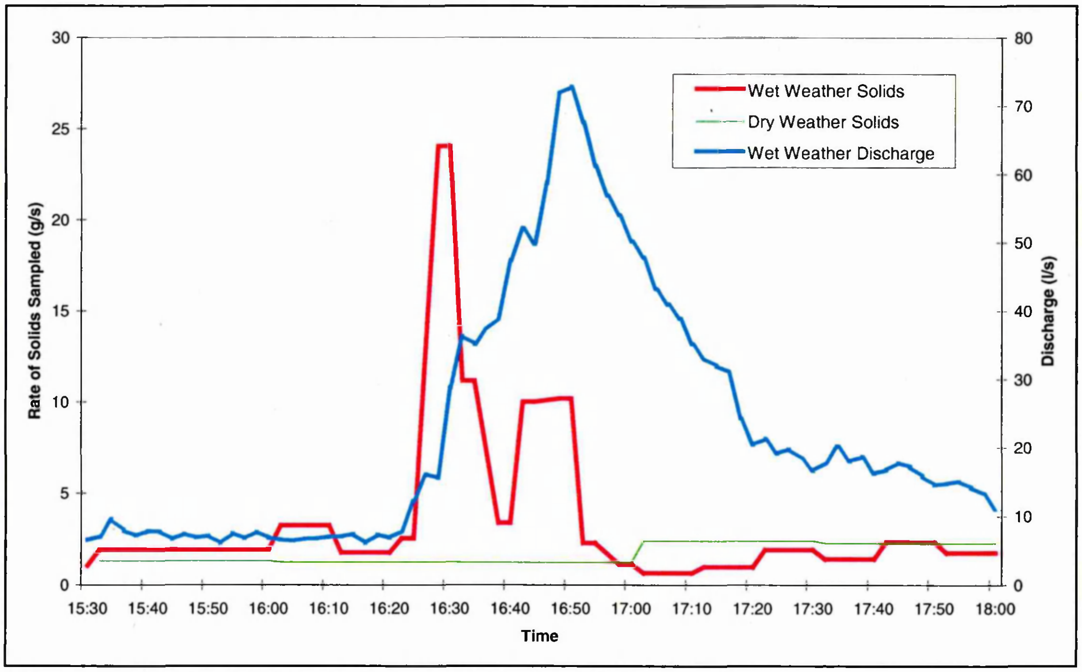


Figure 4.28 Sampled storm GS2 for the whole of the low income catchment

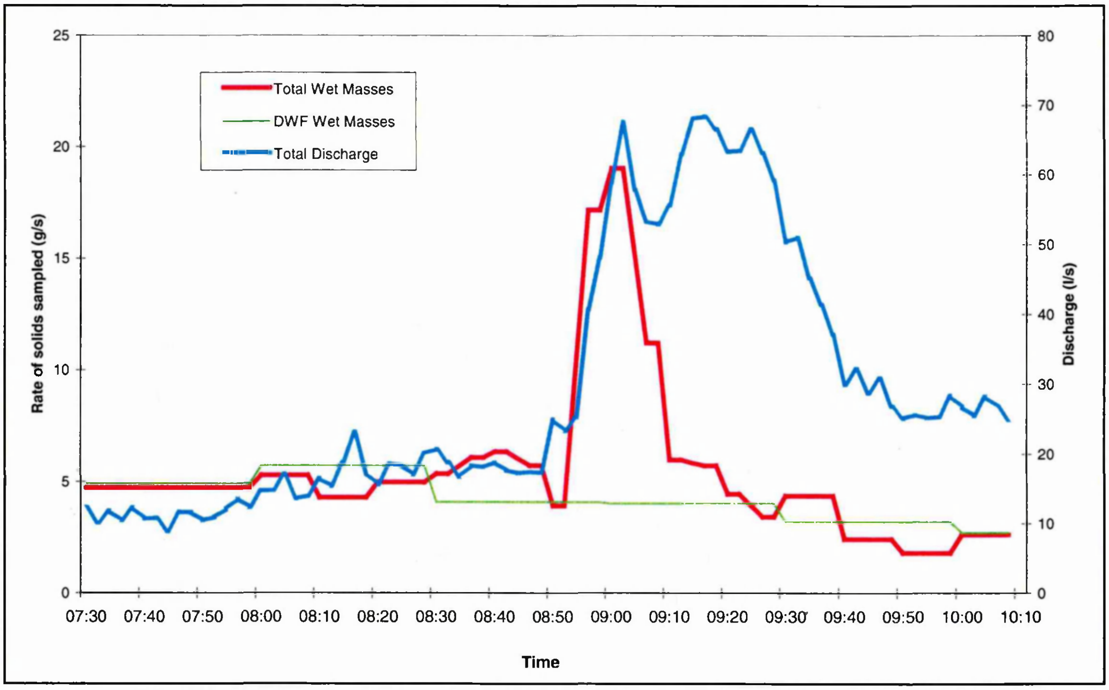


Figure 4.29 Sampled storm GS3 for the whole of the low income catchment

Table 4-2 Summary details of storms sampled at the Low income catchment

Storm Number	GS1	GS2	GS3
Date of Storm	1/11/99	29/11/99	8/2/00
Start Time of Solids Flushed	15:00	16:25	08:55
Finish Time of Solids Flushed	15:25	16:50	09:20
Peak Rainfall (mm/hr)	2	6	3
Effective Rainfall during Solids Flushing Period (mm)	0.3	1.2	1.1
Contributing Antecendent Dry Weather Period (Hours)	48	37	21
Quantity of Solids Flushed (g)	9788	17642	17754

4.3.1.2 Characterised solids

To enable further comparison of the storms sampled, the characterised solids provided greater details to the type and quantity of solids sampled and potentially stored. A significant quantity of faecal material was sampled in the morning storm of GS3 compared to GS2 (Figure 4.30). The difference in faecal material was probably in relation to the time the storm was sampled. A significant quantity of toilet tissue was sampled in storm GS2 compared to GS3, a reverse of the faecal sample. This may be related to the fact that at this site in dry weather, toilet tissue was flushed out before the faeces in the morning. This was before the start of storm GS3. Significant quantities of other pollutants were sampled in storm GS2 including kitchen roll (2 kg), which was not sampled in the other storms.

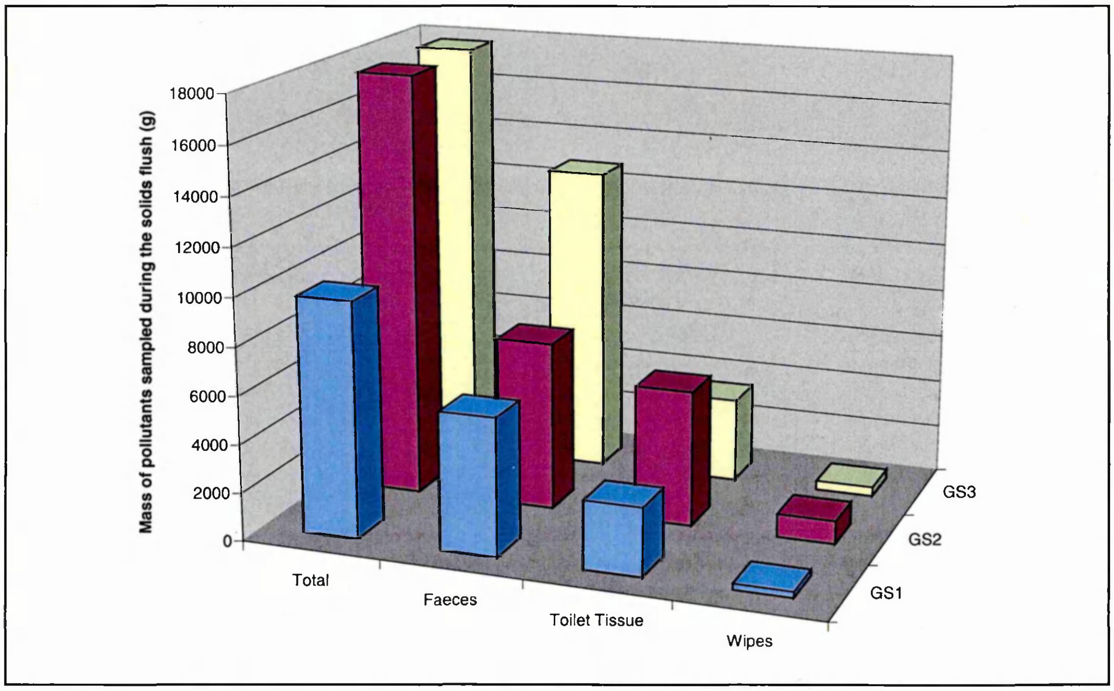


Figure 4.30 Main pollutants by mass flushed during sampled storms at the low income catchment

The number of pollutants sampled was greatest in storm GS2. The fewest solids were sampled in storm GS1, which also confirms that despite it having the greatest ADWP a full flush did not occur. Tampons were the most common SANPRO item to be flushed from the system. This is different to dry weather sampling that indicated that tampons constituted 19% of the total SANPRO items sampled. This suggests that tampons were most likely to be stored in the system. Rise and settle velocity tests of the tampons sampled at this catchment indicated that all tampons would sink (section 4.4). This was not the case for the other SANPRO pollutants that would rise and fall. This explains why tampons were most commonly stored. The number of wipes sampled in storm GS2 was large compared to the other storms. Although this indicates the potential for wipes to be stored, it also identifies the variability of the solids that may be input into the system and stored.

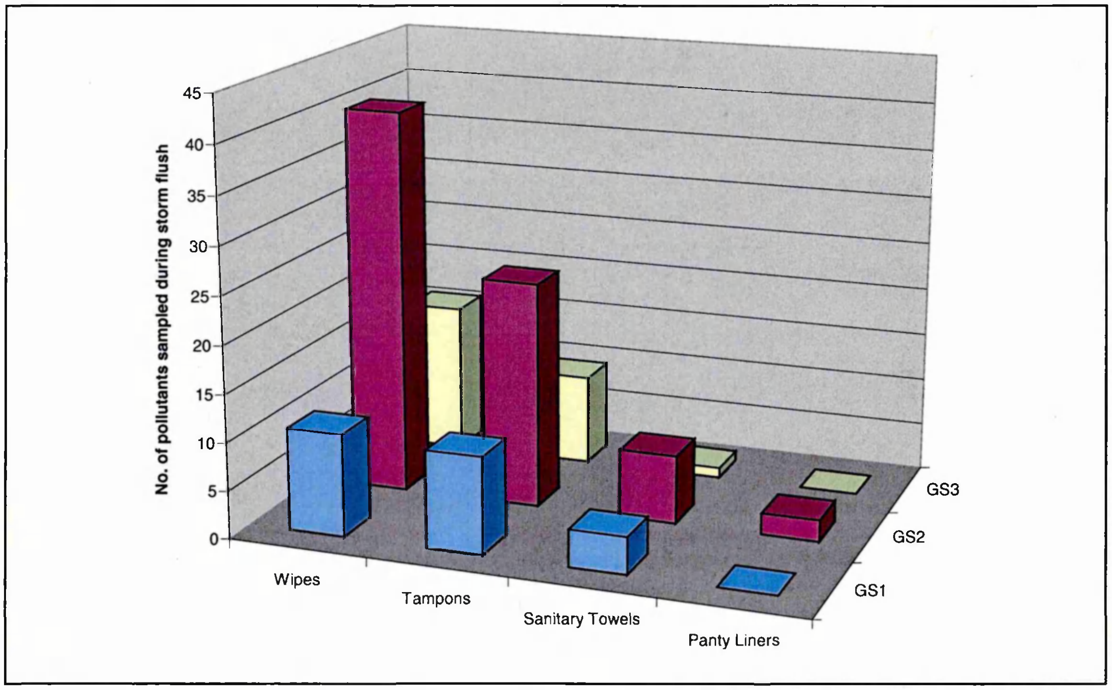


Figure 4.31 SANPRO items and wipes flushed out during storms sampled at the low income catchment

4.3.2 High income catchment

4.3.2.1 Total wet masses sampled

Four storms were sampled at the high income catchment which clearly showed an increase in the solids flushing rate. Other storms were sampled but did not show a significant increase above the dry weather solids loading. Three storms were sampled in the summer of 2000 followed by a fourth in June 2001. Two storms (DS1, Figure 4.32 and DS6, Figure 4.35) were of a short duration with a high peak rain intensity whereas two storms (DS3, Figure 4.33 and DS5, Figure 4.34) were over a longer duration and lower peak rain intensities. The flushing profiles of solids for the short and long duration storms had similarities in their flushing profiles, however the quantity of solids flushed was significantly different.

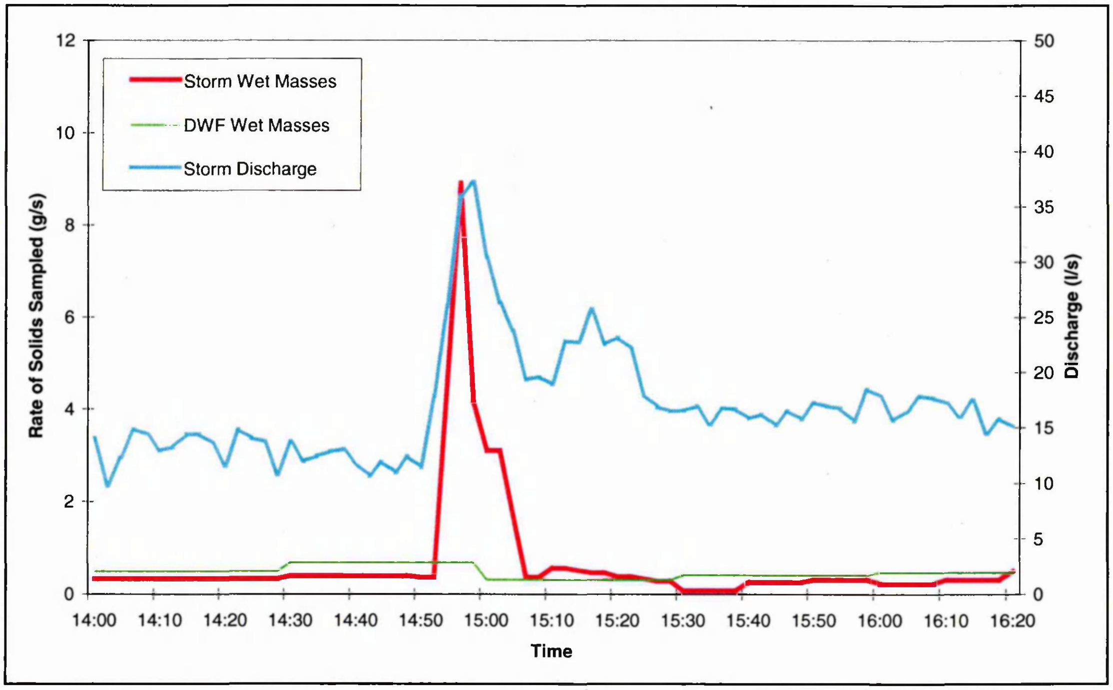


Figure 4.32 Sampled storm DS1 at the high income catchment

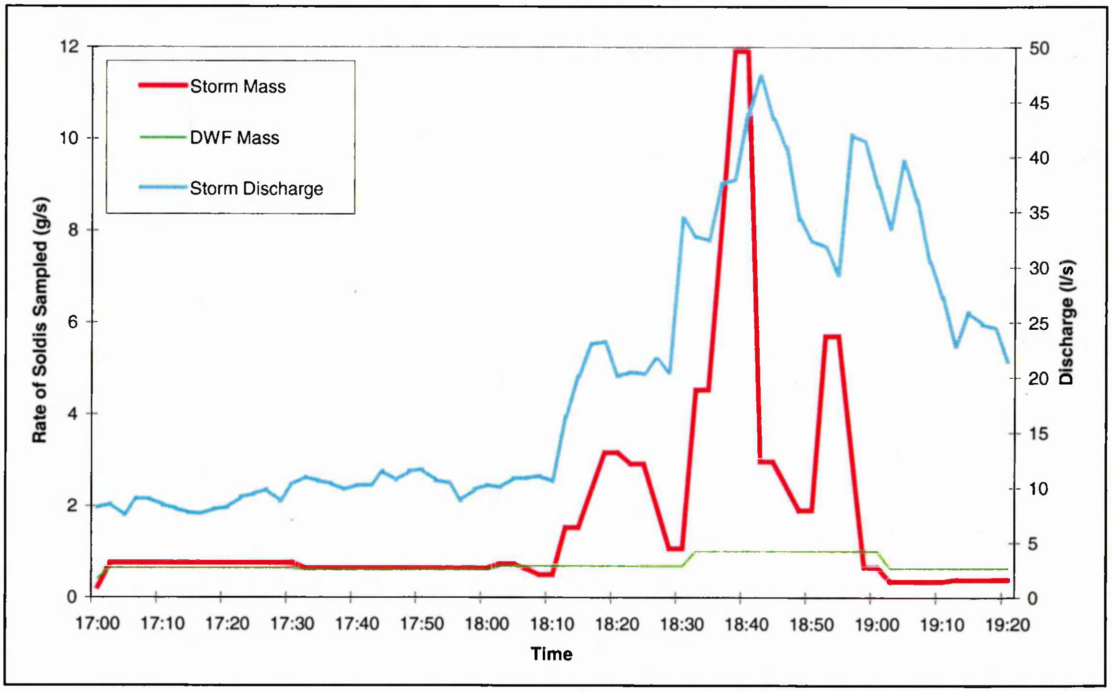


Figure 4.33 Sampled storm DS3 at the high income catchment

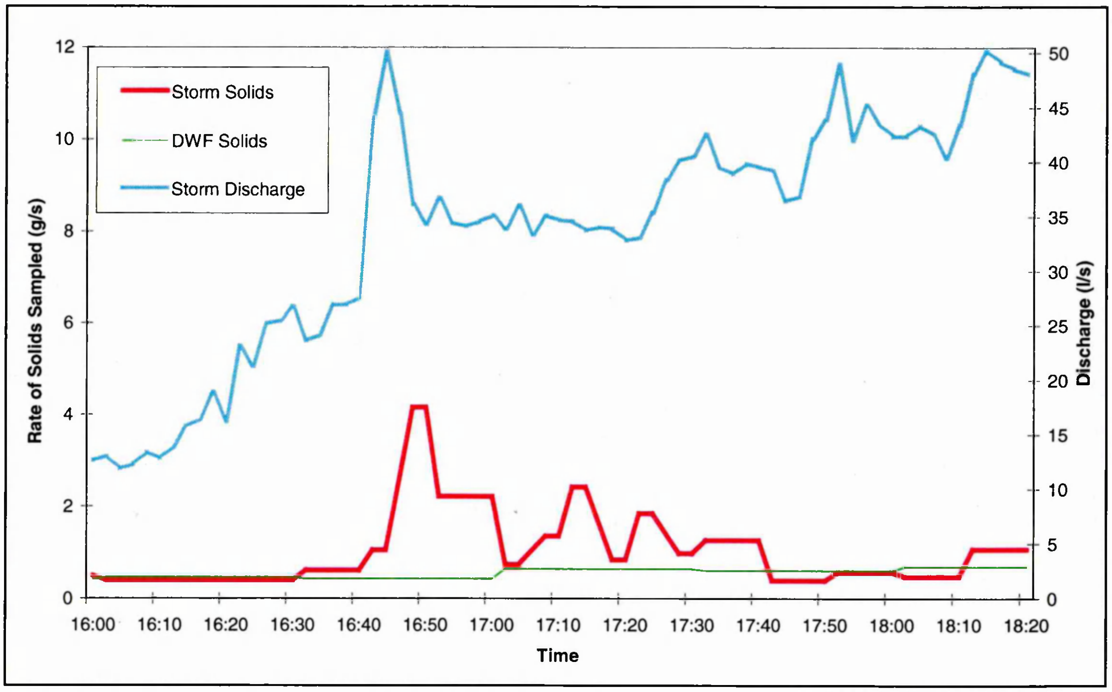


Figure 4.34 Sampled storm DS5 at the high income catchment

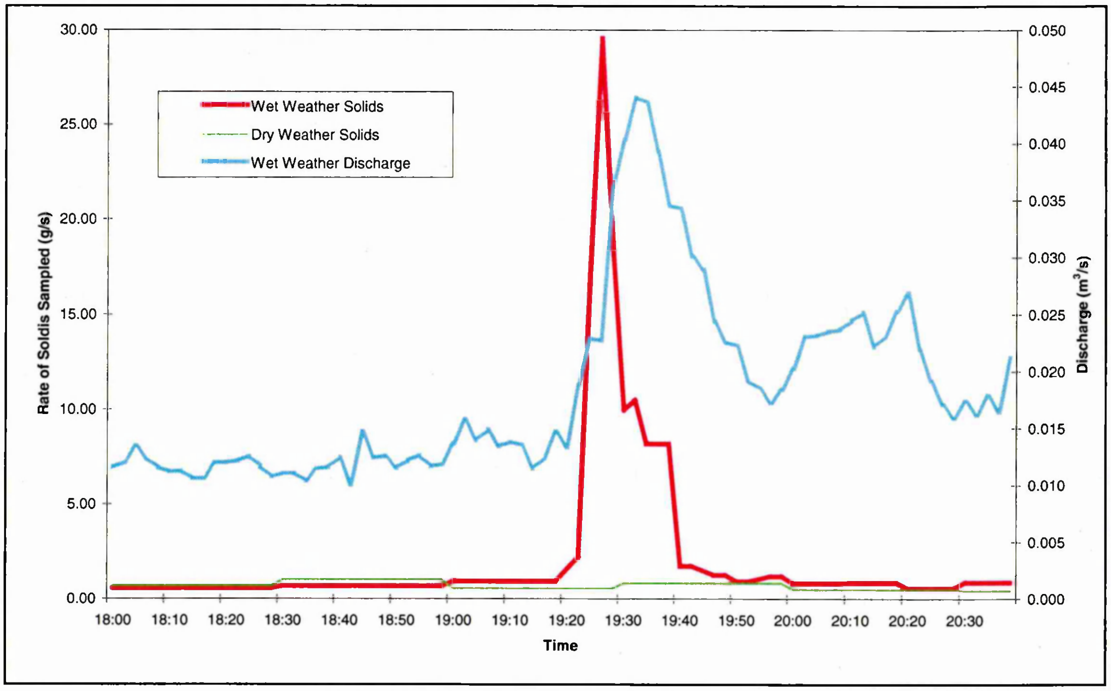


Figure 4.35 Sampled storm DS6 at the high income catchment

A trend between the measured solids flushed during the storms and the ADWP was observed at this catchment (Table 4-3). A significant increase in loading occurred for the storms with a longer ADWP (DS3 and DS6). This increased loading was attributable to solids being stored in the catchment during dry weather. Therefore the deposition of solids in the catchment was likely to be greater, the longer the ADWP.

A large difference between the time taken to flush solids was observed. The longer duration, lower peak rain intensity storms indicated that solids would be flushed over a greater period of time than the shorter duration high peak rain intensity storms. Flushing of the system could range between 10 and 60 minutes, therefore the loadings presented to CSOs could be significant at different times of a storm. This would be particularly important when trying to prevent pollutants being discharged to receiving waters.

Table 4-3 Summary details of storms sampled at the high income catchment

Storm Number	DS1	DS3	DS5	DS6
Date of Storm	28-Jul-00	31-Aug-00	19-Sep-00	14-Jun-01
Start Time of Solids Flushed	14:55	18:10	16:40	19:21
Finish Time of Solids Flushed	15:05	18:55	17:40	19:40
Peak Rainfall (mm/hr)	12	6	3	12
Effective Rainfall during Solids Flushing Period (mm)	1.2	2.2	2.6	1.4
Contributing Antecendent Dry Weather Period (Hours)	15	91.5	21	113.5
Quantity of Solids Flushed (g)	3032	10726	6112	14098

4.3.2.2 Characterised masses

All sacks were characterised from the storms sampled and indicated that solids loading increased as ADWP increased with the exception of wipes (Figure 4.36). A large quantity of faeces was sampled in storm DS5 however this is partly attributable to the long flushing period of solids. The mass of wipes sampled was significantly greater in DS3 than the other storms including DS6, suggesting the variability that could occur with solids entering or being stored in the system.

The solids produced by number identify the type of SANPRO items and wipes sampled during the storms (Figure 4.37). A large quantity of wipes and tampons were sampled from storm DS3, greater than those sampled during storm DS6. The increase of these sampled solids may be interconnected where the solids were flushed within a ten minute period. However the flush of solids in DS3 was over longer storm duration than DS6. Tampons were clearly the largest SANPRO item flushed during the storms, hence when combined with the dry weather numbers of tampons sampled, indicate that they were most common item disposed of in the catchment. No sanitary towels were sampled during the storms, however panty liners did indicate a trend with the ADWP in the number that were sampled as shown in Figure 4.37.

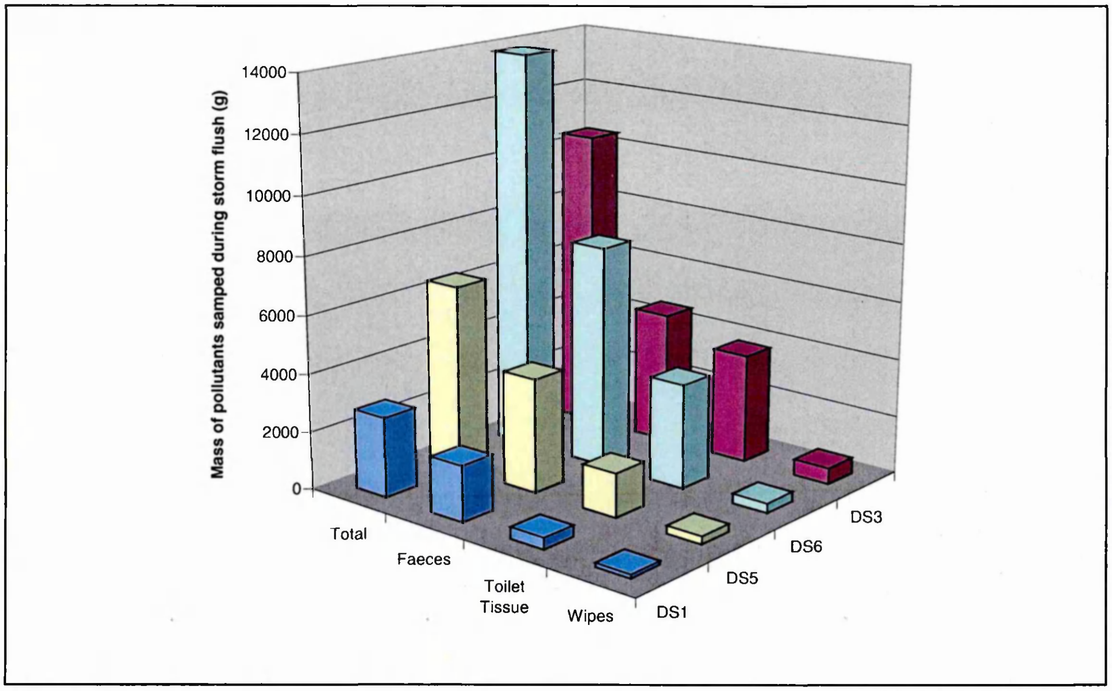


Figure 4.36 Main pollutants by mass flushed out during storms sampled at the high income catchment

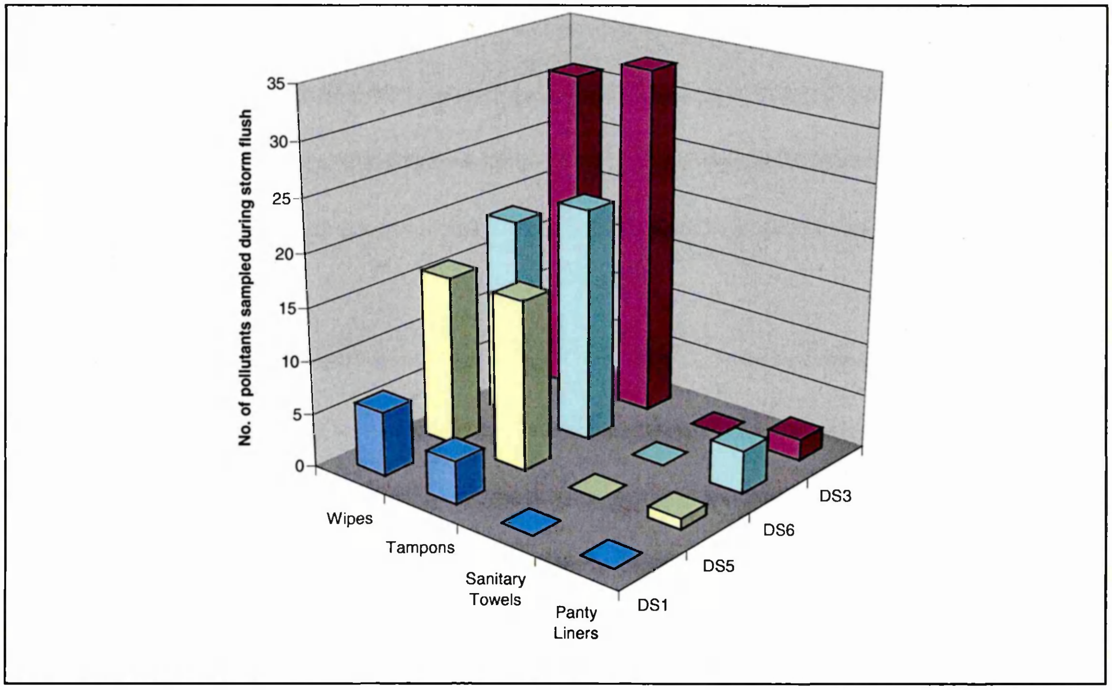


Figure 4.37 SANPRO items and wipes flushed out during storms sampled at the high income catchment

4.3.3 Ethnic catchment

4.3.3.1 Total wet masses sampled

Three storms which clearly showed solids being flushed were sampled between September 2000 and April 2001 at the ethnic catchment. The storms sampled had low peak rain intensities over a long duration in comparison to the storms sampled at the other catchments. Therefore the flushes of solids occurred over a longer period of time (Figure 4.38, Figure 4.39 and Figure 4.40). The solids peak flushing rate was a maximum of 6.5 g/s, which was probably due to the rain intensity not exceeding 6 mm/hr (Table 4-4). In addition the lower flush could be attributed to the time of flow in dry weather in the catchment. The time of flow was substantially smaller in this catchment than in others due to its relatively small size. The time of flow was calculated using calibrated HydroWorks models of the sewer systems. Hence the quantity of solids in motion would have been significantly smaller resulting in less solids available to be transported through at an increased rate during a storm. The link between ADWP and solids sampled was observed with the quantity of solids sampled greater for the 40 hour ADWP storms (Table 4-4). However the storms sampled were over similar ADWPs, therefore could be subject to a variation in the quantity of solids entering and being stored. Storms with greater ADWPs were sampled but the rain intensity and duration was substantially less than the storms detailed in Table 4-4.

Flow monitoring was problematic at the catchment because of the low depths and high velocity of the water, which was resolved by increasing the size of the weir located downstream of the flow monitoring point. The flow monitoring of the sampled storms was not as accurate as preferred because the depth recorded would sporadically ‘drop out’.

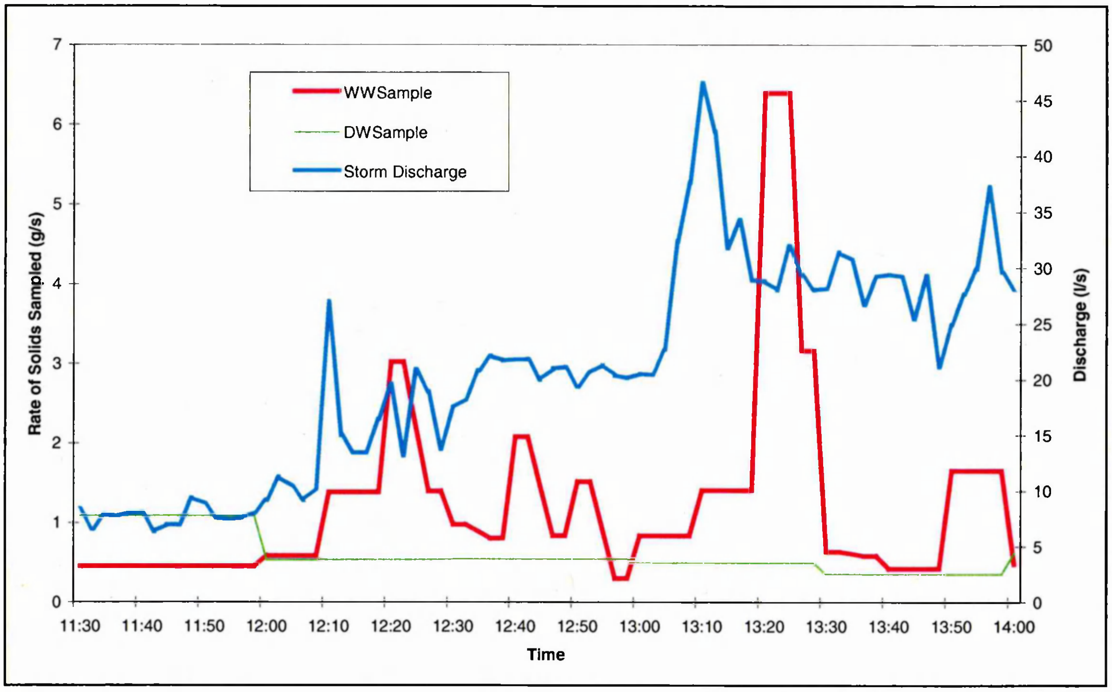


Figure 4.38 Sampled storm OS2 at sub-catchment SC1 in the ethnic catchment

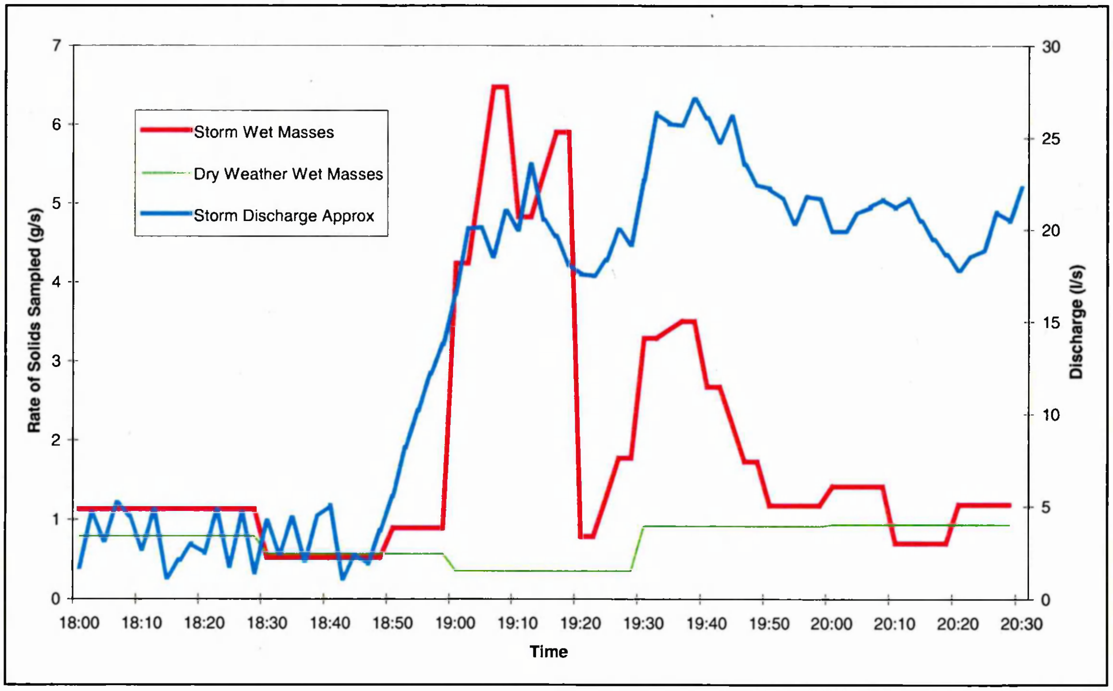


Figure 4.39 Sampled storm OS4 at sub-catchment SC1 in the ethnic catchment

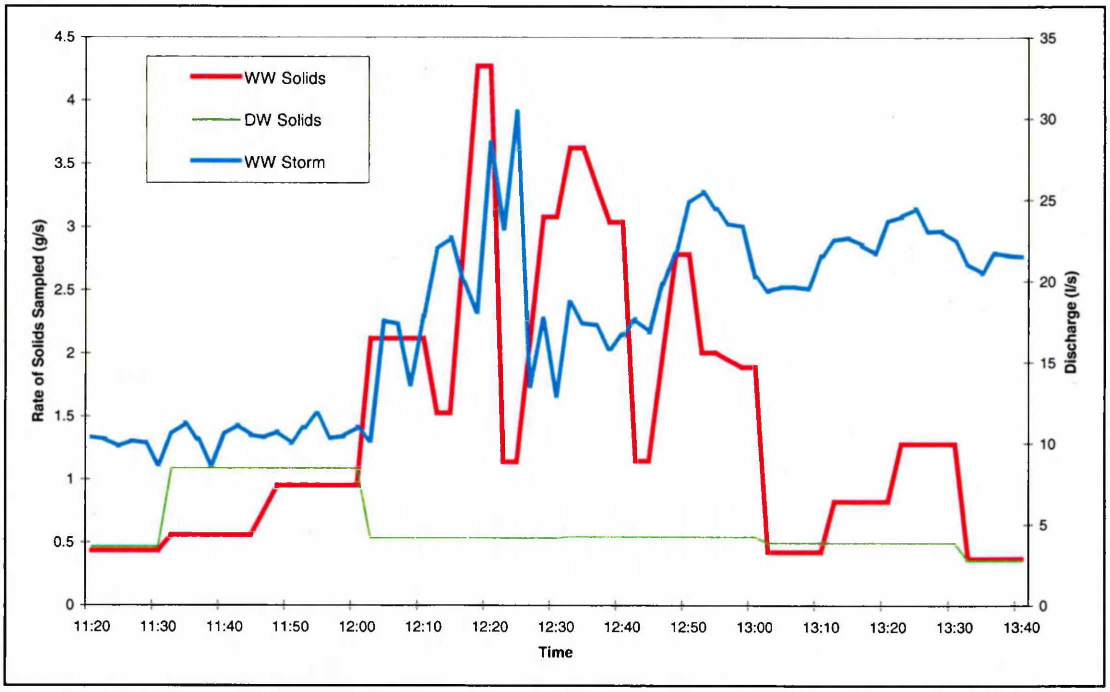


Figure 4.40 Sampled storm OS5 at sub-catchment SC1 at the ethnic site

Table 4-4 Summary details of storms sampled at sub-catchment SC1 at the ethnic site

Storm Number	OS2	OS4	OS5
Date of Storm	9-Oct-00	7-Dec-00	5-Apr-01
Start Time of Solids Flushed	12:10	19:00	12:00
Finish Time of Solids Flushed	14:00	19:50	13:00
Peak Rainfall (mm/Hr)	4.4	6	6
Effective Rainfall during Solids Flushing Period (mm)	3	2.6	2.48
Contributing Antecendent Dry Weather Period (Hours)	40	40	34
Quantity of Solids Flushed (g)	10294	10816	8976

4.3.3.2 Characterised storm solids

All sacks were characterised at the ethnic site during storm sampling. More faeces were sampled during storm OS4 than OS2, whereas the opposite was observed for toilet tissue (Figure 4.41). The smallest quantities of faecal and toilet tissue were sampled during storm OS5. A significant number of wipes were sampled in storm OS2, nearly twice as many as sampled in OS4 (Figure 4.42). Both of these storms produced more wipes than that of storm OS5. The main SANPRO item flushed during a storm was the tampon. More tampons were flushed during the longer ADWP storms than for OS5. The second main pollutant to be flushed was panty liners followed by sanitary towels. The number of panty liners sampled during the storms was similar to the number sampled in dry weather in one day. This suggests that panty liners at this catchment were more likely to be stored and is supported by the rise and settle velocity tests on panty liners of which 77% settled.

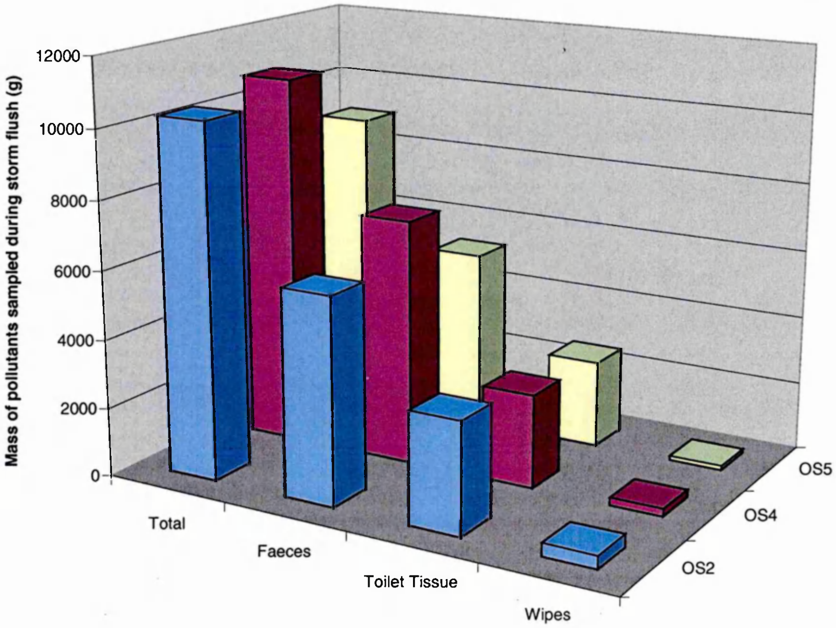


Figure 4.41 Main pollutants by mass flushed out during storms at sub-catchment SC1 at the Ethnic site

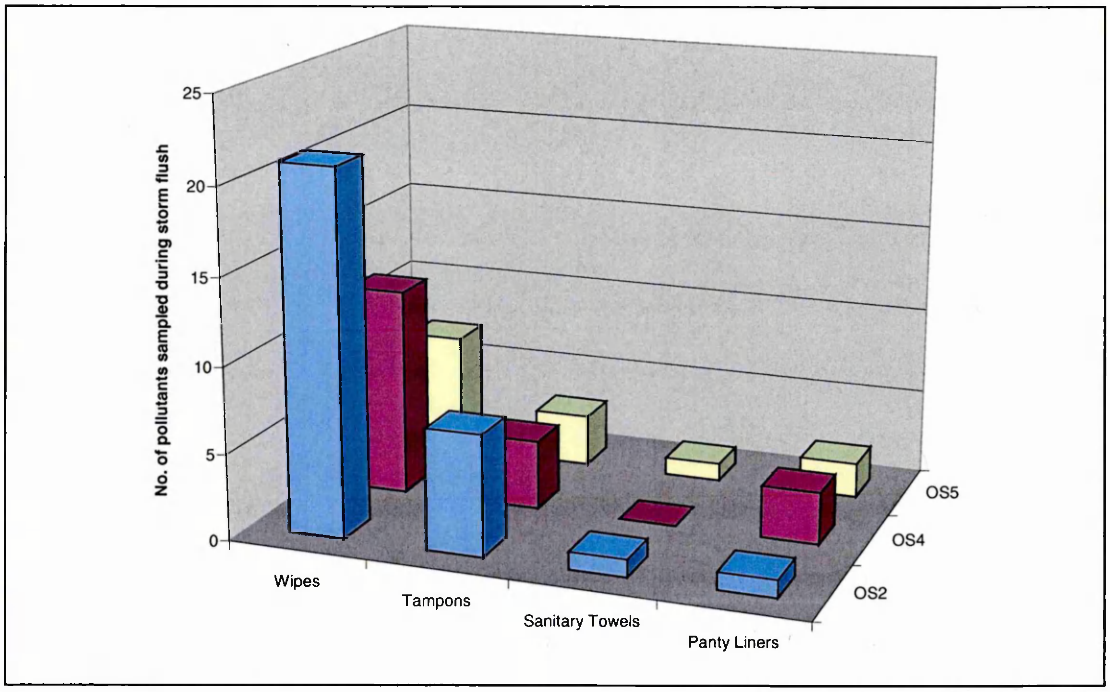


Figure 4.42 SANPRO items and wipes flushed out during sampled storms at sub-catchment SC1 at the Ethnic site

4.3.4 Comparison of wet weather results

4.3.4.1 The effects of Rainfall on solids' flushes

Sampling under wet weather conditions has indicated that shape and magnitude of the solids' flush is variable depending upon the quantity of solids to be flushed, the cacthments' sewer system and the rainfall. The results suggest that different shape and magnitude of hyetographs affect how the flushing of solids' occurs. Results indicate that if the peak rain intensity reaches 6 mm/hr then the flushing of the stored solids is likely to occur in short duration storms of less than 30 minutes. This generally creates a flush of solids over a concentrated period of time as observed in storms GS2, DS1 and DS6 and OS4. If the rain intensity is lower than 6 mm/hr or takes more than 30 minutes to reach this value, it is possible for stored solids to be flushed out of the system if the runoff creates flows that are 1.5 to 2 times the value of the peak DWF. This is likely to occur in longer duration storms as observed in GS3, DS3, DS5, OS2 and OS5.

4.3.4.2 Comparison of dry and wet weather SANPRO items and Wipes

SANPRO items and wipes are the most likely of all pollutants spilt from a CSO to cause public complaint. This is because they do not easily degrade and are recognisable as being from the sewer. These pollutants also have the potential to be caught on branches and foliage at a water course because of their fibrous nature.

It was possible to estimate the number of solids that would have entered the sewer during one day from the dry and wet weather sampling. This enabled a comparison between the catchments for solids' disposed via the WC. The quantity of dry weather solids has already been shown and the numbers sampled during the storms. An estimate of the number that would have been stored was obtained using the storm numbers sampled. The number of pollutants sampled during the corresponding period of the storm was subtracted from the number sampled during the storm. The remaining number was divided by the ADWP and multiplied by 24 to estimate the number of solids stored in 24 hours. This value was then added to the dry weather value to obtain an estimate of the quantity of solids entering the sewer in one day.

As part of the collaborative project, a survey was undertaken of the populations living in the catchments to determine their product usage (Houldsworth 1999a). Postal questionnaires were sent to 250 properties in each catchment and a response rate of over 60% was obtained from each catchment. Information from the returned questionnaires from the three catchments provided details of number and types of

SANPRO items and baby wipes used in the catchment only. Distinction was made between how they were disposed of, either via the solid waste disposal method or the WC (Houldsworth 1999b, Houldsworth 2000, Houldsworth 2001) as shown in section 2.1.

This data was used to compare the quantity of solids used and disposed of via the WC as estimated by people in the catchment, to that sampled from the sewer (Table 4-5). Ideally the survey and sampling data would produce a close match. Clear differences were observed between the sewer solids sampled and survey questionnaire data in the quantity of products. The questionnaire was generally 2-3 times greater than the sampled values for SANPRO products. This could have been due to:

- misinterpretation of the questionnaire
- reporting total numbers rather than those disposed at home only
- reporting the numbers they believe they use or think they should use, rather than what they actually use
- sampling occurred during a time period when less females were menstruating
- incorrect reporting on quantity binned or flushed

The quantity of wipes reportedly flushed compared to those measured was under predicted in the Low and High Income catchment but over estimated in the Ethnic catchment. This could be due to the first and fifth reason above, or that the wipes measured in sampling were stronger and more of a cloth origin than ‘nappy wipes’ which have a consistency more comparable to a strong toilet tissue. Hence the incorrect question was probably posed in the questionnaire and different ‘wipes’ categories should have been introduced during the characterisation process.

Table 4-5 Comparison of the surveyed (flushed) and sampled quantity of the SANPRO products by a 1000 population in one day

	Low Income	Low Income	High Income	High Income	Ethnic	Ethnic
Pollutant	Quest' Flushed	Sampled	Quest' Flushed	Sampled	Quest' Flushed	Sampled
Panti Liners	36	17	33	11	14	5
Sanitary Towels	31	22	5	3	13	2
Tampons	42	19	113	48	45	17
SANPRO Total	109	57	151	63	73	24
Wipes	17	135	16	79	73	22

The over prediction theory suggested in discussion of Table 4.5, may be reinforced when considering the percentage of the total SANPRO products (Table 4-6). The percentage of each item flushed or sampled in each catchment was very similar, with a maximum variation of ± 8%. Therefore the proportion of the type of solids was correct, however the quantities were greater than was actually sampled. Sampling error may have been the reason for the large difference although this was unlikely when examining the quantity of solids sampled during the long ADWP storms at the high income catchment.

Table 4-6 Comparison of the surveyed (flushed) and sampled quantity of SANPRO products expressed as a percentage of the total products sampled or flushed in each catchment

	Low Income	Low Income	High Income	High Income	Ethnic	Ethnic
Pollutant	Quest' Flushed	Sampled	Quest' Flushed	Sampled	Quest' Flushed	Sampled
Panti Liners	33	30	22	18	20	20
Sanitary Towels	29	38	3	5	18	10
Tampons	39	32	75	77	62	70
Total	100	100	100	100	100	100

The number of tampons sampled during storm DS3 was 33, equivalent to 25 tampons for a 1000 population. Considering this was the storage over 5 days of dry weather, it would suggest that the number of tampons entering in the catchment was more similar to that sampled in the sewer rather than estimated in the survey questionnaire. Despite the difference in quantity, the survey does provide evidence that the different populations as identified from sampling used different types of the pollutants in the catchments.

4.4 Aesthetic Pollutant Velocity Distributions

A significant number of pollutants were tested during the sampling of the three catchments. The main pollutants tested were:

- Panty liners
- Sanitary towels
- Tampons
- Wipes
- Toilet tissue (unused)

Other pollutants were tested however data the data was not presented due to an insufficient number of particles available for testing. These pollutants included:

- Cotton buds sticks always rose at a velocity approximately equal to 0.33 m/s although only a small number were tested at each catchment.
- Faeces collected in the sack in one lump and could not be separated.
- Toilet tissue collected in large lumps hence testing of used samples was not possible.

- Sanitary towel shells.
- Tampon applicators generally had degraded somewhat by the time they had been sampled and plastic applicators were not sampled.

Rise / settle velocity tests on ***panty liners*** showed the largest number of pollutants sank in the velocity band 0.0 to 0.05 m/s in all catchments. However very different velocity profiles for panty liners at each catchment was observed (Figure 4.43). This difference was for the quantity of pollutants that would rise or fall. At the ethnic catchment 77 % of pollutants sank compared to 49 % at the high income catchment and 46 % at the low income catchment. Only 14 panty liners were tested at the low income catchment which compared to the other number of pollutants tested at the other catchments was small (due to the characterisation process). Hence a change in the profile could occur if more pollutants had been sampled. However if the profiles are correct, then the number of panty liners deposited on the sewer bed may be greater in ethnic catchments due to the type of product used or purchased.

Sanitary towels tested from all catchments were more likely to float (Figure 4.44). In the low income catchment 67 % of all sanitary towels floated compared to 57% in the high income catchment and 87% in the ethnic catchment. However the number of pollutants tested from all the catchments was small. The particle velocity tests suggests that sanitary towels are unlikely to be stored in general because of their tendency to float. This explains why a low number of sanitary towels were sampled during all storms, as they tend to be transported in dry weather.

Tampons tested during rise and settle velocity tests indicated that all pollutants would settle. The profiles of the three catchments are very similar with 93% of all pollutants sinking between 0.05 m/s and 0.13 m/s. Shredded tampons tended to sink slower than those un-shredded. The results suggest that tampons of all the SANPRO items are most likely to be deposited on the sewer bed and stored. This was observed during storm sampling where tampons were the most common SANPRO item to be sampled.

Wipes were generally observed to sink slowly with 99 % of all the pollutants sinking. The distribution profiles were all very similar for the pollutants sampled at each catchment despite having different sizes and masses. Wipes from the high income and ethnic catchment peaked at the same velocity band (0.02 to 0.03 m/s). The low income profile was not as distinct as the other catchments due to the low number sampled with 27 of 28 pollutants tested sinking and 79% sinking within a band of 0.02 to 0.05 m/s. All the pollutants settle slowly therefore although the tests would suggest that the pollutants would have the potential to be deposited, it would be possible for these to move slowly within the DWF, possibly as part of the bed load.

It was not possible to collect ***toilet tissue*** to be tested during sampling due to it being degraded once retained in the sack. It was not possible to determine whether it had degraded in the sewer prior to reaching the sampling point due to the loss of visible definition from it being saturated. Therefore tests were performed on unused 2 and 3 sheet sections of toilet tissue. A total of ten different types of unused toilet tissue were tested. The velocity distributions for four types of toilet tissue are presented which represent different quality in the types of toilet tissue available. These were quilted velvet, double velvet, ultra soft and an economy brand. The velocity profiles were all similar to each other, with 82% of all the tested toilet tissue sinking in the velocity band 0.02 to 0.035 m/s. This was particularly important as it suggests that various types of toilet tissue that could potentially be used by various population types behave similarly.

Table 4-7 Comparison of mean terminal velocities and standard deviations (S.D) for each pollutant tested at the different catchments

	Catchment							
	Low Income		High Income		Ethnic		ALL	
Pollutant	Mean Vel. (m/s)	S.D. (m/s)	Mean Vel. (m/s)	S.D. (m/s)	Mean Vel. (m/s)	S.D. (m/s)	Mean Vel. (m/s)	S.D. (m/s)
Panty Liner	-0.040	0.077	-0.039	0.126	-0.002	0.090	-0.026	0.109
Sanitary Towel	-0.048	0.075	-0.076	0.115	-0.072	0.090	-0.064	0.090
Tampon	0.080	0.030	0.090	0.025	0.081	0.020	0.086	0.024
Wipes	0.035	0.015	0.030	0.011	0.031	0.013	0.031	0.012
Toilet Tissue	-	-	-	-	-	-	0.029	0.006

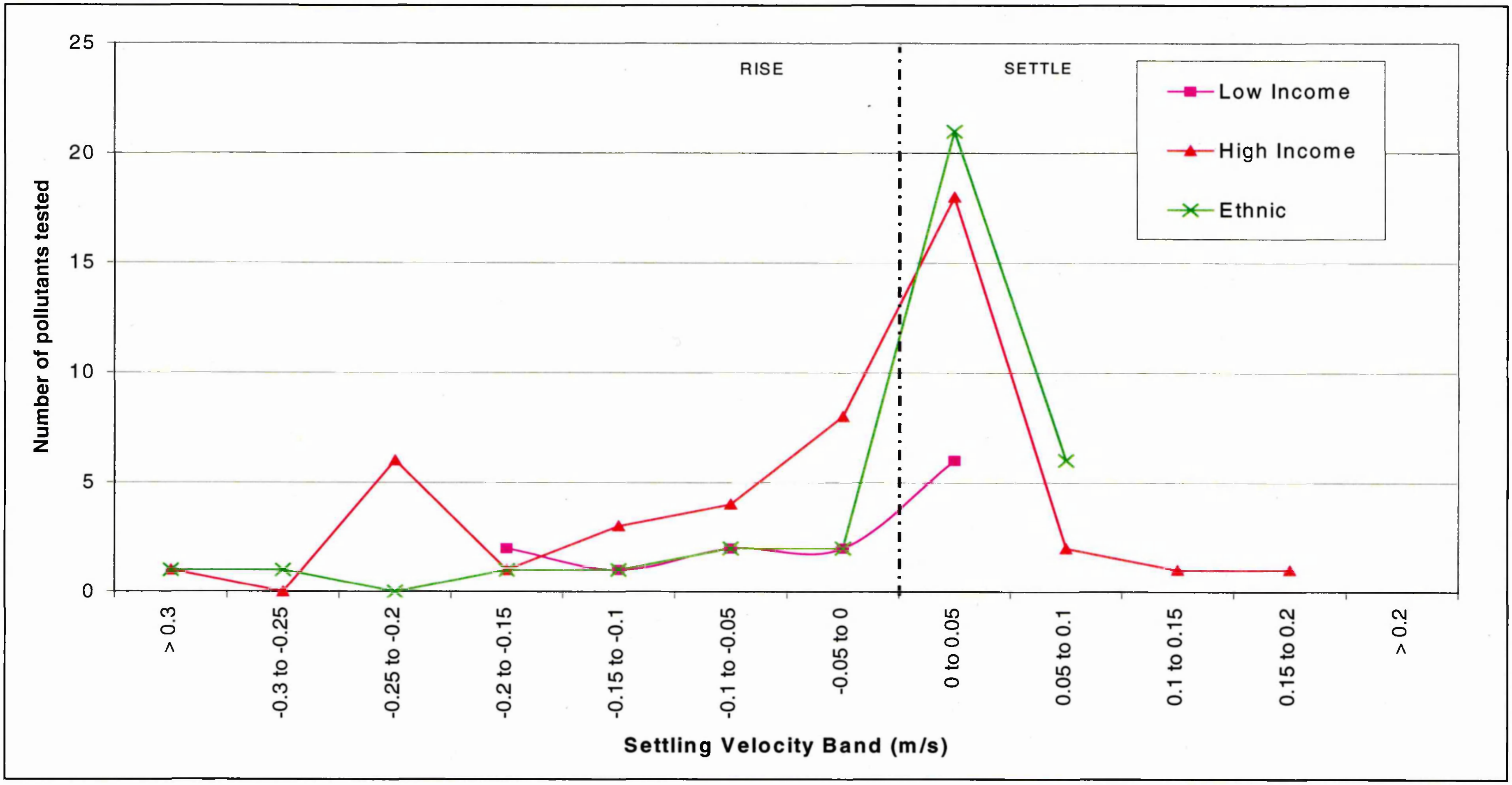


Figure 4.43 Aesthetic pollutant velocity distribution for panty liners tested from each catchment

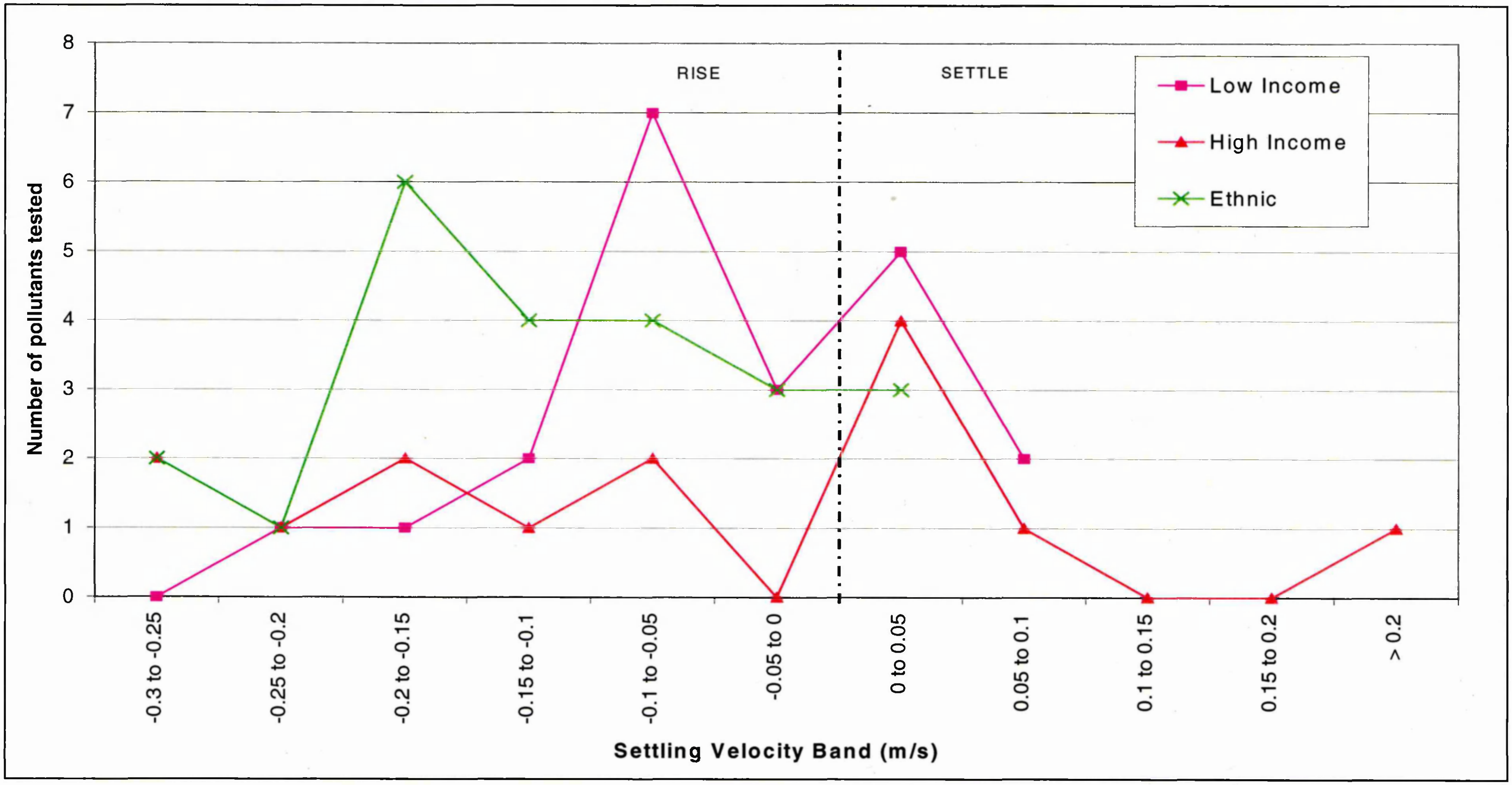


Figure 4.44 Aesthetic pollutant velocity distribution for sanitary towels tested from each catchment

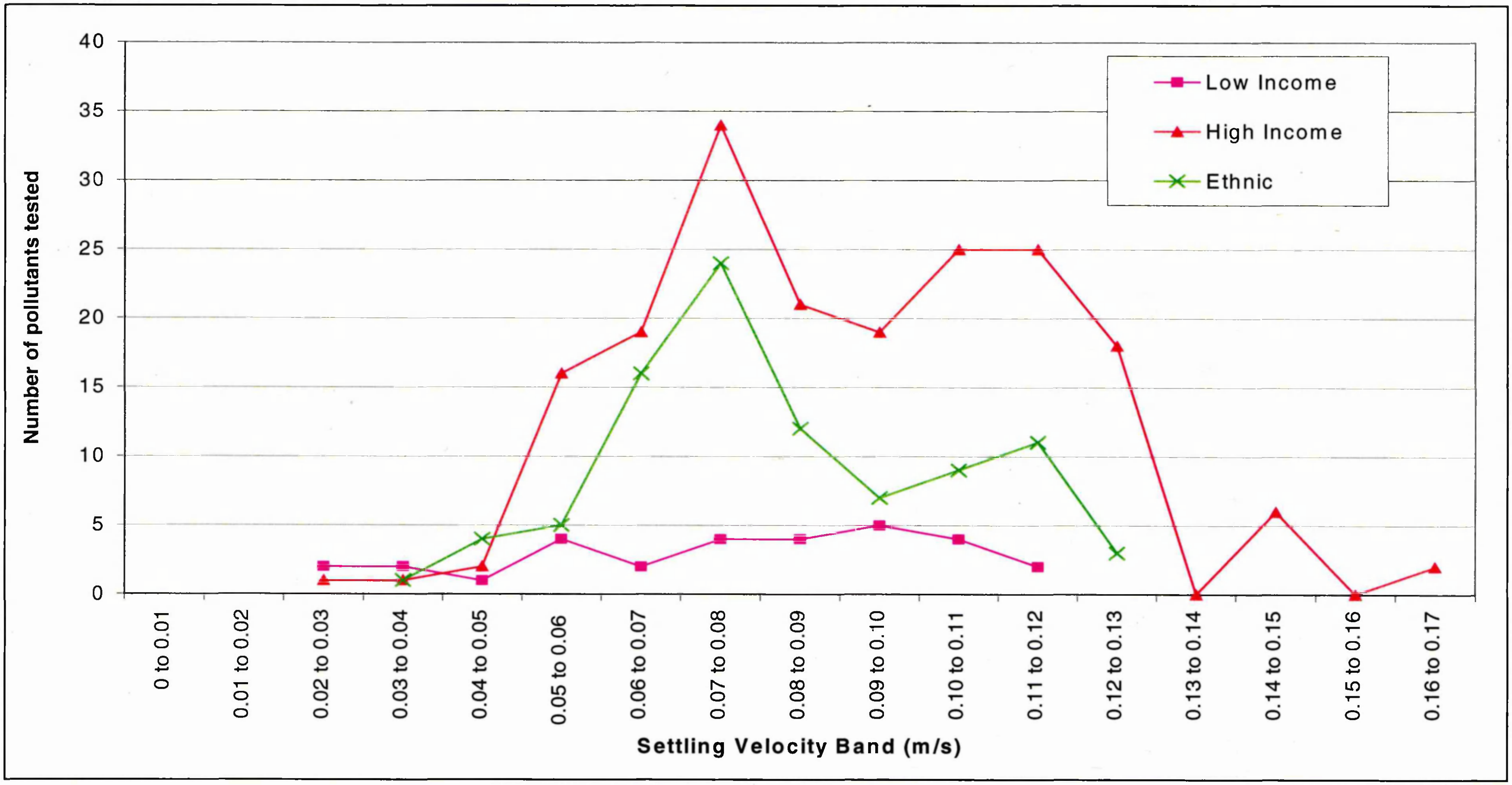


Figure 4.45 Aesthetic pollutant velocity distribution of tampons sampled at each catchment

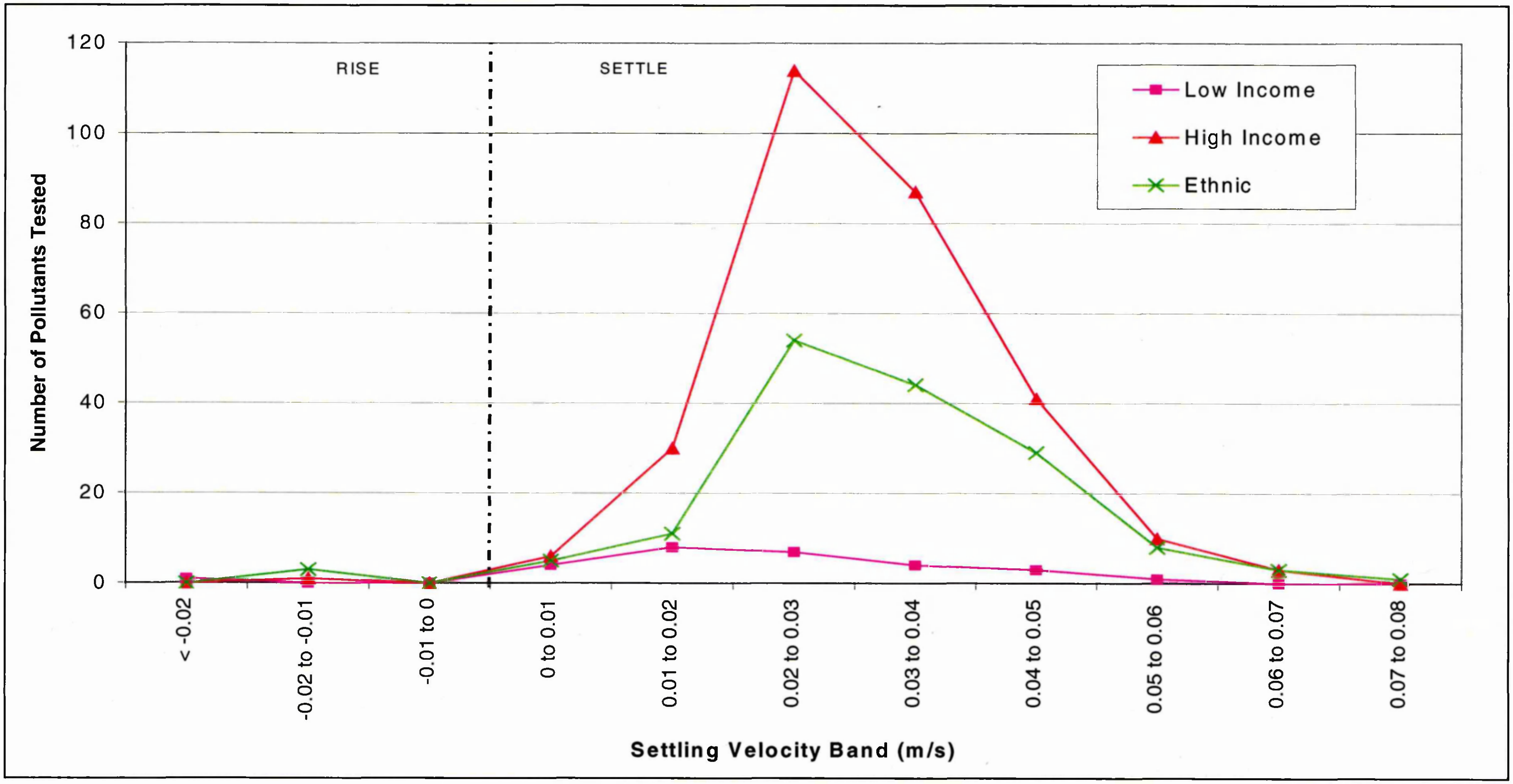


Figure 4.46 Aesthetic pollutant velocity distribution of wipes sampled at each catchment

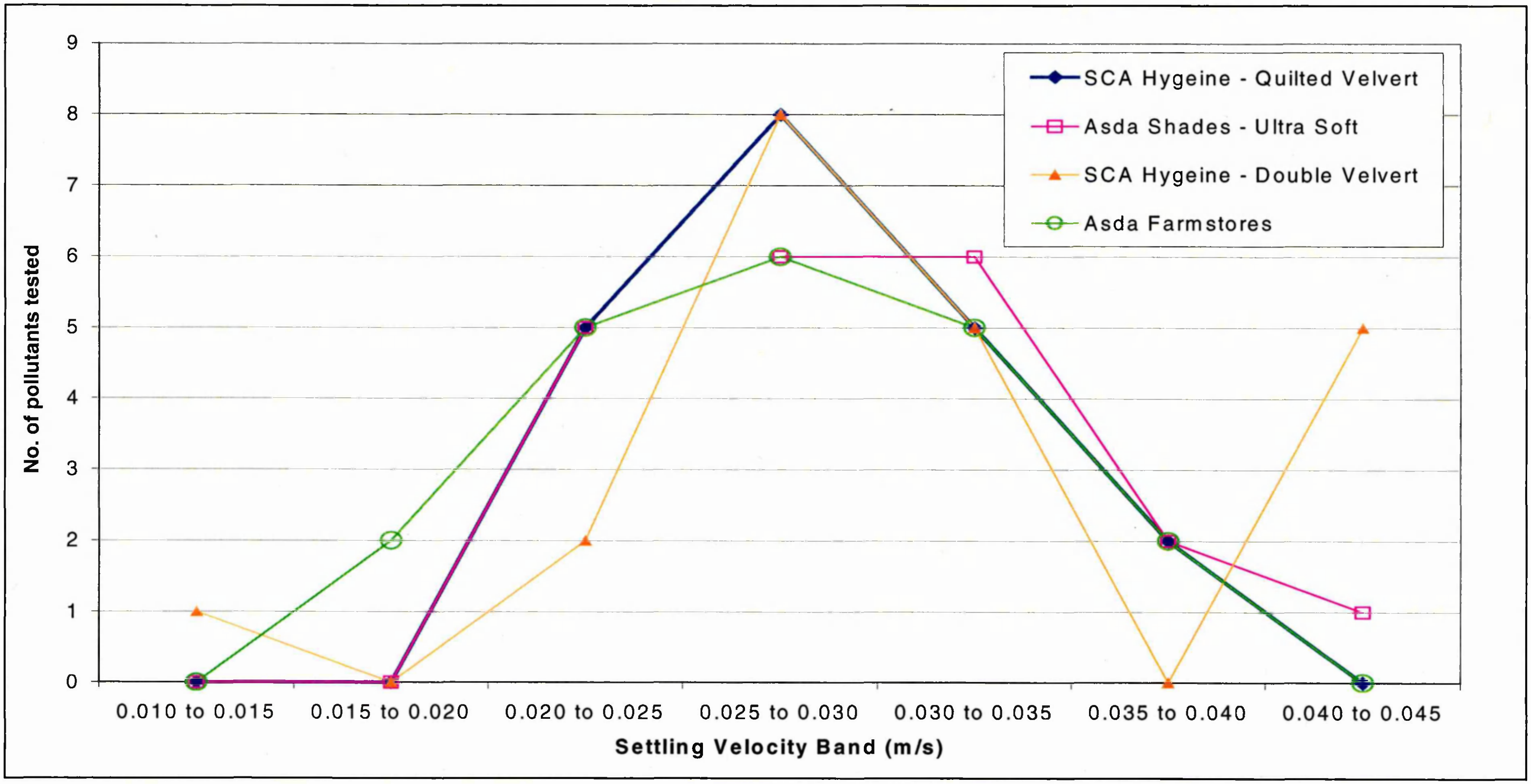


Figure 4.47 Aesthetic pollutant velocity distribution for wetted unused toilet tissue

4.5 Measurement Errors

The dry weather sampling on different days has identified the potential variation from the average value of the solids being sampled, approximately ± 40% of the average value. The sampling methodology defined in Chapter 3 also identified that a number of errors could occur. The changing of the sacks in dry and wet weather identified a potential error source with solids passing through the blanking plate during the changing period. This changing period was small (approximately 5 seconds) and Table 4-8 shows the predicted quantity of solids that could have passed without being sampled. These values are generally small and although a slight under measurement may occur, the values were small enough not to consider adjusting the figures to incorporate these solids.

Table 4-8 Quantity of solids not sampled during the changing of sacks for different loading rates.

Rate of solids sampled (g/s)	Quantity of solids not being sampled (g)
1	5
2	10
4	20
8	40
16	80
32	160

4.6 Field monitoring summary

Dry and wet weather sampling has clearly indicated different population types passing different quantities of aesthetic pollutants into the sewer system. The low income catchment was observed to pass twice the quantity of faecal and toilet tissue in comparison to the other catchments. The high income and ethnic populations produced similar quantities of faeces and toilet tissue. The population of the low income catchment produce more faecal and toilet tissue than the populations of the other catchments. The ethnic catchment was observed to have a low income therefore the low income factor does not appear to be the primary cause of the difference. The major factor that was different between the low income population and the other populations was the high proportion of elderly people residing in the area. Although they are more likely to remain in the catchment during the day, the Sunday sample indicated that more solids were still passed at the low income site therefore residency may be relatively insignificant in producing this large difference. If the population had been calculated incorrectly, the quantity of solids would change, however the population would have to be approximately twice the size of the present value, therefore any error would be likely to have a marginal effect. Therefore the elderly population would appear to be the main reason for the large increase in faeces and toilet tissue. Further sampling at similar sites would be required though to confirm this.

The types of SANPRO products used clearly indicated a difference in the type used and the disposal habits of the population, however it was not possible to discern this from sampling. At the low income catchment, an approximate even distribution between tampons, sanitary towels, and panty liners occurred, with the majority of tampons being sampled during the wet weather events. At the high income catchment, tampons were clearly the main SANPRO item disposed of. At the ethnic catchment, tampons followed by panty liners were most commonly disposed. The approximate numbers disposed per day were greatest in the high income catchment (56), followed by the low income catchment (47) and the ethnic catchment (21). A comparison was undertaken with questionnaire survey work completed by Houldsworth (1999a) by estimating the quantity of solids entering in 24 hours from the sampling data. This indicated that the quantity of SANPRO items used was 2-3 times greater in the questionnaire than measured during fieldwork. However when comparing the two studies as a percentage of the types of pollutants disposed via the WC of the total number disposed, the percentages were very similar.

Wet weather sampling clearly identified a first foul flush at all the catchments. The shape and magnitude of the hyetograph has a clear effect on the temporal distribution and magnitude of the solids flush' as well as the type of catchment. The quantity of solids' flushed is linked with the time of day and ADWP. Storms sampled during the morning produced a large flush of solids because more solids had entered the system, because of the time of day. A clear trend was observed that as the ADWP increased so did the quantity of solids' flushed. The solid's that were most observed during storms were faeces, toilet tissue and tampons.

The significant difference in the type and quantities of solids disposed of is important when understanding the types of pollutants that may enter a WWTW or CSO from different populations. The SANPRO products clearly have different settling velocities and therefore have the potential to behave differently in CSO structures as well as different numbers being stored.

5 Chapter 5 – Calculation of the quantity of solids stored in combined sewerage systems

This chapter describes an investigation into the quantity of solids that are stored in upstream combined sewerage systems. A method to determine the initial quantity of stored solids is described. Factors that influence the storage of solids are discussed and measurable parameters are used to improve the relationship between mass stored and the ADWP. A method to predict the quantity of solids is presented with equations to determine the quantity of solids entering in one day and the quantity of solids that are stranded in upstream pipes in dry weather.

5.1 Stored solids in combined sewerage systems

Aesthetic pollutants entering combined sewers via the WC have the potential to be deposited on the sewer invert. This can occur if the water depth and or velocity are too low to transport the solids. This is likely to occur in sewers at the top end of the system, for example in private drains, where low and intermittent flows are present in dry weather because a small population contributes water to the system. Quantifying the number and types of solids stored in upstream catchments has not previously been achieved. Laboratory and field based experiments have been conducted by others to investigate the velocity and depth at which aesthetic pollutants are transported through the system, and have been discussed in Chapter 2.

Knowing the quantity and type of solid being deposited on the sewer bed is important. If a calculation of the solids presented to a CSO or STW during a storm event is based on a proportion of DWF, then the solids loading may be underestimated. These solids may be passed direct to the watercourse as result of unexpected blinding of a screen in a CSO. Therefore to predict this possible blinding it is crucial to determine the quantity and type of solids presented to a CSO.

An investigation of the sampling data during dry and wet weather was undertaken to help predict the quantity and type of solids stored in a combined sewerage system. The aim of this investigation was to determine the quantity of solids stored in different catchments and identify parameters that may affect the quantity deposited (see section 1.5).

5.2 Predicting the Quantity of Solids at each catchment

5.2.1 Components of solids movement during a storm

Storm sampling at the three catchments identified an increased rate and quantity of solids that reach a sampling point during the early part of a wet weather event. These flushes probably contained solids deposited and those already in motion before the storm (Figure 5.1). These have been conceptually categorised into three main components:

- Solids already being transported through the system at the moment the storm occurs (normally transported out during dry weather)
- Solids that enter the sewer after the storm starts and are transported through the system before the end of the flushing period
- Solids that are deposited on the sewer bed and are flushed out during higher discharges than dry weather peak flows

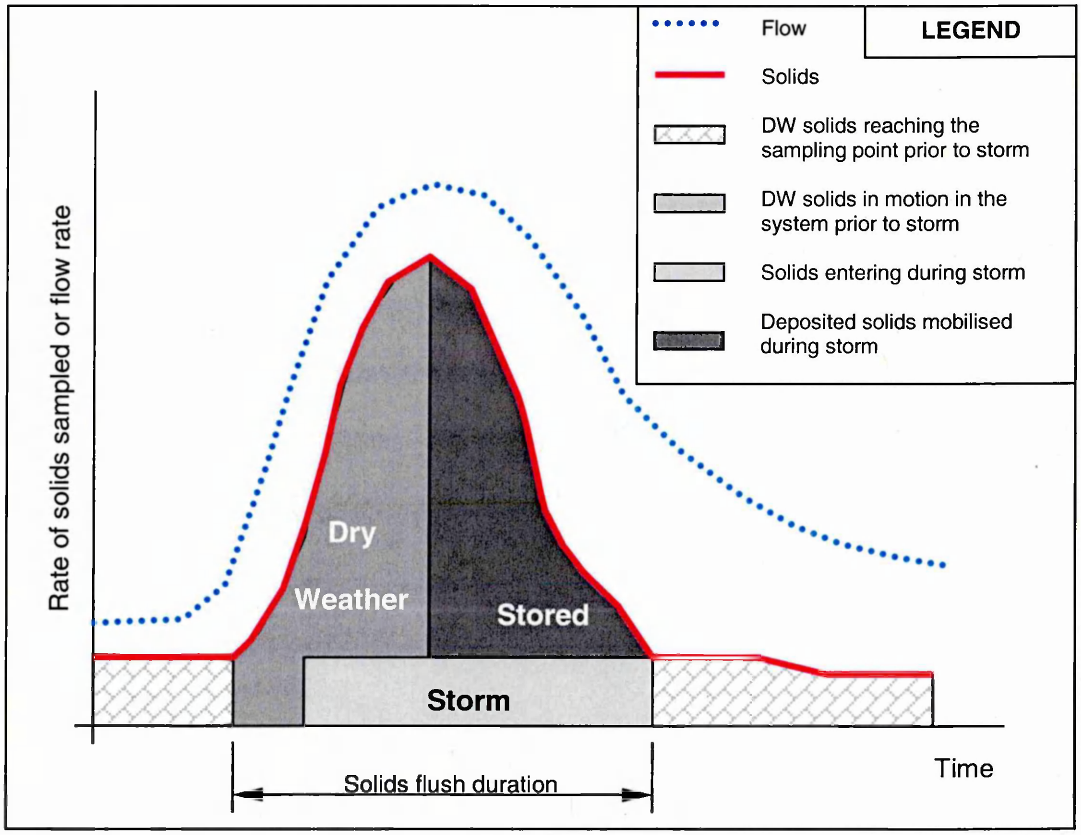


Figure 5.1 Conceptual approach to the composition of solids flushed during a storm. Volumes indicated are subject to change depending upon the length of storm and ADWP.

The solids in motion are likely to be the first solids to be transported at an increased rate. Therefore these will be the first to be flushed. Solids that enter during the storm will start to arrive at the sampling point after the start of the storm as they will have to travel through the system. Once these solids reach the sampling point they will continue arriving throughout the storm. The solids that were deposited during dry weather are mobilised due to the increased water depths and velocities. These will be transported behind the dry weather solids in motion and arrive at the sampling point towards the end of the solids flush. This approach is highly simplified, as it is possible that some of the deposited solids may reach the sampling point prior to all the dry weather solids depending on the configuration of the network. However it conceptually defines the solids distribution during a storm.

The solids deposited on the sewer bed prior to being flushed out can be determined if the solids in motion and those that enter during a storm can be calculated (Equation 5-1).

$$M_s = M_{STORM} - M_{MOTION} - M_{ENTERING} \tag{5-1}$$

Where: M_S = Quantity stored

M_{STORM} = Quantity measured during storm

M_{MOTION} = Quantity of solids in motion prior to the storm

$M_{ENTERING}$ = Quantity of solids entering during storm

5.2.2 Methodology to predict the solids not stored

5.2.2.1 Dry weather solids in motion

The quantity of solids in a system varies throughout the day. This was observed from the flushing profiles of various solids produced by Friedler et al. (1996) and also from the dry weather sampling data at each catchment. Distinct morning and evening peaks occurred in this data, therefore it can be deduced that more solids are present in the system during these times.

Two variables are therefore important in determining the quantity of solids being transported in the system at any one time. Firstly, the rate at which solids entered the system and secondly, the time taken for these solids once entered to travel through the system (Figure 5.1). This was calculated by assuming that the solids are transported at the same velocity as the mean flow velocity. This may not be strictly true, but the approximation was used to enable an estimation of the time it would take solids to travel through the system. Hence the product of the rate of solids entering and time taken for the solids to reach the downstream sampling point determined the quantity of solids in the system.

The rate at which solids enter the system is representative of the population in each catchment. Field monitoring clearly identified different quantities of pollutants being used and input into the system. Flushing rates for various types of solids entering the system are available from previous research conducted by Friedler et al. (1996), however this was not associated with any specific population type. The rate of solids measured from the field monitoring was related to specific population types and therefore the dry weather solids rate was used in conjunction with the time of flow to determine the quantity of solids in the system.

The time of flow is representative of the time required for the majority of solids to exit the system in each catchment. Often, the time of flow in a catchment is considered to be from the end point of the longest sewer branch. However, in this case it would not be representative, as solids entering further downstream would be flushed out in significantly less time than from the top of the catchment. Hence the concept of an average time of flow was considered.

This average time of flow was perceived to be the time to travel an average distance along the main sewer branch in the catchment. Two variables were considered in calculating this average distance:

1. The population that represents the quantity or rate of solids that enter into the system
2. The distance at which the population is from the downstream point of the system (in this case the sampling point). Populations were clustered at each node in the network as assigned when constructing hydraulic models.

Hence by effectively taking moments, a weighted average distance of where solids entered the system was calculated (Equation 5-2).

$$\text{Average Distance} = \frac{\Sigma\ (\text{Population x Distance})}{\Sigma\ \text{Population}} \qquad \textbf{(5-2)}$$

This average distance was therefore used to represent the location where the total population in the catchment would be if a single pipe existed between them and the downstream sampling point (Figure 5.2). An example of the average distance with the populations and their distance from the downstream end is shown in Figure 5.3.

Following the calculation of the average distance, the time of flow from this location was determined. As stated, the location for the average time of flow was positioned on the main sewer branch. This enabled the time of flow to be easily calculated by using velocity output files from HydroWorks dry weather simulations. HydroWorks models were initially constructed to predict flows throughout the network to enable a comparison with flows produced by the mathematical model (Chapter 6). The time of flow in each pipe was calculated by dividing the length by the velocity. The time of flow from the average distance to the downstream sampling point was then determined by summing the time of flow in all the links between these two points (Equation 5-3).

$$\text{Time of Solids Movement} = \sum_{\text{D/S Point}}^{\text{Av. Dist.}} (\text{Link length} / \text{Velocity in link}) \qquad \textbf{(5-3)}$$

Time of flow was plotted against distance and regression analysis was performed to determine an equation for a curve that passed through the data points (Figure 5.4). This enabled the time of flow to be calculated from the average distance at any time of day.

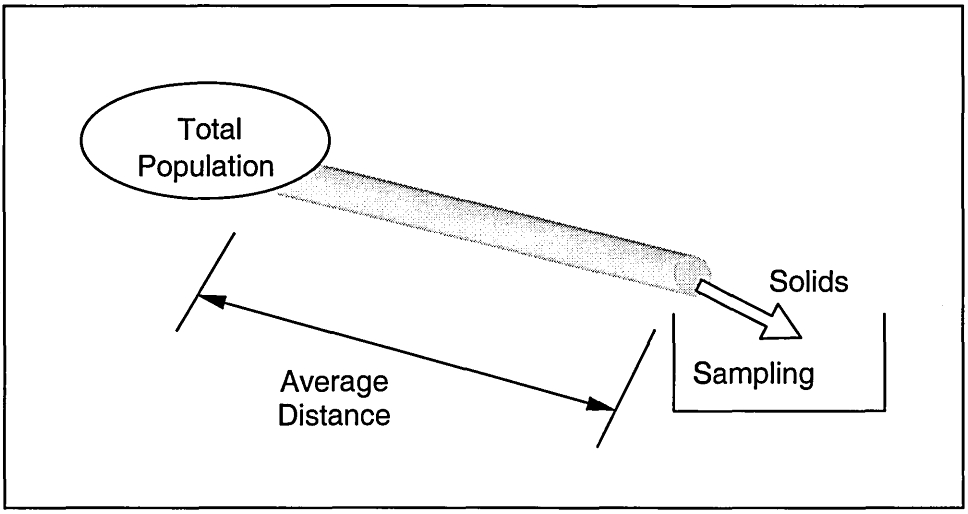


Figure 5.2 Simplification of the population in a catchment to a single point, at an average distance from a downstream point as calculated using Equation 5-2.

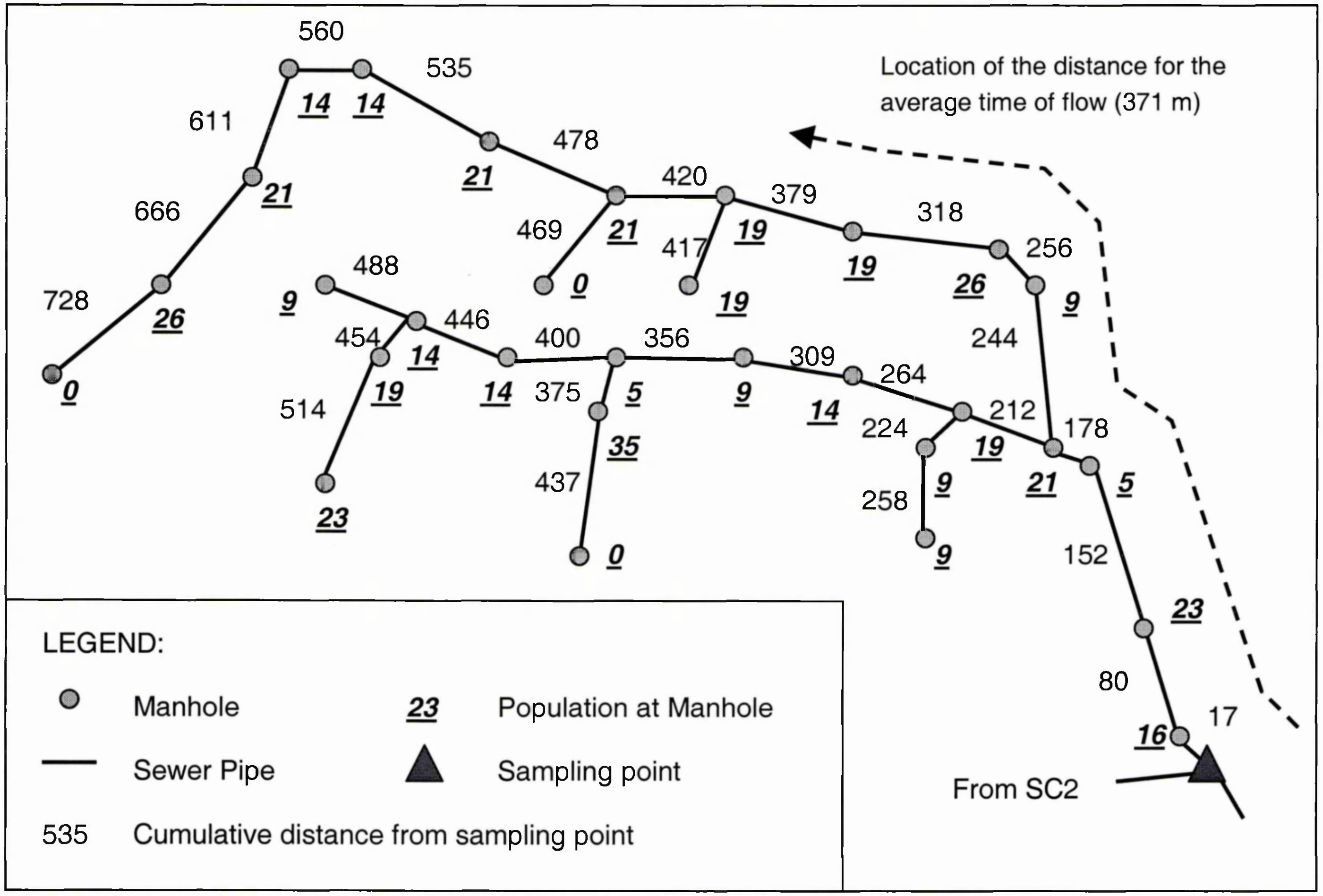


Figure 5.3 Location of the average distance, population and the distance away from the sampling point in SC1 at the low income catchment

Once the time for solids to move through the system had been calculated, it was multiplied by the dry weather solids rate just prior to the storm commencing at time, t (Equation 5-4). This assumes that the solids rate entering the sewer remains constant over the time of flow. Although this assumption is strictly not correct, the largest change in the rate of solids entering occurs in the morning when the time of flow is at its lowest. When the time of flow is greater, during periods of inactivity in the home, the rate of solids entering is close to being constant. Therefore the assumption approximately represents the solids that were in motion in dry weather at the start of the storm and therefore could be transported out.

$$\begin{array}{c}\text{Mass of solids in}\\ \text{system in dry weather}\\ \text{at time of day, t}\end{array} = \begin{array}{c}\text{Time of}\\ \text{flow at}\\ \text{time, t}\end{array} \times \begin{array}{c}\text{dry weather}\\ \text{solids rate}\\ \text{at time, t}\end{array} \tag{5-4}$$

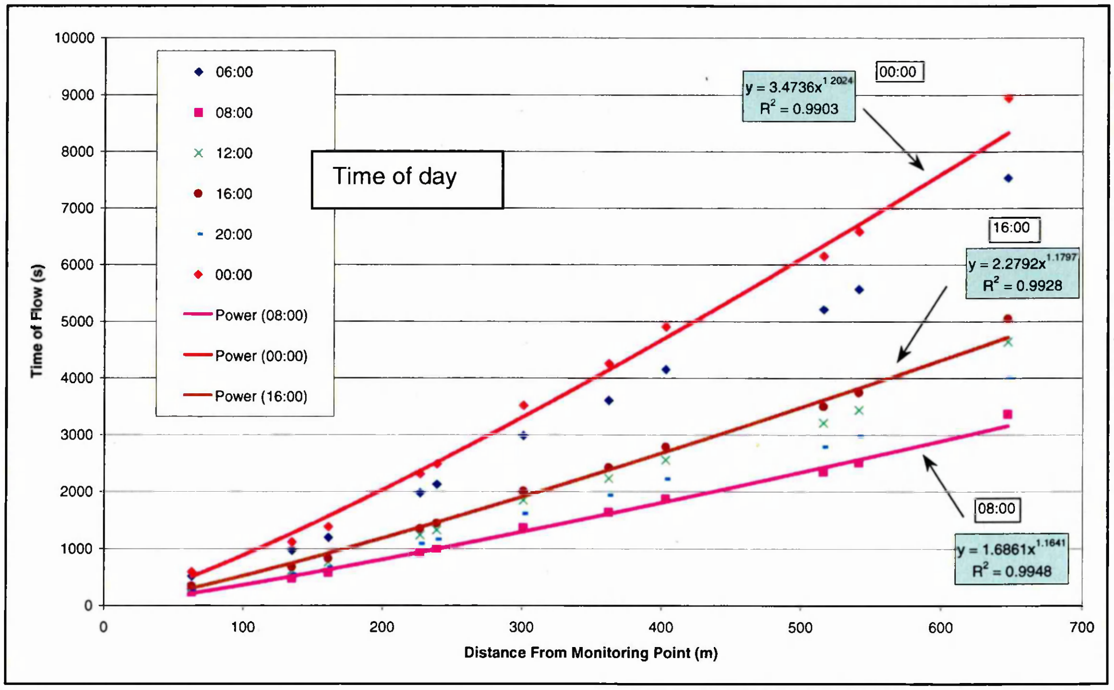


Figure 5.4 Example of the time of flow at 0:00, 08:00 and 16:00, at distances upstream of the monitoring point (Low Income catchment, SC1)

5.2.2.2 Solids entering a system during a storm

The quantity of solids entering the system during a storm is dependent upon the duration of the flush and the rate at which the solids entered. The dry weather sampling data was used to determine the solids entering into the system during the time duration predicted. The product of the time for solids to enter and the time of flow produced the quantity of solids that would be flushed during the storm duration (Equation 5-5).

$$\begin{array}{c} \text{Solids entering} \\ \text{during storm} \end{array} = \begin{array}{c} \text{time for solids} \\ \text{to enter} \end{array} \times \begin{array}{c} \text{dry weather solids rate at} \\ \text{time during storm} \end{array} \qquad \textbf{(5-5)}$$

The quantity of solids that entered the system during a storm was dependent upon the population number and type, the time of day and the duration of the storm. These solids were transported out at a faster rate than in dry weather. This was because of the higher water depth and velocity in the system. This quantity of solids could have formed a significant part of the total sampled storm solids depending upon the length of the storm flush. If a solids' flush of a longer duration was observed (because of low intensity rainfall event) then a large proportion of the solids sampled would contain solids' entering the system. However if the solids flush were over a short duration (due to a high rain intensity event) then the time for solids to enter the system and be transported out during the storm would be small.

Initially, the quantity sampled in dry weather for the corresponding time period of the storm duration was used to represent these solids. However, this was not representative of all the solids that would enter the system, because a proportion of the solids would not be transported to the sampling point during the duration of the solids flush. To account for this, the time of flow at the end of the storm was calculated to determine the average time when solids would enter the system but not reach the sampling point before the end of the storm. This time was subtracted from the storm duration to determine the time that solids would enter the system and were flushed once the storm had started (Equation 5-6). To enable this prediction the end of the storm was defined by identifying when the rate of solids sampled decreased to that of similar values measured in dry weather. The end of the storm was determined by identifying when

$$\begin{array}{c} \text{Time for solids to enter} \\ \text{after storm starts} \end{array} = \text{Storm duration} - \begin{array}{c} \text{Time of flow at end of} \\ \text{solids flushing period} \end{array} \qquad \textbf{(5-6)}$$

The time of flow at the end of the storm was predicted in a similar manner to the time of flow at the start of the storm (section 5.2.2.1). The same average distance was used which was dependent upon the population (representative of the distribution of impermeable area) and the distance they were located from the downstream sampling point. Hydroworks was used to simulate the storm event to produce output velocities for each link at the end of the solids flushing period (Figure 5.1). The velocities were used (as in section 5.2.2.1) to calculate the time of flow in each pipe from the average distance. This enabled the time for solids to enter in each storm to be calculated.

5.2.2.3 Calculation of the Total Quantity of Stored Solids

The total quantity of solids stored prior to each storm was calculated using Equation 5-1 and these are shown in Table 5.1. Negative values for storm 1 at the low income catchment in SC1 were recorded for the time for solids to enter during the storm. This was because the time of flow for the storm was greater than the storm duration itself, hence producing a negative value. Therefore no solids entered the system at the average distance and reached the sampling point before the end of the storm.

Although the quantity of solids in dry weather and entering during the storm had been calculated, further work was required to understand what processes affected the observed values to achieve a useful comparison between the catchments sampled.

Table 5.1 Components of the solids in motion and those entering during the storm to determine the quantity of all solids stored in each catchment being flushed out

Site	Storm No.	Storm Start Time	Storm Finish Time	Storm Duration (min)	Tme of flow in DW (s)	Time of flow storm (s)	Time of flow in DW (min)	Time of flow at end of storm (min)	Time for solids to enter during storm (min)	Total Solids entering during storm (g)	Total Solids in motion in dry weather (g)	Total Solids in motion and entering (g)	Total Solids measured during storm (g)	Total Solids stored in system (g)
L - SC1	1	15:00	15:10	10	2660	690	44.34	11.50	-1.50	0	559	559	2146	1587
L - SC1	2	16:25	16:50	25	2446	331	41	6	19	302	347	649	4590	3941
L - SC1	3	8:55	9:25	30	1692	544	28	9	21	1109	2133	3242	6267	1849
L - SC2	1	15:00	15:05	5	2038	549	34	9	-4	0	387	387	438	51
L - SC2	2	16:20	16:50	30	1864	229	31	4	26	398	450	848	2372	1524
L - SC2	3	8:55	9:10	15	1280	373	21	6	9	546	1541	2086	2854	186
L - SC3	1	15:05	15:20	15	2639	1629	44	27	-12	0	844	844	858	14
L - SC3	2	16:25	16:50	25	2441	371	41	6	19	339	1023	1363	3321	1959
L - SC3	3	8:55	9:15	20	1670	609	28	10	10	442	1592	2035	4292	684
L - SC4	1	15:05	15:25	20	3723	1866	62	31	-11	0	2122	2122	5234	3112
L - SC4	2	16:25	16:50	25	3275	341	55	6	19	486	1646	2132	7094	4962
L - SC4	3	8:55	9:20	25	2301	480	38	8	17	1436	3731	5167	9651	1892
H	1	14:55	15:05	10	1220	495	20	8	2	72	840	912	2469	1557
H	3	18:10	18:55	45	1020	1000	17	17	28	1323	667	1991	10310	8319
H	5	16:40	17:40	60	1140	445	19	7	53	1703	561	2264	6436	4172
H	6	19:21	19:40	19	1005	424	17	7	12	438	546	984	13797	12813
E - SC1	2	12:10	13:30	80	431	225	7	4	76	1891	220	2111	8516	6405
E - SC1	4	19:00	19:50	50	422	190	7	3	47	1875	259	2133	10816	8683
E - SC1	5	12:00	13:00	60	429	212	7	4	56	1651	365	2017	8976	6959
E - SC2	2	12:10	12:30	20	788	464	13	8	12	127	136	264	2492	2228
E - SC2	4	19:00	19:45	45	767	216	13	4	41	697	476	1173	6748	5575
E - SC2	5	12:00	13:00	60	788	261	13	4	56	903	489	1392	7208	5816

5.3 Comparison of the total quantity of solids stored with different catchment characteristics

The catchments and their populations contain many different variables that contribute to the different numbers and types of solids that enter combined sewerage systems. The principal factors that may affect the quantity of solids stored are:

- Population size
- Population type (socio-economic and ethnic factors)
- ADWP
- Bed slope of sewer pipes
- Length of sewer system
- Size of catchment
- Number of connections into the system
- Size of sewers

5.3.1 Comparison of the total quantity of solids stored in each catchment with population

The first factor considered is the population. The total quantity of solids stored is divided by the population to give mass per person (Equation 5-7).

$$M_P = \frac{M_S}{P} \tag{5-7}$$

where:

- M_P = Calculated stored mass per person
- M_S = Calculated stored mass from each storm
- P = Total population in each catchment

The second important factor is the time in which the stored mass could accumulate. This period of time allowing pollutants to be stored has previously been observed for gross solids with rags at CSOs by Jefferies and Ashley (1994) as well as in the field studies conducted during this project. Theoretically, the longer the ADWP, the greater the potential for solids to be deposited and stored. This was generally observed when the total stored solids were plotted against ADWP (Figure 5.5).

The resulting graph was encouraging, however outlying data was observed for three storms. Firstly the results from the storms sampled at the ethnic site, SC2 confirmed that solids were becoming trapped rather than deposited and only being flushed out during a wet weather event due to large quantities of root intrusion (see section 4.3.3). Therefore on the steepest catchment of all sampled, the smallest deposits of solids would theoretically be expected, however this clearly was not the case.

Secondly the data for storm GS1 at the low income site indicated very little or no build up of solids. This suggested that the solids flushed were those in motion or those that entered into the system during the storm (see section 4.3.1). The storm had a low rain intensity and was over a short duration therefore it was assumed that it was not large enough to flush all the stored solids which would have been retained during the ADWP. This ADWP was also the largest of the three storms sampled at the low income catchment.

Thirdly the sub-catchment SC1 at the low income catchment contained a serious pipe defect at the downstream end of the system, close to the sampling point. The pipe was rutted and collected solids in an area approximately 30 cm by 30 cm at the invert of the pipe. An estimation of the roughness at the invert of the pipe based upon Appendix J, Volume 2 in the Sewer Rehabilitation Manual WRc (1994) was K_s = 15 mm significantly greater than normal. The pipe therefore consistently stored up solids during dry weather and hence would affect the validity of the results.

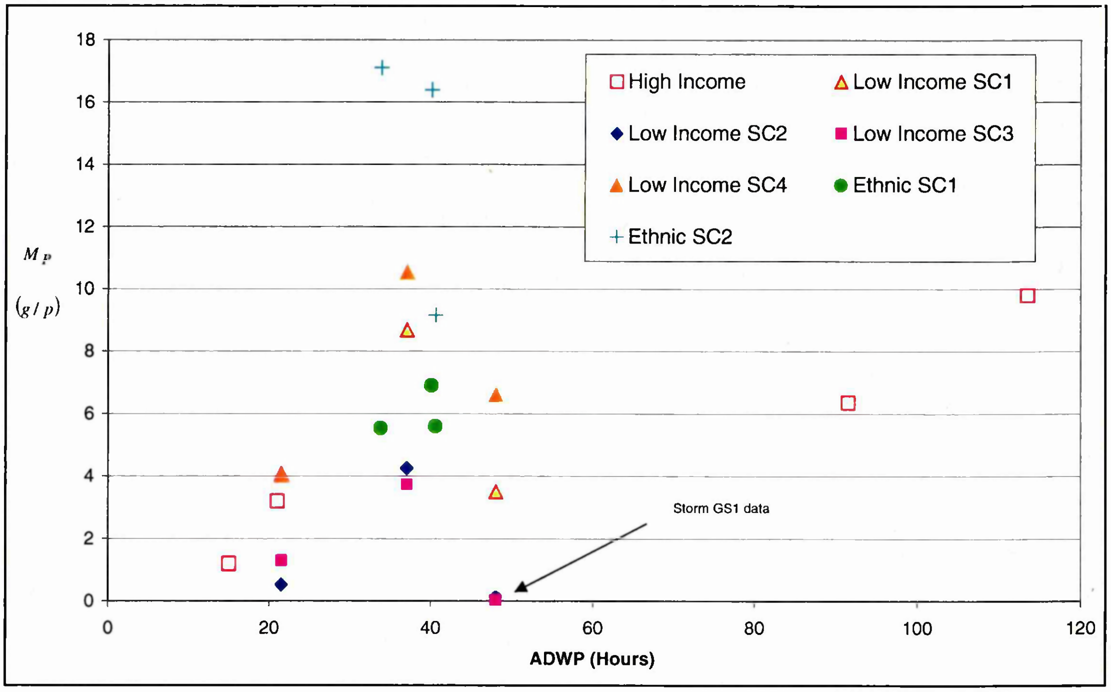


Figure 5.5 Comparison of mass per person and the ADWP for each storm event at the catchments

These points were removed from the graph, which immediately reduced the scatter in the data. Regression analysis was carried out and a trendline fitted (Figure 5.6). The correlation co-efficient indicated a reasonable fit of the data, and the resultant equation of the trendline enabled the quantity of solids to be predicted for an ADWP. The trendline indicated that as the ADWP became large, the rate of solids being deposited decreased. Hypothetically this could be understood where, as more solids are deposited, some of the solids stored would be re-entrained and start to move through the system. This could happen particularly as the solids build up could produce a small dam and enable the hydraulic conditions to change. Therefore as the ADWP becomes large, an equilibrium state will occur in the sewer. The equation of the line when differentiated indicates an asymptotic trend, as ADWP becomes large (Equation 5-8).

$$M_P = a(1 - e^{-bT})$$
$$M_P = a - ae^{-bT}$$
$$\frac{dM_P}{dT} = bae^{-bT} \qquad \textbf{(5-8)}$$

If T approaches infinity then $\frac{dM_P}{dT}$ tends to zero

If: M_P = the stored solids per a 1000 population,

T = the ADWP

a & b are constants

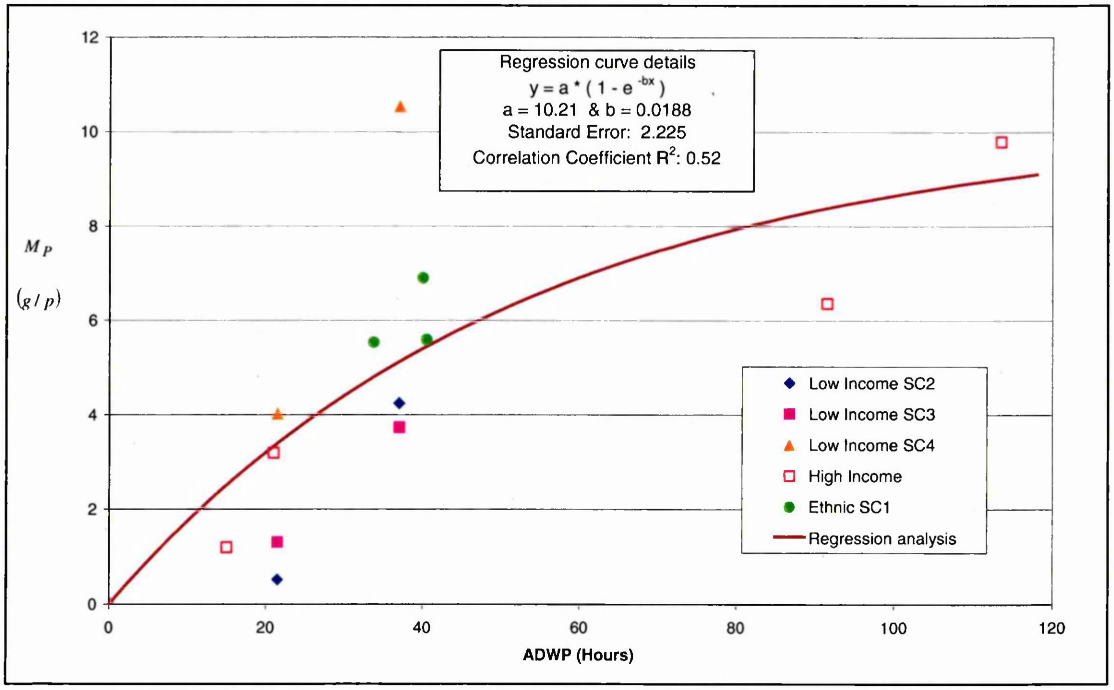


Figure 5.6 Relationship between the total mass of solids per person and the ADWP excluding the outlying data.

5.3.2 Comparison of solids stored with the quantity of solids entering in a day

The previous section indicated that a relationship existed between the mass stored per person and the ADWP. However, the correlation coefficient ($R^2 = 0.52$) from the resulting regression analysis did not indicate a very good fit. The data obtained from aesthetic pollutant sampling in the 3 catchments clearly indicated different production or degradation rates of solids in the sewer. Nearly twice the quantity of faeces and toilet tissue per person was sampled in the low income catchment than at the high income and ethnic catchments. If the production rates were similar in each catchment then population would be a good measure to compare the quantity of solids stored. However, as the quantity of solids measured in the system was different, then population alone is not ideal in comparing these values.

To account for this difference in the quantity of solids that have entered (or reduced due to degradation) in one day, an estimate of the quantity of solids that would be sampled in one day if no deposition occurred was used. This allowed for the three population types producing different quantities of solids that would influence the quantity of solids that could be stored in the system. Hence the mass stored (M_S) was considered as a proportion of the mass entering in one day (M_T). This would account for socio-economic or ethnic factors that influence the quantity and type of solids that would enter the system.

To calculate M_T, the dry weather sampling data and an estimate of the quantity of solids that would have been stranded in one day in dry weather was used (Equation 5-9). It was considered that the deposition of solids was directly proportional to the ADWP (Equation 5-10).

$$M_T = \text{Solids measured in dry weather} + \text{Estimated quantity stored in a 24 hour period} \quad \textbf{(5-9)}$$

$$\text{Estimated quantity stored in a 24 hour period (Linear)} = M_S \times (24/\text{ADWP}) \quad \textbf{(5-10)}$$

The largest estimated quantity stored in one day was approximately 10% of the dry weather mass. Therefore although M_T contained a proportion of M_S, it did not form a significant part of it.

Regression analysis was conducted using the values plotted of M_S/M_T against ADWP with a correlation of all sampled data for each catchment of $R^2 = 0.7$ (Figure 5.7). This improved the previous correlation produced from M_S against ADWP of 0.54. The relationship between the M_S/M_T and ADWP was linear indicating that the quantity of solids stored was related to the ADWP and the quantity of solids that enter the system. However the gradient of the trendline fitted to the data of each individual catchment identified a different rate of increase for each catchment. Unfortunately the data at the low income and ethnic catchment respectively was over similar, shorter ADWPs. The rate of increase was greatest at the ethnic catchment and lowest at the low income catchment. The most reliable data was obtained at the high income catchment where short and long ADWP storms were sampled. The difference in the rate of solids deposition after accounting for the quantity of solids entering suggests that other factors influence storage.

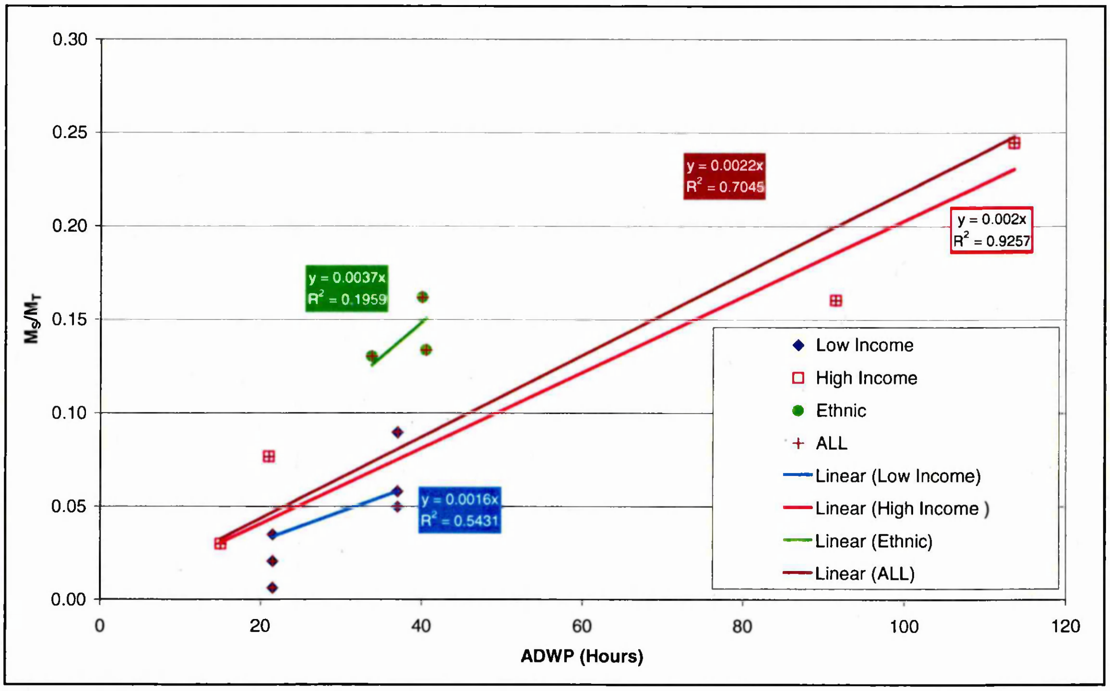


Figure 5.7 Comparison of the total mass stored as a proportion of the total mass in one day against ADWP, with the catchment data for the low income site categorised together

5.3.3 Comparison of solids stored with catchment characteristics

Various catchment characteristics are likely to influence the quantity of solids stored. Figure 5.8 suggests that certain characteristics of each catchment may influence the quantity that is stored in the sewer system. The first objective of using catchment characteristics is to show the rate of increase of the individual catchment data to be similar. The second objective is to improve the overall correlation of the data from $R^2 = 0.7$. The best characteristics to use would be those which are easily measurable. This would facilitate the use of the resulting graphs and equations by engineers. Two other characteristics that are considered to be important are the sewer gradient and the distribution of the population throughout the catchment.

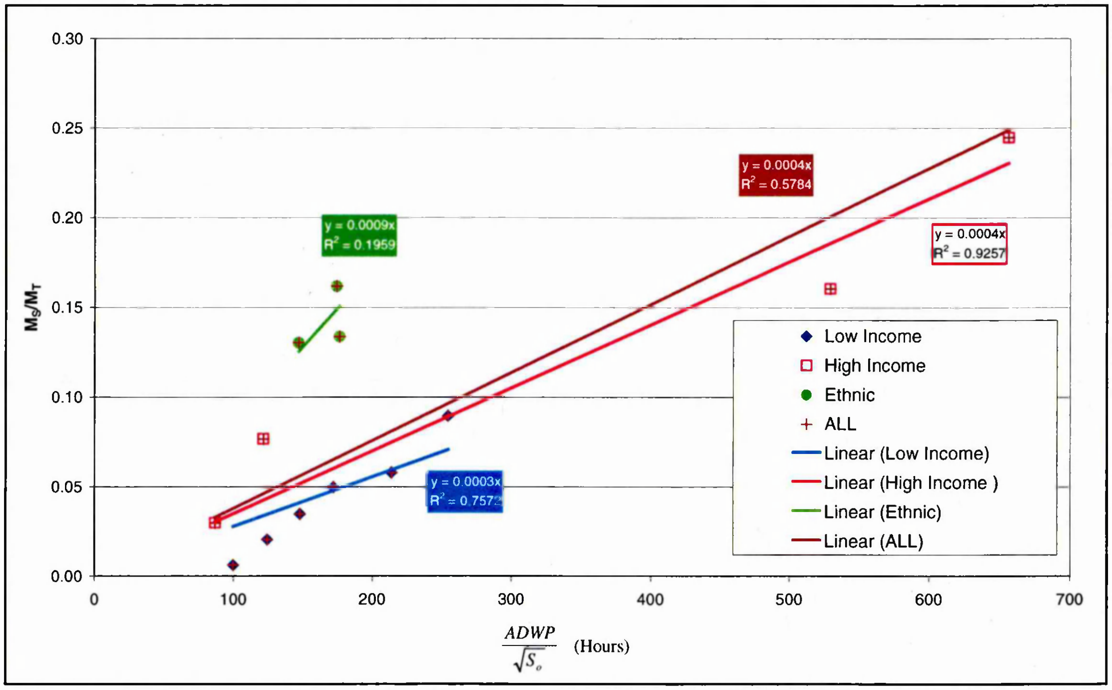


Figure 5.8 Comparison of stored mass as a proportion of the total mass against ADWP and bed slope.

Davies et al. (1996) conducted laboratory tests that showed that the shallower the gradient the more likely it was that the pollutant would be deposited. Mean water velocity, water depth and shear stress at the wetted perimeter was recorded for 50% deposition of solids during tests. It was shown that the shear stresses consistently reduced (for 50% deposition), as the bed slope became shallower. *'When considering sediments the mode of transport are dependent upon the relative magnitude of the lifting effects due to turbulence measured by the shear velocity (U_*) and the settling velocity (W_S). Ratios of U_*/W_S define the mode; suspension, saltation or bed load'* (Butler and Davies 2000). This could also be applied to gross solids, as a relationship exists between shear stress (τ_c) and shear velocity. This could also be expressed as being proportional to the square root of the bed slope (Butler et al. 1996) (Equation 5-11).

$$U_* = \sqrt{\frac{\tau_c}{\rho}} = \sqrt{gRS_0} \qquad \textbf{(5-11)}$$

Where:

ρ = density of the fluid (kg/m^3)

g = gravity (m/s^2)

R = Hydraulic radius (m)

S_0 = Bed slope

If the bed slope increased i.e. became steeper, then the shear velocity would increase at 50% solids deposition, hence fewer solids would be stored. Hence the quantity of solids deposited (M) is likely to be inversely proportional to the square root of the bed slope Equation 5-12.

$$M \propto \sqrt{\frac{1}{S_0}} \qquad \textbf{(5-12)}$$

The ADWP was divided by the square root of the bed slope and plotted against M_S/M_T to determine if the correlation improved. Regression analysis identified that the overall correlation ($R^2 = 0.58$) and the gradients for each individual catchment became worse with the introduction of bed slope. It was expected this would have improved the overall correlation, however the desired effect may not have occurred as all the catchments are relatively steep. The shallowest average gradient was 1:47, therefore although bed slope did not improve the correlation, it may be more important for shallower pipes.

The second main characteristic that was clearly different between the catchments was the relative size of the total and impermeable areas. The low and high income catchment has similar ratios of impermeable area to total area (PIMP). However at the ethnic catchment, the housing was mainly terraced with a PIMP value over twice that of the other catchments.

There are a number of different ways of expressing this catchment characteristic using the areas assigned to each catchment and the population. These are:

- Population density, P_P (Population / Total Area)
- PIMP (Impermeable area / Total Area)
- Housing Density, H_d (Roof area / Total Area)

These three expressions of the distribution of the housing in the catchment is combined with the ADWP. In a high PIMP catchment, the flow in the sewer will be interrupted by a greater number of inputs per a length of sewer, than in a low PIMP catchment. These inputs will include water and solids and may have an affect on the momentum of the flow, reducing the chance for the flow becoming steady within the sewer. With potentially more unsteady flow in the sewer throughout the network, the solids may not be as likely to be mobilised and transported once they have entered. Therefore there is more potential for the solids to become deposited and not eroded because of the unstable flow regimes within the more densely populated areas. Hence the ADWP was multiplied by the each of the three definitions to determine the best correlation with the M_S/M_T.

The best correlation and convergence of the individual gradients was observed when housing density was plotted against M_S/M_T (Figure 5.9). Regression analysis was carried out and showed a linear relationship with a correlation co-efficient of ($R^2 = 0.92$). The overall correlation values for the three measures of the population distribution for the catchments against ADWP and the square root of the bed slope is shown in Table 5.2. The use of bed slope improved the correlation when used with population density but reduced the correlation for housing density and PIMP. This was expected following the comparison of bed slope with ADWP only, which indicated that bed slope, did not improve the correlation. The introduction of housing density improved the earlier correlation of M_S/M_T against ADWP ($R^2 = 0.70$). The gradient of the trendlines fitted to the individual catchment data showed a convergence to the overall gradient. The regression analysis forced the linear relationship through zero as no solids are likely to be stored during a wet weather event and equally once an event has concluded solids have the potential to be deposited.

Table 5.2 Comparison of correlation R^2 values by combining the catchment characteristics and plotting against mass stored as a proportion of the total mass

Catchment Parameters	ADWP	$\frac{\text{ADWP}}{\text{SQRT So}}$
Housing Density	0.923	0.884
PIMP	0.800	0.723
Population Density	0.838	0.9308

The mass stored in an upstream catchment can be calculated using the equations produced following regression analysis on the data (Equation 5-13). Bed slope is not included in the equation although its effect may be more significant on shallower catchments. However it was not possible to sample flat catchments therefore this characteristic has not been included within the predictive equation. The equation relies upon knowing the mass entering the system in one day. A method to determine this mass is described in section 5.5.

$$M_S = 0.0118 \times M_T \times H_d \times ADWP \qquad \textbf{(5-13)}$$

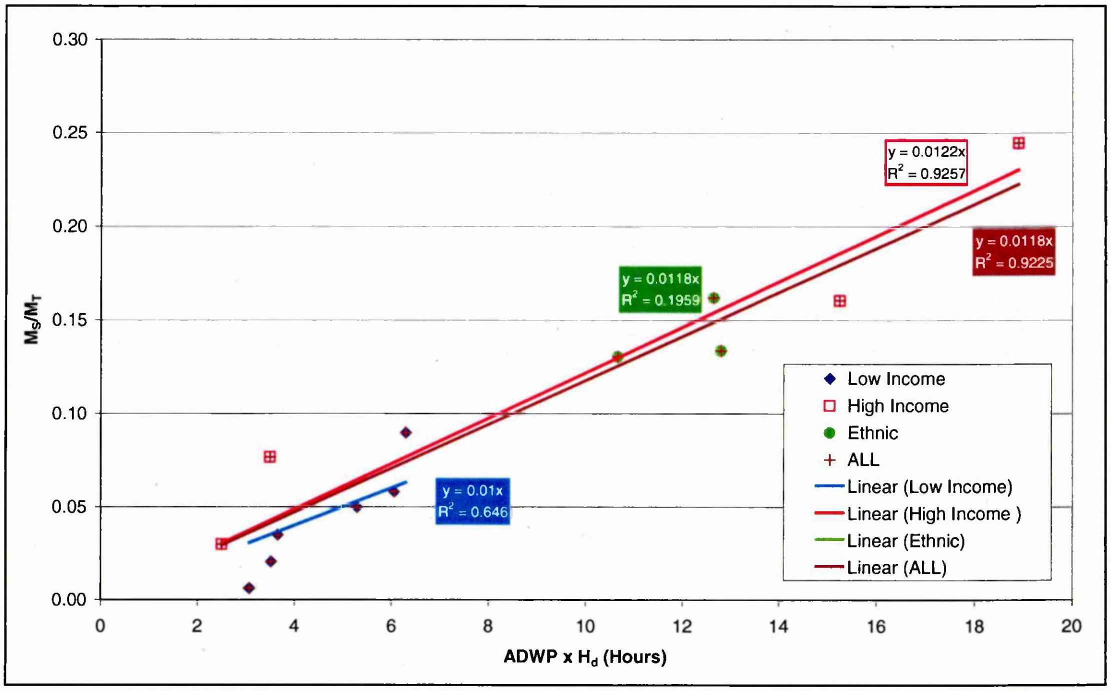


Figure 5.9 Comparison of stored mass as a proportion of the total mass against ADWP and Housing density.

A total of 22 storms were sampled between the three catchments. Only 13 storms of the 22 sampled could be used with the other 9 being discarded for reasons discussed in this chapter. Ideally further storms sampled would have provided more data to make the regression analysis more reliable, however this was not possible due to time constraints. Also an ADWP of at least 5 days prior to each storm sampled was required. A limitation of this data was that the catchments sampled were relatively steep. The steepest average catchment gradient was a 1:18 at SC1 at the ethnic site and the shallowest was a 1:47 at SC4 at the low income site. Further sampling to verify the linear relationship and determine if bed slope is an important factor for shallower catchments is required.

5.3.4 The effect of varying the time of flow on the solids stored

The calculation of the quantity of solids stored was dependent upon the methodology presented being representative of the solid's physical behaviour in the sewer. This used the time of flow in the catchment in two ways. Firstly for dry weather to predict the quantity of solids in motion at the start of the storm. Secondly it was used at the end of the solids' flush to determine at what point solids would enter the system but not arrive at the sampling point before the end of the solid's flush. An investigation was conducted to check the sensitivity of the predicted quantity of solids stored prior to the storm. The time of flow was varied by ± 25 % for the time of flow in dry weather and the storm, and the solids stored were re-calculated. These values were divided by the total mass entering in one day and plotted against the product of ADWP and Housing density (Figure 5.10).

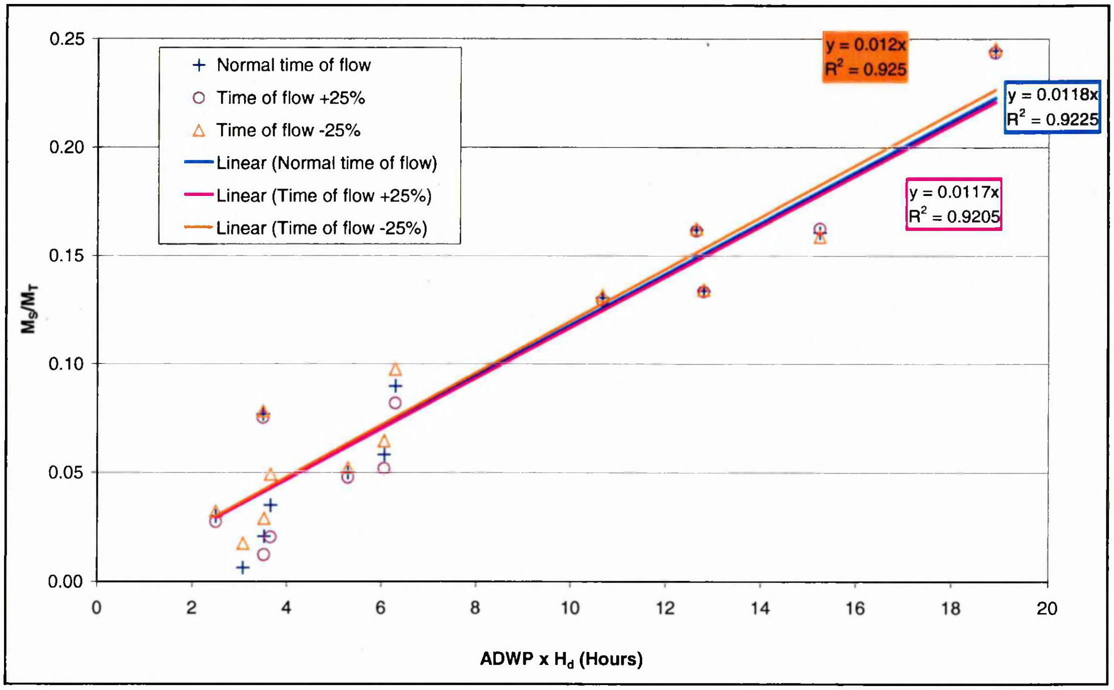


Figure 5.10 Comparison of mass stored using time of flows varied by ± 25 % as a proportion of the total mass against ADWP and housing density

Regression analysis was conducted on the data points and compared. The correlation values were all very similar (R^2 = 0.9205 to 0.925) as were the gradients (0.0117 to 0.012). These results suggest that the method used to predict the quantity of solids stored was not particularly sensitive to the magnitude of the time of flow.

5.4 Prediction of Individual Stored Solids

5.4.1 Methodology to calculate individual stored solids

The calculation of individual solids is potentially more useful than the total solids. Individual solids such as SANPRO items are often cause for public complaint if discharged from CSOs. These can become entwined on branches or deposited on river banks due to their fibrous nature and are slow to breakdown.

The solids considered for individual prediction were those which were likely to be deposited on the sewer bed. These solids had been flushed during storm sampling and had sunk during rise and settle velocity tests. These were:

1. Faeces
2. Toilet tissue
3. Tampons
4. Panty liners
5. Wipes

The methodology used to predict the total quantity of solids was also used to predict the individual solids stored in the system. However the solids rate used to calculate the solids in motion and those entering during the storm, were obtained from characterisation. The outlying data was not used to predict the individual solids stored because of reasons previously stated (section 5.3.1).

5.4.2 Calculation of individual stored solids

The quantity of stored ***faeces*** was calculated for each sub-catchment. These values were added to 50% of the mush mass (as stated in section 4.2.1.2). These values were then used to predict the quantity of stored faeces (Figure 5.11). A very good correlation was achieved for all the data ($R^2 = 0.77$) indicating a linear relationship between the plotted parameters. The gradients of all the lines as observed in Figure 5.11 were very similar, all being within 13% of the overall gradient. A predictive storage equation for faeces was determined from the regression analysis (Equation 5-14).

$$M_{S:Faeces} = 0.0108 \times M_{T:Faeces} \times H_d \times ADWP \qquad \textbf{(5-14)}$$

The quantity of stored ***toilet tissue*** was calculated for each sub-catchment. These values were combined with 50% of the mush values (as stated in section 4.2.1.2). These values were then used to predict the quantity of stored toilet tissue (Figure 5.12). An excellent correlation was achieved for all the data following regression analysis ($R^2 = 0.91$) indicating a linear relationship between the plotted parameters. The gradients of all the lines as observed in Figure 5.12 were similar, all being within 24% of the overall gradient. Rise and settle velocity tests indicated that different toilet tissue types behaved very similarly. A predictive storage equation for toilet tissue was determined from the regression analysis (Equation 5-15).

$$M_{S:ToiletTissue} = 0.0108 \times M_{T:ToiletTissue} \times H_d \times ADWP \quad \textbf{(5-15)}$$

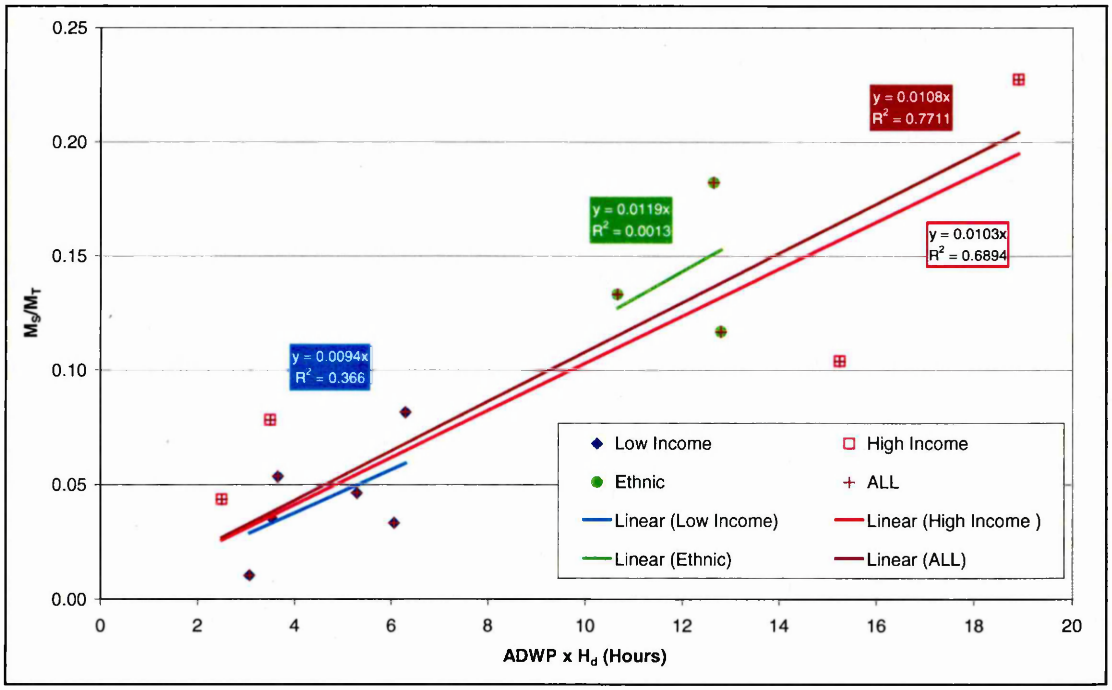


Figure 5.11 Relationship between stored faeces as a proportion of the total entering against ADWP and housing density.

The quantity of stored **tampons** was calculated for each storm and the correlation of the data was poor following regression analysis (Figure 5.13). A linear relationship was observed for the high income and ethnic catchment together, with a reasonable correlation (R^2 = 0.67).

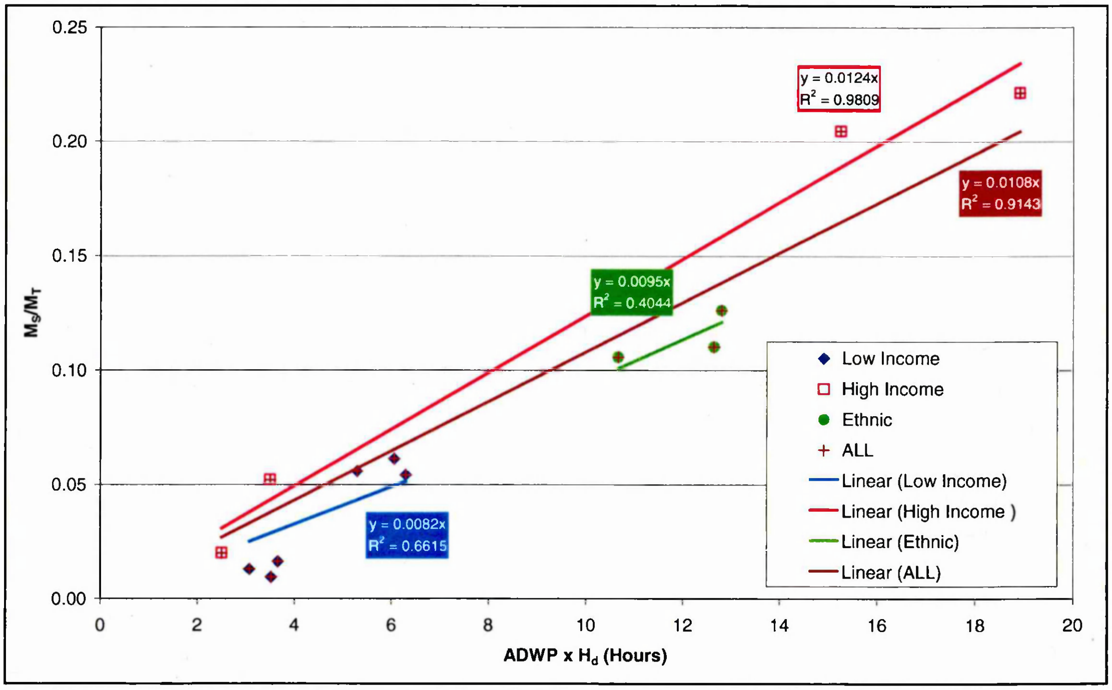


Figure 5.12 Relationship between stored toilet tissue as a proportion of the total entering against ADWP and housing density.

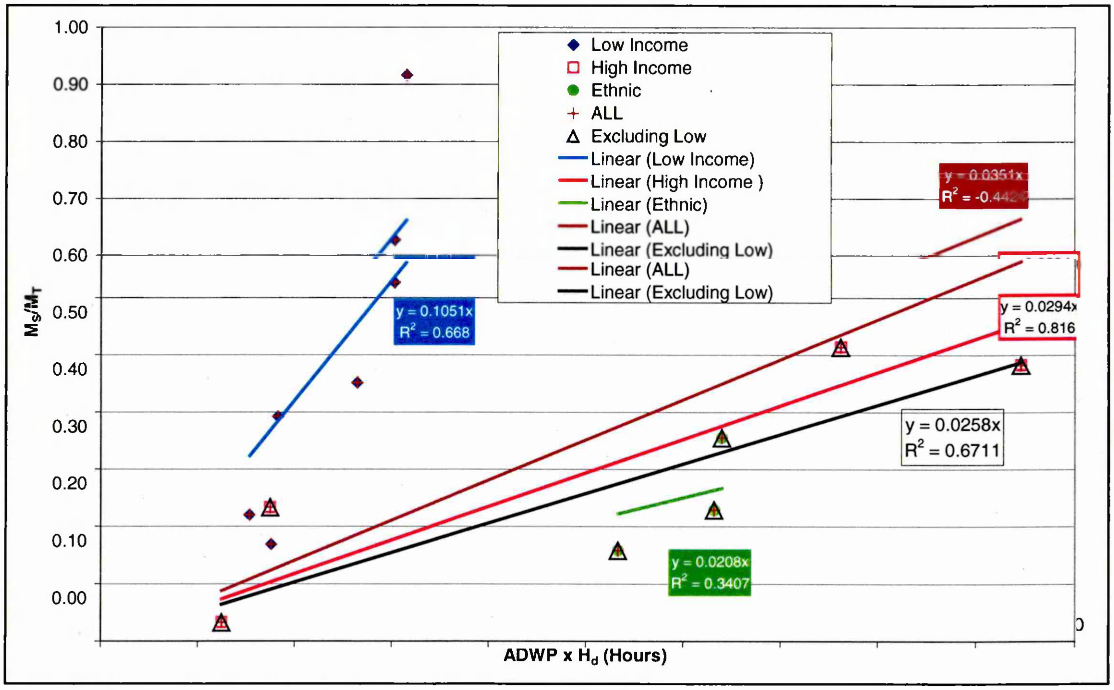


Figure 5.13 Relationship between stored tampons as a proportion of the total entering against ADWP and housing density.

The data at the low income catchment was affected by a large number of tampons being sampled in one sack over a 5 minute period. Only one in four sacks were characterised at this catchment, and due to the low number of tampons sampled in dry weather and high number from one sack in the storm, the resulting M_S/M_T was high in comparison to the other catchments. A good correlation of the data was expected due to the similar rise and settle velocity profiles of tampons sampled at each catchment (Figure 4.45), which was observed in the ethnic and high income catchment but not the low income catchment. Equation 5-16 predicts the quantity of tampons stored utilising the relationship observed at the high income and ethnic catchment.

$$M_{S:Tampon} = 0.0258 \times M_{T:Tampon} \times H_d \times ADWP \qquad \textbf{(5-16)}$$

The quantity of stored ***panty liners*** was calculated for each storm. Negative values were calculated for storm GS3 at the low income catchment and for storm DS1 at the high income catchment. This occurred because the number of panty liners sampled in dry weather was greater than the quantity sampled during the solids' flush during the storm. These two storms had an ADWP of less that 24 hours. This highlights the variability in the quantity and timing of when SANPRO items enter the system (the number of SANPRO items being significantly less than the quantity of faeces and toilet tissue entering). This problem is likely to become less important as the ADWP increases and more solids can enter and be stranded. Also the method of characterisation as discussed for tampons may have influenced the result for GS3, where panty liners may have been sampled but not characterised. These points were not plotted, resulting in only 9 data points on the graph (Figure 5.16). The correlation of the data following regression analysis indicated a poor fit for the data ($R^2 = 0.44$).

Rise and settle velocity tests had indicated different profiles for the panty liners sampled at each catchment. These tests identified that more panty liners from the ethnic catchment settled than from the low and high income catchment. The panty liners from the ethnic catchment had a mean settling velocity of -0.002 m/s compared to -0.040 and -0.039 m/s for the low and high income catchments respectively. This suggested that panty liners at the ethnic catchment were more likely to become deposited than at the other catchments. The results suggest that more panty liners were deposited in the ethnic catchment as a proportion of the number entering than the other catchments. The rise and settle velocity tests indicate that more panty liners sink in the ethnic catchment as well. Hence the quantity of panty liners deposited was likely to be related to the specific type of product used, represented by $U_{\%SINK}$, that was the proportion of the panty liners that settled in each catchment (Equation 5-17). In the ethnic catchment 79 % of panty liners settled, whereas in the low and high income catchments 46 % and 49 % of panty liners sunk. This was used to improve the correlation of the panty liner substantially from $R^2 = 0.44$ to $R^2 = 0.82$ (Figure 5.15) and a resultant predictive equation was produced (Equation 5-18).

$$M_S \propto U_{\%SINK} \tag{5-17}$$

$$M_{S:\text{Panty Liner}} = 0.0591 \times M_{T:\text{Panty Liner}} \times ADWP \times H_d \times U_{\%SINK} \tag{5-18}$$

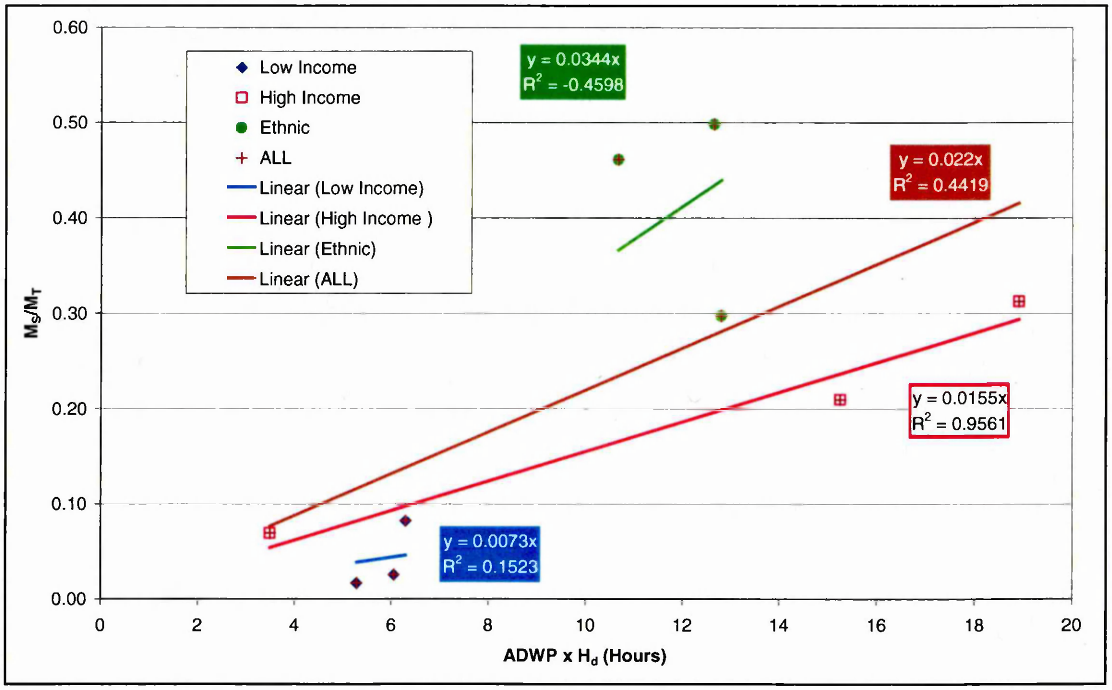


Figure 5.14 Relationship between stored panty liners as a proportion of the total entering against ADWP and housing density.

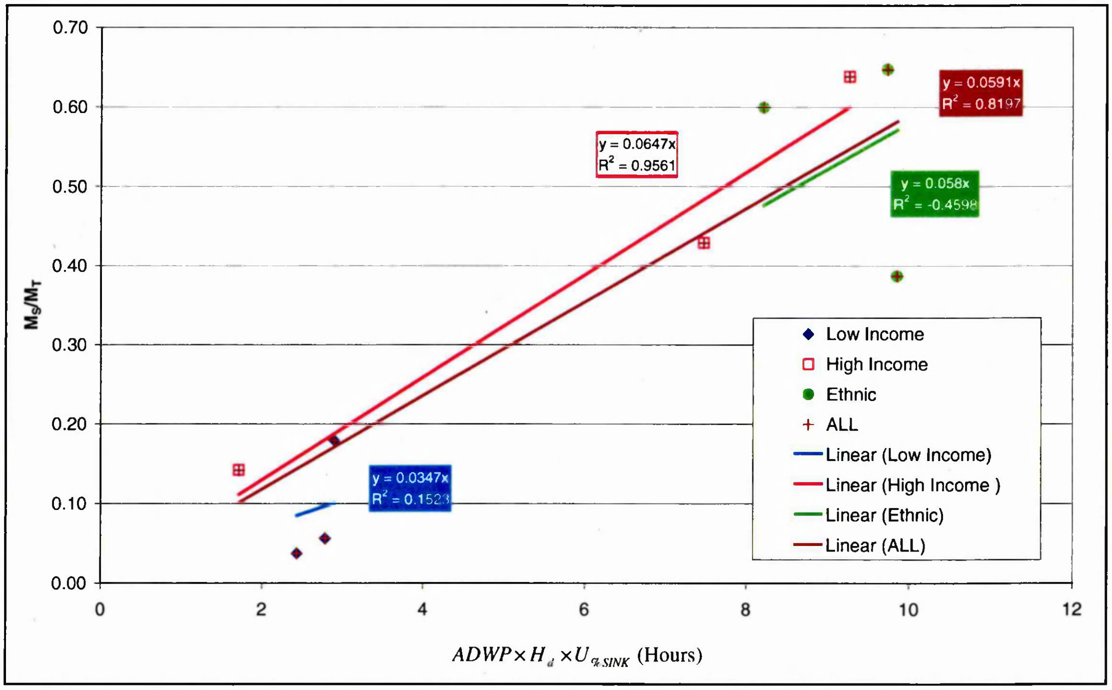


Figure 5.15 Relationship between stored panty liners as a proportion of the total entering against ADWP, housing density and the percentage of the pollutant sinking from each catchment following rise and settle velocity tests.

The quantity of stored ***wipes*** was calculated for each storm. Negative quantities of solids were calculated for the short ADWP storm, GS3 at the low income catchment. These values were plotted and regression analysis indicated a poor correlation of the data ($R^2 = 0.46$) mainly due to two measured results, those of storm DS6 at the high income catchment and storm OS2 at the ethnic catchment. Regression analysis without the outlying data produced a good correlation ($R^2 = 0.79$). A predictive equation was developed from the regression analysis to determine the quantity of wipes stored (Equation 5-19).

$$M_{S:\mathrm{Wipes}} = 0.018 \times M_{T:\mathrm{Wipes}} \times ADWP \times H_d \qquad \textbf{(5-19)}$$

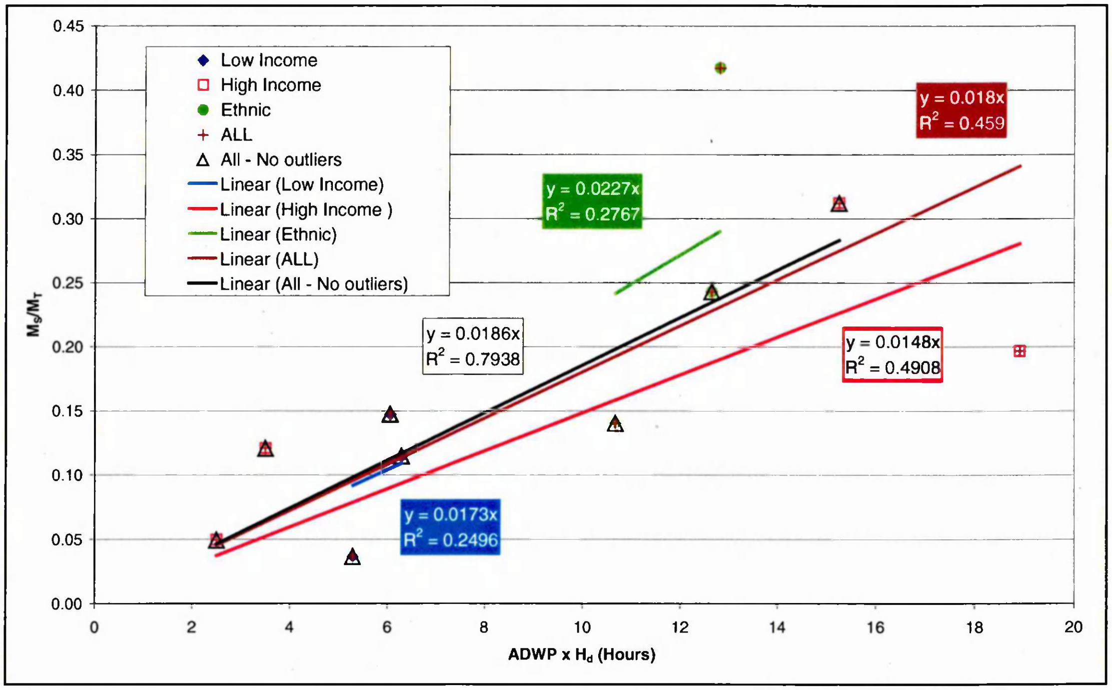


Figure 5.16 Relationship between stored wipes as a proportion of the total entering against ADWP and housing density.

5.5 Development of a standard solid value and SEED factor to predict the quantity entering and stored in a system

Field results following sampling clearly indicate that different population types pass different quantities of aesthetic pollutants into the sewer. The factors that have been defined in this study that affect the quantity of solids entering are socio-economic, ethnic and demographic. To enable the development of a model to predict the temporal distribution of different solids moving through a sewer system, the quantity of solids that enter the system must be determined. In addition, the storage equations for each pollutant type defined in section 5.4.2 also require the quantity of solids produced by a person in one day. This value was calculated by considering a standard production value (SPV) and factor that accounts for socio-economic, ethnic and demographic differences in the population (SEED). The product of these two components produces a value that applies to a particular population type (Equation 5-20).

$$\begin{array}{c} \text{Quantity of solids} \\ \text{produced per person} \\ \text{per day, M} \end{array} = \begin{array}{c} \text{Standard production} \\ \text{Value per person} \\ \text{per day} \end{array} \times \text{SEED factor} \qquad \textbf{(5-20)}$$

Field monitoring results have identified six main aesthetic pollutants that regularly enter the sewer system and are considered to be visibly offensive when discharged from CSOs:

- Faeces
- Toilet Tissue
- Panty Liners
- Sanitary Towels

- Tampons
- Wipes

5.5.1 Calculation of SPV and SEED Factors

5.5.1.1 Faeces and Toilet Tissue

An average SPV was calculated from the estimated total solids entering the system per person. These values were used to determine the M_T component for each solid type in each catchment as defined in section 5.4.2. The quantity of faeces produced per person is highly variable depending upon diet, lifestyle and age. This not only affects the quantity, but the strength of the faecal stool to resist degradation. In SC4 at the low income catchment, a very high value of faeces (56 g/person/day) was measured. This sub-catchment contained a nursing home and a large number of housing for the elderly. This suggests that the majority of their faeces enter the system at home and that either a large quantity is produced per person or the faeces are very strong and do not readily break down. In diets, that are high in fibre, higher faecal stool weights have been observed, however the faeces are softer and more likely to degrade than faeces produced from low fibre diets (Burkitt et al., 1972 and Stasse-Wolthius et al., 1979). Table 5.3 shows the estimated quantities of faeces and toilet tissue produced per person per day. The ethnic and high income catchments have very similar masses for faeces and toilet tissue.

The average SPV enables a SEED value to be calculated for each catchment where sampling was undertaken (Equation 5-21). SEED values for the catchments sampled are shown in Table 5.4. The table is split up into two age categories and the population types. The age categories are used to describe the age profile of the population. An ‘average’ age distribution is used to describe the age profiles of the high income and ethnic populations and an ‘elderly’ description of the population in the low income catchment. Age distribution profiles for these catchments have been presented in Chapter 3. An attempt was made to estimate SEED values for population types with different age profiles that were not sampled. The values were estimated assuming an elderly population will produce faeces that were stronger and use more toilet tissue. It was considered that the high income and ethnic populations produced faeces that were more degradable as well as using less toilet tissue. These values are only an estimate but may be of use if the SEED values were required for different population types. These values can only be confirmed if further sampling is undertaken.

$$SEED\ FACTOR = \frac{Catchment\ SPV}{Average\ SPV} \qquad \textbf{(5-21)}$$

Table 5.3 Quantity of faeces and toilet tissue measured at each catchment

	Mass measured per person per day (g/p/d)	
Population Type	Faeces	Toilet Tissue
Low Income SC1	27.1	19.0
Low Income SC2	40.9	31.8
Low Income SC3	31.8	23.8
Low Income SC4	56.6	44.4
Low Income Total	38.9	29.5
High Income	24.2	11.9
Ethnic	24.7	14.6
Average SPV	34.2	24.2

Table 5.4 SEED factors for each catchment, with estimated values for unmeasured age categories shown in highlighted boxes

	Faeces		Toilet Tissue	
	Population Age Catergory			
Catchment	Average	Elderly	Average	Elderly
Low Income SC1	0.80	0.79	0.80	0.78
Low Income SC2	0.80	1.19	0.80	1.31
Low Income SC3	0.80	0.93	0.80	0.98
Low Income SC4*	0.80	1.65	0.80	1.83
Low Income Total	0.80	1.14	0.80	1.22
High Income	0.71	1.00	0.49	1.00
Ethnic	0.72	1.00	0.60	1.00

* Elderly value higher due to large number of elderly in the sub-catchment

5.5.1.2 Wipes

The SPV and SEED value for wipes was calculated using the same method as for faeces and toilet tissue. An estimate of the possible SEED factors for catchments of the same population type but different age category are given. These are only estimates and further work is required to determine these values.

Table 5.5 SPV and SEED factors for wipes for each catchment, with estimated values for unmeasured age categories shown in highlighted boxes

		SEED Factor for Population Age Catergory	
Population type	SPV (g/person/day)	Average	Elderly
Low Income	2.94	1.00	1.86
High Income	1.16	0.74	1.20
Ethnic	0.63	0.40	0.80
Average	1.57		

5.5.1.3 SANPRO items

SEED and SPV values for SANPRO items have been produced for each catchment, as calculated for wipes. These values were compared to SEED factors produced by Houldsworth (2002) following analysis of questionnaire data, as part of the EPSRC project. Values of SPV and SEED values for ***panty liners*** (Table 5.6), ***sanitary towels*** (Table 5.7) and ***tampons*** (Table 5.8) were calculated. Panty liner SEED values were reasonably similar with the field measurement being ± 30 % of the questionnaire data. The SEED values for sanitary towels did not compare very well for the high income and ethnic catchments, although the low income value was more accurate. The SEED values for tampons compared very well for every catchment with the field measured values being within ± 5 % of the questionnaire values. A comparison of the quantities produced per person in each catchment for the field measurement and questionnaire data has been undertaken in Chapter 4. Overall the SEED values are reasonably similar considering the very different methods in determining this information.

Further work undertaken by Houldsworth (2002) used the questionnaire data to examine the influence of age on the number of SANPRO products flushed by the female population only, and for each population type. These values are shown in Table 5.9,Table 5.10 and Table 5.11, and are used with the SPV measured from the catchment to determine the quantity of solids that would enter the system in a day, if demographic information were available. The method to determine the quantity or mass of solids entering for each catchment in one day is shown in Equation 5-22.

$$M_{SOLID\ ENTERING\ per\ DAY} = \Sigma\,(SPV \times P_{age\ category} \times SEED_{age\ category}) \qquad \textbf{(5-22)}$$

Table 5.6 Panty liners SPV values for three catchments sampled and a comparison of the SEED values from field measurement and questionnaire data

Population Type	SPV (g/person/day)	SPV (No./person/day)	Field measurement SEED Factor	Questionnaire SEED Factor
Low Income	0.250	0.0186	1.65	1.24
High Income	0.146	0.0094	0.97	1.21
Ethnic	0.059	0.0038	0.39	0.55
Average	0.152	0.0106		

Table 5.7 Sanitary towels SPV values for three catchments sampled and a comparison of the SEED values from field measurement and questionnaire data

Population Type	SPV (g/person/day)	SPV (No./person/day)	Field measurement SEED Factor	Questionnaire SEED Factor
Low Income	0.628	0.0122	2.16	1.82
High Income	0.130	0.0023	0.45	0.32
Ethnic	0.113	0.0016	0.39	0.86
Average	0.290	0.0053		

Table 5.8 Tampons SPV values for three catchments sampled and a comparison of the SEED values from field measurement and questionnaire data

Population Type	SPV (g/person/day)	SPV (No./person/day)	Field measurement SEED Factor	Questionnaire SEED Factor
Low Income	0.406	0.0141	0.60	0.60
High Income	1.179	0.0394	1.73	1.69
Ethnic	0.461	0.0137	0.68	0.71
Average	0.682	0.0224		

Table 5.9 Panty liner SEED values for each population type for different age categories of females only, adapted from Houldsworth (2002)

	Age Category				
Population Type	18-29	30-44	45-59	60-74	75+
Low income	0.00	1.75	1.94	0.94	0.00
High Income	0.84	1.26	0.65	1.16	0.00
Ethnic	1.45	0.06	0.53	0.81	0.00

Table 5.10 Sanitary towel SEED values for each population type for different age categories of females only, adapted from Houldsworth (2002)

	Age Category				
Population Type	18-29	30-44	45-59	60-74	75+
Low income	0.93	3.11	1.96	0.00	0.00
High Income	0.00	0.35	0.44	0.00	0.00
Ethnic	1.50	0.17	1.08	0.00	0.00

Table 5.11 Tampon SEED values for each population type for different age categories of females only, adapted from Houldsworth (2002)

	Age Category				
Population Type	18-29	30-44	45-59	60-74	75+
Low income	1.43	0.50	0.52	0.00	0.00
High Income	1.88	1.65	1.27	0.00	0.00
Ethnic	0.43	0.55	1.01	0.00	0.00

5.6 General observations for predicting quantity of solids stored

The method used to predict the quantity of solids stored for the catchments has produced good results for the majority of the pollutants that are deposited. The quantity of solids stored are expressed as a proportion of the solids entering, therefore accounting for the socio-economic and ethnic factors that influence solid production in each catchment. An investigation into catchment characteristics that may affect the quantity of solids stored has been undertaken, highlighting that housing density was the most important factor. The inclusion of the bed slope did not improve the relationship of the solids against ADWP. However this may be related to all the catchments being relatively steep, all greater than 1:47.

Excellent correlation of the data was achieved for total solids, faeces, toilet tissue, and panty liners (Table 5.12). The correlation value achieved for wipes were reasonable as two outlying data points significantly reduced the value. The variability of wipes as well as SANPRO products entering the system are always likely to affect the consistency of data and produce outlying data. The tampons plot identified two trends, one for the low income catchment and one for the high income and ethnic catchments. All trendlines fitted following regression analysis indicated the same principle, that the quantity of solids stored was directly proportional to ADWP. The regression analysis produced equations that would predict the quantity of individual solids stored in the sewer system. These equations take into account catchment characteristics that are easily obtainable. Unfortunately the largest ADWP sampled storm was for 113 hours, and longer ADWP storms would have been desirable to determine if the linear relationship continued or if the rate at which solids are stored reduces for longer ADWPs. It was not possible to use all the sampled data where 9 storms from the 22 sampled could not be used. The number of storms used to determine predictive equations for panty liners and wipes reduced to 9 and 10 respectively following negative values being recorded. This highlights the variability of solids entering from day to day that could affect the quantity of solids stored in short ADWP storms. This was shown in the maximum / minimum plots of sampled data against the mean in Chapter 4 for each catchment.

Predicting the quantity of stored solids is defined by Equation 5-23 that uses the SPV and SEED values stated in section 5.5.1 depending upon the information available and co-efficient *k* in Table 5.12.

Table 5.12 Summary of the correlation co-efficient and equation co-efficient for the different stored solids

Pollutant	Total Solids	Faeces	Toilet Tissue	Panty Liners*	Tampons	Wipes
Correlation Coefficient R^2	0.923	0.771	0.914	0.820	0.671	0.459
Equation co-effcient, k	0.0118	0.0108	0.0108	0.0591	0.0258	0.0180

* Panty liners include a factor for the proportion sinking, $U_{\%SINK}$, where Low = 0.46, High = 0.49 & Ethnic = 0.79

$$M_{S:Pollutant} = k \times ADWP \times H_d \times P \times SEED \times SPV \times [U_{\%SINK}]_{Panty\ Liner\ Only} \quad \textbf{(5-23)}$$

6 Chapter 6 – Model to Predict the Temporal Distribution of Solids Flushed during a Storm

This chapter describes the methodology used to produce a model to predict the temporal distribution of solids flushed during a storm. The first phase of the model development was to identify an effective method to predict the sewer flow volume and discharge from test catchments. The second phase utilised the predicted flows to develop a solids transportation method. The model is calibrated against the low income catchment using empirical solid quantities. Refinement of the model is presented followed by the validation of the model against data measured at the high income and ethnic catchments. Further developmental work on the model is presented in Chapter 7.

6.1 Aims and Objectives

The aim of the model was to predict the temporal distribution of aesthetic pollutants during a storm from combined sewerage systems. The objectives were to:

- Develop a standalone model not reliant upon other specialist computation packages.
- Predict the flows leaving a catchment under storm conditions.
- Develop a solids transportation technique to predict the rate of solids leaving the system.
- Obtain a good comparison between measured and predicted values of discharge and solids.

6.2 Conceptual Ideas

6.2.1 HydroWorks Total Suspended Solids Model

The first investigation in the construction of a model to predict the temporal distribution of aesthetic pollutants examined the possible use of a tool that already existed. Jeffries (1992) developed a relationship between total suspended solids (TSS) and gross solids. If it could be proven that a hydraulic computer simulation model which includes TSS modelling could be related to aesthetic pollutants, then the need for a new model would have been unnecessary.

HydroWorks models of the catchments sampled had been constructed and hydraulically fully verified. The low income catchment was selected to simulate TSS using this function in the software and then compared with sampling data. Default values within HydroWorks were used and an initial dry weather period was run prior to the storm. The dry weather profile of the TSS was similar to the aesthetic pollutants sampled in dry weather.

The storm TSS profile was compared with the total solids sampled for storm GS2 at the low income catchment. The TSS profiles did not compare well with the measured solids (Figure 6-1 and Figure 6-2). Although a first foul flush was observed for the TSS at both sub-catchments, the magnitude was not as significant as the measured solids. The shape of the storm profiles was different for each sub-catchment with a significant late second peak occurring at SC4. The length of the flush of TSS was similar for the sub-catchments, however this was approximately twice the duration of the measured solids flush.

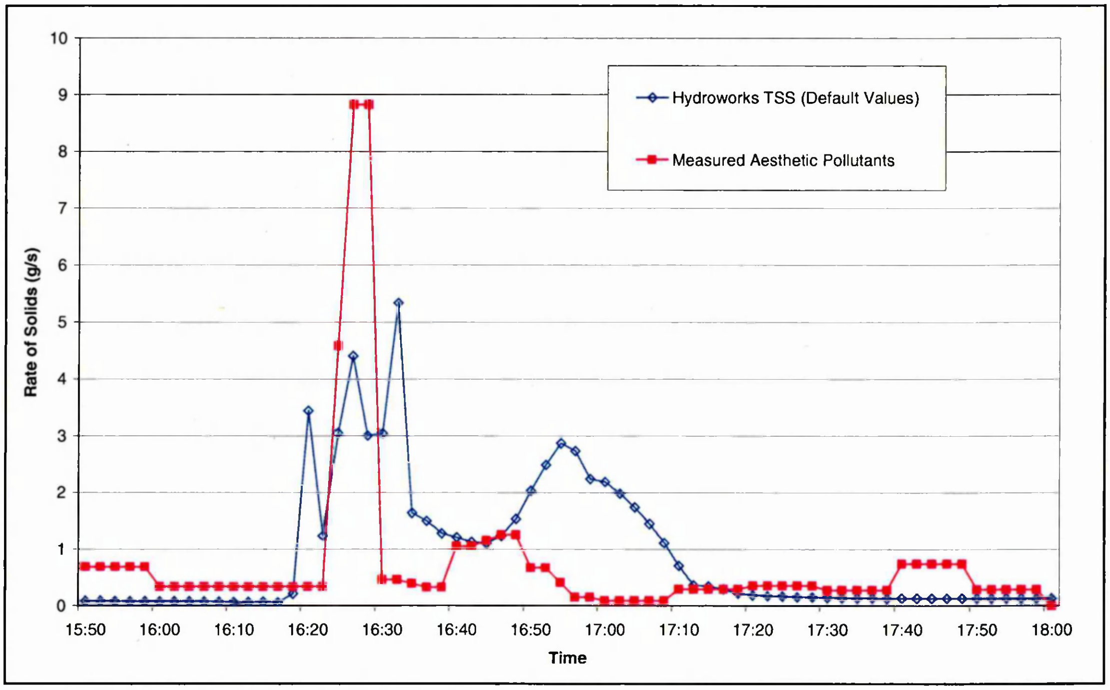


Figure 6-1 Comparison between total sampled aesthetic pollutants and HydroWorks simulated TSS for storm GS2 at SC3 at the low income catchment

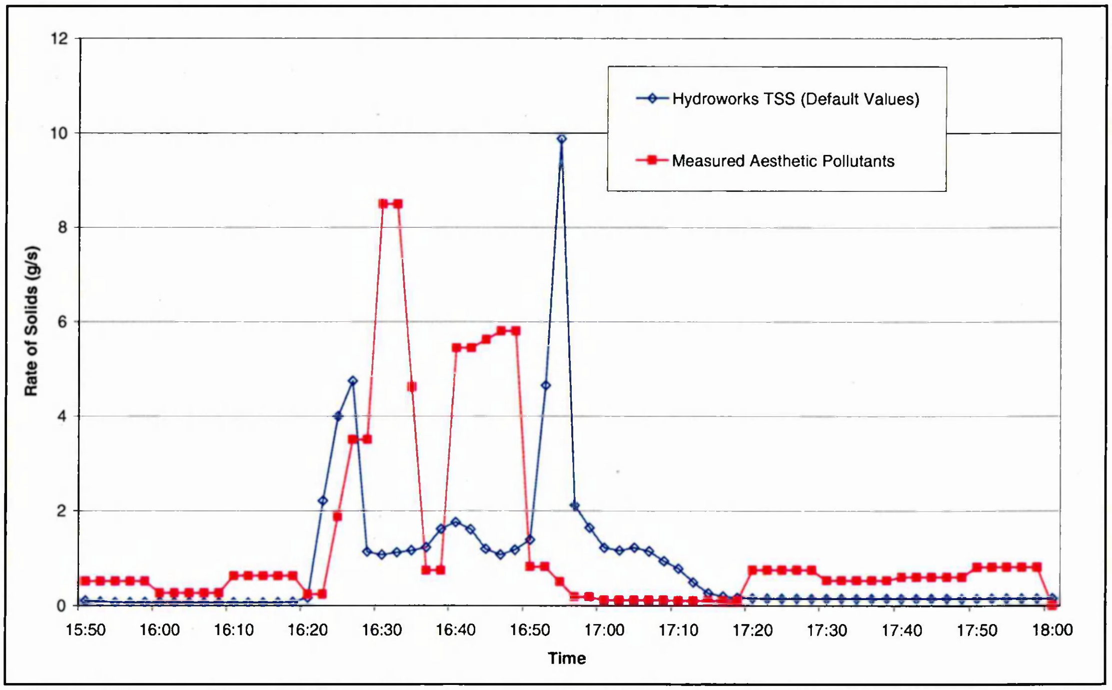


Figure 6-2 Comparison between total sampled aesthetic pollutants and HydroWorks simulated TSS for storm GS2 at SC4 at the low income catchment

The length of solids flush and the variability in the timing and magnitude of the peaks indicated that the TSS simulation could not fully replicate the aesthetic pollutant movement. Therefore a new model was required in an attempt to improve the temporal distribution of solids leaving the sewer system.

6.3 Development of a flow replication model

The TSS model within HydroWorks did not fully replicate the solids sampling data under storm conditions. Fieldwork undertaken during this project has identified an increase in the rate of solids leaving a catchment when the storm flows increase. Previous research by Balmforth and Meeds (1997) identified that the solids in the dry weather volume could be presented to a screen under storm conditions. A model was developed to predict the quantity of sanitary products presented to a screen in a CSO. This has been discussed in section 2.3. The principle of the model was to assume that the solids flushed were present in the DWF volume just prior to the storm. The quantity of solids present was estimated by considering product usage by females in the catchment. These entered the CSO before the time to peak, and the volume of water that was spilt during this period contained a proportion of the solids in the DWF. The model showed good results in predicting the quantity of SANPRO items spilt in comparison with measured field results. HydroWorks was used to determine the DWF volume and the hydrograph at the CSO. However, the model did not predict the temporal distribution of solids or account for the different quantity or type of solids in the system at different times of day. It also required HydroWorks to estimate the volume of water in the system and the flow entering the CSO. The model developed in this chapter attempts to address these issues.

6.3.1 Runoff model

The replication of a storm event requires the inflow from runoff entering the sewer system to be determined. This process considers that overland flow is represented by surface water runoff generated by rainfall falling on impermeable area (Figure 6-3). Initial losses are accounted for using a depression storage calculation (Equation 6-1) that uses the average catchment gradient estimated from the average sewer gradient in the catchment (Butler and Davies, 2000). This accounts for rainfall that does not enter the system at the start of the event. The remaining rainfall is combined with the impermeable area of the actual sewer system to calculate the inflow hydrograph to the reservoir during a storm (Equation 6-2).

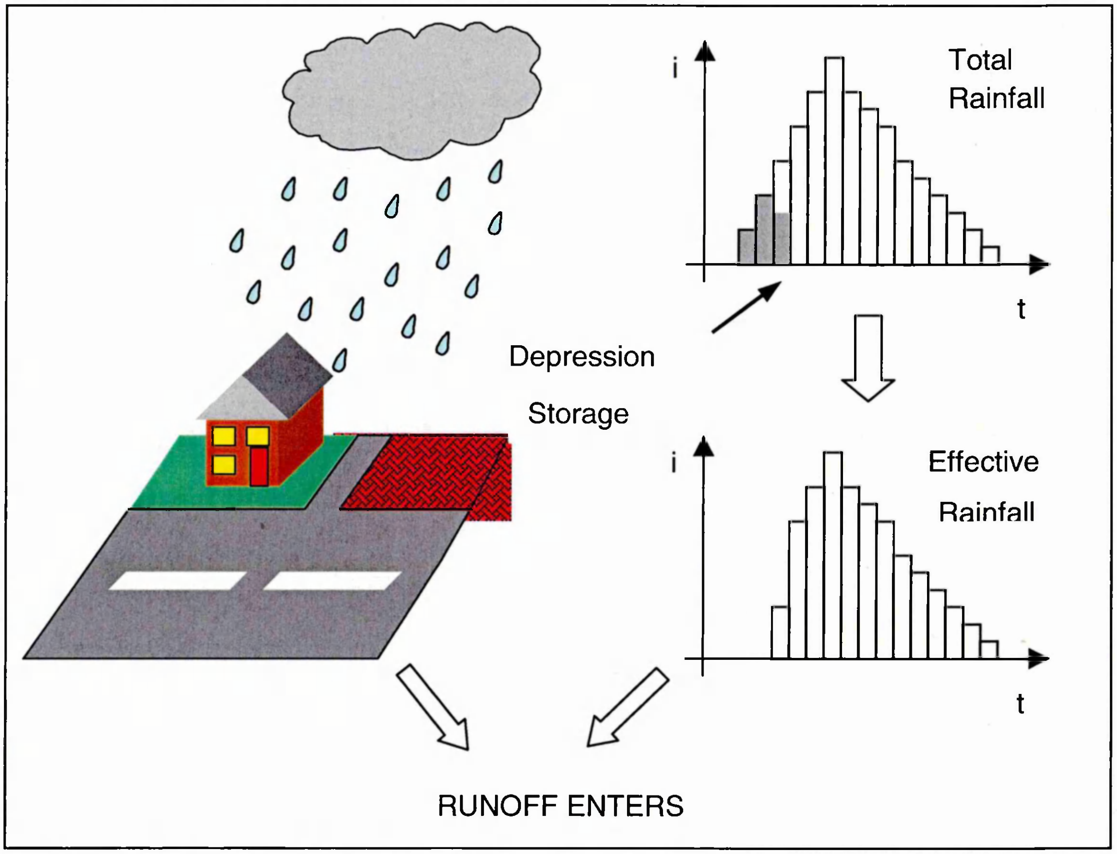


Figure 6-3 Over land flow process to generate inflows into reservoir model.

$$d_s = \frac{k_1}{\sqrt{s}} \qquad \textbf{(6-1)}$$

Where: d_s = depression storage (mm)

k_1 = surface type coefficient (impervious surfaces 0.07 and permeable surfaces 0.28) (mm)

s = ground slope (-)

$$Qin_{runoff\Delta T} = Area_{IMP} \times R_{Depth\Delta T} \qquad \textbf{(6-2)}$$

Where: $Qin_{runoff\ \Delta T}$ = Flow generated from runoff at each time step

$Area_{IMP}$ = Impermeable Area

$R_{DEPTH\ \Delta T}$ = Rainfall depth at each time step after depression storage

The impermeable area in each catchment is measured from background plans using AutoCAD and used not only as part of this model development but used to verify the HydroWorks models. Therefore there is confidence in the accuracy of the impermeable area. The simplified runoff model generates the inflows without any delay (after depression storage) between the rainfall falling and assumes 100% runoff from impermeable area entering the system. A more complex percentage runoff model could have been developed, however due to the small size of the catchments that the model is used with, the simplified model is more than adequate.

6.3.2 Routing Methods to estimate flows

During storm sampling, a first foul flush of solids had been observed to occur with an increase in the measured flow (see section 4.3). In an attempt to replicate these occurrences by linking the movement of solids to the flow, it was necessary to develop a method to predict the flows during a storm. In developing a method to predict the flows it was important to accurately calculate the volume within the sewer system. The volume within the system controls the rate in which solids will leave the system.

Although a number of hydraulic computational packages exist (eg: HydroWorks and Mouse), they are not regularly used to predict the flows in upstream catchments due to the time required to build and verify these areas. Therefore the intention was to develop a model that was standalone and not reliant upon such software packages and also to better replicate the processes in private drains and small sewers.

A number of routing methods were evaluated to determine an easy, accurate and efficient way to predict flows within a system and have the potential to model the movement of the aesthetic pollutants within the sewer system. Three methods were considered to predict flows:

- Routing method using the Muskingham theory (Wilson 1990)
- Routing method using a linear reservoir (Viessman et al. 1977)
- Routing method using a non-linear reservoir. (Shaw 1994)

The consideration to use routing followed research that has used reservoir models to predict flows in urban drainage systems. The reservoir routing approach simplifies the system into one or more reservoirs that may predict flows leaving a network. The modelling packages SIMPOL (FWR 1998) and KOSIM (Schütze 2002) both use reservoir models to predict flows in various parts of the network including the sewers. SIMPOL is part of the UPM procedure (FWR 1998) and uses EXCEL to determine the flows through a sewer system before arriving at a CSO. KOSIM uses a cascade of reservoirs to determine the flow through a series of sub-catchments (Schütze 2002). Vaes and Berlamont (1998) have also used reservoir models to predict the flows in the sewer system to determine inputs into CSOs to save on computational time, whilst retaining a good degree of accuracy.

The three routing approaches are now considered in more detail. The **Muskingham method** was used as described by Wilson (1990). An initial sub-catchment was selected for use at the Low Income catchment, SC2. The storage equation of the Muskingham method required two constants to be determined (Equation 6-3).

$$S = K\left[xI + (1-x)O\right] \qquad \textbf{(6-3)}$$

Where: I = Inflow (m^3/s)

O = Outflow (m^3/s)

x = dimensionless constant for a certain network

K = storage constant with dimensions of time that must be found from observed hydrographs of inflow and outflow (s)

K and x were determined using data from a measured storm GS2 at the sub-catchment with the inflow calculated based upon the runoff model described in section 6.3.1. K and x were determined to be 2259 s^{-1} and 0.2 respectively from the storm (Figure 6-4). These values were then used to determine the outflow for the storm event GS2 at SC2. The results from this method are discussed in section 6.3.3.

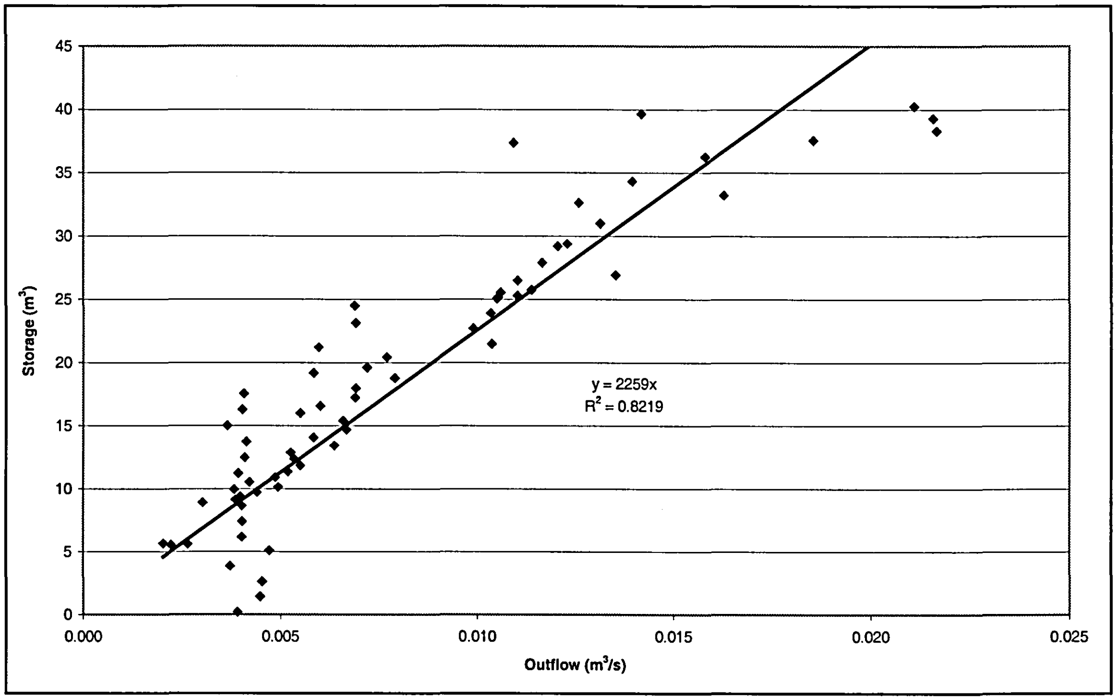


Figure 6-4 Linear relationship between storage and outflow for the measured storm GS2 when x = 0.2 for the Muskingham Routing Method.

A **linear reservoir** was next trialled to replicate the flows in a sub-catchment using the methodology described by Viessman et al. (1977). The assumption is made that the discharge from the catchment is directly proportional to the storage within the network and is a special case of the Muskingham routing method where x = 0. Therefore Equation 6-3 becomes Equation 6-4.

$$S = KQ \qquad \textbf{(6-4)}$$

where: S = Storage (m^3)

Q = discharge (m^3/s

K = Storage constant for reservoir (s)

The storage constant was obtained by plotting storage against outflow for the measured storm GS2 as shown in (Figure 6-5). To determine the storage the inflow entering the reservoir was generated from the runoff model described in section 6.3.1. The slope of the line fitted to the data was determined to be equal to 1541 seconds.

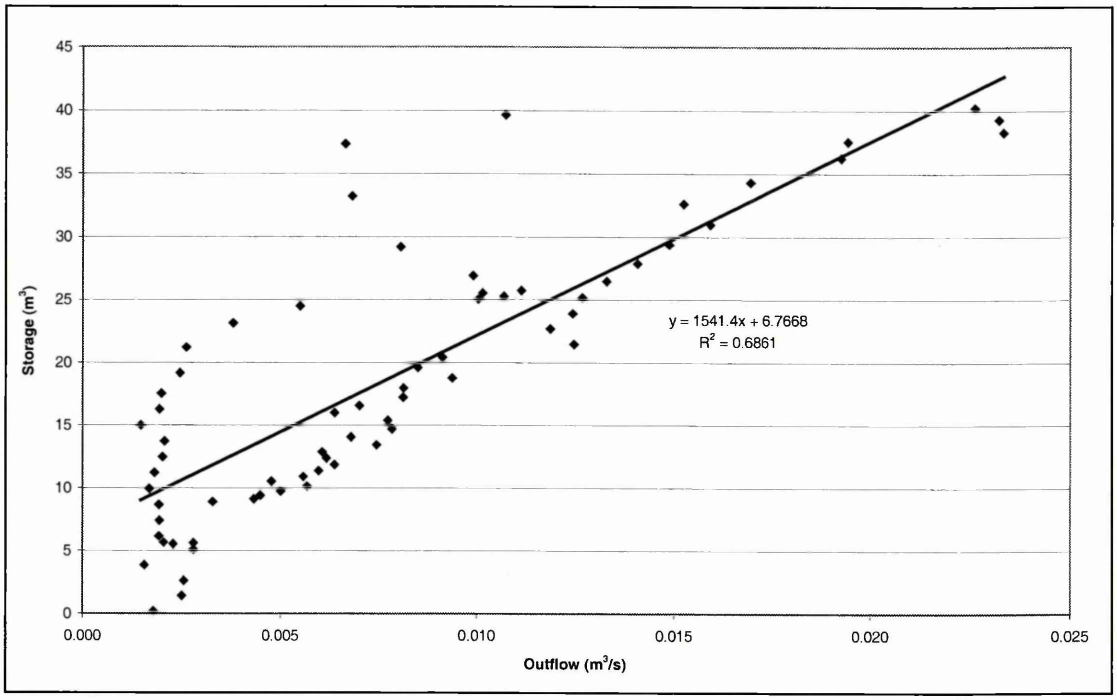


Figure 6-5 Linear relationship between storage and outflow for the measured storm GS2 when x = 0 for the special case of the Muskingham Routing Method for a linear reservoir

A single linear reservoir was considered to represent the whole catchment upstream of the flow monitor in sub-catchment SC2 and the methodology described by Viessman et al. (1977) was used. The discharge from the reservoir was calculated using finite time steps at a suitable increment, typically 2 minutes. The results from this method are discussed in section 6.3.3.

The next method considered was to use a **non-linear reservoir** to represent the flow in a catchment. In this case to represent the catchment the reservoir was considered to be a single rectangular open channel. Viessman et al. (1977) showed that non-linear reservoirs are commonly governed by a flow control at the downstream end. To determine an equation to predict the flow from the rectangular channel, the flows within the channel were initially considered. If the depth of water in a wide rectangular channel was considered to be critical (Equation 6-5) then:

$$d_c = \left(\frac{q_c^2}{g} \right)^{1/3} \tag{6-5}$$

If the channel had a fixed width b, the flow at critical depth can be determined (Equation 6-6).

$$d_c = \left(\frac{Q_c^2}{gb^2} \right)^{1/3} = \left(\frac{Q_c}{g^{1/2} b} \right)^{2/3} \tag{6.6}$$

Therefore the flow at critical depth can be determined (Equation 6-7).

$$Q_c = d_c^{3/2} g^{1/2} b \tag{6-7}$$

And the relationship between flow and depth exists (Equation 6-8).

$$Q_c \propto d_c^{3/2} \tag{6-8}$$

Where: dc = Critical depth

Qc = Critical flow

g = gravitational constant

b = breadth

It was then considered that the equations to predict the flow have a similar relationship to that of flow over a weir, a common control from non-linear reservoirs (Viessman et al. (1977)). Therefore a notional broad crested weir was positioned at the downstream end of the channel with a similar relationship (Equation 6-9).

$$Q \propto h^{3/2} \tag{6-9}$$

Where: Q = Discharge over the weir (m^3/s)

H = Depth of water over weir (m)

The full equation for flow over the weir (Equation 6-10) controls the flow leaving the reservoir and enables the flow from the reservoir to be determined at any depth. If Equation 6-10 is combined with Equation 6-11 the storage can also be calculated (Equation 6-12) as shown in Viessman et al. (1977).

$$Q = CBH^{3/2} \tag{6-10}$$

$$S = AH \tag{6-11}$$

Then:

$$S = KQ^{2/3} \tag{6-12}$$

where: S = Storage (m^3)

A = Plan area of reservoir (m^2)

C = weir constant

B = weir width (m)

K = Storage constant calculated for reservoir $= A\left(\frac{1}{CB}\right)^{2/3}$

Flood routing in the reservoirs was then determined using a non-linear reservoir technique discussed by Shaw (1994). The discharge hydrograph at the downstream end of the channel was obtained by routing the inflow through the system at discrete time intervals (Equation 6-13).

$$I - Q = \frac{dS}{dt} \qquad \textbf{(6-13)}$$

Where: I = Inflow (m^3/s)

Q = Outflow (m^3/s)

t = time (s)

The second stage of the non-linear reservoir method was to determine the reservoir area size and the downstream weir width. A number of parameters were considered and these were based around the conceptual idea that the reservoir was to act as a pipe conveying flow and solids, like the sewer system it is representing. The parameters considered were those that represented the sewer system and were easily obtainable, to enable the model to be easily set up. The parameter groupings considered to determine the reservoir area were:

- The product of the main sewer length and average main sewer length diameter
- The product of total sewer length and average total length diameter
- The sum of the product of each sewer length and diameter

The first grouping was initially selected due to the ease in which the parameters could be obtained and trialled with the methodology below. The width of the weir was set equal to the average diameter value. The inflow into the reservoir was determined as described in section 6.3.1. The discharge from the reservoir was calculated using finite time steps at a suitable increment, typically 2 minutes. A starting outflow in dry weather was required and this was taken from measured values initially, with the value of 'H' back calculated. This value is dependent upon the time of day. The results from this method are discussed in section 6.3.3.

6.3.3 Evaluation of routing methods and results

The three methods to determine flows in sub-catchment SC2 were compared, to evaluate the best method to replicate the flows measured within the sewer system. As part of the evaluation, the ease of use at other sub-catchments for each method was also considered. Figure 6-6 shows the results from the three methods to determine flows for storm GS2 at sub-catchment SC2 in the low income catchment. All the methods produced relatively similar results for the timing of the peak and peak values, however the non-linear reservoir method produced the highest peak of the three methods compared with the measured data.

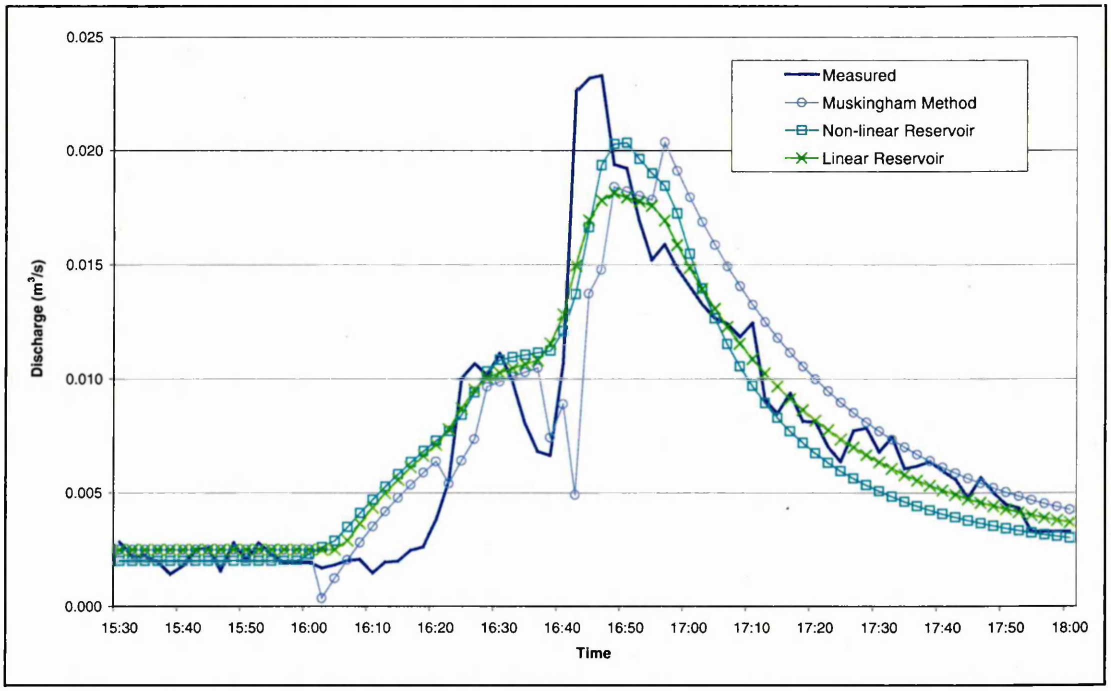


Figure 6-6 Comparison of the three methods to determine sewer flows against measured data.

The Muskingham method and linear reservoir method both require measured flow data to determine values before they can be used to predict flows. Therefore the same procedure of obtaining measured data to enable the model to predict flows would have to be undertaken at each catchment. This would be problematic if the model is used to predict flows where no flow data is available. This would restrict the use of these methods and require that the system the model is replicating to be monitored and essentially a calibration exercise undertaken. The non-linear reservoir method uses the outflow that passes over a notional weir to control the discharge. This equation and the method to size the reservoir can be applied to other catchments relatively simply and quickly, and has been tested against other sub-catchments and shown in later sections of this chapter. Although it could be argued that flow data is required to verify the model, the non-linear reservoir allows flows to be predicted based upon catchment data. The non-linear reservoir method does not require measured data to calculate the outflows therefore it can be more easily used to predict the flows.

Following the trials the non-linear reservoir model was considered the best approach due to its simplicity and its reasonable representation of the flows. A comparison between a single and multiple non-linear reservoirs is discussed in section 6.3.4 and the method to predict the movement of the solids is described in section 6.4

6.3.4 Comparison of single and non-linear reservoir models

6.3.4.1 Three Reservoir Model Theory

The single non-linear reservoir model has been identified to be the most suitable of the three methods of predicting flows leaving a small upstream network as described in section 6.3.3. A variation of the selected approach using multiple non-linear reservoirs was considered to identify if a series of smaller reservoirs would produce more accurate results. It was decided to trial 3 reservoirs in series to replicate the sewer system instead of a single reservoir. The conceptual idea was that more reservoirs would be representative of the grouping of sewers observed in the system where smaller diameter sewers are found in the upstream reaches and larger diameter sewers in the downstream section of the system.

The reservoirs were sized by dividing the main sewer length into 3 equal parts. The width of each reservoir was equal to the average sewer diameter within the section it was representing. In the 3 reservoir system, each reservoir was assigned an equal impermeable area. The same calculation procedure and equations were used for the first reservoir of the 3 reservoir model as described in section 6.3.3. The outflow from the upstream reservoir was combined with the runoff from the impermeable area assigned to the second reservoir using the method described in section 6.3.1 and the routing procedure was applied. This process was repeated at the next downstream reservoir to determine the final outflow from the system.

6.3.4.2 Comparison of routing accuracy

The routing model was initially calibrated against the sub-catchments in the low income area. This enabled the single and three reservoir models to be compared to evaluate which system produced the most accurate flow. The routing models were compared with the measured flow over a range of different storms that varied in their magnitude and duration (Figure 6-7 and Figure 6-8).

The simulation of measured storms by the reservoir system indicated that both methods replicated the flow well, within tolerances defined in the 'Code of practice for the hydraulic modelling of sewer systems' Wastewater Planning Users Group (1998). Both the timing and magnitudes of the peaks of the simulations are similar to the measured data. The discharge from the reservoir system at the downstream end indicated that the three reservoir system had a slightly higher discharge rate than the single reservoir system so producing higher peak flows. Both systems showed a good response to the rainfall compared with measured. Both systems indicated that they could replicate flows in the system accurately, therefore both were used in conjunction with the solids' transportation techniques (see section 6.4).

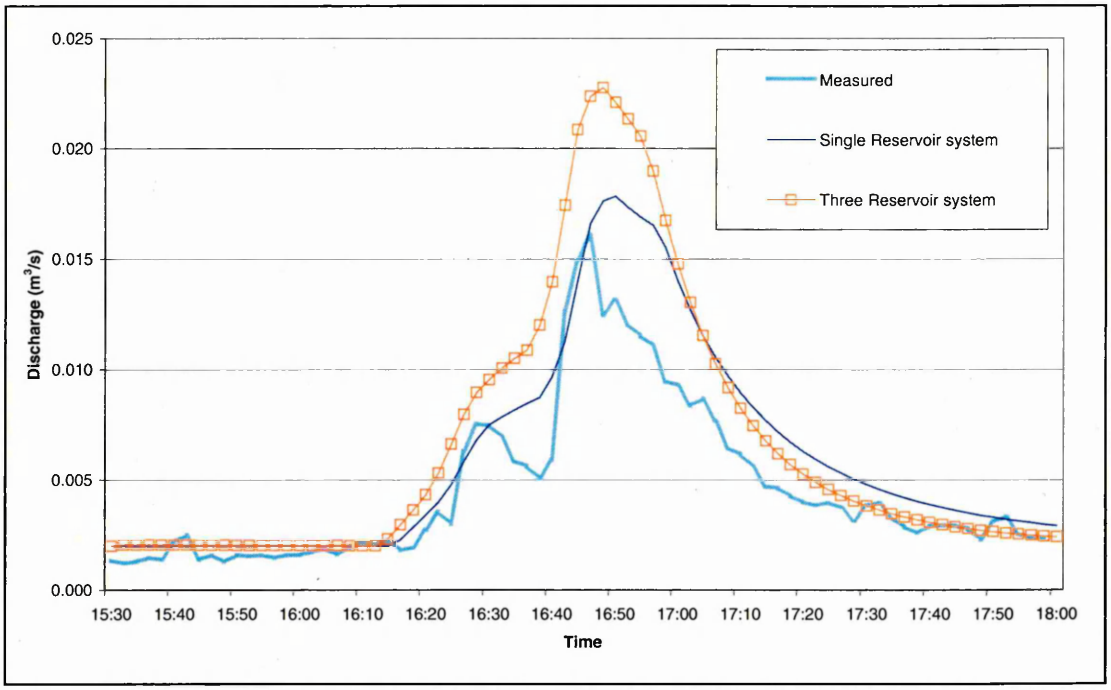


Figure 6-7 Comparison between measured, single reservoir and three reservoir systems for storm GS2 at SC1 in the low income catchment.

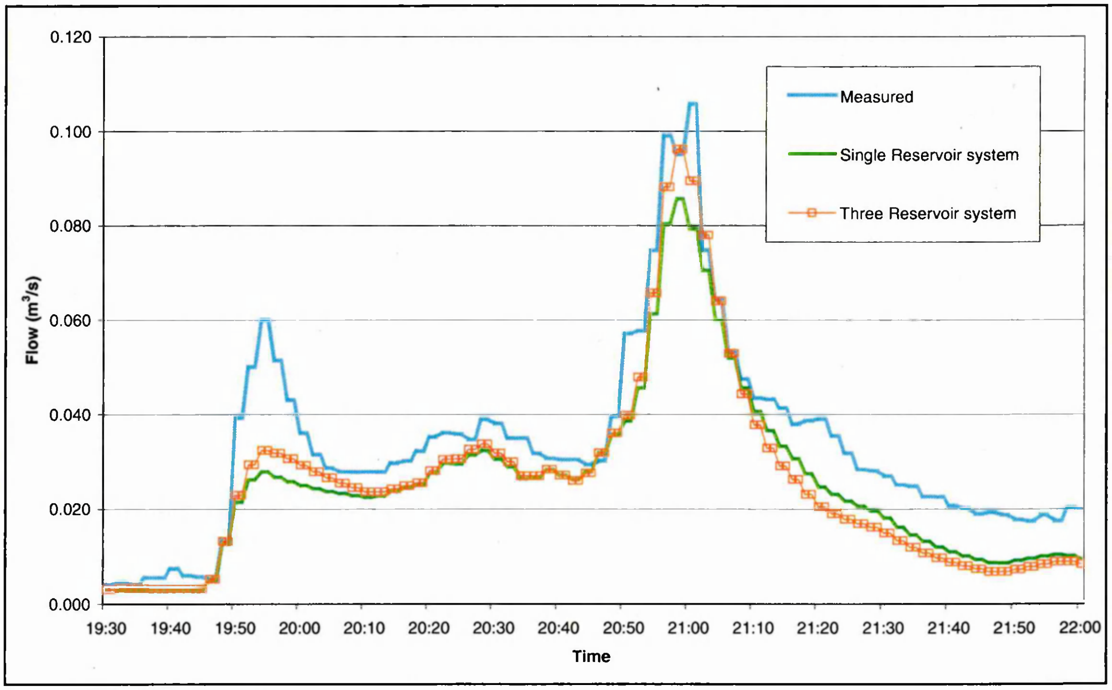


Figure 6-8 Comparison between measured, single reservoir and three reservoir systems for storm GS11 at SC3 in the low income catchment.

6.4 Solids' Transportation Model

The second phase of the model requires a solid transportation technique to predict the movement of solids leaving the catchment. Two methods have been developed to predict the movement, the Dilution Method and the Specific Volume Method.

6.4.1 Dilution Method

The distribution of solids flushed from the sewer system was categorised in Chapter 5. This indicated that solids were either deposited on the sewer bed, were in motion during dry weather or entered during the storm. The Dilution method assumes that these solids are uniformly distributed throughout the initial dry weather volume in the reservoir (Figure 6-9).

Initially during the model development stage the quantity of solids in the model was the total quantity measured during the storm. Comparisons between the model and measured data have used the total quantity of solids sampled and not individual solid types. This made comparisons with measured data more representative, as the sample size of some of the individual solids was small. This also ensured that the magnitude and timing of the solids flush could be compared with measured data to evaluate the solids' transportation mechanism. This prevented any inaccuracies in the quantity of solids predicted affecting the magnitude of the solids flush, as magnitude is linked in part to the quantity. Comparisons of the individual solids predicted against measured data are shown in Chapter 8.

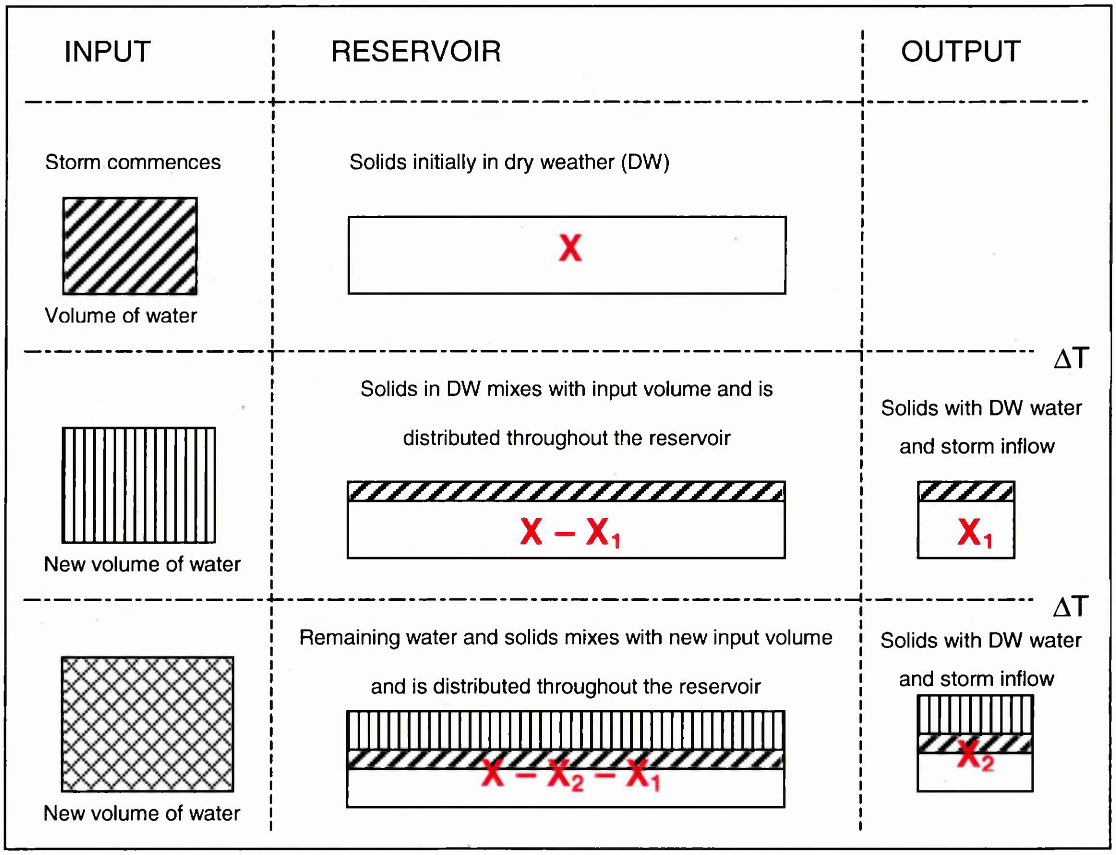


Figure 6-9 Representing the transportation of dry weather solids (X) from the reservoir using the 'Dilution method', where inflow water mixes with the remaining solids reducing the concentration at each time step.

At each time step, the effective rainfall that enters the reservoir is mixed completely with the existing solids and water within the reservoir. Thus the concentration of the pollutants within the channel is reduced. The mass of solids that flows out of the reservoir at the downstream end is therefore dependent on the solids concentration and the magnitude of the outflow at any particular time step (Equation 6-14). Solids start to leave the system once the storm flow is generated at the downstream end.

Quantity of solids leaving, (g/s) $X_L = X\frac{O\Delta t}{V}$ **(6-14)**

Where: X = Solids in the pipe (g)

O = Outflow (m^3/s)

Δt = Time step (s)

V = Volume of water in reservoir (m^3)

6.4.2 Dilution method evaluation

The dilution method was initially compared with the measured data at the low income sub-catchment SC1 using the single and three reservoir systems (Figure 6-10). The three reservoir system produced the best distribution of solids of the two systems with a peak of 2.7 g/s compared to 2 g/s of the single system. The temporal distribution was over a longer time period than the measured storm and the peak values were substantially lower with measured values at 9.7 g/s, more than three times greater than that calcualted from the three reservoir system.

The dilution method clearly did not replicate the significant rate of solids flushed from the sewer network at the start of the storm. The dilution method is reliant upon the continuous mixing of solids and water and does not represent the movement of solids out of the system. This is likely to be due to the method itself where the quantity of solids within the system is diluted as more water enters (rather than transporting solids specifically with the flow). Previous research by Ackers et al. (1967) had identified solids moving at the front of a storm wave therefore a system to represent this flushing effect was investigated.

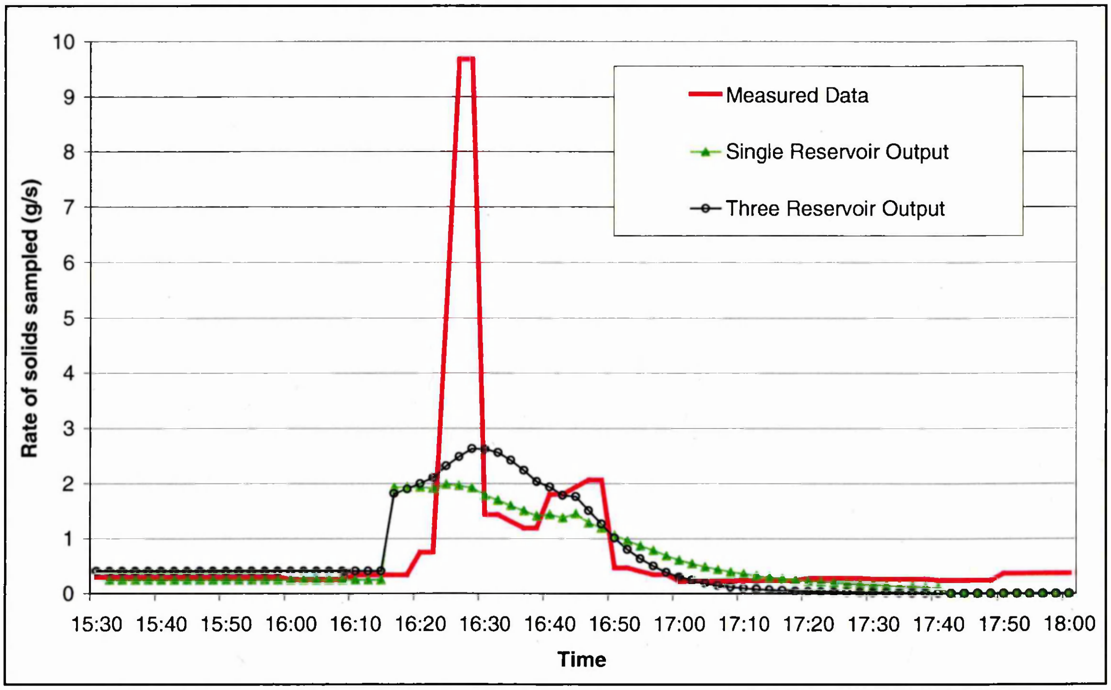


Figure 6-10 Storm GS2 at SC1 Low income catchment using the dilution method combined with the single and three reservoir model.

6.4.3 Specific Volume Method

The second concept, the Specific Volume Method, stemmed from an investigation by Ackers et al. (1967) who observed that very little longitudinal mixing occurred at the front of a storm wave between the existing steady foul flow and the storm water. It was also observed that prior to the flood wave arriving, an increase in depth and discharge would occur. At the front of this storm wave an undiluted foul flush was observed to be present.

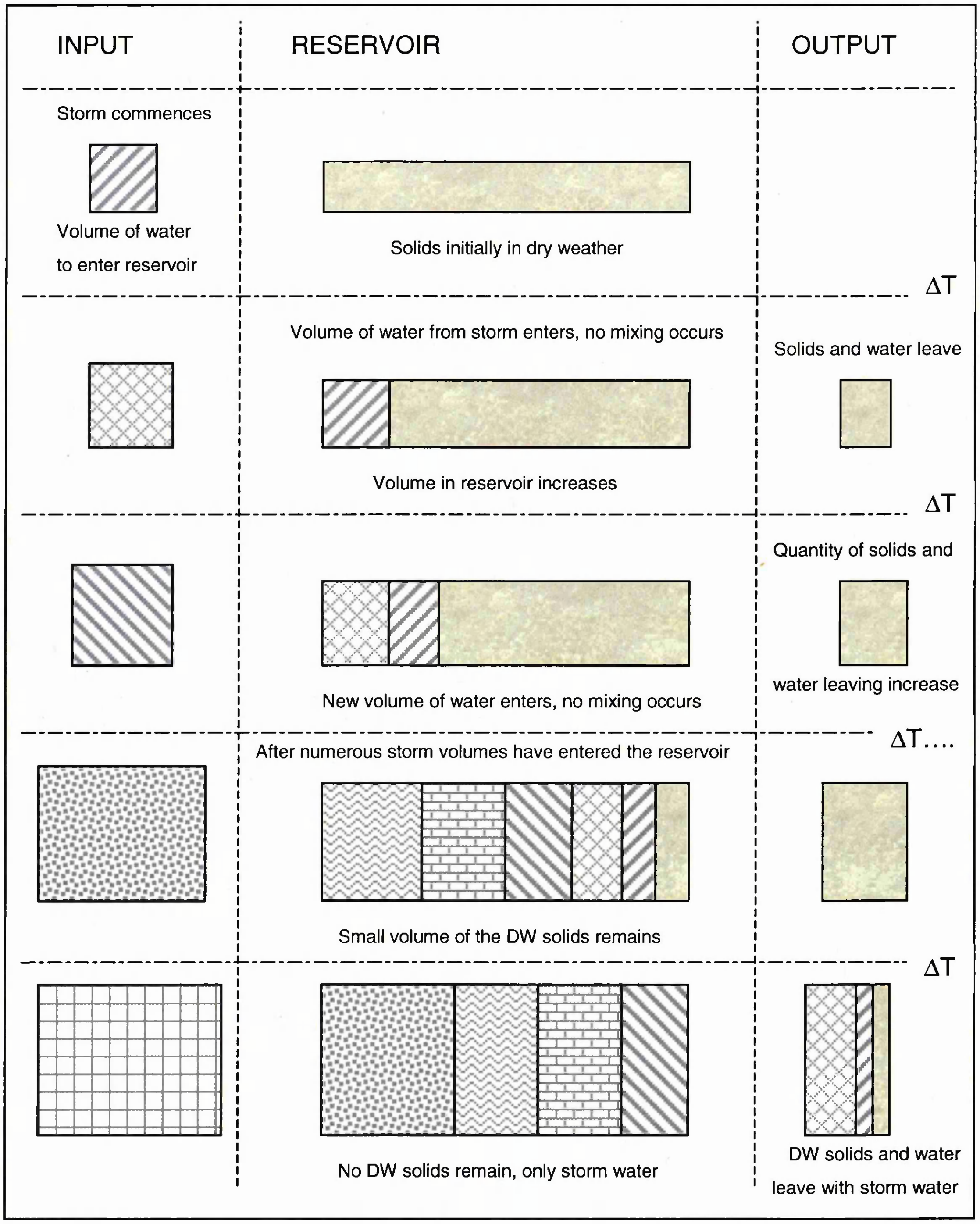


Figure 6-11 Representing the transportation of dry weather solids from the reservoir using the 'Specific Volume method', where no mixing of the volumes occurs and the solids concentration of the dry weather solids remains the same.

The Specific Volume method simulates the movement of discrete flow volumes within the reservoir. At the upstream end of the reservoir, the flow volume that enters as a result of the runoff from impermeable area does not mix with the existing water in the reservoir, but shunts it along before it (Figure 6-11). In this way each parcel of water retains its individual solids concentration. Therefore the quantity of solids leaving the reservoir is dependent upon the outflow and the corresponding solids concentration within that volume only. In the 3 reservoir system, runoff discharged to intermediate pipes is mixed with solids and flow from the upstream reservoir before the routing procedure is repeated. Solids start to leave the system once the storm flow is generated at the downstream end of the system.

6.4.4 Specific Volume Calibration

The single reservoir, specific volume method produced the best simulation with regard to the magnitude of the peak of the flush (Figure 6-12). The timing of the flush was over a similar period of time, concluding when all the solids in the reservoir had been shunted out with the dry weather volume. The three reservoir simulation for the specific volume method indicated that solids would be flushed over a longer period than in the single reservoir, with three distinct peaks related to the number of reservoirs. These were related to solids leaving each upstream reservoir before eventually leaving the downstream end of the system.

A significant quantity of solids were not flushed out in practice until the flow had increased to approximately twice that measured in peak dry weather. Simulations with storm GS2 and GS3 were conducted on other sub-catchments and identified similar findings. This development of the model is discussed in section 6.5.2.

The single reservoir in conjunction with the specific volume method was found to be the best way to replicate solids being flushed out during a storm, as shown in Figure 6-12 compared with Figure 6-10. Figure 6-13 and Figure 6-14 shows the overall performance of the preferred method with storm GS3 at SC4 in the low income catchment. This method is also significantly simpler to compute than the three reservoir system using the specific volume method. Solids were initially flushed out prior to those measured in the field. This was clearly observed when comparing the flow and solids' transportation together. This occurred in all simulations as solids were programmed to leave the system as soon as the rainfall affected the flows.

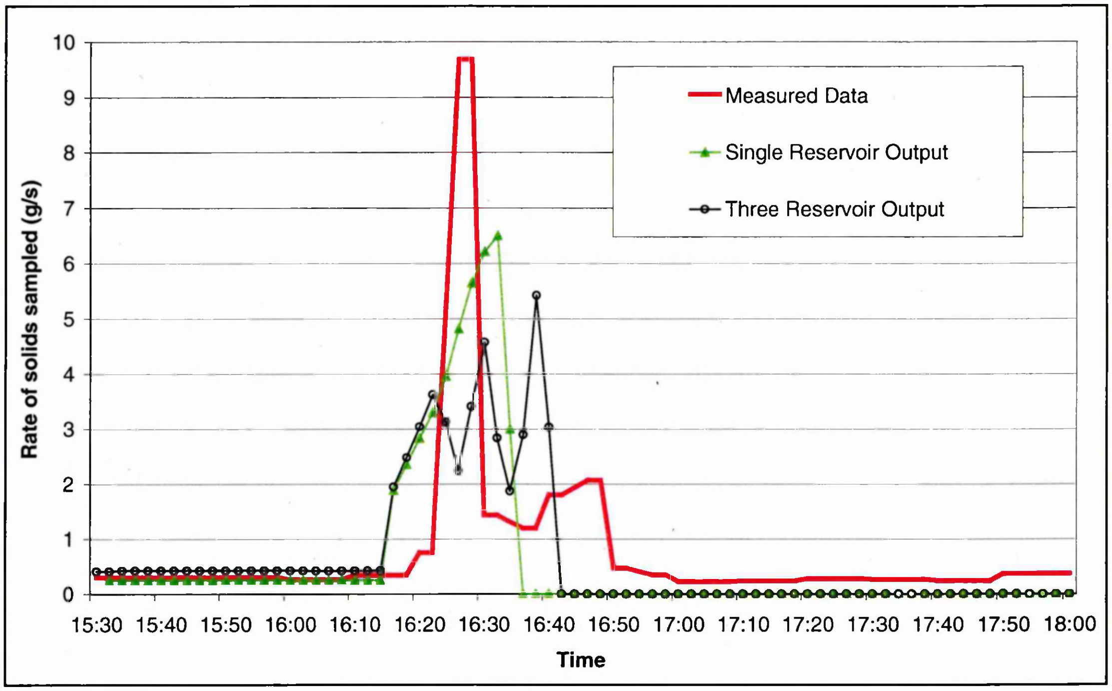


Figure 6-12 Storm GS2 at SC1 Low income catchment using the specific volume method combined with the single and three reservoir model.

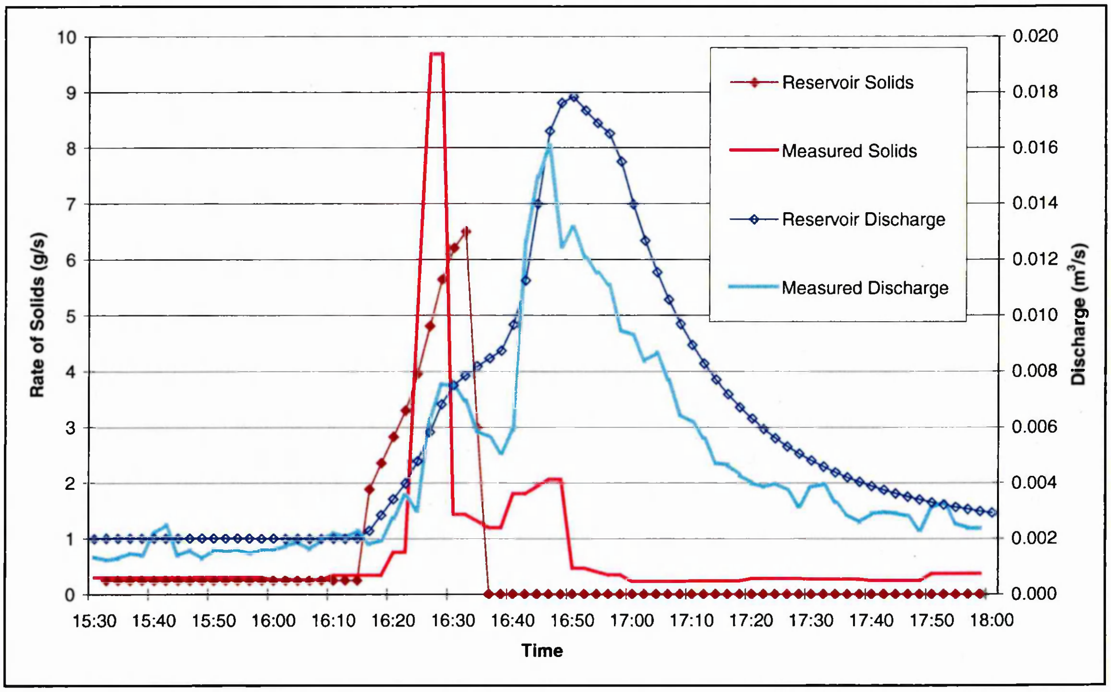


Figure 6-13 Comparison of solids and discharge measured and simulated using single reservoir (specific volume) method for GS2 at SC1 in the low income catchment

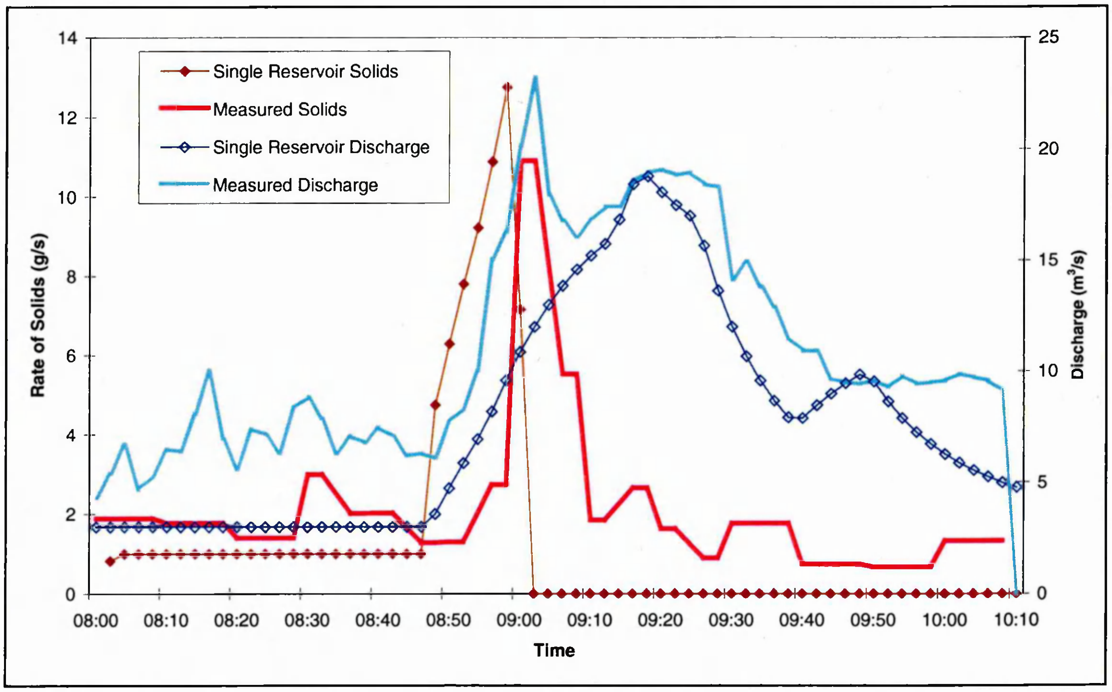


Figure 6-14 Comparison of solids and discharge measured and simulated using single reservoir (specific volume) method for GS3 at SC4 in the low income catchment

Simulations using the single reservoir specific volume method indicated that the timing and magnitude of the peak was generally good, with a variation in the peak rate of solids being ± 30% of the measured values for 5 of the 8 storms. The three remaining storms were within ± 50% of the measured peak values. The quantity of solids leaving was the same as that measured, as empirical values had been used to determine the initial solid quantity.

6.4.5 Initial Model Verification

Data from the high income catchment was used to verify the model for total solids sampled. This enabled the model to be tested against a catchment with different catchment characteristics as well as higher intensity and longer duration storms. This tested both the routing technique and solids' transportation method.

The storms sampled at the high income catchment were of two distinct types. These were short duration high rain intensity storms and longer duration low rain intensity storms. For measured storm DS1, the simulated peak flow was 20 % below the measured (Figure 6-15). The timing of the increase of the simulated discharge occurred slightly earlier, however this may be related to the location of the raingauge situated at the Western edge of the catchment (see section 3.4.2). In addition with only one rain gauge, it was not possible to obtain the temporal distribution of rainfall across the catchment. The solids flush prediction was poor compared with the measured solids duration and peak. The peak rate of solids leaving the reservoir was 2.2 g/s, significantly less than that measured. The measured solids did have a very distinct peak and if this value were taken over a 5 minute period, the peak would reduce to 7 g/s instead of 9 g/s improving the comparison between measured and simulated. The duration of the flush was also twice as long as that measured in the field.

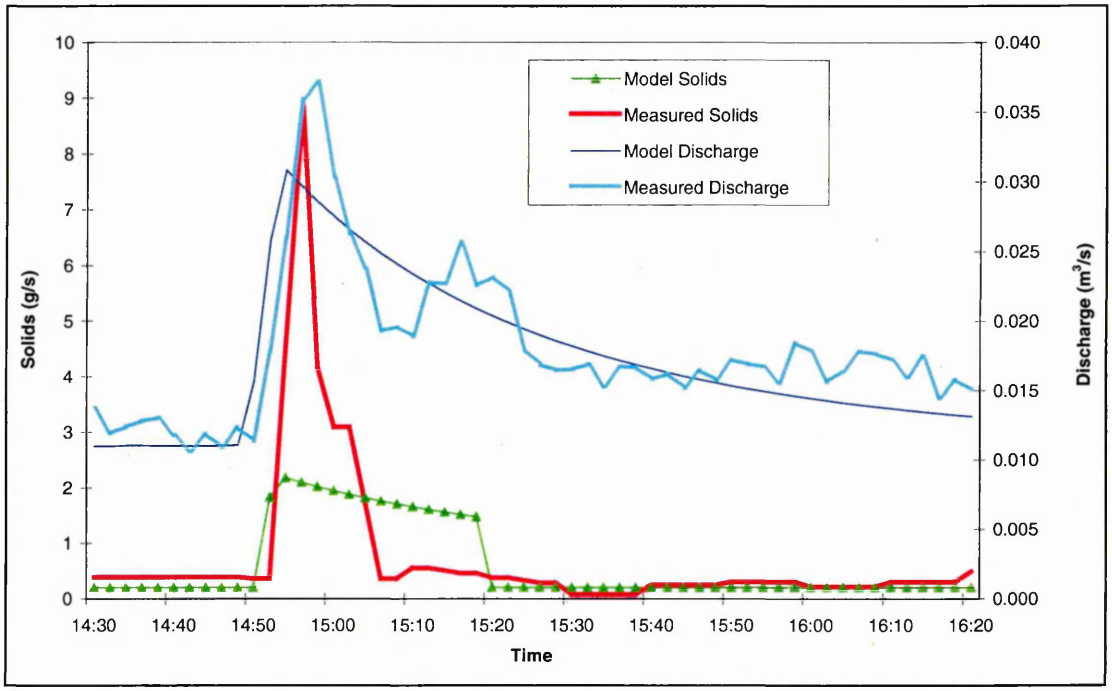


Figure 6-15 Comparison of solids and flow measured against simulated for storm DS1 at the high income catchment

Storm DS3 had a very different rain profile to DS1 that was sampled. The measured and simulated flow peak was similar with the simulated peak occurring 4 minutes later (Figure 6-16). The solids flush occurred over a 30 minute period compared with 45 minutes for the measured storm and a peak of 8.7 g/s compared with 11.9 g/s for the measured. This peak occurred at the same time. The aesthetograph shape was completely dependent upon the shape of the hydrograph as clearly observed in DS3.

The simulation of these two storms indicated that the magnitude of the solids flush was dependent upon the quantity of solids in the system and the rate of outflow from the reservoir. The discharge from the reservoir for storms with a sudden heavy rainfall produces a simulated outflow that is less than the measured rate of flow. This was particularly significant if the predicted outflow was smaller than that measured during the sampled storms. This was observed for the storm DS24 where flow only was recorded and the predicted outflow was significantly less as shown in Figure 6-17. The initial verification process identified that it was necessary to increase the predicted peak rate of solids leaving the reservoir. To achieve this it was considered that a more accurate replication of the rate of flow leaving the system would improve the solids profile. Therefore the method by which the reservoir was sized was investigated further.

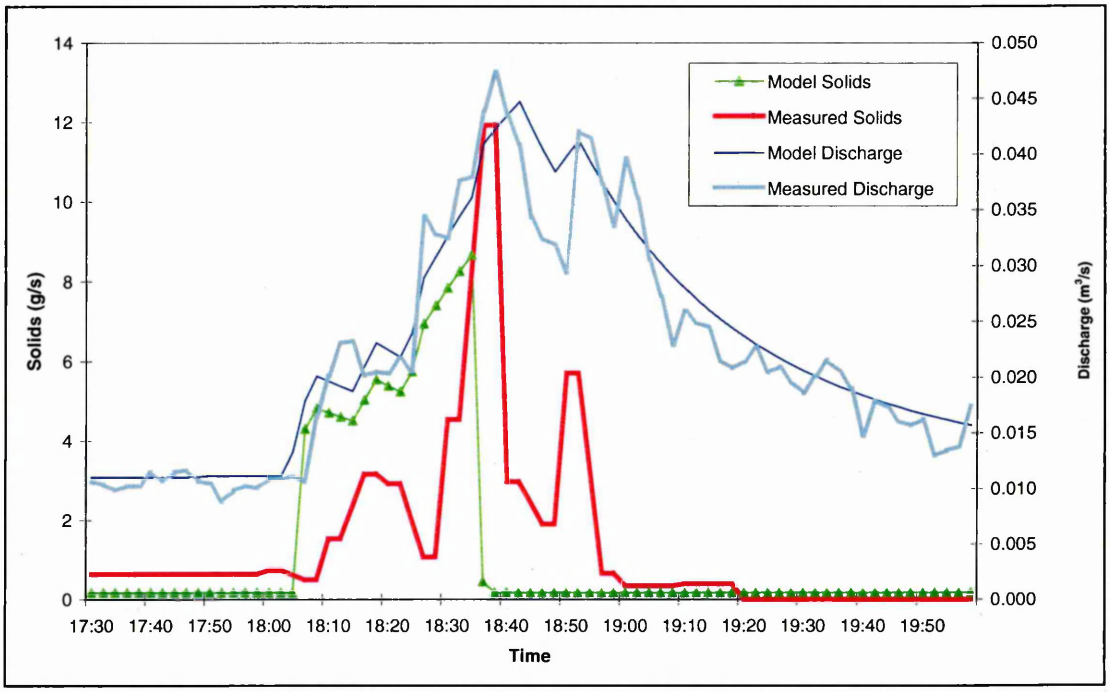


Figure 6-16 Comparison of solids and flow measured against simulated for storm DS3 at the high income catchment

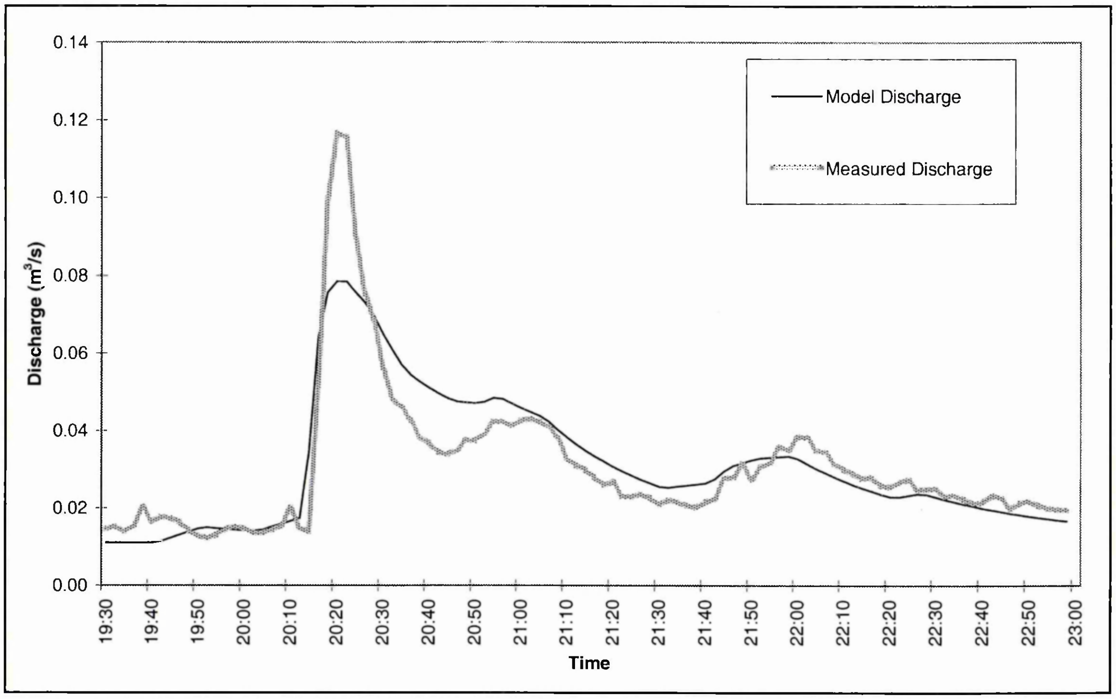


Figure 6-17 Comparison of discharge in the high income catchment between simulated and measured for storm DS24

6.5 Further Model development

The initial verification process identified that the model was not suitable to represent solids transportation at different catchments to a desired accuracy and further development was required. The transportation of solids out of the reservoir is dependent upon the volume in the reservoir prior to a storm occurring and the weir at the downstream end that controls the rate of discharge from the system. The timing of solids leaving the system is also crucial in representing the magnitude and duration of the solids flush. The model described in this chapter so far has been developed further to more readily represent the quantity and rate of solids exiting the system, as well making the model more user friendly when applied to other systems.

6.5.1 Reservoir sizing

A new method to size the reservoir was required for three reasons:

- To improve the discharge rate from the reservoir to be more representative of that measured in the field.
- To produce a volume in the reservoir in dry weather that was more representative of that found in a sewer system.
- To enable the reservoir to be sized more quickly to reduce the time required obtaining the main sewer length and average main sewer diameter.

Initially the reservoir was sized considering the main sewer length and the average diameter of the sewer in the catchment. This required the lengths and diameters of the sewer network to be collated and subsequent calculations to enable the parameters to be determined. Ideally whilst improving the accuracy of the model through the selection of a new method to size the reservoir, the parameters identified would be more easily obtainable.

It was observed that the volume of water in the High income catchment model was significantly greater than the dry weather volume computed in HydroWorks. In comparison, at the low income sub-catchments, the reservoir volumes were more similar to those computed in HydroWorks. Therefore it was important to reduce the volume of water in the reservoir at the high income catchment whilst retaining a similar volume to that observed at the low income sub-catchments.

Relationships between various catchment characteristics were examined to obtain a new method of sizing the reservoir. Initially a comparison of the water in the reservoir in dry weather and a volume simulated in dry weather from HydroWorks were compared. The volumes were similar at the low income catchment whereas the reservoir volume at the high income catchment was significantly greater than the HydroWorks volume. The reservoir areas that formed an important part of the volumes were then considered.

The model has been developed to represent the flows in the sewer system that runoff from the catchment. Theoretically it could be considered that a sewer system should have sufficient capacity to convey runoff generated from rainfall falling on hard impermeable areas in a catchment. Therefore it was considered that the size of the reservoir could be linked to the size of the impermeable area. The impermeable area was compared with the reservoir area for the low income sub-catchments and the high income catchment. A relationship between the two areas existed with the low income data but not the high income data (Figure 6-18). Linear regression of the low income data was plotted and forced through zero as no reservoir area would be likely to exist without any impermeable area in an upstream combined sewerage system. Due to the small sample size and the relative size of the catchments the spread of data is small, however due to the limited sampling data no other data was available to be considered. A relationship was established that indicated that the reservoir area at the low income catchment was approximately 1% (0.01) of the impermeable area.

The relationship observed at the low income catchment indicated that this relationship could be used to size the reservoir with the reservoir area set to 1% of the impermeable area. The effect from this change in the reservoir sizing method on the discharge and the solids transportation is discussed in section 6.5.3 and 6.5.4.

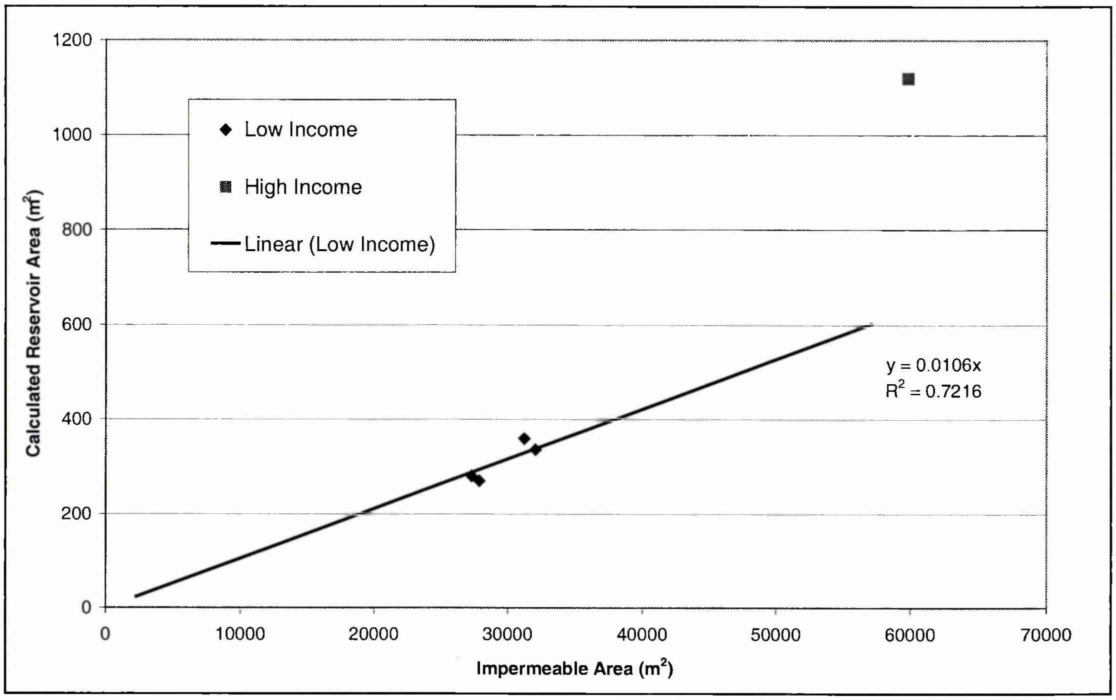


Figure 6-18 Comparison of impermeable area against initial reservoir area for the low income and high income catchments

6.5.2 Solids' transportation

The solids' flush from the reservoir occurred as soon as the rainfall started to have an impact on the outflows. However this was not the case in the field studies which indicated that the discharge at the sampling point reached between 1.5 - 2 times the peak dry weather flow value before the flush of solids commenced. The flow rate at which solids were flushed from the sewer during storms was identified in terms of multiples of dry weather flows. The average multiple of peak dry weather flows was calculated to be 1.85 with a standard deviation of 0.68 for all the storms sampled. Laboratory studies by others have shown that the movement of deposited solids only occurs once the velocity and depth reach critical values Brown et al. (1995), Davies et al. (1996), Davies et al. (1998a), Davies et al. (1998b). It was therefore logical to implement a delay on the solids leaving the system. Solids were held within the system until the discharge reached 1.85 times the peak dry weather flow value. At this point the dry weather volume originally in the reservoir was shunted out with the solids. This delayed the flush of solids which was particularly important during low intensity long duration storms where a significant flush of solids did not occur at the start of the storm.

6.5.3 Re-calibration of total solids' model

The adapted model was re-calibrated against the total measured solids at the low income sub-catchments to observe the outflows and solids' flush in comparison with measured values. The developments to the model after the initial calibration showed a slight improvement in the predicted solids flush and discharge. At the low income catchment 75 percent of the solids' flushes within ± 30% of the measured solids peak, with the start time of the flush commencing at the same time as the measured data or within one time step (Figure 6-19 and Figure 6-20). No large improvement was expected due to the model development being based upon the low income reservoir size in the first place.

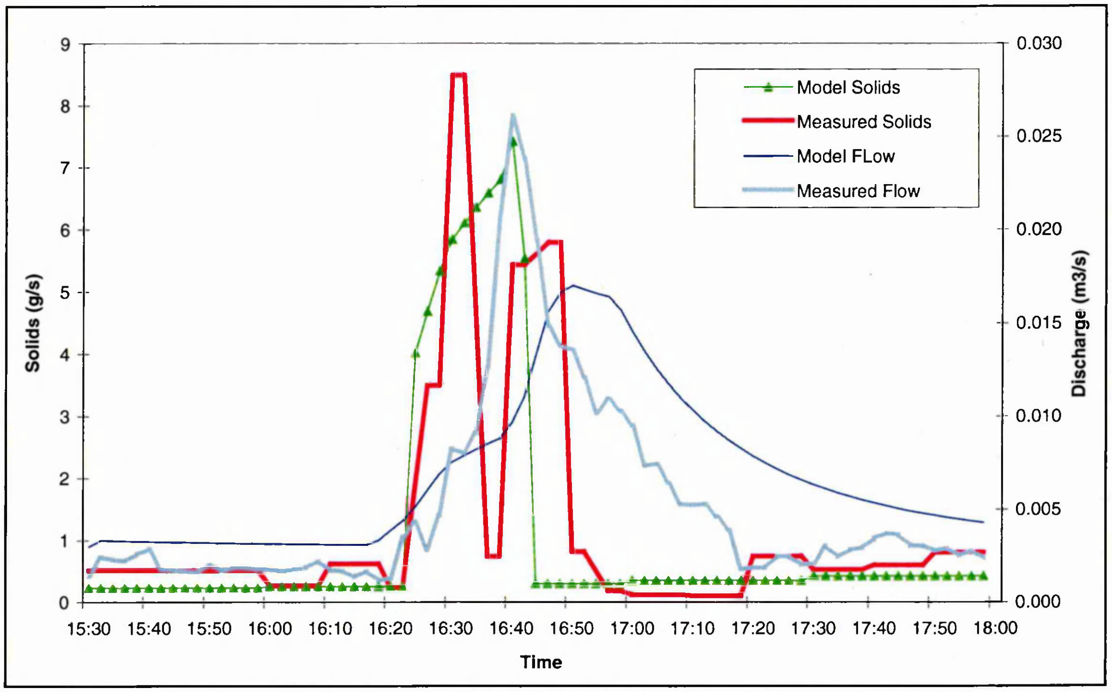


Figure 6-19 Comparison between measured and simulated values for solids and discharge for storm GS2 at SC4 in the low income catchment (calibration event)

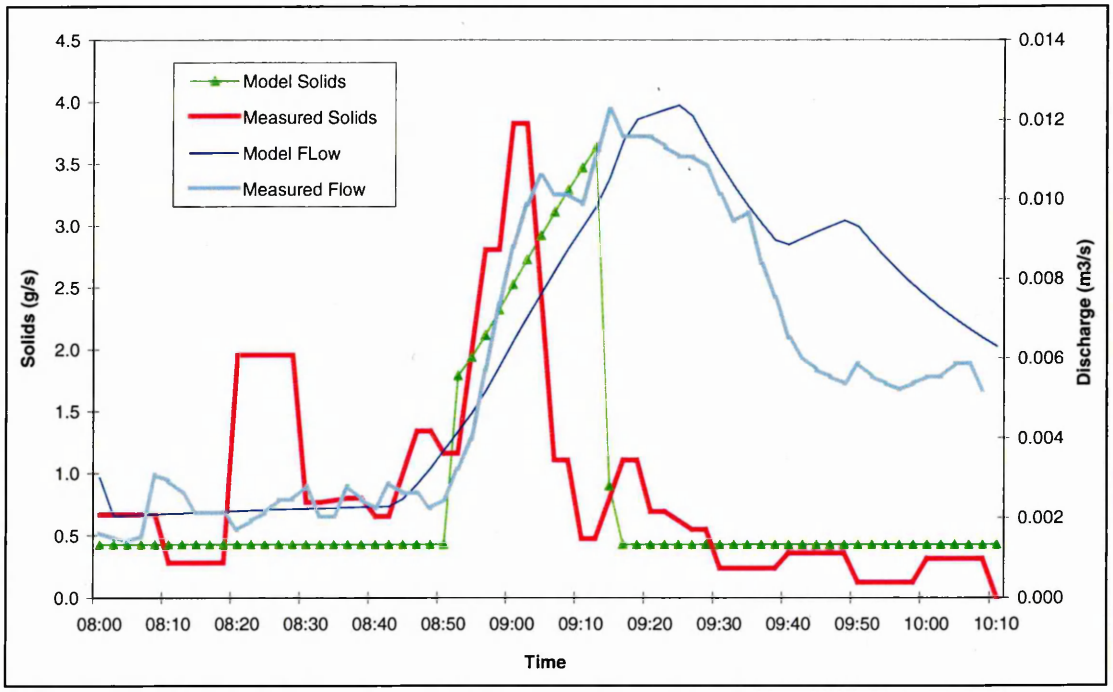


Figure 6-20 Comparison between measured and simulated values for solids and discharge for storm GS3 at SC2 in the low income catchment (calibration event)

6.5.4 Total Solids Model Verification

The model had been calibrated and developed against the low income catchment data. Independent verification of the model was achieved using measured data from the high income and ethnic catchments.

At the high income catchment which was initially used to verify the model, an improvement in the discharge and reservoir volume also improved the solids flush during the short duration high intensity storms. In storm DS6, the duration of the storm was shortened by 25 %, and the solids peak increased by 36 % therefore more accurately representing the flush (Figure 6-21). The change in discharge had a limited effect on the solids flush in the longer duration storms, increasing the rate of discharge slightly, yet the duration of the flush was over a similar period of time compared with the previous model (Figure 6-22). This change was a direct result of the dry weather volume being reduced by approximately 20 % which was more representative of the actual dry weather volume calculated in HydroWorks.

At the ethnic catchment the timing of the flush was very good for two of the three storms (Figure 6-23 and Figure 6-24). One of the long duration, low intensity storms (storm OS2) produced a large over prediction of solids as no significant peak occurred during sampling (Figure 6-23). The timing of the model flush for the storm was very good, only 2 minutes in advance of the measured data. The predicted peak value of solids was twice the amount measured. This was not surprising due to the nature of the storm (long duration low intensity) as the quantity of solids used in the model was based upon the total measured during the storm. The quantity sampled during the storm whole storm was twice the quantity of that measured during the main solids flush. Therefore an over prediction of this peak could be expected when the storm was simulated. The solid input model described in Chapter 7 addresses this issue. This problem was also experienced with a similar type of storm OS5, where no significant flush was measured and an over prediction occurred.

The timing of the flush replicated by the model for storm OS4 occurred at the same time as the measured data. The peak of the flush over predicted the magnitude of solids leaving the system by 47%. The model generally over estimated the flows by approximately 40%, however this is likely to be due to the inaccuracy of the flow survey due to poor site conditions. This has been discussed previously in section 4.3.3.

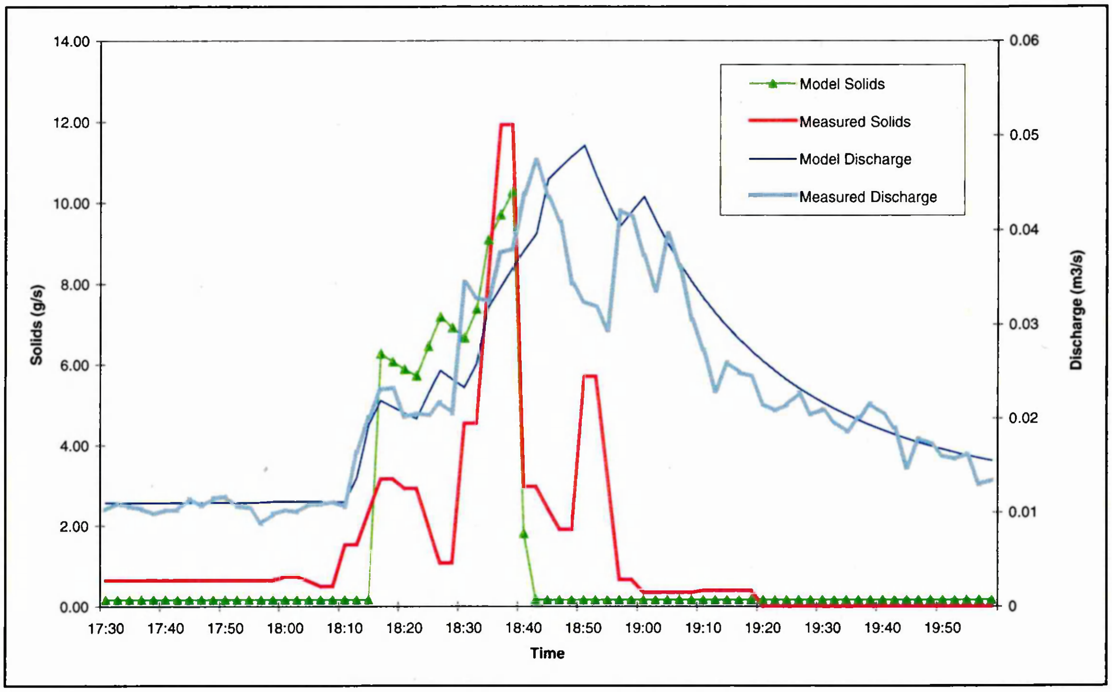


Figure 6-21 Comparison between measured and simulated values for solids and discharge for storm DS3 at the high income catchment (verification event)

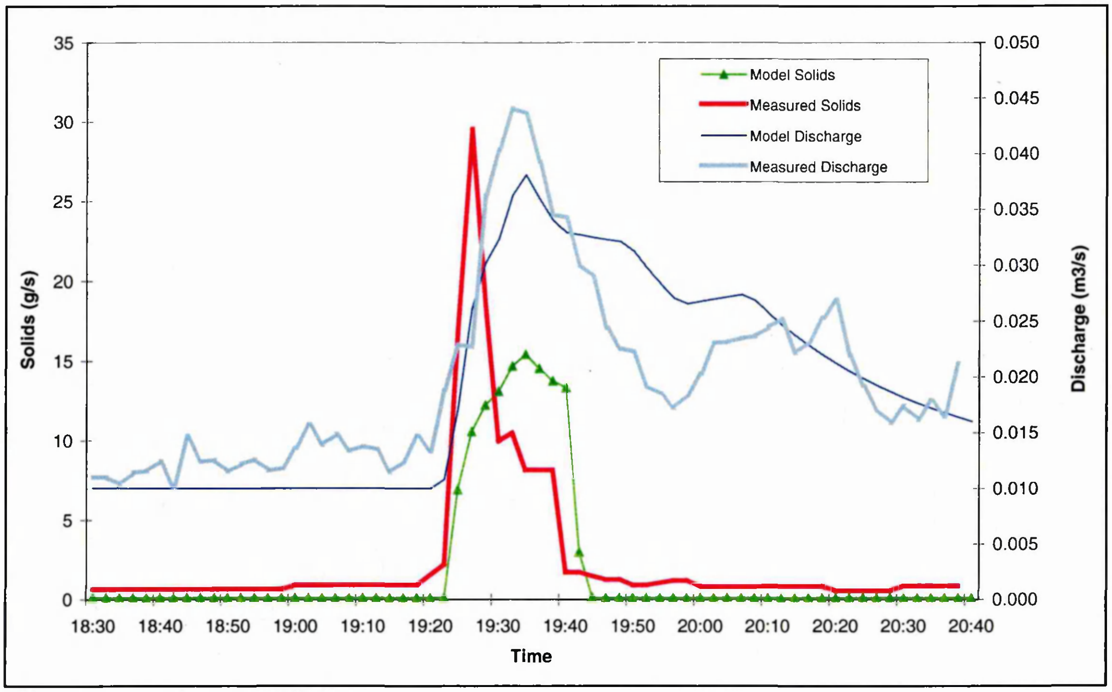


Figure 6-22 Comparison between measured and simulated values for solids and discharge for storm DS6 at the high income catchment (verification event)

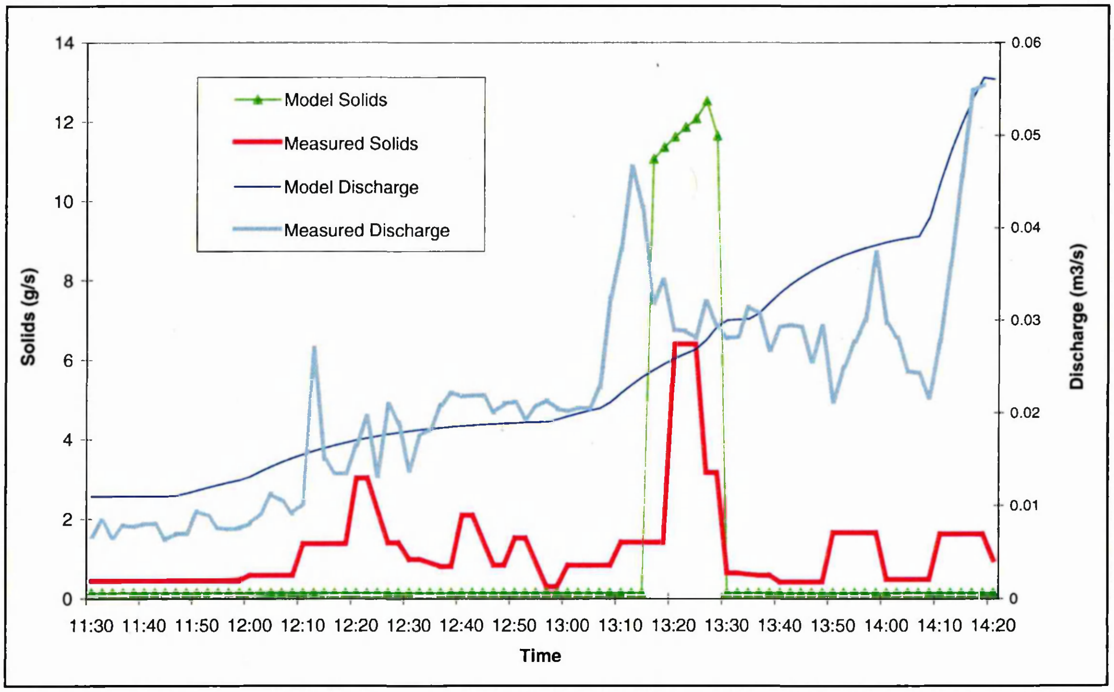


Figure 6-23 Comparison between measured and simulated values for solids and discharge for storm OS2 at the ethnic catchment (verification event)

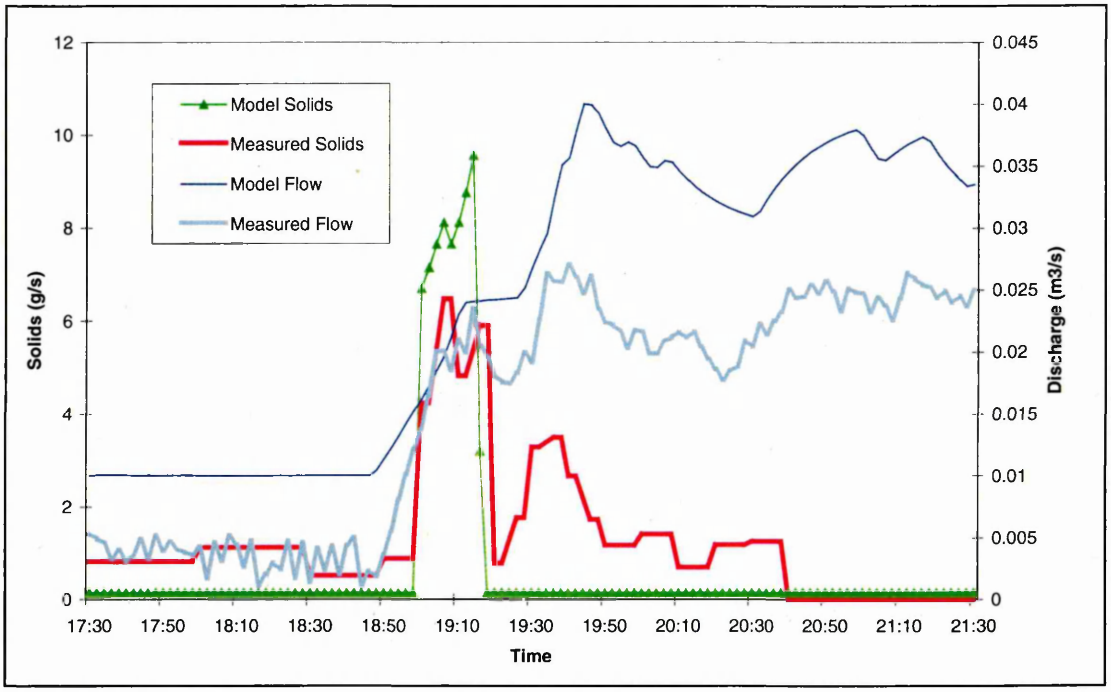


Figure 6-24 Comparison between measured and simulated values for solids and discharge for storm OS4 at the ethnic catchment (verification event)

A summary of the percentage difference of the predicted and measured peak rate of solids leaving the reservoir is shown in Table 6-1. Overall average percentage differences for all storms shows the model to under or over predict by 42% with a standard deviation of 39.4. The average has been calculated without consideration of whether they under or over predict. Results show that the model over predicts the lower intensity storms such as those at the Ethnic catchment while it under predicts higher intensity storms as observed at the high income catchment for storms DS1 and DS6. This under prediction occurs due to the high peak measured over a very short space of time, that the model cannot fully replicate. The opposite occurs for the low intensity storms where an over prediction occurred, as solids will likely to have been slowly eroded as the flows increased before the flows significantly increase. Therefore the quantity of solids that are flushed from the model included the quantity before the main flush, hence an over prediction was always likely to occur. Two particular over predictions occurred at the Ethnic catchment, and if these are removed from the calculations, the mean percentage difference and standard deviation are significantly reduced to 30% and 18 respectively.

Table 6-1 Percentage difference between the predicted and measured peak rate of solids for each storm, with a summary of the data. Negative value indicates an under prediction.

	LOW INCOME - Sub-catchments			
Storm No.	SC1	SC2	SC3	SC4
GS2	-36.3	13.5	-30.4	-12.6
GS3	-29.8	-5.0	54.6	-15.6

HIGH INCOME	
Storm No.	Catchment
DS1	-61.2
DS3	25.7
DS5	8.9
DS6	-45.6

ETHINC	
Storm No.	Catchment
OS2	92.2
OS4	47.7
OS5	156.9

STATISTICS SUMMARY (Only considering the percentage difference, not whether it is under or over predicited)

All Results	
Mean	42.4
St. Dev.	39.4

Exclusion of outliers (orange)	
Mean	29.8
St. Dev.	18.4

The use of empirical data to develop the solid transportation and sizing of the model enabled the results to be compared with the measured data. This generally removed the possibility of the quantity of solids being incorrect (with the exception at the ethnic catchment). This enabled the comparison of the timing of the solids flush and its magnitude to be separately evaluated. The model has been calibrated and verified and the results demonstrate that the model is reasonably accurate at predicting the peaks at an average of ±30%. The next stage of the model development was to predict the quantity of solids entering the reservoir and this is discussed in Chapter 7.

7 Chapter 7 – Development of a Solids Input and Dry Weather Solid Transportation Model

This chapter describes the development of a solid input model that builds upon the work in chapter 5 where the quantity of solids entering and those being stored was predicted. Previously in Chapter 6 the model required empirical values of the total quantity of solids. An input model is developed in this chapter that predicts the quantities of the six major individual solids. The new input model is combined with a dry weather solids transportation model that predicts the quantity of solids leaving and the quantity stored in dry weather prior to a storm event occurring.

7.1 Introduction

The prediction of the quantity and temporal distribution of solids leaving the reservoir during a storm is dependent upon the quantity of solids in the system prior to the storm occurring. To enable the quantity of solids in the reservoir to be determined at any point in time, the model has been adapted to include a solid input and dry weather solid transportation model. This enables the model to run under dry weather conditions. Conceptually, when solids enter the reservoir, they are either stored or are available to leave during dry weather. During a storm all the solids in the reservoir are transported out including those stored and those that were in motion under dry weather conditions. The overall model concept is shown Figure 7-1 where a number of components act as inputs into the reservoir model. The new model components are discussed further in the following sections.

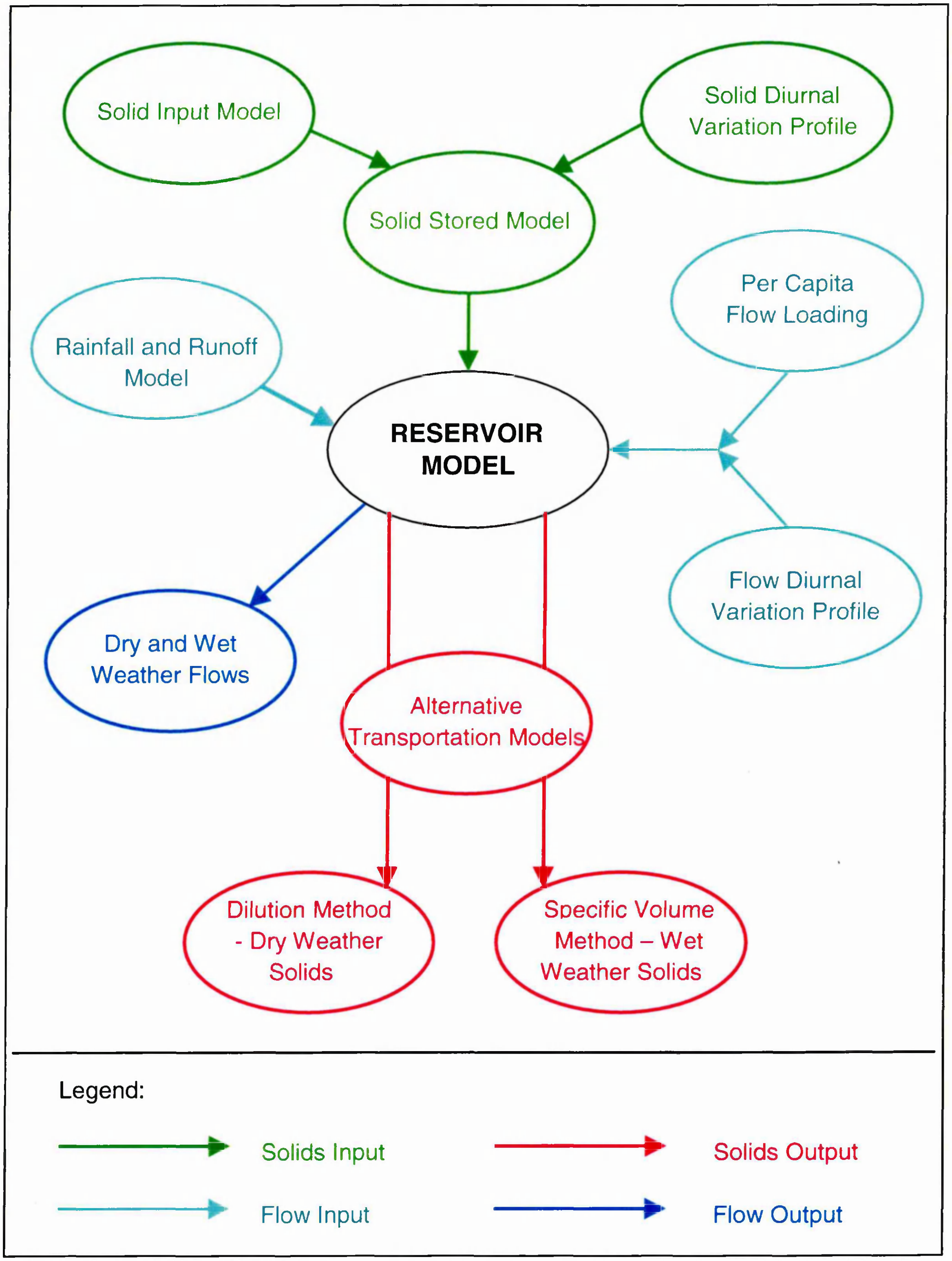


Figure 7-1 Schematic showing the components of the reservoir model identifying the inputs and outputs.

7.2 Dry Weather Model Components

7.2.1 Wastewater Model

In Chapter 6, to enable a solids transportation technique to be developed, it was necessary to determine the storm flows. Therefore to develop a solid transportation technique in dry weather, a method to predict the DWFs was necessary. Flows are simulated by routing an inflow through the non-linear reservoir, sized according to the method defined in Chapter 6. For dry weather simulations the inflow needed to include dry weather waste flows produced by a population, and flows from other sources.

The method of simulating waste water inflows is based upon the HydroWorks waste water generator file. Water consumption figures that have an allowance for schools, industry etc as described by Butler and Davies (2000) are combined with population numbers and the CIRIA time of day factor (Ainger et al. 1998), to determine the inflow per second which is given by:

$$Q_{IN} = \frac{P \times W_C \times T_F}{24 \times 60 \times 60} \qquad \textbf{(7-1)}$$

Where:

- Q_{IN} = Inflow (m^3/s)
- P = Population
- W_C = Water consumption figure (m^3/person/day)
- T_F = Time of day factor (from Ainger et al. (1998))

The wastewater generator model has enabled the development of a new method to determine the initial reservoir volume. This supersedes the earlier version discussed in Chapter 6 that required the user to estimate the dry weather flow rate at the start of the storm. The new initial volume is calculated using an approximation of the depth of flow leaving the reservoir and the reservoir area (Equation 7-2), therefore eliminating the need to estimate the flow. The initial flow leaving the reservoir is considered to be equal to the flow entering. This is a good approximation as the flow leaving is likely to be similar to that entering at the start of the ADWP prior to the storm. Therefore if flow in equals flow out, the depth of flow can be calculated by combining Equation 7-1 with Equation 6-2 to produce Equation 7-3.

$$V = AH_{OUT} \tag{7-2}$$

$$H_{OUT} = \left(\frac{Q_{IN}}{BL} \right)^{2/3} \tag{7-3}$$

Where:

- V = Volume (m^3)
- A = Reservoir Area (m^2)
- H_{OUT} = Water depth leaving the reservoir (m)
- C = Weir constant
- B = Width of weir (m)

The wastewater inflows continuously occur during wet and dry periods. During a rain event the wastewater inflows are combined with the runoff produced by rainfall falling on the impervious area after depression storage has been accounted for (discussed in section 6.3).

To model the ADWP, a rain event requires the dry period to be included before the rain occurs. To achieve this, a rainfall file is used with zero rain intensity starting from the conclusion of the previous rainfall event thus allowing solids to be stored. An example of a rain event with an ADWP is shown in Figure 7-2.

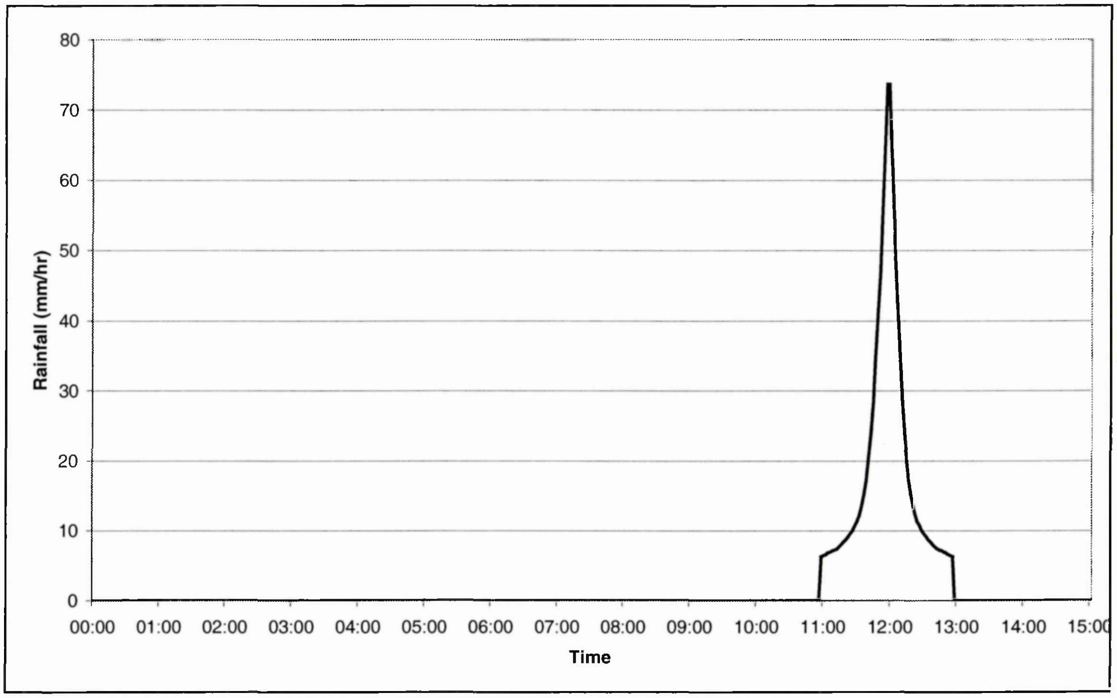


Figure 7-2 Example of a design rainfall hyetograph with a preceding period of zero intensity rainfall for 11 hours generated using HydroWorks^{TM}.

7.2.2 Solid input model

To enable the solids to be predicted in dry weather it was necessary to determine the temporal distribution of solids that enter the system, through a solid input model. The input model in conjunction with the solid transportation technique discussed in section 7.2.3 enables solids to be present in the system (stored and in motion) prior to a storm occurring.

The quantity of solids entering in one day is dependent upon the population, SPV and SEED, determined in section 5.5. Flushing profiles produced by Friedler et al (1996) control the rate at which solids enter the reservoir. These profiles are for faeces, toilet tissue and SANPRO products and have been produced for weekdays and weekends. An example for faeces is shown in Figure 7-3. The quantity and rate entering in a time step is defined by Equation 7-4. The SPV and SEED have all been developed from measured values therefore the solids input is a partially calibrated one, with the SPVs determined from the estimated quantity of solids entering the system.

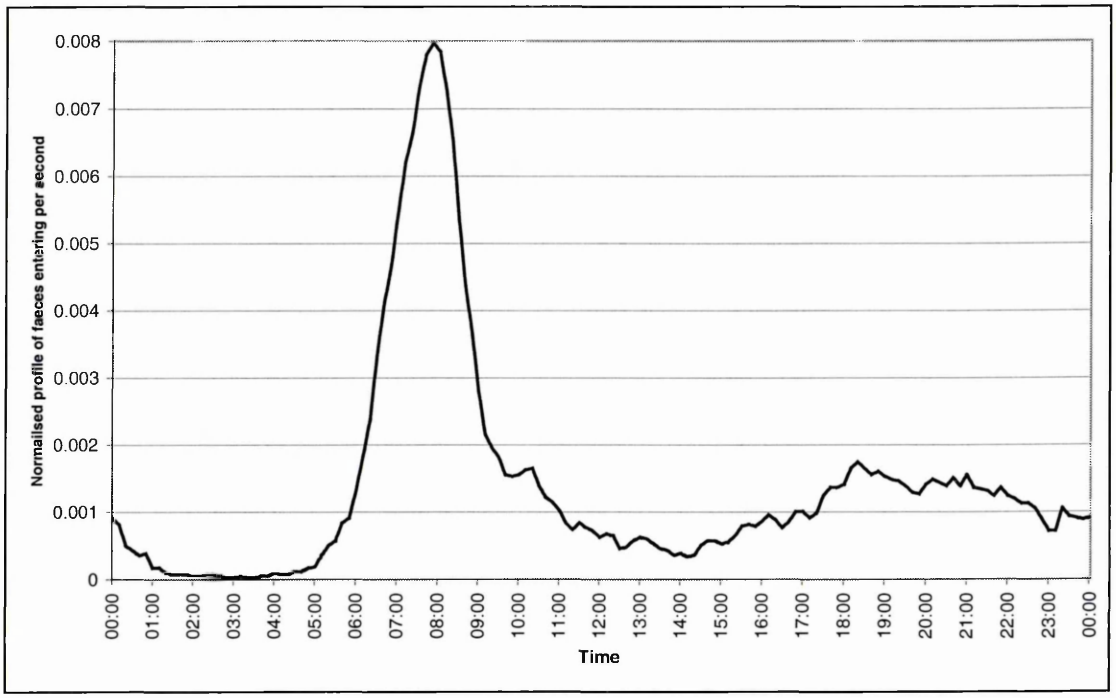


Figure 7-3 Normalised profile showing the rate at which faeces enter the sewer during a week day, adapted from Friedler, et al (1996)

$$M_{\Delta T} = P \times SPV \times SEED \times T_S \tag{7-4}$$

Where:

- $M_{\Delta T}$ = Mass entering in one timestep
- P = Population
- SPV = Standard production value (quantity / person day)
- SEED = Socio-economic ethnic day factor
- T_S = Rate of solids entering factor depending upon time of day (per time step) [from Friedler et al (1996)].

A proportion of the solids that enter the reservoir are stored. These are determined from the storage equations for each solid type presented in Chapter 5. The solids remain in the reservoir until the flow reaches the threshold value above the peak dry weather flow during a storm, at which point they are transported out of the reservoir. The remaining solids entering are not stored and are available to be discharged in dry weather. These solids enter the volume of water stored in the reservoir and are distributed equally throughout this volume in each time step. At the start of the dry weather simulation the reservoir is primed with solids. This is an estimate of the quantity in motion at that time of day. This initial solids concentration in the reservoir is determined using Equation 7-5.

$$S_{C\text{ at time zero}} = \frac{M_{E\Delta T} - M_{S\Delta T}}{V_{I\,\Delta T}} \qquad \textbf{(7-5)}$$

Where:

- $S_{C\text{ at time zero}}$ = Solids concentration at start of the event to be modelled
- $M_{E\Delta T}$= Mass entering in the first time step
- $M_{S\Delta T}$ = Mass stored
- $V_{I\,\Delta T}$ = Volume entering in the first time step

The mass stored in each time step is calculated using the equation determined in Chapter 5 and shown below:

$$M_{S:Pollutant} = \frac{k \times \Delta T \times H_d \times P \times SEED \times SPV \times [U_{\%SINK}]_{Panty\ Liner\ Only}}{24 \times 60 \times 60} \qquad \textbf{(5-24)}$$

Where:

- *$M_{S:Pollutant}$ = Quantity stored of each solid type (Mass or Number)*
- *k = gradient of solid stored regression analysis trendline*
- *ΔT = Time step (s)*

- *H_d = Housing Density*
- *P = Population (Person)*
- *SEED = Socio-economic and ethnic day factor (Number)*
- *SPV = Standard production value (Quantity / Person / Day)*
- *$U_{\%SINK}$ = Percentage of pollutant sinking (panty liners only)*

All the variables are easily obtained from existing data therefore the mass or quantity of solids can be calculated. The remaining solids are those that are transported through the reservoir in dry weather.

7.2.3 Dry Weather Solids' Transportation

The quantity of solids in the system prior to a storm occurring is dependent upon the quantity of solids that enter, the quantity that are stored and the remaining solids that are transported through the network in dry weather. The quantity that enter the reservoir and the quantity that are stored at each time step have been determined in section 7.2.2. The dry weather transportation model will enable the quantity of solids leaving the system as well as the quantity of solids that can be flushed during a storm to be predicted.

In Chapter 6 two methods were evaluated that transported solids out of the reservoir under storm conditions. The specific volume method was observed to produce a quicker flush of solids from the system compared with the dilution method that delayed the solids leaving the system with a lower peak. Therefore it was considered that the dilution method would predict the solids more accurately under dry conditions.

In dry weather, wastewater flows that enter a sewer network are attenuated at the downstream end of a network with a stretched profile and lower peaks. This principle can also be applied to solids entering and leaving a sewer network and is observed when a Frielder et al distribution (1996) is applied to a total quantity that enters in a day and compared with measured sampling data (Figure 7-4). Within the sewer system, solid transportation in dry weather could be considered as a mixing and deposition process rather than a flushing process (observed under storm conditions). The dilution method is likely to replicate this best as a quantity of solids that enter the top end of the reservoir will be mixed throughout the reservoir which will reduce the peak of solids that can leave the reservoir. This produces the same affect that is observed with dry weather flows entering and leaving a network. The specific volume method retains the integrity of the solids that enter in individual volumes therefore the peak values will be very similar to those that enter, less the quantity of solids that are stored.

The two transportation methods were trialled under dry weather conditions (Figure 7-5) and compared with measured results. The specific volume method produced larger peaks due to its method of moving specific volumes rather than mixing the concentrations in the reservoir as used in the dilution method. The dilution method produced lower peaks and delayed the solids leaving the reservoir in comparison with the specific volume method. Therefore the dilution method was selected to replicate solid transportation in dry weather.

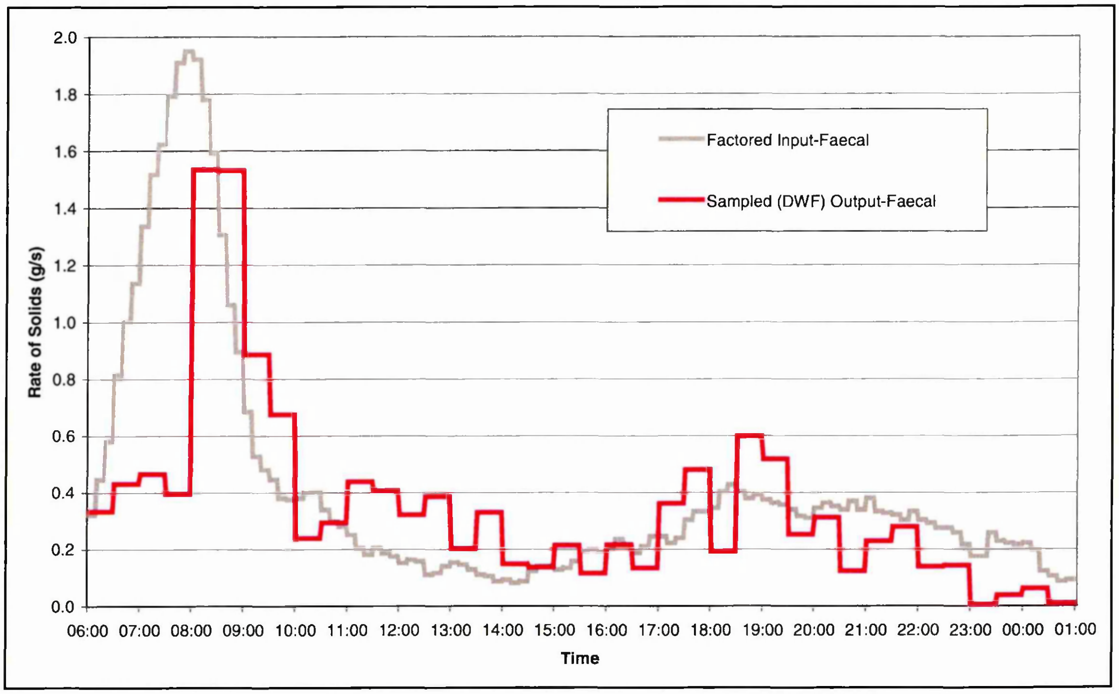


Figure 7-4 Comparison of a Friedler et al input distribution for faeces and measured data from the Low income catchment.

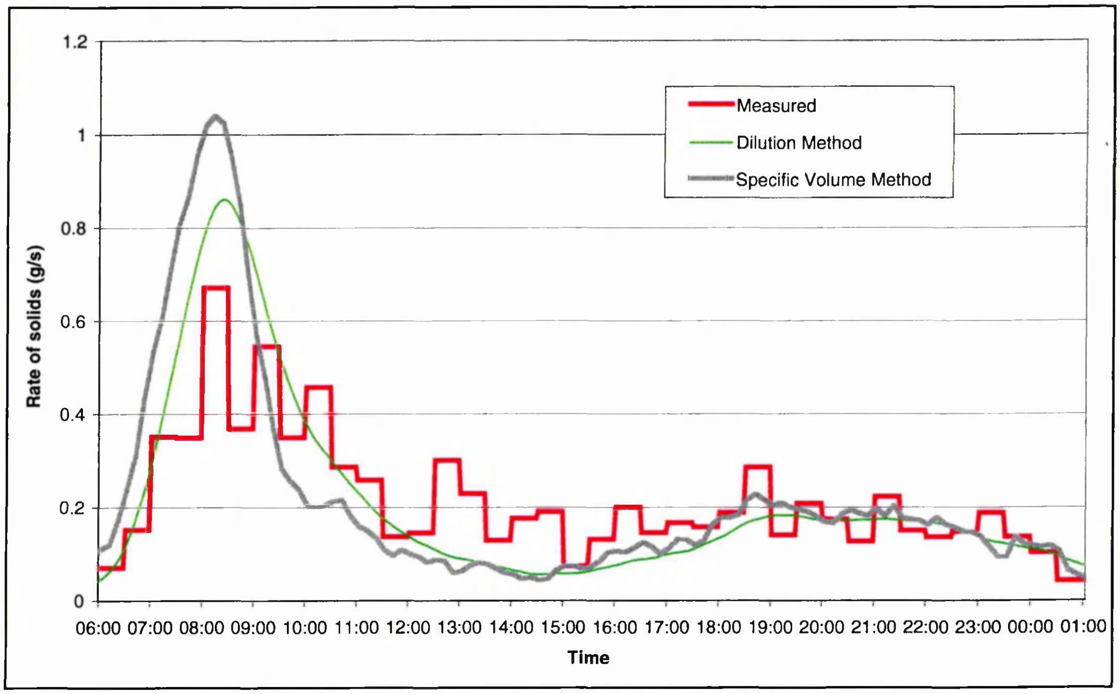


Figure 7-5 Comparison of the specific volume technique and the dilution method with measured data to predict the movement of solids in dry weather using toilet tissue at the high income catchment.

In wet weather the solids leave the model in the same manner as described in Chapter 6 using the specific volume technique. At the point where the flow is 1.85 times the peak dry weather flow, the stored solids and the solids in motion are flushed out (see section 4.3.4.1 and 6.5.2). The predicted storm quantities have been compared with the measured wet weather data for individual and total solids in Chapter 8.

7.3 Comparison of predicted against measured data in dry weather

Dry weather simulations for each catchment have been completed for each solid type. The results from the simulations have been compared with the measured data for the quantity of solids leaving the system from 06:00 to 01:00. In particular the magnitude, profile shape and quantity of solids leaving the model have been compared. This comparison also provides a check to ensure that the quantity of solids predicted by the model is similar to that measured. The SPV used to determine the quantity of solids entering is determined from an estimation of the quantity stored in one day from the analysis of storm data. Therefore the quantity that is predicted should be similar to that measured. However it would not be expected that the quantities were exactly the same due to the variability of the quantity of solids sampled. This variability is compounded when for certain solid types only small quantities of each pollutant were measured. This variability can be observed in Table 7-1 which shows the quantity of predicted solids produced in one day for each catchment compared with the measured quantity and the percentage difference.

Table 7-1 Results of the simulated and measured solid quantities for each catchment during dry weather.

Catchment	Value	Faeces	Toilet Tissue	Panty Liners	Sanitary Towels	Tampon	Wipes
Low Income	Predicted (g)	65996	50301	594	2139	571	4885
	Measured (g)	67010	52120	492	1922	449	5360
	% Difference from measured	-2	-3	21	11	27	-9
High Income	Predicted (g)	29640	14611	169	366	1370	1411
	Measured (g)	29893	14908	185	257	1334	1397
	% Difference from measured	-1	-2	-8	42	3	1
Ethnic	Predicted (g)	28500	16933	39	218	618	714
	Measured (g)	28569	17198	55	198	499	667
	% Difference from measured	0	-2	-30	10	24	7

The accuracy of the quantity predicted is very good for faeces and toilet tissue, good for wipes and variable for panty liners, sanitary towels and tampons. The high income catchment contained the best overall results of the three catchments. The model is very accurate when large quantities of solids were measured such as faeces and toilet tissue. Good accuracy is observed for wipes where reasonably large quantities were sampled. Poor accuracy is observed for SANPRO items except where large sample quantities were measured. This is clearly shown in Figure 7-6 where the accuracy significantly improves as the sample size becomes large.

The predicted and measured quantities have been plotted and linear regression analysis conducted (Figure 7-7). The correlation coefficient of the linear regression is 0.998 indicating an excellent fit as expected. The equation of the line from the regression analysis indicates that the average predicted value is 98% of that measured. The comparison indicates that the model is working correctly and can be assessed for the dry weather profile and also for storms.

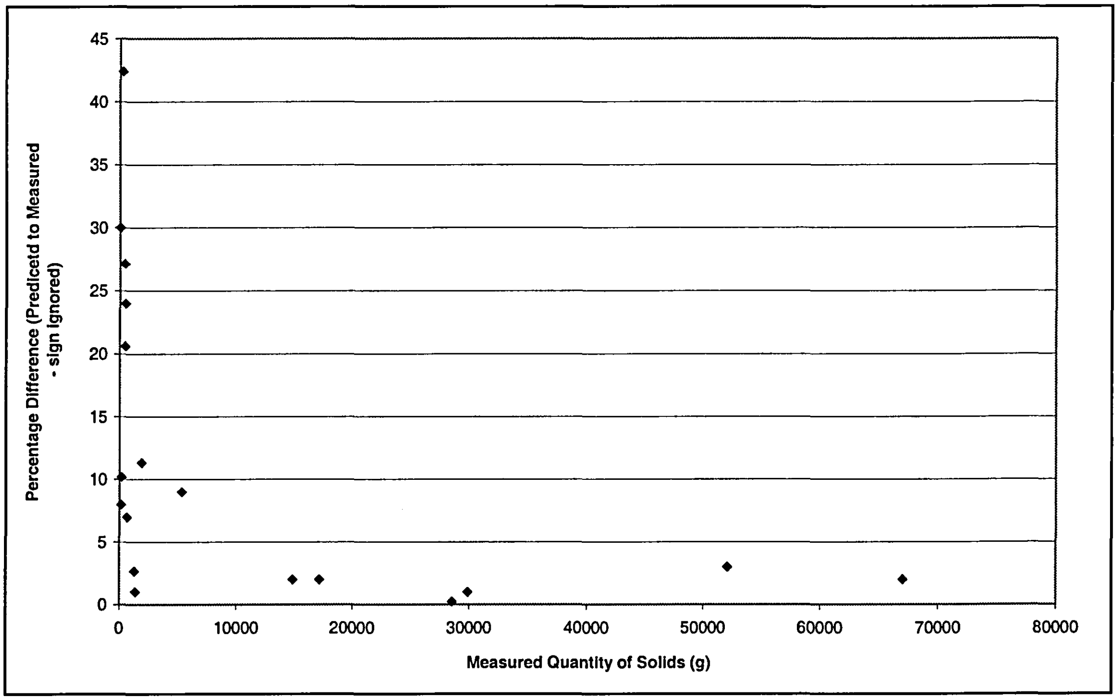


Figure 7-6 Comparison of the quantity of solids measured against the accuracy of the model to predict the quantity in dry weather.

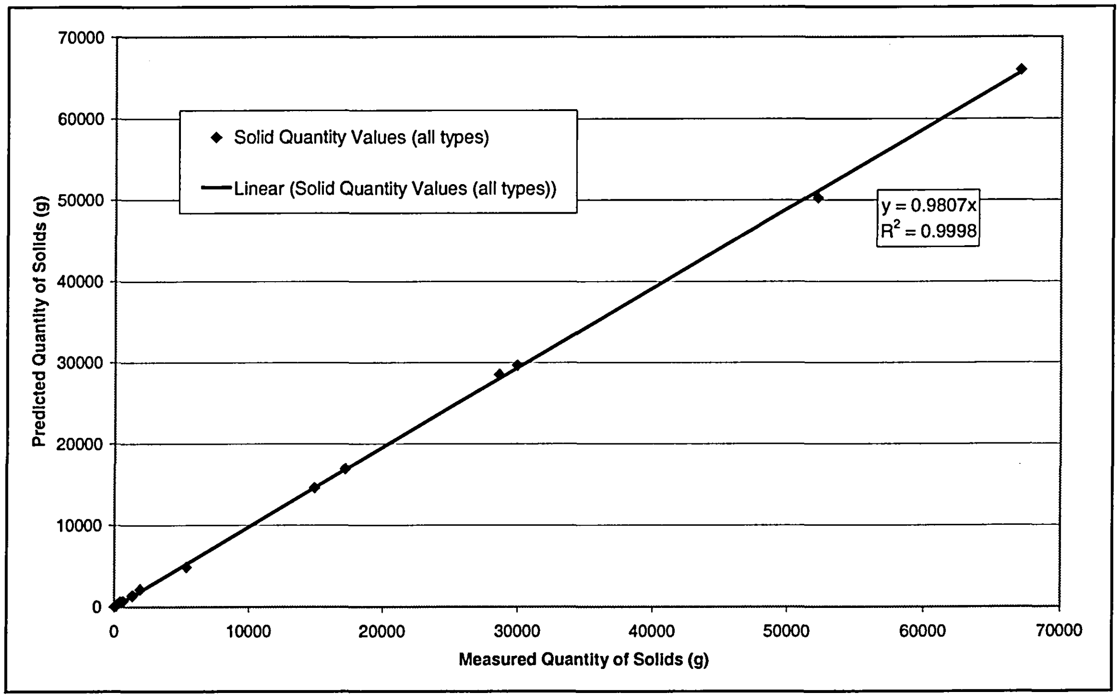


Figure 7-7 Comparison of all solids quantities measured against predicted during dry weather for each catchment.

The dry weather profile of the solids leaving the catchments has been produced for each solid type for each catchment. Two of these profiles are shown in Figure 7-8 and Figure 7-9. The magnitude of the solids leaving is generally greater than that measured in dry weather in the morning and slightly lower during the day. The diurnal distribution is dependent upon the flushing profiles produced by Friedler et al (1996). This suggests that potentially too many flushes and hence solids were leaving the system in comparison to measured data. Flushing profiles will also be affected day to day by the variability of when solids will enter. However the profiles were the best available and although they are not tailored to socio-economic or ethnic factors, they are currently the best estimate of the distribution of solids that enter.

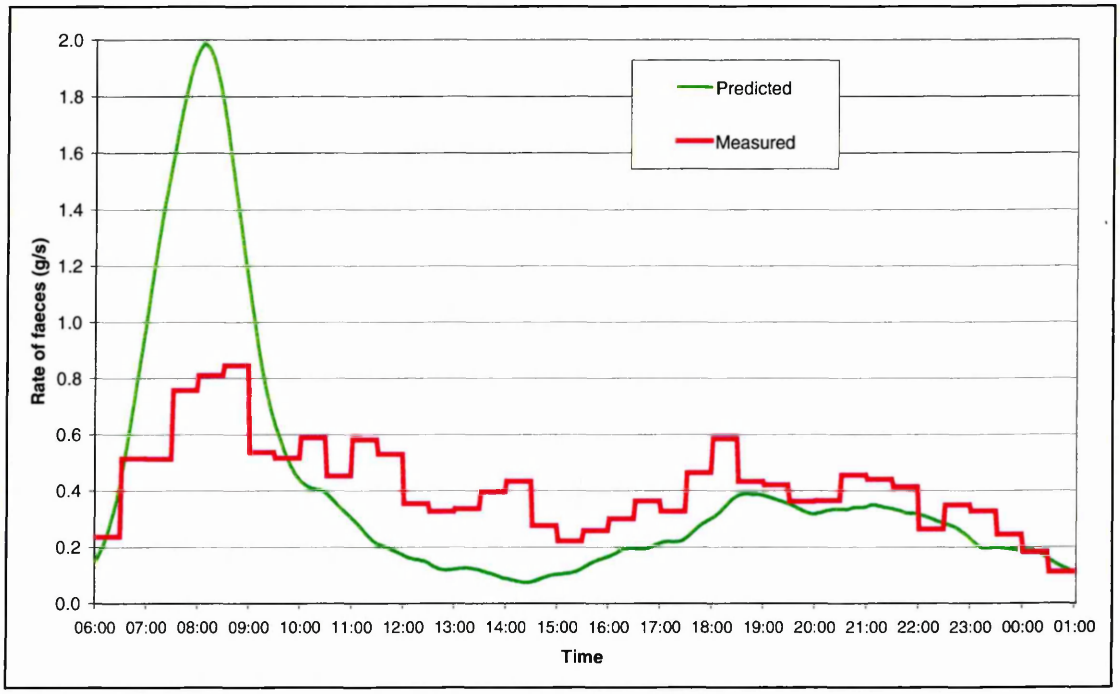


Figure 7-8 Comparison of simulated against measured results for faeces during dry weather at the High Income catchment.

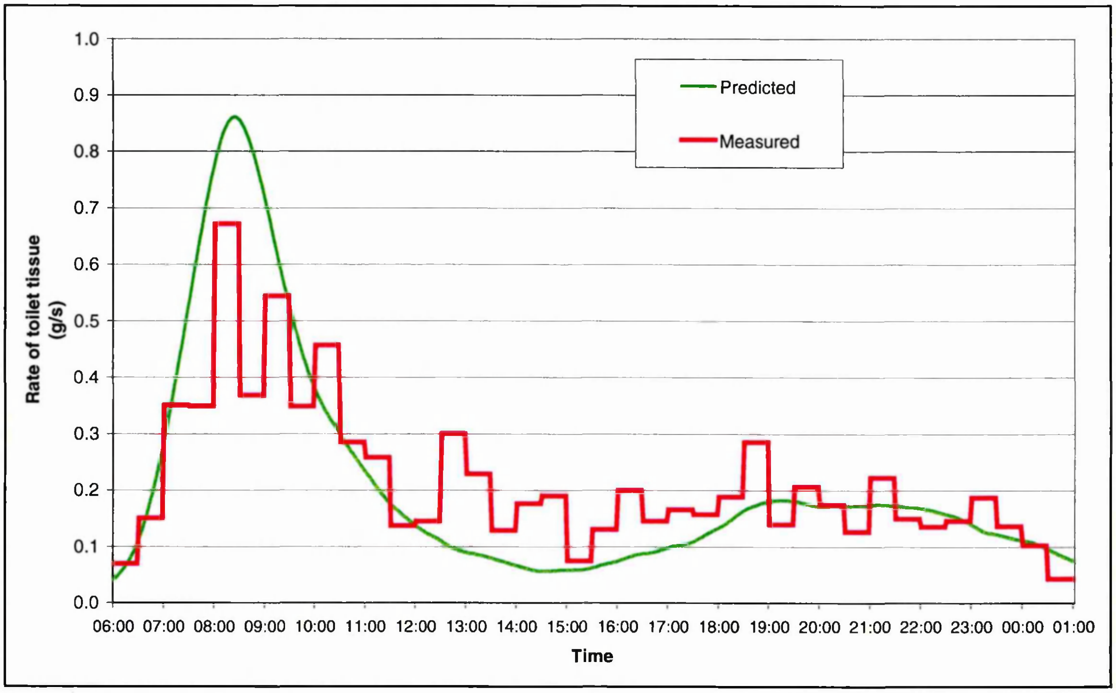


Figure 7-9 Comparison of simulated against measured results for toilet tissue during dry weather at the Ethnic catchment.

7.4 Summary

The development of the dry weather model has enabled the quantity of solids prior to a storm commencing to be determined. This has enabled the model to be tested under storm conditions and is discussed in Chapter 8. The dry weather model has shown a good accuracy in predicting the solids leaving the reservoir in dry weather. However the results do highlight the significant variability of the quantity and type of solids that can enter a combined sewerage system.

8 Chapter 8 – Comparison of Model and Measured Storm Data

This chapter uses the models and methodologies developed in chapters 5, 6 and 7 to predict individual solids loading during storm events. The model is used to predict the solids loading at each catchment for the storms that were sampled. A comparison between predicted and measured data is undertaken that focuses on the total quantity of solids, the peak rate of solids and the timing and temporal distribution profiles.

8.1 Prediction of solids in storm conditions

8.1.1 Prediction of the quantity of solids flushed

The work undertaken in chapter 7 developed the solid input model and dry weather solid transportation technique. This work enabled the prediction of the quantity of solids that would be present within the reservoir at the start of the storm. This has been used by the model to predict the rate and temporal distribution of solids leaving under storm conditions without the need for empirical data.

The model was used to simulate all the sampled storms from the three catchments and compare the predicted quantity and temporal distribution of solids leaving the system with measured data. Table 8-1 shows the measured and simulated quantity of solids flushed, the timing and the peak rate of solids leaving for the six main solid types.

Table 8-1 Results of the predicted and measured data for the storms sampled at each catchment for each solid type, including the time of the solids peak.

Catchment / Storm	Solid Type / Measurement	Feacal	Toilet Tissue	Panty Liner	Sanitary Towel	Tampon	Wipes	Time of Peak
Low Income Storm GS2	Model Quantity (g)	5020	2814	234	99	365	561	16:38
	Model Peak (g/s)	6.0	3.3	0.3	0.1	0.4	0.7	
	Measured Quantity (g)	5249	4046	22	263	499	710	16:30
	Measured Peak (g/s)	5.53	5.97	0.07	0.45	1.20	1.38	
Low Income Storm GS3	Model Quantity (g)	13304	7456	94	174	958	1035	09:08
	Model Peak (g/s)	17.0	9.5	0.1	0.2	0.8	1.3	
	Measured Quantity (g)	15355	7300	0	289	84	435	09:08
	Measured Peak (g/s)	9.19	3.98	0.00	0.46	0.28	1.04	
High Income Storm DS1	Model Quantity (g)	1788	881.39	14	6	102	1	14:56
	Model Peak (g/s)	6.78	2.92	0.01	0.01	0.12	0.32	
	Measured Quantity (g)	2038	693	0	0	81	108	14:56
	Measured Peak (g/s)	5.54	0.72	0.00	0.00	0.57	0.63	
High Income Storm DS3	Model Quantity (g)	5235	2581	74	6	534	389	18:32
	Model Peak (g/s)	6.36	3.13	0.09	0.01	0.65	0.47	
	Measured Quantity (g)	4480	3741	52	0	814	558	18:36
	Measured Peak (g/s)	3.31	6.28	0.13	0.00	1.57	0.71	
High Income Storm DS5	Model Quantity (g)	1709	842	7	5	145	113	17:04
	Model Peak (g/s)	1.78	0.88	0.01	0.00	0.15	0.12	
	Measured Quantity (g)	3937	1513	18	0	490	270	16:46
	Measured Peak (g/s)	2.84	0.98	0.03	0.00	0.51	0.49	
High Income Storm DS6	Model Quantity (g)	8164	4024	108	13	783	584	19:34
	Model Peak (g/s)	10.07	4.96	0.13	0.02	0.93	0.72	
	Measured Quantity (g)	10227	6195	67	0	741	327	19:26
	Measured Peak (g/s)	14.92	7.17	0.28	0.00	2.14	1.26	
Ethnic Storm OS2	Model Quantity (g)	4339	2537	40	3	177	176	13:28
	Model Peak (g/s)	3.95	2.31	0.04	0.00	0.16	0.16	
	Measured Quantity (g)	5593	2409	25	136	341	370	13:30
	Measured Peak (g/s)	3.00	2.36	0.04	0.29	0.37	0.73	
Ethnic Storm OS4	Model Quantity (g)	4995	2921	41	6	189	192	19:26
	Model Peak (g/s)	4.08	2.39	0.03	0.01	0.15	0.28	
	Measured Quantity (g)	7145	2717	44	0	132	214	19:10
	Measured Peak (g/s)	5.77	1.72	0.11	0.00	0.23	0.27	
Ethnic Storm OS5	Model Quantity (g)	3995	2336	34	5	154	156	12:42
	Model Peak (g/s)	4.00	2.34	0.03	0.00	0.15	0.16	
	Measured Quantity (g)	5241	2543	38	16	92	120	12:20
	Measured Peak (g/s)	2.36	0.82	0.07	0.05	0.31	0.20	

Figure 8-1 shows a comparison of the predicted against measured solid quantities during the storms. A small quantity of scatter is observed following linear regression analysis of the data where a correlation co-efficient of 0.962 was calculated. The gradient of the linear regression analysis indicates that model predicted quantity is 83% of that measured and therefore is under-predicting.

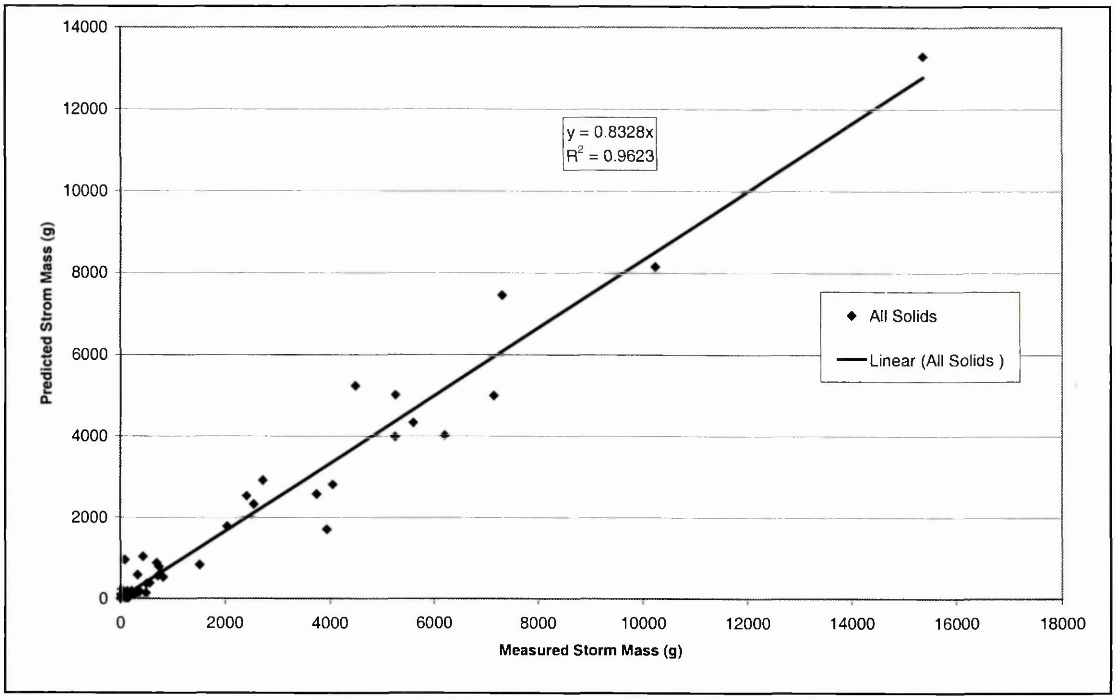


Figure 8-1 Comparison of measured and predicted total mass of solids flushed during storms

Table 8-2 shows the percentage differences between the predicted and measured individual quantities of the solids. The under prediction can be clearly observed for faeces and toilet tissue. The accuracy reduces for the SANPRO solids which coincides with a small sample size for these solid types. An exception to this is tampons sampled at the high income catchment where a larger number were sampled. Overall the accuracy of the results were better at the high income and ethnic catchments compared with the low income catchment. Two particularly large percentage errors were observed at the low income catchment for panty liners and tampons. Due to their low usage and deposited numbers, it is possible that the characterisation of 1 in 4 sacks from the catchment has led to a misrepresentation of the sample results. There were a number of results where less than one solid was predicted compared to no measured data (<1*), in particularly for sanitary towels. This was due to the low number of these solids entering, hence there low sample size.

Table 8-2 Percentage difference of simulated and measured aesthetic pollutant masses sampled during storm events (negative values indicate an under prediction).

Catchment	Storm	Faeces	Toilet Tissue	Panty Liner	Sanitary Towel	Tampons	Wipes
Low Income	GS2	-4	-30	950	-62	-27	-21
	GS3	-13	2	(6*)	-40	1045	138
High Income	DS1	-12	27	(<1*)	(<1*)	25	-99
	DS3	17	-31	42	(<1*)	-34	-30
	DS5	-57	-44	-60	(<1*)	-70	-58
	DS6	-20	-35	60	(<1*)	6	79
Ethnic	OS2	-22	5	60	-98	-48	-52
	OS4	-30	8	-7	(<1*)	43	-10
	OS5	-24	-8	-12	-71	67	30

(<1*) indicates zero solids were measured and less than one whole solid was predicted by the model

(6*) indicates zero solids were measured and approximately six solids was predicted by the model

The variability of the quantity of solids entering and the physical nature of the pollutants are likely to have had a significant effect on the accuracy of the model. This variability was observed on different days that sampling was undertaken in dry weather where the percentage difference from the average values could be ± 40% of the total sampled (as discussed in Chapter 4 and 6). Other factors that will influence the accuracy of the model are the Friedler profiles and the accuracy of the solids stored equations developed in Chapter 5. Figure 8-2 shows the variation of the quantity of faeces sampled at the high income catchment on three separate occasions during a morning period. Figure 8-3 shows the variation of tampons sampled at the high income catchment on three separate evenings. These graphs clearly indicate the variation of solids that can potentially enter the sewer system. In addition not only do the quantity of solids vary, but the physical properties of each solid can vary in size, shape and mass which could influence their transportation. Therefore in the context of the uncontrolled environment of solids entering the sewer, the accuracy of the model is quite reasonable. If it had been possible to collect more data then it is likely that this variability of solids entering could have been demonstrated further.

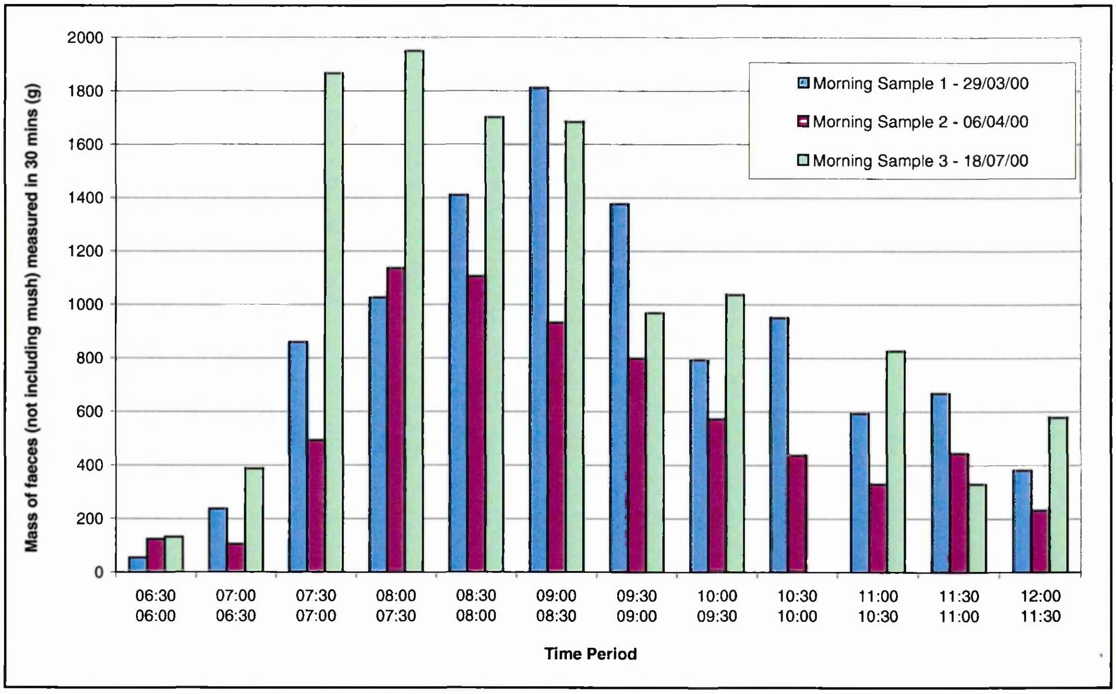


Figure 8-2 Quantity of faeces sampled on three different mornings at the high income catchment.

The accuracy of the model to predict the correct quantities of solids has been grouped together in defined percentage ranges as shown in Figure 8-4. The graph indicates that 30 out of 54 results (56% of results) have a ±30% accuracy and 34 out of 54 results (63% of results) are within ±40%. Overall the model gives a reasonable representation of the quantity of solids that leave the catchments during a first foul flush.

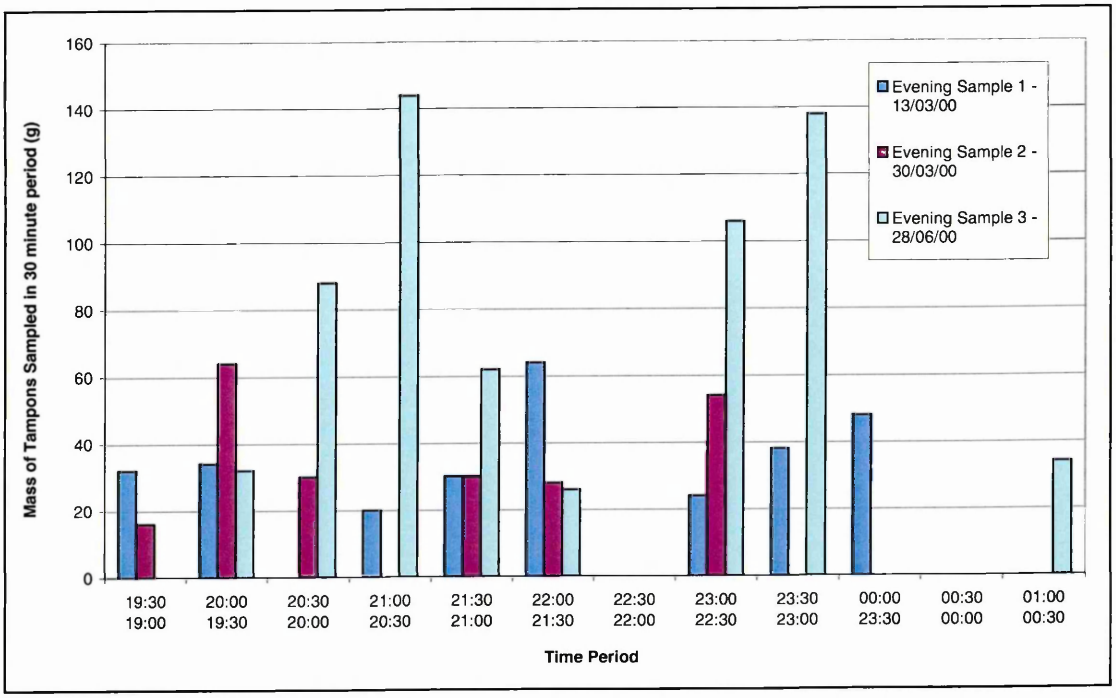


Figure 8-3 Quantity of tampons sampled on three different evenings at the high income catchment.

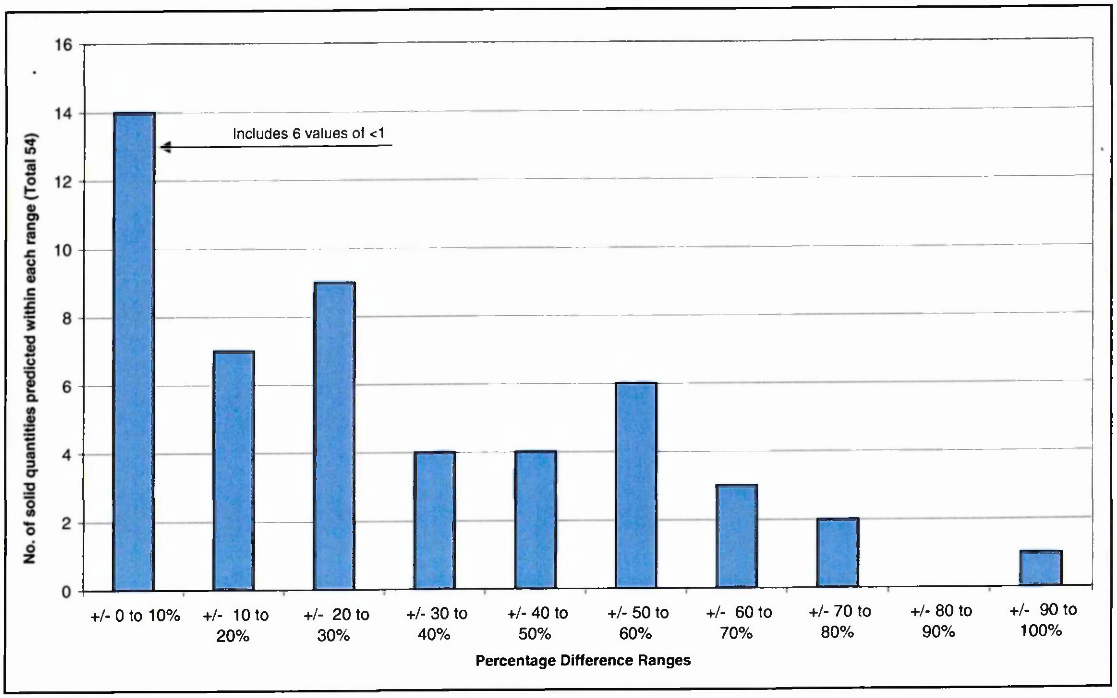


Figure 8-4 Number of storms within percentage difference ranges of the predicted quantities compared to measured

Not shown in Figure 8-4 are 4 of 54 of the storms (7% of results) that are considered to be outliers in the data that are greater than ±100%. All of these quantities occurred at the low income catchment where the level of characterisation was 1 in 4 sacks, compared to the other catchments where all sacks were characterised.

These large differences were due to a very small number of pollutants being measured. Generally this occurred because of the relatively small sample size and the possible un-representative nature of the characterisation particularly during storms at the low income catchment.

8.1.2 Prediction of the peak rate of solids

Another important output from the model is the peak rate at which solids will leave the system. This would be particularly important for CSO screen design. A comparison of predicted against measured peaks are shown in Figure 8-5 where regression analysis is conducted. A poor correlation co-efficient of 0.69 is observed, as there is a large degree of scatter. The resultant gradient of the linear regression analysis indicates that the peak rate on average is under-predicted by 3.5%.

The temporal distributions of the solids leaving the system under storm conditions will all be very similar for each solid type per storm with the magnitude and quantity of solids being the factors that will vary. A number of aesthtographs are shown for different solid types leaving the system in Figures 8-6 to 8-12.

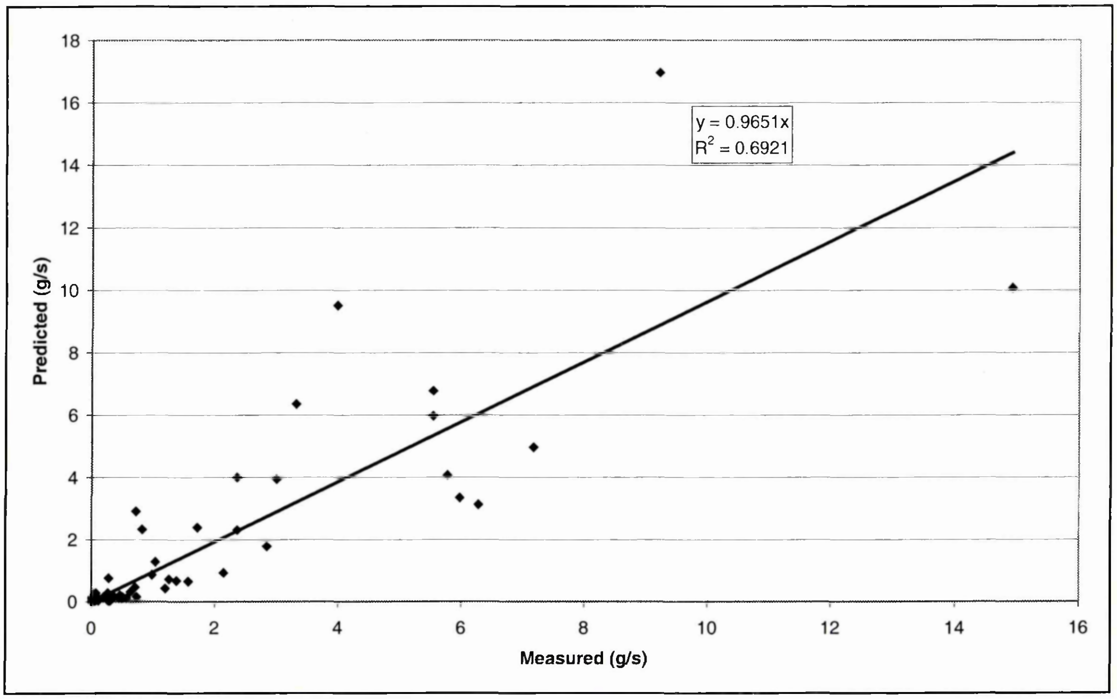


Figure 8-5 Comparison of measured and predicted peak values of the quantity of solids leaving under storm conditions for all solid types.

Generally the model replicates the timing and magnitude of the peak rate of solids leaving the system reasonably well as observed in the Figures 8-6 to 8-12 and Appendix B. At the low income catchment, the results from the models at each sub-catchment have been combined together. This is shown in Figure 8-6 where the results for all solid types were combined and plotted to compare the predicted results against measured data. The model under predicts the peak value by approximately 25%. The timing of the start of the solids flush is very good and a smaller second peak is also observed. The other graphs (Figures 8-7 to 8-12) display the measured and predicted values for different solid types at different sub-catchments.

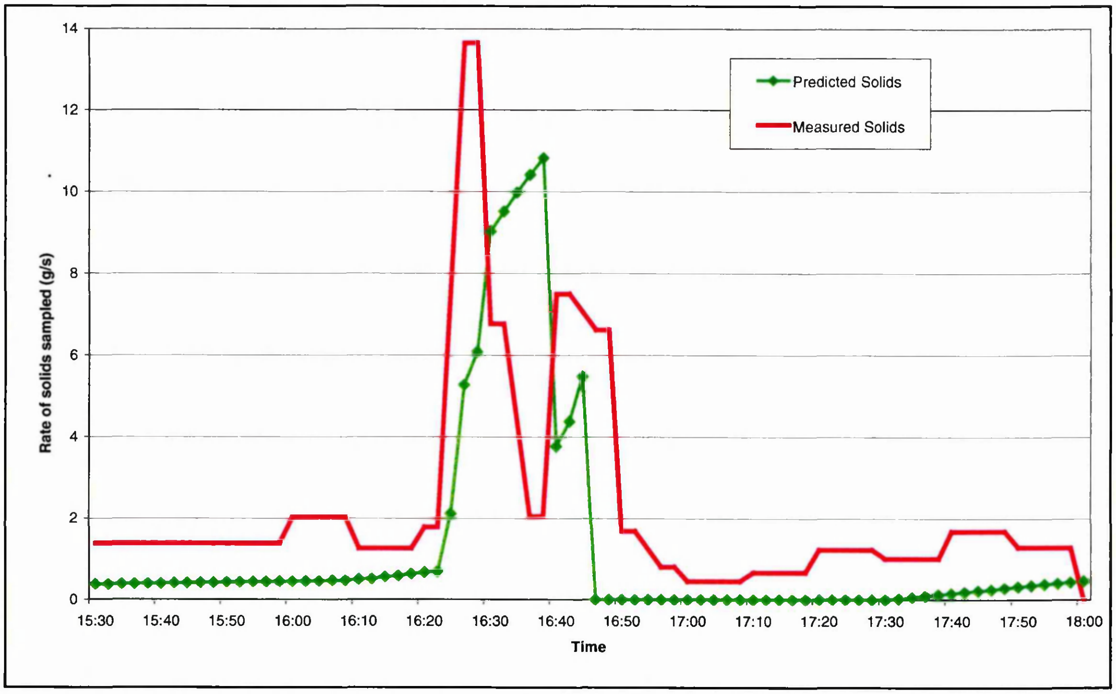


Figure 8-6 Comparison of simulated and measured total quantity of solids for storm GS2 at the Low Income catchment

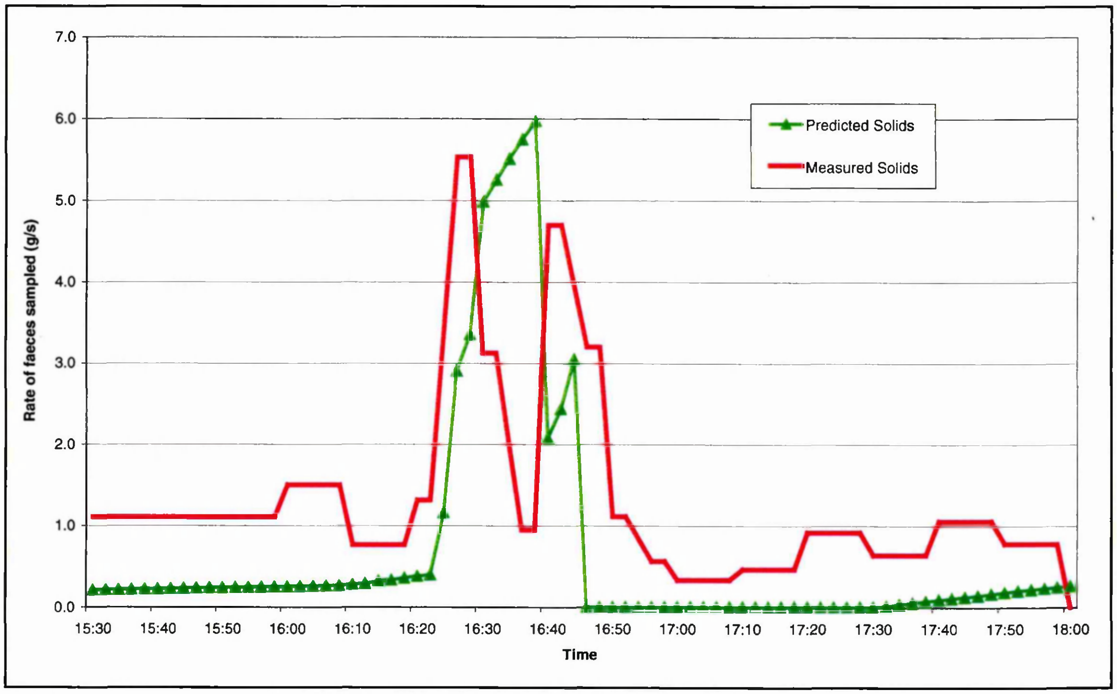


Figure 8-7 Comparison of simulated and measured faeces for storm GS2 at the Low Income catchment

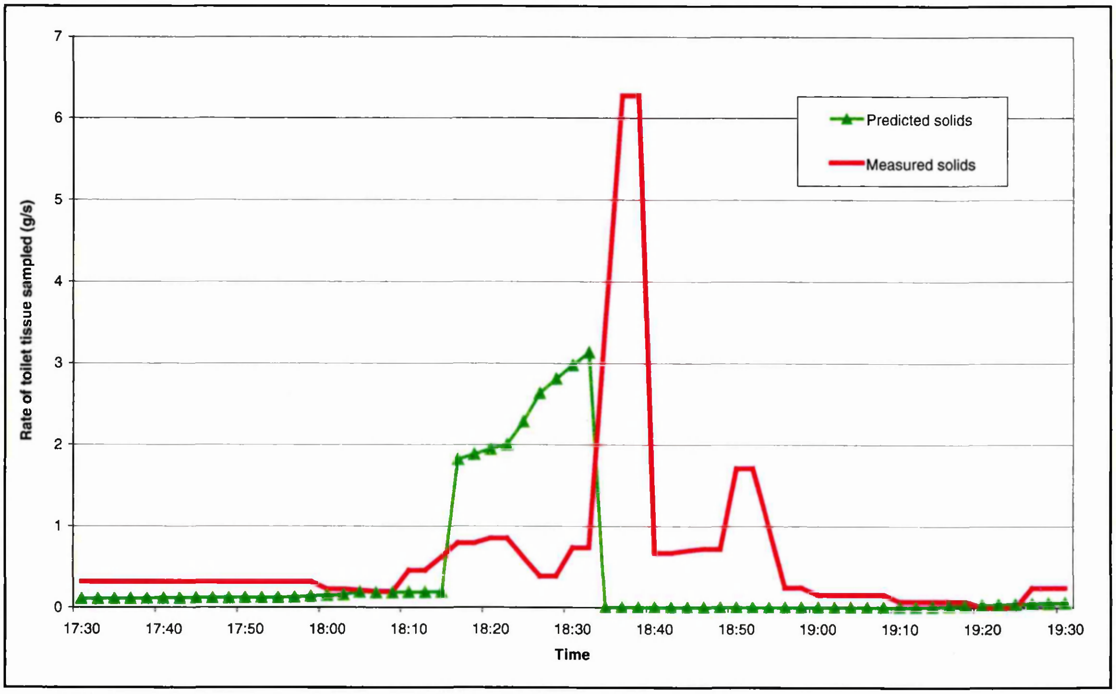


Figure 8-8 Comparison of simulated and measured toilet tissue during storm DS3 at the high income catchment

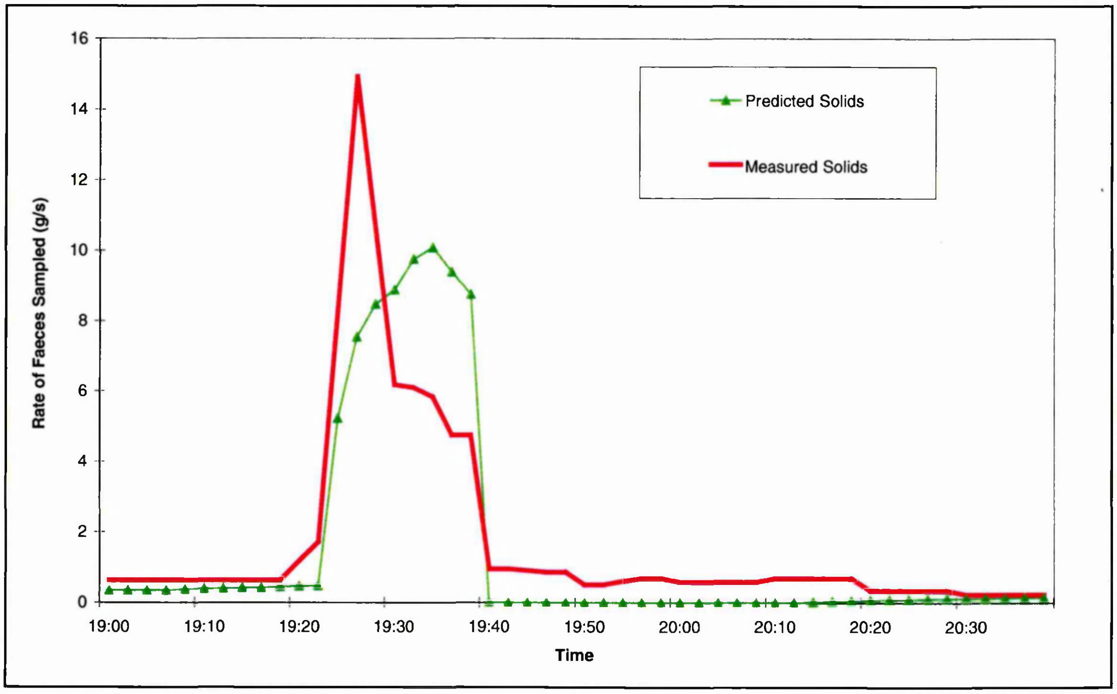


Figure 8-9 Comparison of simulated and measured faeces during storm DS6 at the High Income catchment

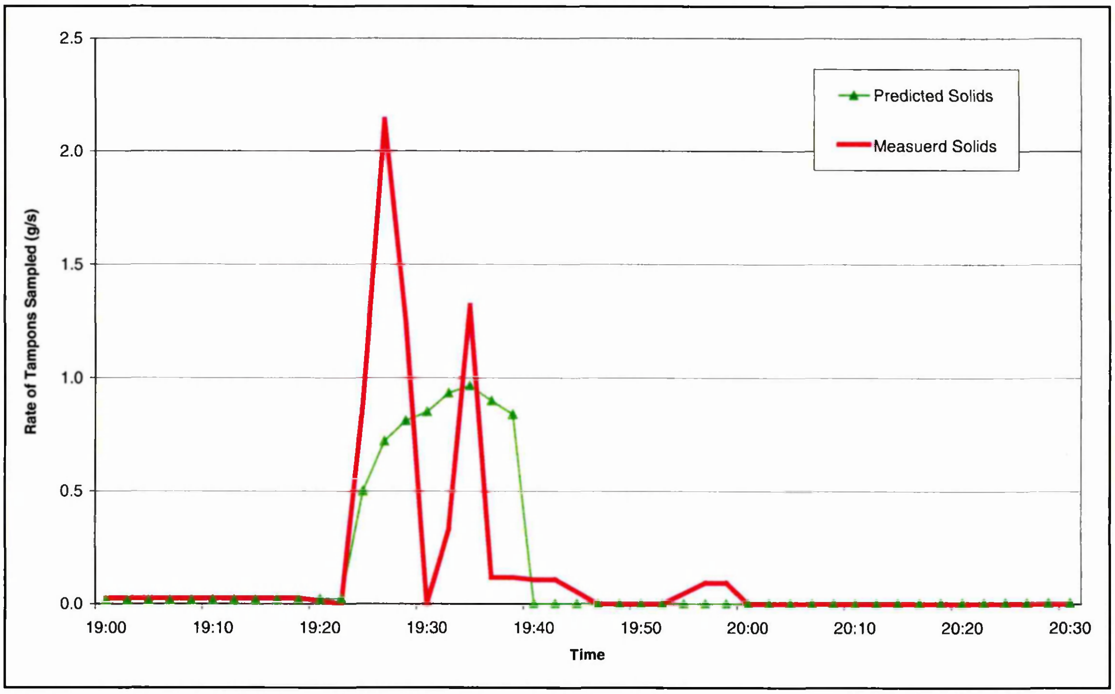


Figure 8-10 Comparison of simulated and measured tampons during storm DS6 at the High Income catchment

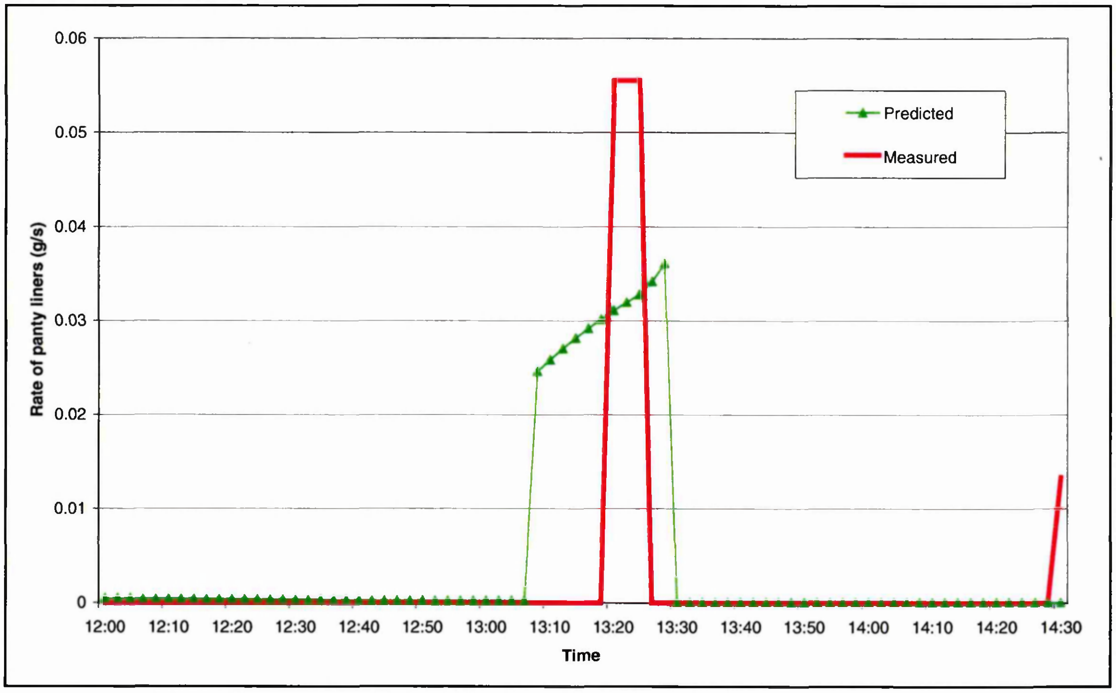


Figure 8-11 Comparison of simulated and measured panty liners during storm OS4 at the Ethnic catchment.

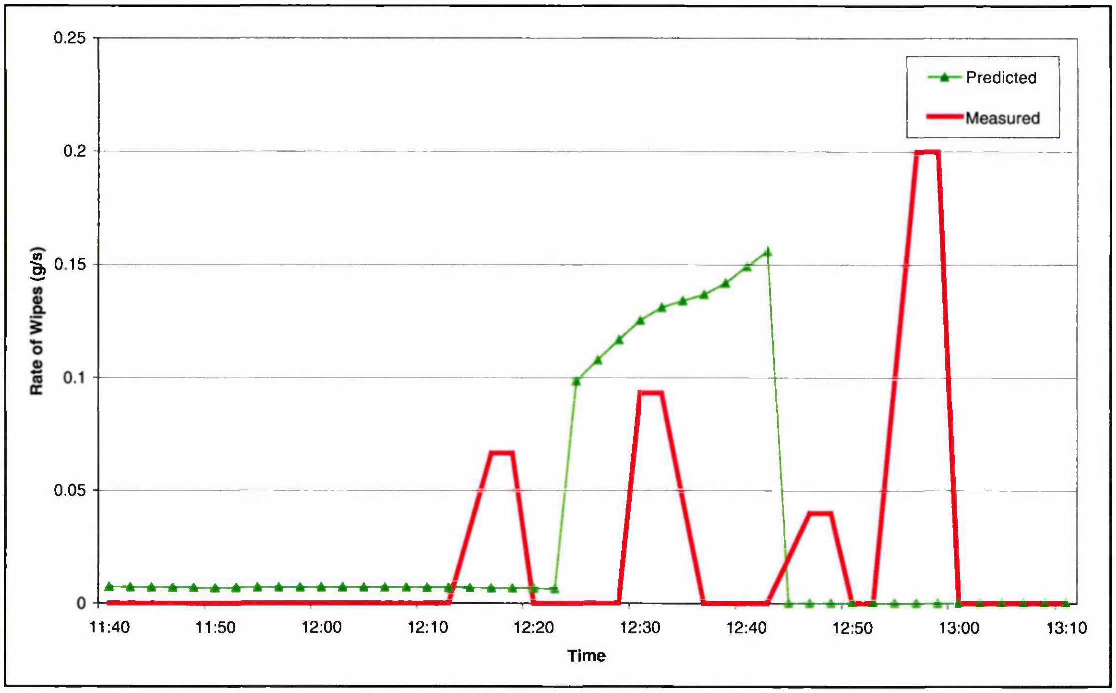


Figure 8-12 Comparison of simulated and measured wipes during storm OS5 at the Ethnic catchment.

Table 8-3 shows a comparison of the predicted individual solid peak values against measured data. The percentage differences clearly show a wide variability in the accuracy already displayed in Figure 8-5. The table also indicates the overall accuracy of the model where the average prediction value is ± 66%. The accuracy improves when a number of the outliers are removed, where 64% of all the results have a mean predictive value of 36% and a standard deviation of 17%.

Table 8-3 The percentage difference between simulated and measured solid peak values for the sampled storms, where negative values indicate an under prediction.

	Solid Types					
Catchment and Storm No.	Feacal	Toilet Tissue	Panty Liner	Sanitary Towel	Tampon	Wipes
Low Income GS2	8	-44	275	-73	-64	-51
Low Income GS3	85	139	N/A	-53	174	25
High Income DS1	22	307	N/A	N/A	-78	-50
High Income DS3	92	-50	-29	N/A	-59	-33
High Income DS5	-37	-11	-63	N/A	-70	-76
High Income DS6	-33	-31	-52	N/A	-56	-43
Ethnic OS2	32	-2	-18	-99	-57	-78
Ethnic OS4	-29	39	-70	N/A	-32	6
Ethnic OS5	70	185	-50	-91	-50	-22

STATISTICS SUMMARY (Only considering the percentage difference, not whether it is under or over predicited)

Percentage Difference Ranges	+ / - 310%	+ / - 200%	+ / - 150 %	+ / - 100%	+ / - 70%
Count	47	45	43	42	30
Count as a Percentage of all results	100	96	91	89	64
Mean	66	56	51	48	36
Standard Deviation	61	37	28	25	17

Colour Legend:

Orange = Values between + / - 310% and 200%

Green = Values between + / - 200% and 150

Purple = Values between + / - 150% and 100%

Turquoise = Values between + / - 100% and

Clear = Values + / - 70%

The best simulated peak rate results were observed at the ethnic catchment. The mean percentage difference at the ethnic catchment and high income catchment for the sampled storms is 55% and 63% respectively. In comparison, the mean percentage difference at the low income catchment is 90%. At the low income catchment there is the potential that the characterised data was not fully representative of what was collected during storm sampling. Considering the measurement errors discussed earlier these results indicate the model as a useful tool to predict the quantity and temporal distribution of solids under storm conditions is reasonable.

8.2 Model Summary

The accuracy of the model to predict the peak rate of solids leaving the model is dependent upon the ability of the model to predict the correct quantity of solids in the system and the dry weather volume prior to the start of the storm. The other consideration is that there is a large daily variation in the quantity, type and timing of solids entering, and in their physical nature. Within this context the accuracy of the model to predict the peak rate and duration of the solids flush is favourable. The model is good at predicting the quantity of solids flushed under storm conditions. Also the model importantly predicts the timing of when solids leave upstream combined sewerage systems during storm events.

9 Chapter 9 - Conclusions and Recommendations

9.1 Introduction

At the start of this project a number of key objectives were set out as described in Chapter 1. In summary these were to:

- Gain an understanding of aesthetic pollutant movement and their characteristics through a programme of field monitoring.
- Gain an understanding of the influence of socio-economic and ethnic factors on the production of aesthetic pollutants.
- Gain an understanding of how catchment characteristics have an effect on solid transportation.
- To build and verify a solid transportation model.

To achieve these objectives, two main phases of work were undertaken. The first phase concentrated in collecting and analysing field data through a dedicated programme of flow monitoring and in sewer sampling of aesthetic pollutants. This programme was undertaken in three different catchments that contained different population types. Analysis of this data was undertaken to estimate the quantity of solids that can be stored in dry weather. The second phase built upon the knowledge obtained from a programme of fieldwork to develop a solid transportation model. The model initially used empirical data to calibrate and verify the flow and solid transportation techniques. A solid input model was then developed that enabled the model to be compared against measured data for individual solid types.

9.2 Main Conclusions

1. A methodology has been developed to sample aesthetic pollutants from sewerage systems. The methodology enables all the solids within the flow to be sampled. It allows individual solid quantities, temporal distributions and characteristics to be determined. This technique has been proven to work during low flows in dry weather and the higher flows found in wet weather.

2. Clear diurnal distributions of faeces and toilet tissue have been observed within the sewer system from different population types. Different population types produce and dispose of different quantities of solids. Faeces and toilet tissue account for over 80% of all solids sampled.

3. Clear diurnal distributions for the remaining solid types, sanitary towels, tampons, panty liners and wipes, are not as apparent. Sampling identified that different population types dispose of different sanitary products.

4. The quantity of solids sampled during dry weather can vary from day to day by approximately ±40% from a calculated mean value.

5. A first foul flush of solids has been measured at all catchments under storm conditions. This flush occurs when the flows reach approximately 1.5 – 2 times the peak dry weather flow. The first foul flush was generally observed within the rising limb of the hydrograph.

6. It can be inferred from analysis of the solids sampled during the first foul flush that solids are either in motion during dry weather or have been deposited on the sewer bed prior to a storm

7. The quantities of solids flushed during a storm are dependent on the time of day and the preceding antecedent dry weather period. The longer the antecedent dry weather period the larger the quantity of solids likely to be sampled during storm.

8. Relationships have been developed that link the antecedent dry weather period and housing density with the mass stored expressed as a proportion of the mass entering in one day.

9. A solid input and transportation model has been developed that predicts the rate of solids leaving small upstream sewer networks under dry weather and storm conditions. The solids' transportation model uses two different solid movement techniques to represent solids' movement during dry and wet weather.

10. The solids' transportation model has been calibrated and independently verified using data from three catchments.

11. The solid transportation model more accurately represents the movement of faeces and toilet tissue than other solids. Overall the model reasonably represents all solids leaving upstream catchments with an accuracy of ± 66% for all simulations and ± 36% for 64% of the storms simulated. This is reasonable when the variation of the solids entering is taken into account. The model clearly replicates a first foul flush under storm conditions.

12. The model has the ability to predict the quantity of solids that could enter an upstream CSO, for six different solid types. The model has been joined together with a solid tracker model (developed by Imperial College) to produce GROSSIM, a tool that can be used to predict solid movement throughout a large sewer network. This can be used to predict the quantity of solids at any point in a modelled sewer system, in particular at a CSO and help in the selection of the most suitable CSO screens.

9.3 Further Work and Recommendations

The development of the model and sampling work formed part of a larger project as discussed in Chapter 1. The reservoir model has been integrated into a solid tracker model developed by Imperial College. The solid tracker model replicates the individual movement of solids through a hydraulically modelled catchment using sewer network, flow, velocity and depth files that enable it to determine when a solid is deposited, mobilised and the time taken for it to be transported through a system. Hydraulic models constructed in the UK do not model every pipe in the sewer network with many of the upstream pipes excluded. A typical cut off for the models are those pipes that are 300 mm or smaller although many models are curtailed with larger diameter sewers at the upstream end. To represent the large contributions of solids entering in these upstream areas, particularly as a result of solids stored in dry weather, the reservoir model developed as part of this work has been used to represent the private drainage and un-modelled sewer system. This enables solids movement to be represented in un-modelled systems, importantly providing a temporal distribution of solids to enter the solids tracker model. The algorithms used in the spreadsheet based reservoir model have been programmed to form a joint model called GROSSIM. GROSSIM also has the capability to represent the discharge of solids from CSOs.

Following the completion of the development of the reservoir model and GROSSIM, the GROSSIM model is currently being assessed by industry to aid the design of CSOs, particularly with the use of storage tanks retaining the first foul flush. GROSSIM has already been used to predict the quantity of solids being retained in a tank downstream of a CSO. This has led to the selection of a more cost effective solution at a failing CSO by reducing the screen cost. Dissemination of the model has been undertaken with a UKWIR seminar to water company representatives (Butler et al 2002). A number of papers have been published and presented (Saul et al 1999, Digman 2001, Digman et al 2001 and Digman et al 2002) that present the research findings from the project and the GROSSIM model (see Appendix C). The reservoir model has formed an important part of the GROSSIM model.

The model constructed as part of this work and GROSSIM has been calibrated and verified against three catchments with different population types and catchment characteristics. Further sampling would enable the model to be tested against other catchments. The types of catchments where further sampling may be beneficial can be split into two categories. The first type of catchment are those that contain similar catchment characteristics and population types to confirm the quantities and pollutants measured during this work. The second type of catchment would be a flatter area that was not sampled as part of this work. This type of catchment would enable an investigation into whether the gradient of the catchment influences the deposition of solids. Work at other catchments would also hopefully sample longer duration ADWP storms.

9.4 Summary

A simplified modelling approach for replicating flows and aesthetic pollutant loads in small upstream sewerage systems has been developed. The model has been compared with measured values and clearly demonstrates with reasonable accuracy the ability to predict the quantity and temporal distribution of aesthetics discharged from combined sewerage systems. This has enabled the simulation of a first foul flush of pollutants under storm conditions that is known to occur in urban drainage systems.

The model can be used to predict the quantity and temporal distribution of six solid types that could enter a CSO under storm conditions from upstream combined sewerage systems. This model has been incorporated into GROSSIM, which can be used by industry to aid the selection of screens in CSOs to develop more cost effective solutions in comparison with current design philosophy based upon flow loadings to screens.

References

Ackers, P, Harrison, A. J. M., and Brewer, A. J. (1967) *Laboratory studies of storm overflow with unsteady flow*, Institution of Civil Engineers - Symposium on Storm Sewage Overflows, 1967, London, 37-50

Ainger, C. M., Armstrong, R. J., and Butler, D. (1998) *Dry weather flows in sewers*. Report 177, CIRIA.

Amin, N. U. (1996) *Use and Management of public open spaces with particular reference to the Pakistani Community in Sheffield*, University of Sheffield.

Arthur, S. and Ashley, R. M. (1998) *The Importance of Near Bed Solids Transport in Sewers*. Wat. Sci and Tech,

Ashley, R. M., Souter, N., Dunkerley, J., Hendry, S, Blackwood, D. J., Moir, J., Davies, J. W., Cook, A., and Butler, D. (1999) *Domestic Sanitary Waste DIsposal: Sustainability of Alternative Strategies*. EPSRC Towards Sustainable Cities: Grant Reference GR/K62125, GR/K63375, GR/K63269.

Babaeyan-Koopaei, K., Butler, D., and Davies, J. W. (1999) *Modelling of Gross Solids Transport in Sewers*. 8th International Conference on Urban Storm Drainage, 1999, Sydney, Australia.

Baker, B. and Binnie, A. R. (1891) *Main Drainage of London - Joint report*. London County Council, London.

Balmforth, D. J. and Henderson, R. J. (1988) *Guide to the Design of Combined Sewer Overflows*. Report ER 304E, WRc.

Balmforth, D. J. and Meeds, E. H. (1997) *The Potential for Predicting Aesthetic Pollutants*. WaPUG97, England, Blackpool, 1997

Balmforth, D. J. (1999) *CSO's: To screen or not to screen?* HYDRO International Seminar – Scotland, February 1999.

Balmforth, D. J., Butler, D., Davies, J. W., Meadowcroft, J., and Saul, A. J. (1998) *EPSRC/WITE Case for Support - Predicting Aesthetic Pollutant Loadings from Combined Sewer Overflows*, Sheffield Hallam University, 1998

Balmforth, D. J., Saul, A. J., and Clifforde, I. T. (1994) *A Guide to the Design of Combined Sewer Overflow Structures*. FWR Report No. FR0488, FWR.

Balmforth,D.J., Lonsdale,K., Nussey,B.B., and Walsh,M. (1995*) A Methodology for Monitoring the Performance of Combined Sewer Overflows*. JICWEM.

BBC Education. (2000) *Medicine Through Time, Prehistory and Ancient World, Public Health*. http://www.bbc.co.uk/education/medicine/nonint/prehist/ph/prphcs1.shtml

Bertrand-Krajewski,J.L. (1992) *A model for solids production and transportation for small urban catchments: Preliminary results*. Wat.Sci.Tech. 25 (8), 29-35.

Binnie, A. R. (1899) *Report Upon the Main Drainage of London - 1899.* London County Council, London.

Birch, T. (2001) *Sewerage system in the Ethnic Catchment*, Personal communication.

Brown, D. M., Butler, D., Orman, N. R., and Davies, J. W. (1995) *Gross Solids Transport in Small Diameter Sewers*, Proc. of Int. Conf. on Sewer Solids, 1995,129-133

Brown,D.M., Butler,D., Orman,N.R., and Davies,J.W. (1996*) Gross solids transport in small diameter sewers.* Water Science & Technology 33 (9), 25-30.

Butler,D. (1991) *A Small-Scale Study of Wastewater Discharges from Domestic Appliances.* JIWEM 5 (April), 178-185.

Butler,D. and Davies,J.W. (2000) *Urban Drainage.*, E & FN Spon.

Butler,D., May,R.W.P., and Ackers,J.C. (1996) *Sediment transport in sewers Part 1: Background.* Proc.Instn Civ.Engrs Wat.Marit.& Energy 118 (June), 103-112.

Butler, D., Saul, A.J., Balmforth, D.J., Digman, C.J., Littlewood, K., Houldsworth, J.K. (2002) *"Predicting Aesthetic Pollutant Loadings from Combined Sewer Overflow"*, Presentation to UKWIR water company representatives, London, May 2002.

Burkitt D. P., Walker A. R. P., Painter N. S. (1972). *Effect of dietary fibre on stools and transit times, and its role in the causation of disease.* The Lancet, December 30, 1972, 1408-1411.

Chadwick, E. (1842) *Report on the Sanitary Condition of the Labouring Population of Great Britain.* London.

Cootes, T. F. (1990) *The Field Testing of a Vortex Storm Overflow.* PhD Thesis, Sheffield City Polytechnic.

Crabtree,R.W. (1989) *Sediments in Sewers.* JIWEM 3 (6), 569-578.

Davies, J. W. and Sekuloski, V. (1996) *Advection and Deposition of Gross Solids in Sewers - A laboratory Study.* 7th International Conference on Urban Storm Drainage. 1996, Hannover, Germany, 839-844.

Davies, J. W. (1987) *Laboratory Study Related to the First Foul Flush in Combined Sewers.* Fourth International Conference on Urban Storm Drainage, 198, 747-48.

Davies, J. W. (1990) *Laboratory study related to the modelling of stormwater quality in combined sewers.* Int. Proc. of 5th Int. Conf. on Urban Storm Drainage, 1990, 215-219.

Davies, J. W., Xu, Y. L., and Butler, D. (1995) *Laboratory Study and Computer Model Development Related to Gross Solids' Movement in Combined Sewers.* Proc. of Int. Conf. on Sewer Solids, 1995.

Davies,J.W., Butler,D., and Xu,Y.L. (1996a) *Gross Solids' Movement in Sewers: Laboratory Studies as a Basis for a Model.* JICWEM 10 (February), 52-58.

Davies,J.W., Butler,D., and Xu,Y.L. (1996b) *Gross solids' movement in sewers: laboratory studies as a basis for a model.* Water and Environmental Management 10 (1), 52-58.

Davies,J.W., Butler,D., Small,J.L., Sekuloski,V., and Jefferies,C. (1998a*) Gross solids transport and degradation.* Water Science & Technology 37 (1), 61-68.

Davies,J.W., Sekuloski,V., and Butler,D. (1998b) *Inclusion of Gross Solids Advection and Deposition in Urban Drainage Models.* Wat.Sci.Tech. 365-372.

Dept.of Scientific & Industrial Research. (1964) *Effects of Polluting Discharges on the Thames Estuary.* Water Pollution Research - Technical Paper No. 11. 1964. London, HMSO.

Detectronics. (1992) *IS Survey Logger and Rain Logger Manual.*

Digman, C.J. (2001) *Predicting Aesthetic Pollutant Loadings in Combined Sewerage Systems* CIWEM Young Authors Competition – Tyne and Humber Branch, Leeds, 2001

Digman, C. J., Spence, K. J., and Balmforth, D. J. (2001) *Aesthetic Pollutant Loadings in Small Upstream Combined Sewerage Systems.*. Novatech 2001 - Innovative Technologies in Urban Drainage. Lyon, France 2001, 219-226

Digman C.J., Littlewood K., Butler D., Spence K.J., Balmforth D.J., Davies, J., Schütze M. (2002) *A Model to Predict the Temporal Distribution of Gross Solids Loading in Combined Sewerage Systems* 9th Int. Conf on Urban Drainage, Portland, Oregan, 2002

Environment Agency. (2000) *Achieving the Quality.*

EU Directive No.91/271/EEC (1991) *Urban Waste Water Treatment Directive.* Official Journal L135 40.

Friedler, E. (2000) *Raw data used in the 'Study of WC Derived Sewer Solids' by Friedler,E.; Brown,D. and Butler,D (1996),* Personal Communication

Friedler,E., Brown,D.M., and Butler,D. (1996) *A Study of WC Derived Sewer Solids.* Wat.Sci.Tech.

FWR. (1994) *Final Summary Report on Aesthetic Pollution.* Report FR 0440, 1994, FWR.

FWR. (1998) *Urban Pollution Management Manual - Second Edition.* FWR.

Gayman, M.A. (2000) *Glimpse into London's Early Sewers.* http://swopnet.com/engr/londonsewers/londontext1.html ..

Health and Safety Commision. (1997) *Confined Spaces Regulations.* Health and Safety Executive.

Houldsworth, J. K. (2002) *Predicitng Aesthetic Pollutant Loadings from Combined Sewer Overflows - Steering Group Report March 2002*, EPSRC Grant GR/M16337.

Houldsworth, J. K. (2000a) *Predicitng Aesthetic Pollutant Loadings from Combined Sewer Overflows Steering Group Report – February 2000*, EPSRC Grant GR/M16337.

Houldsworth, J. K. (1999a) *Predicitng Aesthetic Pollutant Loadings from Combined Sewer Overflows Steering Group Report – June 1999*, EPSRC Grant GR/M16337.

Houldsworth, J. K. (2000b) *Prediciting Aesthetic Pollutant Loadings from Combined Sewer Overflows Steering Group Report – June 2000*, EPSRC Grant GR/M16337.

Houldsworth, J. K. (2001) *Prediciting Aesthetic Pollutant Loadings from Combined Sewer Overflows Steering Group Report – March 2001*, EPSRC Grant GR/M16337.

Houldsworth, J. K. (1999b) *Prediciting Aesthetic Pollutant Loadings from Combined Sewer Overflows Steering Group Report – June 1999*, EPSRC Grant GR/M16337.

Humphries, G. W. (1930) *Main Drainage of London - Descriptive Account.* London City Council, London.

Hydraulics Research Station. (1965) *Hydraulics Research 1964*. London, HMSO.

Jefferies, C. and Ashley, R. M. (1994) *Gross Solids in Sewer Systems – Temporal and Catchment Based Relationships.* IAWQ 17th Biennial Conference, Budapest, Hungary, 1994

Jefferies,C. (1992) *Methods of Estimating the Discharge of Gross Solids from Combined Sewer Systems.* Wat.Sci.Tech. 26 (5-6), 1295-1304.

London County Council. (1909) *Main Drainage of London - General Description 1909.* LCC Library No. G106, London.

Meeds, E. H. (1995) *Investigation of the Performance of Combined Sewer Overflows Screens.* PhD Thesis, Sheffield Hallam University.

Milne, D. A., Jefferies, C., and Ashley, R. M. (1995) *Pollutional Aspects of Gross Solids and Their Interaction with Sewer Sediments..* Proc. The Int. Conf. on Sewer Solids - Characteristics, Movement, and Control, Dundee, 1995

Milne, I. and Clarke, S. J. (1994) *User Guide for Assessing the Impact of Combined Sewer Overflows.* Report FR0466. FWR.

Milne,D.A., Jefferies,C., and Ashley,R.M. (1996) *Pollutional aspects of gross solids and their interaction with sewer sediments.* Water Science & Technology 33 (9), 31-37.

Ministry Of Housing and Local Government (1970) *Technical Committee on Storm Overflows and the Disposal of Storm Sewage.* Final report.

Mutzner, H. (1987) *Visible Pollution from Combined Sewer Overflows.* Proc. 4th ICUSD, Lausanne, 1987

National Bag It and Bin It Campaign. (1995) *National Bag It and Bin It Campaign 1995.* Leedex Public Relations, London

National Rivers Authority. (1993) *General Guidance Note for Preparatory Work for AMP2.* Version 2.

OFWAT (1999). *Final Determinations - Future Water and sewerage charges 2000-05.*

O'Kelly, L. (1992) *Disposable Assets.* Cosmopolitan.

Pisano, W. C. (1995) *Summary; United States "Sewer Solids" Settling Characterization Methods, Results, Uses and Perspective.*

Porter,D. (1999) *Health, Civilization and the State – A history of public health from ancient to modern times.* Routledge, London.

Reed, E. C. (1982) *The assessment of the problem in the UK.* Restoration of Sewerage Systems - Proc. Int. Conf organised by the Inst. of Civ. Eng, Thomas Telford Ltd, London.

Russac,D.A.V., Rushton,K.R., and Simpson,R.J. (1991) *Insights into domestic demand from a metering trial.* JIWEM 5 (3), 342-351.
Saul, A. J., Gupta, K., and Stovin, V. R. (1998) *Gross Solids Characteristics and an Event-Based CSO Efficiency Prediction Methodology.* UDM98.

Saul,A.J. (1998) *CSO State of the Art Review: A UK Perspective.* Wat.Sci.Tech.

Schütze, M., Butler, D., Davies, J. W., and Jefferies, C. (2000) *Modelling Aesthetic Pollution in Sewer Systems.* 1st International Conference on Urban Drainage on the Internet, 2000

Schütze,M., Butler, D., and Beck, M.B. (2002) *Modelling, simulation and Control of Urban Wastewater Systems,* Springer Verlag.

Shaw,E.L. (1994) *Hydrology in Practice.* Chapmann & Hall, London.

Souter, N., Ashley, R. M., Dunkerley, J., Hendry, S, Blackwood, D. J., Moir, J., Davies, J. W., Cook, A., and Butler, D. (1999) *Why Bagging Sanitary Waste is more Sustainable than Flushing.* Hydro International Conference, February 1999.

Stasse-Wolthuis M., Hautvast J. G., Hermus R. J., Katan M. B., Bausch J. E., Rietberg-Brussaard J. H., Velema J. P., Zondervan J. H., Eastwood M. A. and Brydon W. G. (1979). *The effect of a natural high-fiber diet on serum lipids, faecal lipids and colonic function.* The American Journal of Clinical Nutrition, 32(9), September, 1979, 1881-1888.

Stovin,V.R., Saul,A.J., Drinkwater,A., and Clifforde,I. (1999*) Field testing CFD-based predictions of storage chamber gross solids separation efficiency.* Water Science & Technology 39 (9), 161-168.

theplumber.com. (2000) *The History of Plumbing – Greece.* http://www.theplumber.com/greek.html . 2000.

theplumber.com. (2000) *The History of Plumbing – Jerusalem.* http://www.theplumber.com/jerus.html . 2000.

Tyak, J. N., Hedges, P. D., and Smisson, R. P. M. (1995) *A Study of the Relationship Between Settling Velocity Grading and the Characteristics of the Contributing Catchment.*

UK Government. (1994) *The Urban Waste Water Treatment (England and Wales) Regulations 1994.* No. 2841.
UKWIR. (1995) *Design of Combined Sewer Overflows to Meet the Aesthetic Regulatory Requirements.* WW-01 Combined Sewer Overflows, UKWIR.

UKWIR. (1997) *Development of Software for Aesthetic Design of Combined Sewer Overflows.* 97/WW-01/1 Combined Sewer Overflows, UKWIR.

Vaes,G. and Berlamont,J. (1998) Modelling of Overflow Emissions in Flanders. Wat.Sci.Tech. 38, (10), 41-48.

Wastewater Planning Users Group (1998) *Code of practice for the hydraulic modelling of sewer systems.* Wastewater Planning Users Group.

Wilson,E.M. (1990) *Engineering Hydrology,* 4th Edition, MacMillan, London

Woodward, P. (2000) *Yorkshire Water consumption figures for the low income, high income and ethnic catchments.* Personal Communication, 2000

Scottish Development Department. (1977) *Storm sewage: separation and disposal.* Report of Scottish Working Party on storm sewage, Edinburgh, HMSO

WRc (1987) *A guide to short term flow surveys of sewer systems.* WRc Engineering.

WRc. (1994) *Sewerage Rehabilitation Manual.* Volume 2. WRc.

Bibliography

Arthur, S., Ashley, R. M., and Nalluri, C. (1995) *Near Bed Solids Transport In Sewers*. Proc. of Int. Conf. on Sewer Solids, 1995

Arthur,S. and Ashley,R.M. (1998*) The influenceof near bed solids transport on first foul flush in combined sewers*. Wat.Sci.Tech. 17 (1), 131-138.

Arthur,S., Ashley,R.M., Tait,S., and Nalluri,C. (1999) *Sediment transport in sewers - a step towards the design of sewers to control sediment problems*. Proc.Instn Civ.Engrs Wat.Marit.& Energy 136 (March), 9-19.

Ashley,R.M., Arthur,S., Coghlan,B.P., and McGregor,I. (1994) *Fluid sediment in combined sewers*. Wat.Sci.Tech. 29 (1-2), 113-123.

Ashley,R.M., Wotherspoon,D.J.J., Coghlan,B.P., and McKeown,J. (1992) *The Erosion and Movement of Sediments and Associated Pollutants in Combined Sewers*. Wat.Sci.Tech. 25 (8), 101-114.

Balmforth, D. J., Blanksby, J. R., and Jackson, M. (1998) *CSO Design Guide and Aesthetisizer User Guide*. UK Water Industry Research Ltd.

Bhargava,D.S. and Rajogopal,K. (1992) *Simplified procedure for calculating particle settling velocities*. Proceedings of the Institution of Civil Engineers: Water Maritime and Energy 55-57.

Blanksby, J. R. (2001) *Neutrally buoyant range for aesthetic pollutants*. Personal Communication, 2001.

Chadwick,A. and Morfett,J. (1986) *Hydraulics in Engineering.*, Allen & Unwin.

Coghlan,B.P., Ashley,R.M., and Smith,G.M. (1996) *Empirical Equations for Solids Transport in Combined Sewers*. Wat.Sci.Tech. 33 (9), 77-84.

Cootes,T., Balmforth,D.J., Russell,S., and Doughty,G.M. (1990) Monitoring a vortex storm sewage overflow with peripheral spill. *Water Science & Technology* 22 (10/11), 189-195.

Digman, C. J. and Littlewood, K. (2001) *Predicitng Aesthetic Pollutant Loadings from Combined Sewer Overflows - Joint Steering Group Report December 2001*, EPSRC Grant GR/M16795.

Digman, C. J. (2000) *Predicitng Aesthetic Pollutant Loadings from Combined Sewer Overflows - Steering Group Report June 2000*, EPSRC Grant GR/M16795.

Digman, C. J. (2001) *Predicitng Aesthetic Pollutant Loadings from Combined Sewer Overflows - Steering Group Report March 2001*, EPSRC Grant GR/M16795..

Digman, C. J. (2001) *Predicitng Aesthetic Pollutant Loadings from Combined Sewer Overflows - Steering Group Report September 2001*, EPSRC Grant GR/M16795.

Dinius, S.H., (1981) *Public Perception in Water Quality Evaluation.* Water Resources Bulletin, Vol 17

Ellis, J.B. (1977) *The characteirsation of particulate solids and quallity of water discharged from an urban catchment.* Proc. IAHS-UNESCO, IAHS publ No. 123, Amstredam, 1977.

FWR (1994) *Urban Pollution Management Manual: A planning guide for the management of urban wastewater discharges during wet weather.* FWR

Geiger, W.F. (1984) *Characteristics of combined sewer runoff* Proc. Third International Conf. On Urban Storm Drainage, Goteburg, Sweden, 1984.

Gupta, K. and Saul, A. J. (1995) *Suspended solids in combined sewer flows.* Proc. of Int. Conf. on Sewer Solids. (1995) 312-319

Haddon, M., (1995) *Out of sight? Out of your mind,* Water Bulletin, 17 Feb 1995.

Hedley, G. and King, M.V., (1971) *Suggested correlations between Storm Sewage Overflow Characteristics and Storm Overflow performance.* Proc. Inst. Civil Engineers, Vol. 48, pp 399-411.

House, M. A. (1994) *Public Perceptions of Aesthetic Pollution.* FWR.

Jefferies,C. and Ashley,R.M. (1994) *The behaviour of gross solids in sewer systems.* European Water Pollution Control 4 (5), 11-17.

Jefferies,C., Allinson,C.L., and McKeown,J. (1998) *The performance of a novel combined sewer overflow with perforated conical screen.* Water Science & Technology 37 (1), 243-250.

Littlewood, K. (2001) *Predicitng Aesthetic Pollutant Loadings from Combined Sewer Overflows - Steering Group Report September 2001.*

May,R.W.P. (1994) Self Cleansing Sewer Gradients. *JIWEM* **8** (August), 360-361.

Morris, G. (1991) *Consent standards for storm sewage overflows.* Proc. Seminar Storm Overlfows – Practice and Performance, Birmingham University and Hydro Research and Development, April 1991.

Realey G., (1995) *A chamber of horrors.* Water Bulletin

Sadgrove, J., (1992) *The protection racket.* The Guardian, Tuesday June 9 1992.

Saul, A. J., Gupta, K., and Stovin, V. R. (1998) *Gross Solids Characteristics and an Event-Based CSO Efficiency Prediction Methodology.* UDM98.

Saul, A. J., Houldsworth, J. K., Meadowcroft, J., Balmforth, D. J. , Digman, C. J., Butler, D., and Davies, J. W. (1999) *Predicitng Aesthetic Pollutant loadings from Combined Sewer Overflows..* 8th International Conference on Urban Storm Drainage, Sydney, Australia, 1999

Saul,A.J. and Harwood,R. (1998) *Gross solid retention efficiency of hydrodynamic separator CSOs.* Proceedings of the Institution of Civil Engineers.Water 130 (2), 70-83.

Schütze, M. (2000) *Predicting Aesthetic Pollutant Loadings from Combined Sewer Overflows - Steering Group Report June 2000*, EPSRC Grant..

Sharma, S.K., (1984) *An experimental Investigation of the Transport of solids in Building Drains.* J Inst Engineers (India) Vol 65, October 1984.

Stanfield, G., (1982) *Disposal of Sewage from Coastal Towns.* Royal Society of Health journal, Vol2 pp 53-58, 1982.

Stotz, G and Krauth, K. (1984) Factors Affecting First Flushes in Combined Sewers. Proc. 3rd Int. Conf. on Urban Storm Drainage, 1984.

Welsh Water and Friends of the Earth Cymru, (1993) *Odds and Pods Report*

Wohl,A.S. (1984) *Endangered Lives: Public Health in Victorian Britain.*, Methuen.

Women's Environmental Network, (1993) *Sanitary Protection, Women's Health and the Environment.* WEN, April 1993.

1.1 Low Income Catchment Dry Weather – Wet Masses sampled at each sub-catchment

Time In	Time Out	Sub-catchment				Sub-catchment				Sub-catchment			
		SC1	SC2	SC3	SC4	SC1	SC2	SC3	SC4	SC1	SC2	SC3	SC4
06:00	06:30	542	470	270	528	404	216	240	1078	762	202	638	494
06:30	07:00	1720	482	1556	942	1280	510	2186	1092	1512	292	1988	848
07:00	07:30	2022	530	1160	1548	2412	2032	4794	614	2156	1032	4988	838
07:30	08:00	2070	1030	5952	1150	2348	1674	2006	1256	2620	1388	3354	1728
08:00	08:30	1894	1986	2864	1314	2078	3980	3258	1722	3334	2724	3564	2114
08:30	09:00	2108	2274	2190	1536	2180	664	3034	1240	1302	2212	2080	1264
09:00	09:30	2078	1748	3084	814	1192	536	3218	1392	1112	1520	3554	1512
09:30	10:00	864	2298	2184	1222	570	1156	2210	1394	954	620	2740	1026
10:00	10:30	488	276	1688	1094	964	370	2170	1300	1220	1070	2752	1230
10:30	11:00	810	258	1378	2750	1082	238	1040	1092	678	178	1164	1432
11:00	11:30	230	370	1856	1200	346	246	1158	1274	300	228	820	1792
11:30	12:00	316	210	1650	646	666	412	1552	860	448	326	1238	1598
12:00	12:30	586	332	1434	584	624	116	508	626	605	224	971	605
12:30	13:00	300	474	1136	866	410	336	618	374	826	374	286	838
13:00	13:30	144	168	624	530	598	92	1114	860	274	206	438	574
13:30	14:00	242	464	1090	748	400	180	388	2288	342	88	572	1182
14:00	14:30	712	178	652	696	184	58	1516	336	476	206	782	1300
14:30	15:00	404	258	436	224	412	564	468	834	477	340	406	690
15:00	15:30	226	548	1782	414	530	80	932	700	388	416	366	828
15:30	16:00	174	256	372	552	258	294	1406	1104	514	148	1500	522
16:00	16:30	260	306	598	774	404	154	608	986	838	348	840	558
16:30	17:00	228	420	714	384	350	878	430	90	708	298	1196	898
17:00	17:30	1860	770	674	674	2074	2504	1066	790	840	412	770	508
17:30	18:00	1274	294	2720	508	420	506	2658	758	822	1086	760	518
18:00	18:30	480	638	1480	732	892	452	1790	598	810	1144	1602	1452
18:30	19:00	1020	822	1582	2172	594	454	1348	1468	1834	1030	2636	578
19:00	19:30	744	394	2106	610	444	508	1100	1874	488	232	3854	420
19:30	20:00	174	660	806	1084	142	238	1124	1126	288	198	584	1180
20:00	20:30	1062	832	812	116	332	196	1238	690	296	174	1774	726
20:30	21:00	390	680	580	376	178	1146	1004	538	438	1394	788	602
21:00	21:30	880	226	620	519	518	380	468	578	654	138	1220	638
21:30	22:00	358	268	436	714	1386	256	796	330	580	234	652	432
22:00	22:30	690	312	1776	474	348	258	1102	710	624	200	1368	270
22:30	23:00	300	250	382	488	354	158	492	442	1214	196	780	312
23:00	23:30	920	394	204	274	370	1094	1034	710	266	324	1160	372
23:30	00:00	88	148	940	244	262	142	594	308	124	88	140	798
00:00	00:30	408	82	288	258	140	82	204	274	166	86	650	654
00:30	01:00	66	112	126	356	74	56	196	56	116	68	106	186

1.2 Low Income Catchment Dry Weather – Characterised Data

Date Sampled	Time Sac In	Time Sac Out	Sub-catchment	Total Contents in (g)	Mush in Sac (g)	Cigeratte Filter (g)	Cotton Bud Sticks (g)	Faecal Material (g)	Fat (g)	Kitchen Roll (g)	Leaves (g)	Pant Liner (g)	Paper Towel (g)	Sanitary Towel (g)	Sanitary Wrappinç (g)	Tampon (g)	Toilet Roll (g)	Wipes (g)	Remaining Weigh (g)	Condom (g)
17/06/1999	06:00	06:30	SC1	492	135			305							7		6			
22/06/1999	06:00	06:30	SC1																	
29/06/1999	06:00	06:30	SC1	686	146			352		34				28	6		68	34		
17/06/1999	06:30	07:00	SC2	455	147			212				8					57		1	
22/06/1999	06:30	07:00	SC2	466	194	1		25									242		3	
29/06/1999	06:30	07:00	SC2	266	156	1		110												
17/06/1999	07:00	07:30	SC3	1466	706	5					12				1		721	7	5	
22/06/1999	07:00	07:30	SC3	3966	712	6	1	1750									1450	10	33	
29/06/1999	07:00	07:30	SC3	3932	808	4	1	21								29	2974	49	17	
17/06/1999	07:30	08:00	SC4	1081	345	1									1		559	166		
22/06/1999	07:30	08:00	SC4	1148	627		1	201									259	92	33	
29/06/1999	07:30	08:00	SC4	1630	420		1	360			1	38					586		3	
17/06/1999	08:30	09:00	SC1	1916	287			1277		15		19						55		
22/06/1999	08:30	09:00	SC1	1566	197	2		1147				9				38	39	149		
29/06/1999	08:30	09:00	SC1	1218	302			763									81			
17/06/1999	09:00	09:30	SC2	1466	475			389		105	7						434	25	10	
22/06/1999	09:00	09:30	SC2	542	240	1		187									92		19	
29/06/1999	09:00	09:30	SC2	1434	456	1		794	4	10				14	5		104		6	
17/06/1999	09:30	10:00	SC3	1966	835		1	763		126			47				120	27		
22/06/1999	09:30	10:00	SC3	2066	702	3		914		129		12					189	51	41	
29/06/1999	09:30	10:00	SC3	2328	706			757	3	291		17					400		35	
17/06/1999	10:00	10:30	SC4	1037	372												650			
22/06/1999	10:00	10:30	SC4	1186	467			349					1				321			
29/06/1999	10:00	10:30	SC4	908	462			153							4		245	25		
17/06/1999	11:00	11:30	SC1	206	67	1		122					9		7				1	
22/06/1999	11:00	11:30	SC1	340	119	1		164		28							18			
29/06/1999	11:00	11:30	SC1	282	108			76								11	33		45	
17/06/1999	11:30	12:00	SC2	176	75			63									37			
22/06/1999	11:30	12:00	SC2	402	99			171							1		117		8	
29/06/1999	11:30	12:00	SC2	316	118			124			1						68		2	
22/06/1999	12:00	12:30	SC3	516	259			24		153									69	
24/06/1999	12:00	12:30	SC1	586	91	4		369		21							97			
10/06/1999	12:30	13:00	SC1	282	86			155.5									24		4	
24/06/1999	12:30	13:00	SC2	329	130			197											3	
10/06/1999	13:00	13:30	SC2	157	78			46									7		16.5	
24/06/1999	13:00	13:30	SC3	1053	416			380									241	10		
10/06/1999	13:30	14:00	SC3	576	79			399										35	64	
24/06/1999	13:30	14:00	SC4	1916	546	1											1300		75	
10/06/1999	14:00	14:30	SC4	687	358			35									151		135	
24/06/1999	14:00	14:30	SC1	398	128			96									174			
10/06/1999	15:00	15:30	SC1	221	121			43									32		13	
24/06/1999	15:00	15:30	SC2	80	50			29												

Date Sampled	Time Sac In	Time Sac Out	Sub-catchment	Total Contents in Sa (g)	Mush in Sac (g)	Cigeratte Filter (g)	Cotton Bud Sticks (g)	Faecal Material (g)	Fat (g)	Kitchen Roll (g)	Leaves (g)	Pant Liner (g)	Paper Towel (g)	Sanitary Towel (g)	Sanitary Wrapping (g)	Tampon (g)	Toilet Roll (g)	Wipes (g)	Remaining Weight (g)	Condom (g)
10/06/1999	15:30	16:00	SC2	251	78			150							1		8		7	
24/06/1999	15:30	16:00	SC3	1346	614			102									598			
10/06/1999	16:00	16:30	SC3	478	302	6		106									70		91	
24/06/1999	16:00	16:30	SC4	689	240	2		267			1						178			
10/06/1999	16:30	17:00	SC4	547	237			103									108		71	
24/06/1999	16:30	17:00	SC1	1866	245	2		374		181		14		51		62	400	57	3	
10/06/1999	17:30	18:00	SC1	1161	141	1		504						237			197		45	
24/06/1999	17:30	18:00	SC2	473	159			104										181	31	
10/06/1999	18:00	18:30	SC2	181	0															
24/06/1999	18:00	18:30	SC3	1766	744	1	1	305				10			1		579		56	
10/06/1999	18:30	19:00	SC3	1224	419			484					13	106			171	12	164	
24/06/1999	18:30	19:00	SC4	1446	435	1	1	519		123					4		250	60	2	
14/06/1999	19:00	19:30	SC1	691	125			332									150	62	20	
01/07/1999	19:00	19:30	SC1	436	78			131						135	8		65			
06/07/1999	19:00	19:30	SC1	479	169			174									95			
14/06/1999	19:30	20:00	SC2	648	157			179									295		19	
01/07/1999	19:30	20:00	SC2	235	124	4		76									33			
06/07/1999	19:30	20:00	SC2	193	91			93									5			
14/06/1999	20:00	20:30	SC3	787	412			171				9		42			92	9	50	
01/07/1999	20:00	20:30	SC3	1235	488	3		526								29	170			
06/07/1999	20:00	20:30	SC3	1706	539			681			2		3	18	6	36	246		39	
14/06/1999	20:30	21:00	SC4	366	139			66							3		150		4	
01/07/1999	20:30	21:00	SC4	509	251			104			4						106		29	
06/07/1999	20:30	21:00	SC4	635	428			56									151			
14/06/1999	21:30	22:00	SC1	345	85			47									170	40		
01/07/1999	21:30	22:00	SC1	1009	137			465	8				1	9			260	34	23	
06/07/1999	21:30	22:00	SC1	558	109	2		300				16				38			17	
14/06/1999	22:00	22:30	SC2	305	128			106	13		5						65			
01/07/1999	22:00	22:30	SC2	244	145			20				6			1		59		9	
06/07/1999	22:00	22:30	SC2	201	127												36			
14/06/1999	22:30	23:00	SC3	368	243	5		53				8					42	5	9	
01/07/1999	22:30	23:00	SC3	480	224	2		168				15					31		30	
06/07/1999	22:30	23:00	SC3	0	0															
14/06/1999	23:00	23:30	SC4	270	233			6									31			
01/07/1999	23:00	23:30	SC4	698	176					349		22								
06/07/1999	23:00	23:30	SC4	0	0	1														
14/06/1999	00:00	00:30	SC1	395	76			66									253		2	
01/07/1999	00:00	00:30	SC1	136	55			37									24		14	
06/07/1999	00:00	00:30	SC1	164	83	1		25									18	32		
14/06/1999	00:30	01:00	SC2	98	72	2		13											11	
01/07/1999	00:30	01:00	SC2	53	48												4			
06/07/1999	00:30	01:00	SC2	66	66															

1.3 Low Income Catchment Wet Weather - Wet Masses

Storm GS2

Time In	Time Out	SC1	SC2	SC3	SC4	**Total**
12:30	13:00	306	410	702	362	**1418**
13:00	13:30	606	260	610	706	**1476**
13:30	14:00	146	194	600	808	**940**
14:00	14:30	350	270	118	510	**738**
14:30	15:00	198	308	452	650	**958**
15:00	15:30	292	450	480	630	**1222**
15:30	16:00	722	544	1238	926	**2504**
16:00	16:10	1422	156	204	160	**1782**
16:10	16:20	272	204	202	374	**678**
16:20	16:25	356	226	102	72	**684**
16:25	16:30	608	2908	2648	1050	**6164**
16:30	16:35	236	430	138	2548	**804**
16:35	16:40	334	358	98	222	**790**
16:40	16:45	514	542	316	1632	**1372**
16:45	16:50	324	620	376	1740	**1320**
16:50	16:55	94	140	202	246	**436**
16:55	17:00	128	104	46	56	**278**
17:00	17:10	116	136	56	72	**308**
17:10	17:20	192	144	176	62	**512**
17:20	17:30	312	166	214	448	**692**
17:30	17:40	196	160	168	318	**524**
17:40	17:50	438	148	446	362	**1032**
17:50	18:00	158	222	174	486	**554**

Storm GS3

Time In	Time Out	SC1	SC2	SC3	SC4	**Total**
07:00	07:30	1110	476	348	1450	**3384**
07:30	08:00	3930	1576	270	2750	**8526**
08:00	08:10	402	568	1078	1134	**3182**
08:10	08:20	168	930	416	1068	**2582**
08:20	08:30	1174	224	758	840	**2996**
08:30	08:35	230	224	256	898	**1608**
08:35	08:40	240	184	798	604	**1826**
08:40	08:45	196	560	538	608	**1902**
08:45	08:50	402	552	380	384	**1718**
08:50	08:55	348	166	270	388	**1172**
08:55	09:00	842	2996	498	820	**5156**
09:00	09:05	1148	552	744	3272	**5716**
09:05	09:10	332	572	808	1658	**3370**
09:10	09:15	142	538	560	554	**1794**
09:15	09:20	332	338	250	798	**1718**
09:20	09:25	208	404	238	488	**1338**
09:25	09:30	164	148	448	268	**1028**
09:30	09:40	142	644	780	1060	**2626**
09:40	09:50	214	434	358	446	**1452**
09:50	10:00	74	176	432	402	**1084**
10:00	10:10	188	240	364	796	**1588**

1.4 Low Income Catchment Wet Weather – Characterised Data

Storm GS2

Time In	Time Out	Sub-catchment	Total Contents in Sac	Mush in Sac	Cigeratte Filter	Cotton Bud Sticks	Faecal Material	Fat	Kitchen Roll	Leaves	Pant Liner	Paper Towel	Sanitary Towel	Sanitary Wrapping	Tampon	Toilet Roll	Wipes	Remaining Weight	Condom
13:00	13:30	SC1	212	68			76			44							10		
13:30	14:00	SC4	852	494			228			8						130			
14:00	14:30	SC3	146	96			0									44			
15:00	15:30	SC2	252	90			90		76										
15:30	16:00	SC2	254	94			152												
15:30	16:00	SC1	470	192			266			10									
16:00	16:10	SC2	1370	284			706						158					204	
16:10	16:20	SC1	160	122			32												
16:20	16:25	SC4	156	76			62												
16:20	16:25	SC1	172	88			84												
16:25	16:30	SC3	2578	630			477		454				64	22	48	540	220	44	
16:40	16:45	SC2	460	84			246									130			
16:45	16:50	SC4	1766	320			694		96				80		72	260	82	122	
16:45	16:50	SC1	560	106			72				22				286		22		
16:50	16:55	SC3	228	90			104								32				
17:00	17:10	SC2	154	68			74			1						6			
17:10	17:20	SC4	102	72														28	
17:10	17:20	SC3	242	122			128												
17:20	17:30	SC1	118	52			50			1								8	
17:50	18:00	SC4	496	228			182									82			

Storm GS3

Time In	Time Out	Sub-catchment	Time In	Time Out	Sub-catchment	Total Contents in Sac	Mush in Sac	Cigeratte Filter	Cotton Bud Sticks	Faecal Material	Fat	Kitchen Roll	Leaves	Pant Liner	Paper Towel	Sanitary Towel	Sanitary Wrapping	Tampon	Toilet Roll	Wipes	Remaining Weight	Condom
07:00	07:30	SC2	1106	226	2		640									228						
07:30	08:00	SC1	1532	404	1		822									292						
08:00	08:10	SC4	1014	586			56	6								356						
08:10	08:20	SC3	1052	512			328			1						206			6			
08:10	08:20	SC3	828	370			328			1					44	66	24					
08:30	08:35	SC2	264	128			104								26	6						
08:30	08:35	SC1	210	146			30									14	14					
08:40	08:45	SC4	622	250			272									54	6					
08:45	08:50	SC3	364	146			102						54			52						
08:55	09:00	SC2	870	268			518									70						
09:00	09:05	SC1	588	186			346			1					28		14					
09:00	09:10	SC4	1766	332	2		792		90	6			28	52		246	108					
09:10	09:15	SC3	602	190			402										6					
09:20	09:25	SC2	240	108			126															

1.5 High Income Catchment Dry Weather – Wet Masses

Time In	Time Out	1st Sample	2nd Sample	3rd Sample
06:00	06:30	132	480	154
06:30	07:00	552	630	1140
07:00	07:30	2478	1324	2540
07:30	08:00	1772	2058	3676
08:00	08:30	3050	1758	6790
08:30	09:00	3396	1864	3534
09:00	09:30	2274	3494	2926
09:30	10:00	2178	1444	1272
10:00	10:30	1778	1314	3360
10:30	11:00	2552	850	1260
11:00	11:30	1516	1078	1656
11:30	12:00	752	894	890
12:00	12:30	980	1244	922
12:30	13:00	1856	698	2372
13:00	13:30	1260	700	1472
13:30	14:00	830	666	536
14:00	14:30	898	784	978
14:30	15:00	1392	1490	788
15:00	15:30	604	506	530
15:30	16:00	610	894	714
16:00	16:30	304	1342	844
16:30	17:00	648	722	914
17:00	17:30	1104	970	1382
17:30	18:00	806	1314	1170
18:00	18:30	1330	1568	826
18:30	19:00	1364	2622	1454
19:00	19:30	984	1298	640
19:30	20:00	1492	2196	768
20:00	20:30	1054	1504	116
20:30	21:00	966	696	578
21:00	21:30	1148	1994	1716
21:30	22:00	1104	986	952
22:00	22:30	572	1114	398
22:30	23:00	710	1174	1210
23:00	23:30	1168	806	936
23:30	00:00	858	638	826
00:00	00:30	282	682	294
00:30	01:00	218	312	242

1.6 High Income Catchment Dry Weather – Characterised Data

Dry weather morning samples

Date	Time	Time	Total Contents in Sac	Mush in Sac	Cigeratte Filter	Cotton Bud Sticks	Faecal Material	Fat	Kitchen Roll	Leaves	Pant Liner	Paper Towel	Sanitary Towel	Sanitary Wrapping	Tampon	Toilet Roll	Wipes	Remaining Weight	Condom
29-Mar-00	06:00	06:30	166	100	0	0	54	0	0	0	0	0	0	0	0	10	0	0	0
06-Apr-00	06:00	06:30	476	276	0	0	124	0	0	0	0	0	0	0	0	106	0	0	0
18-Jul-00	06:00	06:30	294	116			132											30	
29-Mar-00	06:30	07:00	588	304	0	0	238	0	0	0	0	0	28	0	0	0	20	2	0
06-Apr-00	06:30	07:00	610	426	0	0	106	0	0	0	0	0	0	0	0	0	10	10	0
18-Jul-00	06:30	07:00	626	222	3		388												
29-Mar-00	07:00	07:30	2498	1162	1	0	860	0	0	0	0	0	0	0	152	152	142	0	0
06-Apr-00	07:00	07:30	1312	576	0	0	492	0	0	0	16	0	0	0	50	158	0	2	2
18-Jul-00	07:00	07:30	3328	996			1866		274					3	70	88			
29-Mar-00	07:30	08:00	1808	472	0	4	1026	0	0	0	0	0	0	4	16	166	52	0	0
06-Apr-00	07:30	08:00	2830	684	0	0	1136	0	0	1	0	0	0	0	32	0	22	150	0
18-Jul-00	07:30	08:00	3848	1460	1		1950		26				74	2	62	164	58	26	
29-Mar-00	08:00	08:30	3058	1182	0	0	1410	0	0	0	0	0	0	0	150	252	48	4	0
06-Apr-00	08:00	08:30	1776	478	1	0	1106	0	0	0	14	0	0	0	86	0	62	0	0
18-Jul-00	08:00	08:30	2508	682	3		1702				26					68			
29-Mar-00	08:30	09:00	3382	1046	0	0	1812	0	0	0	0	0	0	2	0	464	24	40	0
06-Apr-00	08:30	09:00	1880	534	0	0	932	0	22	0	0	0	0	0	0	384	0	2	0
18-Jul-00	08:30	09:00	2830	608			1684								182	238	50		
29-Mar-00	09:00	09:30	2292	648	0	0	1376	0	0	0	6	0	0	0	60	54	108	0	0
06-Apr-00	09:00	09:30	3464	642	0	2	798	0	0	1	0	0	0	0	114	1736	158	10	0
18-Jul-00	09:00	09:30	1854	620	2	4	968								30	162	22		
29-Mar-00	09:30	10:00	2226	774	0	0	792	0	0	0	0	0	0	0	32	378	24	0	0
06-Apr-00	09:30	10:00	1436	382	2	0	572	0	0	0	0	0	10	0	32	386	22	4	0
18-Jul-00	09:30	10:00	2226	590	6		1036									568			
29-Mar-00	10:00	10:30	1800	722	0	0	950	0	0	0	0	0	0	0	58	62	0	0	0
06-Apr-00	10:00	10:30	1044	422	1	0	436	0	0	0	0	0	0	0	0	184	0	2	0
18-Jul-00	10:00	10:30	1538	310												792	16		
29-Mar-00	10:30	11:00	2544	1426	0	0	592	0	14	168	0	0	0	0	0	0	0	0	0
06-Apr-00	10:30	11:00	862	446	3	0	328	0	0	0	0	0	0	0	0	28	20	20	0
18-Jul-00	10:30	11:00	2042	892	2		826	30							52	288		22	
29-Mar-00	11:00	11:30	1530	572	0	0	668	0	0	2	16	0	0	0	0	184	64	0	0
06-Apr-00	11:00	11:30	1090	426	0	0	444	0	16	0	0	0	0	0	0	118	72	0	0
18-Jul-00	11:00	11:30	1028	320			328						96			264	12		
29-Mar-00	11:30	12:00	784	318	0	0	382	0	0	0	0	0	0	0	0	42	22	0	0
06-Apr-00	11:30	12:00	896	482	1	0	232	0	16	0	0	0	0	0	90	82	12	0	0
18-Jul-00	11:30	12:00	1000	314	2		578								56		18	5	

Dry Weather

Date	Time	Time	Total Contents in Sac	Mush in Sac	Cigeratte Filter	Cotton Bud Sticks	Faecal Material	Fat	Kitchen Roll	Leaves	Pant Liner	Paper Towel	Sanitary Towel	Sanitary Wrapping	Tampon	Toilet Roll	Wipes	Remaining Weight	Condom
16-Mar-00	12:00	12:30	972	282	0	0	526	0		10	0	0	0	0	0	118	30	1	0
20-Mar-00	12:00	12:30	1266	340	0	0	598	4	18	0	0	0	0	0	0	130	150	0	0
04-May-00	12:00	12:30	948	352	0	0	476	0	14	2	14	0	0	0	0	48	60	1	0
16-Mar-00	12:30	13:00	1966	526	1	0	558	0	132	2	0	0	0	0	498	68	48	1	0
20-Mar-00	12:30	13:00	730	412	0	0	162	0	0	0	0	0	0	0	0	104	30	0	0
04-May-00	12:30	13:00	2240	594	0	0	890	0	0	1	24	0	0	0	20	682	48	0	0
16-Mar-00	13:00	13:30	1368	420	0	0	484	0	22	14	0	22	0	0	38	270	12	6	0
20-Mar-00	13:00	13:30	720	418	0	0	214	0	0	6	0	0	0	0	0	32	30	0	0
04-May-00	13:00	13:30	1506	558	0	0	348	0	12	0	0	0	0	0	90	236	198	0	0
16-Mar-00	13:30	14:00	854	312	0	0	380	0	0	24	0	0	0	0	0	128	0	4	0
20-Mar-00	13:30	14:00	704	304	0	0	204	0	0	0	0	0	0	0	26	122	50	0	0
04-May-00	13:30	14:00	578	274	0	0	27	0	0	0	0	0	0	0	0	0	42	0	0
16-Mar-00	14:00	14:30	936	326	1	0	300	0	0	16	0	0	0	0	0	270	0	1	0
20-Mar-00	14:00	14:30	714	328	1	0	324	0	0	1	16	0	0	0	0	0	30	0	0
04-May-00	14:00	14:30	1008	502	0	0	380	0	0	0	0	0	0	0	0	104	8	0	0
16-Mar-00	14:30	15:00	1370	358	2	1	608	0	0	12	0	0	68	0	0	246	12	1	0
20-Mar-00	14:30	15:00	1530	488	0	0	570	0	88	8	0	0	0	0	122	130	62	0	0
04-May-00	14:30	15:00	816	376	0	0	276	0	0	0	14	0	0	0	36	40	60	0	0
16-Mar-00	15:00	15:30	358	220	0	0	110	0	0	0	0	0	0	0	0	28	0	1	0
20-Mar-00	15:00	15:30	542	192	0	0	328	0	0	0	0	0	0	0	0	0	20	10	0
04-May-00	15:00	15:30	560	252	0	0	202	0	0	0	22	0	44	0	0	42	0	0	0
16-Mar-00	15:30	16:00	672	344	0	0	276	0	0	0	0	0	0	0	0	32	16	1	0
20-Mar-00	15:30	16:00	1144	320	3	0	388	0	0	0	22	0	0	0	0	98	70	0	0
04-May-00	15:30	16:00	752	302	0	0	344	0	1	2	0	0	0	2	0	94	0	0	0
16-Mar-00	16:00	16:30	644	232	0	0	192	0	0	0	0	0	0	0	0	156	56	0	0
20-Mar-00	16:00	16:30	1360	282	0	0	760	0	0	1	0	0	0	0	32	174	78	0	0
04-May-00	16:00	16:30	926	402	0	0	166	0	0	0	0	0	0	0	18	294	0	0	0
16-Mar-00	16:30	17:00	694	236	1	1	308	0	0	12	0	0	0	0	0	142	0	0	0
20-Mar-00	16:30	17:00	766	314	0	0	304	0	0	2	8	0	0	0	0	60	66	0	0
04-May-00	16:30	17:00	956	224	0	0	520	0	0	0	0	0	0	0	0	196	8	0	0
16-Mar-00	17:00	17:30	1114	384	0	0	498	0	0	16	0	0	0	0	40	168	18	0	0
20-Mar-00	17:00	17:30	1018	330	0	0	552	0	0	1	0	0	0	0	0	112	0	0	0
04-May-00	17:00	17:30	1072	372	0	0	346	0	0	8	0	0	0	0	152	74	54	12	0
16-Mar-00	17:30	18:00	866	354	0	0	270	0	0	0	10	0	78	0	24	64	20	0	0
20-Mar-00	17:30	18:00	1332	422	2	0	686	0	12	1	0	0	0	0	28	108	26	2	0
04-May-00	17:30	18:00	1212	480	1	1	500	0	0	0	0	0	0	0	56	50	92	17	0
16-Mar-00	18:00	18:30	1364	400	2	0	704	0	10	0	0	0	0	0	0	90	88	44	0
20-Mar-00	18:00	18:30	1394	292	0	0	818	0	0	1	0	0	48	0	0	358	56	4	0
04-May-00	18:00	18:30	862	394	0	0	352	0	0	2	22	0	0	0	0	26	22	0	0
16-Mar-00	18:30	19:00	1396	532	0	0	756	0	0	0	14	0	0	0	0	28	30	14	0
20-Mar-00	18:30	19:00	2672	912	0	0	984	0	68	1	20	0	16	0	146	394	52	6	0
04-May-00	18:30	19:00	1536	412	0	0	736	0	0	2	36	0	0	0	24	192	30	1	0

Date	Time	Time	Total Contents in Sac	Mush in Sac	Cigeratte Filter	Cotton Bud Sticks	Faecal Material	Fat	Kitchen Roll	Leaves	Pant Liner	Paper Towel	Sanitary Towel	Sanitary Wrapping	Tampon	Toilet Roll	Wipes	Remaining Weight	Condom
13-Mar-00	19:00	19:30	954	300	0	0	500	0	0	0	0	0	0	0	32	102	12	0	0
30-Mar-00	19:00	19:30	1336	320	4	0	600	0	0	0	0	0	130	5	16	154	92	30	0
28-Jun-00	19:00	19:30	642	262	0	0	256	0	0	0	22	0	0	0	0	56	10	0	0
13-Mar-00	19:30	20:00	1514	454	0	0	792	0	0	1	16	0	56	0	34	110	34	2	0
30-Mar-00	19:30	20:00	2174	670	0	0	894	0	20	0	0	0	0	0	64	328	168	16	0
28-Jun-00	19:30	20:00	750	210	0	0	466	0	0	0	0	0	0	0	32	14	10	0	0
13-Mar-00	20:00	20:30	1084	484	0	0	386	0	0	0	0	0	0	0	0	196	0	0	0
30-Mar-00	20:00	20:30	1520	508	0	0	944	0	0	0	14	0	0	0	30	24	70	0	0
28-Jun-00	20:00	20:30	1128	292	0	0	578	0	0	1	0	0	0	0	88	80	76	0	0
13-Mar-00	20:30	21:00	902	396	0	0	290	0	0	0	0	0	0	0	20	190	0	0	0
30-Mar-00	20:30	21:00	732	300	0	0	346	0	0	0	0	0	0	0	0	58	10	0	0
28-Jun-00	20:30	21:00	548	174	0	0	196	0	0	0	0	0	0	0	144	0	14	0	0
13-Mar-00	21:00	21:30	1176	306	0	0	530	0	0	0	0	0	0	0	30	280	28	0	0
30-Mar-00	21:00	21:30	2180	536	0	0	1162	0	0	0	0	78	0	0	30	292	0	0	0
28-Jun-00	21:00	21:30	1672	385	0	0	1165	0	0	0	16	0	0	0	62	16	0	0	0
13-Mar-00	21:30	22:00	1136	370	0	0	528	0	0	1	0	0	0	0	64	84	64	8	0
30-Mar-00	21:30	22:00	1026	318	0	0	454	0	0	0	0	0	32	0	28	166	20	0	0
28-Jun-00	21:30	22:00	944	366	0	1	334	0	18	0	18	4	4	0	26	32	76	2	0
13-Mar-00	22:00	22:30	626	300	0	0	270	0	0	1	0	0	0	0	0	38	0	1	0
30-Mar-00	22:00	22:30	1160	442	0	0	524	0	0	2	0	0	0	0	0	192	2	0	0
28-Jun-00	22:00	22:30	404	200	0	0	142	0	0	0	0	0	0	0	0	32	16	0	0
13-Mar-00	22:30	23:00	738	304	0	0	358	0	0	1	18	0	0	0	24	18	0	1	0
30-Mar-00	22:30	23:00	1208	446	0	0	426	0	0	0	0	0	28	0	54	178	22	2	0
28-Jun-00	22:30	23:00	1184	290	0	0	610	0	0	0	10	0	0	0	106	74	54	0	0
13-Mar-00	23:00	23:30	1212	410	0	0	460	0	0	1	24	0	0	0	38	130	32	87	0
30-Mar-00	23:00	23:30	842	322	0	0	240	0	0	0	0	0	0	0		323	4	8	0
28-Jun-00	23:00	23:30	936	318	0	0	302	0	0	0	10	0	0	0	138	36	60	0	0
13-Mar-00	23:30	00:00	900	342	0	0	304	0	0	0	0	0	0	0	48	150	30	0	0
30-Mar-00	23:30	00:00	680	30	1	0	272	0	0	0	0	0	0	0	0	80	0	1	0
28-Jun-00	23:30	00:00	792	284	0	0	268	0	0	0	18	0	0	0	0	178	20	0	0
13-Mar-00	00:00	00:30	320	164	0	1	78	0	0	0	16	0	0	0	0	50	0	1	0
30-Mar-00	00:00	00:30	714	254	1	0	212	0	0	0	0	0	0	0	0	178	58	0	0
28-Jun-00	00:00	00:30	292	192	0	0	58	0	0	6	0	0	0	0	0	22	0	10	0
13-Mar-00	00:30	01:00	238	140	0	0	92	0	0	1	0	0	0	0	0	0	0	0	0
30-Mar-00	00:30	01:00	336	152	0	0	142	0	0	0	0	0	0	0	0	0	32	2	0
28-Jun-00	00:30	01:00	234	148	0	0	38	0	0	1	0	0	0	0	34	10	0	0	0

1.7 High Income Catchment Wet Weather - Wet Masses

STORM DS1 - 28/07/2000		
Time In	Time Out	Wet Mass (g)
13:00	13:30	582
13:30	14:00	680
14:00	14:30	600
14:30	14:50	472
14:50	14:55	108
14:55	14:58	1604
14:58	15:00	498
15:00	15:05	930
15:05	15:10	108
15:10	15:15	166
15:15	15:20	138
15:20	15:25	114
15:25	15:30	86
15:30	15:40	48
15:40	15:50	154
15:50	16:00	184
16:00	16:10	132
16:10	16:20	184
16:20	16:30	298

STORM 3 - 31/08/2000		
Time In	Time Out	Wet Mass (g)
11:30	12:00	846
12:00	12:30	806
12:30	13:00	780
13:00	13:30	1038
13:30	14:00	780
14:00	14:30	1068
14:30	15:00	622
15:00	15:30	500
15:30	16:00	750
16:00	16:30	734
16:30	17:00	406
17:00	17:30	1372
17:30	18:00	1158
18:00	18:05	222
18:05	18:10	150
18:10	18:15	460
18:15	18:20	950
18:20	18:25	878
18:25	18:30	322
18:30	18:35	1362
18:35	18:40	3578
18:40	18:45	892
18:45	18:50	572
18:50	18:55	1712
18:55	19:00	198
19:00	19:10	208
19:10	19:20	236

STORM 5 - 19/09/2000		
Time In	Time Out	Wet Mass (g)
15:55	16:00	150
16:00	16:30	718
16:30	16:40	370
16:40	16:45	314
16:45	16:50	1248
16:50	16:55	666
16:55	17:00	664
17:00	17:05	222
17:05	17:10	408
17:10	17:15	728
17:15	17:20	252
17:20	17:25	554
17:25	17:30	294
17:30	17:40	762
17:40	17:50	234
17:50	18:00	342
18:00	18:10	282
18:10	18:20	644
18:20	18:30	404

STORM 6 - 14-06-01		
Time In	Time Out	Wet Mass (g)
18:00	18:30	1004
18:30	19:00	1192
19:00	19:21	1178
19:21	19:25	532
19:25	19:27	3848
19:27	19:29	3250
19:29	19:33:30	2694
19:33:30	19:36	1810
19:36	19:40	1964
19:40	19:45	522
19:45	19:50	378
19:50	19:55	280
19:55	20:00	360
20:00	20:10	496
20:10	20:20	512
20:20	20:30	338
20:30	20:40	524

1.8 High Income Catchment Wet Weather – Characterised Data

STORM DS1																							
Time	Time	Sac No.	Total Contents in Sac	Mush in Sac	Cigeratte Filter	Cotton Bud Sticks	Faecal Material	Fat	Kitchen Roll	Leaves	Pant Liner	Paper Towel	Sanitary Towel	Sanitary Wrapping	Tampon	Toilet Roll	Wipes	Remaining Weight	Condom	Wipes Shredded	Panti Liner Shield	Sanitary towel shell	Total Wipes
In	Out		(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	
13:00	13:30	1	660	248			266									52	90						90
13:30	14:00	2	672	206			314									84	42						42
14:00	14:30	3	636	244			192	22		80					52	8	14						14
14:30	14:50	4	532	218			280									10	24						24
14:50	14:55	5	146	98			44																0
14:55	14:58	6	1336	170			912			42					16	36	114						114
14:58	15:00	7	522	172			260								68			10					0
15:00	15:05	8	894	364			390			12								74		14			14
15:05	15:10	9	146	118						1								30					0
15:10	15:15	10	210	36			54											16					0
15:15	15:20	11	178	134			34																0
15:20	15:25	12	154	114			30																0
15:25	15:30	13	134	88			46																0
15:30	15:40	14	94	76			10																0
15:40	15:50	15	202	116			74																0
15:50	16:00	16	230	112			82				24												0
16:00	16:10	17	162	78			66									2	12						12
16:10	16:20	18	216	110			40											56					0
16:20	16:30	19	334	122	1		188									12							0

STORM DS3																							
Time	Time	Sac No.	Total Contents in Sac	Mush in Sac	Cigeratte Filter	Cotton Bud Sticks	Faecal Material	Fat	Kitchen Roll	Leaves	Pant Liner	Paper Towel	Sanitary Towel	Sanitary Wrapping	Tampon	Toilet Roll	Wipes	Remaining Weight	Condom	Wipes Shredded	Panti Liner Shield	Sanitary towel shell	Total Wipes
In	Out		(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	
16:30	17:00	11	404	230			168													80			80
17:00	17:30	12	1284	522			516								60		4	8		158			162
17:30	18:00	13	1612	738			452				14				118	200	56						56
18:00	18:05	16	222	136			82																0
18:05	18:10	14	188	118			38								28								0
18:10	18:15	15	444	132		1	104									70	76			34			110
18:15	18:20	17	854	274			336								110	102		20					0
18:20	18:25	18	874	348			434									82							0
18:25	18:30	S1	316	184			106									24							0
18:30	18:35	S2	1354	442			312								472		18						18
18:35	18:40	S3	3484	920			534				38					1424	212	70				26	212
18:40	18:45	S4	884	315			246								166	44	28	21		46			74
18:45	18:50	S5	566	242			94				14					96	34	16		42			76
18:50	18:55	S6	1682	1030			458								66		68						68
18:55	19:00	S7	200	108			46									20		5					0
19:00	19:10	S8	192	116			44									36							0
19:10	19:20	S9	234	88			76								54								0

STORM DS5

Time	Time	Sac No.	Total Contents in Sac	Mush in Sac	Cigeratte Filter	Cotton Bud Sticks	Faecal Material	Fat	Kitchen Roll	Leaves	Pant Liner	Paper Towel	Sanitary Towel	Sanitary Wrapping	Tampon	Toilet Roll	Wipes	Remaining Weight	Condom	Wipes Shredded	Panti Liner Shield	Sanitary towel shell	Total Wipes
In	Out		(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	
15:55	16:00	1	180	110			26									28	18						18
16:00	16:30	2	748	312			350									622	14						14
16:30	16:40	3	410	200			156									50							0
16:40	16:45	4	350	156			170									20							0
16:45	16:50	5	1270	338			684					54			154	42							0
16:50	16:55	6	688	264			404										14						14
16:55	17:00	7	696	298			310								32		42	4					42
17:00	17:05	8	264	202			52								4								0
17:05	17:10	9	448	238			106									46				50			50
17:10	17:15	10	710	196			208									84	148				1		148
17:15	17:20	11	290	158			70								48								0
17:20	17:25	12	594	158			276								142	6							0
17:25	17:30	13	328	132			136								28	36		1					0
17:30	17:40	14	798	362			270			2	18				82	28	16						16
17:40	17:50	15	274	174			48				16					20	14						14
17:50	18:00	16	382	220			70						42				26						26
18:00	18:10	17	320	210			110																0
18:10	18:20	18	678	252			192		20	2			44		56		26	28				18	26
18:20	18:30	19	438	190			178								28	12				12		6	12

STORM DS6

Time	Time	Sac No.	Total Contents in Sac	Mush in Sac	Cigeratte Filter	Cotton Bud Sticks	Faecal Material	Fat	Kitchen Roll	Leaves	Pant Liner	Paper Towel	Sanitary Towel	Sanitary Wrapping	Tampon	Toilet Roll	Wipes	Remaining Weight	Condom	Wipes Shredded	Panti Liner Shield	Sanitary towel shell	Total Wipes
In	Out		(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)
18:00	18:30	1	988	312		1	414				12		48			192							
18:30	19:00	2	1176	502			472				16					76	82						
19:00	19:21	3	1124	302			646				22				32	58	28						
19:21	19:25	4	514	160			332																
19:25	19:27	5	3814	810			1380			538	28				214	534	212	34					
19:27	19:29	6	3134	1224			1184			106	38				300	170	90						
19:29	19:33:30	7	2664	1140			1096									42	8		6				
19:33:30	19:36	8	1814	830			460			160					198	128							
19:36	19:40	9	1894	1022			628			58					28	146	16						
19:40	19:45	10	512	286			140			48					32								
19:45	19:50	11	380	170			174					26											
19:50	19:55	12	270	170			68					16					14						
19:55	20:00	13	358	128			142								28	48	10						
20:00	20:10	14	474	152			276									48							
20:10	20:20	15	504	182			318																
20:20	20:30	16	332	206			100									18		4					
20:30	20:40	17	512	134			76									284							
				5186			7673				66		0		740	3613	326						

1.9 Ethnic Catchment Dry Weather – Wet Masses

Time Start	Time Finish	1st Sample (g/s)	2nd Sample (g/s)	3rd Sample (g/s)
06:00	06:30	0.72	0.22	0.80
06:30	07:00	0.57	1.14	1.04
07:00	07:30	1.07	1.13	1.05
07:30	08:00	1.67	1.33	1.40
08:00	08:30	1.58	1.55	1.07
08:30	09:00	1.36	1.20	1.57
09:00	09:30	1.07	0.80	1.12
09:30	10:00	0.51	0.55	1.00
10:00	10:30	0.66	1.32	1.36
10:30	11:00	0.46	0.76	0.87
11:00	11:30	0.47	1.44	0.88
11:30	12:00	1.09	0.52	0.94
12:00	12:30	0.53	0.63	0.37
12:30	13:00	0.54	0.48	0.36
13:00	13:30	0.49	0.74	0.25
13:30	14:00	0.35	0.59	0.99
14:00	14:30	0.62	0.95	0.39
14:30	15:00	0.55	0.41	0.22
15:00	15:30	0.39	0.34	0.27
15:30	16:00	0.43	0.36	0.48
16:00	16:30	0.30	0.44	0.56
16:30	17:00	0.41	0.26	0.79
17:00	17:30	0.58	0.42	0.40
17:30	18:00	0.69	0.89	0.68
18:00	18:30	0.79	0.80	1.19
18:30	19:00	0.57	0.53	0.75
19:00	19:30	0.35	0.65	1.00
19:30	20:00	0.92	0.53	0.52
20:00	20:30	0.94	0.44	0.66
20:30	21:00	0.78	0.81	0.82
21:00	21:30	0.64	0.67	1.05
21:30	22:00	0.76	1.83	0.91
22:00	22:30	0.46	0.47	0.45
22:30	23:00	0.47	0.45	0.74
23:00	23:30	0.42	0.31	1.11
23:30	00:00	0.22	0.51	0.33
00:00	00:30	0.23	0.32	0.38
00:30	01:00	0.15	0.14	0.24

1.10 Ethnic Catchment Dry Weather – Characterised Data

	Time	Time	Sac	Total Contents in Sa	Mush in Sac	Cigeratte Filter	Cotton Bud Sticks	Faecal Material	Fat	Kitchen Roll	Leaves	Pant Liner	Paper Towel	Sanitary Towel	Sanitary Wrapping	Tampon	Toilet Roll	Wipes	Remaining Weight	Condom	Wipes Shredded	Panti Liner Shield	Sanitary towel shell	Total Wipes
Date	In	Out	No.	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)
13/9/00	06:00	06:30	1	1244	356	3	0	164	0	0	0	48	0	0	0	24	0	62	0	0	0	0	0	0
14/11/00	06:00	06:30	1	426	280	0	0	134	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0
21/12/00	06:00	06:30	1	1440	1312	0	0	0	0	0	0	0	0	0	0	0	120	0	1	0	0	0	0	0
13/9/00	06:30	07:00	2	1042	602	0	0	306	0	0	0	18	0	0	0	0	100	0	0	0	0	0	0	0
14/11/00	06:30	07:00	2	1932	868	0	0	516	0	0	0	0	0	70	0	54	404	0	0	0	0	0	0	0
21/12/00	06:30	07:00	2	1798	936	0	0	750	0	0	0	0	0	0	0	0	74	26	0	0	0	0	0	0
13/9/00	07:00	07:30	3	1864	966	0	0	268	0	0	0	16	0	0	0	0	600	0	0	0	0	0	0	0
14/11/00	07:00	07:30	3	1972	982	0	0	596	0	0	0	18	0	0	0	0	334	18	0	0	0	0	0	0
21/12/00	07:00	07:30	3	1866	1856	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
13/9/00	07:30	08:00	4	2940	1508	0	0	1000	0	0	0	0	0	0	1	40	280	84	0	0	0	0	0	0
14/11/00	07:30	08:00	4	2286	1054	0	0	908	0	0	0	0	0	0	0	52	278	0	0	0	0	0	0	0
21/12/00	07:30	08:00	4	2538	1692	0	0	54	0	0	0	0	0	0	0	0	696	62	0	0	0	0	0	0
13/9/00	08:00	08:30	5	2742	954	0	0	1368	0	0	0	0	0	0	8	0	338	42	0	0	0	0	0	0
14/11/00	08:00	08:30	5	2810	968	0	0	1248	0	0	0	0	0	0	0	0	488	86	0	0	0	0	24	0
21/12/00	08:00	08:30	5	1850	1594	0	0	0	0	0	0	0	0	0	0	236	12	0	0	0	0	0	0	0
13/9/00	08:30	09:00	6	2424	1126	0	0	1150	0	0	0	0	0	0	0	0	158	0	4	0	0	0	0	0
14/11/00	08:30	09:00	6	2146	782	0	3	1008	0	0	0	0	0	0	0	0	340	0	0	0	0	0	0	0
21/12/00	08:30	09:00	6	2368	748	0	1	1078	0	0	0	0	0	0	0	0	354	136	0	0	0	0	0	0
13/9/00	09:00	09:30	7	1910	964	0	0	474	0	0	44	0	0	0	0	0	284	132	0	0	0	0	0	0
14/11/00	09:00	09:30	7	1444	568	0	0	688	0	0	0	0	0	0	0	0	188	0	0	0	0	0	0	0
21/12/00	09:00	09:30	7	1936	1936	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13/9/00	09:30	10:00	8	944	316	0	0	612	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
14/11/00	09:30	10:00	8	1038	402	0	0	562	0	0	0	0	0	0	0	0	58	0	0	0	0	0	0	0
21/12/00	09:30	10:00	8	1786	884	0	0	814	0	0	0	0	0	0	0	0	82	0	0	0	0	0	0	0
13/9/00	10:00	10:30	9	1214	606	0	1	558	12	0	0	0	0	0	0	0	68	0	0	0	0	0	0	0
14/11/00	10:00	10:30	9	2392	826	0	0	694	0	0	0	0	0	0	0	40	694	98	4	0	0	0	0	0
21/12/00	10:00	10:30	9	2440	1562	0	1	428	0	0	0	0	0	0	0	0	442	0	0	0	0	0	0	0
13/9/00	10:30	11:00	10	870	396	0	0	416	0	0	0	0	0	0	0	0	56	0	0	0	0	0	0	0
14/11/00	10:30	11:00	10	1402	814	0	1	484	0	0	0	0	0	0	0	0	54	0	48	0	0	0	0	0
21/12/00	10:30	11:00	10	1584	784	0	0	548	0	0	0	0	0	0	0	0	180	46	0	0	0	0	0	0
13/9/00	11:00	11:30	11	846	346	3	0	413	0	0	0	0	0	0	0	0	66	0	0	0	0	0	0	0
14/11/00	11:00	11:30	11	2542	748	0	0	962	0	0	0	0	0	0	0	0	364	194	232	2	0	0	0	0
21/12/00	11:00	11:30	11	1560	578	0	0	924	0	0	0	0	0	0	0	0	54	0	0	0	0	0	0	0
13/9/00	11:30	12:00	12	1934	738	0	0	912	0	0	0	0	0	0	0	0	256	0	0	0	0	0	0	0
14/11/00	11:30	12:00	12	958	568	0	0	232	0	0	0	0	0	0	0	0	78	64	0	0	0	0	0	0
21/12/00	11:30	12:00	12	1704	800	0	0	664	0	0	0	0	0	0	0	40	122	54	0	0	0	0	0	0

Date	Time In	Time Out	Sac No.	Total Contents in Sa (g)	Mush in Sac (g)	Cigeratte Filter (g)	Cotton Bud Sticks (g)	Faecal Material (g)	Fat (g)	Kitchen Roll (g)	Leaves (g)	Pant Liner (g)	Paper Towel (g)	Sanitary Towel (g)	Sanitary Wrapping (g)	Tampon (g)	Toilet Roll (g)	Wipes (g)	Remaining Weight (g)	Condom (g)	Wipes Shredded (g)	Panti Liner Shield (g)	Sanitary towel shell (g)	Total Wipes (g)
24/7/00	12:00	12:30	1	940	500	1	0	354	0	0	0	0	0	0	0	0	40	20	0	0	0	0	0	0
23/10/00	12:00	12:30	1	1114	530	0	0	518	10	0	0	0	0	0	0	0	50	0	1	0	0	0	0	0
11-Jan-00	12:00	12:30	1	708	272	0	0	388	0	0	0	0	0	0	0	0	40	0	1	0	0	0	0	0
24/7/00	12:30	13:00	2	946	522	0	0	420	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23/10/00	12:30	13:00	2	874	404	0	0	428	0	0	0	0	0	0	0	0	38	0	0	0	0	0	0	0
11-Jan-00	12:30	13:00	2	664	262	0	0	318	40	0	0	0	0	0	0	0	32	0	0	0	0	0	0	0
24/7/00	13:00	13:30	3	876	338	1	0	536	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23/10/00	13:00	13:30	3	1290	406	0	0	544	0	0	0	0	4	0	0	0	116	16	1	0	0	0	0	0
11-Jan-00	13:00	13:30	3	486	190	0	0	266	0	0	0	0	0	0	0	0	16	0	8	0	0	0	0	0
24/7/00	13:30	14:00	4	640	260	1	0	306	0	0	0	0	0	0	1	0	116	0	0	0	0	0	0	0
23/10/00	13:30	14:00	4	1068	400	0	0	460	0	0	10	0	0	0	0	0	182	0	0	6	0	0	0	0
11-Jan-00	13:30	14:00	4	1806	556	0	0	762	0	0	0	0	0	0	0	230	144	20	0	0	0	0	0	0
24/7/00	14:00	14:30	5	1080	448	3	0	554	0	0	0	16	0	0	0	0	36	0	2	0	0	0	0	0
23/10/00	14:00	14:30	5	1696	546	0	0	770	0	0	0	0	0	0	0	0	328	28	8	0	0	0	0	0
11-Jan-00	14:00	14:30	5	738	330	0	0	356	0	0	1	0	0	0	0	0	44	0	0	0	0	0	0	0
24/7/00	14:30	15:00	6	1238	446	0	0	370	0	0	0	0	0	0	0	0	150	16	0	0	0	0	0	0
23/10/00	14:30	15:00	6	770	298	0	4	442	0	0	0	0	0	0	0	0	22	0	0	0	0	0	0	0
11-Jan-00	14:30	15:00	6	434	204	0	0	200	0	0	0	0	0	0	0	0	20	0	0	0	0	0	0	0
24/7/00	15:00	15:30	7	694	292	1	0	280	0	0	0	0	0	54	0	0	52	0	4	0	0	0	0	0
23/10/00	15:00	15:30	7	638	302	0	1	318	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0
11-Jan-00	15:00	15:30	7	526	194	0	0	200	0	0	0	20	0	0	0	0	84	0	0	0	0	0	0	0
24/7/00	15:30	16:00	8	832	458	1	0	260	0	0	0	0	0	0	0	18	18	0	10	0	0	0	0	0
23/10/00	15:30	16:00	8	666	322	0	0	268	0	0	2	0	0	0	0	0	48	0	0	0	0	0	0	0
11-Jan-00	15:30	16:00	8	768	350	0	0	298	0	0	0	0	0	0	0	0	124	0	0	0	0	0	0	0
24/7/00	16:00	16:30	9	544	290	0	0	248	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23/10/00	16:00	16:30	9	802	352	0	0	332	6	0	0	0	0	0	0	0	74	20	10	0	0	0	0	0
11-Jan-00	16:00	16:30	9	1068	310	0	0	560	0	0	0	0	0	0	0	0	166	0	0	0	0	0	0	0
24/7/00	16:30	17:00	10	724	343	3	0	338	0	0	0	0	0	0	0	0	8	0	10	0	0	0	0	0
23/10/00	16:30	17:00	10	508	230	0	0	354	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0
11-Jan-00	16:30	17:00	10	1430	514	0	0	720	0	0	0	0	0	0	0	0	180	0	6	0	0	0	0	0
24/7/00	17:00	17:30	11	1270	400	4	1	512	0	0	0	0	0	0	0	0	312	0	0	0	0	0	0	0
23/10/00	17:00	17:30	11	796	396	0	0	308	0	0	0	0	0	0	0	0	42	0	14	0	0	0	0	0
11-Jan-00	17:00	17:30	11	794	244	0	0	422	0	0	0	0	0	0	0	0	30	42	6	0	0	0	0	0
24/7/00	17:30	18:00	12	1140	646	0	0	460	0	0	0	0	0	0	0	0	50	0	0	0	0	0	0	0
23/10/00	17:30	18:00	12	1570	718	0	0	584	0	0	0	0	0	0	0	0	220	24	0	0	0	0	0	0
11-Jan-00	17:30	18:00	12	1238	432	0	0	560	0	0	0	0	0	0	0	112	126	0	0	0	0	0	0	0
24/7/00	18:00	18:30	13	1340	332	0	0	634	0	0	0	0	0	0	0	0	358	0	4	0	0	0	0	0
23/10/00	18:00	18:30	13	1436	690	0	0	554	0	0	0	0	0	0	0	36	144	0	1	0	0	0	0	0
11-Jan-00	18:00	18:30	13	2142	656	0	0	1126	0	0	0	0	0	0	0	66	238	18	0	0	0	0	0	0
24/7/00	18:30	19:00	14	986	366	0	0	582	0	0	0	0	0	0	8	0	0	22	0	0	0	0	0	0
23/10/00	18:30	19:00	14	972	386	1	0	518	0	0	0	0	0	0	0	0	20	0	0	0	42	0	0	42
11-Jan-00	18:30	19:00	14	1352	518	0	0	600	0	0	0	0	0	0	0	0	80	128	0	0	0	0	0	0

	Time	Time	Sac	Total Contents in Sac	Mush in Sac	Cigeratte Filter	Cotton Bud Sticks	Faecal Material	Fat	Kitchen Roll	Leaves	Pant Liner	Paper Towel	Sanitary Towel	Sanitary Wrapping	Tampon	Toilet Roll	Wipes	Remaining Weight	Condom	Wipes Shredded	Panti Liner Shield	Sanitary towel shell	Total Wipes
Date	In	Out	No.	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)
19/10/00	19:00	19:30	1	674	268	0	0	394	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29/11/00	19:00	19:30	1	1204	474	0	1	542	0	0	0	0	0	0	0	0	172	0	0	0	0	0	0	0
01-Sep-00	19:00	19:30	1	1764	1224	0	0	352	0	0	0	14	0	0	0	0	0	32	0	8	0	0	120	0
19/10/00	19:30	20:00	2	1588	836	0	0	466	0	0	0	0	0	0	0	0	222	48	0	0	0	0	0	0
29/11/00	19:30	20:00	2	978	328	0	1	328	0	0	0	0	0	82	0	0	240	0	0	0	0	0	0	0
01-Sep-00	19:30	20:00	2	966	526	0	1	312	0	0	0	0	0	0	0	0	0	118	0	0	0	0	0	0
19/10/00	20:00	20:30	3	1528	628	0	0	364	0	0	0	0	0	0	0	168	352	0	0	0	0	0	0	0
29/11/00	20:00	20:30	3	834	400	0	0	406	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01-Sep-00	20:00	20:30	3	1198	840	0	0	262	0	0	0	0	0	0	0	0	32	0	47	0	0	0	0	0
19/10/00	20:30	21:00	4	1366	572	0	0	230	0	0	0	0	0	0	0	0	550	0	0	0	0	0	0	0
29/11/00	20:30	21:00	4	1460	598	0	0	636	0	0	0	0	0	0	0	0	216	0	0	0	0	0	0	0
01-Sep-00	20:30	21:00	4	1512	768	0	0	618	0	0	0	0	0	0	0	0	110	0	0	0	0	0	0	0
19/10/00	21:00	21:30	5	1158	586	0	0	470	0	0	0	0	0	0	0	0	60	20	8	0	0	0	0	0
29/11/00	21:00	21:30	5	1200	610	0	0	484	0	0	0	0	0	0	0	30	56	0	0	0	0	0	0	0
01-Sep-00	21:00	21:30	5	1832	1476	0	0	86	0	0	0	0	0	68	0	0	132	44	0	0	0	1	0	0
19/10/00	21:30	22:00	6	1818	542	0	0	548	2	0	6	0	0	0	0	0	222	46	6	0	0	0	0	0
29/11/00	21:30	22:00	6	3086	878	0	0	182	0	0	0	16	0	0	0	146	1662	130	0	0	0	0	0	0
01-Sep-00	21:30	22:00	6	1598	1590	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0	0	0	0	0
19/10/00	22:00	22:30	7	856	450	2	0	208	0	0	0	0	0	126	0	0	50	0	0	0	0	0	0	0
29/11/00	22:00	22:30	7	886	346	0	0	274	0	0	0	0	0	0	0	56	152	32	0	0	0	0	0	0
01-Sep-00	22:00	22:30	7	818	426	0	3	328	0	0	0	0	0	0	0	0	58	0	0	0	0	0	0	0
19/10/00	22:30	23:00	8	866	458	0	0	316	0	0	0	0	0	0	0	0	88	0	0	0	0	0	0	0
29/11/00	22:30	23:00	8	822	508	0	0	260	0	0	0	0	0	0	0	0	54	0	0	0	0	0	0	0
01-Sep-00	22:30	23:00	8	1352	958	0	0	342	0	0	0	0	0	0	0	0	22	0	16	2	0	0	0	0
19/10/00	23:00	23:30	9	764	446	0	0	194	0	0	0	0	0	0	0	0	104	0	0	0	0	0	0	0
29/11/00	23:00	23:30	9	580	430	0	0	142	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01-Sep-00	23:00	23:30	9	2018	678	0	0	648	0	0	0	0	0	0	0	148	508	0	4	0	0	0	0	0
19/10/00	23:30	00:00	10	430	286	0	0	116	0	0	0	0	0	0	0	0	16	0	0	0	0	0	0	0
29/11/00	23:30	00:00	10	956	494	0	0	446	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01-Sep-00	23:30	00:00	10	616	482	0	0	126	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0
19/10/00	00:00	00:30	11	438	250	0	0	136	0	0	0	0	0	0	0	0	44	0	0	0	0	0	0	0
29/11/00	00:00	00:30	11	610	266	0	1	298	0	0	0	0	0	0	0	0	38	0	1	0	0	1	0	0
01-Sep-00	00:00	00:30	11	718	520	0	0	24	0	0	0	0	0	18	0	0	122	24	0	0	0	0	0	0
19/10/00	00:30	01:00	12	290	152	0	0	102	0	0	0	0	0	30	0	0	0	0	0	0	0	0	0	0
29/11/00	00:30	01:00	12	278	160	0	0	108	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01-Sep-00	00:30	01:00	12	412	292	0	0	88	0	0	0	0	0	0	0	0	28	0	0	0	0	0	0	0

1.11 Ethnic Catchment Wet Weather - Wet Masses

STORM OS2 - 10/09/2000		
Time In	Time Out	Mass (g)
10:30	11:00	888
11:00	11:30	1052
11:30	12:00	816
12:00	12:10	352
12:10	12:20	832
12:20	12:25	908
12:25	12:30	420
12:30	12:35	294
12:35	12:40	242
12:40	12:45	626
12:45	12:50	252
12:50	12:55	456
12:55	13:00	90
13:00	13:10	502
13:10	13:20	848
13:20	13:26	2304
13:26	13:30	760
13:30	13:35	192
13:35	13:40	176
13:40	13:50	254
13:50	14:00	996
14:00	14:10	288
14:10	14:20	974
14:20	14:30	586
14:30	14:35	872

STORM OS4 - 12/07/2000		
Time In	Time Out	Mass (g)
16:30	17:00	1428
17:00	17:30	1334
17:30	18:00	1474
18:00	18:30	2038
18:30	18:50	628
18:50	19:00	536
19:00	19:05	1272
19:05	19:10	1944
19:10	19:15	1448
19:15	19:20	1772
19:20	19:25	236
19:25	19:30	532
19:30	19:35	988
19:35	19:40	1052
19:40	19:45	802
19:45	19:50	520
19:50	20:00	708
20:00	20:10	854
20:10	20:20	422
20:20	20:30	714
20:30	20:40	756

STORM OS5 - 04/05/2001		
Time In	Time Out	Mass (g)
11:15	11:30	390
11:30	11:45	502
11:45	12:00	856
12:00	12:10	1272
12:10	12:15	458
12:15	12:20	1282
12:20	12:25	342
12:25	12:30	924
12:30	12:35	1088
12:35	12:40	912
12:40	12:45	344
12:45	12:50	836
12:50	12:55	602
12:55	13:00	568
13:00	13:10	254
13:10	13:20	496
13:20	13:30	770
13:30	13:40	222

1.12 Ethnic Catchment Wet Weather – Characterised Data

STORM OS2																							
Time In	Time Out	Sac No.	Total Contents in Sac (g)	Mush in Sac (g)	Cigeratte Filter (g)	Cotton Bud Sticks (g)	Faecal Material (g)	Fat (g)	Kitchen Roll (g)	Leaves (gulley Entrants (g)	Pant Liner (g)	Paper Towel (g)	Sanitary Towel (g)	Sanitary Wrapping (g)	Tampon (g)	Toilet Roll (g)	Wipes (g)	Remaining Weight (g)	Condom (g)	Wipes Shredded (g)	Panti Liner Shield (g)	Sanitary towel shell (g)	Total Wipes (g)
10:30	11:00	1	906	398			472									24							
11:00	11:30	2	1072	488			486								42	36							
11:30	12:00	3	838	376			306									148							
12:00	12:10	4	392	176			206																
12:10	12:20	5	876	344			218								224	32		10					
12:20	12:25	6	948	512			306									56	40					1	
12:25	12:30	7	454	196			190	6								44						4	
12:30	12:35	8	344	114			162									82							
12:35	12:40	9	276	126			86									28		36					
12:40	12:45	10	666	296			360																
12:45	12:50	11	482	142			68						86			156							
12:50	12:55	12	302	198			94									4							
12:55	13:00	13	126	110			12																
13:00	13:10	14	378	276			46									34							
13:10	13:20	15	574	320			216									8	14						
13:20	13:26	16	2298	828			666				20					436	264						
13:26	13:30	17	792	164			560										52						
13:30	13:35	18	226	172			52															4	
13:35	13:40	S1	210	138			66																
13:40	13:50	S2	300	218			84																
13:50	14:00	S3	1042	396			522								40	68							
14:00	14:10	S4	324	180			86									36							
14:10	14:20	S5	1064	418			144			268			50		36	52							
14:20	14:30	S6	628	250			102			242						10							
14:30	14:35	S7	858	364						394	4				34	6	34						

STORM OS4

Time In	Time Out	Sac No.	Total Contents in Sac (g)	Mush in Sac (g)	Cigeratte Filter (g)	Cotton Bud Sticks (g)	Faecal Material (g)	Fat (g)	Kitchen Roll (g)	Leaves (gulley Entrants (g)	Pant Liner (g)	Paper Towel (g)	Sanitary Towel (g)	Sanitary Wrapping (g)	Tampon (g)	Toilet Roll (g)	Wipes (g)	Remaining Weight (g)	Condom (g)	Wipes Shredded (g)	Panti Liner Shield (g)	Sanitary towel shell (g)	Total Wipes (g)
16:34	17:00	1	1434	776			558									88							
17:00	17:30	2	1314	518			620			2		14				156	20						
17:30	18:00	3	1496	614			448									416	16						
18:00	18:30	4	2028	718			1116				14	8				132	24						
18:30	18:50	5	664	294			312									30	26						
18:50	19:00	6	574	252			118								40	152							
19:00	19:05	7	1298	402			372					6			68	314	102	1					
19:05	19:10	8	1962	604		1	1128								34	132	52						
19:10	19:15	9	1460	364			1034										20				1		
19:15	19:20	10	1754	402		1	1092				10					198	18				12		
19:20	19:25	11	260	134			106			20													
19:25	19:30	12	572	134		2	348								30	32	22						
19:30	19:35	13	1036	326			386			58						244							
19:35	19:40	14	1080	244			664			78	34					52							
19:40	19:45	15	834	246			244			218						122							
19:45	19:50	16	560	190			248			16						100							
19:50	20:00	17	730	142		1	300			78	16					170							
20:00	20:10	18	894	236			508				8				20	70	30						
20:10	20:20	S1	450	132			152									98	26	32					
20:20	20:30	S2	786	178			456									58	50						
20:30	20:40	S3	772	336			336						80			12							

STORM OS5

Time In	Time Out	Sac No.	Total Contents in Sac (g)	Mush in Sac (g)	Cigeratte Filter (g)	Cotton Bud Sticks (g)	Faecal Material (g)	Fat (g)	Kitchen Roll (g)	Leaves (gulley Entrants (g)	Pant Liner (g)	Paper Towel (g)	Sanitary Towel (g)	Sanitary Wrapping (g)	Tampon (g)	Toilet Roll (g)	Wipes (g)	Remaining Weight (g)	Condom (g)	Wipes Shredded (g)	Panti Liner Shield (g)	Sanitary towel shell (g)	Total Wipes (g)
11:15	11:30	1	430	216			176									28							
11:30	11:45	2	578	320			152									92							
11:45	12:00	3	860	250			530									86							
12:00	12:10	4	1318	374			832									98							
12:10	12:15	5	500	242			194									54							
12:15	12:20	6	1322	468			372								92	278	20	70					
12:20	12:25	7	382	186			192									4							
12:25	12:30	8	946	284			546				18					90							
12:30	12:35	9	1112	320			548				20					86	28						
12:35	12:40	10	940	276			270						16			348							
12:40	12:45	11	376	158			216																
12:45	12:50	12	856	222			98			502							12						
12:50	12:55	13	628	302			202			52						60							
12:55	13:00	14	596	202			254			40						8	60						
13:00	13:10	15	280	178			36			38						18							
13:10	13:20	16	524	184			292									40							
13:20	13:30	17	804	190			456						100		38	6							
13:30	13:40	18	256	164			64										22						

Appendix B – Model Predictions Compared With Measured Sampling Data under Storm Conditions

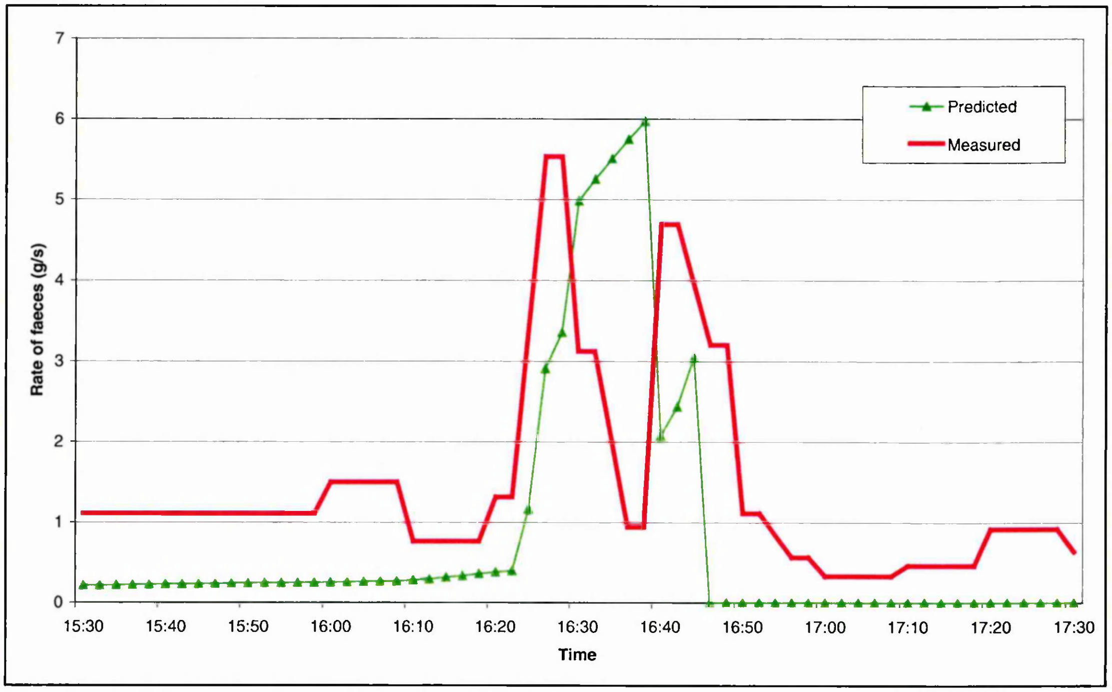


Figure 1 Comparison of simulated against measured results for faeces during storm GS2 at the Low Income catchment

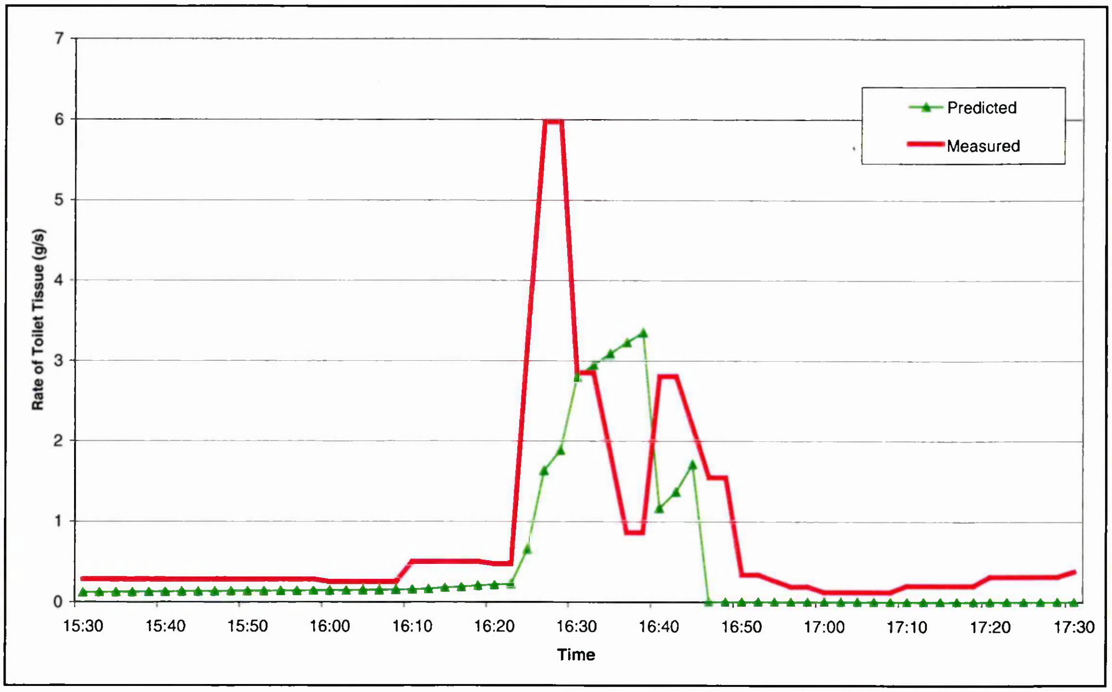


Figure 2 Comparison of simulated against measured results for toilet tissue during storm GS2 at the Low Income catchment

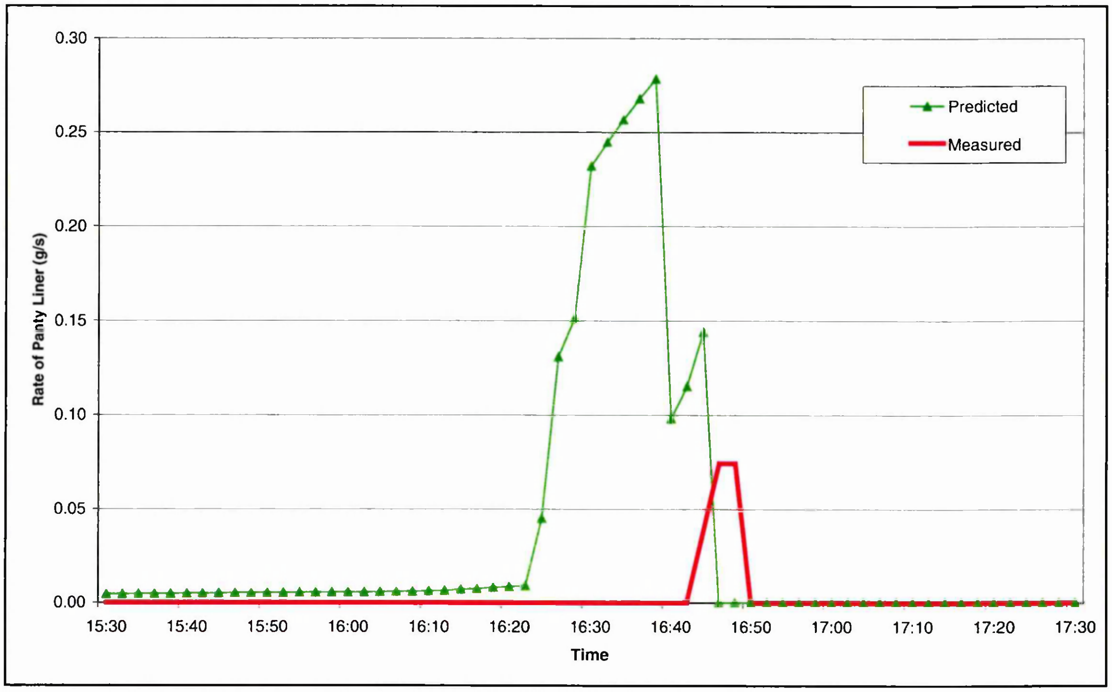


Figure 3 Comparison of simulated against measured results for panty liners during storm GS2 at the Low Income catchment

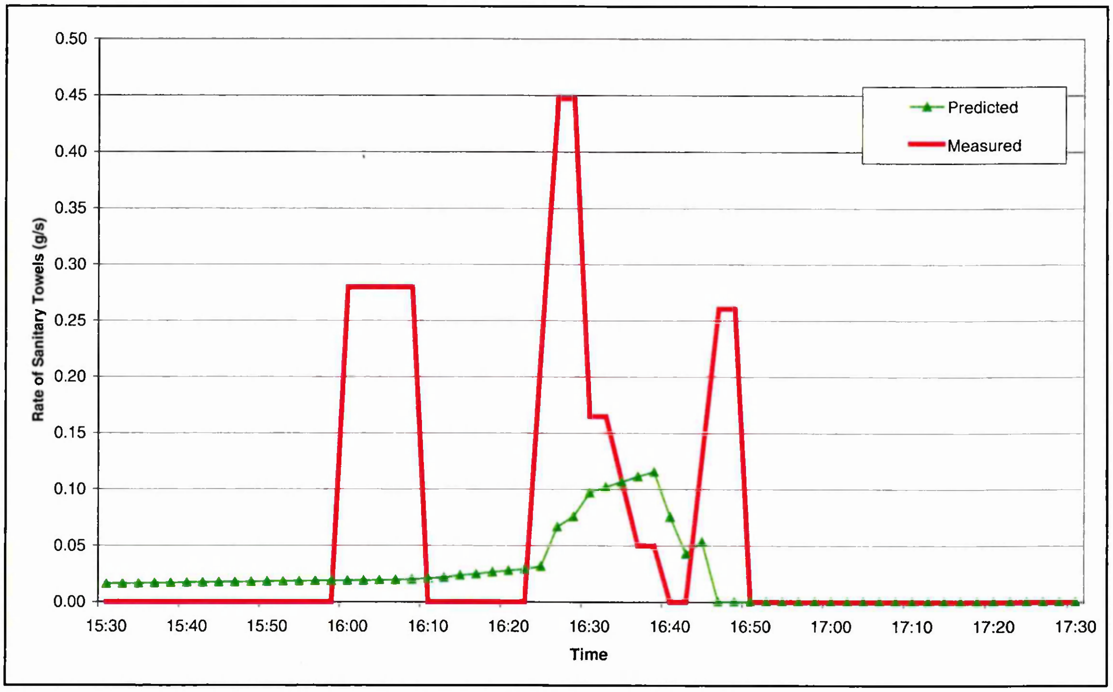


Figure 4 Comparison of simulated against measured results for sanitary towels during storm GS2 at the Low Income catchment

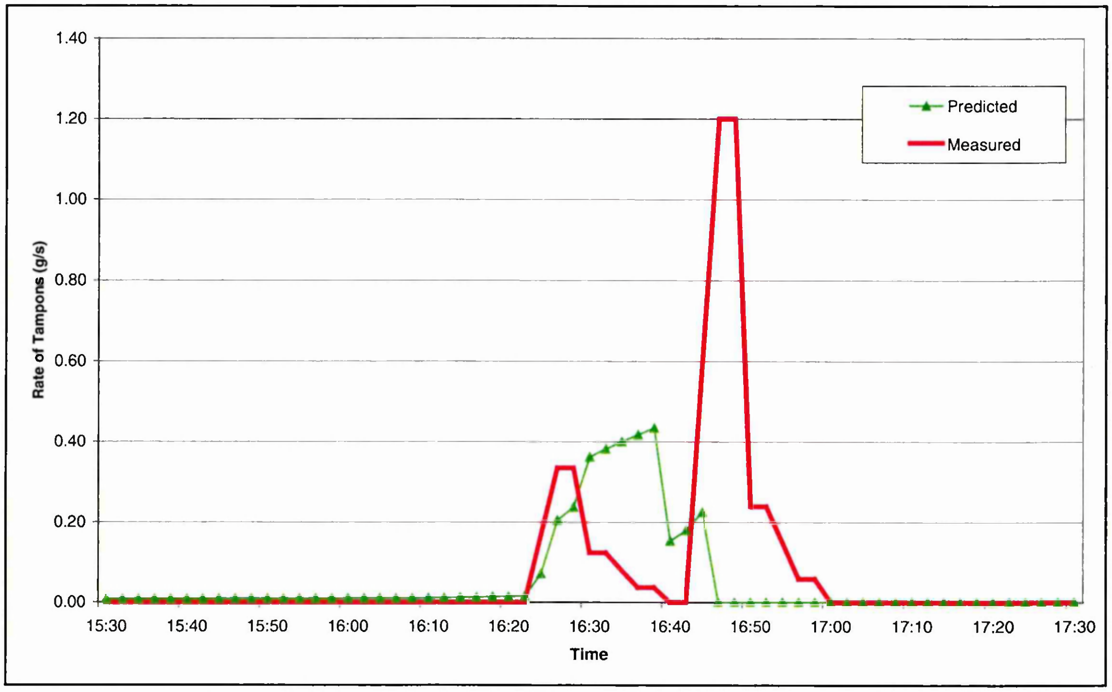


Figure 5 Comparison of simulated against measured results for tampons during storm GS2 at the Low Income catchment

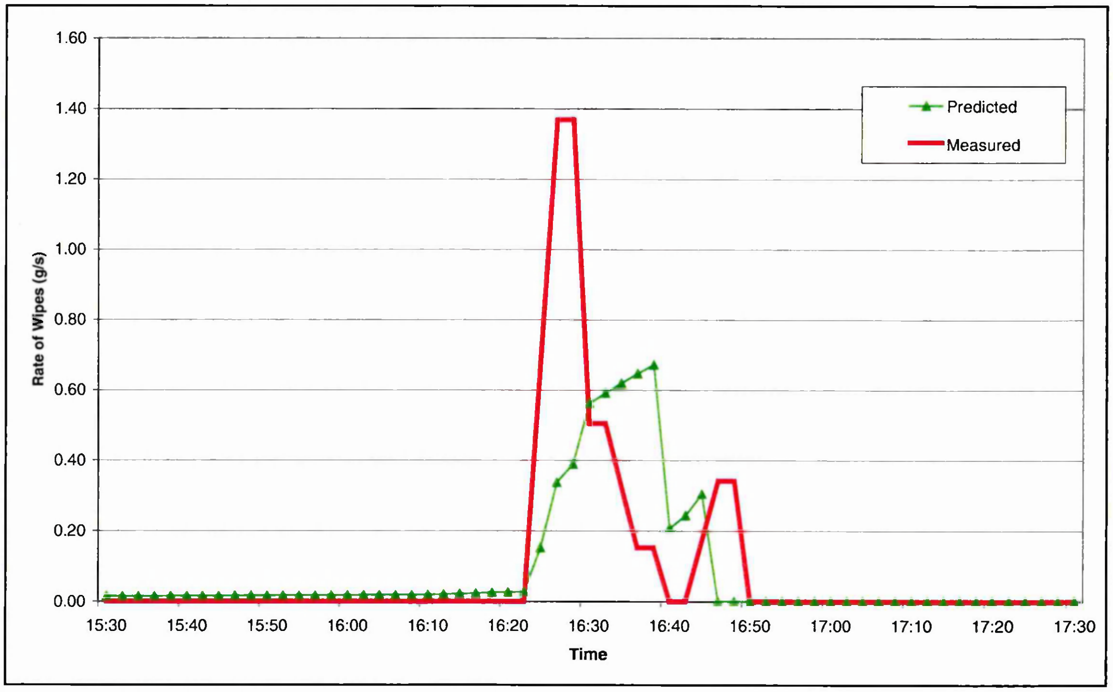


Figure 6 Comparison of simulated against measured results for wipes during storm GS2 at the Low Income catchment

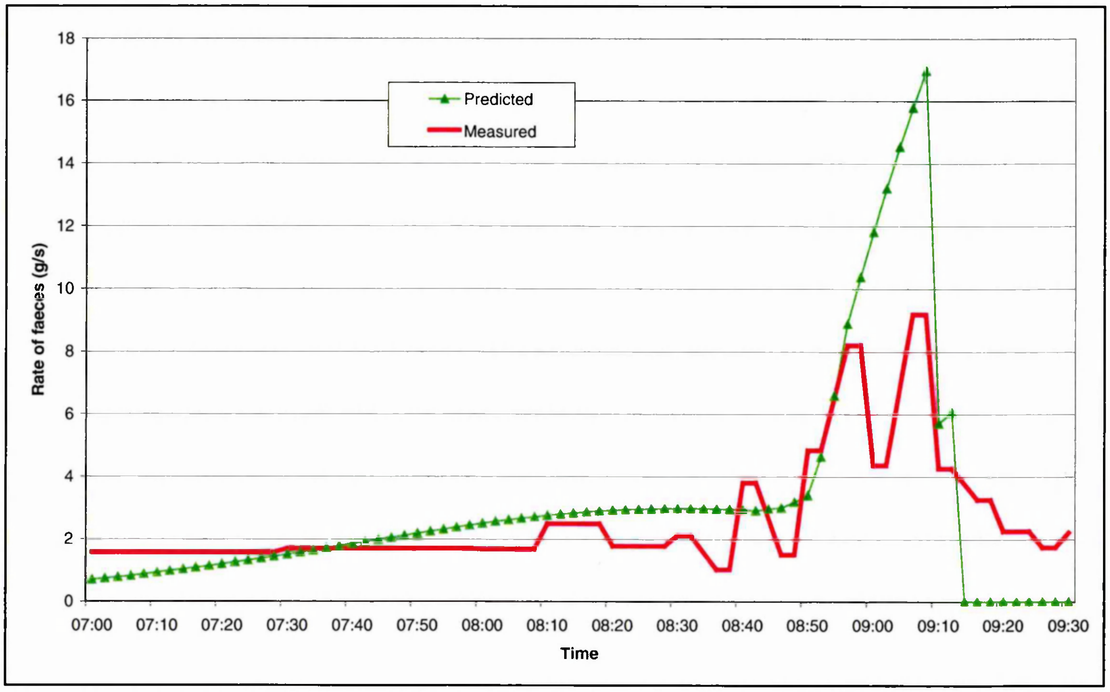


Figure 7 Comparison of simulated against measured results for faeces during storm GS3 at the Low Income catchment

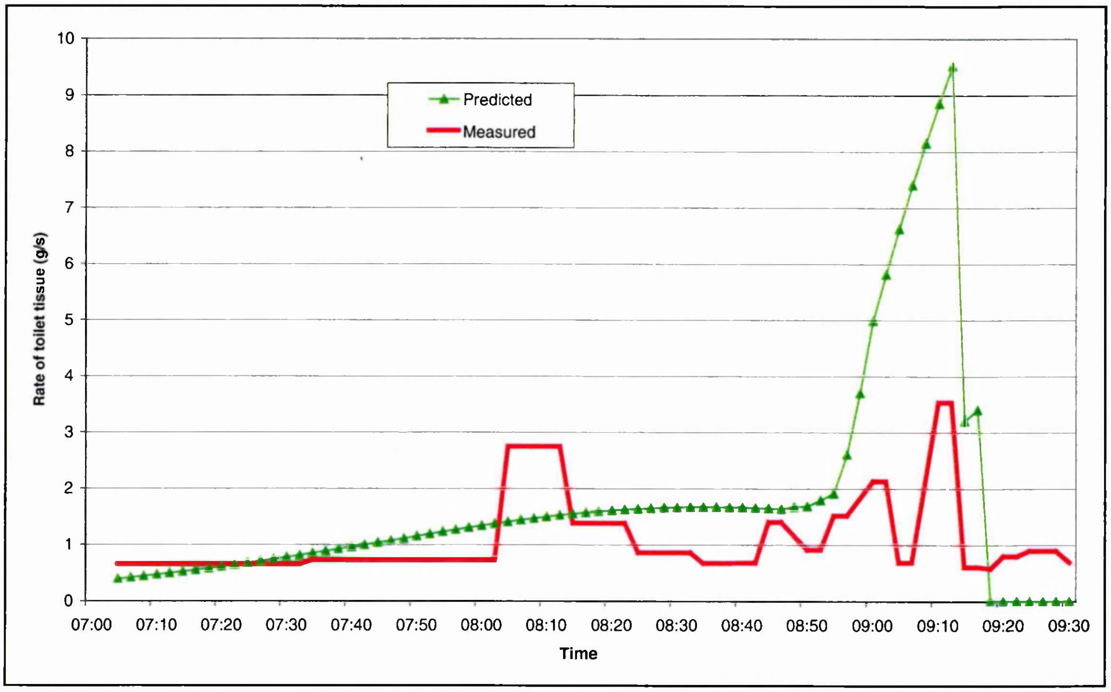


Figure 8 Comparison of simulated against measured results for toilet tissue during storm GS3 at the Low Income catchment

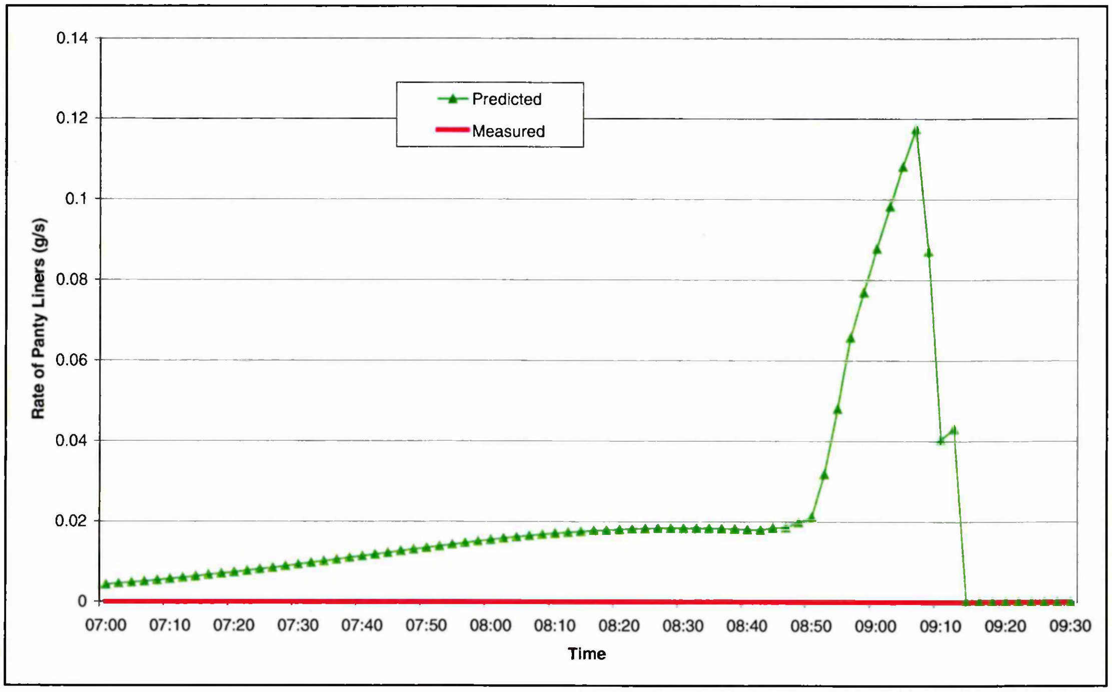


Figure 9 Comparison of simulated against measured results for panty liners during storm GS3 at the Low Income catchment

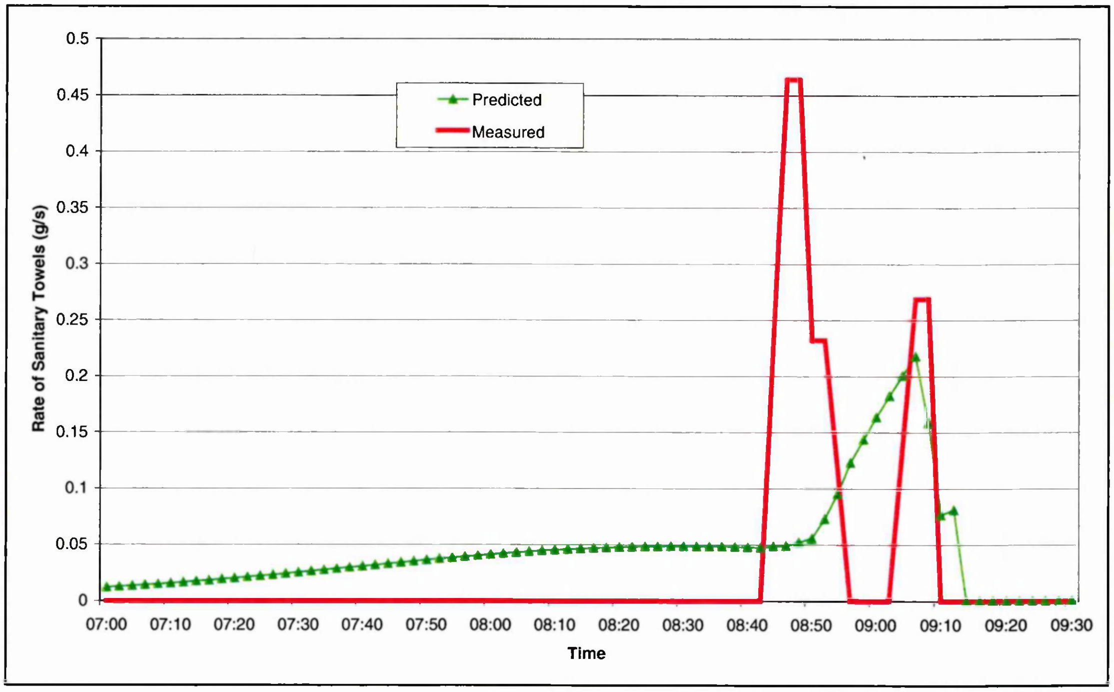


Figure 10 Comparison of simulated against measured results for sanitary towels during storm GS3 at the Low Income catchment

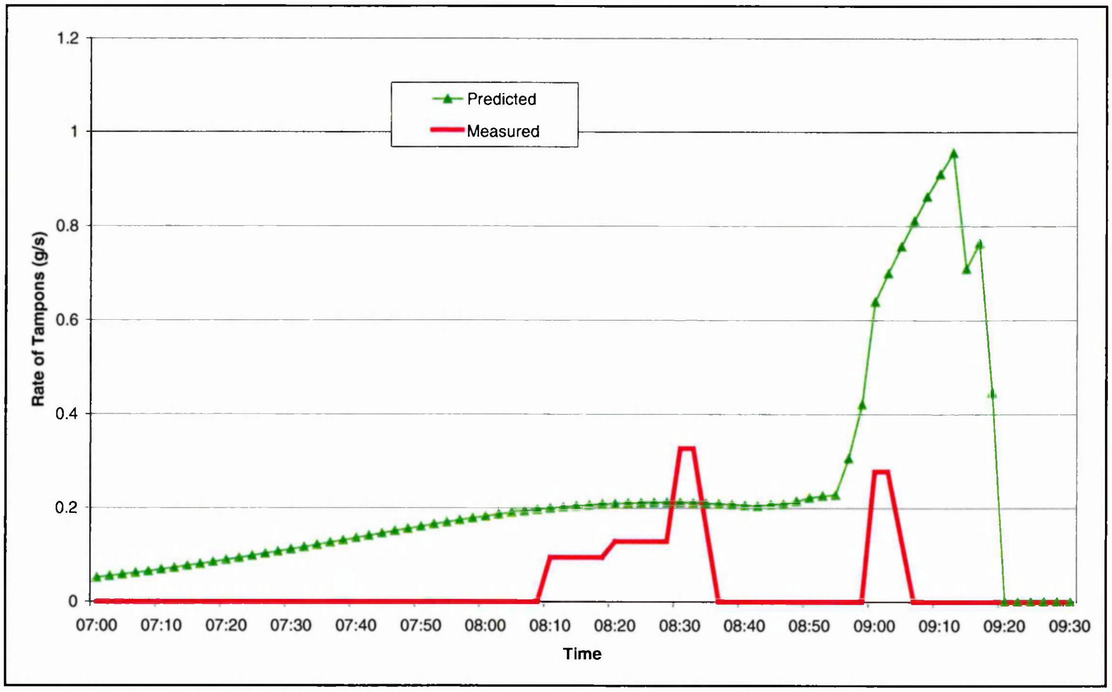


Figure 11 Comparison of simulated against measured results for tampons during storm GS3 at the Low Income catchment

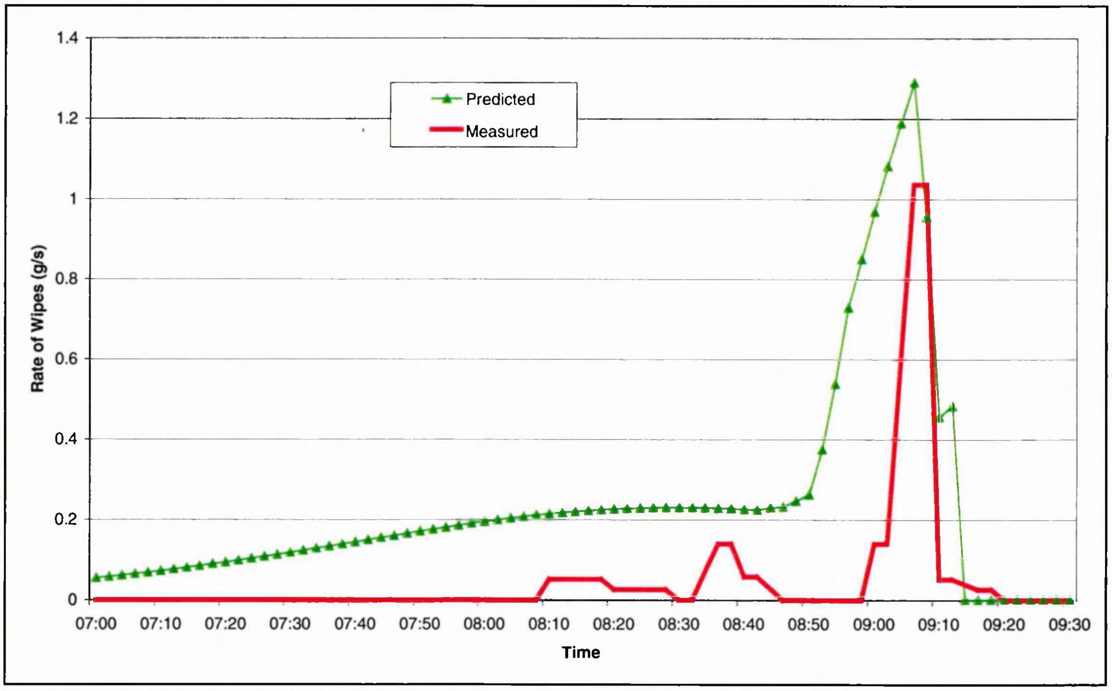


Figure 12 Comparison of simulated against measured results for wipes during storm GS3 at the Low Income catchment

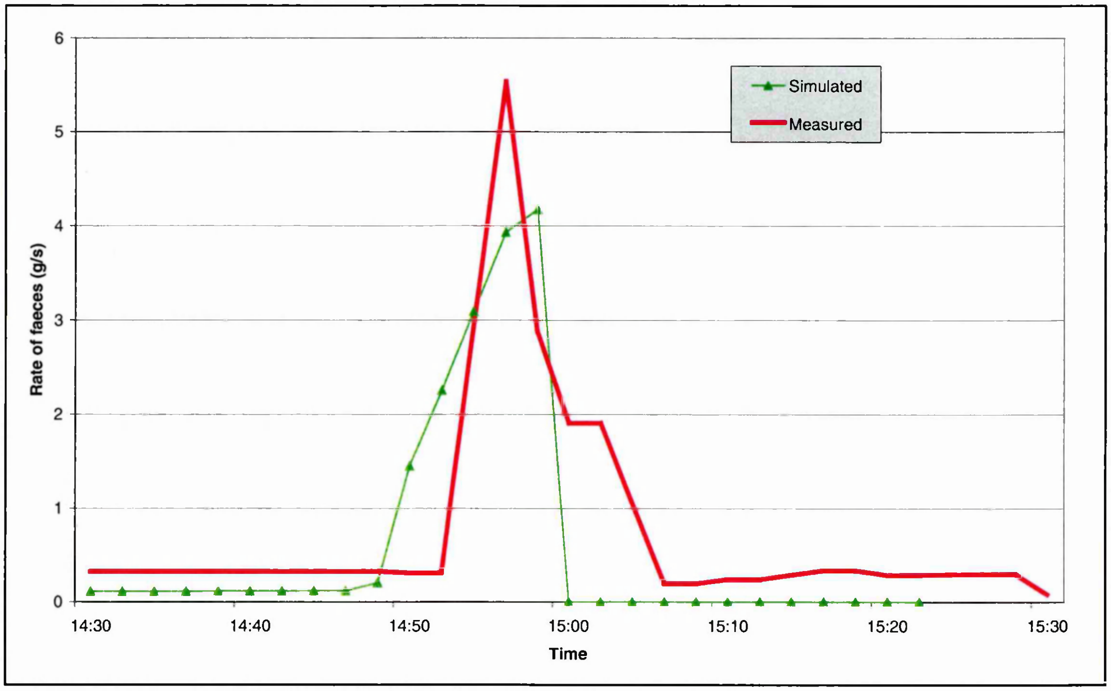


Figure 13 Comparison of simulated against measured results for faeces during storm DS1 at the High Income catchment

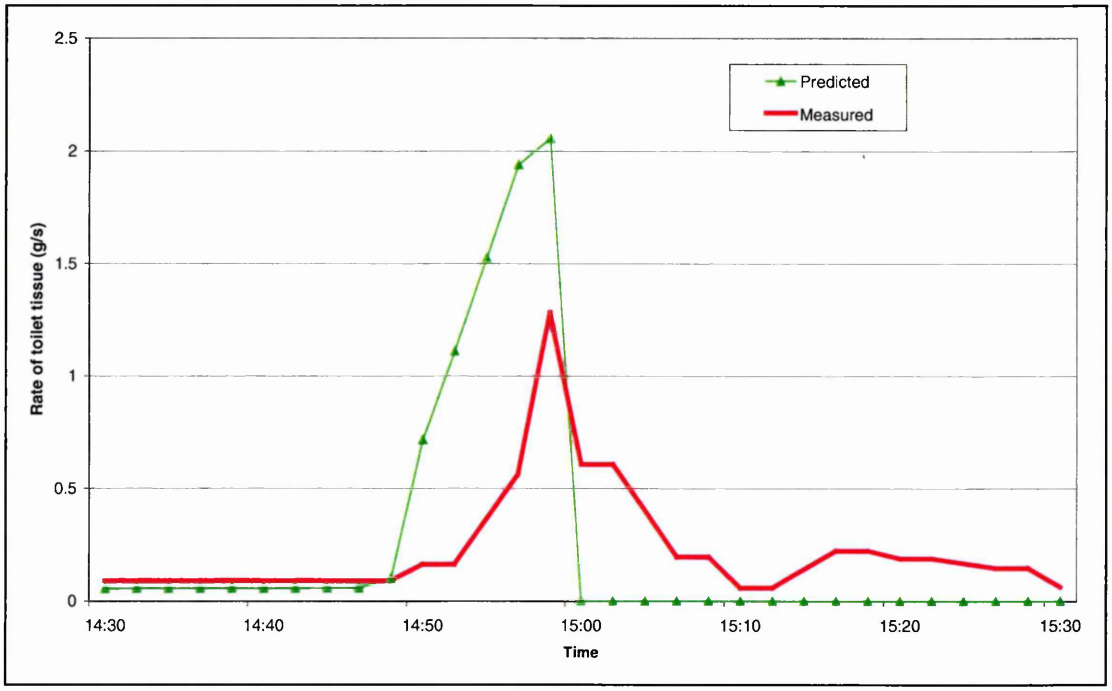


Figure 14 Comparison of simulated against measured results for toilet tissue during storm DS1 at the High Income catchment

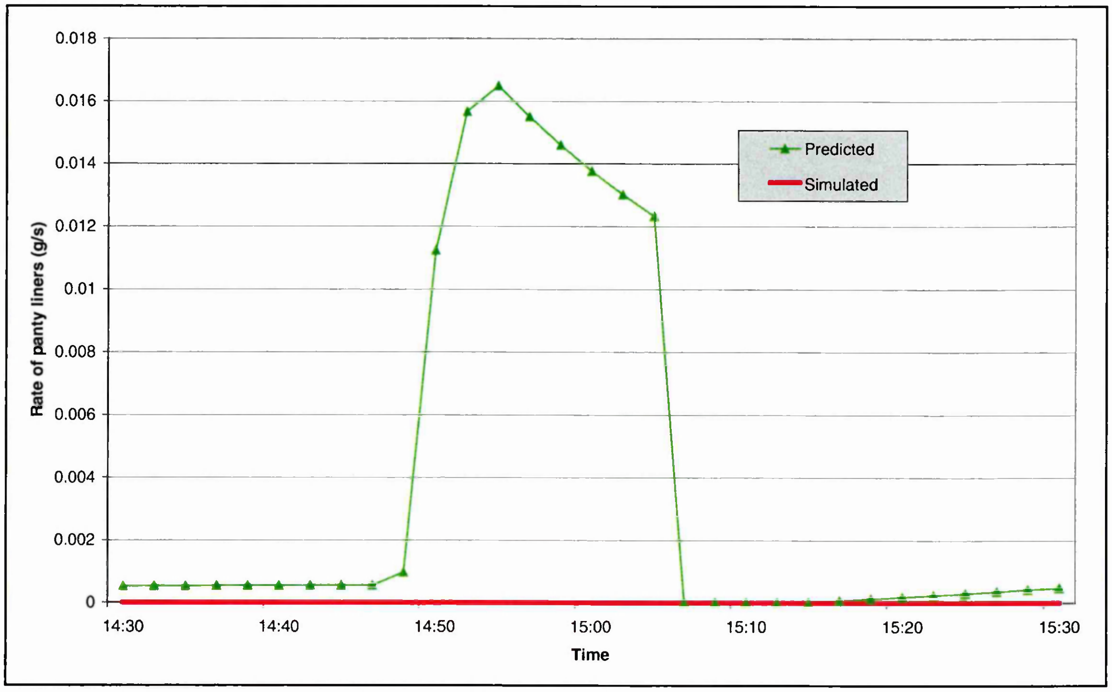


Figure 15 Comparison of simulated against measured results for panty liners during storm DS1 at the High Income catchment

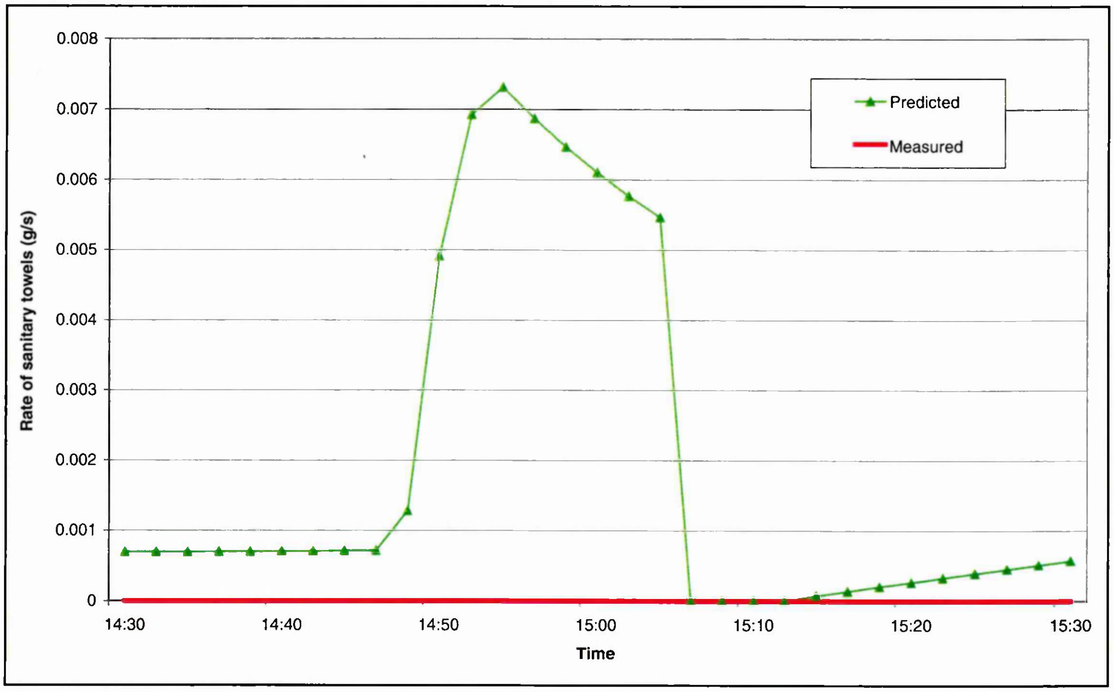


Figure 16 Comparison of simulated against measured results for sanitary towels during storm DS1 at the High Income catchment

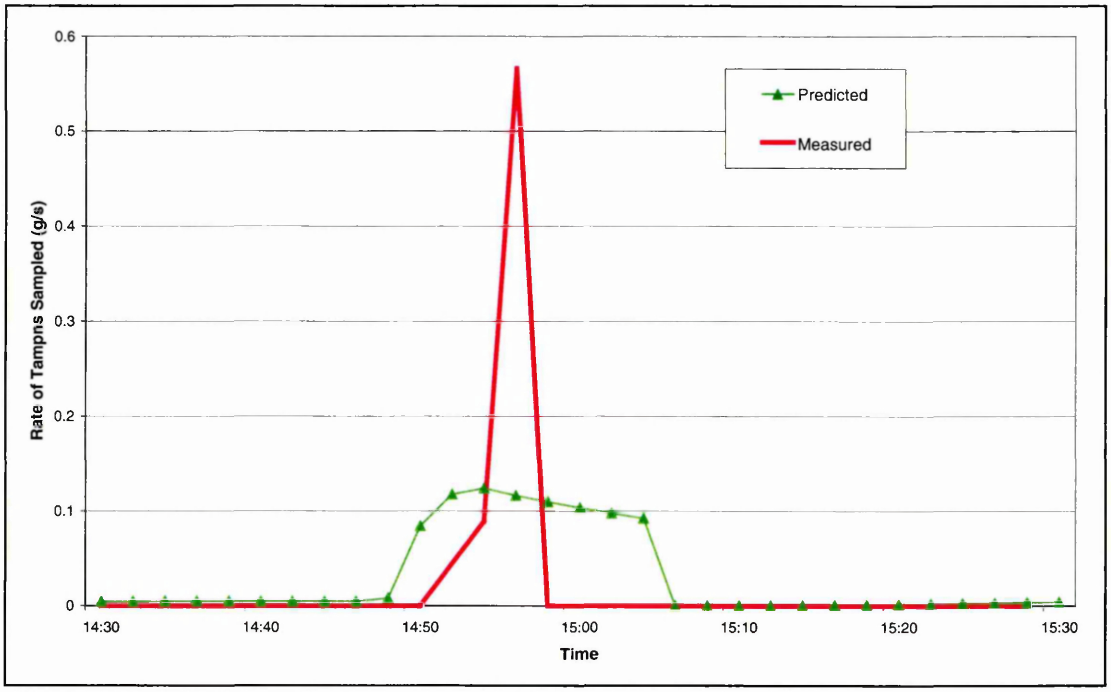


Figure 17 Comparison of simulated against measured results for tampons during storm DS1 at the High Income catchment

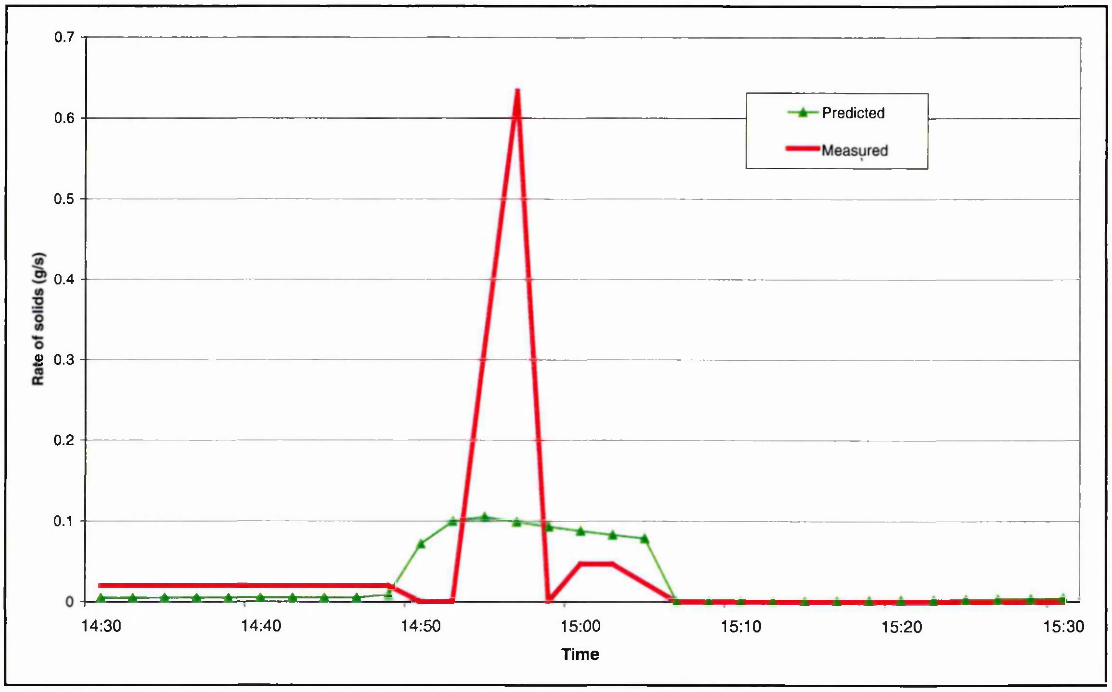


Figure 18 Comparison of simulated against measured results for wipes during storm DS1 at the High Income catchment

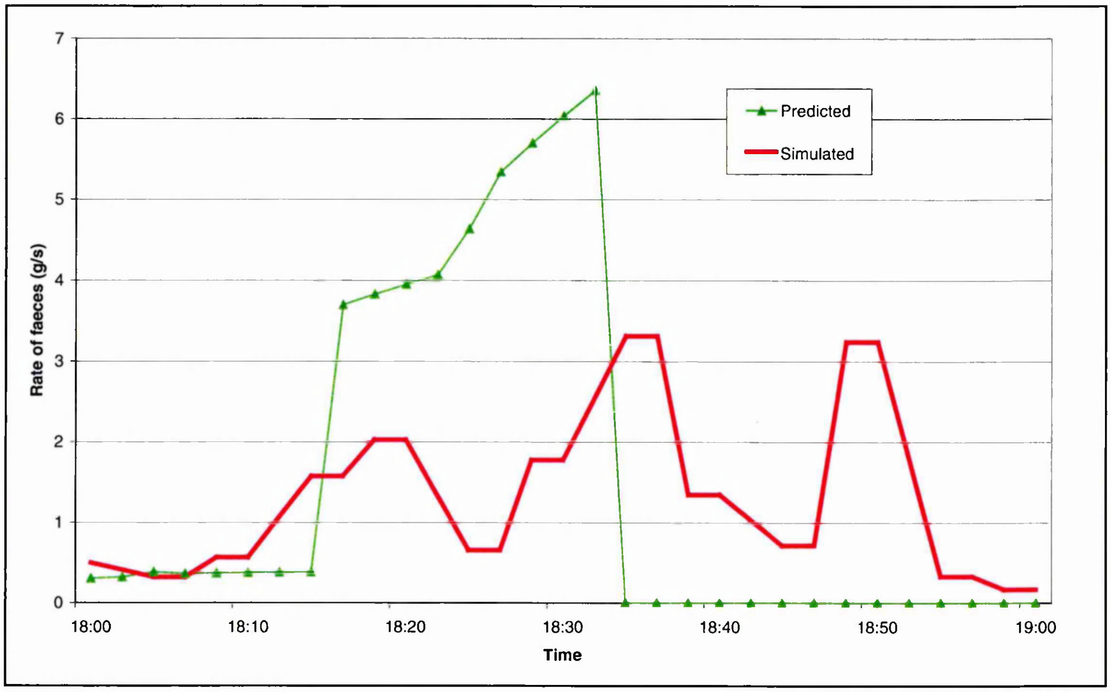


Figure 19 Comparison of simulated against measured results for faeces during storm DS3 at the High Income catchment

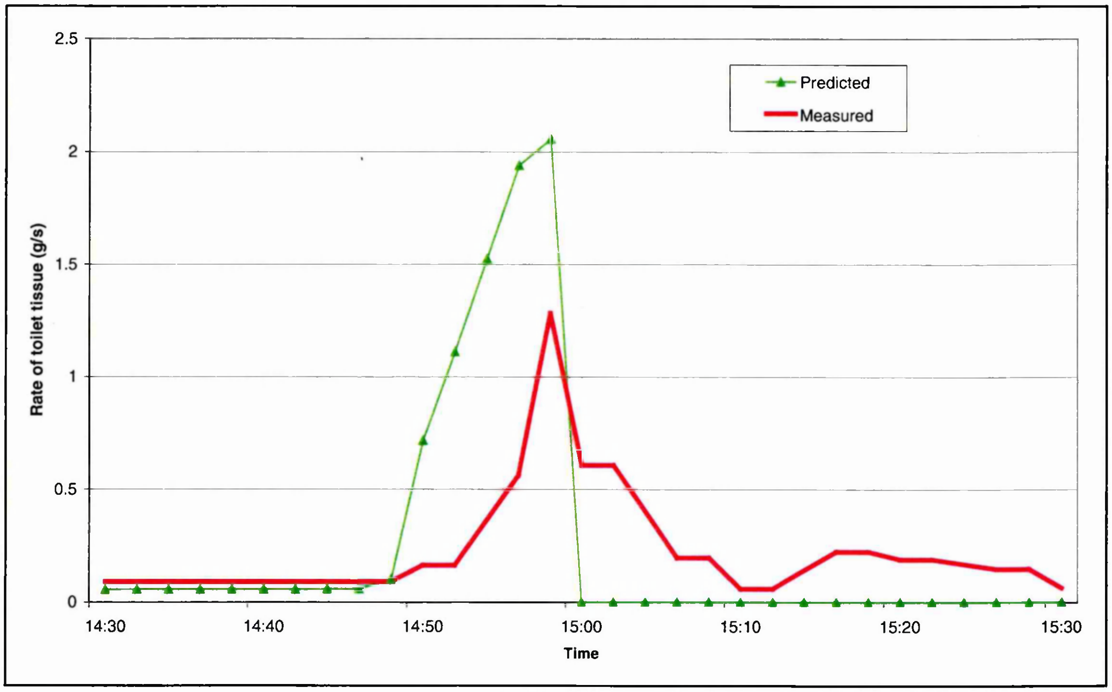


Figure 20 Comparison of simulated against measured results for toilet tissue during storm DS3 at the High Income catchment

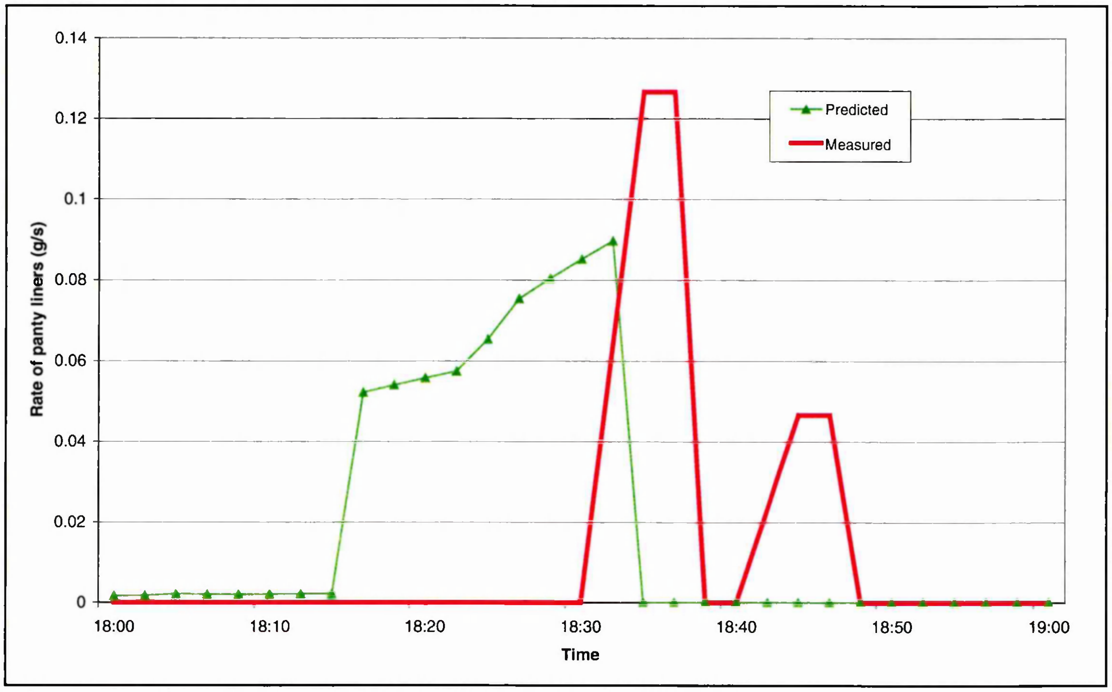


Figure 21 Comparison of simulated against measured results for panty liners during storm DS3 at the High Income catchment

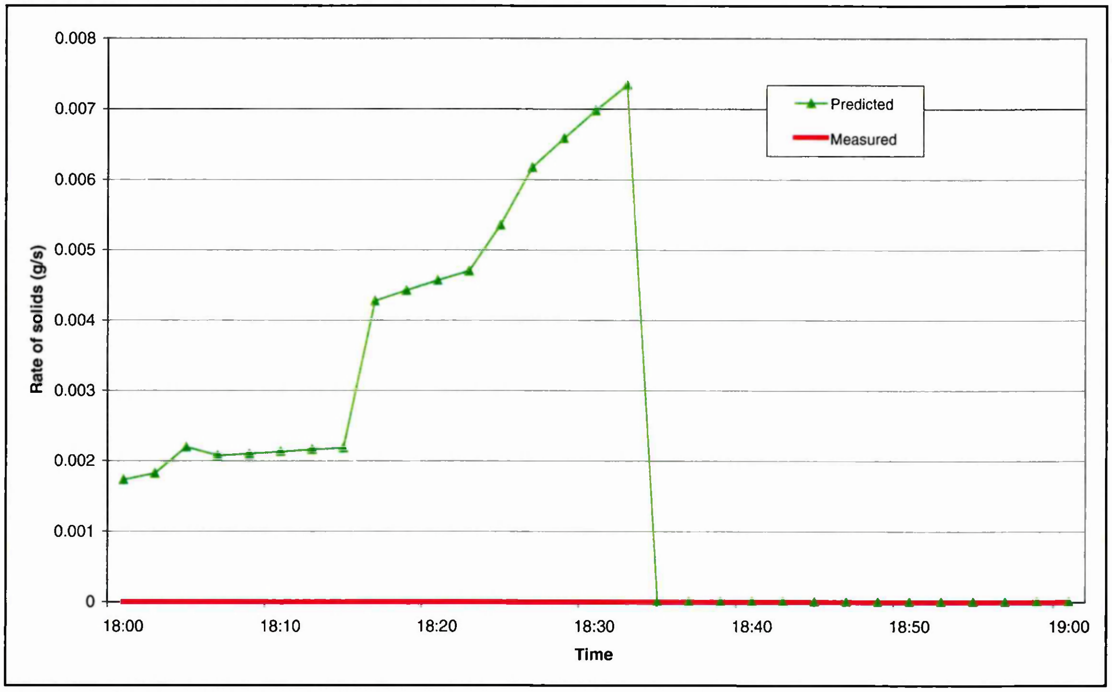


Figure 22 Comparison of simulated against measured results for sanitary towels during storm DS3 at the High Income catchment

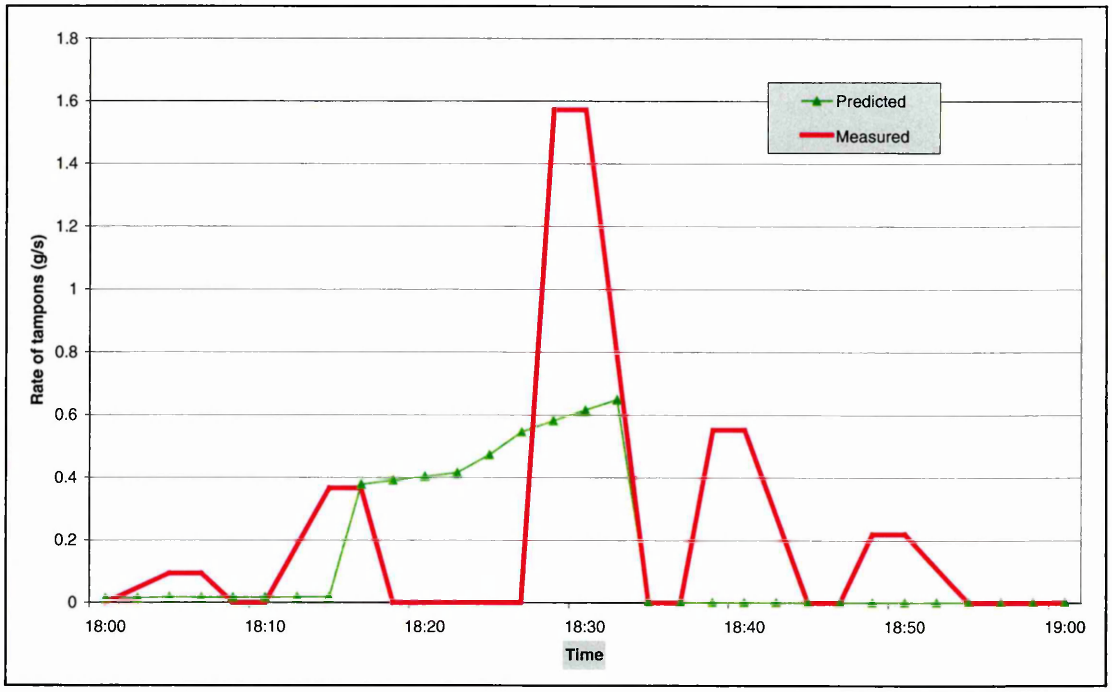


Figure 23 Comparison of simulated against measured results for tampons during storm DS3 at the High Income catchment

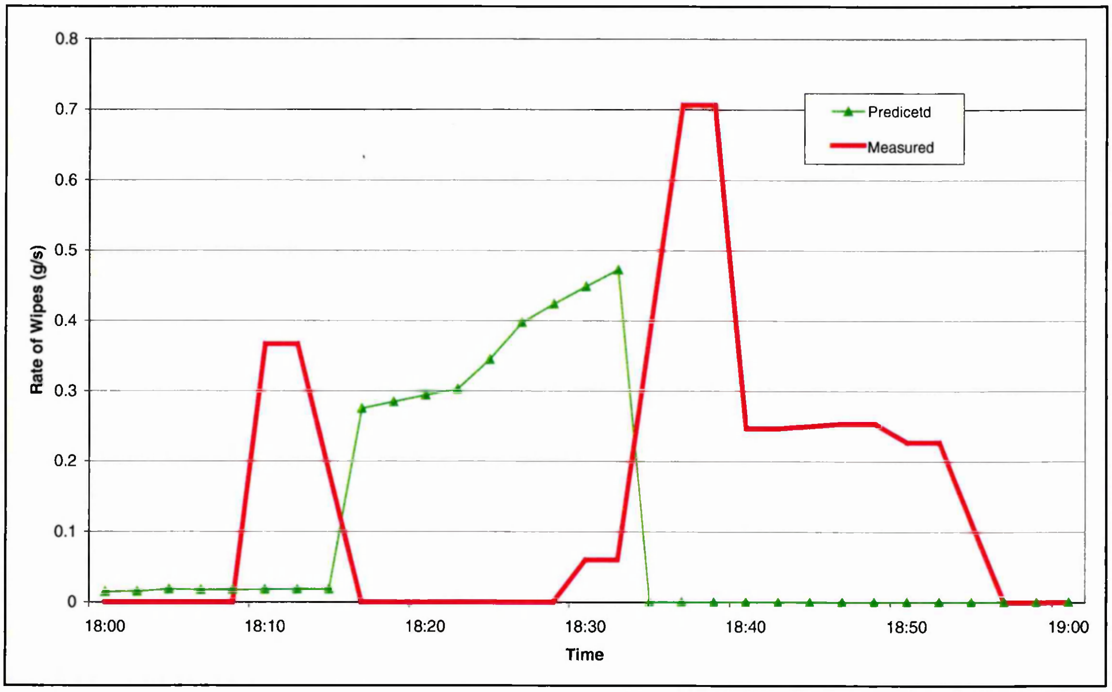


Figure 24 Comparison of simulated against measured results for wipes during storm DS3 at the High Income catchment

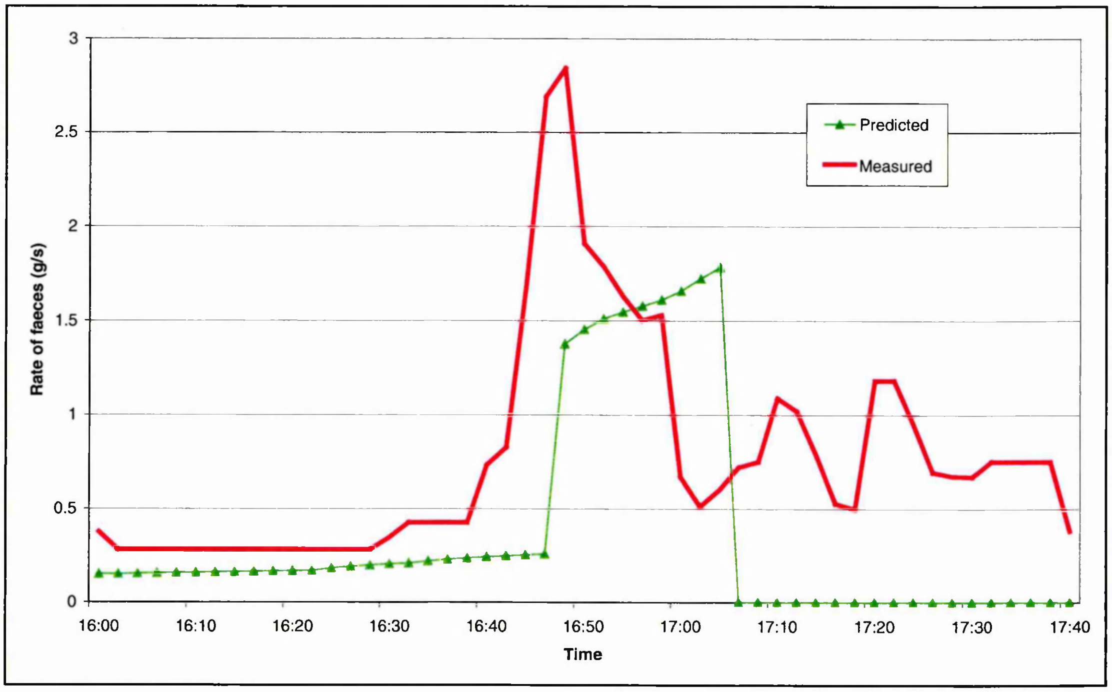


Figure 25 Comparison of simulated against measured results for faeces during storm DS5 at the High Income catchment

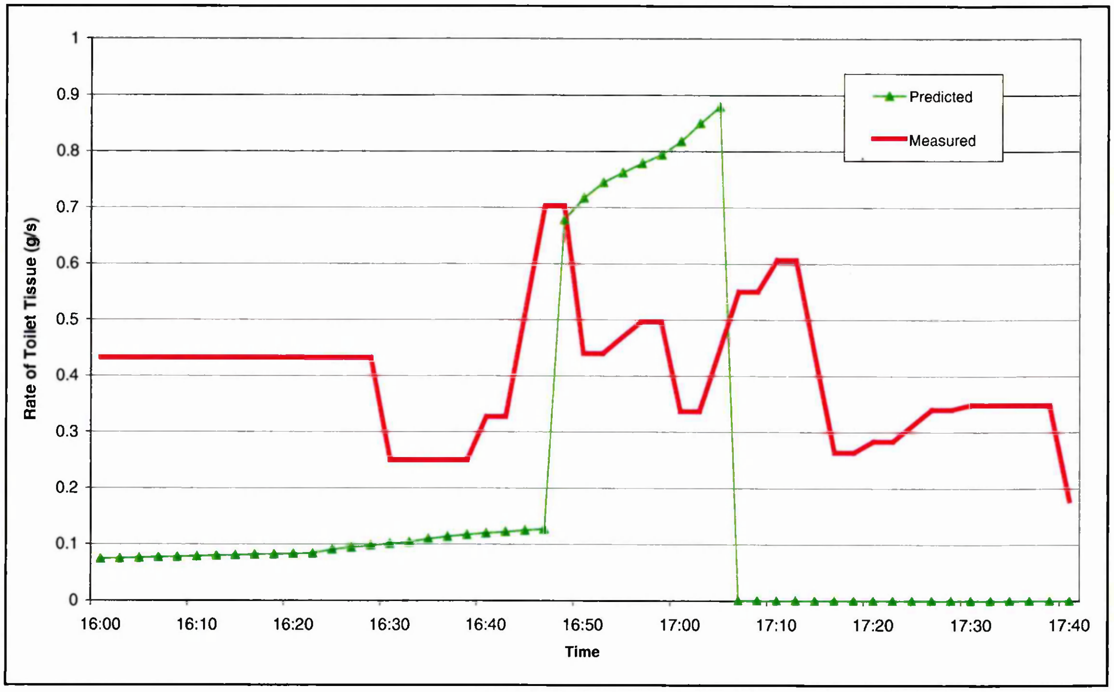


Figure 26 Comparison of simulated against measured results for toilet tissue during storm DS5 at the High Income catchment

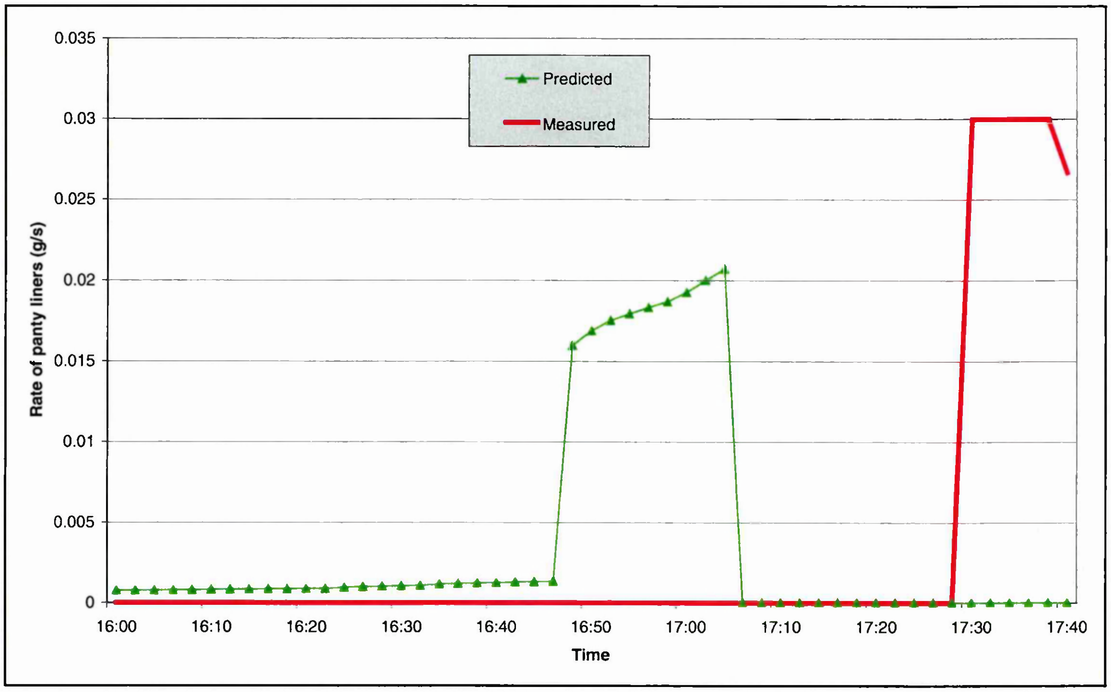


Figure 27 Comparison of simulated against measured results for panty liners during storm DS5 at the High Income catchment

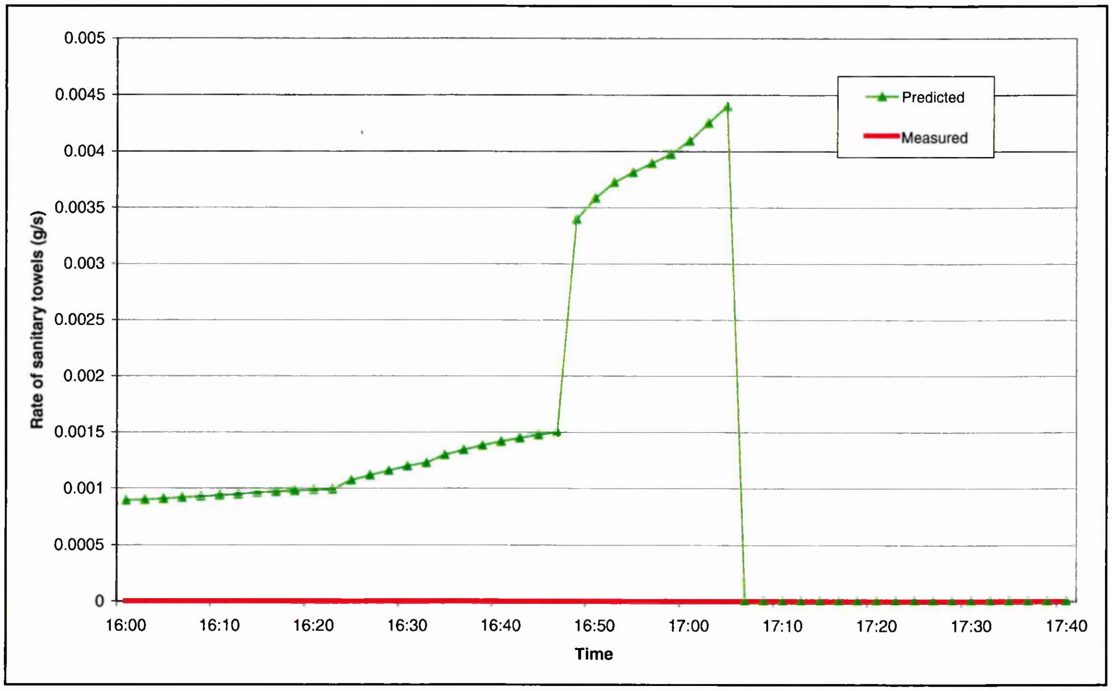


Figure 28 Comparison of simulated against measured results for sanitary towels during storm DS5 at the High Income catchment

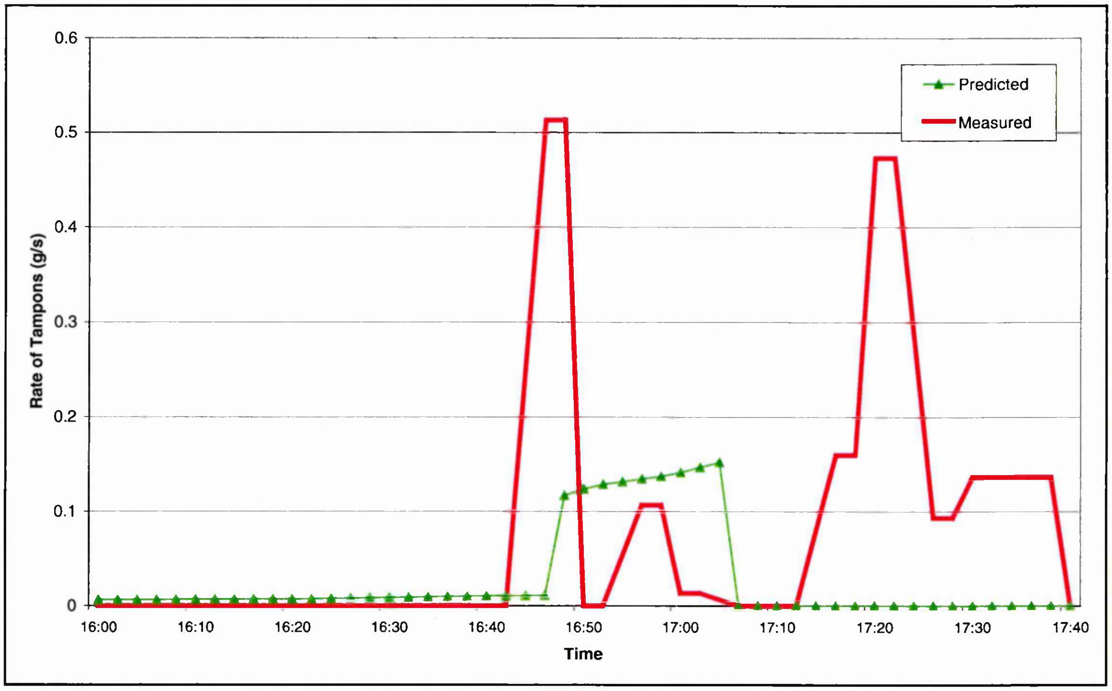


Figure 29 Comparison of simulated against measured results for tampons during storm DS5 at the High Income catchment

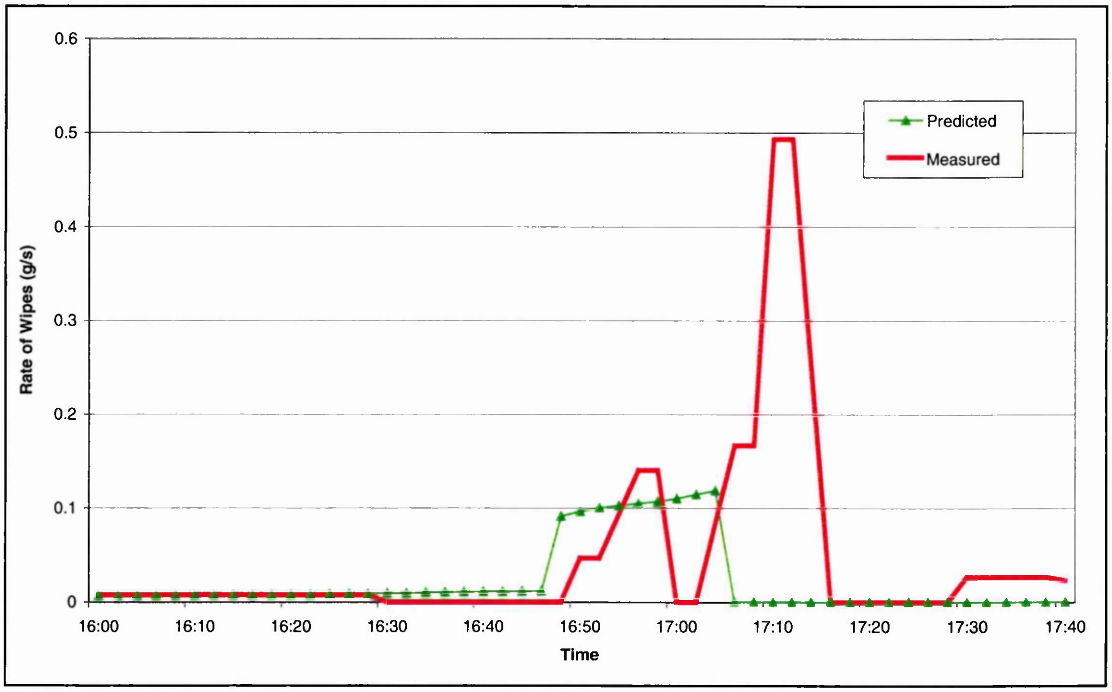


Figure 30 Comparison of simulated against measured results for wipes during storm DS5 at the High Income catchment

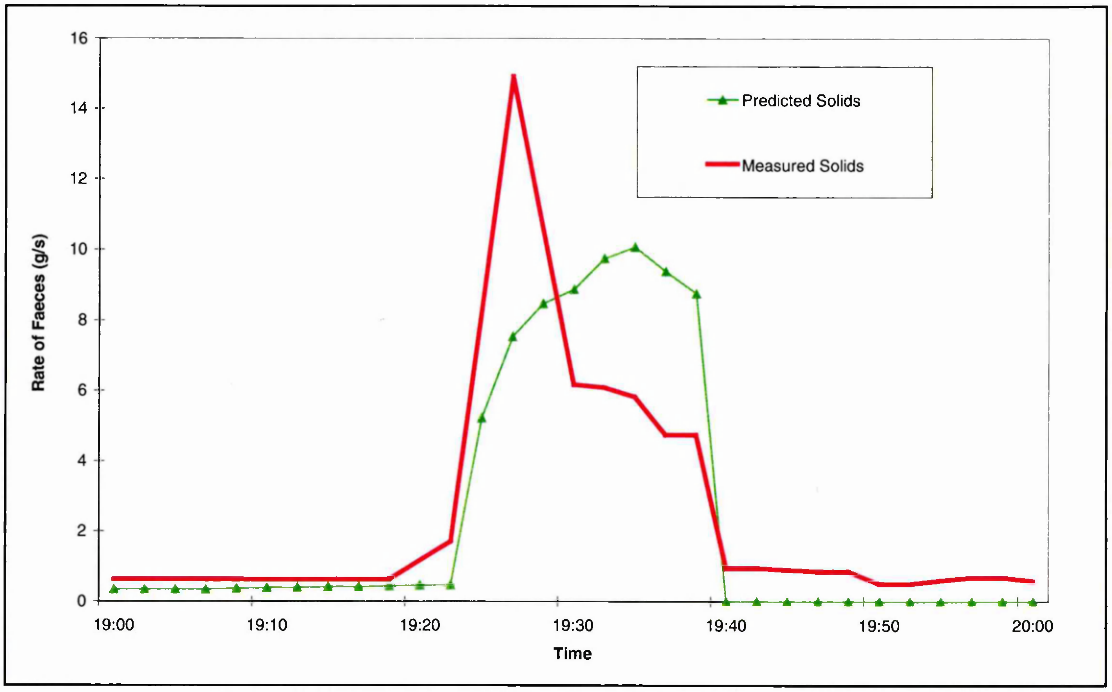


Figure 31 Comparison of simulated against measured results for faeces during storm DS6 at the High Income catchment

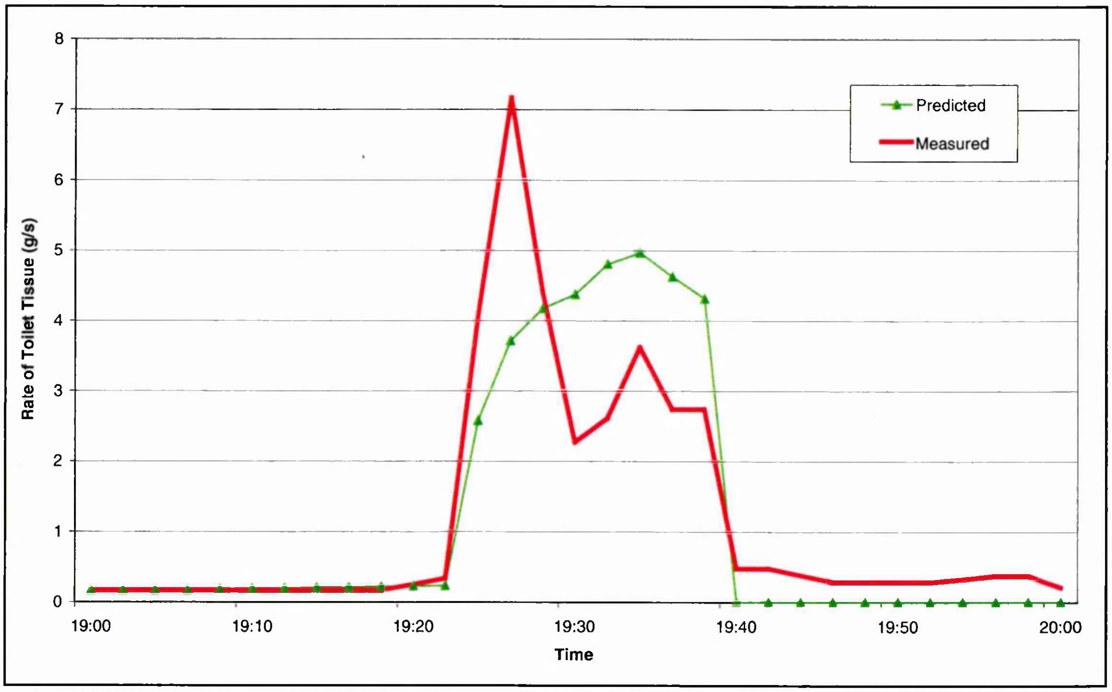


Figure 32 Comparison of simulated against measured results for toilet tissue during storm DS6 at the High Income catchment

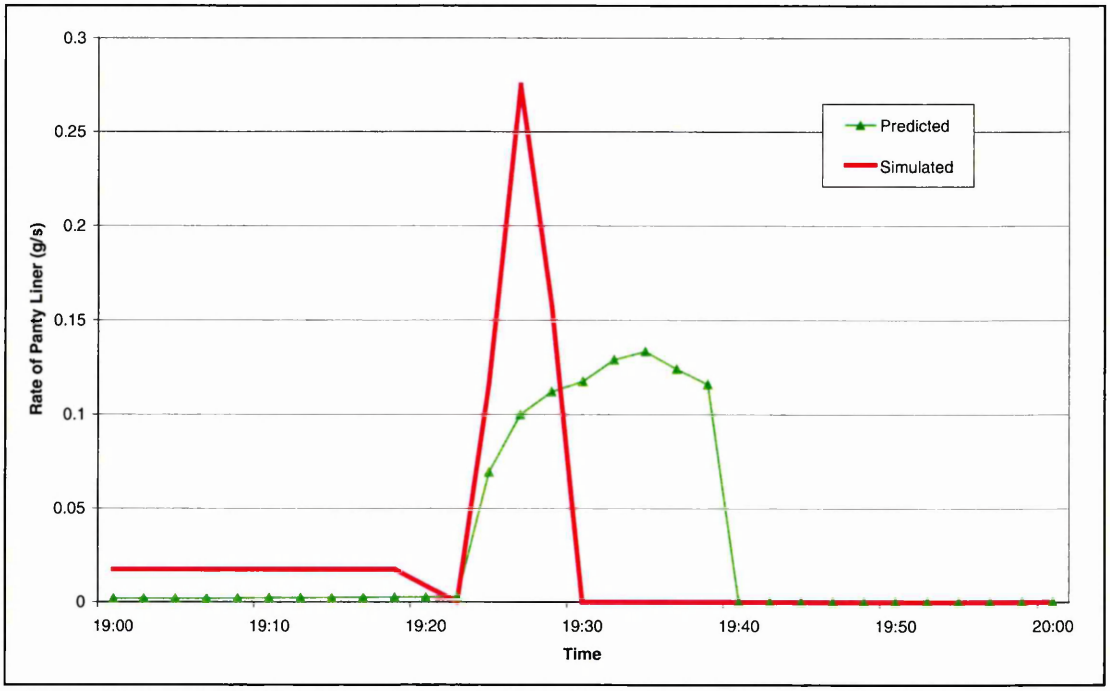


Figure 33 Comparison of simulated against measured results for panty liners during storm DS6 at the High Income catchment

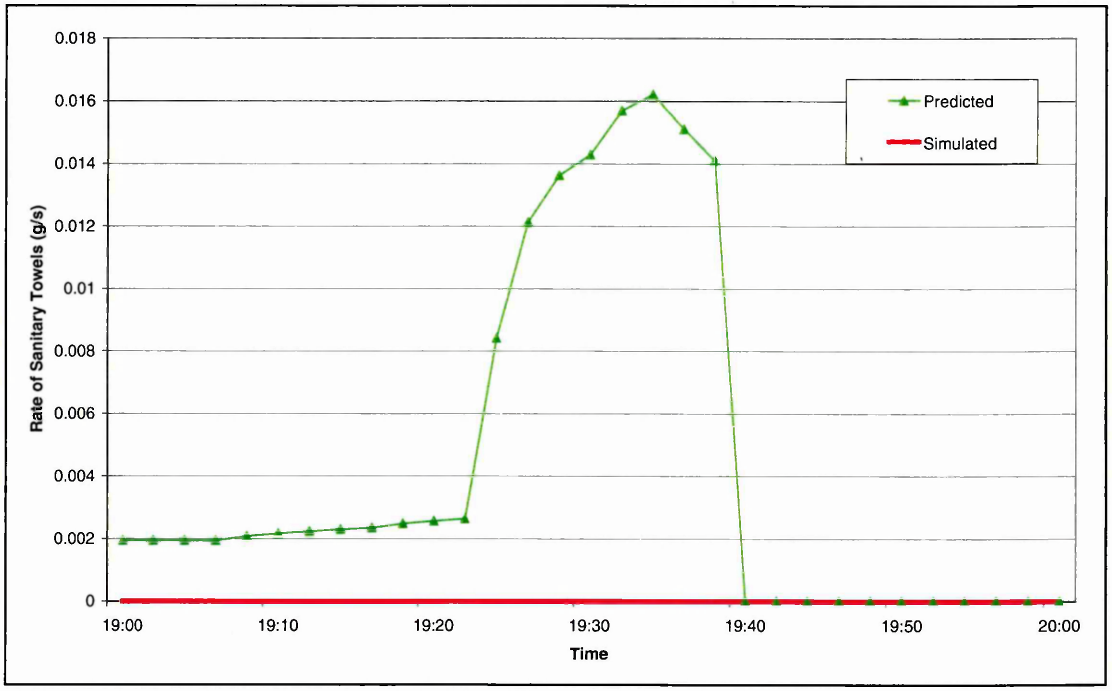


Figure 34 Comparison of simulated against measured results for sanitary towels during storm DS6 at the High Income catchment

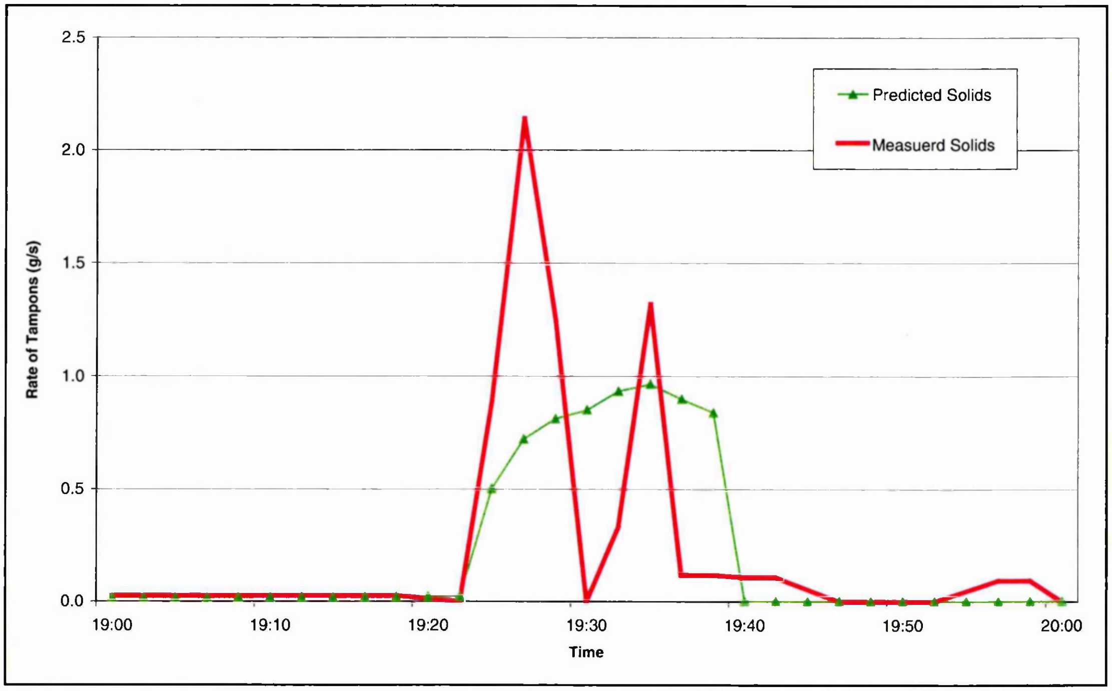


Figure 35 Comparison of simulated against measured results for tampons during storm DS6 at the High Income catchment

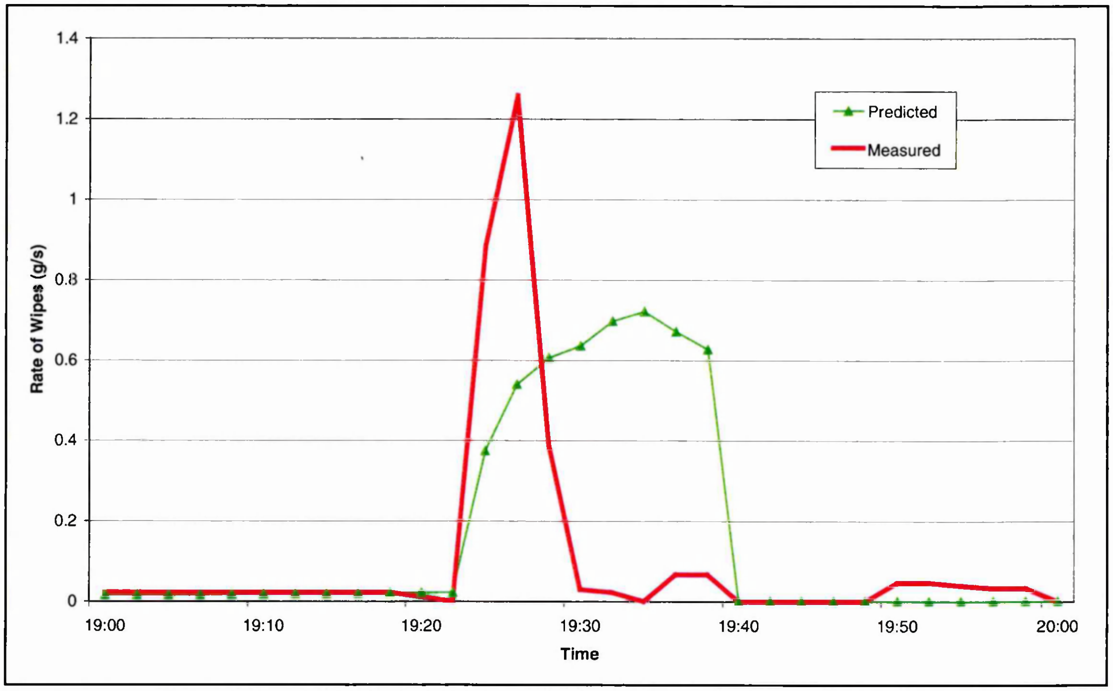


Figure 36 Comparison of simulated against measured results for wipes during storm DS6 at the High Income catchment

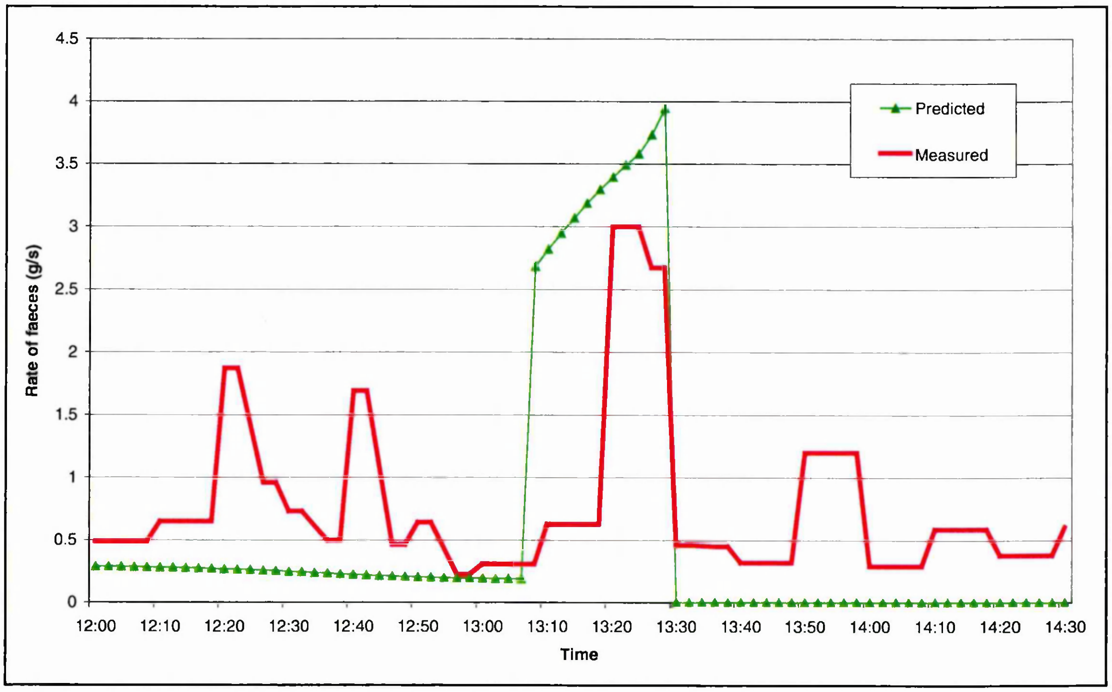


Figure 37 Comparison of simulated against measured results for faeces during storm OS2 at the Ethnic catchment

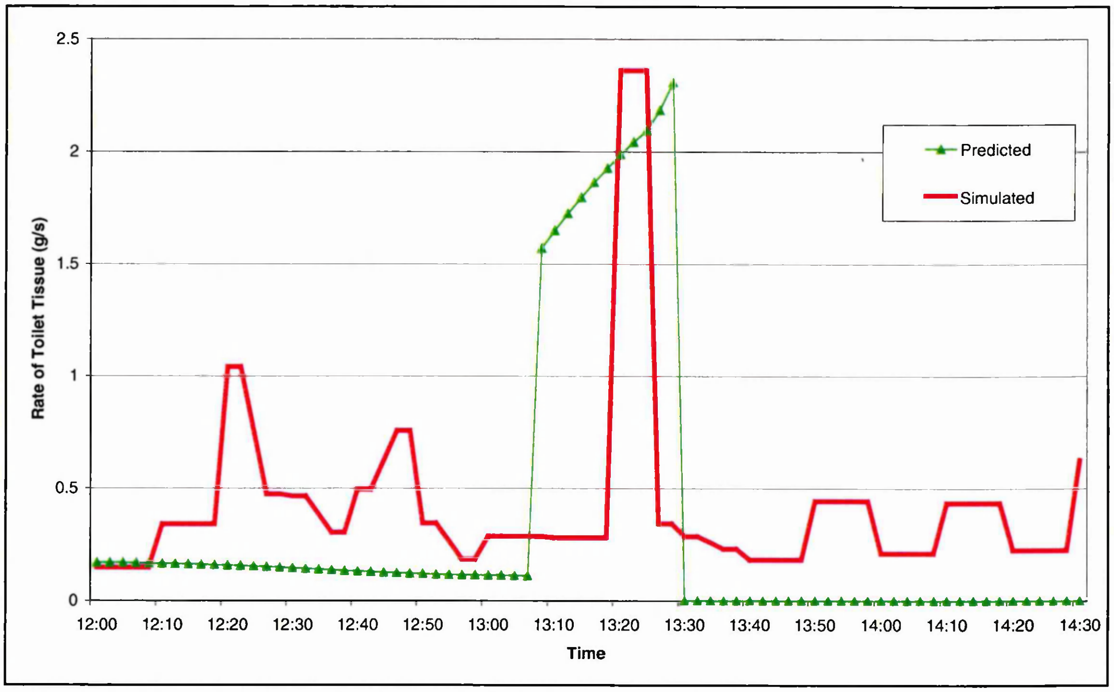


Figure 38 Comparison of simulated against measured results for toilet tissue during storm OS2 at the Ethnic catchment

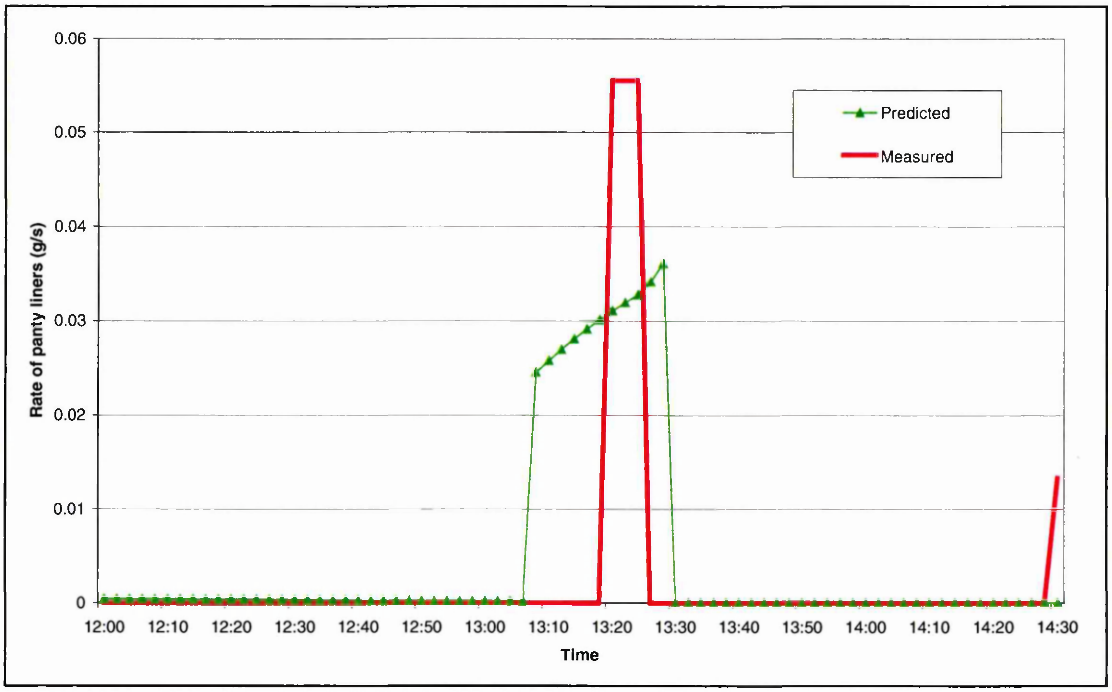


Figure 39 Comparison of simulated against measured results for panty liners during storm OS2 at the Ethnic catchment

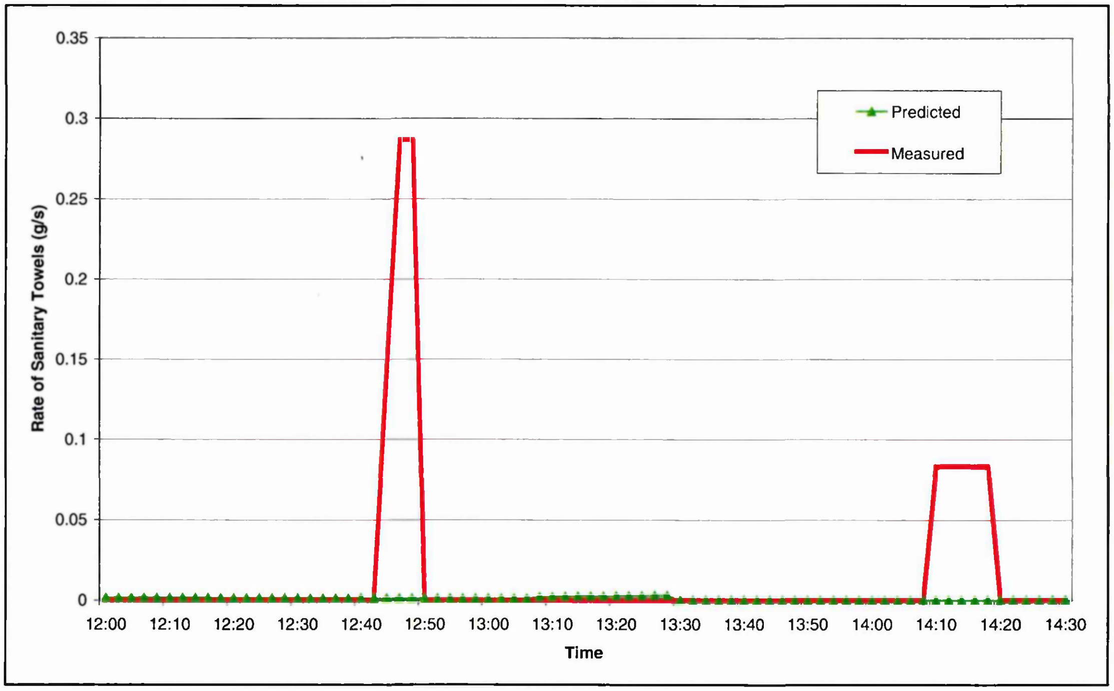


Figure 40 Comparison of simulated against measured results for sanitary towels during storm OS2 at the Ethnic catchment

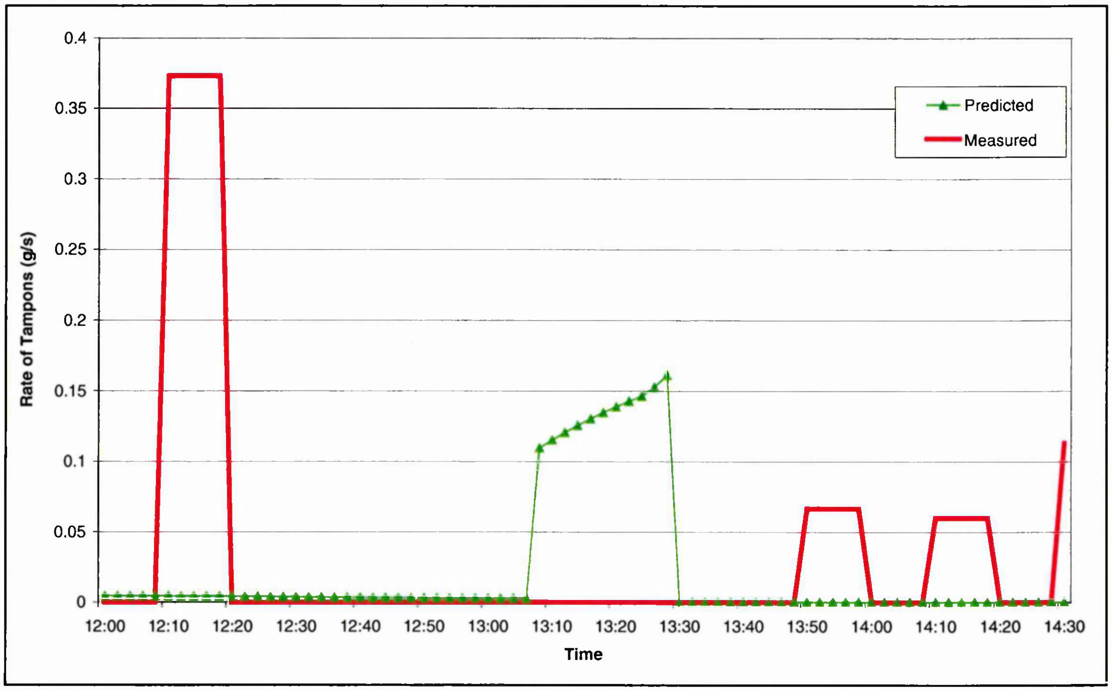


Figure 41 Comparison of simulated against measured results for tampons during storm OS2 at the Ethnic catchment

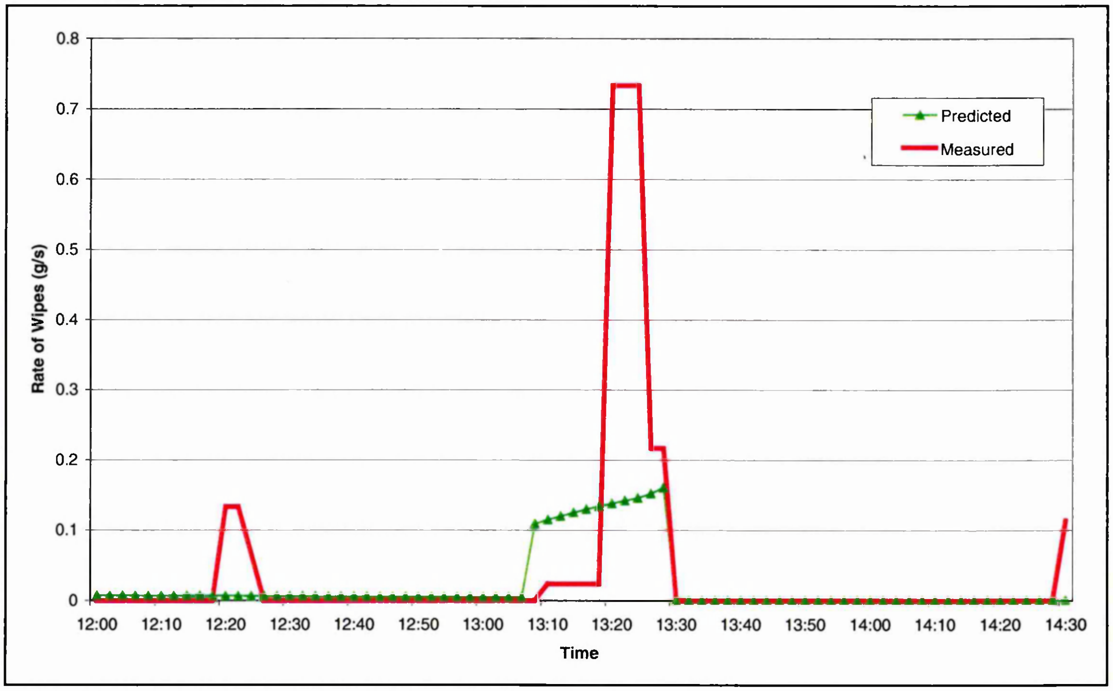


Figure 42 Comparison of simulated against measured results for wipes during storm OS2 at the Ethnic catchment

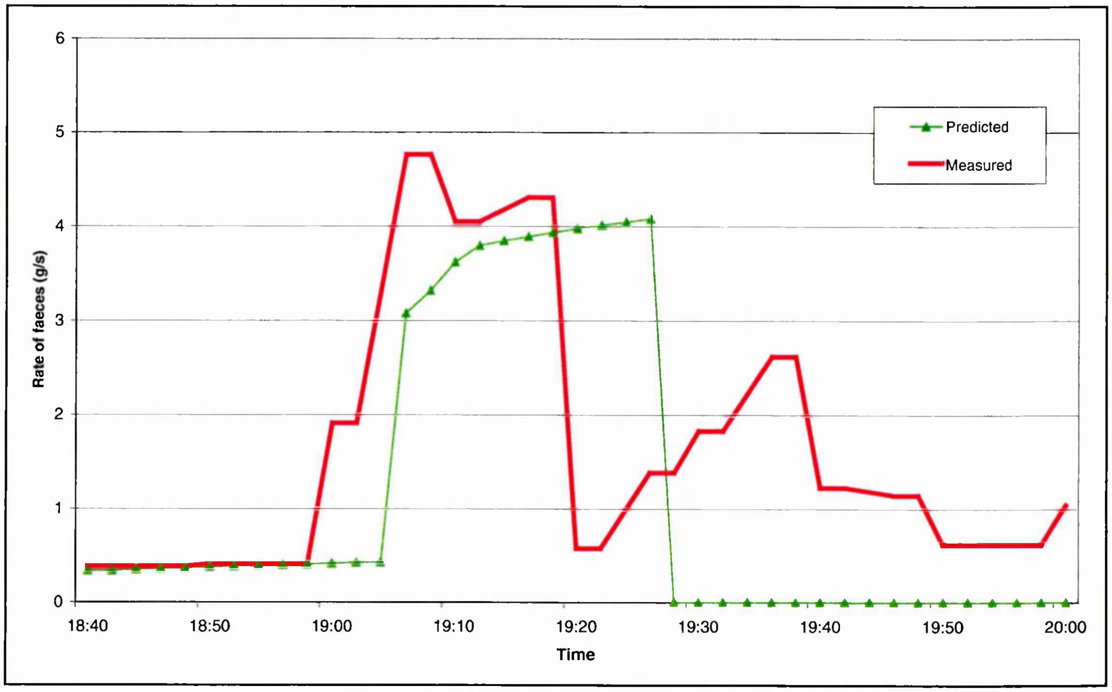


Figure 43 Comparison of simulated against measured results for faeces during storm OS4 at the Ethnic catchment

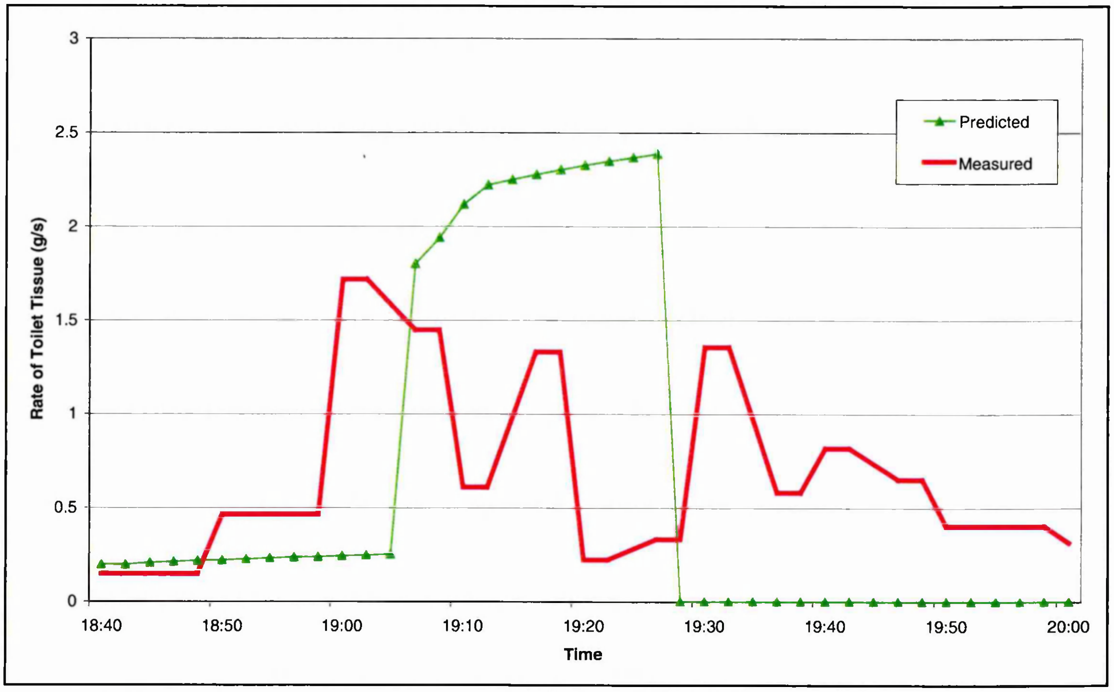


Figure 44 Comparison of simulated against measured results for toilet tissue during storm OS4 at the Ethnic catchment

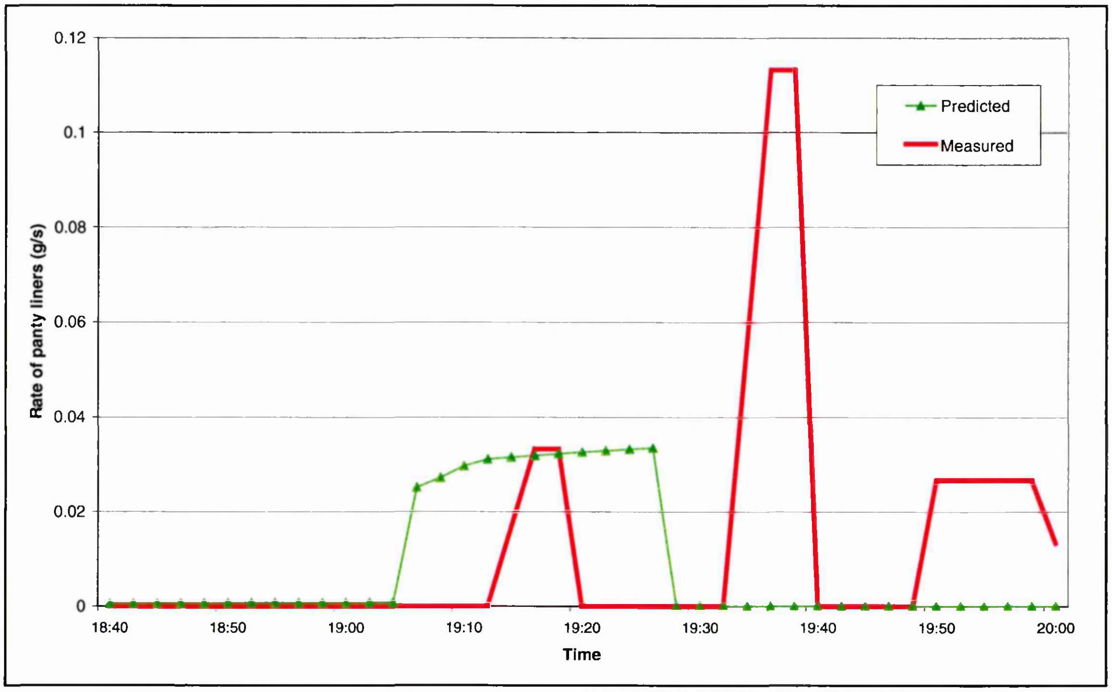


Figure 45 Comparison of simulated against measured results for panty liners during storm OS4 at the Ethnic catchment

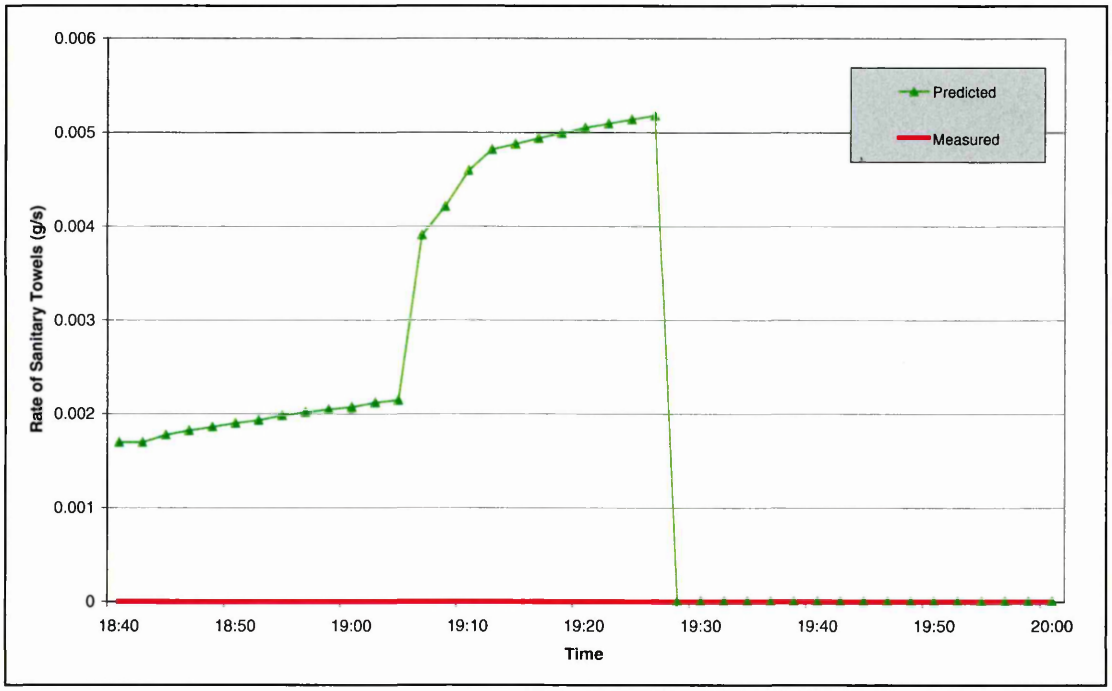


Figure 46 Comparison of simulated against measured results for sanitary towels during storm OS4 at the Ethnic catchment

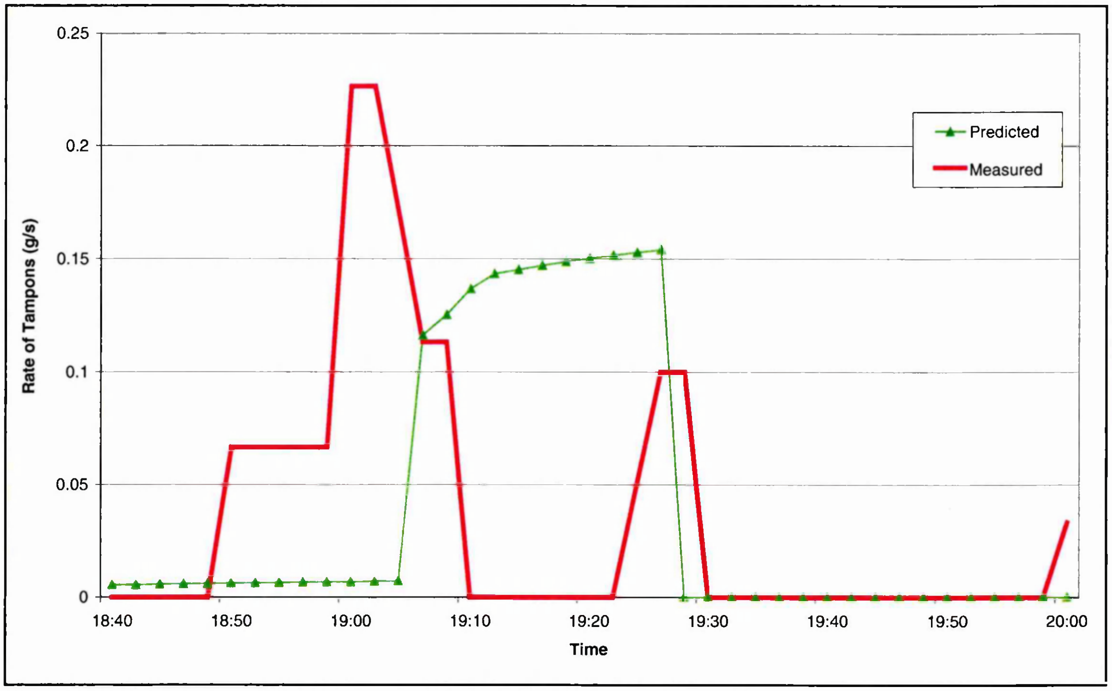


Figure 47 Comparison of simulated against measured results for tampons during storm OS4 at the Ethnic catchment

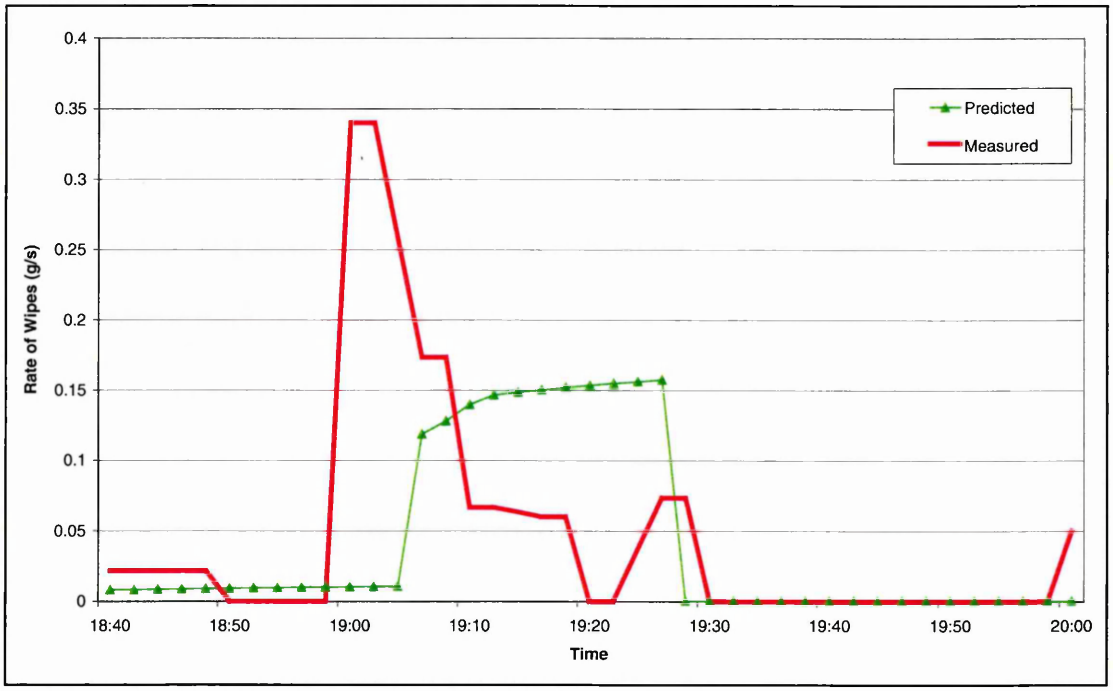


Figure 48 Comparison of simulated against measured results for wipes during storm OS4 at the Ethnic catchment

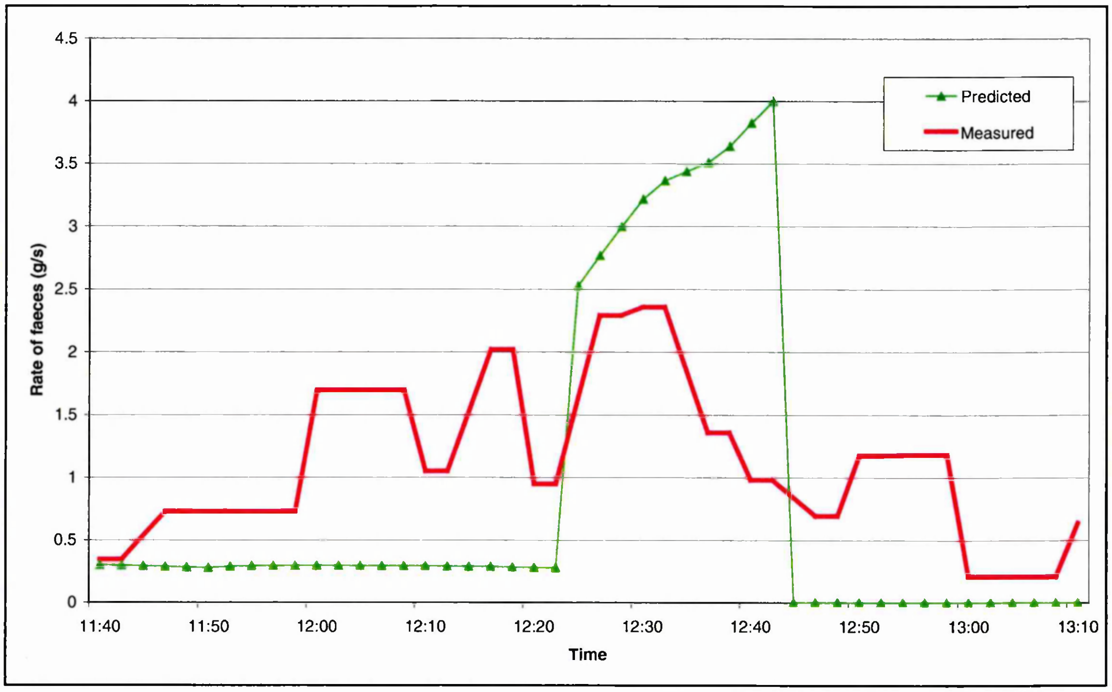


Figure 49 Comparison of simulated against measured results for faeces during storm OS5 at the Ethnic catchment

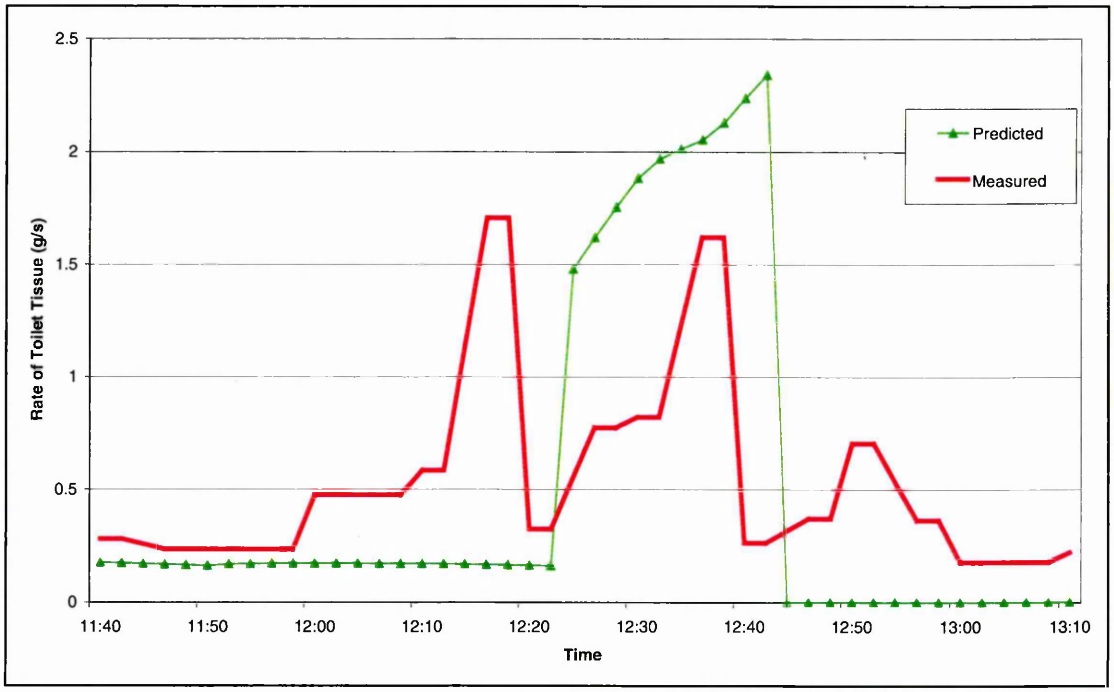


Figure 50 Comparison of simulated against measured results for toilet tissue during storm OS5 at the Ethnic catchment

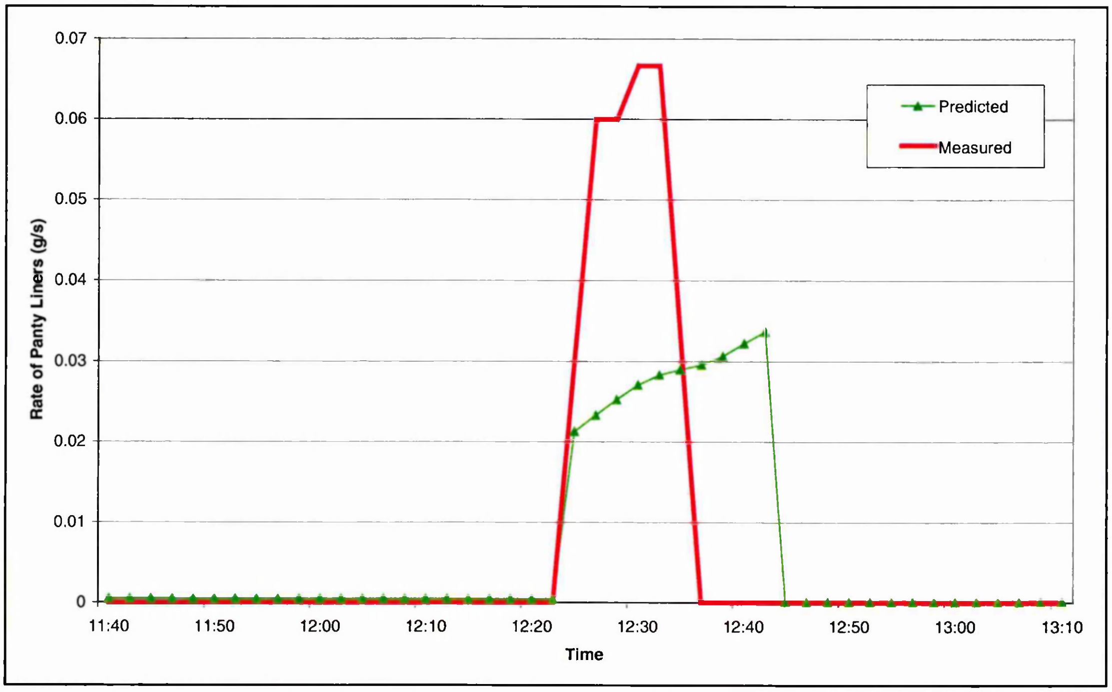


Figure 51 Comparison of simulated against measured results for panty liners during storm OS5 at the Ethnic catchment

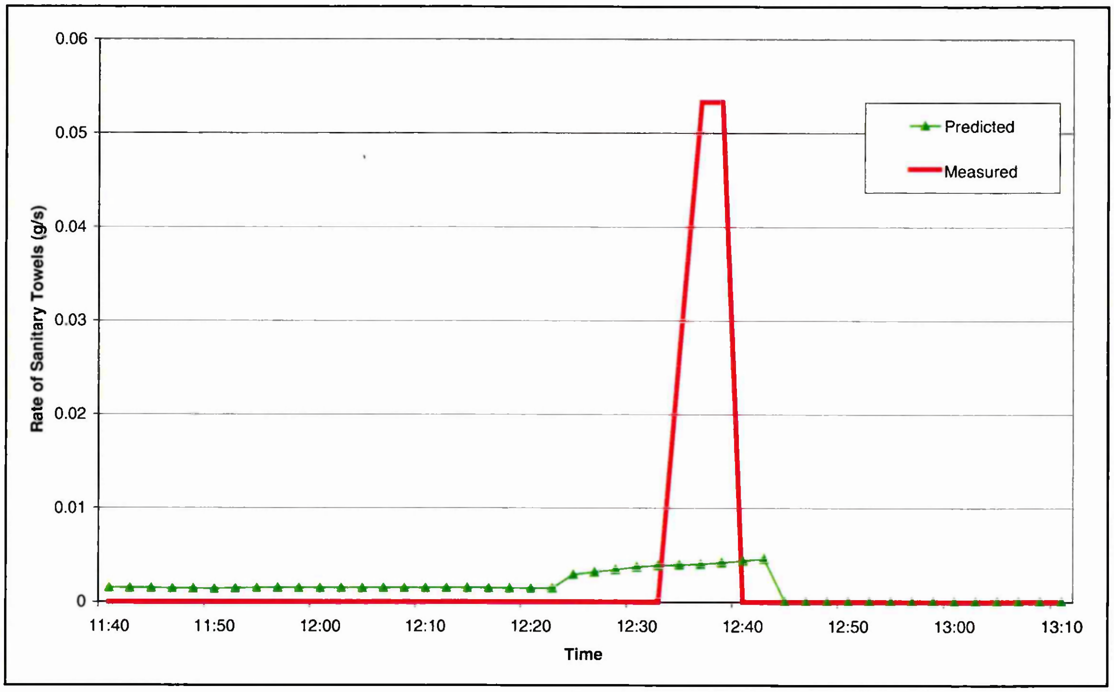


Figure 52 Comparison of simulated against measured results for sanitary towels during storm OS5 at the Ethnic catchment

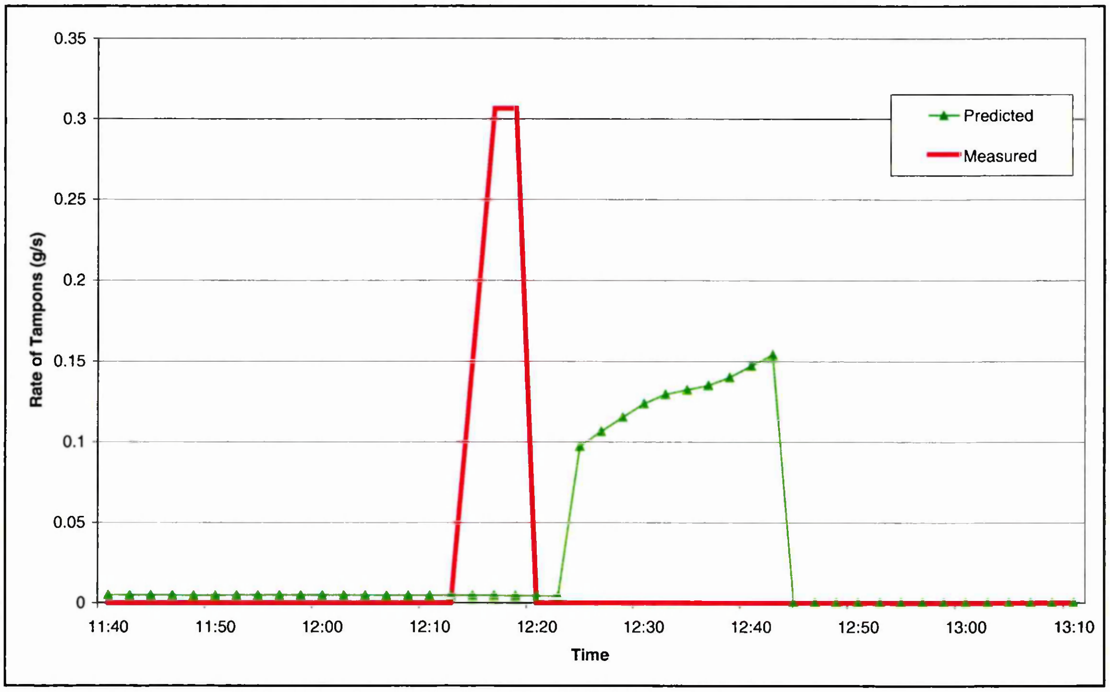


Figure 53 Comparison of simulated against measured results for tampons during storm OS5 at the Ethnic catchment

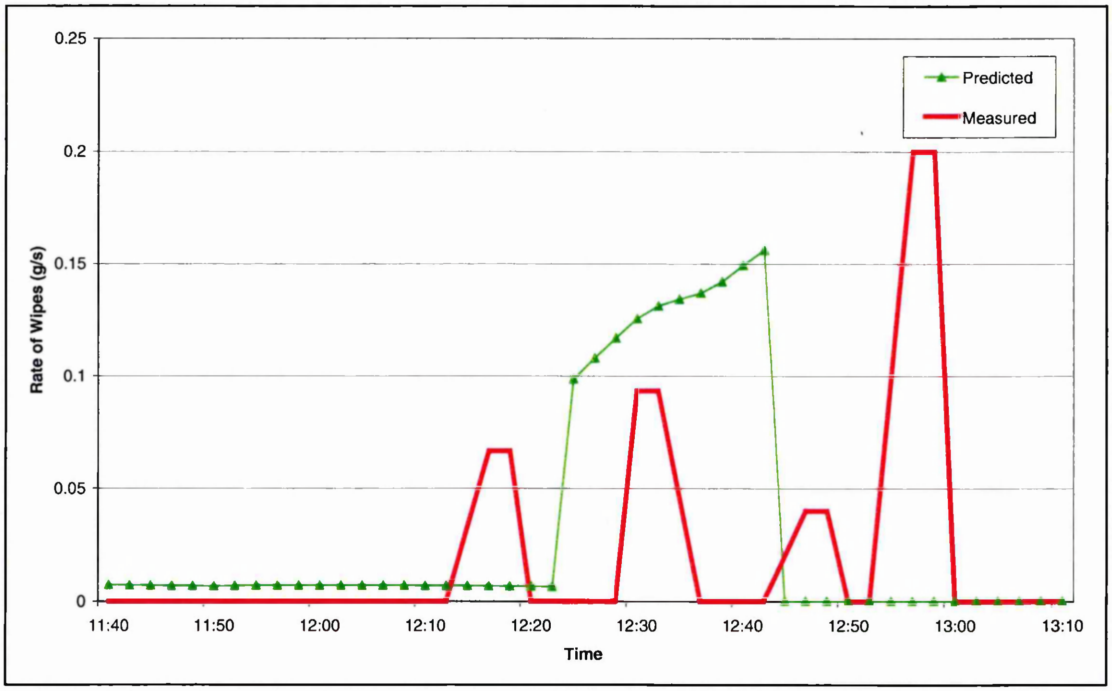


Figure 54 Comparison of simulated against measured results for wipes during storm OS5 at the Ethnic catchment

PREDICTING AESTHETIC POLLUTANT LOADINGS FROM COMBINED SEWER OVERFLOWS

A. J. Saul*, J. K. Houldsworth*, J. Meadowcroft**, D. J. Balmforth***, C. J.Digman***,
D. Butler****, J. W. Davies*****

**Department of Civil & Structural Engineering, University of Sheffield, Sir Frederick Mappin Building, Mappin Street, Sheffield, S1 3JD, UK*
***Department of Political Studies, University of Sheffield, Elmfield, Northumberland Road, Sheffield, S10 2TU, UK*
****School of Construction, Sheffield Hallam University, City Campus, Sheffield S1 1WB, UK*
*****Department of Civil Engineering, Imperial College of Science, Technology & Medicine, London SW1 2BU, UK*
******School of the Built Environment, Coventry University, Priory Street, Coventry, CV1 5FB, UK*

ABSTRACT

'Aesthetic' pollutants from CSO's often lead to public complaint. Although recent work has provided a better understanding of their physical characteristics, little work has been undertaken to determine their variability either spatially or temporally. Yet without this understanding optimal methods for their control cannot be developed. The answer will in part be given by gaining a better understanding of the production of solids, especially the effects of social, economic and ethnic factors. This paper describes the initial stages of a research programme which will monitor the aesthetic pollutant production at input in catchments of different socio-economic characteristics and an in-sewer sampling programme to record downstream aesthetic pollutant production in these same catchments. The socio-economic survey is currently underway at the first of four sites and this will provide demographic data relevant to aesthetic pollutant production. Approaches currently being adopted include household questionnaires, product sales surveys and meetings with targeted groups. The second phase of the work is concerned with a field evaluation of the gross solids characteristics at four different catchments. Preliminary thinking has identified hydraulic performance of a CSO chamber and the terminal velocity distribution of the gross solids to be the primary variables to influence the pollutants retention performance of the chamber. The primary aim of the work is therefore to establish the changes in such characteristics of the gross solids from catchment to catchment and to assess how such solids degrade through the system such that the performance of CSO chambers may be predicted. Preliminary results have been used to highlight the way forward.

KEYWORDS

Aesthetics, combined sewer overflows, in-sewer sampling, gross solids characteristics, socio-economic survey, solids degradation

INTRODUCTION

The majority of sewers in the UK operate as combined sewers where stormwater and wastewater are conveyed in the same pipe. This is especially true in large municipal areas. To prevent overloading of sewer networks, and subsequent flooding, and to limit the flow passed to treatment works so as to avoid overload and subsequent river pollution, combined sewer overflows (CSO's) are installed at strategic points on the sewer network. These inevitably lead to pollutant discharges to receiving waters in wet weather.

Pollutants may be in solution, in fine suspension, or transported as larger solids as bed load, suspended or floating material. Larger 'gross' solids (>6 mm) that are obviously of sewage origin frequently lead to complaints from the public. Such 'aesthetic pollutants' which consist largely of faecal matter, toilet tissue and feminine hygiene products are often difficult to retain at CSO's and have stimulated substantial development in the design of CSO chambers and screens. Although recent work has provided a better understanding of their physical characteristics, little work has been undertaken to determine their variability either spatially or temporally. Yet without this understanding optimal methods for their control cannot be developed. It has been identified that the answer will in part be given by gaining a better understanding of the production of solids, especially the effects of social, economic and ethnic factors.

It is intended that the data gathered on the production of solids will be used to generate a mathematical model and once combined with transportation and degradation mechanisms, the model will be able to predict the temporal distributions of aesthetic pollutants at a specific point in a sewerage system under storm conditions. The model will be verified by comparison with the results of an in-sewer sampling programme. The model will then be extended using results from known CSO performance data to enable the pollutant loading from individual CSO's to be predicted. Cost effective solutions to sewerage upgrading proposals may then be established.

This paper describes how these objectives have been met up to the present time. The first objective was to study the effects of socio-economic factors on aesthetic pollutant production. This work has commenced and two approaches have been adopted. Firstly, surveying aesthetic pollutant production at input in catchments of different socio-economic characteristics and secondly, by setting up an in-sewer sampling programme to record aesthetic pollutant production at several points in these same catchments.

SOCIO-ECONOMIC SURVEY

The objectives of the socio-economic survey are to be met by several stages of work which are now described.

Literature review

It is widely reported that although recent work has allowed a better understanding of gross solids characteristics, little is known about their production in relation to the social, economic and ethnic factors.

The main emphasis of the literature review was directed to any previous work on the survey of domestic wastewater use within the household. In particular attention was focused on surveys that had attempted to gather socio-economic data on the households, and use of the WC especially in terms of product disposal habits. Many studies have surveyed domestic wastewater in terms of appliance usage over a period of time.

Appliances typically being the WC, kitchen sink, wash basin, bath, shower and washing machine. One such study, Butler et al. (1995) consisted of three parts. A questionnaire that provided background information such as details of occupants and appliance ownership. A survey where participants were asked to fill in diary sheets every time an appliance was used and finally, a number of simple experiments that participants were asked to conduct on their appliances to provide estimations of average volumes and discharges for each appliance. As a result wastewater flows from each appliance were determined over a 24 hour period. Wastewater quality values for each appliance were also derived using typical pollutant loadings. Other studies, such as Friedler and Butler (1996), conducted their own appliance wastewater quality tests. Other similar studies concentrating on appliance usage were carried out by Zanoni and Rutkowski (1972), Ligman et al. (1974), Siegrist et al. (1976), Hall et al. (1988) and Butler (1991).

This study will concentrate on the products that are disposed of via the WC. This is because the WC is considered to be the main contributor of aesthetic pollutants. Friedler et al. (1995) reported the results of a study which concentrated solely on the WC and furthermore on its different modes of use. The study again consisted of a questionnaire and diary sheets. A questionnaire was given to each household to obtain information on dwelling occupants, WCs in the household and toilet paper in use. A diary sheet was supplied for each WC in the house and participants were asked to record time of use, mode of use, number of sheets of toilet paper used and other substances disposed of down the WC. Data was presented on four different modes of use that were identified: faeces only, urine only, faeces and urine and other. Other refers to occasions when the WC was flushed for a second time, when it was flushed after cleansing and when it was used for the disposal of sanitary refuse. Data on per capita toilet paper usage was also presented, as was a list of all types of solid refuse that were flushed down the WC, along with a indication of their quantity. Tampons, wet wipes and tissue paper were the most commonly flushed items.

It is the intention of this survey to obtain a good sized sample for the chosen catchments. With this in mind it was thought that the survey should be quick and easy to complete. The study discussed above required the use of diary sheets for seven consecutive days. It was thought that this method of approach would stop many householders participating. This therefore led to the conclusion that this survey should only be a survey of the usual disposal methods of sanitary products that could be completed in a few minutes of the participant's time. This meant that faeces, which are one significant aesthetic pollutant, could not readily be surveyed at input. However, there is sufficient data available to overcome this problem and faeces will still be recorded as part of the downstream in-sewer sampling programme.

Souter et al. (1998) surveyed the disposal habits for sanitary products. This survey formed part of the 'Think before you flush' campaign designed to raise public awareness about the alternative solid waste disposal option. A survey of disposal habits was conducted before and after the campaign to determine if attitudes had changed. This was carried out in four catchments with different demographic profiles. Both surveys were conducted using a questionnaire designed for face to face interviews. The questionnaires were designed based on the results of a series of focus group discussions which qualified what required to be addressed. The before survey asked about relevant demographic data (sex, age, housing type, number of dependants), sanitary product disposal habits, reasons for the preferred method and frequency of disposal of 13 items.

These items being cotton buds, nappies, cotton wool, condoms, disposable razors, plastic packaging, unused medicine, food waste, sanitary towels, backing strips, panty liners, tampon applicators and tampons. The after survey asked similar questions about only six items, as they were found to be the items most frequently flushed. These being cotton buds, condoms, sanitary towels, panty liners, applicators and tampons. Questions relating to campaign effectiveness were also asked. Relevant conclusions were that the principle sanitary waste items currently being flushed are the six listed above. Secondly, women in the age range 18-44 years are responsible for 75% of all sanitary waste items that are flushed. Finally, there are no significant differences between the communities in attitudes to flushing sanitary waste items. The work which is currently ongoing as part of this project will involve similar approaches to that adopted by Souter.

Site selection

The selection of suitable catchments is seen as an on going process. This has the advantage of not wasting time choosing several sites only to find that results from earlier sites indicate the need for site reselection. However all sites to be chosen will be in the Sheffield area and are anticipated to represent different socio-economic groups. With this in mind the first site selected was the Glenholme Road Council estate, which is a specific socio-economic group representing a disadvantaged area. The layout of the catchment is shown in Figure 1 and there is one major CSO chamber located at the downstream end of the catchment. This chamber is of stilling pond type and has dimensions 7.52m length, 2.44m width and a full width transverse weir of height 1.32m. It is proposed to monitor the solids which enter the chamber via the 0.975m diameter inflow pipe and at two other locations throughout the system, which split the site into four sub-catchments (See Figure 1). The other locations, were selected as they represent strategic points on the catchment to provide the optimum data to assess the role of individual sub-catchments on the solids monitored at the downstream end of the catchment. This should provide the necessary inputs to the development of the degradation model to be constructed by Imperial College.

Other possible sites at this stage are seen as an upper social class area, a middle social class area and an ethnic area. More specifically, the ethnic area will consist mainly of the Pakistani community, as this is the major ethnic group in Sheffield. It is also possible that a catchment will be chosen with a diverse range of socio-economic groupings in order to facilitate a more rigorous statistical analysis of the results. At this stage it is not envisaged that systems with a large industrial input will be studied.

Census data

In order to evaluate the socio-economic factors on aesthetic pollutant production use has been made of the UK 1991 Census data. ‘Supermap’, a piece of software for census data extraction has been utilised for this purpose. It was decided that the socio-economic factors that effect sewage, or more specifically aesthetics, production are; total population, gender, age, income and ethnicity. Census data can be retrieved from Supermap at various resolutions. The finest of which is by what is known as an Enumeration District (ED). EDs are logically defined blocks of areas that make up a ward. The four sub-catchments contained parts of several EDs. In order to present the demographic data for a complete sub-catchment the EDs were simply proportioned accordingly. Census data for the Glenholme Road site in terms of the four sub-catchments is shown in Tables 1 to 3. Using the census data has two major problems. Firstly, the 1991 Census data is 8 years out of date, and secondly the occupations of residents and not their income are listed. To overcome these problems a household survey questionnaire approach will first be adopted.

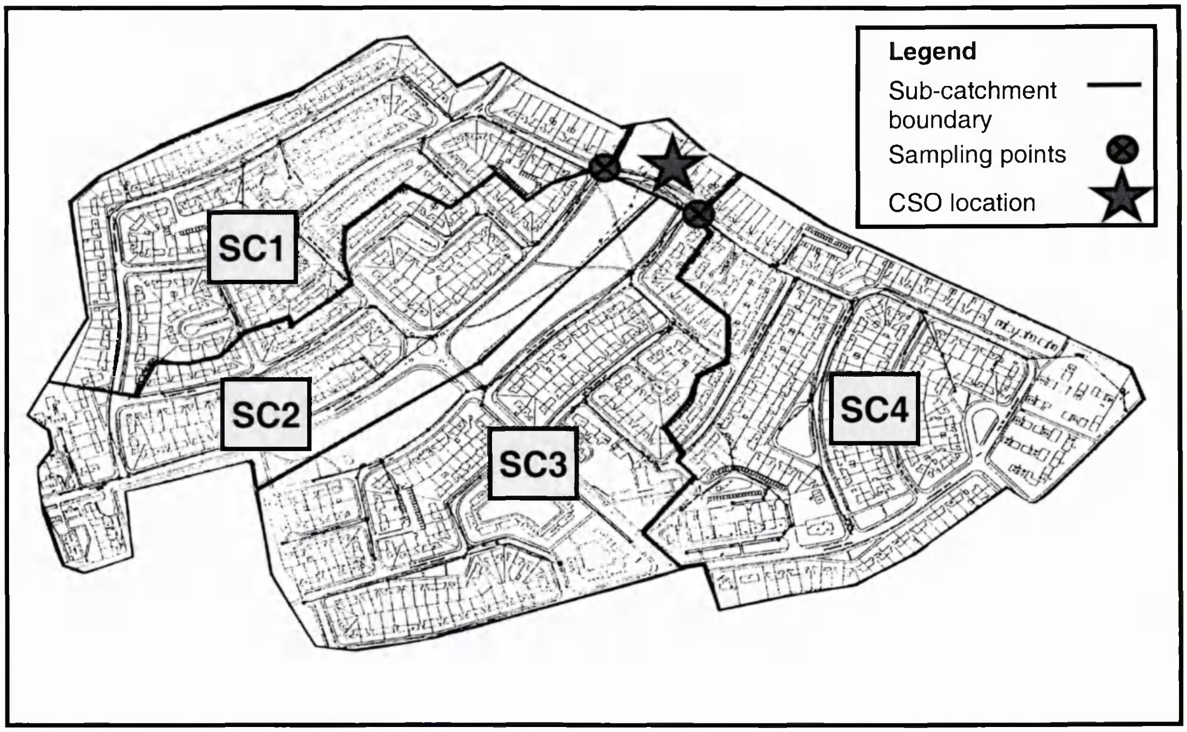


Figure 1. Glenholme Road site split into four sub-catchments

Table 1. Population and gender data for Glenholme Road. (Office of Population Census & Survey, Census 1991).

Sub-catchment	Present residents	Present males	Present females
SC1	366	158	208
SC2	324	144	180
SC3	476	223	253
SC4	553	253	300

Table 2. Age profile of Glenholme Road. (Office of Population Census & Survey, Census 1991).

Sub-catchment	0-9	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80-89	90 & over
SC1	10	19	26	20	39	42	98	102	21	2
SC2	11	23	24	19	40	37	81	81	17	1
SC3	28	37	46	33	58	50	99	105	37	5
SC4	34	34	51	39	58	59	124	142	45	7

Table 3. Ethnic profile of Glenholme Road. (Office of Population Census & Survey, Census 1991).

Sub-catchment	White	Black Caribbean	Black African	Other Black	Indian	Pakistani	Bangladeshi	Chinese	Other Asian	Other ethnic group
SC1	379	0	1	0	1	0	0	0	0	0
SC2	333	0	0	0	0	0	0	0	0	0
SC3	493	0	0	0	4	0	0	0	0	0
SC4	582	0	1	1	9	0	0	0	1	0

Household survey

The questionnaire was designed to illicit the details of sanitary waste disposal habits, but specifically was aimed at qualifying and quantifying WC inputs. Demographic data of all occupants of the household, gender, age band, income band and ethnic group were also requested. In line with the recommendations of Hague (1993), all questions were closed response.

The questionnaire is currently being piloted with a small number of households in the Glenholme Road catchment and results are being compiled. Similarly a number of focus groups are being established. The next stage will be to refine the methodology with an enhanced questionnaire which will then by used in a full study of the Glenholme Road catchment, or simply to expand the number of individual focus groups. The information collected from this part of the study will be used to establish a gross solids input model to the sewer system which will subsequently be used to enhance the degradation model (Imperial College) and CSO design procedures (Sheffield and Sheffield Hallam).

IN-SEWER SAMPLING

Methodology to measure gross solids

To estimate the characteristics of the gross solids captured within the combined sewer system, the methodology has been based on the procedure adopted at the National CSO test facility and of previous studies of Balmforth et al. (1994). Solids are collected at each site by the immersion of a 6 mm mesh sack into the flow. The solids contained within each sack are separated into mush and gross solids. The mush is defined as that material which could not be readily shaken from the sacks. It is anticipated that upto 50% of each sample will be classified as mush. The solids are subsequently categorised into 41 types, e.g. vegetable matter, faeces, sanitary towels etc and the total mass of each category is recorded. Subsequently to provide information appropriate to the regulatory standards for aesthetics in the UK, i.e. the retention of a significant quantity of solids with size greater than 6 mm in two dimensions, solids having such size characteristics are separated within each category of solids. The proportion of 6 mm solids in each category is then established by weight. The three orthogonal dimensions, length, width and height of each gross solid are measured and the settling velocity of a number of typical particles within each category are recorded. This gives the distribution and numbers of each type of particle corresponding to the particular flow regime within the sewer. It is anticipated that such distributions will be a function of the dry weather flow (DWF), the rising and recession limbs. The settling velocity is measured by recording the time taken for a particle to fall (or rise) one metre in a Perspex column filled with water. Previous studies (UKWIR, 1997) have identified that the settling velocities across the whole range of particle types are within the range -0.3 m/s to +0.7 m/s. Note that a particle with a negative settling velocity has a positive rise velocity (floater), whilst a positive settling velocity indicates a sinker.

Analysis of data

The total mass of each particle collected in each test, together with the corresponding results for particle settling velocity is used to generate a plot of settling velocity against total mass for each particle type. A cumulative settling velocity curve, as shown in Figure 2(a) is derived at each location. The objective of the study is to assess how this settling velocity curve differs at different locations and as to how this distribution changes in dry weather and storm flow conditions. As explained earlier, these differences will be related, if possible, to the catchment characteristics and to the social, ethnic and economic factors which may be identified.

Implementation and application of results

It has been well documented (Halliwell and Saul, 1980) that the gross solids retention efficiency of a particular design of CSO chamber is a function of the ratio of the continuation flow to the inflow and the characteristics of the individual particles which enter the chamber. The primary variable which has been used in most previous studies to describe the characteristics of the particulates has been terminal velocity. In general, the retention efficiency of an individual particle in each type of chamber is reduced as the inflow to the chamber is increased and the continuation flow is held constant. The higher the ratio of continuation flow to inflow the higher the retention efficiency. Efficiency values range from 100% for particles with large terminal velocity (grit and polystyrene) to values approximately equal to or slightly less than the flow ratio for the neutrally buoyant particles. The retention efficiency for particles with intermediate terminal velocity form a characteristic cusp shape. The shape of the cusp is slightly different for the different designs of CSO chamber. A typical family of cusps is shown in Figure 2(b).

The processing of results and the implementation of the design software will involve an integration of the hydraulic performance of the CSO chamber and the retention efficiency of the known distribution and terminal velocity of the particulate corresponding to the flow regime - rising or recession limb of the storm hydrograph and the characteristics of the dry weather flow at the start of the storm event. The methodology is outlined in Figures 2(a) to 2(c), where by the distribution in Figure 2(a) is used together with the results in Figure 2(b) corresponding to each time interval dt in Figure 2(c). For individual storm events or time series events, equation 1 may be used to predict the total gross solids retention efficiency. This methodology will subsequently be written into the design software.

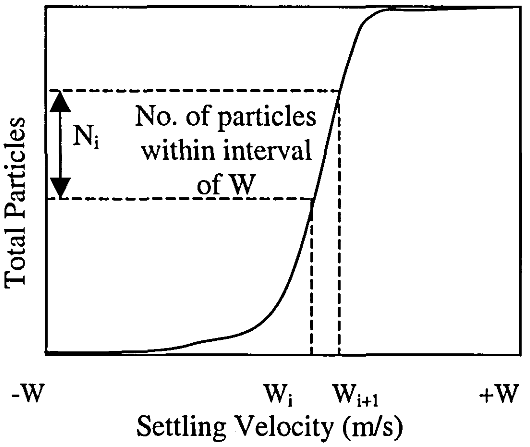


Figure 2(a). Gross solids settling velocity curve

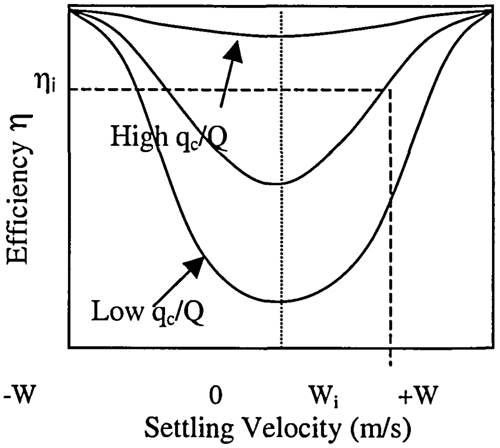
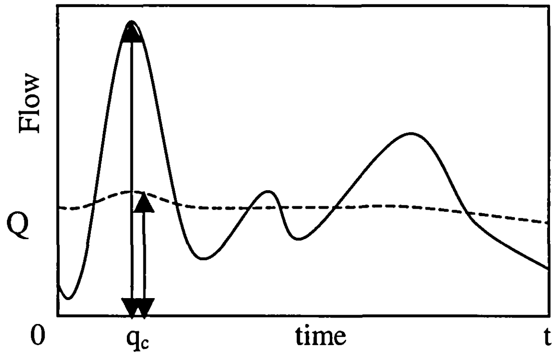


Figure 2(b). Typical efficiency cusps



$$\eta_{total} = \sum^{dt=t} q_{ci}/Q_i \left(\sum_{W_i=0}^{W_i=\pm W} \eta_i . N_i \right) \qquad (1)$$

Figure 2(c). Time series storm events showing the relationship between inflow Q and continuation flow q_c for each time interval dt.

CONCLUSIONS

Optimal methods for CSO design cannot be achieved without a better understanding of spatial and temporal variations of gross solids characteristics. It has been identified that the answer will in part be given by gaining a better understanding of the production of solids, especially the effects of social, economic and ethnic factors, and the way in which solids degradate through the sewer system.

The socio-economic survey has been initiated by reviewing current literature and selecting the first site, the Glenholme Road catchment. Priority socio-economic factors considered to influence aesthetic production were; total population, gender, age, income and ethnicity. Census data has been used to establish these parameters. A household survey has been designed in the form of a postal questionnaire. Its aim being to gather data on the aesthetic pollutant production by asking what products are disposed of via the WC and in what quantities. This questionnaire is currently being piloted in the Glenholme Road catchment and results are being compiled. Similarly a number of focus groups are being established to further illicit such sensitive information.

An in-sewer sampling programme has been designed to establish the characteristics of gross sewage solids collected from different catchments. The methodology is presented. Social, economic and ethnic parameters will be linked to the characteristics of these solids. The study commenced in November 1998.

The gross solids collected from the system are categorised into a number of different types, and these are classified by their size and terminal velocity. Initial results suggest that the terminal velocity distribution within each category of particulate follows a normal distribution and that the majority of the particulate has a neutrally buoyant fall velocity. The terminal velocity distribution of the particulate is the most important of the solids characteristics when consideration is given to the solids separation performance of CSO chambers.

A methodology to improve the prediction of CSO retention efficiency and to improve the selection procedure of the most appropriate CSO chamber has also been presented. This is based on the anticipated gross solids distribution of the particulate which enters the chamber. Results are currently being collected and these will form the major part of the paper presentation.

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REFERENCES

Balmforth D. J., Lonsdale K., Nussey B. B. and Walsh M. (1994). Methodology for monitoring the
performance of combined sewer overflows. *J. CIWEM*, 9(5), 510-518.
Butler D. (1991). A small-scale study of wastewater discharges from domestic appliances. *J. IWEM*, 5, 178-185.
Butler D., Friedler E. and Gatt K. (1995). Characterising the quantity and quality of domestic wastewater inflows. *Wat. Sci. Tech.*, 31(7), 13-24.
Friedler E., Brown D. M. and Butler D. (1995). A study of WC derived sewer solids. *Proc. Int. Conf. On Sewer Solids - Characteristics, Movement, Effects & Control*, Dundee, UK, 5-8 September, 1995,
31- 38.
Friedler E. and Butler D. (1996). Quantifying the inherent uncertainty in the quantity and quality of domestic wastewater. *Wat. Sci. Tech.*, 33(2), 65-78.
Hall M. J., Hooper B. D., Postle S. M. (1988). Domestic per capita water consumption in South West
England. *J. IWEM*, 2, 626-631.
Halliwell A. R. and Saul A. J. (1980). The use of hydraulic models to examine the performance of storm- sewage overflows. *Proc. Instn Civ. Engnrs, Part 2*, 69, June, 245-259.
Hague P. (1993). *Questionnaire Design*. Kogan Page, London.
Ligman, K., Hutzler, N. and Boyle, W. C. (1974). Household wastewater characterisation. *J. Envir. Eng., ASCE*, 100(1), 201-213.
Office of the Population Census and Survey (OPCS). *Census 1991*.

Siegrist, R., Witt, M. and Boyle, W. C. (1976). Characteristics of rural household wastewater. *J. Envir. Eng., ASCE*, 102(3), 533-548.

Souter N., Swain A. and Ashley, R. (1998). 'Think before you flush'. People's attitudes and a methodology for change. Report WW 5008R/3, Waste Water Technology Centre, University of Abertay Dundee.

UKWIR (1997). CSO performance evaluation: Results of a field programme to assess the solids retention efficiency performance of side weir and stilling pond chambers. Report 97/WW/08/1.

Walton R. W., Saul A. J. and Sims, J. (1997). Characteristics of sewage particulates. CSO Research Group, Project WW08/97/002, Department of Civil and Structural Engineering, University of Sheffield.

Zanoni, A. E. and Rutkowski, R. J. (1972). Per capita loadings of domestic wastewater. *J. WPCF*, 44(9), 1756- 1760.

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Predicting Aesthetic Pollutant Loadings in Combined Sewerage Systems

Mr Christopher J Digman

School of Environment and Development, Sheffield Hallam University, City Campus, Howard St, Sheffield, S1 1WB

ABSTRACT

Improvements to Combined Sewer Overflows (CSOs) have occurred over the last decade and will continue during the current Asset Management Plan (AMP3). One aim of these improvements is to reduce the quantity of aesthetic pollutants spilt during a storm. This paper outlines the initial work undertaken to measure and model the quantity, composition and temporal variation of solids that arrive at a CSO during a storm at three sites in Sheffield. Each catchment was selected to represent different socio-economic and ethnic population types. A methodology has been developed to obtain aesthetic pollutant samples from combined sewerage systems in dry and wet weather. This has enabled the quantity, composition and temporal distribution of aesthetic pollutants to be determined. Solids sampled during the storm events clearly indicate a first foul flush and a simple numerical model has been developed to replicate this effect. A summary of this model is presented and the results are compared with values measured from the first catchment. Potentially, the practical application of this model could provide an expedient method for determining loading rates presented to CSOs.

KEYWORDS

Aesthetic pollutants; combined sewer overflow; first foul flush; gross solids; sampling; transport; urban drainage systems.

INTRODUCTION

The majority of sewerage systems in the UK are combined, conveying waste water and storm water together. Large quantities of pollutants such as sanitary products, faeces and toilet tissue enter into the sewer with the waste water in dry weather. These solids are more commonly known as aesthetic pollutants or gross solids. Aesthetic pollutants are classified as being greater than 6 mm in two dimensions and are aesthetically unpleasant to the eye. During a storm, these pollutants can be discharged into water courses via CSOs.

One of the objectives of the current AMP3 is to remove aesthetic pollutants from UK watercourses. This will be achieved by upgrading CSOs by the installation of screens or increased storage. In order to facilitate the design of effective screens, the temporal distribution and the total quantity of solids delivered to a CSO should be determined. To accomplish this a mathematical model of solids' transportation is needed. This has been achieved in the project by using theoretical analysis that is substantiated by field measurements.

THEORETICAL APPROACH

The model develops previous work performed at Sheffield Hallam University (SHU), which indicated the potential for modelling aesthetic pollutant loadings in combined sewerage systems (1). This earlier work could not generate the quantity of solids or their temporal distribution under storm conditions, which limited its application.

As part of collaborative work with Imperial College London (IC) and the University of Sheffield (UofS), a model will be produced to predict the temporal distribution of solids at any point in a combined sewerage system and subsequently the loading presented to a CSO. The aim of the current work at SHU is to construct a model of the upstream pipes in the sewer network to predict the temporal distribution of solids before linking into a transportation and degradation model being produced by IC. The output from the IC model forms the input into the UofS model to determine the performance of CSOs at separating and retaining aesthetic pollutants.

The first stage of the SHU model generates flows from measured or design rainfall events using a non-linear reservoir model (2) (Figure 1). Initial losses from depression storage are accounted for at the start of the storm (3). The sewer network is represented by a single non-linear reservoir. This was chosen after investigating a number of single and multiple reservoir compositions (4). The size of the reservoir is determined by considering it as a rectangular open channel. The length is equal to that of the main sewer branch and the width is equal to the average diameter of the sewer pipes in the main branch.

The second stage is to determine the quantity of solids in the system, prior to a storm, that could potentially be flushed out during that storm. The solids in the system can be categorised into three main components:

- deposited on the bed and stored
- in motion during dry weather
- entering the system once the storm commences and flushed out in less time than normal in dry weather

Therefore a predictive tool based upon these three solids categories, population, catchment characteristics and the antecedent dry weather period is currently being developed. As an interim measure, the quantity of solids in the channel (the quantity measured during the main flush of solids) has been determined from field measurements. This has then been separated into two components to have a continuous base flow of solids as observed during dry weather sampling and a flush of solids when the storm commences.

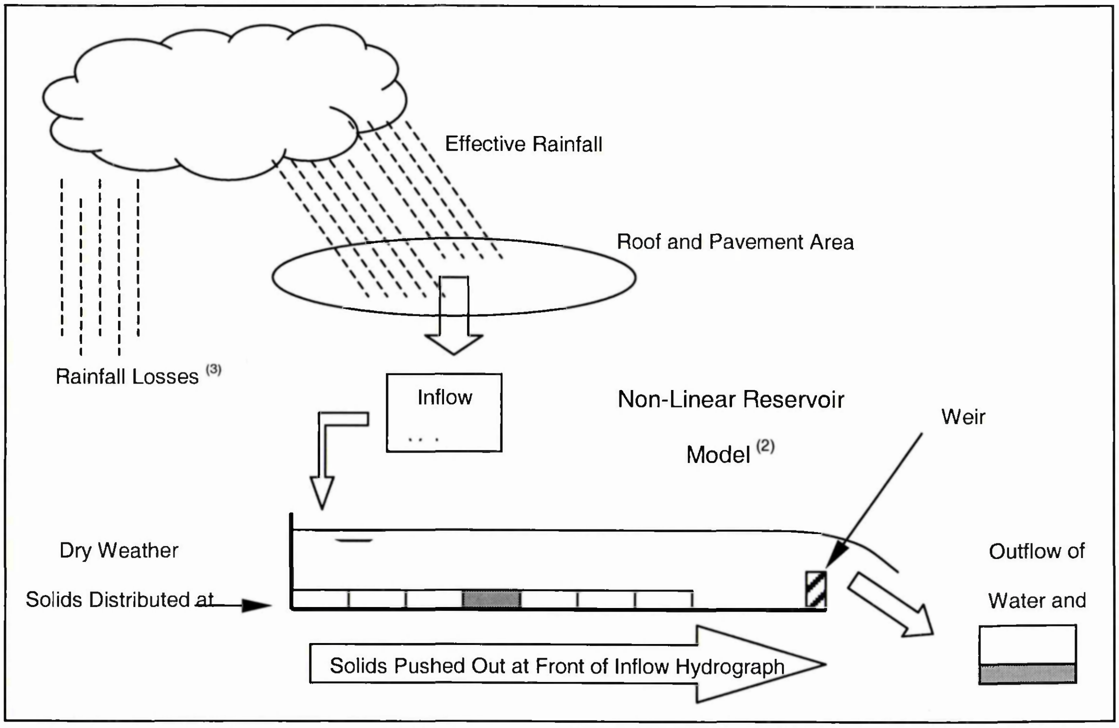

Figure 1 – Theoretical Approach to model solids' transportation in a simplified sewer network

The third stage uses flow volumes generated by the non-linear reservoir model. Prior to a storm commencing, the solids in the reservoir are assumed to be distributed within the DWF volume (Figure 1). At each timestep an inflow volume is generated from the rainfall and enters the reservoir. This does not mix with the DWF and solids but pushes them out of the reservoir. The volume leaving the reservoir is known, therefore the total quantity of solids can be determined as the solids concentration is constant. The transportation of solids is dependent upon the flow rate reaching a particular level. This threshold value was found to be approximately 1.5 times the magnitude of the peak DWF rate. Hence part of the DWF volume must leave the reservoir in advance of the solids. Therefore the model has been constructed so that when the outflow of the reservoir goes above this threshold value, solids begin to leave the system.

FIELD MONITORING

An extensive monitoring programme has been undertaken at three catchments in Sheffield. Each catchment represents different socio-economic and ethnic populations. This will enable an investigation to determine whether these population types affect the quantity and composition of solids entering a combined sewerage system.

In the first catchment sampled, the population of 1810 was classified as ageing with a low income (5). The catchment area of 32 ha, contained urban dwellings and one school. The sewer system was split into 4 sub-catchments for monitoring work, with Detectronic intrinsically safe depth and velocity monitors placed upstream of the sampling points and a Casella 0.2 mm tipping bucket raingauge sited at the school. The second site sampled contained a high income population of 1309 and was smaller in size, with an area of 22 ha. The third site was an inner city area of 10 ha, with dense housing and contained a large proportion of ethic minorities within a total population of 1599.

Aesthetic pollutant sampling has been undertaken in dry and wet weather. The general arrangement of the equipment is shown in Figure 2. All the water and solids were directed through a rectangular orifice in a steel frame inserted into the sewer. The pollutants were retained in mesh sacks (apertures 6 mm x 4 mm) manoeuvred into position from above ground. These sacks were attached to the rear of the frame. To determine the temporal distribution of solids, sacks were changed every 30 minutes in dry weather and every 5 to 10 minutes during a storm. When each sack was removed, it was left for 30 minutes to enable excess water to drain, before being weighed. Contents of the sacks were characterised in the laboratory, where pollutants were separated into individual categories, weighed, and dimensions recorded.

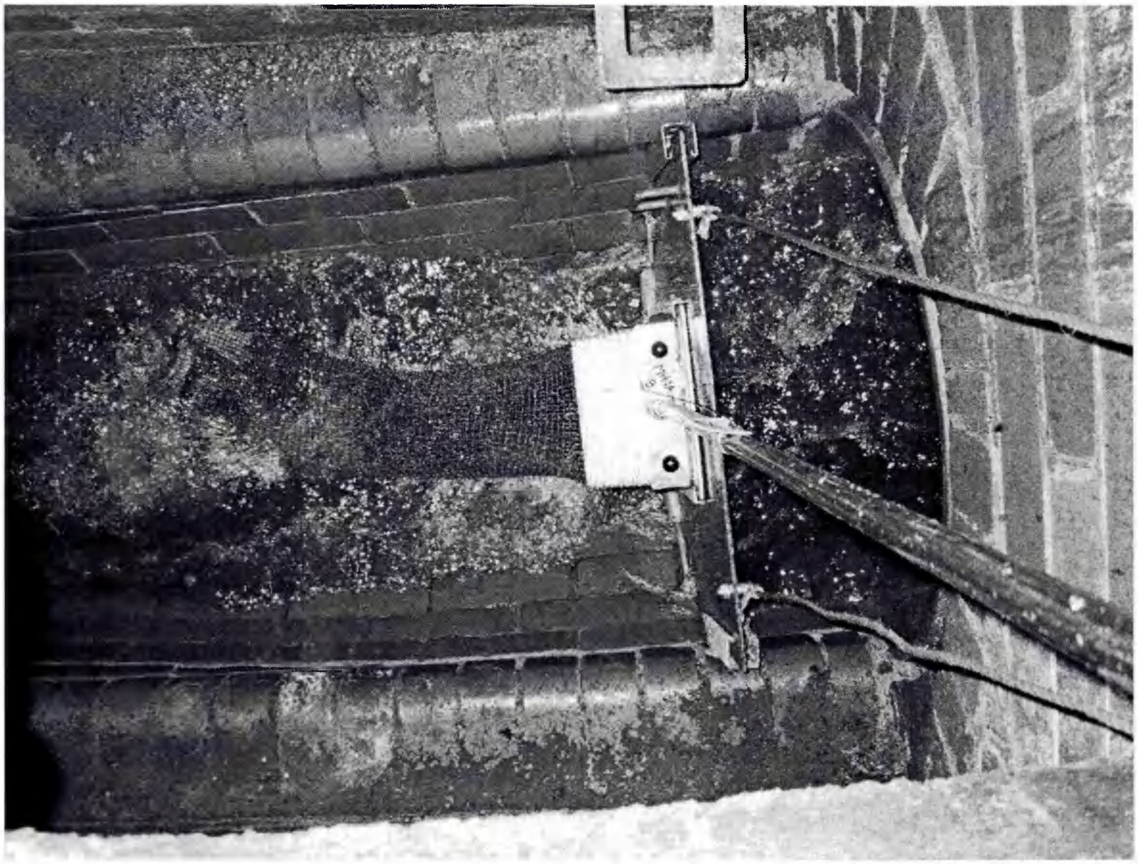

Figure 2 – Arrangement of sampling equipment with solids being collected in a mesh sack under storm conditions

DRY AND WET WEATHER RESULTS (Low Income Site, Sub-catchment SC1)

In dry weather sampling at the first catchment, a clear diurnal distribution of the quantity and composition of aesthetic pollutants was observed. Results for sub-catchment SC1 of the first site sampled can be seen in Figure 3. These diurnal distributions are similar in shape to WC flushing profiles of faeces determined by Friedler et al (6). The main types of aesthetic pollutants flushed during dry weather were found to be; toilet tissue, faecal material, sanitary towels, panty liners, tampons and wipes. Toilet tissue and faeces accounted for 87% of the total mass of solids sampled in dry weather, with wipes accounting for a further 4%. The remaining mass consisted of sanitary protection items and other solids.

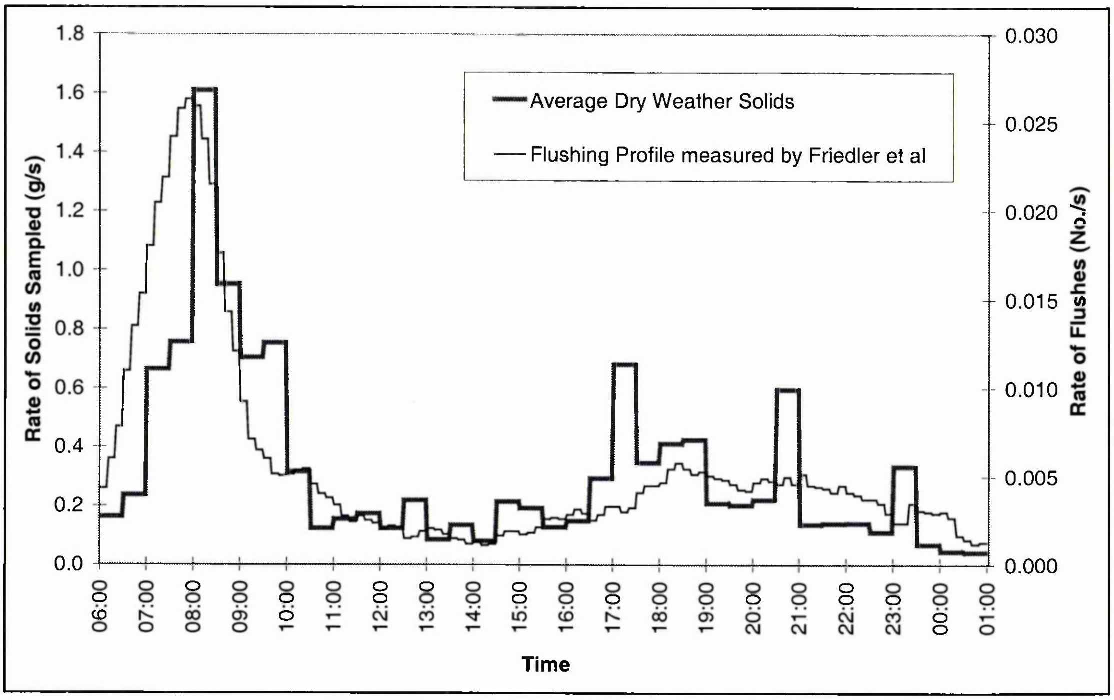

Figure 3 – Dry Weather Loadings at sub-catchment SC1 against Friedler Faecal Related Flushing Profile for a weekday

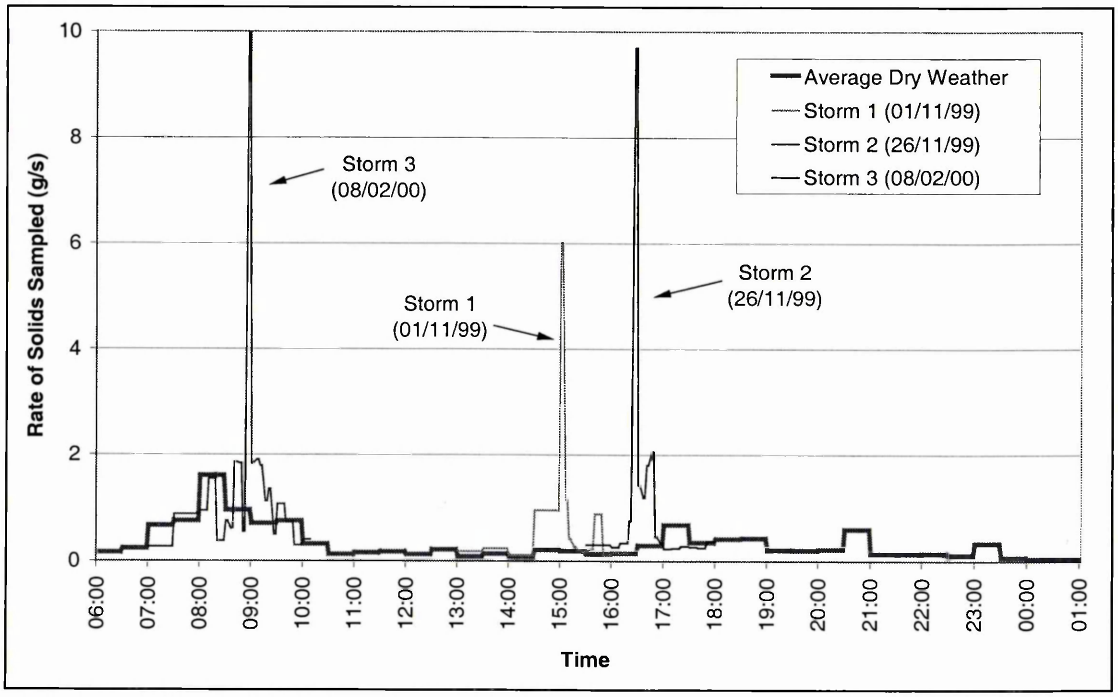

Figure 4 – Dry and Wet Weather Loadings Sampled at sub-catchment SC1

Results show that during storm events, the solids loading is significantly greater than in dry weather (Figure 4). This effect is presented more clearly in Figure 5 (Storm 2). The temporal distribution of the solids is evident and shows a first foul flush. This solids' flush occurs on the rising limb of the hydrograph, indicating solids are being transported at the front end of the storm flow. A secondary, smaller peak occurs after the first flush which coincides with the second increase in rain intensity, and the peak of the storm (Figure 6). The quantity of solids sampled during this and all other storms was larger than the corresponding time period in dry weather. In storm 2 at SC1, a total of 4.9 kg was sampled in comparison to 0.4 kg for the same period in dry weather. A proportion of this increase was due to the solids in motion, approximately 0.4 kg. The remaining increase suggests that solids have been deposited on the sewer bed in the antecedent dry weather period. The main types of solid sampled during this and other storms were found to be: faeces, toilet tissue, wipes and tampons. These are solids that generally have a density greater than unity and therefore sink.

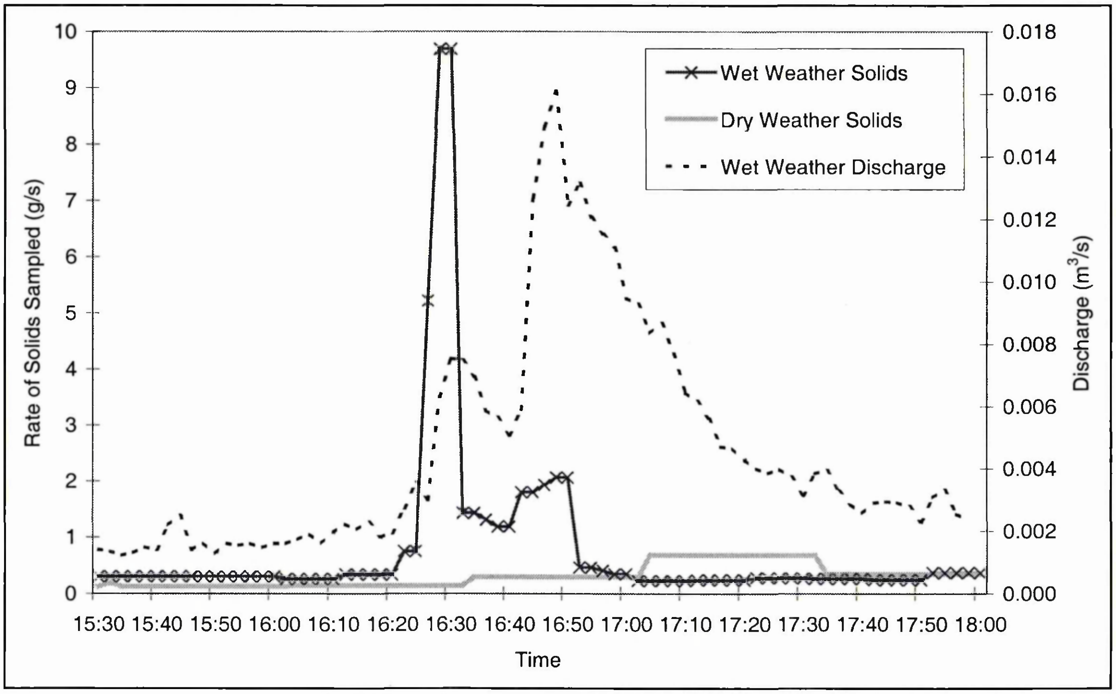

Figure 5 – Measured solids and discharge from Storm 2 for sub-catchment SC1 compared with measured dry weather solids

COMPARISON OF THEORETICAL MODEL AND SAMPLED STORM DATA

The results of the flows generated by the non-linear reservoir model for the single channel system have been compared to the measured values for Storm 2 in sub catchment SC1 (Figure 6). The simulated hydrograph shows a slightly earlier response to rainfall and produces flows slightly greater than the measured data. Possible explanations for this are:

- the calculation for rainfall losses is slightly low, and further losses should be accounted for during the storm
- the areas used in the model are greater than actual
- the depth and velocity monitor under predicted the flow

However the differences between the measured and simulated values are well within the criteria for flow verification, in accordance with WaPUGs 'Code of practice for the hydraulic modelling of sewer systems' (7).

Results from modelling the solids have also been compared to measured field data sampled during the storm event (Figure 7). The theory accurately represents the peakedness of the first foul flush of solids with a good replication of the timing and peak rate of solids. The solids peak occurs slightly earlier than that measured due to the early response of the modelled flow.

The current version of the model tends to under predict the peak rate of solids and over predicts the flow somewhat on this sub-catchment. However, model simulations of other sub-catchments do not always reflect these trends, but a close agreement between these measured and predicted variables is obtained. Throughout these simulations the timing of the peak for solids and flow is very good, which is important in the effective control of solids within urban drainage systems.

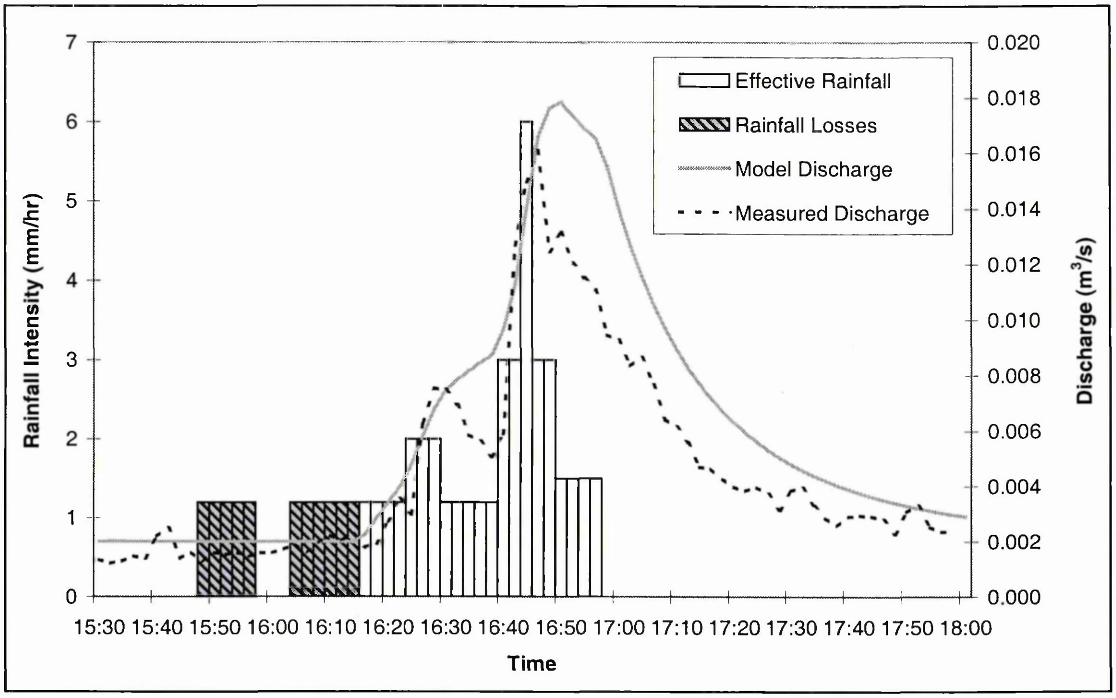

Figure 6 – Rainfall intensity with measured and model discharge in sub-catchment SC1 for storm 2

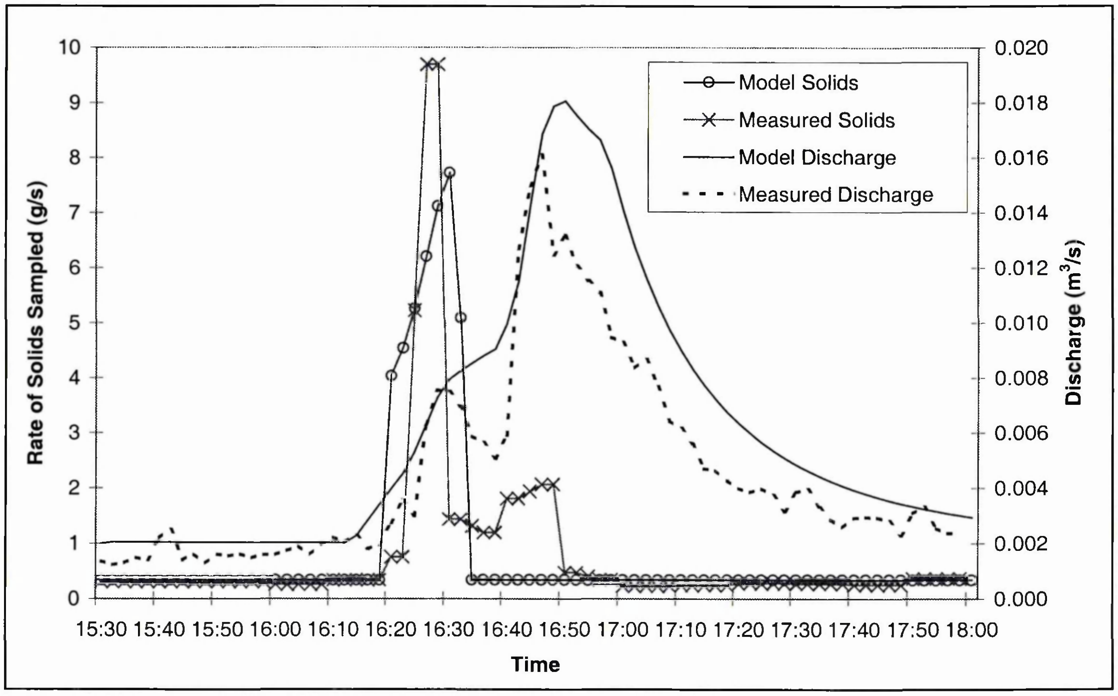

Figure 7 – Comparison of measured and theoretical single channel model results for flow and solids in sub-catchment SC1, for Storm 2

The model currently developed uses the measured quantity of solids to predict the temporal distribution during a storm. This will be improved to use the predicted quantity of solids dependent upon population, catchment characteristics and ADWP. Verification of the model is to be undertaken by simulating different storm events in other catchments sampled. This will provide an indication of the models suitability in other sewer network configurations and different population types.

CONCLUSIONS

A substantial volume of data has been collected to identify the quantity, composition and temporal distribution of solids in dry and wet weather periods. A non-linear reservoir model has been developed that accurately simulates sewer flow in small urban areas and reliably replicates solids' transportation by direct displacement of specific volumes. The model has been substantiated by a large quantity of reliable field data that clearly identifies the quantity, composition and temporal distribution of solids in dry and wet weather periods. Significantly it also identifies the solids' movement during a storm, and the first foul flush effect. The ability to replicate this effect has not previously been available. Further testing will enable the model to be applied with confidence across different types of sewer networks. This will allow engineers to provide means of controlling aesthetic pollutants more cost effectively.

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REFERENCES

(1) Balmforth D.J. and Meeds E.H. The Potential for Modelling Aesthetic Pollutants. *WaPug97*, 1997

(2) Shaw E.M. *Hydrology in Practice*, Chapman & Hall, London, 1994

(3) Butler D. and Davies J.W. *Urban Drainage,* EF Spon, London, 2000

(4) Digman, C.J. *Steering Group Report – March 2001*, EPSRC Grant GR/M16795, Predicting Aesthetic Pollutant Loadings from CSOs, Unpublished, 1999

(5) Houldsworth J.K. *Steering Group Report – February 99*, EPSRC Grant GR/M16795, Predicting Aesthetic Pollutant Loadings from CSOs, Unpublished, 1999

(6) Friedler, E., Brown D.M. and Butler, D. A study of WC derived sewer solids, *Wat. Sci. Technol.* Vol 33, No. 9, pp 17-24, 1996

(7) WaPUG *Code of practice for the hydraulic modelling of sewer systems,* Version 2, WaPUG, 1998

Novatech 2001 – Innovative Technologies in Urban Drainage,

Lyon, France 2001

Aesthetic Pollutant Loadings in Small Upstream Combined Sewerage Systems

Charges en pollutants visuel des systèmes unitaires amont de petite taille

Mr Christopher J Digman*
Dr Kevin Spence*
Dr David J Balmforth**

*School of Environment and Development, Sheffield Hallam University, City Campus, Howard St, Sheffield, S1 1WB, UK
**Montgomery Watson, Unit 1B, Wakefield 41 Business Park, South Park Way, Wakefield, WF2 0XJ, UK

RÉSUMÉ

Au Royaume-Uni, les progrès sur les déversoirs d'orages ont été réalisés au cours des dix dernières années et devraient se poursuivre. Un des objectifs est de réduire la quantité des polluants visuels déversés pendant un orage. Pour accomplir cela, il est utile de connaitre la quantité, la composition et la variation temporelle des solides qui sont amenés jusqu'au déversoir d'orage. Cet essai présente dans les grandes lignes la première étape d'un projet entrepris afin de déterminer ces variables dans le cas de réseaux unitaires amont de petites tailles. Les polluants visuels ont été échantillonnés et analysés au cours d'événements pluvieux à Sheffield, Angleterre, et comparés aux résultats d'un model numérique simple qui a été développé. La technique d'un réservoir non-linéaire a été utilisé pour calculer les débits dans une version simplifiée du réseau d'assainissement. La valeur de débit ainsi obtenue est ensuite utilisée pour prédire le transport des solides. Deux méthodes différentes ont été développées afin de reproduire le transport des solides au sein du réseau d'assainissement. Ces deux méthodologies sont présentées dans cet essai et les résultats sont comparés aux résultats des mesures réalisées sur le terrain. Le model "favoris" a le potentiel pour une application générale en assainissement urbain par temps de pluie.

ABSTRACT

In the UK, improvements to Combined Sewer Overflows (CSOs) have occurred over the last decade and are set to continue. One improvement is to reduce the quantity of aesthetic pollutants spilt during a storm. To accomplish this, it is beneficial to know the quantity, composition and temporal variation of solids that are presented to a CSO chamber. This paper outlines the first stage of work undertaken to determine this data for small upstream combined sewerage systems. Aesthetic pollutants have been sampled during storm events in Sheffield, England, and compared to results from a simple numerical model that has been developed. A non-linear reservoir technique has been used to calculate flows through a simplified version of the sewer system. The flow produced is then used to predict solids transportation. Two alternative methods of replicating solids' transportation in the sewer system have been developed. These are presented and compared with values measured in the field. The preferred model demonstrates potential for general application in urban drainage.

KEYWORDS

Aesthetic pollutants; gross solids; urban drainage systems; transport; first foul flush; combined sewer overflow

INTRODUCTION

Large quantities of sanitary products, faeces and toilet tissue are disposed of through the sewerage system in the UK. These solids are more commonly known as aesthetic pollutants. The majority of sewerage systems in the UK are combined, conveying waste water and storm water together. During a storm, the pollutants that have entered the system during dry weather can be discharged into a water course via combined sewer overflows (CSOs). This can often lead to public complaint. The control of aesthetic pollutants is governed by the Urban Waste Water Treatment Regulations (1994), which stem from the EU Urban Waste Water Treatment Directive (1991). The quantities of aesthetic pollutants spilt depend upon the size of the wet weather event, the number of persons in the catchment, the catchment characteristics, socio-economic factors and the type of CSO.

This paper presents selected results from a three year project funded by UK Government and UK Water Industry Research Ltd, which involves three collaborating institutions: Imperial College of Science, Technology and Medicine, University of Sheffield and Sheffield Hallam University. The study will enable a greater understanding of the production and transportation of aesthetic pollutants in a sewerage system under storm conditions. This will enable the aesthetic pollutant variability to be modelled in time and space in combined sewerage systems. The aesthetic pollutant model will be linked to a CSO model to enable the pollutant loading from CSOs to be predicted and compared with regulatory standards to arrive at cost effective solutions to sewerage upgrading proposals.

The paper describes the development of a numerical model to predict the quantity of solids arriving at a location upstream of a CSO. The model's preliminary performance is compared with flow and aesthetic solids measured in dry weather and storm conditions.

NUMERICAL MODEL

The aim was to produce a simple model that would determine the temporal distribution of solids at any point in a small upstream combined sewerage system. The model has been developed from previous work at Sheffield Hallam University (Balmforth et al, 1997) which indicated the potential for modelling aesthetic pollutant loadings in combined sewerage systems by using a single channel to represent the catchment. However this earlier model could not generate the total amount of solids nor predict their temporal variation.

The current model has been developed in three stages. The first stage is concerned with determining the quantity of solids in the system prior to a storm. At present this has been calculated using measured field data. However, it is intended in the future to determine the quantity of solids dependent upon characteristics of the population. The second stage generates flows from measured rainfall data using a non-linear reservoir model. The final stage predicts the temporal distribution of solids in the system by approximating the transportation of solids through the system using two alternative methods.

FLOW CALCULATION AND SEWER SYSTEM SIMPLIFICATION

The sub-catchment, SC1 at the Glenholme Rd site, in Sheffield, England, has been chosen for the initial investigation of simplifying a real sewer system (Figure 1 and 2). Flow calculations are achieved by routing inflows through a simplified network. The inflow to the sewer system is determined using measured rainfall data at the site with initial losses accounted for by using a depression storage calculation (Butler and Davies, 2000). This is then combined with the impermeable area of SC1 to determine the inflow into the system during a storm. The impermeable area has been measured from background plans using AutoCAD.

The sewer system in SC1 has been modelled using a simplified system of rectangular open channels. This shape has been chosen to enable easy flow calculation. Two levels of simplification were used: single and 3 channel networks. The single channel consists of one channel, 750 m in length and a width of 0.300 m. Two 3 channel networks are considered. Both of these consist of 3 channels in series, all 250 m in length. The first network has a constant width of 0.300 m, chosen to enable a comparison with the single channel network. The other network has varying channel widths with the upstream at 0.150 m, followed by 0.300 m and finally 0.450 m. This network represents the increasing diameter of the sewer system in SC1 as it progresses downstream (Figure 2). The total length of the networks are equal to the longest pipe branch in the sub-catchment.

Flood routing in the channels is determined by using a non-linear reservoir technique (Shaw, 1994). The outflow from the channels is controlled by a notional weir at the downstream end of the channel, yielding the following equations (Equations 1 & 2):

$$S = AH \quad \ldots\ldots\ldots (1)$$

$$Q = CLH^{3/2} \quad \ldots\ldots\ldots (2)$$

Combining equation 1 and 2 gives:

$$S = KQ^{2/3} \quad \ldots\ldots\ldots (3)$$

where: S = Storage (m^3)
A = Plan area of channel (m^2)
C = weir constant
Q = discharge (m^3/s),
H = head over weir (m)
L = weir length (m)

K = Storage constant calculated for each individual channel $= A\left(\frac{1}{CL}\right)^{2/3}$

The single channel system has one entry point for flow at the upstream end to which the whole impermeable area is assigned. The discharge hydrograph at the downstream end of the channel is obtained by routing the inflow through the system at discrete time intervals. In the 3 channel system, each channel is assigned an equal impermeable area. The same calculation procedure is used for the first channel of the 3 channel system. The outflow from the upstream channel is then combined with the runoff from the impermeable area assigned to the second channel to generate the inflow for this channel. This process is repeated to determine the final outflow from the system.

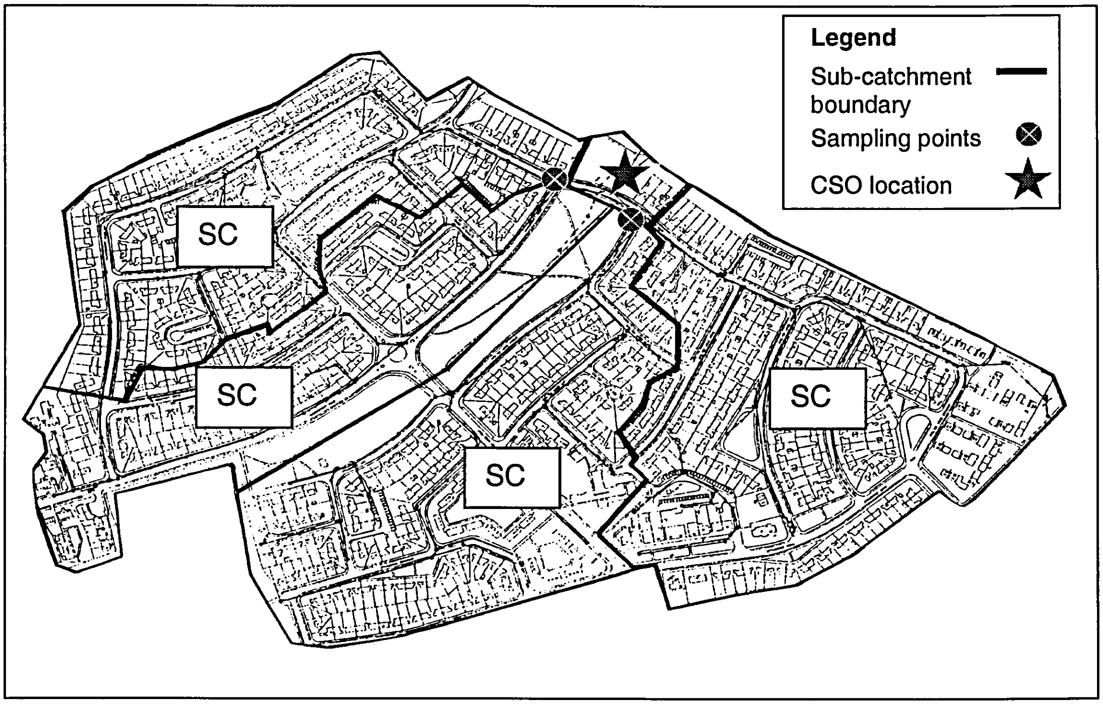

Figure 1 – The four sub-catchments of Glenholme Rd, Sheffield

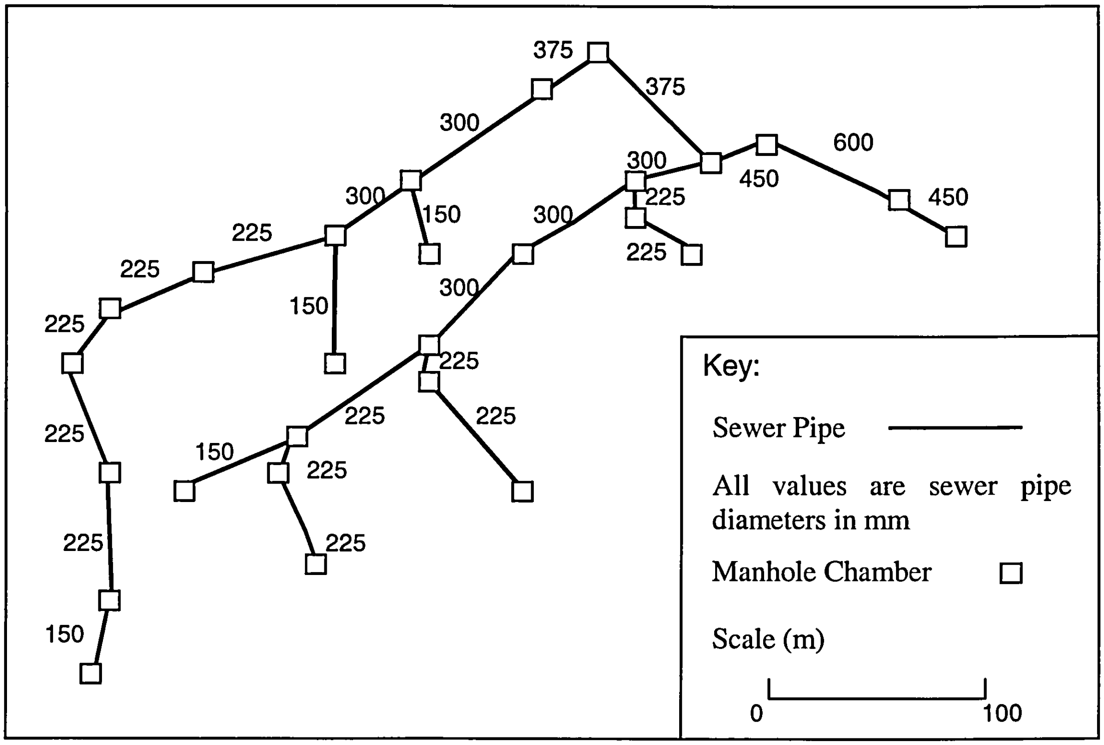

Figure 2 – Sub-catchment SC1 at Glenholme Rd

SOLIDS' TRANSPORT MODELS

Two alternative methods of solids' transportation have been developed: the Dilution method and the Specific Volume method. The total quantity of solids has been

obtained from the measured values. Prior to the storm commencing, all these solids are distributed at a uniform concentration throughout the channel.
In the Dilution method, at each time step, the effective rainfall that enters the channel is mixed completely with the existing solids and water within the channel. Thus the concentration of the pollutants within the channel is reduced. The mass of solids that flows out of the channel at the downstream end is therefore dependent on the solids concentration and the magnitude of the outflow at any particular time step.

The Specific Volume method simulates the movement of discrete flow volumes within each channel. At the upstream end of each channel, the flow volume that enters (as defined by the inflow hydrograph), does not mix with existing water in the channel, but pushes it along before it. In this way each parcel of water retains its individual solids concentration. Therefore the quantity of solids leaving the channel is dependent upon the outflow and the corresponding solids concentration within that volume only. In the 3 channel model, runoff discharged to intermediate pipes is mixed with solids and flow from the upstream channel before the routing procedure is repeated.

FIELD MONITORING

An extensive monitoring programme has been undertaken in a combined sewerage system at the Glenholme Rd site. This contained mainly urban dwellings with one school. It had a total population of 1820 and was classified as a low income area (Houldsworth, 1999). The site (Figure 1) was conveniently split into 4 sub-catchments for the purpose of flow monitoring and aesthetic pollutant sampling. Depth and velocity monitors were placed upstream of the sampling points at the first suitable manhole and were visited weekly to be cleaned and checked. A raingauge was also sited at the school.

A methodology has been developed to sample aesthetic pollutants from various types of sewer and manhole configurations. This involved all the water in the sewer being directed through a rectangular orifice in a steel frame inserted into the sewer pipe. Attached to the rear of this frame was a mesh sack (apertures 6mm x 4mm). For the first 40 minutes from the start of the storm, the sacks were changed every 5 minutes and then every 10 minutes for the next 40 minutes. When each sack was removed, it was left for 30 minutes before being weighed. Contents of the sacks were characterised in the laboratory, where pollutants were separated into individual categories, weighed and their dimensions recorded if possible.

COMPARISON OF THEORETICAL AND SAMPLED STORM DATA

Results of the non-linear reservoir technique for the single and 3 channel systems have been compared to the measured values for a storm sampled on the 26/11/99 (Figure 3). The simulated hydrographs show a slightly earlier response to rainfall than the measured data. In the single channel system, the non-linear reservoir technique produces flows slightly higher than measured. However the 3 channel systems produces flows far greater than the measured and single channel system. Both of the three channel networks investigated produced very similar flows, indicating that the change in channel widths has a very limited effect on the magnitude and shape of the routed hydrograph. Of the methods presented, the single channel system produces the closest fit to measured data.

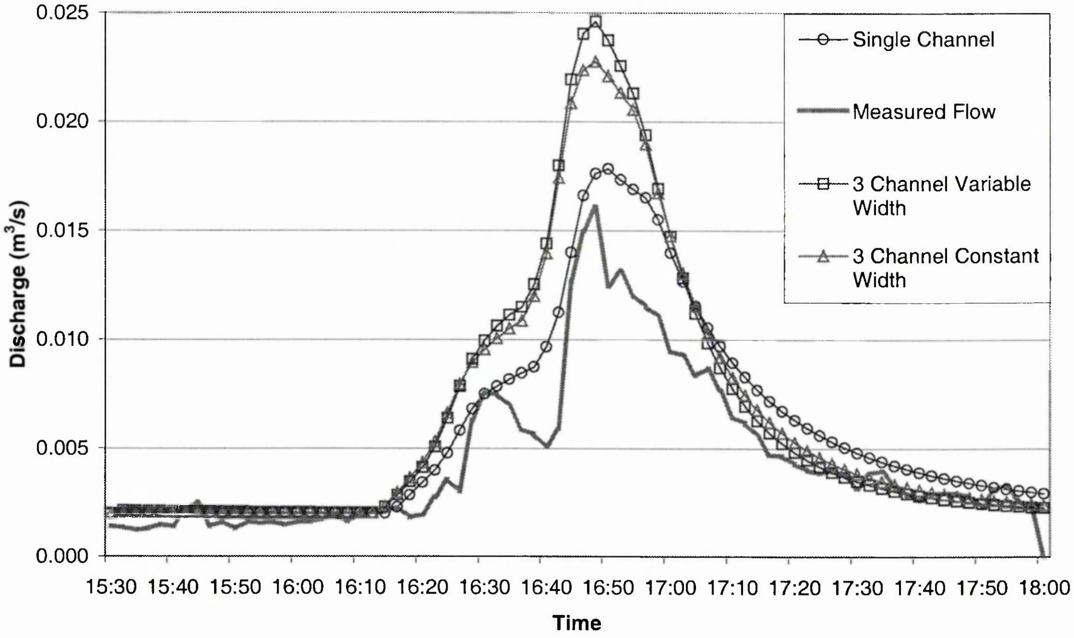

Figure 3 - Comparison of Outflow from downstream point of simplified channel system at SC1 with measured data, Glenholme Rd for Storm 26/11/1999

Results from modelling the solids within the system have been compared to measured field data sampled during the storm event. The measured data clearly indicates a high first foul flush of aesthetic pollutants at the beginning of the storm as the discharge increases above the dry weather flow (Figure 4). The Dilution method produces a modest first flush effect with a peak rate occurring before the peak of the flow hydrograph. However the solids are distributed over too long a time base with this method. The specific volume method more accurately represents the peakedness of the first foul flush of solids with a good replication of the timing and peak rate of solids.

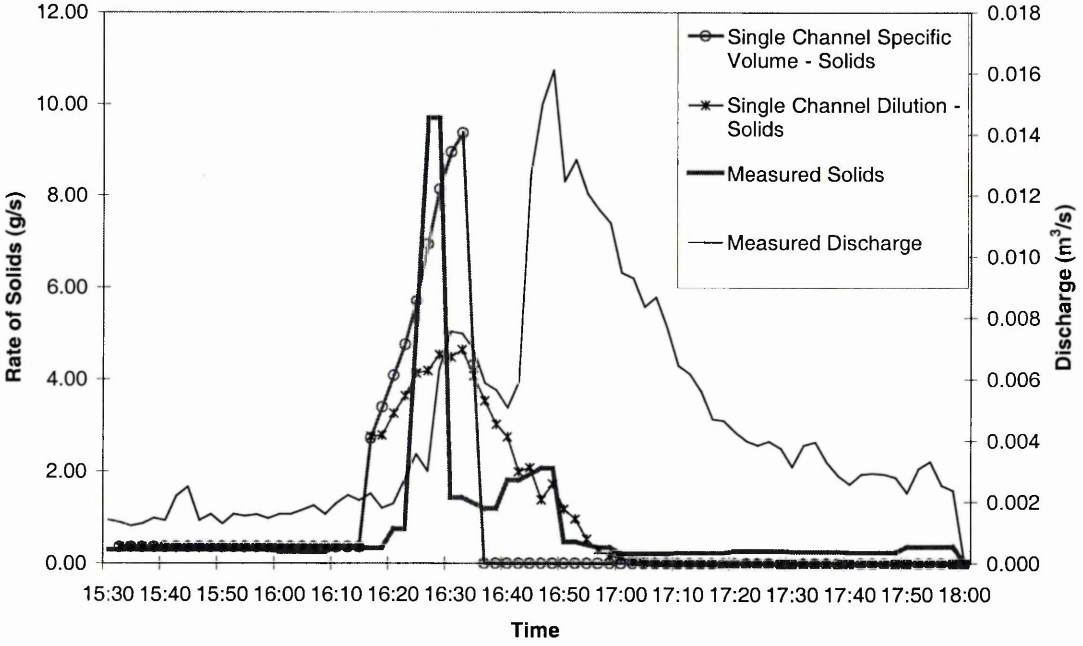

Figure 4 – Comparison of measured and theoretical single and three channel model results for flow and solids in SC1, Glenholme Rd for Storm 26/11/99

The Specific Volume method for the single channel gives the best approach to determine the rate and temporal distribution of solids leaving the system. This method has thus been used on different sub-catchments; SC3 and SC4 at Glenholme Rd (Figure 1). Each pipe branch in the sub-catchments has been simplified and single channel systems created as previously with SC1. A simulation of flows and solids leaving each system is undertaken, and compared to measured data (Figures 5 and 6).

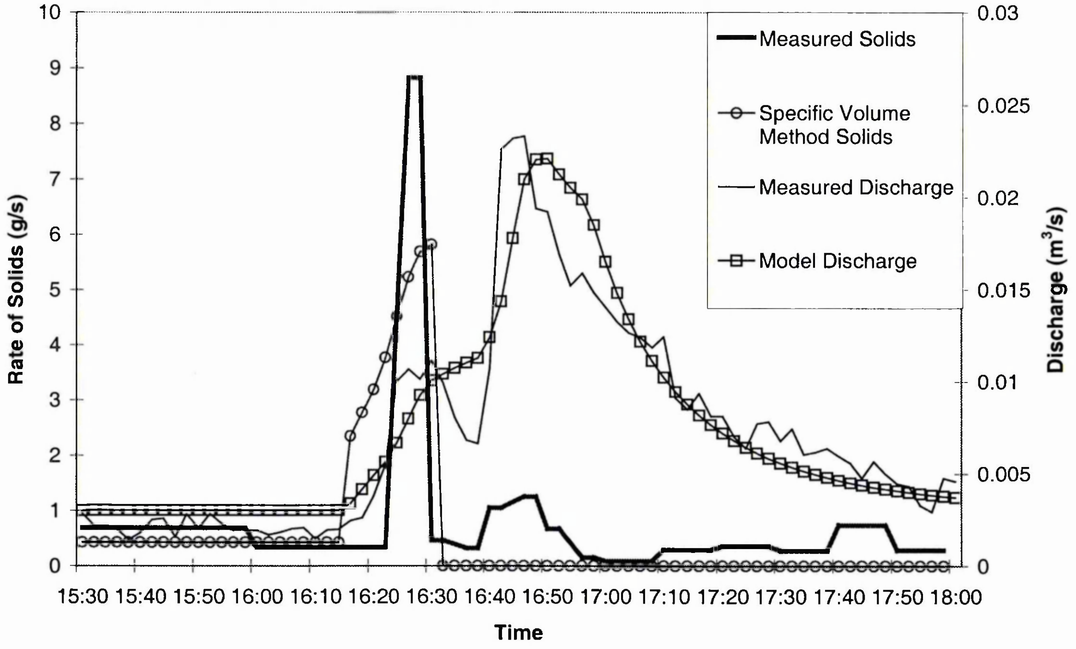

Figure 5 – Comparison of measured and theoretical single channel model results for flow and solids in SC3, Glenholme Rd for Storm 26/11/99

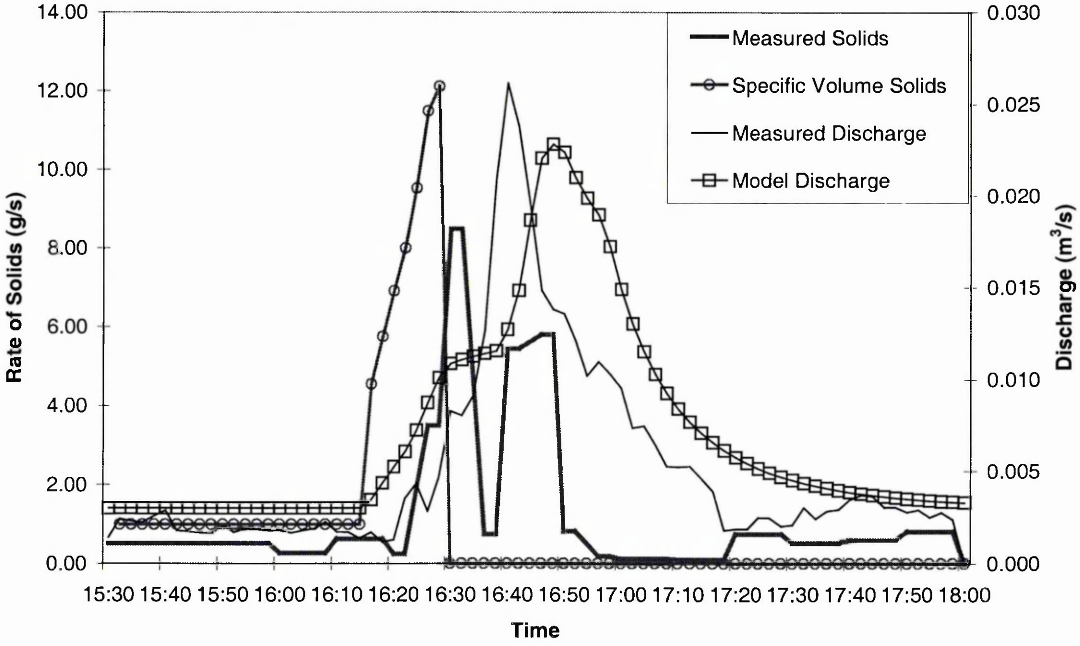

Figure 6 - Comparison of measured and theoretical single channel model results for flow and solids in SC4, Glenholme Rd for Storm 26/11/99

In SC3, the simulated hydrograph is been similar in magnitude and shape to the measured flow. However the solids flush is lower than the peak measured in the field. In SC4, the simulated hydrograph is slightly smaller than the measured flow with the time to peak occurring later. The single solids flush from the model is greater than the first flush measured. In the SC4 simulation the solids leave the system earlier due to the early response of the system to the rainfall.

The model produces a reasonable prediction of the magnitude of the first foul flush and an excellent prediction of the timing of the peak. The latter is crucial in effective solids control in urban drainage systems. These simulated results clearly demonstrate the potential of this model approach to be developed further.

Further work is now necessary to enable the quantity of solids produced by the population to be predicted. Tests will also be conducted with different storm events and in different catchments.

CONCLUSIONS

A simplified model approach for replicating flows and aesthetic pollutant concentrations in small upstream sewerage systems has been developed. Comparison with measured values clearly demonstrates the potential of the model for predicitng the temporal distribution of aesthetics at CSOs. This lays the foundation for accurately simulating a first foul flush of pollutants that is known to occur in urban drainage systems. This will enable more cost effective solutions to control aesthetics to be developed, compared to the existing models that rely on average solids concentration only. Further work is planned to enable the quantity of solids generated to be predicted from population characteristics.

ACKNOWLEDGEMENTS

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REFERENCES

Balmforth D.J. and Meeds E.H. (1997) "The Potential for Modelling Aesthetic Pollutants", WaPug97
EU (1991) "Urban Waste Water Treatment Directive", EU Directive No. 91/271/EEC, Official Journal L135, 30 May 1991, p40
(1994) "The Urban Waste Water Treatment (England and Wales) Regulations", HMSO
Houldsworth J.K. (1999) "Steering Group Report – February 99", EPSRC Grant GR/M16795, Predicting Aesthetic Pollutant Loadings from CSOs, Unpublished
Shaw E.M. (1994) "Hydrology in Practice", Chapman & Hall, London
Butler D. and Davies J.W. (2000) "Urban Drainage", EF Spon, London

A Model to Predict the Temporal Distribution of Gross Solids Loading in Combined Sewerage Systems

Mr. C.J. Digman*, Dr. K. Littlewood**, Prof. D. Butler**, Dr. K. Spence*
Dr. D.J. Balmforth***, Dr. J. Davies****, Dr M. Schütze******

**School of Environment and Development, Sheffield Hallam University, City Campus, Howard St, Sheffield, S1 1WB, UK; c.j.digman@shu.ac.uk / k.j.spence@shu.ac.uk*
**Dept of Civil and Environmental Engineering, Imperial College of Science, Technology & Medicine, Imperial College Road, London, SW7 2 BU, UK; kim@kim-littlewood.co.uk / d.butler@ic.ac.uk
***Montgomery Watson Harza, Unit 1B, Wakefield 41 Business Park, South Park Way, Wakefield, WF2 0XJ, UK; david.balmforth@mwhglobal.com
*****School of Science and the Environment, Coventry University, Priory Street, Coventry, CV1 5FB, UK; j.w.davies@coventry.ac.uk*
*****ifak – Institute for Automation and Communication Magdeburg e.V, Steinfeldstr. 3, D-39179 Barleben, Germany; mas@ifak.fhg.de

Abstract

Computational packages are traditionally used to model urban drainage systems. This enables the flow, suspended solids and other water quality parameters to be predicted at Sewage Treatment Works (STWs) and Combined Sewer Overflows (CSOs). However, the authors are unaware of a model capable of predicting the quantity and temporal distribution of gross solids presented to these structures. An improvement to the standard of discharges from these structures is necessary to meet the challenges set by the EC Urban Waste Water Treatment Directive (1991). Therefore a tool to assist the water industry in meeting the regulatory standards would be valuable. This was recognised by the initiation of a collaborative research project by the UK funding bodies, EPSRC and UK Water Industry Research Ltd, that has been carried out at Sheffield Hallam University (SHU), Imperial College (IC) and University of Sheffield (UofS).

A computational model has been developed to predict the movement of gross solids in a combined sewerage system. The model has been designed to link directly with industry standard modeling software. A Hydroworks model of the drainage system is used to obtain network data, depth and velocity output files that are used as an initial input into the gross solids simulator (GSS). The second input to the model utilises a series of diurnal solid profiles based upon earlier work at Imperial College and gross solids sampling work undertaken during this project at SHU. In dry weather flows, a proportion of solids entering the system is deposited in the upstream sections of the pipe network, which are not normally represented in the modelled network. A storage equation modifies the diurnal solids profile to account for the solids that are stored. The next rainfall event will then mobilise some or all of the solids. These, together with solids that are already being transported will arrive at a downstream location in the form of a 'first foul flush'. A non-linear reservoir model of the upstream pipes predicts this temporal distribution. This forms an input to the modelled network during a storm event. In the main sewer network, solids are tracked individually because their advection velocity differs from the mean fluid velocity. Deposition and subsequent re-erosion of the solids is modelled based on velocity and depth criteria developed from laboratory experiments.

The GSS has been calibrated using an extensive set of data sampled from three combined sewerage systems. Potentially, the practical application of this model could provide an expedient method for determining loading rates presented to CSOs and STWs. This will enable engineers to provide more cost effective solutions to control the discharge of gross solids from these structures.

Introduction

The majority of sewers in the UK are combined, conveying wastewater from domestic and industrial sources and storm water together. The domestic wastewater is likely to contain dissolved pollutants, fine solids and larger solids. These larger solids referred to as gross solids or aesthetic pollutants are greater than 6 mm in two dimensions and enter predominately from the water closet (WC). These solids consist of faeces, toilet tissue, wipes, condoms and sanitary protection items. During a wet weather event these solids are transported through the sewer system at an increased rate. These can enter a CSO and have the potential to be discharged to a receiving watercourse. The public view these pollutants as being aesthetically unpleasant and this leads to complaints. The need to reduce the quantity of gross solids discharged stems from the EU Urban Waste Water Treatment Directive (1991). The quantities of gross solids discharged depend upon a number of factors including the size of the wet weather event, the number of persons in the catchment, the antecedent dry weather period, the catchment characteristics, socio-economic factors and the type of CSO. Despite considerable investment in recent years, there are still a large number of aesthetically unsatisfactory CSOs in the UK. A better understanding of the production and transportation of aesthetic pollutants is required if cost effective solutions are to be found in the future.

A collaborative research project funded by UK Government and UK Water Industry Research Ltd has been undertaken with an aim to build a greater understanding of gross solids movement. Three institutions, IC, UofS and SHU have undertaken this work. The aim of the study was to enable a greater understanding of the composition and transportation of gross solids in a sewerage system under storm conditions. This would allow the gross solids variability to be modeled in combined sewers in time and space. The gross solids model would then be linked to a CSO model to enable the pollutant loading from CSOs to be predicted and compared with regulatory standards to arrive at cost effective solutions to sewerage upgrading proposals.

One of the primary objectives of the project was to build and verify a mathematical model for predicting the composition, quantity and temporal distribution of gross solids in urban drainage systems. This objective was delivered through a program of fieldwork, the development of a simple mathematical model in upstream sewers and a simple transportation model for the downstream sewers.

This paper describes work by Imperial College and Sheffield Hallam University in the construction, development and initial testing of this mathematical model. The model's preliminary performance is compared to gross solids measured in dry weather and storm conditions. The model has been built with the advice from industrial partners in its format and application. The model utilises output from Hydroworks in order to make efficient use of existing information. These hydraulic models of the drainage networks, are or have been built by industry, therefore the model could be used with existing Hydroworks models and potentially in the future with other hydraulic computer simulation packages.

Model Overview

When constructing a computational model of an urban drainage system it is convenient to consider the drainage system in two parts. The first consists of surface area flow and includes the small pipes associated with these areas. These typically include private drains within the boundaries of individual properties and the small pipes within the public sewer, up to 300 mm diameter. They are collectively known as the upstream system. The second part consists of the public sewer with pipes of 300 mm diameter and larger. This is called the downstream system and normally forms the modelled sewer network. The Gross Solids Simulator (GSS) model combines these two distinct parts. Linked to the GSS is a solid input model that determines the rate and quantity of solids that enter. The output from the GSS is connected to a CSO model to predict the behavior of solids in the chamber. The CSO model is not discussed in this paper.

Solids will enter the upstream system in a diurnal pattern, and the flow in the sewers will also follow a diurnal pattern. The flow is likely to be intermittent, with little or no flow at quiet periods, for example 02:00-04:00 hours. Solids which enter the upstream system may become stranded, either temporarily until the diurnal flow is great enough to move them, or for longer periods until they are mobilised by a storm flow. When this occurs, most of the solids which are stranded in the upper parts of the system will be flushed out into the downstream sewers at the start of the storm. This is modelled using a non-linear reservoir that simulates the flow in the upstream section.

In the downstream system (modelled network), there will still be an underlying diurnal pattern of flow, but there may be no periods of zero flow, so solids are less likely to become stranded. Solids are transported through the sewers with sedimentation and re-suspension behaviour according to the depth and velocity of the flow, and will eventually be carried to the CSO. At the CSO, flow conditions will dictate how much flow is spilling and continuing, and how many solids will be discharged. In the downstream system the network consists of a series of nodes that are connected by links. Each node has an associated population and impermeable area. Each link will have an associated diameter, gradient and length. Figure 1 shows the interaction of the components of the GSS.

There are three different categories of node within the network. The first kind of node has an upstream system connected and is defined as node type A (Figure 1). This will have solids entering from the upstream system during storms, and will have some solids stored upstream of the node during dry weather. The second kind of node has no upstream system, but has an associated population and is shown as node C. In this case, the solid input will follow a diurnal pattern with the quantity being dependent on the population. The third kind of node is an intermediate node defined as B. Inputs into this node are from the output from upstream links and a diurnal input from its associated population.

A summary of the solid inputs into the different kinds of node is given in Table 1. During a storm event, the solids that are stored in the upstream system will be washed out and combined with a diurnal load at node A. At node C, the diurnal input remains the same as in dry weather.

When the inputs at the different nodes are combined, it is possible to track individual solids from their point of entry into the sewer through to them leaving the system. At any time their location is known and the time taken for them to reach the location can be determined (Schütze, et al 2000, Schütze, 2001)

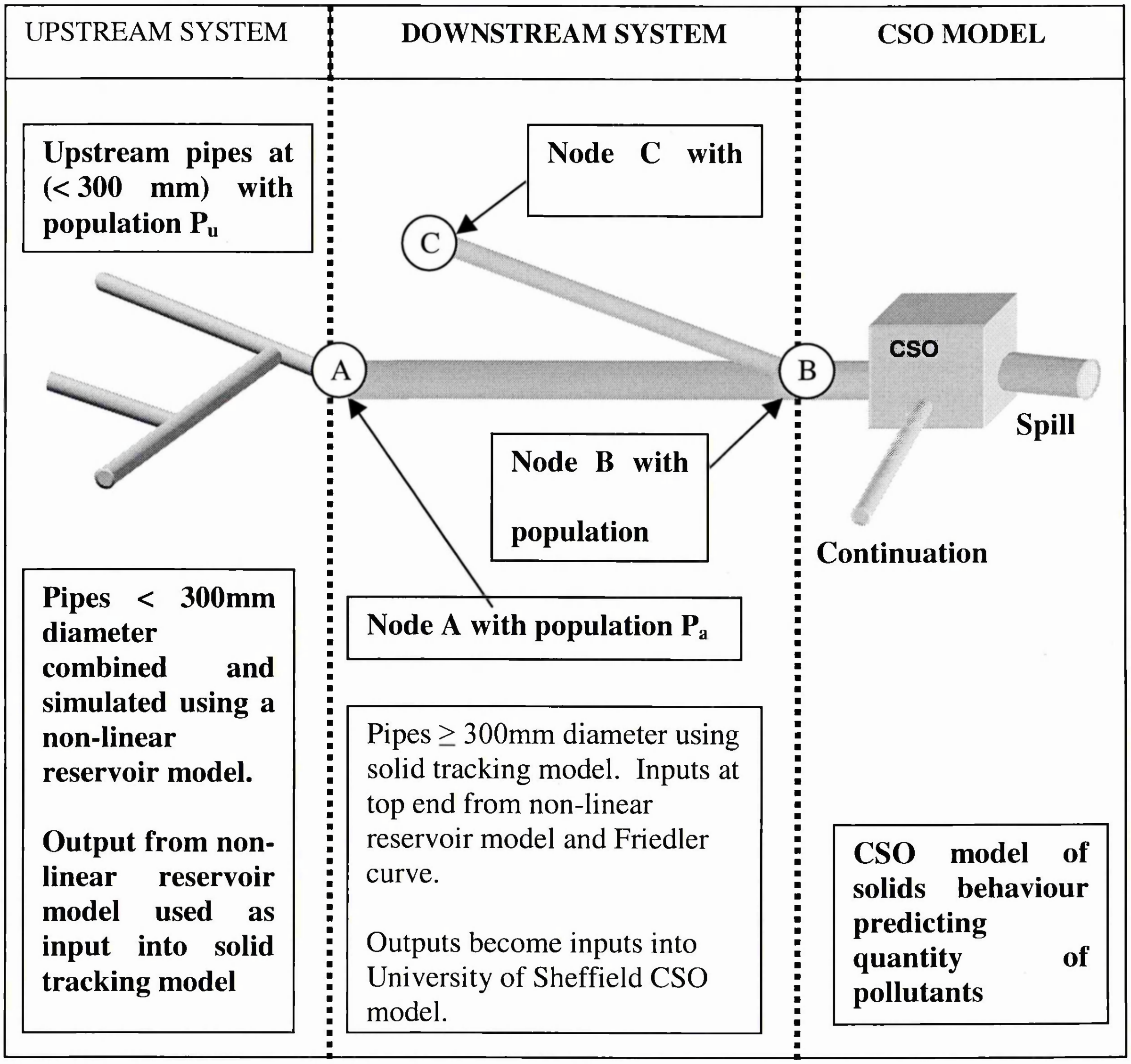

Figure 1 Diagram showing model interaction.

Table 1 Summary of inputs into solid transport model.

	Condition		
Inputs	Dry weather prior to storm	Storm	Dry weather after storm
Node type A	Diurnal pattern of input with a percentage of solids being stored	Output from non-linear reservoir model	Diurnal pattern of input with a percentage of solids being stored
Node type B	Diurnal pattern of input	Diurnal pattern of input	Diurnal pattern of input
Node type C	Diurnal pattern of input	Diurnal pattern of input	Diurnal pattern of input

The GSS has currently been designed to utilise network, flow and depth information that are given by a Hydroworks model of the network studied. The Hydroworks model will generally provide a time series for flow and depth, which will include a storm event. As the velocity and depth of flow increase during the storm, solids will move with greater readiness, and some of the solids that have been deposited will be mobilised, thus giving a first foul flush.

The GSS has currently been programmed to allow tracking of six different kinds of sewer solids; faeces, sanitary towels, tampons, toilet paper, panty liners and wipes.

Model Components

Solids' Input Model

The quantity of solids entering the GSS at the nodes is dependent upon the population number and type. The population type is dependent upon demographic distribution, socio-economic and ethnic factors. The rate at which solids enter will vary according to both the quantity of solids produced by the population and the method by which they are disposed. The accuracy of the gross solids simulator is initially dependent upon the accuracy of the temporal distribution of when solids enter and from what locations. The location depends upon the distribution of the population in the Hydroworks model.

The temporal distribution of when solids enter the system has been defined by previous work undertaken by Friedler, et al. (1996). A diary survey to determine domestic toilet usage collected evidence relating to the flushing of faeces, toilet tissue and sanitary refuse. This enabled distributions to be produced that define when solids enter the sewer via the WC during weekdays and weekends. The profile for faeces is shown in Figure 2. The rate of solids entering was combined with the populations assigned to each node in the Hydroworks model to determine the time when faeces enter the sewer system. Faeces were the first type of pollutant to be tested in the model and are presented in the paper.

The quantity of faeces produced by an individual depends upon a number factors including their age, sex, and diet. Average values identified by Houldsworth, (2000) cited an approximate production for an individual of between 100-150 g/day. Quantities of faeces sampled can be as little as 25 g/person/day (Digman, 2001) due to the degradation of the solid. This suggests that the strength of faecal matter to resist degradation is an important factor and could affect the transportation of the solid. However at present degradation of solids is not predicted, therefore estimations of the quantity of solids entering the system was based upon field survey work. At the catchment where the first sampling was undertaken an approximate value of 40 g/person/day was observed, which was combined with the faecal related flushing profile to determine quantity and rate of solids entering.

During dry weather, the input into the upstream nodes (A) is currently given by a modified Friedler profile (Figure 2), with the number of solids being proportioned according to the time. Some solids are stored, and other solids are passed into the downstream system. This reflects what has been found in practice.

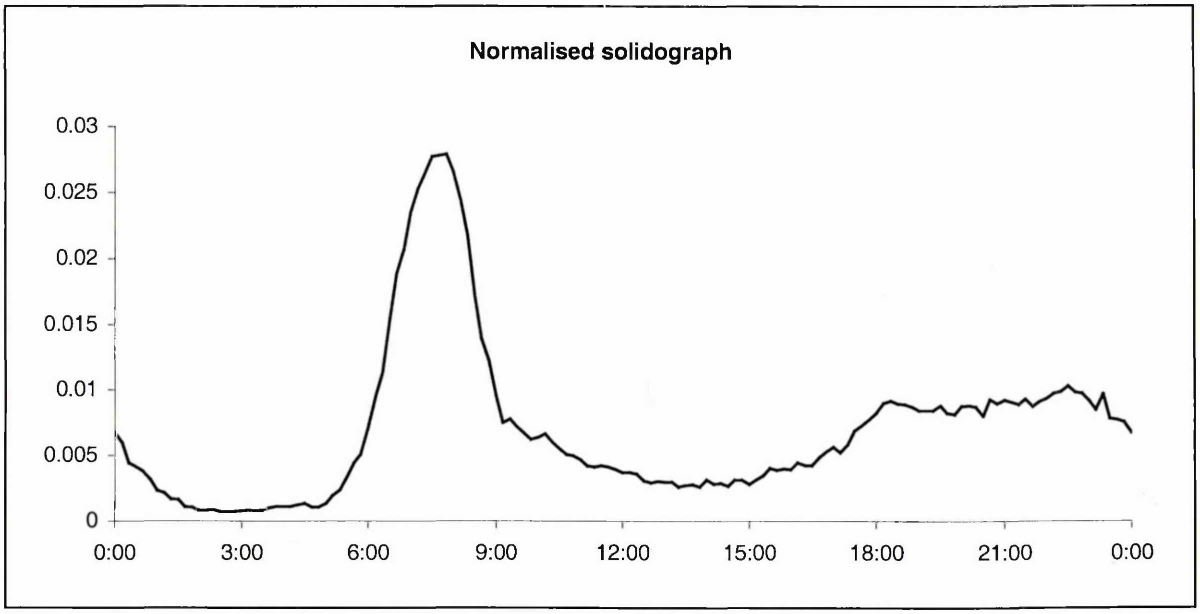

Figure 2 Normalised profile showing the rate at which faeces enter the sewer during a week day, adapted from Friedler, et al (1996)

Upstream system: Non-linear reservoir model

The upstream system uses flow volumes to simulate the transportation of solids. The model has three stages. The first generates flows from measured or design rainfall events using a non-linear reservoir model (Shaw, 1994). Initial losses from depression storage are accounted for at the start of the storm (Butler and Davies, 2000), and the pipe system is represented by a single non-linear reservoir. This was chosen after investigating a number of single and multiple reservoir configurations (Digman,C.J. 2001). The size of the reservoir is determined by considering it as a rectangular open channel. The length of the channel is made equal to that of the main sewer branch in the upstream system, and the width is made equal to the average diameter of the sewer pipes in the main branch. A notional weir located at the downstream end of the channel controls the outflow, and is governed by the following equations:

$$S = AH \quad \& \quad Q = CLH^{3/2}$$

are combined to give $S = KQ^{2/3}$

Where: S = Storage (m^3)
A = Plan area of channel (m^2)
C = weir constant
Q = discharge (m^3/s),
H = head over weir (m)
L = weir length (m)

K = Storage constant calculated a channel = $A\left(\frac{1}{CL}\right)^{2/3}$

The second stage estimates the quantity of solids stored in the reservoir during dry weather. This is based upon analysis of storm samples taken during the project at different catchments (described below). The number of solids deposited was estimated by comparing the quantity of solids in the system in dry weather estimated from the dry weather sampling at the three catchments. It was found that the quantity of solids stored was dependent upon a number of factors; population, antecedent dry weather period (ADWP), bed slope and housing density (Digman and Littlewood, 2002)

The third stage uses flow volumes generated by the non-linear reservoir model. Prior to a storm commencing, it is assumed that the solids in the reservoir are equally distributed within the DWF volume. At each timestep an inflow volume is generated from the rainfall and enters the reservoir. This does not mix directly with the DWF and solids but pushes them out of the reservoir. The volume leaving the reservoir is known, therefore the total quantity of solids can be determined as the solids concentration is constant. The transportation of solids is dependent upon the flow rate reaching a particular level. This threshold value was found to be approximately 1.5 times the magnitude of the peak DWF rate. This was observed following fieldwork that identified the first foul flush of gross solids. Therefore the model has been constructed so that when the outflow of the reservoir goes above this threshold value, the stored solids begin to leave the system. The performance of the non-linear reservoir model is shown in Figure 3. The model was tested against sampling data that measured the solids under storm conditions (Digman, et al. 2001).

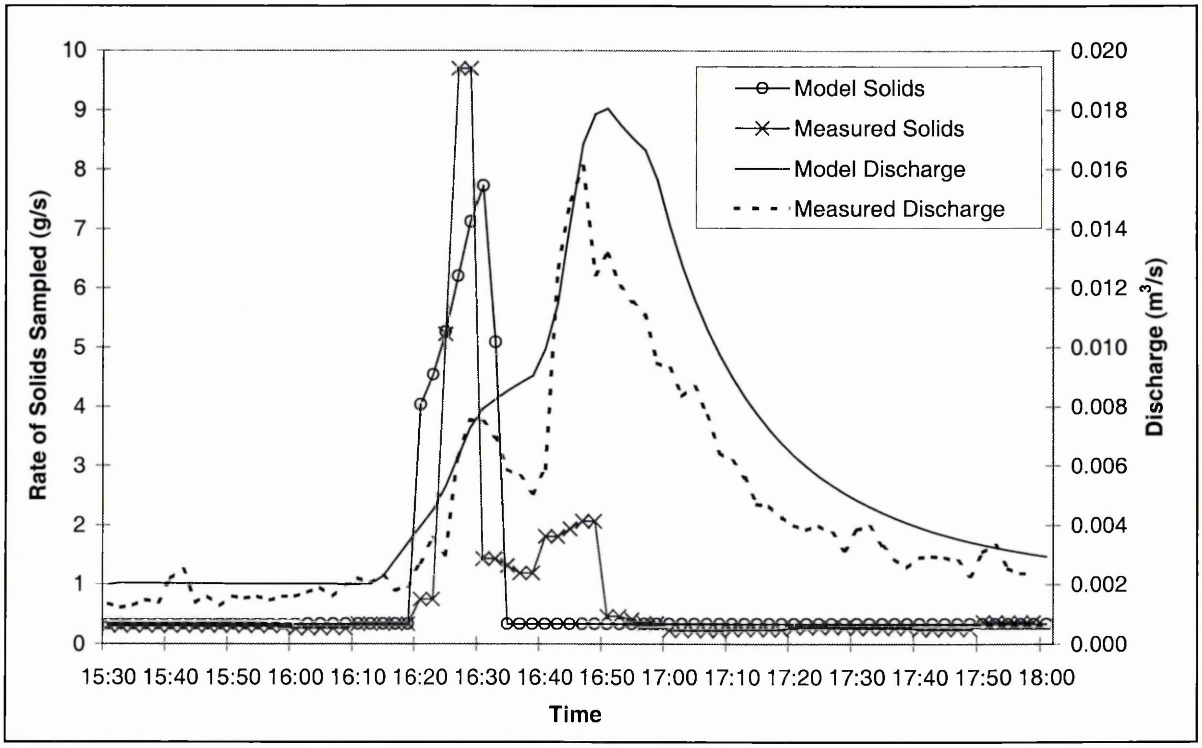

Figure 3 Comparison of measured and non-linear reservoir model results for flow and total solids in sub-catchment SC1 of the low income catchment for GS2

Downstream system: Sewer Solids Tracker

The sewer solids tracker (Schütze, et al 2000, Schütze, 2001) is used to model the movement of solids in pipes with a diameter of 300 mm or more, in the downstream system, conveying flow either to the treatment plant or the CSO. The solid inputs to the sewer solid tracker are taken from the Friedler profile and the non-linear reservoir model. A Hydroworks model of the network to be studied gives network and flow information, and from this information solids can be tracked through the sewer system.

It has been found that solids move in a pipe with a proportion of the fluid velocity

$$V_{GS} = \alpha V_w + \beta$$

where: V_{GS} is the gross solid velocity,
V_w is the water velocity,
α and β are coefficients.

In addition, solids are transported if and only if water level and water velocity exceed certain threshold values, V_{th} and H_{th} . i.e. if

$$V_w > V_{th} \text{ and } H_w > H_{th}$$

then

$$V_{GS} = \alpha V_w + \beta$$

otherwise

$$V_{GS} = 0$$

The solid inputs into the three different kinds of nodes are discussed above. With reference to Figure 1, the input into node C is given by a normalised Friedler profile, multiplied by the population to give the number of solids into the system at each timestep. The input into node A is given by the output from the non-linear reservoir model.

The sewer solid tracker reads the Hydroworks files to obtain network, flow and depth information, and the user then inputs information to control the model run, such as the model timestep. At each timestep, the sewer solids tracker reads the solid input file to ascertain how many solids of each type enter the sewer system within that timestep, and which link they enter. Each solid is then tracked individually through the sewer system at each timestep. The sewer solid tracker takes the velocity and depth for the timestep at any link from the Hydroworks flow files, and moves the solid according to the equations above. If the depth and flow are not great enough for movement, then the solid will remain stationary. The solid may then move to the next pipe in the network, and will eventually be flushed through the system, to exit at the downstream end. The time of exit is recorded, as well as information such as the route the solid took through the sewer system.

The underlying flow pattern during dry weather is diurnal, with low flow in some periods, such as early morning. At this time, solids may become stationary in the larger pipes, but may move again in the morning peak. These solids have therefore been temporarily stranded at some point in the sewer system. This stranding behaviour has been found to be sensitive to the threshold values V_{th} and H_{th}, which has strong implications for drainage design.

Comparison with Measured Field Data

Field Monitoring Procedure

An extensive monitoring program has been undertaken at three catchments in Sheffield, UK. Each catchment represents different socio-economic and ethnic populations. This work has identified that different population types affect the quantity and composition of solids that enter a combined sewerage system.

In the first catchment sampled, the population of 1810 was classified as ageing with a low income (Houldsworth, 1999). The catchment area of 32 ha, contained urban dwellings and one school. The sewer system was split into 4 sub-catchments for monitoring work, with Detectronic depth and velocity monitors placed upstream of the sampling points and a Casella 0.2 mm tipping bucket raingauge sited at the school. The second site sampled contained a high income population of 1309 and was smaller in size, with an area of 22 ha. The third site was an inner city area of 10 ha, with dense housing and a total population of 1599 of which 30% were of a Pakistani origin.

Gross solid sampling was undertaken in dry and wet weather. All the water and solids were directed through a rectangular orifice in a steel frame inserted into the sewer. The pollutants were retained in mesh sacks (apertures 6 mm x 4 mm) manoeuvered into position from above ground. These sacks were attached to the rear of the frame. To determine the temporal distribution of solids, sacks were changed every 30 minutes in dry weather and every 5 to 10 minutes during a storm. When each sack was removed, it was left for 30 minutes to enable excess water to drain, before being weighed. Contents of the sacks were characterised in the laboratory, where pollutants were separated into individual categories, weighed, and dimensions recorded.

Dry Weather Solids Comparison

A comparison of the dry weather profile measured in the field and the GSS at the downstream end of the low income catchment shows very good results (Figure 4). The output from the sewer solid tracker model are averaged over 5 and 9 data points (equivalent to a 10 and 18 minute time interval respectively). This smoothed the solids profile to enable an easier comparison with the measured data that sampled a period of 30 minutes. The 18 minute profiles are very similar to the measured with the 10 minute averaged profile indicating the fluctuating nature of the raw output. The total quantity of solids generated by the GSS model was very similar to the measured values, although this was expected as empirical values had been used to calculate the quantity of solids entering per person. A slightly larger peak was observed in the morning as well as substantially less solids leaving the system during the 11:00 to 16:30 time period. This difference is related to the flushing profile that controls the entry rate of solids and the critical values in the sewer solid tracker model that controls the solids' movement characteristics. No fieldwork was undertaken between 01:00 and 06:00 due to the low number of solids entering and or being transported, hence why no comparison is made over a 24 hour period.

Storm Solids Comparison

A comparison of the storm data for faeces between measured and GSS generated values has been undertaken (Figure 5 and Figure 6). This used the output from the non-linear reservoir model as input to the solid tracker at the upstream nodes. This also shows a good comparison between the measured and simulated faeces data. The timing of the flush is very good, with the predicted peak of solids occurring at a similar time to the measured peak. A substantial flush of faeces occurs in the raw data where the solids in the downstream model are flushed, combined with a second later peak, that was attributable to the reservoir flushing at the upstream nodes. The temporal distribution of these two flushes is very similar to the temporal distribution of the measured flushes. The averaged profiles still indicate the flushing effect however they do reduce the peak substantially. This is more comparable to sampling data that recorded the event in 5 minute intervals during the main flushing period. The quantity of solids predicted as being flushed during the peak of the storm was within 10% of the field data.

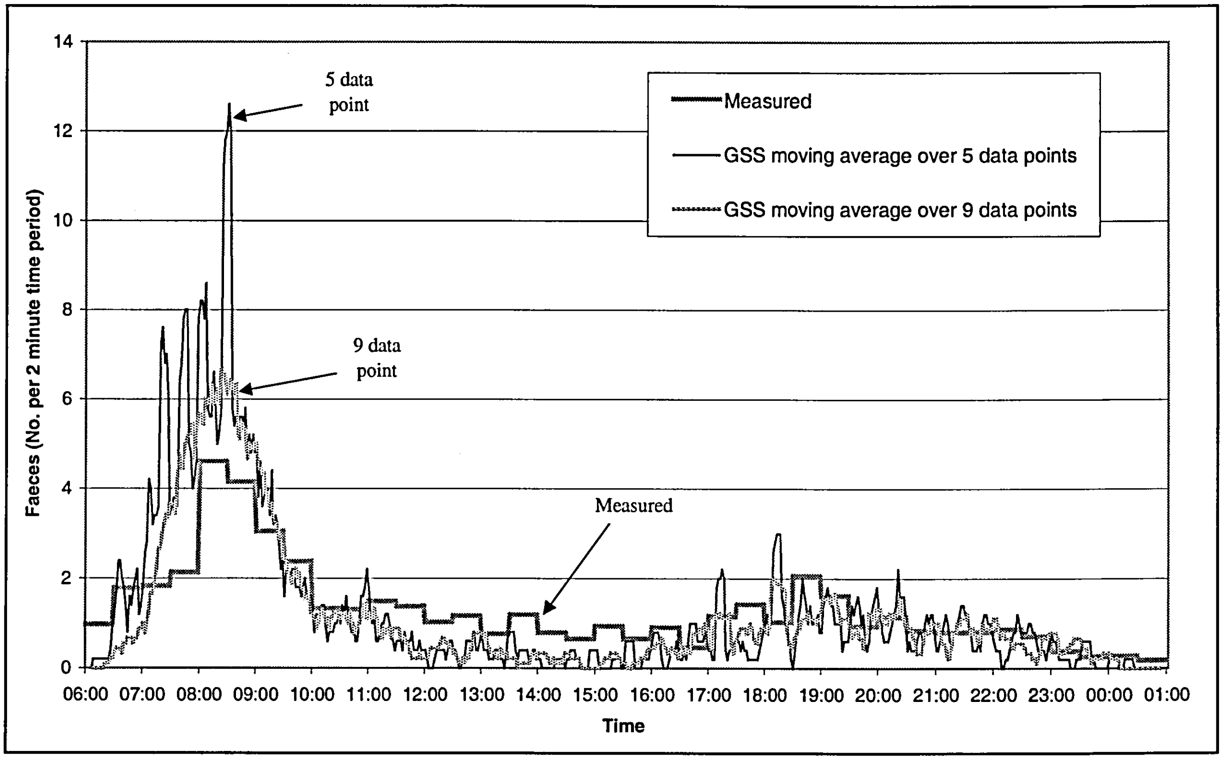

Figure 4 Comparison between measured field data and GSS output for faeces in dry weather at the low income catchment

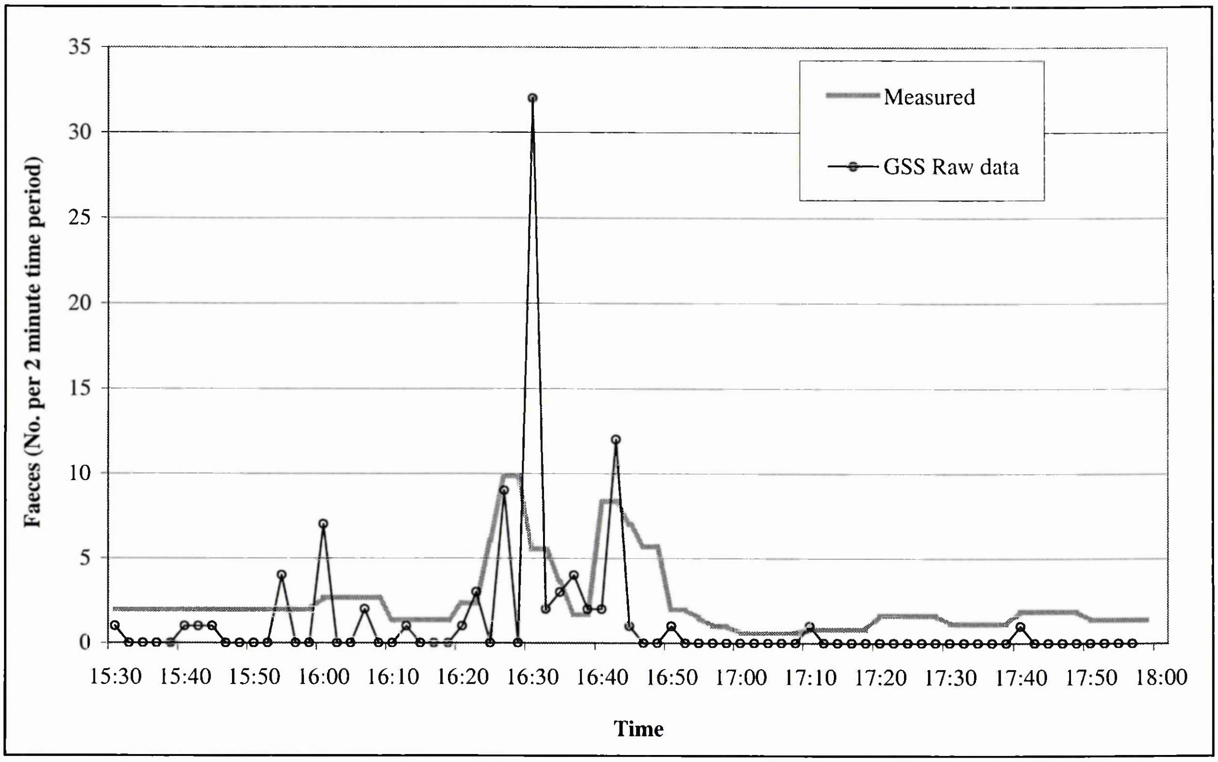

Figure 5 Comparison between measured field data and raw GSS output for faeces in wet weather for storm GS2 for link upstream of the CSO at the low income catchment

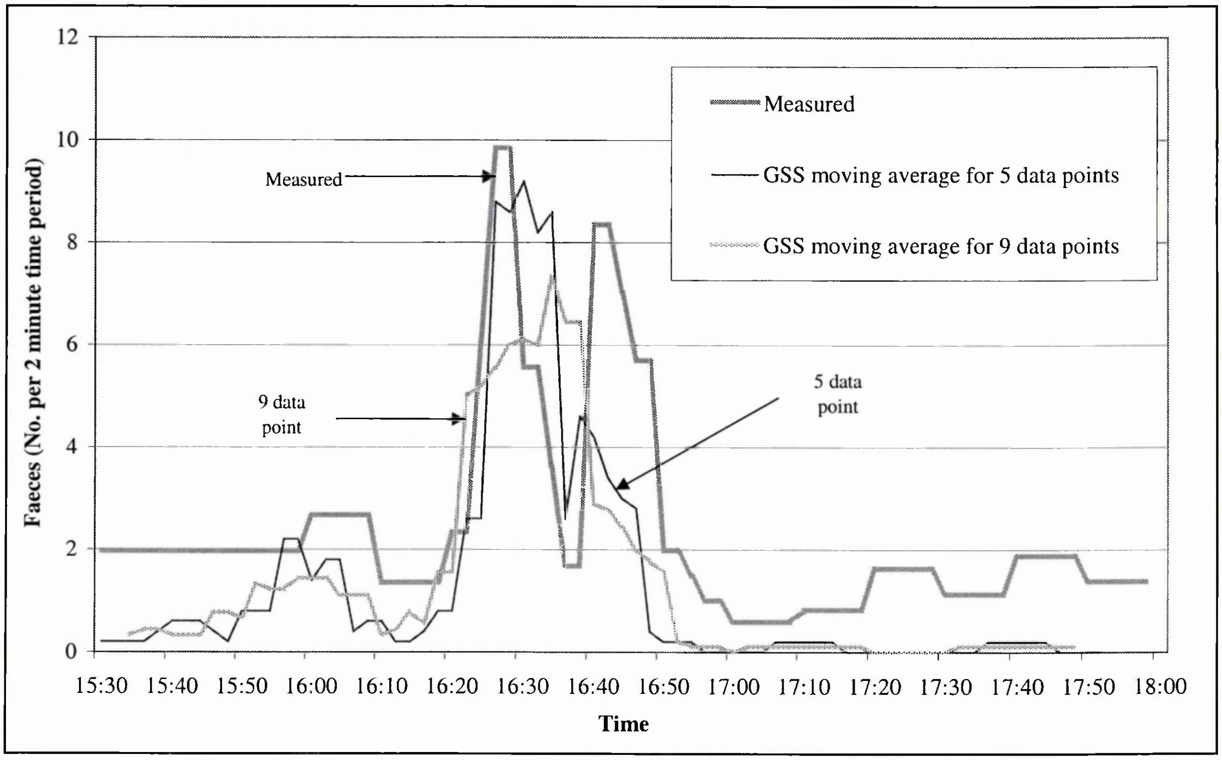

Figure 6 Comparison between measured field data and averaged GSS output for faeces in wet weather for storm GS2 for link upstream of the CSO at the low income catchment

Further Work

Coding of reservoir routing model

The current model has been found to simulate solid transport in the sewer system tested. However, the upstream and downstream models are two separate entities. The output from the upstream system built in Excel is input into the downstream system built in FORTRAN. Work will begin to combine these two sections by coding the upstream system into the FORTRAN program. This will reduce the time taken to run the two models. This will also enable the upstream model to be programmed to predict the solids entering from the diurnal pattern less the quantity that is stored.

Calibration with other solids

The model has currently been calibrated using faeces data. The model has been developed to be able to simulate the movement of various solid types and the next stage of calibration will use these different solid types. Following this, the GSS will be verified using data obtained from the two other catchments sampled.

Conclusions

The GSS has been developed using two separate models to predict the movement of solids in combined sewerage systems. An upstream model predicts the quantity of solids that are stored during an ADWP and their temporal distribution entering the downstream system during a storm. The downstream model has been designed to individually track solids' movement. The GSS has also been designed and built with the consideration of how such a model would be applied and utilised in industry.

The GSS has been tested against data collected from an extensive programme of field monitoring. The GSS has been found to accurately simulate the distribution and quantity of faecal solids arriving at the downstream end of a sewer network for dry weather flow for the catchment tested. The GSS has also been found to predict the quantity and timing of the first foul flush of faecal solids arriving at the downstream end of a sewer network during storm flow.

There is further work to be carried out on the model, in particular increasing usability. The model will then be combined with a CSO model capable of replicating the solids' separation performance in a CSO chamber. This will provide a powerful tool for industry enabling cost effective upgrading of sewerage systems to meet regulatory requirements for aesthetic solids' discharges.

In summary:

- The GSS has been constructed to simulate the movement of gross solids in a combined sewerage system in dry and wet weather

- The GSS has been tested against reliable field data and indicates the model readily simulates the movement of solids as observed in the field

- The GSS has the potential to provide the water industry with a tool to help reduce gross solids' discharges from CSOs during storm events

Acknowledgements

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References

Butler,D. and Davies,J.W. (2000) *Urban Drainage.*, E & FN Spon, London.

Digman, C. J. Predicitng Aesthetic Pollutant Loadings from Combined Sewer Overflows - Steering Group Report March 2001, EPSRC Grant GR/M16795. 2001.

Digman, C. J. and Littlewood, K. Predicting Aesthetic Pollutant Loadings from Combined Sewer Overflows - Joint Steering Group Report December 2001, EPSRC Grant GR/M16795 and GR/M16719. 2002.

Digman, C. J., Spence, K. J., and Balmforth, D. J. Aesthetic Pollutant Loadings in Small Upstream Combined Sewerage Systems. 1, 219-226. 2001. Lyon, France. Novatech 2001 - Innovative Technologies in Urban Drainage.

Friedler,E., Brown,D.M., and Butler,D. (1996) A Study of WC Derived Sewer Solids. *Wat.Sci.Tech* Vol 33, No. 9.

Houldsworth, J. K. University of Sheffield Steering Group Report - June 1999, EPSRC Grant GR/M16337, 1999.

Houldsworth, J. K. University of Sheffield Steering Group Report - June 2000, EPSRC Grant GR/M16337, 2000.

Shaw,E.L. (1994) *Hydrology in Practice.*, Chapmann & Hall, London.

Schütze, M.; Butler, D.; Davies, J.W.; Jefferies, C. (2000): Modelling aesthetic pollution in sewer systems; First International Conference on Urban Drainage on the Internet; 18 26 May 2000

Schütze, M. (2001): Gross Solids Simulator GROSI, Short User Manual, Imperial College of Science, Technology and Medicine, January 2001

PREDICTING AESTHETIC POLLUTANT LOADINGS FROM COMBINED SEWER OVERFLOWS: FINAL REPORT (GR/M16719, GR/M16795 & GR/M16337)

Introduction

The majority of UK sewers are combined where stormwater and wastewater are conveyed together in the same pipe. This is especially true in the larger urban areas. Overflow structures are located at strategic locations within the network to prevent hydraulic overload of the system during wet weather, which might otherwise lead to local flooding, overloading at treatment works and pollutant discharges to receiving waters in wet weather. Pollutants may be in solution, in fine suspension, or larger solids, transported as bed load, suspended load or floating material. Larger gross solids of obvious sewage origin (defined in the consent standards as >6 mm in two dimensions), when discharged to receiving waters, frequently lead to complaints from the public. Such "aesthetic pollutants", consist largely of faecal matter, toilet tissue and feminine hygiene products. It has been shown that these types of solids are often difficult to retain at CSOs and this fact has stimulated substantial development in the design and upgrading of CSO chambers and screens. However, there was a significant lack of knowledge on the numbers, distribution and characteristics of these aesthetic pollutants, of how they move and transform through the system or how screened CSO chambers should be designed. There was also little knowledge on CSO (and screen) performance when time varying flow and aesthetic loadings were discharged into the chamber. This project was formulated to address these needs.

This Final Report summarises the scientific and technical achievements of a collaborative project between Imperial College (GR/M16719), Sheffield Hallam University (GR/M16795), the University of Sheffield, (GR/M16337) and Coventry University (GR/M16719). Some changes of personnel occurred during the project. Dr Manfred Schuetze left Imperial College after having developed the large sewer solids tracker. He was replaced by Dr Kim Littlewood (at no extra cost to the project) who worked on the integrated model GROSSim. Dr David Balmforth left Sheffield Hallam University and joined MWH. However, he remained an active participant, to the positive benefit of the project. Dr Kevin Spence from Sheffield Hallam provided valuable additional support. Committed and regular input into the project was supplied by UKWIR (Barry Thompson), Yorkshire Water (Denis Dring) and Scottish Water (John Cowan). The Environment Agency was also represented in the project.

The aim of the project was to develop a thorough understanding of the correlation of the production, transport and transformation of aesthetic solids in combined sewer systems during storm events, and to relate these to the physical properties of the catchment, the characteristics of the sewer network, and the socio-economic groupings of the population. It also aimed to apply that understanding to produce a predictive model of aesthetic pollutant loadings for use in the design of CSO's, to assess loadings to CSO screens and to screens at treatment works, and to estimate where sewer solids may deposit within the system. This was achieved by a balanced and co-ordinated research effort from the project partners, based on the study of three different catchments. Elements of the research on each catchment included questionnaire surveys, fieldwork, model development and application.

At the beginning of the project, three discrete catchments in Sheffield were identified with different economic, social and ethnic characteristics and classified as 'Low income', 'High Income' and 'Ethnic'. The catchments then formed the basis for study of the aesthetic pollutant inputs into the system determined both by social studies techniques and by physical monitoring.

1 Socio-economic solids input survey

The aim of the solids input survey was to characterise the differences in the numbers and types of gross solids that were input into the system for each of the socio-economic groups. Census data was used to identify the population details and a postal questionnaire was devised and distributed to a random sample of the population on each of the three catchments. The questionnaire enquired about the disposal of eight sanitary products (cotton bud sticks, cotton wool, nappies, condoms, tampons, applicators, sanitary towels and panty liners). For each product respondents were asked how many they 'flushed' and how many they 'binned' over a 28-day period. Relevant socio-economic data about the respondent (sex, age, ethnic group and household income) was also requested. In total, 468 responses were received, which represented a 62% response rate.

Table 1 Comparison of SEED factors for selected aesthetic pollutants

	Tampons		Sanitary Towels		Panty Liners	
Catchment Type	Field	Quest	Field	Quest	Field	Quest
Low Income	0.60	0.60	2.16	1.82	1.65	1.24
High Income	1.73	1.69	0.45	0.32	0.97	1.21
Ethnic Minority	0.68	0.71	0.39	0.86	0.39	0.55

Field = field sewer sampling, Quest = Questionnaire survey

Table 2 Panty liners age related SEED Factors

Age group	High Income	Low Income	Ethnic Minority
18-29	0.84	0.00	1.45
30-44	1.26	1.75	0.06
45-59	0.65	1.94	0.53
60-74	1.16	0.94	0.81
75+	0.00	0.00	0.00

The data collected was used to produce what has been termed the SEED (Social, Economic and Ethnic Day) factor. The SEED for each catchment was derived by analysing the relationship between the reported number of products flushed and the socio-economic factors of the respondent. It was defined as the ratio of the catchment 'flushing' mean to the overall 'flushing' mean. Table 1 shows that differences in flushing habit are evident. For example, tampon flushing is greater in the high income catchment (SEED factor = 1.69) when compared to the low income (0.60) and ethnic minority catchments (0.71). SEED allows a standard diurnal plot of solids to be scaled according to the socio-economic characteristics of the catchment.

This data highlights that social class and ethnicity appear to make a difference to the number and type of solids that are input into the sewer system. However, as this data is affected by the age distribution of the population in the catchment, age related SEED factors were also developed. The catchment mean flushing data was classified into the 5 age groups, with the mean for each catchment plotted against age, and all the data was used to estimate an 'all catchments' age related plot (see Figure 1). The bimodal results illustrate the use of panty liners for two purposes: menstruation in younger women and incontinence in women of older age. Age related SEED factors were established for each solid type with the factors for panty liners shown in Table 2.

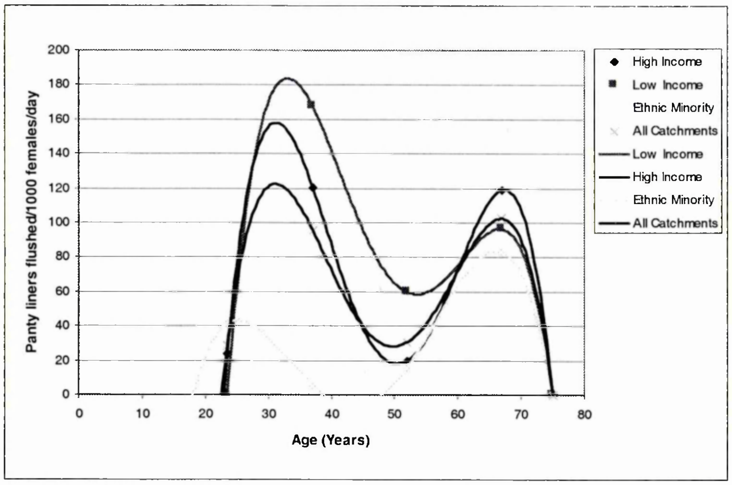

Figure 1: Panty liners flushed by age and catchment

Field monitoring

The field monitoring programme was designed to physically measure whether socio-economic and ethnic factors have a measurable effect on aesthetic pollutant loads in sewers. It was also used to determine whether catchment characteristics and/or sewer network configurations have a significant effect on the transport and temporal distribution of these pollutants.

HydroWorks^{TM} hydraulic models were developed for each catchment. These were fully verified, following industry-standard guidelines, using data derived from a local rain gauge and flow monitors upstream of solid sampling locations. Solids' sampling was achieved by manual collection and exchange of mesh sacks, which were inserted into specially devised blanking plates that direct all the flow through the mesh sacks. Three days of dry weather sampling data were collected at each sub-catchment. Over 30 storms were captured, resulting in 13 useable wet weather events. During dry weather, sacks were changed every 30 minutes to determine their diurnal distribution. During storm events, sacks were changed every 5 or 10 minutes. Following sampling, solids were returned to the laboratory for characterisation for all aesthetic pollutants. Typically, faeces represented 60% of the total mass, toilet tissue constituted 30%, with the remaining 10% including wipes, tampons, sanitary towels, panty liners and cotton bud sticks. This represents a database of exceptional quality and accuracy for use in the model development stage.

The solids data was transformed into a standard format (SSV, SPV & SEED). The Standard Solid Value (SSV), determined for each individual pollutant type, allows conversion between 'mass' (as measured) and 'number of pollutants' (as modelled). A Standard Production Value (SPV) for each solid per capita per day was also calculated. The field data was also used to evaluate SEED factors. As expected, differences between socio-economic groups were noted. For example, between 1.5 and 2 times more faeces and toilet tissue was measured in the low-income sub-catchments compared to the high income and ethnic catchments. The total number of solids produced in a particular type of catchment per day is the product of SEED, SPV and population. The ratio of solid numbers estimated from each questionnaire to measured solid was similar for all sanitary product types and was reflected in the catchment produced SEED values for each data collection method (See Table 1). However, analysis revealed that approximately twice the number of solids was collected in comparison to those measured in the questionnaire survey. The SEED factors were incorporated into *GROSSim* and are used, together with knowledge of the socio economic class and age profile in a particular catchment, to predict the distribution of solids that enters the sewer system in that catchment.

Small sewer solids model

The data was analysed to try and establish the importance of aesthetic solids deposition or storage in the small pipes, constituting the upper reaches of the network. A mass balance can be used to infer the quantity of solids in motion within the network at any particular time, assuming their input quantity and timing is known. During a storm event, the measured quantity of solids flushed from the system was greater than the calculated quantity of both the solids in motion and the additional solids that enter the system during the course of the storm event; the difference being the material stored over the preceding dry weather period (ADWP). The number of solids stored was analysed to try and establish the influence of different catchment characteristics. Regression analysis showed that a linear increase in the non-dimensionalised storage of solids occurred with *increase* in ADWP and housing density. However, incorporation of the average gradient of the sewers in each catchment did not improve the overall correlation with ADWP. Other factors that were investigated but did not improve the correlation included the percentage impermeable area, total sewer length, main sewer length, pipe diameter and pipe capacity.

Simple models were developed that enabled both the hydraulic and the solid behaviour to be predicted during dry and wet weather. Each upstream sub-catchment was represented by a single non-linear reservoir and a routing technique was applied that enabled the movement of solids to be linked to flow. This was driven by a dry weather flow diurnal profile[1], a solids input profile derived from previous work[2] and effective rainfall. The solids in motion, at any particular time, is calculated as the difference between the solids entering the system, using the product of SPV, SEED and population (modified by the Friedler profile[2]), and the solids stored in each time increment (using the relationships developed to predict the mass stored). During dry weather, a good fit between observed and modelled diurnal profile was achieved using a dilution method. This involved distributing the solids that enter and those in motion evenly throughout the reservoir at a particular time increment. The quantity of solids leaving was calculated from the known volume and concentration leaving the reservoir at each time step. The start of a storm event was defined from field observations, which indicated stored solids became mobile when the discharge reached 1.5 times the peak diurnal DWF value. After this time, a specific volume technique was used that 'shunted' discrete volumes of water and solids through the reservoir without any mixing. This method enabled the first foul flush effect to be replicated as observed during the measured storm events. The model has been found to well predict the rising limb, time to peak, peak magnitude and total quantity of solids flushed (See Figure 2).

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[1] Butler, D. & Graham, N.J.D. (1995) Modeling dry weather wastewater flow in sewer networks. *ASCE, Journal of Environmental Engineering Division*, 121, Feb, 161-173.

[2] Friedler, E., Brown, D., Butler, D. (1996) A study of WC derived sewer solids, *Wat. Sci. Tech.*, 33, 9, 17-24.

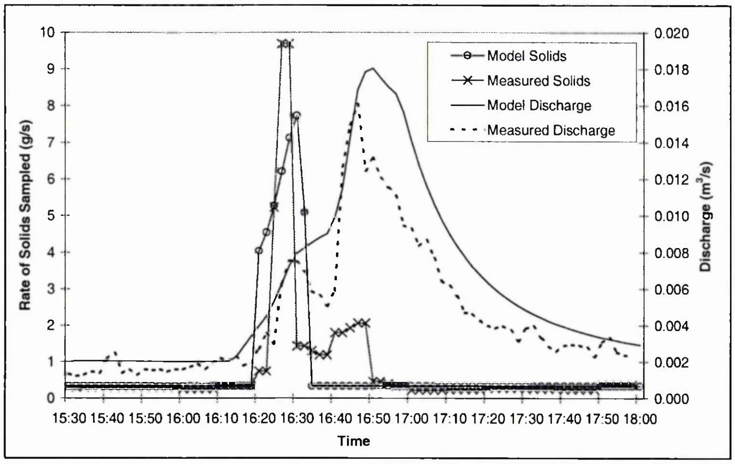

Figure 2: Comparison of measured and non-linear reservoir model results for low-income catchment

Large sewer solids model

The large sewer solids model tracks the progress of individual or groups of individual solids through the larger pipes (> 300 mm diameter). This was developed from an earlier model produced under EPSRC study (GR/K97004) and is valid when flow is mainly continuous. Only a brief description will be repeated here[3]. The model reads hydraulic data of depth and velocity at system nodes and this data is converted to solid velocity using a linear relationship between solid and water velocity.

The velocity of a solid at any position and time is thus known, and this is used progressively to track its movement through the system. If depth or velocity over any section decreases to the level specified as causing deposition for that solid, the progress of solids in the section is halted until this level is again exceeded. The model was calibrated mainly using laboratory data sets, but was subsequently verified in the field in a single, outfall sewer[4].

The model is capable of operating under dry and wet-weather conditions and produces as output: solids location vs. time plots, hydrographs and 'aesthetographs' and summary statistics of average transport and "waiting" times, and numbers of solids entering/leaving the system.

CSO Model

CSO performance was modelled using the FLUENT Computational Fluid Dynamics (CFD) software[5]. The model was applied to a chamber in which accurate flow-field

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[3] Davies J W, Butler D, and XU, Y L. (1996) Gross Solids Movement in Sewers-a Model Based on Laboratory Studies, *J.CIWEM*, 10, Feb.

[4] Davies J.W., Schluter W, Jefferies C and Butler D, Laboratory and field studies to support a model of gross solids transport in sewers. *Proc. 9th Intl. Conf. on Urban Storm Drainage, Portland, Oregon*, September, 2002.

5 Saul A J & Harwood R. Gross Solids Retention Efficiency of Hydrodynamic Separator CSO's. *Proc Instn Civ Engrs. Water Maritime and Energy*, 130, 2, 70-83, 1998.

measurements had been previously recorded in the laboratory[6] together with measurements of the efficiency of retention of large numbers of particles. Good agreement was observed between the experimental and simulated results[7] and hence the same methodology was applied to each of the CSO chambers in the three study catchments. Initially, the hydraulic performance of each chamber was simulated followed by an evaluation of the particle retention efficiency, estimated by recording the destination; either spill flow, continuation flow or trapped in the chamber of a statistically significant number of tracked particles for a series of flow conditions within the chamber. Particle terminal velocities for typical gross solids were established in the laboratory and a family of performance cusps was generated by plotting the retention efficiency against particle terminal velocity at a number of continuation flow to inflow ratios (see Figure 3). Near neutrally buoyant particles are associated with low chamber efficiencies, and efficiencies improve for increased terminal velocity particles (both rise and fall velocities). The resulting cusps were incorporated into *GROSSim*.

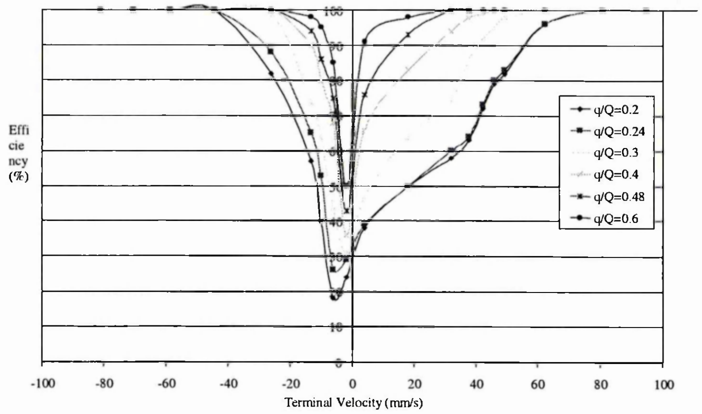

Figure 3 Efficiency cusps for the low-income site chamber

The Combined Model - GROSSim

Each of the elements described above (Socio-economic data, small sewer solids model, large sewer solids model and CSO model) have been integrated into the main deliverable from the project, the model *GROSSim*. This has been designed to automatically read sewer network and hydraulic output data files (*.dsd, *.hyq, *.hyv, *.hyd) for easy 'piggybacking' on industry standard software (*HydroWorks/InfoWorks*). It allows consideration of continuous inflows (dry and wet weather). The model has a user-friendly front end for easy data entry and model experimentation and produces output in a format that is easy to manipulate and plot. Default information is built into the program, based on data obtained in the study. The model is currently being trialled in practice, by MWH.

The output from *GROSSim* has been compared with measured flow and solids information, and good verification has been achieved, as indicated in Figure 4(a & b) for dry and wet weather conditions.

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[6] Stovin V R & Saul A J. A computational fluid dynamics (CFD) particle tracking approach to efficiency prediction. *Wat Sci Tech,* 37, 9, 285 – 29, 1998.

7 Harwood R and Saul A J. The influence of CSO chamber size on particle retention efficiency performance. *Proc 8ICUSD, Sydney,* August, 1999.

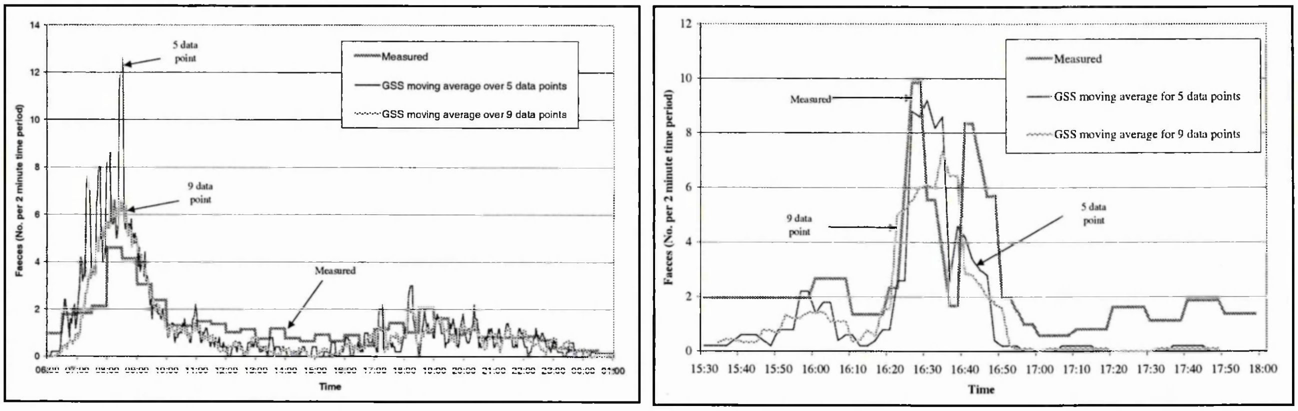

Figure 4 Comparison between field data and *GROSSim* output for faeces in (a) dry weather and (b) wet weather for at the low income catchment

The model has been used in several applications, particularly temporal and spatial. Firstly, the model has been run to produce time-varying plots (aesthetographs) of solids at particular locations such as CSOs. The model accurately replicates the first flush effect that occurs in some networks and catchments. As *GROSSim* incorporates efficiency cusps for the CSO chamber (and performance data for screen) both spill and continuation on aesthetographs are calculated. The overall efficiency, the distribution of the numbers and types of particles that are spilled over the weir and those that are discharged to the downstream sewer are also calculated. This latter use of the model will be particularly useful to screen manufacturers and designers in allowing realistic assessment of the solids load experience during storms. It will also help diagnose cases of screen failure. The same methodology and benefits also apply to screens at WWT Plants.

Secondly, for any particular catchment, it is able to track the position of solids throughout the system. This then enables a picture to be built up of not only the distribution of retention times of solids in the system but also those links where solids deposit for extended periods of time. This can be used as a diagnosis tool for sewers prone to blockage, in particular in analysing whether the cause of the problem is associated with low depths, low flows or some external factor. It can also facilitate maintenance scheduling and prioritisation.

Further areas to exploit in the model include assessment of the effects of socio – economic differences and demographic change within catchments. It is also possible to run 'what if' scenarios such as investigating the impact of 'Bag it and Bin it' campaigns. Better understanding of the quantity and temporal distribution of solids also opens up the possibility of using alternative solutions, such as storage control.

Conclusions

Through this project we have achieved the objectives and produced:

- a better understanding of the production of solids, especially in relation to the social, economic and ethnic make up of the catchment
- a better understanding of spatial and temporal variability of solids throughout the system (both in local and trunk sewers)
- a verified model of the movement of solids into, through and out of the total sewer network

- a methodology for applying the model and insights into its applicability in practice
- a total of 14 publication outputs (mainly conference papers) with a further 7 journal publications in preparation, submitted or in press.

The main deliverable is a user-friendly, holistic modelling tool that will assist the water industry in decision-making in the control of aesthetic pollutants.

A number of related studies are planned to extend this work and preparations are in hand to roll out the existing model on a commercial basis. Options under consideration include the formation of a joint spin-out company or a series of consultancy projects. The model is currently being assessed by MWH and a number of other companies have expressed an interest in using it.