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THE FIELD TESTING OF A VORTEX STORM SEWAGE OVERFLOW

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The Field Testing Of A Vortex Storm Sewage Overflow

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ABSTRACT

A full scale prototype of a vortex storm sewage overflow with peripheral spill has been build in Sheffield, its design being based on the results of model tests. The project described has been involved in monitoring this prototype with the aims of

i) Assessing its hydraulic performance,
ii) Assessing its ability to retain polluting material, particularly large 'gross solids' in the sewer,
iii) To compare its performance with predictions made by the model tests.

A review of previous work concerning storm overflows, the development of vortex overflows and sewer monitoring techniques was undertaken.

The overflow was monitored with flow measurement equipment, bottle samplers and equipment designed to count the numbers of gross solids in the sewage entering and spilling from the chamber. The latter worked by pumping large volumes of sewage through a transparent cell, where it was filmed by a video camera. Objects passing were counted by eye when the film was examined later.

The hydraulic monitoring showed that the overflow was effective at controlling flows in the sewage, and that mathematical and physical models predicted its performance.

Analysis of discrete samples collected using bottle samplers showed little difference between the fine suspended solids and the dissolved material in inlet or spill.

The results from measuring gross solids appeared to show that their concentration in the spill was less than that in the inflow by 20-40%. However insufficient storms were recorded to be sure to what extent the method of sampling affected the results.

The results from the gross solid monitoring bore some resemblance to the predictions made by the model tests using estimates of the nature of particles in the storm sewage. This suggested that model tests using synthetic gross solid particles could give a good indication of the performance of full scale overflows.

Field Testing a Vortex Storm Sewage Overflow

Contents

A List of Figures

A List of Tables

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Nomenclature

a - Vortex air core minimum diameter

b_1, b_2 - Coefficients relating flow to depth

C - Circulation in vortex chamber

C_d - Discharge coefficient

C_p, C_c, C_s - Concentration of particles per unit volume

d - Outlet orifice diameter

D - Equivalent diameter of inlet pipe

Dmin - Minimum diameter of upstream pipe

D_{in} - Head of sewage above inlet invert

$D_{in}(m)$ - Measured head above inlet

D_0 - Head at transition to spill

DWF - Dry Weather Flow

E - Energy head above floor of chamber

f - Fractional air core

F_1, F_2 - Parameters depending only upon fractional air core.

g - Acceleration due to gravity

G_1, G_2 - Parameters depending upon chamber geometry.

h - Head above weir

H - Weir crest height above orifice

I - Industrial discharge into sewer

J - Depth of scumboard lower edge below weir level

k_i, k_c, k_s - Flow coefficients for in, continuation & spill flow

L - Length of weir

N_{in}, N_c, N_s - Number of particles entering/retained/spilling per unit time

OC_x - Mean object count/minute for person x

P - Population of area

P_c - Proportion of particles retained in continuation flow

Q - Flow

Q_{in}, Q_c, Q_s - Inflow, Continuation flow, Spill flow

$Q_{in}(m)$, $Q_c(m)$, $Q_s(m)$ - Measured flows

Q_0 - Estimate of flow required to spill based on Q_{in} - Q_s graph.

Q_{max} - Design flow for sewer

QT - Estimate of total spill and continuation flows.

Q_t - Estimate of inflow as spill begins (from Q vs head graph)

r_1, r_2 - Minimum and maximum radii of spiral wall of Ackers & Crump's vortex chamber

R - Chamber radius

R_c, R_s - Coefficients relating continuation and spill flows to inflow

S - Depth of orifice below inlet invert

t - Depth of air core constriction below chamber floor

tl - Depth of air core constriction below inlet invert

t - Length of timestep

W - Width of inlet channel

V_s - Settling velocity

V_{in} - Mean fluid velocity at inlet

Y_0, Y_1 - Coefficients relating GSM count to flow.

Chapter 1 Introduction

1.1 Sewerage Systems

Sewerage systems are built to achieve a number of objectives;

- To transport household and industrial wastes to a central point for treatment,
- To drain surface rainwater runoff to prevent flooding,
- To safeguard nearby watercourses from pollution.

Three main types of system exist. These are the "separate system", in which separate sewers are used for foul sewage and surface runoff, the "combined system", in which surface runoff is channelled into the foul sewer, and the "partial system", in which some areas (usually rear roofs and gardens) are drained to the foul sewer while others are drained by a separate surface water system.

Surface runoff sewers usually discharge directly into the nearest water course, without treatment. Foul sewers carry wastes, which may be diluted by runoff (the mixture is called "storm sewage") to a sewage treatment works to be processed before discharge into a stream or river.

In a combined system, the channelling of rainwater into the sewers can cause a considerable increase in flow. Where sewers are unable to take all the flow some method of relieving the system of the excess must be included if flooding is to be avoided. A Storm Sewage Overflow is a structure designed to prevent too much storm sewage passing on downstream by allowing a proportion of the flow to spill to a nearby watercourse. Unfortunately this inevitably means polluting the receiving waters. (See below.)

The separate system avoids the problems of spilling diluted foul sewage, since the flow in the foul sewers will not be increased by rainfall. However there is no guarantee that the surface runoff will not itself be polluted by oil, grit or chemicals washed from roads and paved areas. Also it only requires a small number of foul sewers accidentally to be connected for the advantages in not having storm overflows to be lost.(1)

No strong case has yet been made for prefering one system in all situations, and the choice is usually dependent on local conditions.

The Technical Committee on Storm Overflows, in its final report (1970)[2], suggested that a partial system might be used, in which the only areas connected to the foul sewers be those likely to have heavily polluting runoff.

1.2 Storm Sewage Overflows

An ideal storm overflow has the following characteristics:

i) It should not come into operation until the prescribed flow is being passed to treatment,

ii) The flow to treatment should not increase further once the structure begins spilling,

iii) The maximum amount of polluting material should be passed to treatment.

Furthermore;

- It should be fully automatic in operation,
- The design should avoid any complications likely to lead to unreliable operation,
- The chamber should be self cleansing with the minimum risk of blockage,
- It should have the minimum maintainance requirements,
- It should have a minimum construction cost.

In practise an overflow should be designed for a lifespan in excess of 30 years. Care should thus be taken on the choice of materials used, especially when there are corrosive industrial wastes in the sewage. It is wise to include flow bypass arrangements in case maintainence is required. The Technical Committee recommended that throttles should have a cross sectional area of at least 36 square inches (225 sq.cm.) with a minimum dimension of 6 inches (15 cm) in any direction. Projections into the flow must be avoided, as they will tend to 'rag up'. Although it is preferable not to include power driven devices, if they must be used it is best to house the electrical gear in a separate kiosk or cabinet. Such equipment should be inspected and maintained regularly, as should the overflow itself. Access to the structure should be made as easy as possible, with appropriate provision made for safety. There should be good ventilation, provision for lighting and railings and safety chains where necessary.

1.3 A Brief History of the Sewerage System in Britain

Before the nineteenth century sewers were for surface water drainage only - it was a penal offence to discharge offensive matter into them.[(3)] Wastes were dealt with in midden heaps or pits, though some towns had a system of collecting excreta in pails which were taken to a central point for processing into fertilizer.

During the nineteenth century the water closet became more widely used. Early versions discharged into cesspools, but these were often too small or not emptied regularly enough. Overflows were added to let the excess spill into the surface water sewers. This was illegal, but the problems of urban sanitation were so great that it was accepted, and legalised in 1847. The following year the Public Health Act set up Boards of Health to construct special sewers for carrying wastes.

As a result of the Industrial Revolution and the introduction of factory systems, the population of the manufacturing towns rose dramatically in the early 1800's. Edwin Chadwick lead an enquiry into the conditions of the densely populated working-class areas, and discovered a deplorable situation with decaying refuse filling streets and yards, privies scarce and drinking water contaminated. He proposed introducing an 'Arterial System of Drainage', including provision of water supplies to each house, the discharge of domestic wastes into sewers which would convey them to a sewage farm outside the town.

Initially sewers had tended to follow the lines of the surface water channels that they had replaced, discharging sewage directly into the river. Interceptor sewers were built to convey sewage to a treatment point when the river pollution became intolerable.

To avoid flooding during heavy storms, and to avoid having to enlarge the interceptor sewers as the upstream network grew, excess flow was allowed to spill into the river either through the old outfalls, or through new outfalls built for the purpose. These were the first storm sewage overflows.

Over the years there have been a number of Royal Commissions and

Technical Committees set up to investigate the sewerage system and storm sewage overflows. These have highlighted the serious problems of deterioration of the existing sewers, and the large numbers of unsatisfactory overflows. Older designs exercised poor control over the flows through them, and were ineffective at preventing polluting material from spilling from the system. They which were causing much pollution to the recieving watercourses. The investigators have made various increasingly refined recommendations concerning overflows. Such structures should be used sparingly, and not spill so much that they 'cause a nuisance'. Initially it was suggested that they not begin to spill until the inflow rose above a setting of 6 multiples of the dry weather flow (DWF), with greater multiples to protect more sensitive watercourses. In 1970 'Formula A' was put forward :

$$\text{Setting } (Q) = DWF + 1360\,P + 2\,I \quad \text{litres/day}$$

P = population,

I = Industrial discharge (l/d).

In recent years the advent of computer models of sewer systems allow the effects of various types and settings of overflows on the system to be examined in detail. The volumes of storm sewage spilled during various rainfall events can be estimated, and it will soon be possible to predict the effect of the discharges on the watercourse. Design of new and replacement overflows should be such as to minimise the impact on such rivers and streams, taking into account the whole of the sewerage system and treatment works.

Thus the simple surface drainage system of two centuries ago has developed into a large and complex network of pipes designed to convey wastes from their point of origin to a central point for treatment. Through a combination of historical precedent and practical necessity overflow structures have been included to relieve the system of excess flows in times of heavy rain. The pollution problems created are now being addressed by improved sewer design using computer models, and research aimed at developing more efficient storm overflow structures.

1.4 Types of Storm Overflow

1.4.1 Introduction

The first overflows were just holes in manholes which allowed exess storm sewage to spill via a length of pipe,to the nearest stream or river if the level in the manhole rose too much (Fig.1.1).

Another simple form is the leaping weir (Fig.1.2). This can consist of little but a hole in the bottom of a pipe to allow sewage to drop down into a lower pipe and on to treatment. When the flow increases some of the storm sewage has enough momentum to reach the other side of the hole, and continue down the pipe to be discharged into a watercourse. There is a tendancy for the gap to become bridged by objects and solids in the flow, causing the device to spill even in dry weather.

Neither of these structures give much restriction on the flow passing on down the sewer, or are able to divert large quantities of flow. There is no attempt to restrain any types of pollutants from spilling, though the hole-in-manhole may reduce the amounts of grit and denser material discharged to the watercourse.

1.4.2 Low Side Weirs

When large proportions of flow were to be diverted, a low side weir was often used. (See Fig.1.3). Sewage flows along a channel, which may be tapered toward the outlet, bounded on one or both sides by a low weir. Dip plates or scumboards were usually provided in an attempt to restrain some of the floatables from escaping over the weir.

Low side weirs set up a longditudinal roller action which lifts solids over the weir, even at low flows. The inclusion of scumboards seems to have a detrimental effect at low flows, and little effect at higher ones. There is a tendancy for grit and suspended solids near the bed to become entrained in the up-current between weir and plates, causing them to be spilled.[2,7,8]

The device exercises poor hydraulic control, allowing continuation flow to increase significantly after first spill. In operation a steep drawdown is formed as flow accelerates along the chamber. The level above the weir and thus the flow over the weir declines rapidly along the length of the weir. Consequently a considerable proportion of the flow is channelled down to the continuation pipe. At higher flows a steeper drawdown occurs and a greater proportion of the flow continues downstream, rather limiting the structure's ability to restrict the continuation flow to a steady maximum. Its hydraulic performance tends to be further upset by rags and debris wedging at the downstream end of the scumboards.

1.4.3 High Sided Weirs

Of the two overflows recommended by the Technical Committee, one is the High Side Weir (Fig.1.4).

Designs include a (possibly tapered) channel, with single or double high side weirs, scumboards and a throttle on the outlet pipe. The throttle is to allow a steady continuation flow downstream. Such a structure exercises good hydraulic control, and methods are available to allow calculation of the weir length required for a given situation.

Recent work to optimise the chamber[9] gives designs using short "inlet lengths" to allow the flow to settle,and a small storage area between the end of the weir and the throttle,for floatables to gather in (Fig.1.5).

Oblique or End-weir overflows are similar to high side weir overflows except that spill occurs over a weir perpendicular to the channel, above the throttle at the end of the chamber.

Tests reveal that high sided weirs are effective at retaining gross solids and faeces.[7][8]

1.4.4 Stilling Pond Overflows

The second of the two overflows recommended by the Technical Committee is the Stilling Pond.(See Fig.1.6)

This aims to provide a tranquil zone before the weir to allow some settlement of the sewage. Dense particles sink and are entrained into the continuation flow. Floatables will rise to be trapped in the chamber by scumboards and reverse surface currents until the level in the chamber subsides and they can be passed on downstream.

To reduce the velocity of the fluid,the cross section of flow is increased. This is achieved by a combination of increasing width and depth, either with a fan shaped chamber or simply a rectangular one or even simply laying oversized pipes before a drop to a throttle pipe beneath a weir. A semi-circular dry weather flow channel has proved useful in entraining the heavier bed material in storm conditions.

The chamber was devised in 1959 by Sharpe and Kirkbride[14], who recommended dimensions. Further work by subsequent researchers using model tests indicates that the efficiency of the chamber can be increased by lengthening it. This reduces surface turbulence and the consequent re-entrainment of floating particles into the main flow. An 'economic' solution gives a length of 6-8 times the inlet pipe diameter.[15]

The structure gives good hydraulic control, and retains pollutants well. The extended version has a better solid separation performance than the high sided weir, though unlike the latter it requires the inlet sewer to be surcharged to some extent.

1.4.5 Storage Overflows

One effective way to reduce the frequency and volume of discharge from an overflow is to provide storage tanks, either on or off line. The first part of a storm tends to be the most polluting, an effect caused in part by the scouring of the sewers by the first wave of stormwater. This is known as the 'first foul flush'[10,11,12]. Storage overflows are used to retain this more polluted part of the flow. Should they not have enough capacity to retain all the storm sewage, the excess sewage arriving later in the storm will be allowed to spill to a watercourse. Off-line tanks are fed by an overflow structure in a sewer. Once filled further flows are diverted by the structure into the watercourse. When there is sufficient downstream capacity,the tanks are emptied back into the sewer, by pump or gravity.

A typical on-line storage tank overflow is shown in Fig.1.7. They may be simply oversized pipes to provide extra capacity, with a high sided weir upstream to spill excess storm sewage once the tank has filled.

Such structures have a variety of properties. They provide good hydraulic control in the form of a steady continuation flow. The runoff from small storms which would normally cause an overflow to spill will be retained and gradually passed on to treatment. (In one case it was calculated that over 80% of all such storms were restrained from spilling.[13]). The 'first foul flush', often the most polluting part of the storm, can be held in the chamber.[9][10][11] The fluid which does spill will have received a certain amount of treatment by settlement. During the delay of first spill caused by the tank, the flow of the river will increase as a result of the rainfall. Any pollutants discharged will thus receive a greater dilution than if they were spilled immediately.

Like the high sided weir they have good floating solids retention performance. However the inclusion of storage tanks in a system will cause a greater volume of more diluted sewage to arrive at the treatment works, which may produce problems there.[12]

1.4.6 Vortex Overflows

The first vortex overflow was developed by Smisson in the early 1960s[16]. This had a central spill weir (Fig 1.8). Tests suggest that the early designs have poor hydraulic control, and a tendancy to discharge gross solids and faeces over the weir, even when scumboards are included.

Later designs by the Tyneside Joint Sewerage Board for a device with a volute shaped chamber gave better hydraulic performance, but again were poor at retaining floating solids.

Some work was done by the US Enviromental Protection Agency on a 'Swirl Concentrator'[18], a large scale vortex type device with central spill (Fig.1.9). Although it achieved some degree of success it was not considered suitable for the UK, where the ratio of storm to foul sewage is greater. To achieve 'swirl' motion such a structure would have to be considerably larger than conventional UK overflows.

Smisson showed that when in vortex motion occurs in a cylindrical chamber the denser particles in the sewage will tend to settle toward the bottom and be drawn into the centre by secondary currents. The lighter ones will tend to rise to the surface in the middle of the chamber while suspended solids will form a central cone in the chamber.

Fewest solids accumulate at the top of the chamber, around the periphery.

To exploit this an overflow with a spill weir on the circumference of a circular chamber was developed at Sheffield City Polytechnic.[24-29] Flow enters tangentially and the continuation flow passes out through a central orifice in the chamber floor. (Fig.2.4). Balmforth and Lea worked on models to optimise the design, to produce a structure with both good hydraulic control and good performance in separating solids. This generates a forced vortex in the flow, which appears to be more effective at separating solids than the free vortex used in the Swirl Concentrator devices and Smisson's designs.

A prototype Vortex Overflow with Peripheral Spill based on these models was built in Sheffield, and this project was set up in order to study how well it performed.

1.5 Project Aims

The aims of the project were

i) To assess the hydraulic performance of the overflow. (This involved monitoring the flows into and out of the overflow and to estimate the flow required for the chamber to begin spilling)

ii) To assess the effect of the overflow on the quality of the spilling storm sewage (by taking samples of inflow and spill flow to compare the two)

iii) To compare the measured results, both hydraulic and qualitative, with predictions from tests using models of vortex overflows by Balmforth and Lea.

In addition it was hoped to build a computer model of the upstream catchment to estimate flows, and perhaps use the data collected to examine the performance of sewer flow quality computer models.

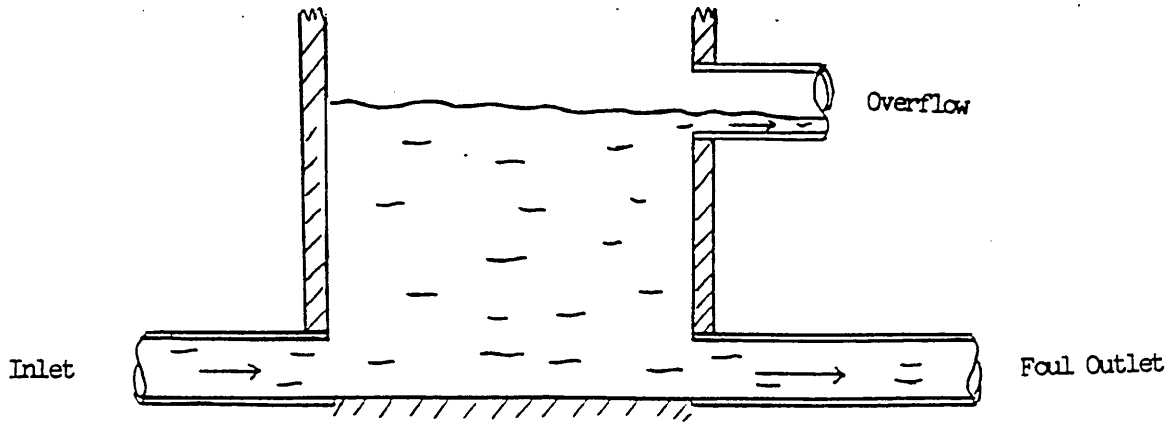


Fig.1.1 Hole in Manhole type overflow.

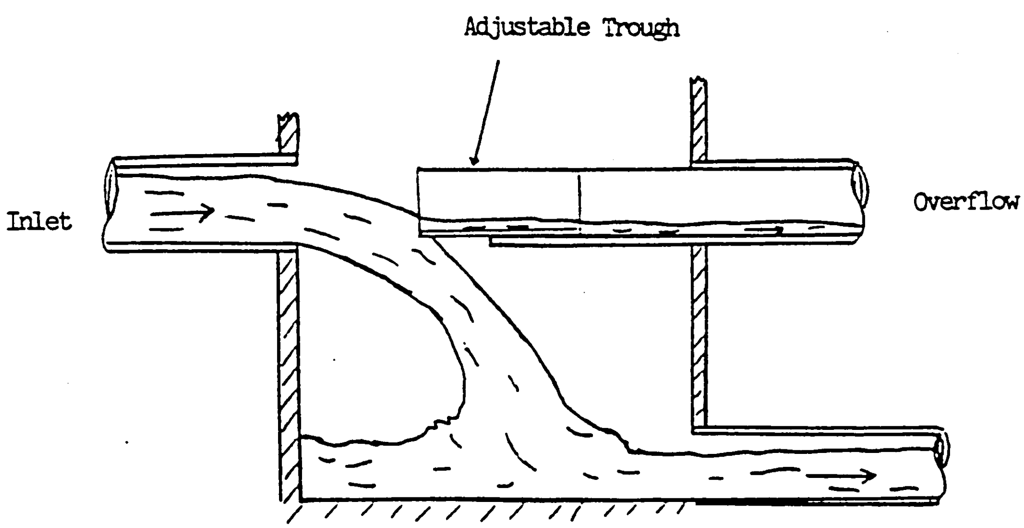
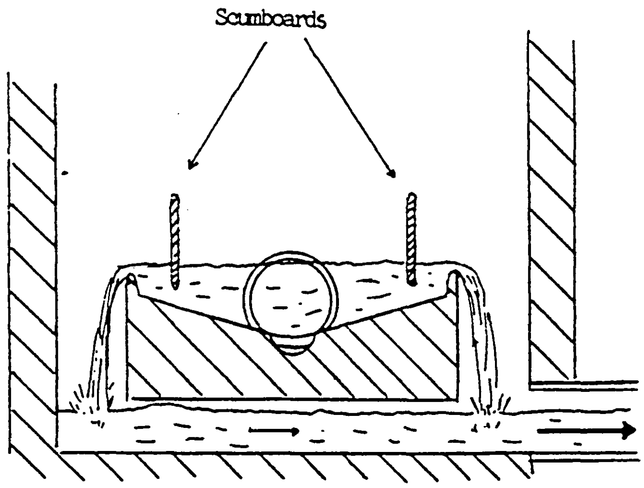


Fig.1.2 Leaping Weir overflow.



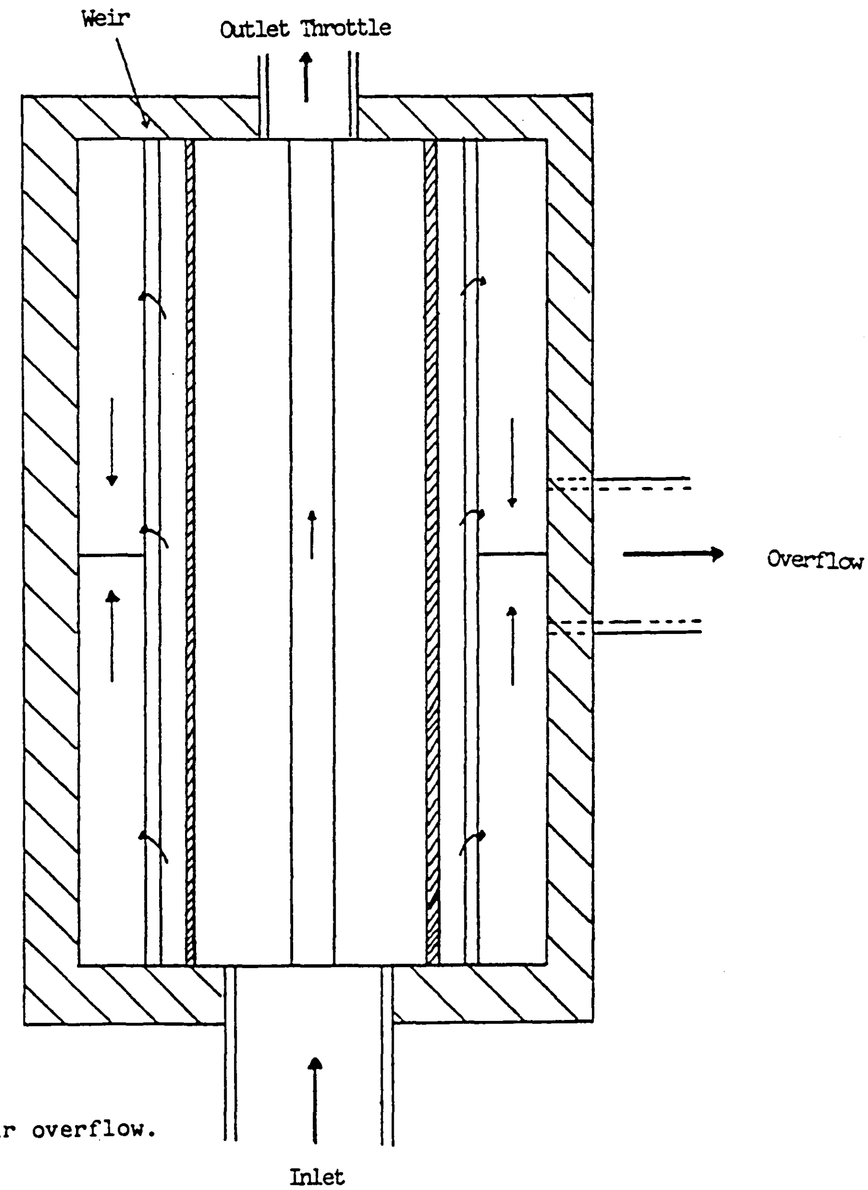


Fig.1.3 Low Side Weir overflow.

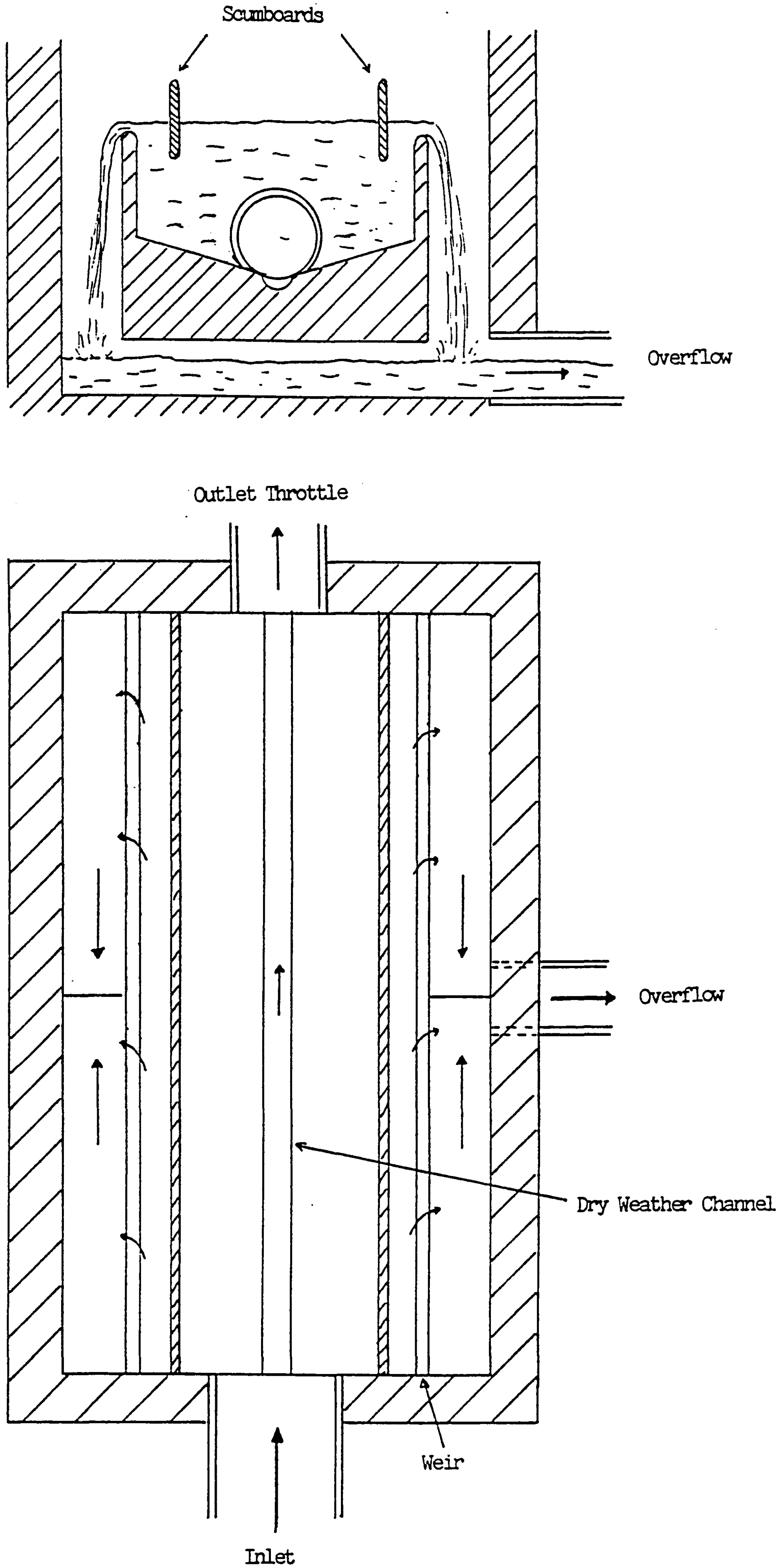


Fig.1.4 Early High Side Weir Overflow

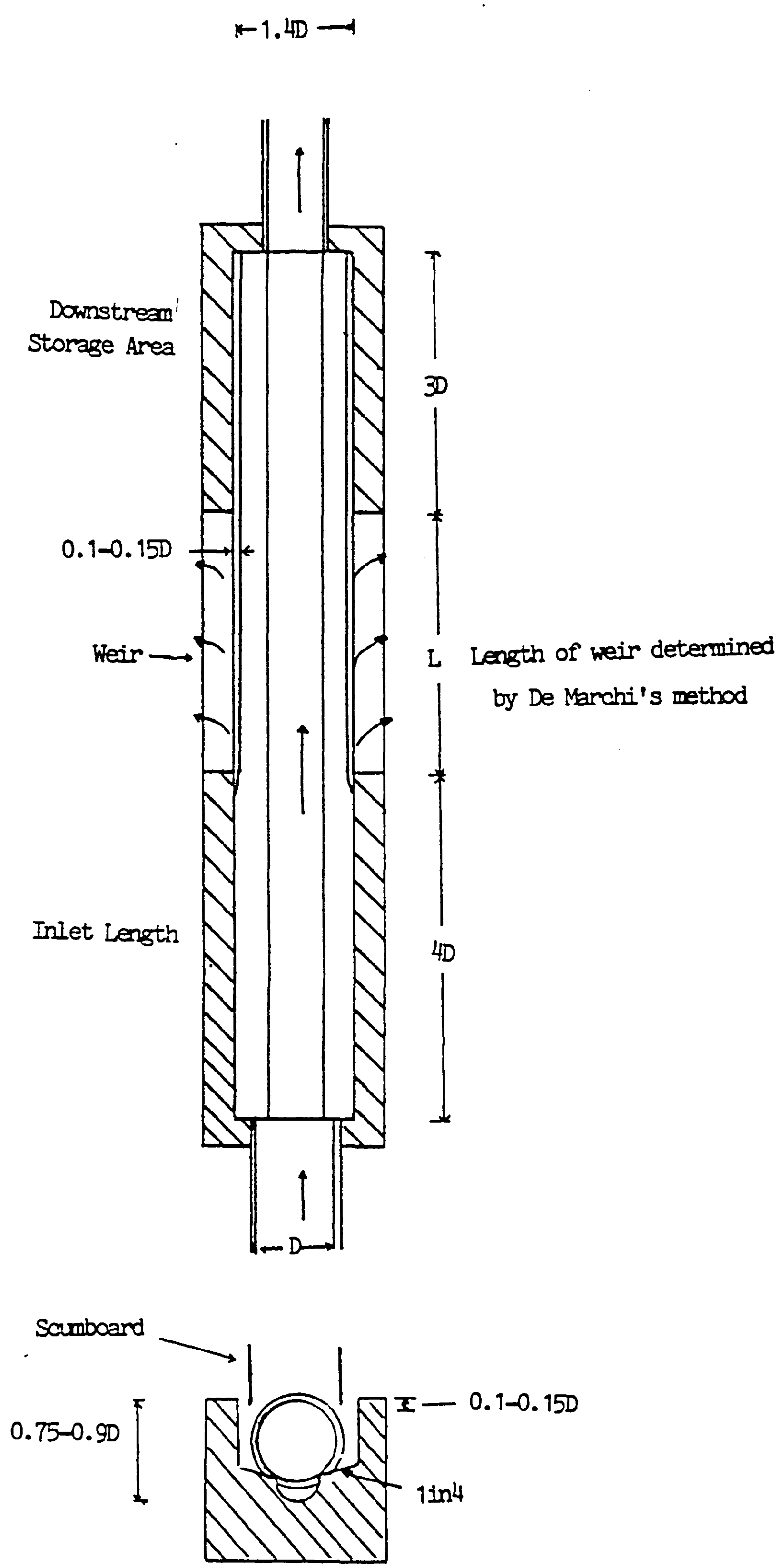
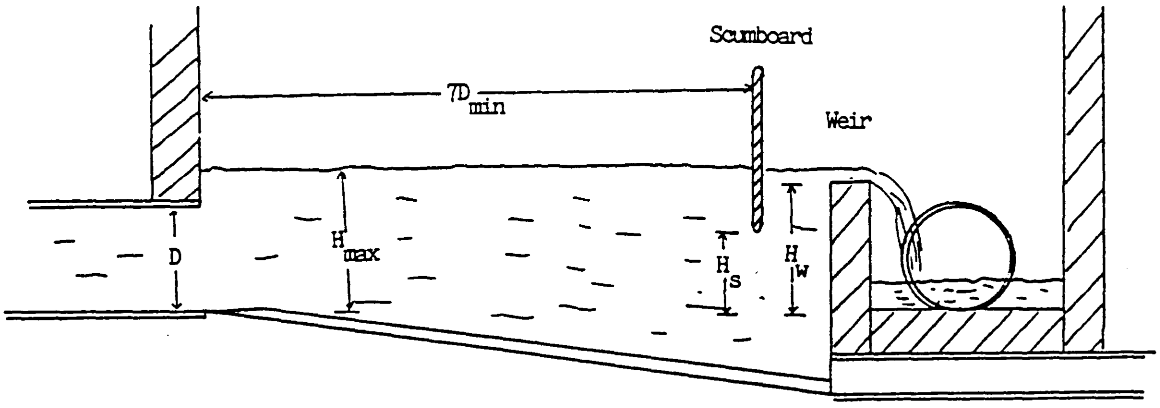


Fig.1.5 Saul & Delo's Modified High Side Weir Overflow



$H_w = WD$	$D_{min} = KQ^{0.4}$	$H_{max} = CD_{min}$	$H_s = SD$
W	K	C	S
0.90	0.848	1.60	0.50
1.00	0.828	1.70	0.60
1.20	0.815	1.85	0.80

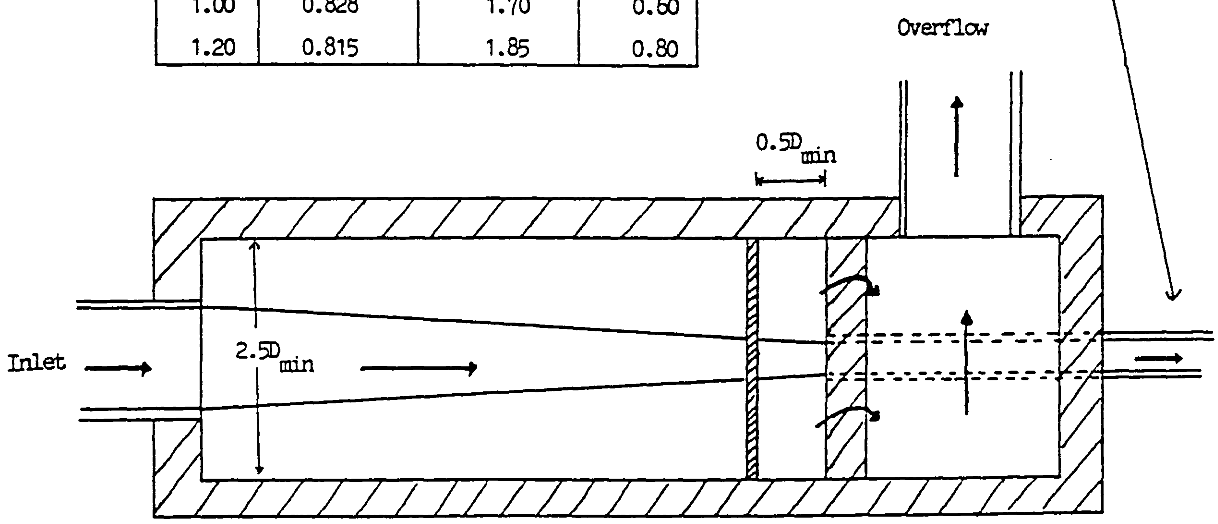
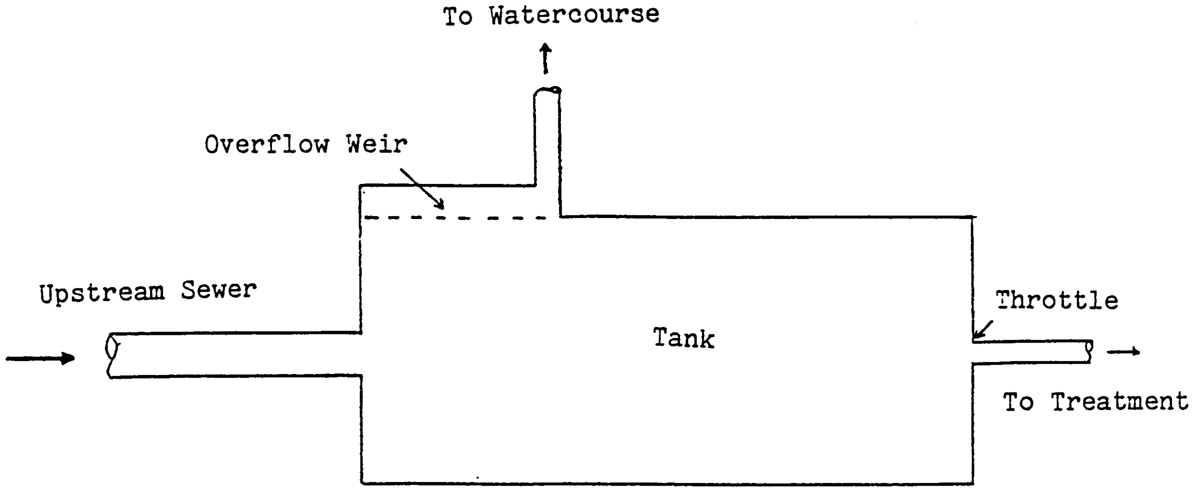
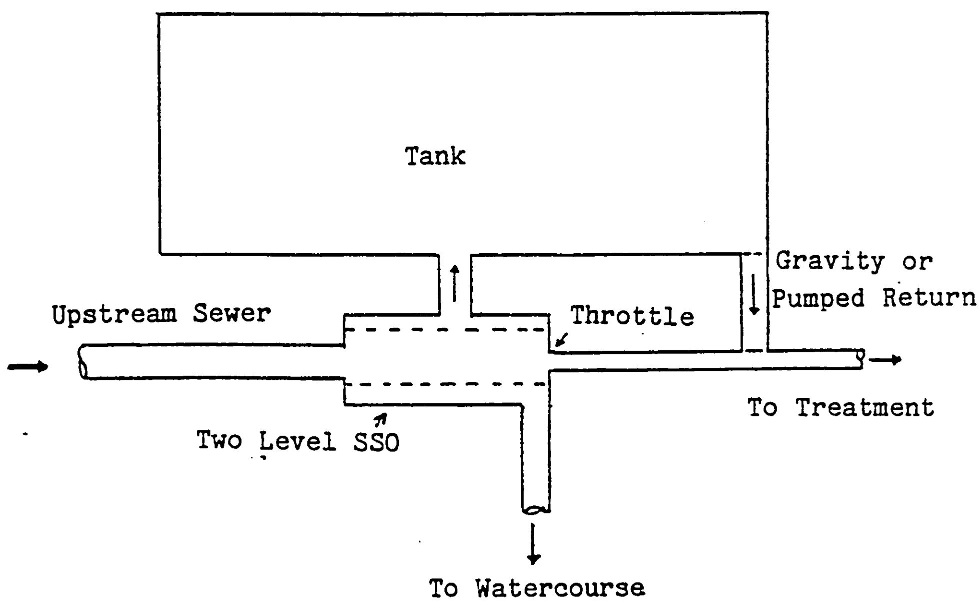


Fig.1.6 Stilling Pond Overflow.



(a) On-Line Tank



(b) Off-Line Tank

Fig.1.7 On-Line and Off-Line Tanks

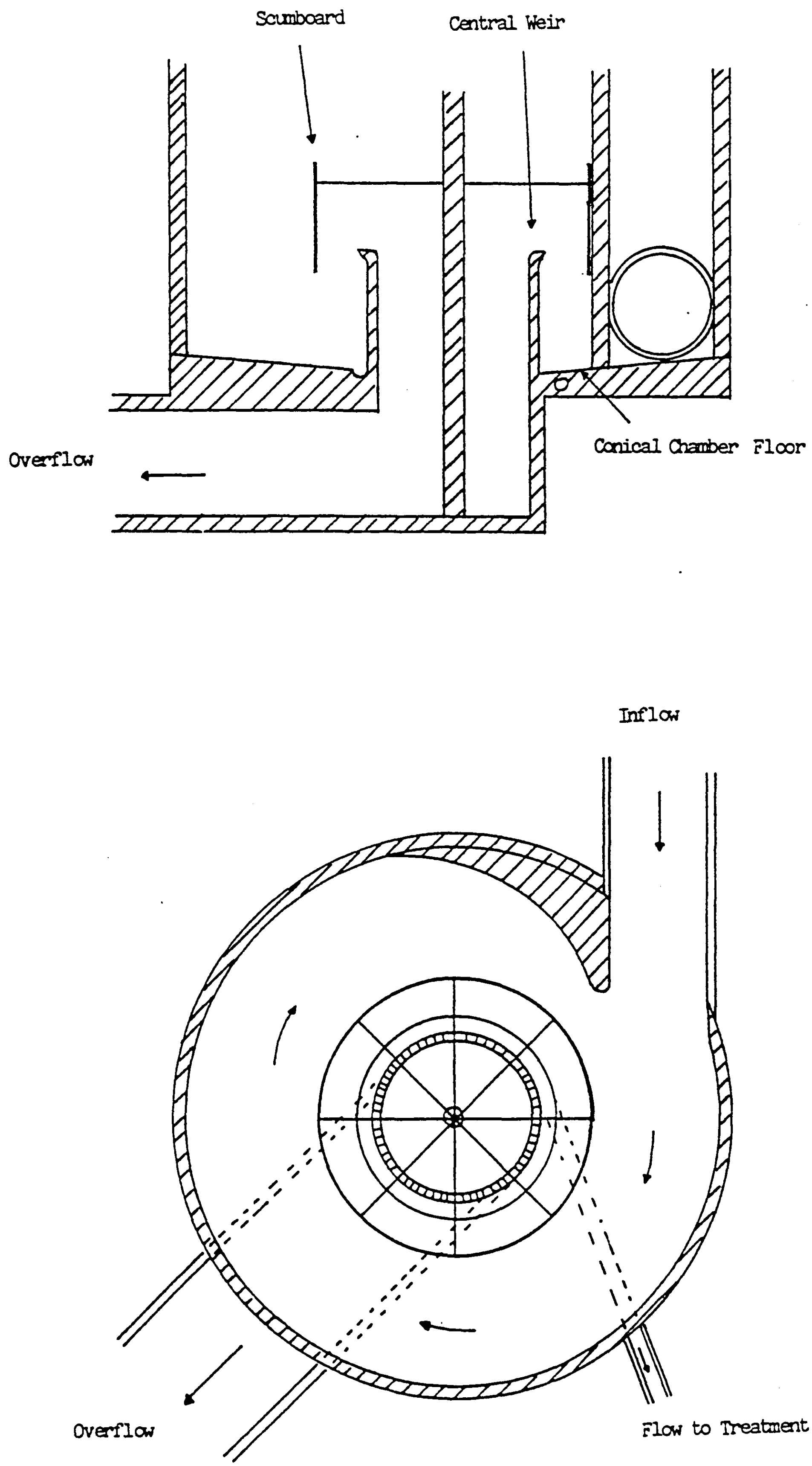


Fig. 1.8 Central Spill Vortex Overflow.

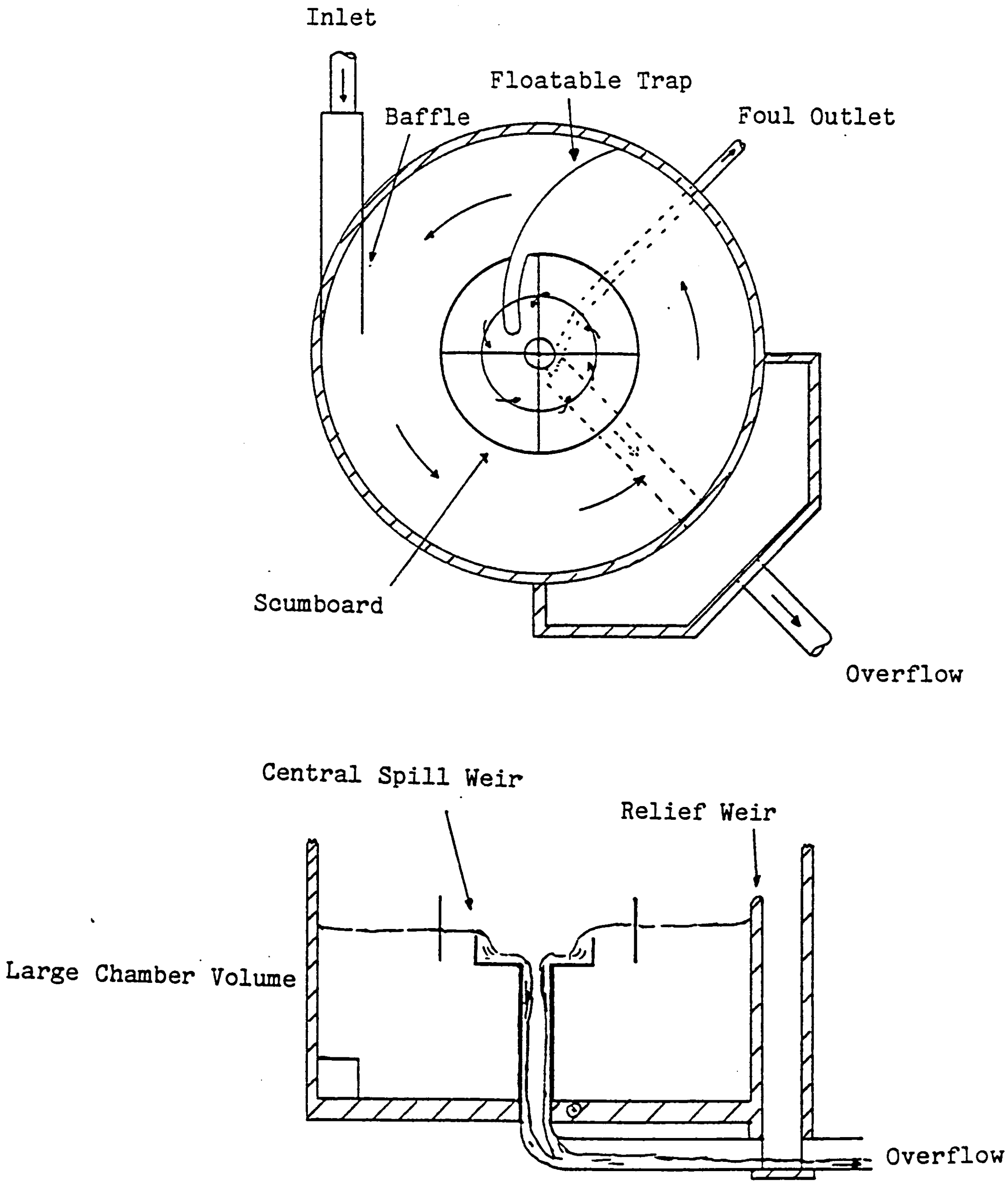


Fig.1.9 Swirl Concentrator/Regulator

Chapter 2 Review of Previous Work

2.1 Previous Work on Vortex Overflows

2.1.1 Introduction

Work has been going on to design and improve storm sewage overflows using vortex flow both to separate the sewage and to exercise a degree of hydraulic control. Early work concentrated upon central spill overflow structures, but research showed it was better to either close the top of the overflow and take the spill from a hole on the roof, or to have a peripheral weir.

2.1.2 "The Vortex Drop" by Ackers and Crump [23]

When designing a vortex overflow it is important to understand the hydraulic properties of the vortex. Ackers and Crump derived head - discharge relationships which have been used in many subsequent works.

They considered how a drop shaft with its inlet in the form of a vortex chamber could be used for transferring fluid flowing in an open channel to a lower level.

By combining the hydraulic properties of a free vortex with the Bernoulli Equation, and applying the principle of maximum discharge, they obtained a relationship between head and discharge (See Fig.2.1)

The equations they derived are;

fractional air core, $f = a^2/d^2$

d = diameter of orifice

a = minimum air core diameter

$F_1 = f^2 /(4(1+f))$

$F_2 = 0.25\ (1/f -1)(2(1-f))^{0.5}$

F_1 and F_2 are parameters depending solely on the fractional air core.

$G_1 = \log_e (r_2/r_1)$

$$G_2 = \frac{d^2}{r_2^2} \left(\frac{r_2^2}{r_1^2} - 1 \right)$$

r_1 and r_2 are the minimum and maximum radii of the spiral wall of the vortex chamber.

G_1 and G_2 are geometric properties depending only on the relative radii of the structural elements.

$$\frac{E}{d} [G_1 - F_1 G_2] = F_2 + (t/_d) F_1 G_2 \qquad \text{(Equation 2.1)}$$

E = Total energy relative to chamber floor.

t = Depth below floor of point of maximum constriction of air core.

$$\frac{C^2}{gd^3} = 4F_1 (E + t)/_d \qquad \text{(Equation 2.2)}$$

C = Circulation in chamber

$$\frac{Q}{g^{1/2} d^{5/2}} = F_2 (4F_1 (E+t)/d)^{0.5} \qquad \text{(Equation 2.3)}$$

Q = Flow into chamber,

g = Acceleration due to gravity.

For a variety of values of the fractional air core, f, the head and discharge are calculated to obtain the discharge-head relationship.

This is shown to be almost linear, which means that the velocity in the inlet channel will vary little for a wide range of discharge. This is important in sewerage applications, since it promotes self cleansing. Sediment would be kept entrained, and the air core would ensure removal of floating scum.

They suggest it could be of use as a control on the foul outlet of a storm sewage overflow because of its ability to deal with both floating and sinking solids.

2.1.3 Smisson's work on Vortex Overflows with Central Spill[16]

Smisson envisaged using rotary motion in a tank to constrain the entering sewage to a long spiral path so as to allow a maximum time for settlement of particles.

Experiments suggested a cylindrical chamber with an inlet tangential to the circumference, a central overflow weir and a foul outlet in the floor below the weir (Fig.1.8). In dry weather flow operation the sewage would circulate round the chamber and out of the foul outlet. In storm conditions the chamber filled till it began spilling over the central weir. The solids content of the continuation flow was many times that which could be accounted for by settlement alone. This was caused by secondary currents sweeping the solids near the floor into the foul outlet.

Many models were built and tested to develop the optimum design, using a variety of types of overflow weir (all centrally positioned) and dip plates. The dip plates were to retain floating solids in the chamber until the flow drops and they are entrained by the foul flow. Sewage particles were simulated with hardwood sawdust and perspex filings in the flow. Vertical plates were included in an attempt to control the swirling waves which tended to form round the weir.

Two full scale devices, 18 feet (6 m), in diameter were built in Bristol. Samples were taken during a storm which caused the chamber to spill. They were taken every 5 minutes from foul outlet and overflow, mascerated and analysed. The concentration of solids in the foul flow was found to be about 15 times that in the spilled flow. Further results gave separating efficiencies of between 35% (for high flows) and 70% (for low flows). Unfortunately the device had a tendancy to spill floatables which even fairly complicated arrangements of dip plates and vertical plates fail to properly repress.

2.1.4 Work on Vortex Overflows at the Hydraulics Research Station

The Hydraulics Research Station undertook a series of tests on full scale storm overflow structures, including a central spill vortex based on Smisson's design. They used crude sewage, and showed that although the vortex overflow provided reasonably satisfactory hydraulic control, it was poor at preventing gross solids from spilling. They pointed out that certain modifications and a size increase may improve this.

The Hydraulics Research Station also briefly investigated a vortex overflow with a peripheral spill weir. The chamber tested was spiral in plan, with a tangential inlet. The foul outlet was located slightly off centre in the floor, and the overflow took place over all of the peripheral wall.

Tests showed that the bed load passed down the foul outlet, and surface material spilled over the weir. It was felt that a scumboard would not improve this situation.

Vortex designs could produce good hydraulic control, and were effective at retaining sinking material, which is concentrated in the centre by secondary currents sweeping inward along the floor. However different approaches were needed to deal with the floating pollutants. Smisson's design could be improved by enlarging it to slow down the flow (the 'Swirl Concentrator' - Section 2.1.5) or by taking the spill through a central hole in the roof of a closed chamber as both Smisson (Section 2.1.6) and Brombach (Section 2.1.7) have done. Alternatively the spill can be taken from a peripheral weir whose length is not so great as to seriously disturb the vortex formed in the chamber. The last is the approach taken at Sheffield City Polytechnic (Sections 2.1.8,9).

2.1.5 The Swirl Concentrator[17,18]

Smisson's overflow was taken as the basis for the design of a "Swirl Concentrator/Regulator" with the aim of using it as a primary settlement tank by the Enviromental Protection Agency in the USA. The programme began by attempting to design the optimum scumboard configuration. This had only limited success since improvements achieved in floatables retention were accompanied by deterioration in settleable solids separation, caused by re-entrainment from the chamber floor into eddies created by the scumboard.

Further work was done to optimise the chamber geometry, enlarging it to slow the flow into a gentle 'swirl' motion. In addition baffles, spoilers and floatable traps were designed.

Monitoring of a full scale prototype suggested that the structure was effective at concentrating solids into the foul continuation flow. It required less space than other primary settling methods available for the low flow rates which occur in the USA. However its effectiveness for use as a storm sewage overflow in the UK is less certain. It is larger and more complicated, and thus more expensive, than comparable storm overflow types used here, and cannot cope with the higher ratios of storm to continuation flow.

2.1.6 Work at Hydro Research and Development

Smisson did some work on a closed top vortex overflow. This consisted of a cylinder with a conical base to aid the transport of solids to the outlet at the bottom. The excess flow is taken from the centre of the top of the tank. The device only separates sinkable solids, floatables were to be removed by a separate weir arrangement. Further work was done on the device at Hydro Research and Development, to produce the 'Storm King' Hydro-Dynamic Separator'[20,21] (Fig.2.2), a prefabricated steel overflow designed to deal with both sinking and floating material. The effect of the chamber geometry is to generate two concentric zones of helical flow meeting at a shear zone which extends from the bottom of the cone up to the dip-plate. The outer helix descends at the perimeter wall and ascends at the shear zone. The inner helix moves up over the surface of the cone, and down at the shear zone. The inner helix is less energetic, allowing the finer particles to settle. The settled material is swept out by the outflow current. There are several projects currently underway to monitor Storm Kings in operation, looking at various aspects of their performance [19,20,21,22]. These have shown that the device concentrates suspended solids and BOD content in the continuation flow and is capable of preventing the discharge of floating material and larger particulates to a receiving stream.

2.1.7 Brombach's Vortex Separator[30]

In an attempt to fill the technical gap between storm overflows and storm overflow tanks, Brombach began to develop a vortex separator. He worked with laboratory models, using plastic particles as a substitute for gross solids, though only sinkable material was modelled.

The resultant design is shown in Fig.2.3, and is similar to Smisson's closed top devices and the Hydro-Dynamic Separator.

It is cylindrical with a tangential inlet, and of greater diameter than height. The outflow is limited by a vortex throttle downstream of the separator.

Overflowed liquid leaves the chamber via an annulus in the top, between a circular scumboard and "guiding screen". It runs round a circular channel on top of the chamber, and away to the outfall.

The scumboard is to prevent floating material escaping out of the top of the chamber. The material in the core, which has been entrained upwards by secondary currents, is restrained from spilling by the guiding screen.

Separating efficiencies were calculated for the various settling velocities of the particles used in experiments and results used to predict the performance of a full scale device. In one example, for a 4m diameter structure, 60% of the polluting matter was being carried on to treatment by the 6.3% of the inflow which didn't spill. To produce comparable results a stilling basin would have to have 3 - 4 times the volume.

The behaviour of floatable material was not studied in the model tests. Preliminary results from full scale prototypes suggest they are not spilled in large quantities.

Brombach has since done further work developing his vortex separator, calling it the 'Fluidsep'[41,42].

2.1.8 Pisano's Work in the USA

Pisano et al have been working with swirl concentrators and the 'Fluidsep' developed by Brombach. The latter are being used in a number of projects in the United States[40,41,42]. They suggest several different configurations in which the Fluidsep can be used, both off and on line. The choice of the most appropriate design of overflow for a given site will depend (amongst other things) on the nature of the sewage (the settling velocity distribution of its particulate matter) and the flow rates expected.

The settling velocity distributions have been assessed from samples taken in a number of ways. Material from grit chambers was gathered, the skin coat of organic material from overflows was collected and mixed with water and large samples of storm sewage were taken. Settling column experiments were used to assess the distributions. Distributions are available for a number of sites and standard "Basis of Design" curves are given.

In one project a Fluidsep was to be used to treat the wet-weather diversion flows at the inlet to a treatment plant. The underflow from the separator was to be returned to be treated, the overspill discharged to a nearby lake. The settling velocity distribution of the storm sewage was assessed by taking samples of first flush from a number of storms. When this was combined with the performance curves of the Fluidsep (based on model tests) estimates could be made of the net percentage suspended solids removal for different diameters of vortex at different flow rates. These were used to choose the final design.

2.1.9 Early work at Sheffield City Polytechnic

A series of model tests were undertaken at Sheffield City Polytechnic in the late 1970's.(24,25,26) Studies on models of vortex overflows with central spill eventually led to the conclusion that the tendancy to spill floatables could not be remedied by arrangements of scumboards, and the problem lay in the design of the chamber itself. Consequently two vortex overflows with peripheral weirs were tested. These showed promise, and it was recommended that further investigations be undertaken to study the effects of varying chamber dimensions.

2.1.10 Balmforth and Lea's work on the Vortex Storm Overflow with Peripheral Spill(27,28,29)

After previous work indicated that taking the spill from a peripheral weir may lead to an effective storm sewage overflow, Balmforth and Lea used hydraulic models to further develop the idea.

They conducted a comprehensive testing program in an attempt to formulate a general hydraulic analysis of flow and determine the optimum chamber geometry and scaling ratios. (See Fig.2.4)

They made a theoretical analysis of flow in two parts, one dealing with the free vortex situation before first spill, the other covering the forced vortex regime at high flows. The theory developed for the former (based on Ackers and Crump's work) only proved accurate to within about 20%, with the theory tending to overestimate by about 10%.

An analysis of flow after first spill was done by combining forced vortex theory with simple side weir equations. A relationship was derived between discharge and water level above the weir crest at the upstream end of the weir.

Results of experiments were used to simplify the resulting equation to

$$Q = 2/3\ (2g)^{1/2}\ C_D\ L\ 17/15\ \left(\frac{1 - h}{H} \right) h^{3/2}$$

where h = Head above weir at upstream end,

H = Weir crest height above orifice,

L = Weir length,

C_D = Discharge coefficient.

A number of changes and improvements to the basic chamber were made.

To deal with two jets which tended to form at the inlet he added a sloping floor and spiral scumboard which directed the flow toward the air core and foul outlet. The sloping floor also promoted self cleansing during periods of dry weather and when emptying.

The inclusion of an inlet channel allowed some settling of the sewage particles before entry into the main chamber. Heavier particles sink and are carried to the foul outlet by currents near the floor. Floatables rise and are directed toward the air core by the scumboard. Particles with a high rise velocity tend to reach the surface in the inlet channel and become trapped there by reverse currents until the level sinks below the weir. If the channel surface becomes full, any further floating solids are directed to the air core and down by the scumboard.

The best separating performance was found to be given by a weir occupying 90 degrees of arc as shown in Fig.2.4, although better hydraulic control was given by a 180 degree weir.

As a result of his work, Lea was able to recommend relative dimensions for an optimum design.

- The inlet pipe diameter, D, is fixed by the upstream sewer size and design discharge.
- The inlet channel width = 1.1 D
- The inlet channel length should be at least 1.25 D.
- The foul outlet diameter, d, should be set using a theoretical analysis for first spill. Typically d/D = 0.18 - 0.29
- The weir should be 90 degrees in the fourth quadrant.
- The scumboard should be spiral, and should be set at a depth,J, which provides approximately equal separation to both rising and falling particles. J/H = 0.25
- The width of the inlet gap to the scumboard should be 1.1 D at the weir.

(See also Appendix A - Design Method)

The hydraulic control of such a device was found to be very good, with little increase in continuation flow after first spill for a wide range of overflow discharge (Fig.2.5). There was a reduction in separating efficiency at high flow rates.

Comparison with results from the Sharpe and Kirkbride Stilling Pond Overflow indicate that the vortex was better at dealing with all but quickly rising particles (Fig.2.6), and gave a marginal improvement of the hydraulic characteristics.

Such an overflow lends itself well to construction in a circular shaft (Fig.3.3) and so will useful in sites with bad ground or deep sewers. However a significant drop in invert of the continuation sewer is required, so the structure may not be suitable for areas with mild gradients.

Balmforth[38] combined settling velocity distributions published by the Scottish Working Party on Storm Sewage[1,40] with model test results for High Side Weirs, Stilling Ponds and the Vortex with Peripheral Spill in order to compare their overall separating efficiency for various inflows, spill flows and inlet pipe diameters. In all cases the Vortex gave the highest efficiencies, though Balmforth comments that there is no single best overflow structure for all situations. The choice of design should be based on individual site conditions.

2.2 Previous Work on Sewer Monitoring

2.2.1 Introduction

Programmes of sewer monitoring have occured almost since sewers were first introduced. In the mid-1800's John Roe, who introduced the egg-shaped sewer, made a series of observations of depth and flow velocity measured every 5 minutes. These he used to prepare a table of sewer sizes.[3]

Since then many more sewers have been studied, for a variety of reasons. Day to day monitoring occurs at treatment works and pumping stations, to ensure their efficient operation. Projects have been undertaken to examine such things as the first foul flush effect, the types of sewage conveyed in a system and the effects of rainfall inputs on it. However equipment has only rarely been set up at storm overflows to examine how well they perform or to measure how much pollution they spill.

Techniques used for these tasks have become increasingly sophisticated over the years, and now can involve considerable computerisation.

A literature survey of the subject was undertaken to study methods used by others. This brought to light the numerous problems which can occur, and suggested some solutions.

A review of some of the more relevant papers is presented below, followed by a summary of the techniques used and problems which have occured.

2.2.2 Field Studies on the Flow and Composition of Storm Sewage [32]

R.N.Davidson A.L.H.Gameson

Studies were made of the quality and quantity of storm sewage in three drainage systems over two to three years. Two of the systems were monitored at double sided low side weir storm overflows.

The flow was measured using stilling chambers and measuring flumes, or calculated from depth measurements after calibration by salt-velocity and salt dilution methods.

An automatic sampler which lowered a scoop into the sewage and delivered the contents to a bottle was used at each site. They were triggered by the increase in flow or depth at the beginning of a storm, and took samples every 5 minutes for the first hour, and every hour till the flows subsided.

Since the samplers were designed to avoid choking by large or stringy solids, some manual samples were taken to gauge how representative the results were. No significant differences were found between manual and automatic samples except that the manual ones contained on average 15% more suspended matter.

Flow results allowed analysis of effects of different overflow settings. It was noted that the low side weirs gave poor hydraulic control, and more efficiently designed structures could reduce the amount spilled by 50 - 65% and still restrict the flow to treatment to acceptable quantities.

The sampler results allowed studies on the dry weather and storm sewage composition, though results tended not to be consistent.

The storm sewage tended to be weakest during the night and its strength decreased with time during the storm.

2.2.3 Storm Overflow Performance Studies Using Crude Sewage[7]

(Ackers,Brewer,Birkbeck & Gameson)

The authors built four full sized storm overflow structures in an empty tank at Luton Sewage Works. They arranged to connect these to a trunk sewer so they could examine their performance in dealing with real sewage in simulated storm conditions.

The structures were
i) A low sided weir,
ii) A high sided weir,
iii) A stilling pond,
iv) A central spill vortex.

The designs used were typical of structures in use at the time. The authors recognised they were not necessarily the best possible configurations.

They examined the hydraulic performance of each of these, measuring

i) Discharge to treatment at first spill,

ii) Discharge to treatment and spill at higher flows,

iii) Water levels in the chambers for these discharges.

The tests were done both with and without scumboards.

Flow to treatment and spilled sewage passed through 0.25 inch screens and into separate tanks, from which samples were taken. The moisture content of the screenings and their dry weight was calculated after each run. It was noticed that some solids were being broken up in the overflow, and by the screens themselves, affecting the results.

The mean percentage difference between pairs of samples from the same source was 8.5% overall, with 3% for ammoniacal nitrogen and 17% for BOD. With none of the structures was there a significant difference between screened sewage passed to treatment and that spilled.

The low weir had poor hydraulic performance and little effect on screenable solids.

The stilling pond tended to discharge faeces over the overflow while paper continued on to treatment. Results indicated that the ratio of screenable solids concentration in the spilled sewage to that in the flow to treatment was between 0.7 and 0.9 .

The central spill vortex tended to spill faeces even with a scumboard, and was not especially effective overall.

The high sided weir with scumboards gave a concentration ratio of 0.5, and was undoubtable the best of the four.

Although the majority of biochemical pollution comes from material which will pass through the screens used in the experiments, it is the screenable material which causes most of the visible pollution and aesthetically offensive conditions.

2.2.4 Guidelines from the Working Party on Storm Sewage (Scotland)[1,40]

As part of their investigations the Working Party oversaw a number of field projects. They considered standardisation, wherever possible, to be necessary wherever meaningful comparisons were to be drawn from the work. Consequently they gave guidance in their report on a number of operations including use of equipment, sampling, monitoring, methods of analysis and data processing.

Automatic equipment was thought to be essential to continuously record certain hydraulic parameters, such as rainfall, flows in sewers, depths in tanks and to take samples of sewage for later laboratory analysis. They suggest a variety of devices to achieve these ends (though some of the equipment has inevitable been superseded by more advanced technology in the intervening years). They also documented past problems and the solutions implimented.

Samplers were required to be robust, portable, easy to install, not subject to corrosion, easily serviced, not susceptable to blockages and able to draw representative samples which should be accurate over a wide range of concentrations of suspended solids.

One problem reported was the occurence of unrepresentative sampling due to the small bore of the sample tube used. The use of manual samples to measure the discrepancy was again suggested. In another case difficulties were caused by a sampler having a long sample cycle caused by the high suction lifts involved in its operation. It was receiving trigger pulses considerably more rapidly than it could take samples. This was in part dealt with by increasing the pumping rates feeding the sampler.

The Working Party recognised a problem in the variable lengths of time for which samples are kept before analysis. They undertook a study to investigate the effect of storage time on the chemical and physical composition of samples. They discovered that 5 day BOD fell off with storage time, but not in any predictable manner, even at a specific site. After 24 hours the 5 day BOD varied between 50 - 100% of its original value. Immediate refrigeration could prove effective in preserving BOD, but this is rarely feasable. Freezing samples is even better, but still does not give completely predictable results.

They concluded that results obtained for 5 day BOD and suspended solids from samples more than 24 hours old could be gravely inaccurate. They recommended that any samples not analysed within 36 hours be disregarded.

The report also describes the method used to obtain the terminal velocity distributions of particulate matter in storm sewage. This can be used to calculate the overall efficiency of an overflow if it is known how well the device retains particles of a given terminal velocity. (Model tests could reveal this).

A report produced for the Working Party[39] describes experiments aimed at assessing the settling velocity distribution of particles in sewage. It describes how samples of sewage were taken at regular intervals with a metal bucket, and how they were analysed. To separate the floating material from the sinking the samples were poured into a 800mm long, 115mm diameter plastic tube with valves at either end and a flap valve in the centre. It was left to stand vertically for at least an hour, after which time the central flap valve was closed dividing the sample in half, the upper half containing the floaters, the lower the sinkers.

The settling velocity distribution was then examined using another tube, 1800mm long, 50mm in diameter, with three valves, one at either end and one 300mm from one end. It stood vertically, fixed at a central pivot so it could be inverted. To examine the sinking material the tube was stood with the double valve end at the top. The sample was poured in and the tube topped up with clean water. The top end valve was closed, and when all the material had sunk to the bottom, the tube was inverted. After 10 seconds the valve 300mm from the bottom was closed, trapping all the material falling more than 1500mm in 10 secs, all that with settling velocities greater than 150mm/s. The bottom valve was then opened to release the subsample, the particulate matter of which was found by filtering, drying and weighing. The tube was topped up with clean water and the process repeated with intervals of 20, 40, 80 and 180 seconds between inversion and closing the valve. The material still unsettled was filtered and weighed. A similar technique was used for the floating material.

The samples taken were predominantly from the dry weather flow. The report gives graphs of the settling velocity distributions obtained for the two sites studied. About 75% of the material sank, and between 23-33% of the material rose or sank faster than 70mm/s.

2.2.5 Studies of two On-Line Storage Chambers[10,11,12,13]

(Thornton,Saul,Pearson & Howard)

Monitoring stations were set up at a pair of high sided weir storage overflows, with a view to monitoring their performance and effects on the local stream, to which they spilled.

Inflow and overflow rates were measured by swingmeters, which had been calibrated by flow survey equipment. The water level in the chambers was measured by ultrasonic level transducer.

Data was recorded on dataloggers or enviromental computers. Rainfall data was collected by tipping bucket raingauges suitably placed about the catchment.

Samples were taken from the overflow and inflow by portable discrete samplers, triggered by float switches or swingmeters, and programmed to take samples every 10 minutes during storms.

The water level of the receiving stream was also monitored, and samples were taken during overflow events by automatic sampler. The latter could be triggered by the computer at the overflow, or by a rise in level of the stream.

The information gathered was used for a variety of purposes. They examined the hydraulic performance of the tanks, assessing how well they reduced the volume spilled and the frequency of overflow, and by how long the first spill was delayed. This was done by comparing results with those that would have been obtained for a theoretical overflow set to Formula A. In one case 63% of storms which would have caused such a theoretical overflow to spill were retained without discharge to the watercourse, in the other 80% were.

It found that the maximum recorded SS and COD concentrations in the first flush are related to the length of the antecedent dry weather period, the quality of the dry weather flow and the maximum rainfall intensity. They went on to study the first foul flush in greater detail, and suggest a partition of storms into types A or B depending on whether levels of SS and COD concentrations are lower or higher than in the dry weather flow respectively.

It was hypothesised that type A flushes are the result of the mixing of dry weather sewage and runoff at the front of the flood wave, whereas type B flushes involve the flood wave washing down deposits built up in the sewer over the preceding days.

Some of the techniques used to monitor the Vortex Overflow are based upon those used by the above authors.

2.2.6 Sewer Flow Monitoring(34,35)

One area where considerable experience has been gained in the Water Industry is that of sewer flow monitoring. The objectives of this can be to establish basic information and trends, to discover deficiencies in the system or to verify the operation of a computer model of the system. Basic information is usually gathered during long term projects, continuously monitoring over a number of years. This will include measuring base flows, pump capacities and overflow settings. When the problems in a system are to be discovered programmes lasting several months are instigated, in which local gauges may be installed and details on incidents of flooding gathered.

In cases where a sewer model has been developed on a computer, using WASSP or similar programmes, it is important that it gives reliable predictions if it is to be used to assess the most appropriate work to be done on a system.

When rehabilitation work is to be undertaken on a system it is common to build a computer model of the sewers in order to assess the impact of proposed work, or to choose the most appropriate project. It is clearly important that the model gives a reliable prediction of the way a network responds to rainfall. To verify how well a model works, short term monitoring takes place, over a period of 5 or more weeks usually.

Monitoring can take a number of forms, but often includes flow survey equipment installed in manholes, or at suitable points in a system. The equipment usually consists of a small sensor head fixed at the base of the sewer by means of an expandable hoop (Fig.2.7). The sensor head contains a pressure transducer to measure depth, and an ultrasonic transmitter and receiver. Sound of a known frequency is emmitted from the transmitter and bounces off particles in the flow. By measuring the doppler shift of the reflected signal it is possible to estimate the velocity of the flow. The sensor head is connected to a computer logging device, usually fitted in the manhole within reach of the surface, which calculates the depth and velocity, recording the information at preset intervals in its memory. The data can be retrieved by a suitable computer. Regular visits are made to the equipment to maintain it, to extract the data recorded, and to make calibration measurements with hand held devices. Computations can be made using the data and calibration checks to find the flow in the sewer at any time. The equipment is usually set to record slowly (perhaps once every 10-60 minutes) until the level rises above a given level, indicating a rainfall event. The recording rate is then increased (30 seconds to a few minutes) until the level falls again. This allows more detailed analysis of the response of the system to storms.

It is recommended[35] that the number of raingauges used for a survey be 1 per 2 - 4 km^2 + 1 or 2. A failure rate of about 20% has been experienced with raingauges, so it is wise to have some backup.

Common failures in flow monitoring are battery failures,poor connections, human error, contamination of the instruments by dirt or dust, distortion of data by poor hydraulic conditions and interference by the public. Raingauges tend to be very prone to the latter unless carefully placed.

Models can be further verified using historical data, including prediction of known instances of flooding. Spot checks of levels and flows, and examination of "tide" marks in the sewer can improve confidence in a model. An acceptable model will predict the locations of known instances of surcharge and flooding, will give a predicted runoff volume of +25% to -10% of measured volume, will predict peak flows to between +20% and -10% of measured values, and will predict surcharge levels to between +0.5m and - 0.1m of the measured levels. Overprediction is more acceptable than underprediction since this will give a margin of error in subsequent sewer rehabilitation.

2.2.7 Summary of techniques and problems.

The research described above and in other works[31] involves a variety of different methods to monitor flows and collect samples.

2.2.7.1 Flow Measurement

The following methods have been used to measure flows in sewers;

- Constant rate of injection dilution technique.
- Calibrated depth sensors/swingmeters.
- Flow survey equipment.
- Measuring flumes.
- Dry weather flow can be calculated from depth-discharge curves and checked against water consumption and sewage volume arriving at treatment works.

Problems which may occur;

- Depth discharge curves are not necessarily accurate, and can be hard to obtain.
- Build ups of deposits can cause incorrect readings of flow and depth.
- Flow survey equipment can be unreliable, particularly at shallow depths.
- Poor hydraulic conditions can lead to distorted data.

2.2.7.2 Sampling

- Automatic samplers:
  - can be scoop or suction,
  - the sample rate can be either time based or flow proportional,
  - representivity can be checked by manual sampling,
  - can be triggered by level switches,swingmeters or clocks.
- samples should be refrigerated when stored.
- It is recommended that results for BOD and SS from samples stored more than 36 hours should be ignored.
- Gross solids have been collected in wire baskets or trapped by screens.
- Equipment should be regularly maintained.

Problems which may occur;

- It can be difficult to obtain representative samples.
- Sampler intakes tend to become clogged with matter in the flow.

- Pump and motor failures hamper projects.
- The sampler may be triggered before it has completed the previous cycle.
- Gross solids may be broken up by overflows and pass through screens.

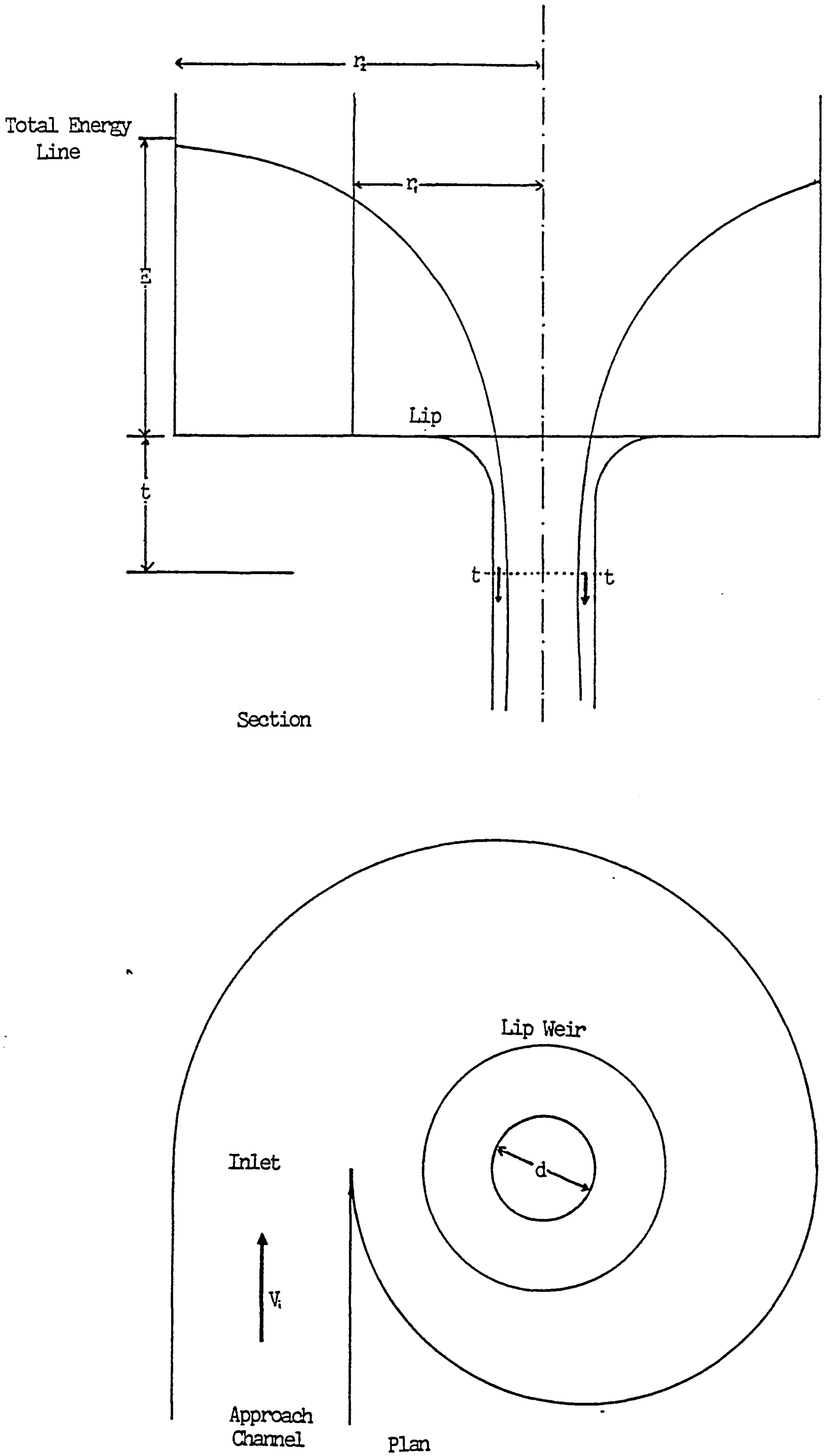


Fig.2.1 Ackers & Crumps Theoretical Vortex Chamber

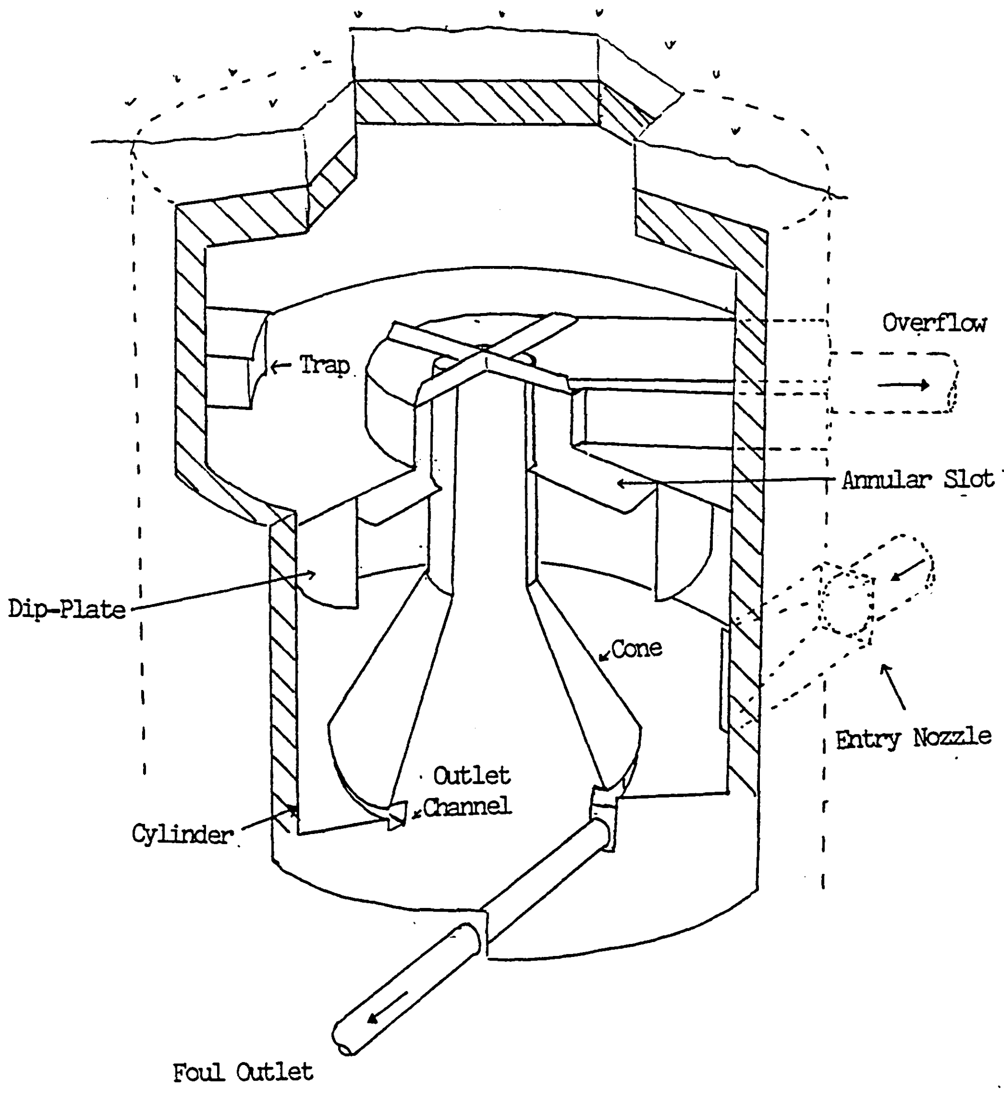


Fig.2.2 Dynamic Separator for Combined Sewage Overflows
(Hydro Research and Development Ltd)

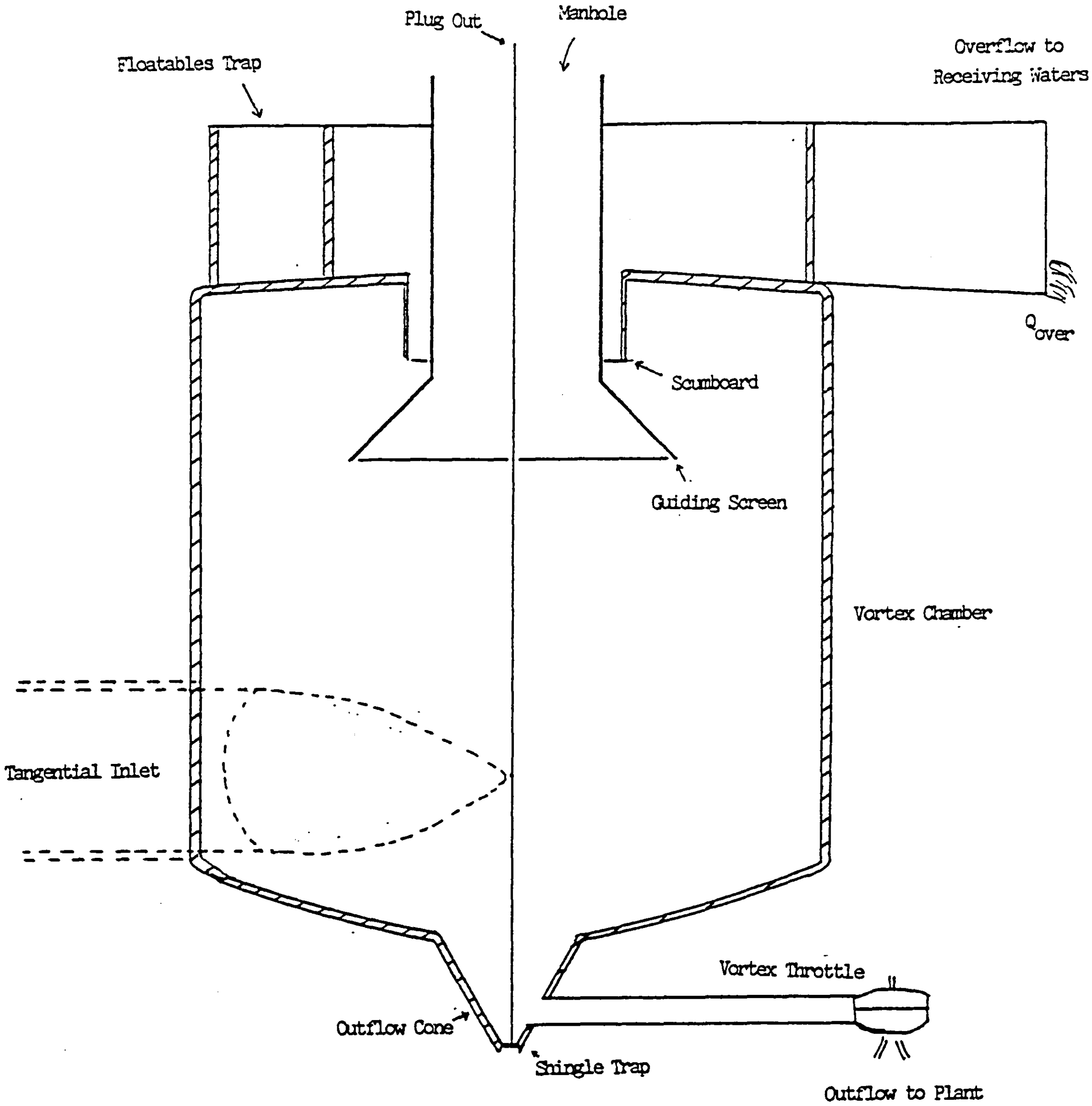


Fig.2.3 Brombach's Vortex Separator

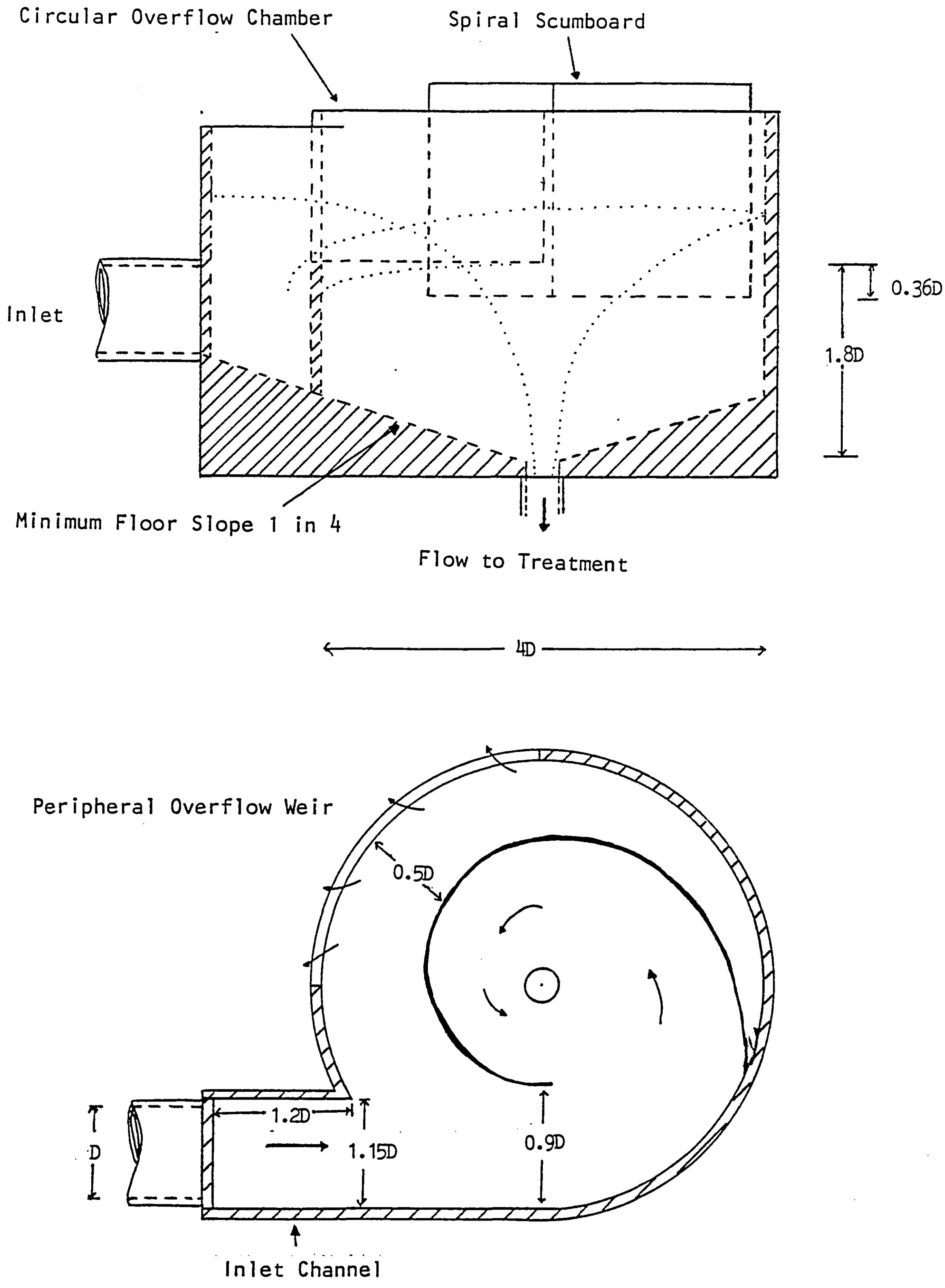


Fig.2.4 Vortex Storm Sewage Overflow With Peripheral Spill

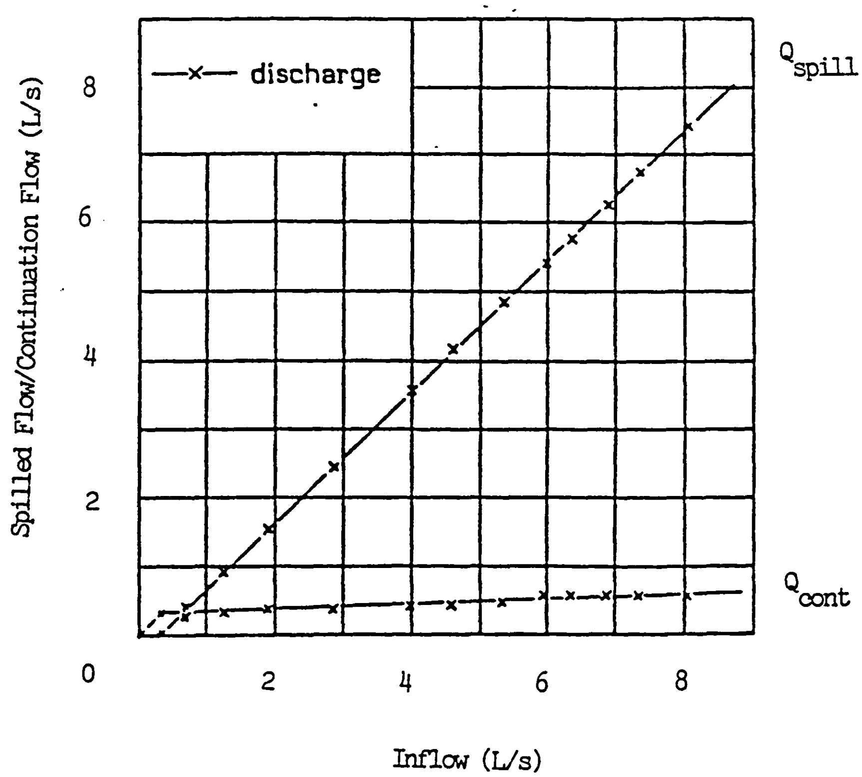


Fig.2.5 The Hydraulic Performance of a Model Vortex Storm Sewage Overflow with Peripheral Spill[26]

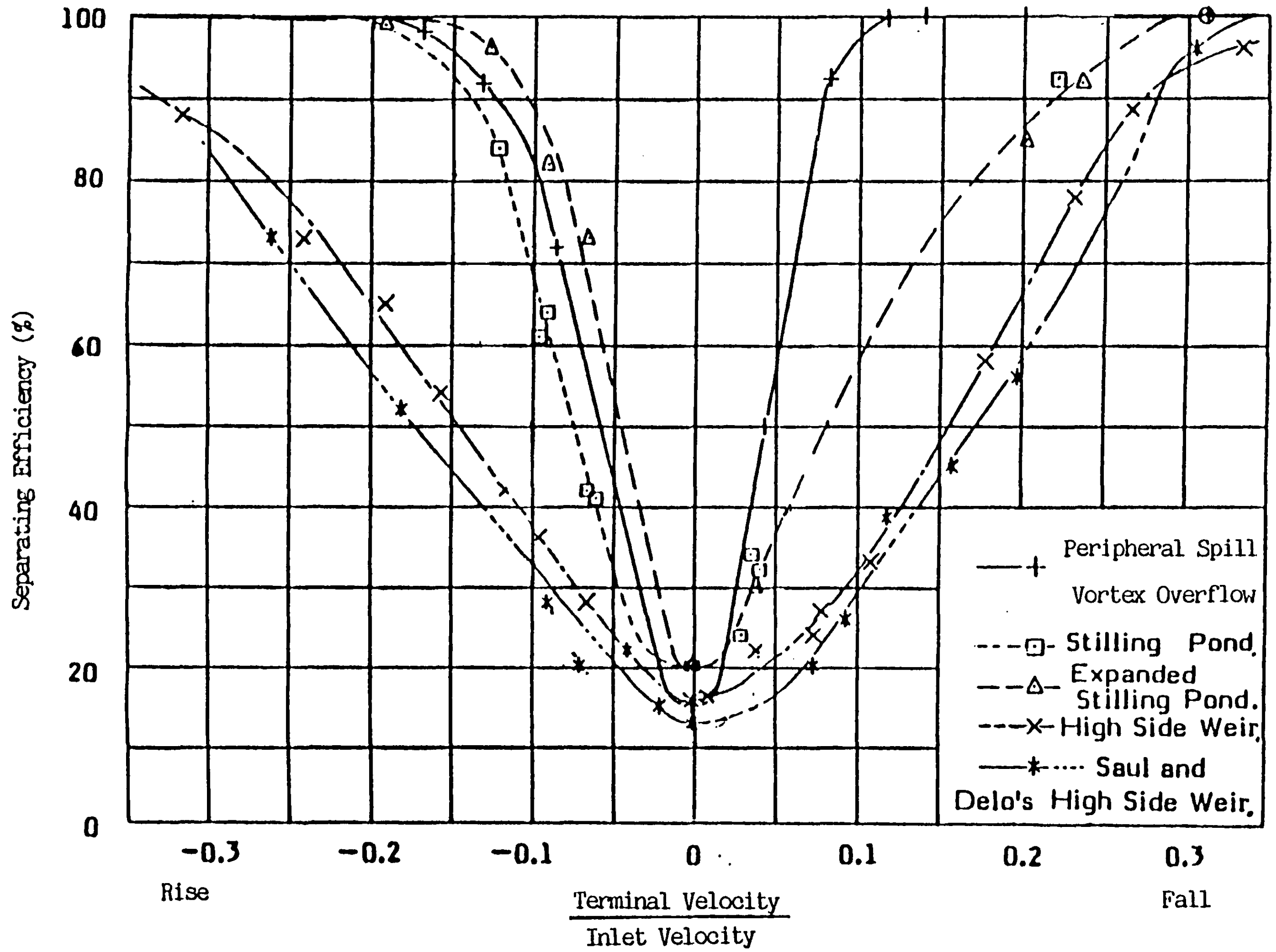


Fig.2.6 Separating Efficiencies of Various Storm Sewage Overflow Designs[26,27]

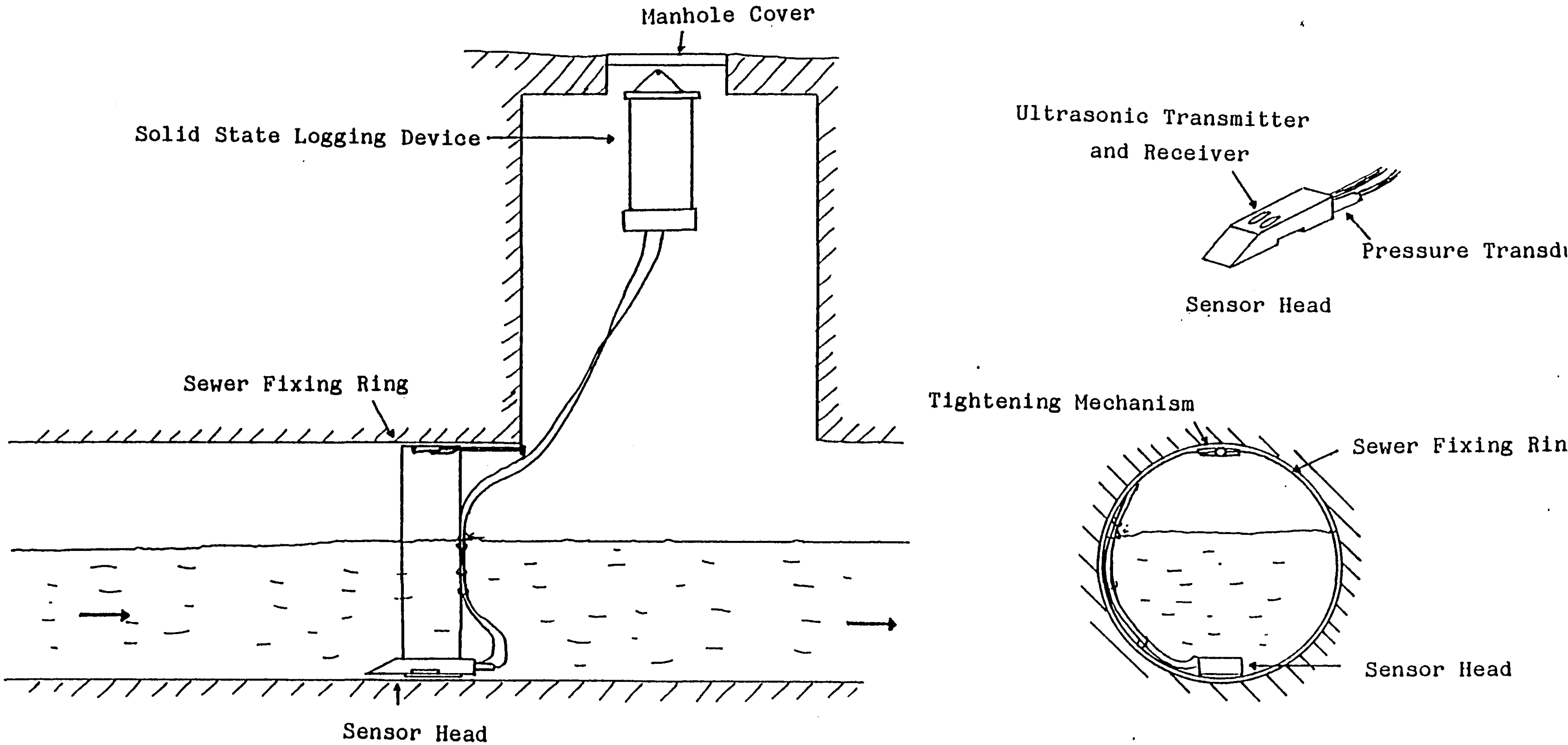


Fig.2.7 Typical Flow Survey Equipment Installation

Chapter 3 The Prototype Vortex Overflow with Peripheral Spill

3.1 Introduction

The work done by Balmforth & Lea[27,28,29] at Sheffield suggested that the Vortex with Peripheral Spill would be a good design for an overflow. The Main Drainage Department at Sheffield City Council agreed to look into building a full scale prototype and to help with a project to monitor the overflow to assess its performance.

A suitable site was found at Bacon Lane in the Attercliffe area of Sheffield, an old leaping weir overflow in a brick sewer which was performing very poorly, constantly spilling into the River Don (Fig.3.1). The overflow consisted of a 915 x 610mm egg shaped brick sewer going straight to the river. Below Bacon Lane there was a hole in the bottom of this allowing sewage to drop down into a similar sewer below, and off to a trunk sewer running parallel to the river. The hole, however, was often bridged by detritus, so that much of the flow, even during dry weather, crossed over and was discharged to the river. This was not an acceptable state of affairs, and it was necessary to replace the overflow with a better design.

The upstream catchment running into the Bacon Lane sewer has an area of 55 hectares, and drops 120m over its 2km length (Fig.3.2). The higher areas encompass housing estates and allotments, the lower areas light industry and wasteland. The catchment is predominantly drained with combined sewers, though there are a few separate systems. Permitted industrial discharges into the sewers are from an abbatoir, an alloy casting firm, a tooling firm and a concrete company. Occasionally tankers empty the effluent cleared from septic tanks into the sewer at the top of Bacon Lane. In addition discharges of large volumes of thick oil have been observed, the source of which is unknown.

3.2 The Vortex Overflow Prototype

It was decided to build a vortex overflow at the Bacon Lane site for several reasons. Other designs which might have been used, such as a stilling pond or high sided weir would have required large rectangular chambers, the construction of which would have proved difficult, and may have required relaying some of the upstream pipes to reduce the steep gradient. The vortex, being more amenable to positioning in a circular shaft, proved an easier and cheaper option. In addition the site had the required drop between inlet and continuation sewer. The vortex needs a drop of about 1.8 times the equivalent diameter of the inlet sewer, to allow for a conical floor and the height of the continuation chamber below (See Appendix A). It was possible to design a new chamber to fit neatly at the position of the old overflow, with only small changes required to the existing pipes. The steepness of the incoming sewer should not hinder the performance.

Based on the work by Balmforth and Lea, a prototype was designed for this site (Fig.3.3). The model tests suggested a chamber diameter of 3.5D - 5.5D where D is the equivalent diameter of the incoming pipe. The smallest factor was chosen for the prototype, giving a chamber diameter of 2.7m. The chamber volume was recommended as $20D^3$, from which the required weir level was deduced.

Having designed this, the continuation flow could then be set by the size of the orifice plate. Because of the uncertainty of the nature of the development expected on the catchment Formula A was not appropriate. Estimates for 6 DWF varied from 111 l/s to 271 l/s, depending upon the amount of development of the catchment. Eventually, after advice from Dr Balmforth, an orifice size of 225mm was chosen. It was thought that it would be relatively easy to replace the orifice plate with one of a different diameter to change the overflow setting should it be necessary. Construction began in the Spring of 1987 and was completed within 3 months.

The vortex chamber fits in the centre of a 4.6m diameter precast concrete segmented circular shaft which was sunk in Bacon Lane around the old overflow. The main components of the design are the overflow chamber itself, the continuation chamber below and the spill channel which takes sewage from the weir to the spill pipe.

In dry weather conditions the sewage flows round the 2.7m diameter overflow chamber and down the central 225mm orifice into the continuation chamber. From there it flows down another 915x610mm egg shaped sewer which joins the Effingham Road trunk sewer 15m further on.

When the flow increases as a result of rainfall, the vortex chamber begins to fill. Eventually it discharges over a peripheral weir, into the spill channel. On the inside wall at the bottom of the spill channel is an opening into the continuation chamber, which can be sealed by an automatic penstock. The Effingham Road trunk sewer has a level sensing device on it, just downstream of its intersection with the outflow pipe from the overflow. Should the level in the trunk sewer be low enough to indicate spare capacity then the penstock will remain open, allowing any storm sewage which spills over the weir to return to the system and continue downstream. However, when the level in the trunk sewer rises above a certain threshhold, the penstock will close. The spill channel, which is bounded at the far end by some steps, will begin to fill. Eventually the level will reach the top of the steps and the sewage will begin to flow along the overflow pipe, another 915x610mm sewer, and down into the River Don. After the storm the level in the trunk sewer will reduce, and as it passes a second threshhold, the penstock will be opened, allowing sewage trapped in the channel by the steps to be released back into the continuation chamber.

This penstock and its control gear have suffered a number of mechanical and electrical problems resulting in it being closed during much of the project. This causes almost all the sewage spilling to go to the river. At the end of the storm, the sewage remaining trapped in the spill channel by the steps seeps under the penstock into the continuation chamber.

The manhole containing the overflow has been fitted with strip lights, which can be turned on from the cabinet on the surface, and safety railing, both of which considerably reduce the difficulties of working in the sewer.

The Bacon Lane Overflow is part of the Don Valley Intercepting Sewer Strategy which aims, amongst other things, to provide capacity for present and future flows in Sheffield and to minimise the pollution to the River Don from sewage.

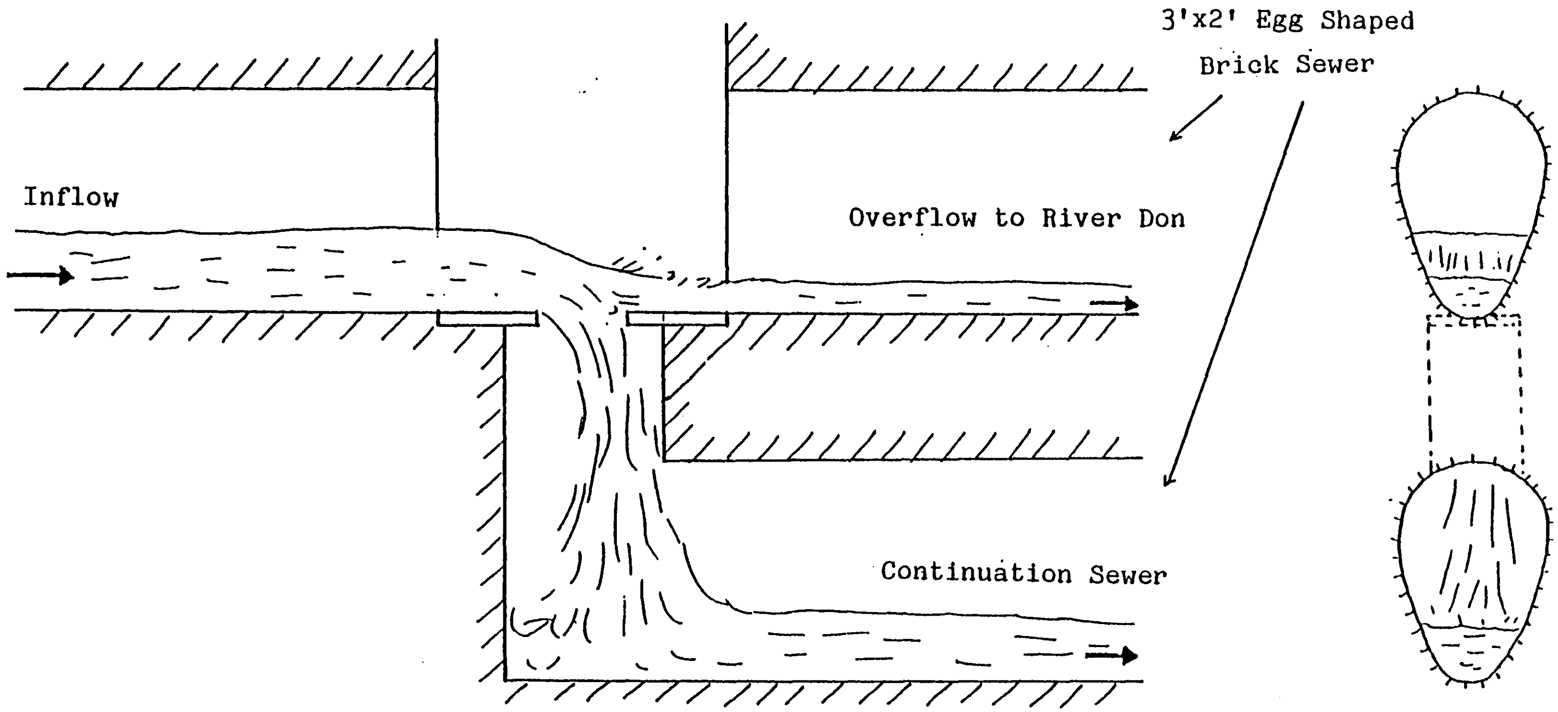
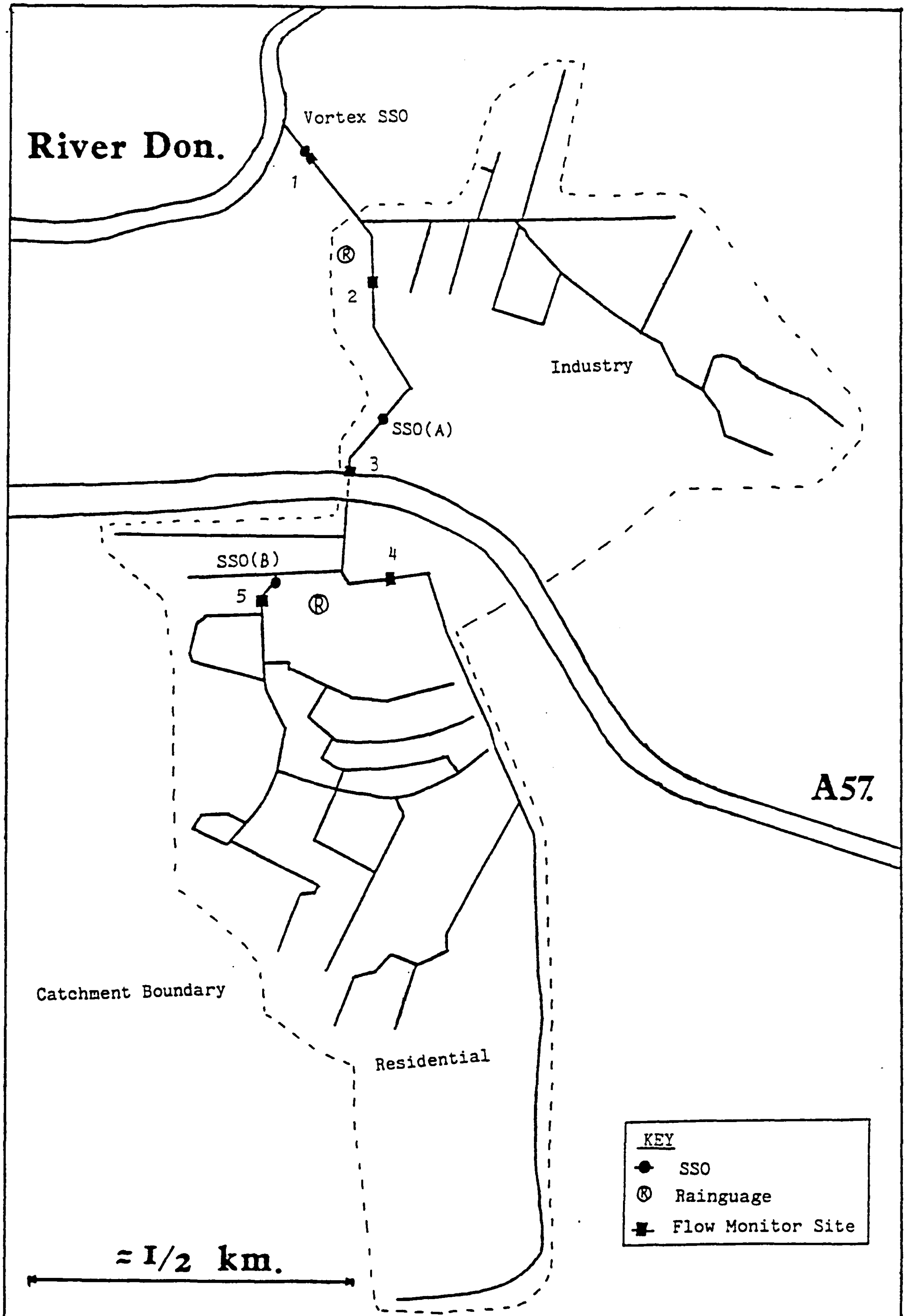


Fig.3.1 Previous Overflow at Bacon Lane Site (Leaping Weir Type)



Bacon Lane Catchment - Sheffield.
Pipe Network Schematic.
Fig.3.2

Based on a figure by
S.P. Gibson.

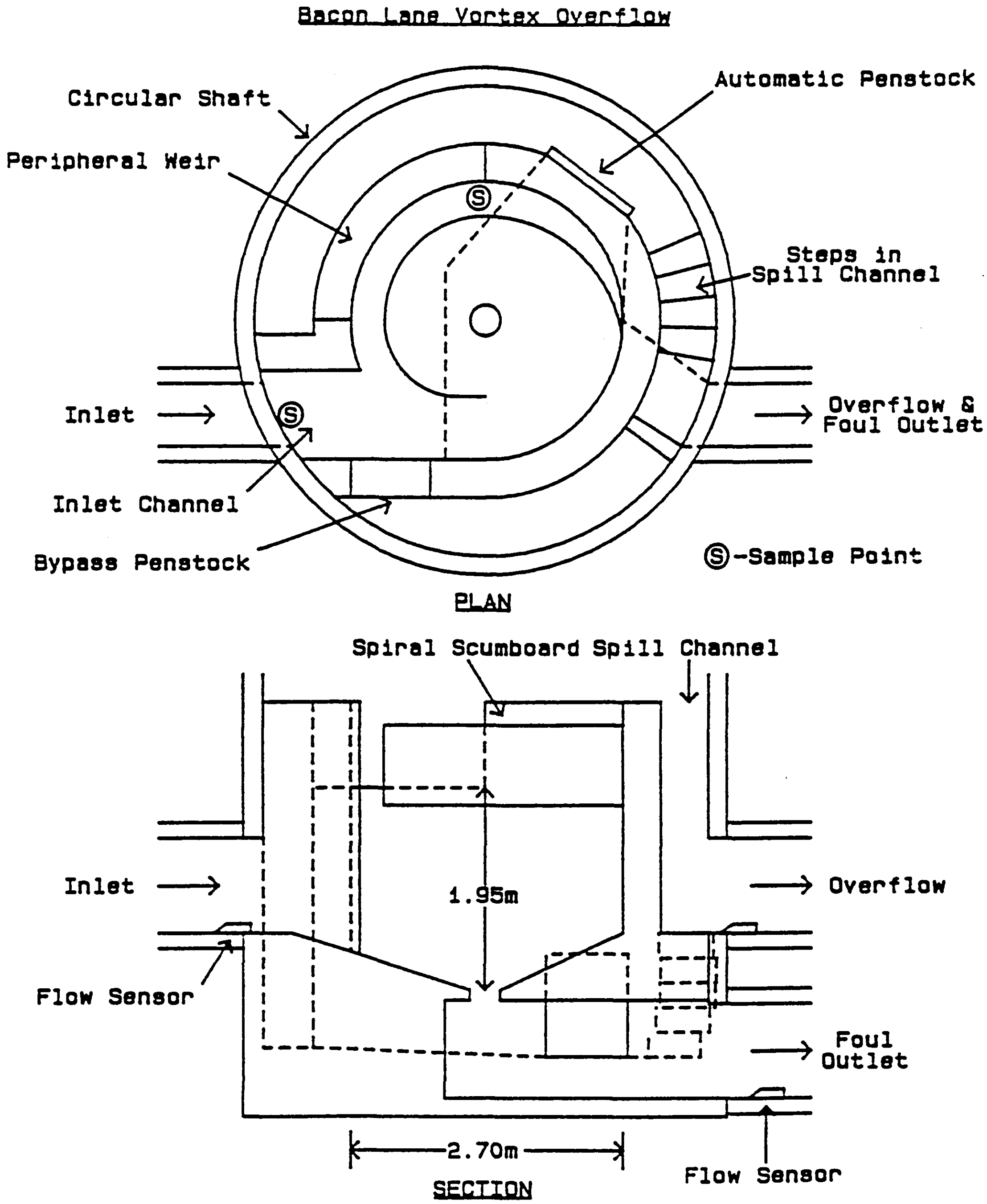


Fig.3.3 Bacon Lane Peripheral Spill Vortex Storm Sewer Overflow

Chapter 4 Equipment and Methods

4.1 The Monitoring Station

In order to achieve the aims of the project, a monitoring station was set up in the corner of a workshop near to the overflow chamber (Fig.4.1)

A small wooden walled office in a machine workshop was leased by the Polytechnic for the duration of the project.

During the construction of the overflow in the street outside, a pit was dug in the floor of the office, and connected to the overflow chamber by a pair of 150mm diameter ducts. These were to allow sampling tubes, sensor cables and so on to be run into the sewer, allowing equipment to be kept in the more agreeable atmosphere above ground.

Technicians from the Polytechnic replaced the wooden walls with bricks, and a mezzanine floor was constructed to give more workspace.

The pit walls were reinforced with a steel braces, and a sump with pump was installed to keep it drained (there was a slow inflow of groundwater).

Since it was connected to a sewer, a continual air extraction system was fitted to ensure there was no danger of gases building up.

Electricity was connected up, both single and three-phase supplies, to run the equipment.

The ability to use mains power, and to keep equipment in a clean and easily accessable area proved invaluable.

4.2 Measuring Hydraulic Characteristics of the Overflow

4.2.1 Introduction

Model tests suggest than the overflow does not increase its continuation flow once spilling has begun, and that one can predict the flow required to begin spilling using Ackers & Crump's work (See section 2.1.2). In order to investigate whether the prototype confirms with these predictions it is necessary to measure the flows into and out of the chamber.

4.2.2 Equipment Used To Measure The Hydraulic Characteristics

Detectronic Flow Survey Units (see section 2.2.6 & Fig.2.7) were used to record the flow. Four of these were lent by WRc for the project.

Sewer fixing rings were made at the Polytechnic, based upon one borrowed from WRc. These were strips of stainless steel curved to fit the sewer pipes, with adjustable caliper mechanisms to expand the ring to fit tightly. They are used to fix the flow monitor sensor unit in place at the bottom of the sewer.

A portable Epson HX-20 computer was borrowed from WRc, along with programs to collect data from the flow monitors.

An IBM-AT personal computer was supplied by WRc for the duration of the project.

4.2.3 Method

In September 1989 the sensor head of a flow monitor was installed in the inlet pipe to the overflow (Fig.3.3). Originally it was held in place by screwing it to a 1m strip of stainless steel fixed to the bottom of the sewer. Later this was replaced by a sewer fixing ring with two tightening mechanisms, one at either side. An extension cable was fitted to the sensor, which was run through one of the ducts to the logging unit which was kept in the monitoring station.

In February 1989, when the monitors used in the flow survey (see Chapter 6) were free, one was installed about one metre down the overflow pipe. The logging unit was kept in the manhole, where it could be maintained easily. In order for the site to be appropriate for the sensor, it was necessary that the automatic penstock, which would allow spilled sewage straight down into the continuation flow when open, be kept closed during the monitoring period. As it happened, the various electical and mechanical problems with the penstock had this effect.

In June a safe access route was discovered to the continuation flow pipe, and a third flow monitor was installed. The relevant logging unit was also kept in the overflow manhole.

The overflow manhole was entered on a weekly basis to collect data, check the equipment, change batteries and clean the inlet sensor. It was occasionally necessary to remove the logging equipment for repairs.

Data was collected using an Epson HX20 Portable Computer, which recorded it temporarily on microcassettes (Fig.4.2). Back in the office, the Epson transferred the data to an IBM PC provided for the project. The depth and velocity data so gathered was processed using WRc's Sewer Survey Analysis Software (SSAS). This package allows data to be transferred from a variety of computers and data collection devices. The size and shape of each pipe in which a sensor is positioned is entered into the program, and any calibration data required for the flow monitors. The program then calculates the flows and depths from the raw depth and velocity readings. It can also produce rainfall hyetographs from raingauge data, and allows the display and output of rainfall, flows, depths and so on for events which can be defined.

The package was used to produce files of flow and depth for the storms recorded, which were then read into a program designed to generate a database. To this database could be added results from any samples taken. The program, written by the author, can display the results in a variety of formats. It is able to analyse the data in a number of ways, such as to look for correlations or to compare measurements of flows into and out of the chamber.

In order to check the depth calibration of the monitor in the inlet pipe an experiment was conducted in March 1990 during which the orifice was plugged causing the chamber to gradually fill with dry weather sewage. The plug was a 500mm diameter disc of wood with a long metal handle attached to its centre. Two ropes were tied to the handle and the plug was lowered over the orifice. The weight of sewage which built up over it held it down and formed a seal. The dry weather flow then filled the chamber in about 40 minutes, and began sewage spilling over the weir. Since the automatic penstock was open, the sewage was diverted back into the continuation sewer so the river was not polluted. While the chamber was spilling the depth reading on the monitor could be checked.

4.2.4 Problems with the Flow Monitors

The monitors placed in the overflow and continuation pipes tended to break down quite regularly, becoming inoperable due to battery failures, waterlogging, damaged sensors, keypad failures and other miscellaneous problems.

Sometimes it was simply that the internal battery had become low, in which case placing it on charge overnight would start it again. Occasionally the battery was completely run down, and would have to be replaced. When a monitor became waterlogged it would have to be left open in a warm dry place for a few days to recover.

The most frustrating problems were when the sensors became damaged. The logger would then have to be cleaned up and sent to the manufacturers for repair, and a spare one installed, if one was available.

The logging unit of the monitor measuring inflows, which was kept in the monitoring station, suffered considerably fewer breakdowns than those kept in the sewer, and could be recharged in-situ when necessary. The flows into the overflow from almost all storms occuring between September 1988 and May 1990 were recorded.

4.3 Measuring the Quality Performance of the Overflow

4.3.1 Introduction

Model tests by Lea & Balmforth(27,28,29) suggest that the vortex overflow will have a significant effect on preventing rapidly floating or sinking particles from spilling. To investigate how the prototype performs the sewage quality has been measured in several ways. Bottle samples were taken during storms to examine the dissolved and smaller particles, and attempts have been made to monitor the larger particles in the flow.

4.3.2 Quality Sampling Equipment

Sirco bottle samplers were used to draw samples from the sewage (Fig.4.3). When triggered, these pumped air down the 10mm diameter sample tube in order to flush it. They then sucked sewage into a perspex cylinder on top of the sampler, until it reached a defined level (approximately 300ml) or a time limit expires. The sample was allowed to flow down through a distributor arm into one of the 24 bottles in the base unit. The arm then moved round to the next bottle ready for the next sample. The entire base unit could be removed when the samples were collected for analysis, and a new one with empty bottles installed. The samplers were battery powered, and a recharged battery was usually installed after each storm. To reduce the risk of blockages, coarse filters were fitted to the end at the sampling point. These consisted of short lengths of 50mm diameter tube with numerous 10mm holes drilled in them.

A Golden River Conquest portable computer was used to trigger the samplers. This was programmable in FORTH, could read a number of inputs and send signals to any equipment connected to its outputs. Although it was battery powered, it was kept on permanent charge as a precaution.

The level in the overflow chamber was monitored by two 'swingmeters' from the Water Research Centre. These were floats on the end of 600mm long arms pivoted at a potentiometer. The latter were fixed to the framework holding the scumboard, about 500mm above the weir level. When the sewage rose to the level of the float, the arm was deflected and the angle could be deduced by measuring the change in resistance of the potentiometer.

4.3.3 Method of Quality Sampling

The two bottle samplers were kept at the bottom of the pit in the monitoring station, and sucked samples of sewage up tubes through the ducts into the chamber (Fig.4.3). They were positioned as low as possible in order to minimise the height and distance though which they had to pull the sewage. One sampled from the incoming sewage, through a coarse filter fixed in the middle of the inlet pipe, the other from the spilling sewage, through a filter just inside the weir.

Initially the spilled sewage was sampled near the bottom of the spill channel. It was noticed that sediment was building up in the channel, and was probably being re-intrained. To avoid biasing the samples, the sample point was moved to the weir.

A program was written for the Conquest computer to monitor the two swingmeters in the chamber. When they were deflected sufficiently to indicate a storm, with the level of sewage within 100mm of the weir, the Conquest began to trigger the samplers, and record the times at which it did so. The first 16 samples were taken at 5 minute intervals, the next 8 at 10 minute intervals, so samples spanning 150 minutes can be taken, should the storm last that long. During the early part of a storm the flows tend to be highest and the concentrations of pollutants change most rapidly, so one wishes to take samples as frequently as possible. The samplers were set with a 60 second cycle time, so they would first flush the tube with air for 60 seconds, then suck for up to 60 seconds. If after this time they did not have a complete sample, they would try twice more before halting and declaring a fault. This time was found to be the shortest necessary to have a good chance of drawing a complete sample on the first attempt.

After a storm event the samples were taken to the Yorkshire Water Laboratories to be analysed for Chemical Oxygen Demand (COD), Suspended Solids concentration (SS), non-volatile suspended solids concentration (Ash), pH, Ammonia concentration, Conductivity (a measure of the concentration of salts in the sewage) and one in 10 were tested for BOD. The suspended solids, COD, BOD and Ash are a measure of the quantity of material in the sewage, its biochemical effect on the river were it to be discharged and its inorganic content. The times of each sample were noted from the Conquest and typed into Yorkshire Water's computer when registering the samples. When the analyses were complete the results could be transferred via floppy discs to the computer at the Polytechnic. There they were read into the database program, where they could be displayed, examined and manipulated. The results came in a text file with an agreed format. The database program had a routine to read these files and add them to its own files. It could then plot them, compare them with the flows, test for correlations and generate pollutographs.

The reliability of the sample analysis was tested by dividing up a bulk sample of storm sewage into six subsamples, getting each analysed and comparing the results.

4.3.4 Problems With Bottle Samplers

Initially there were problems with the samplers which caused loss of samples. The distributor arm on one tended to become stuck if it wasn't used for a couple of days. Regreasing the joint did not help, so a new joint was purchased, which solved the problem.

Occasionally the units successfully drew the first few samples in a storm, but subsequently collected little or no sewage in each bottle. It was thought this was due to blockages or the ragging up of the end of the tube. Fitting a coarse filter reduced the problem.

Sometimes it was not possible to get the samples analysed within two days, so any collected had to be discarded.

4.4 Measuring Gross Solids.

4.4.1 Introduction

Because the bottle samplers only draw up relatively small samples though tubes only 10mm in diameter, they can give little information about the larger objects in the flow. Such things, which may be tissues, rags, faecal matter, plastics and so on, can be the cause of considerable aesthetic dissatisfaction if spilled to a watercourse, particularly if left strewn about on banks and low branches by receding water levels after a storm or settled in shoals on the river bed. In order to investigate whether the vortex is able to prevent such 'gross solids' spilling, a way of monitoring such matter was required.

In response to this need, the 'Gross Solids Monitor' (GSM) was developed at the Water Research Centre. Various techniques were considered, such as using ultra-sonics or methods to take large physical samples, but a visual approach was eventually decided upon as the most appropriate, the others being thought either too expensive or impractical.

4.4.2 The Gross Solids Monitoring Equipment

The principle of the system was to record videos of samples of sewage flowing past a window, and to count the number of large objects visible.

Most of the equipment to achieve this was in the pit in the monitoring station (Fig.4.4, 4.5).

A large peristaltic pump was used to pull sewage up from the chamber through a 100mm diameter flexible hose, and pass it through a steel tube with transparent sections top and bottom. It was illuminated from below by a bank of near infra-red LEDs, and viewed from above with a video camera sensitive to this radiation. The longer the wavelength the less it is scattered by particles in the sewage. However if the wavelength becomes too long the light begins to be absorbed by the water. Near infra-red (880nm) was considered the optimum wavelength to use. Any large objects in the flow appeared as dark shadows on the video image. By counting the numbers of shadows it was hoped to get an estimate of the quantities of large objects in the flow.

By opening and closing a pair of pneumatic valves in the sewer, sewage could be pumped either from the inlet channel or from the spilling effluent. Initially the sample was taken from near the bottom of the spill channel, but in April 1989 the inlet was moved to just inside the weir, after sediment on the floor of the channel was suspected of becoming re-entrained and biasing samples.

Originally the pipe drawing sewage from the inflow was cut off at an angle into the flow (Fig.4.6i) and that drawing from the spill was cut off horizontally just inside, and just below, the weir (Fig.4.6iii). However there was uncertainty as to how representative the samples would be, so after 8 months the inflow pipe inlet was replaced by a longer pipe with three entry points (Fig.4.6ii) in order to draw a mixed sample from the flow at different levels. It was also suspected that the horizontal end of the spill sample pipe may not be drawing samples in quite the same way as the angled inflow pipe, which may be biasing the results. In order to investigate this, a new inlet with an angled entry was fitted (Fig.4.6iv).

When the equipment was triggered, it began pumping sewage from the inlet at a fast rate. It allowed three minutes for the sewage to reach the viewing cell and the air pockets to be cleared before slowing down for one minute, to allow a better view of the sewage. Then the pneumatic valves were adjusted so as to suck from the spill, and the cycle repeated, alternatively sampling from the inlet and spill. During the slow periods one of two tones was recorded on the audio channel of the video tape to distinguish between images of inlet and spilling sewage.

The operation of the equipment was run by a microprocessor in the GSM Controller. This ran through the various cycles, turning the components on and off as necessary. It could detect a number of faults, such as problems with the pump or the pit filling up with sewage. In such cases it would close the system down and sound an alarm if necessary. If it detected a blockage in the pipe, it would reverse the pump in an attempt to dislodge it. If this was unsuccesful it would turn everything off. When testing this facility it was discovered that the perspex viewing tube originally installed wasn't strong enough, as it burst. It was been replaced with a steel tube with stronger windows, and pressure sensors were fitted which would cause the pump to be turned off it the pressure went too high.

4.4.3 Method of Counting Gross Solids

The GSM equipment was triggered by the Conquest when the swingmeters in the sewer indicated the vortex was spilling.

For each storm event the equipment produced a video tape with two minutes of useful film for every eight minutes of spill, the slow periods being identified by the tones on the audio channel.

Originally it was hoped to develop an automatic method of analysis of these tapes. This involved playing the tape into a 'Sight Systems' image processing system connected to a computer. The computer could use the tones on the audio channel to identify the parts of the tape to examine. Images from the tape were converted into digital format, in an array of 256 x 256 pixels, each of which had a brightness level of 0 - 63. Software written by Foster-Finlay was used to attempt to pick out and measure dark areas corresponding to objects in the sewage. Routines were available to capture images from the tape and perform various manipulations, such as subtracting background images, smoothing, threshholding to highlight areas darker than a given brightness and measuring routines to count the size and number of highlighted areas. These procedures were combined in various ways in order to find the best method of analysing the films.

Because of difficulties in getting the automatic system working satisfactorily, each tape was analysed by eye. This involved playing the sections of the tapes labelled with tones and counting the number of objects passing in the minute. Objects appearing larger than about 2-3mm were counted, and each section was examined several times to get an average. Those sections with more objects, or those that were harder to count for some reason, were examined more times. The counts were put into the computer database program to be incorporated with the other data.

4.4.4 Assessing the Repeatability of Counting Objects by Eye

To have confidence in results produced by counting shadows on a minute of tape by eye, it was necessary to examine how repeatable the counts are. To test this two fellow research students watched several sections of film, noting the number of objects they counted. Each section was played several times and the mean result (excluding the occasional outliers) was taken. The results from different people were then compared.

4.5 Attempts to Examine the Gross Solids in the Sewage

4.5.1 Introduction

In order to compare the results from model tests with those from the prototype, it was necessary to gain some knowledge about the nature of the objects in the sewage. The model tests considered the efficiency of the overflow in dealing with various synthetic gross solid particles of different settling velocities. If it were possible to estimate the settling velocity distribution of material in the real sewage, a suitable scaling factor could be applied and comparisons made.

There were several attempts to estimate the settling velocities.

4.5.2 Equipment

To get a crude estimate of the quantity of gross material, a pair of buckets were suspended in the chamber. Each had numerous 20mm holes drilled in the base and sides, and was hung in place on ropes, one in the inlet channel, one over the weir. It was hoped that during storms they would capture a proportion of the material passing through them, which could be weighed each time the sewer was visited. Unfortunately there was little success since it seemed that the force of the flow ensured that all but the largest paper towels were washed through.

To determine the settling velocities of particles, a clear plastic tube, 121cm long, 50mm in internal diameter, was used. This had rubber bungs placed in each end, tightly enough so it could be inverted with minimal danger of the fluid within escaping.

Sampler bottles were used to capture volumes of dry weather flow. Larger samples of the gross material were gathered using 'Copasacs', bag shaped net sacks. These fit on the back of a rectangular plastic inlet (400mm x 80mm in cross-section), and are about 800mm long. The sacks came in a variety of mesh sizes, the ones used having a 4mm square mesh.

4.5.3 Method of Determining Settling Velocities

In order to estimate the settling velocities of sinking particles, a sample containing the particles was put at the bottom of the plastic tube, and the tube was gently filled with tap-water. A rubber bung was placed in the end and the tube inverted. The number of particles reaching the bottom in each five second interval was recorded.

It was assumed that they reached terminal velocity in a relatively short time, so the velocity could be estimated from

$$V_s = \text{(Tube Height)}/\text{(Time to reach bottom)} \qquad \text{(Equation 4.1)}$$

To obtain the velocity of floating material, the sample containing the particles was poured in at the top of the tube when it was almost full of tap-water. The tube was then topped up if necessary, and a bung fitted. The tube was inverted and particles timed as they rise to the top.

Three types of samples were tested;

i) Samples collected from storms by the bottle sampler,

ii) Samples of dry weather flow collected by letting sewage flow into a bottle,

iii) Samples of material collected from the dry weather flow by Copasacs.

The last involved holding the sacks in the sewage in such a way that most of the flow passed through them for a known length of time. The sack was weighed after hanging to drain for a minute or two and brought back to the laboratory sealed in two plastic bags.

The matter collected by the sack was deposited into a bucket by turning the sack inside out and spraying water through. The resulting mixture was left for a few minutes to settle. The matter that floated to the surface was collected with a tea-strainer and tweezers, and subsamples were tested in the tube to determine their settling velocity distribution. The floating matter was then dried and weighed. The matter that sunk to the bottom was similarly tested, after most of the liquid in the bucket had been decanted off. After testing the mixture was poured through a plankton net to capture all the material. Subsamples were taken to estimate the dry weight.

In some cases the matter tended to clump, with fibrous material from paper towels forming a web which prevented the rest of the objects from falling. To reduce the amount of fibrous matter, which tended to sink slowly, the top liquid was decanted off and the sample re-diluted with tap water several times. This drew off much of the troublesome tissue waste, but may also have biased some of the samples by removing a proportion of the slower sinking matter too.

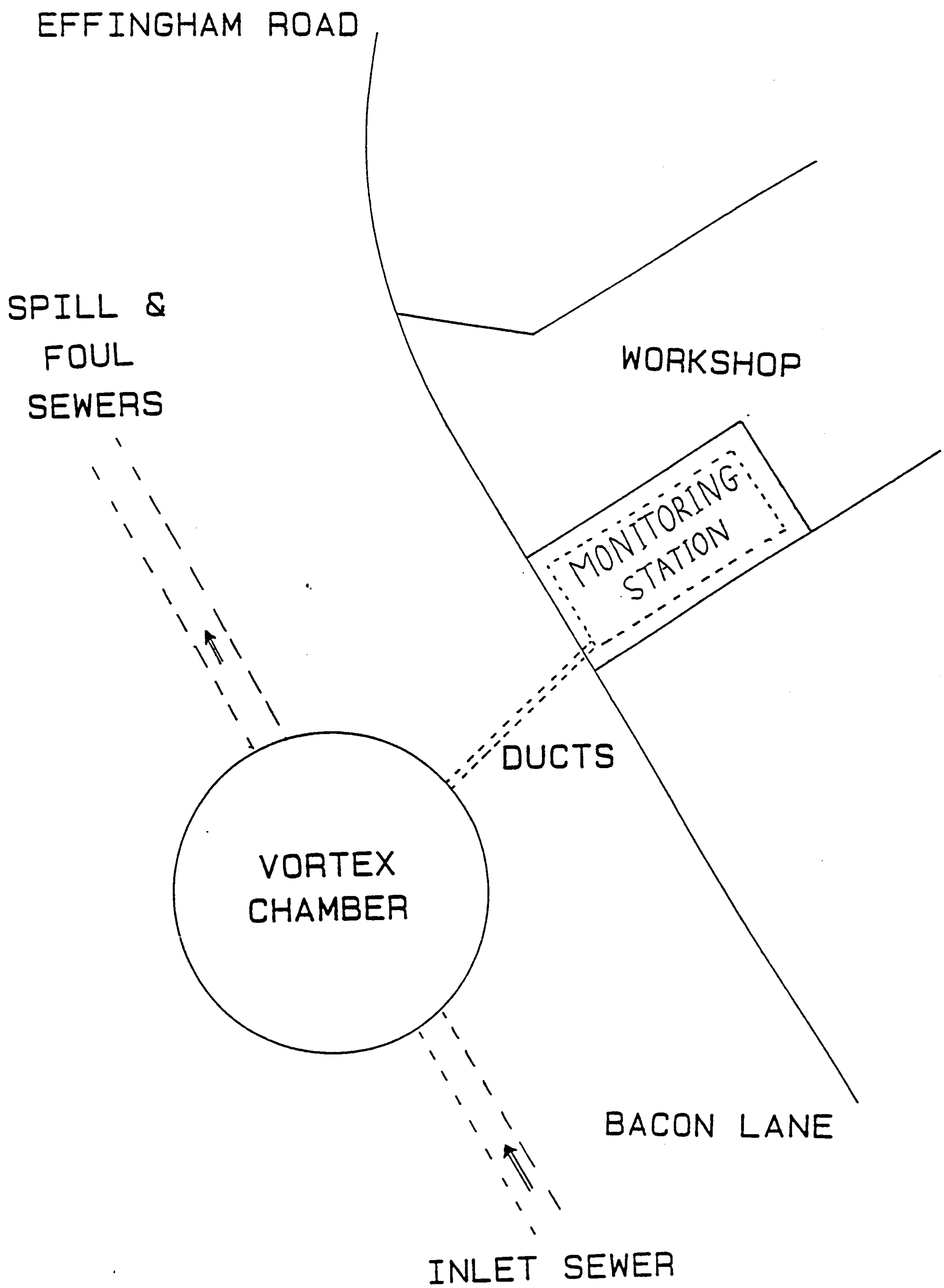


Figure 4.1 Site of Bacon Lane Overflow & Monitoring Station

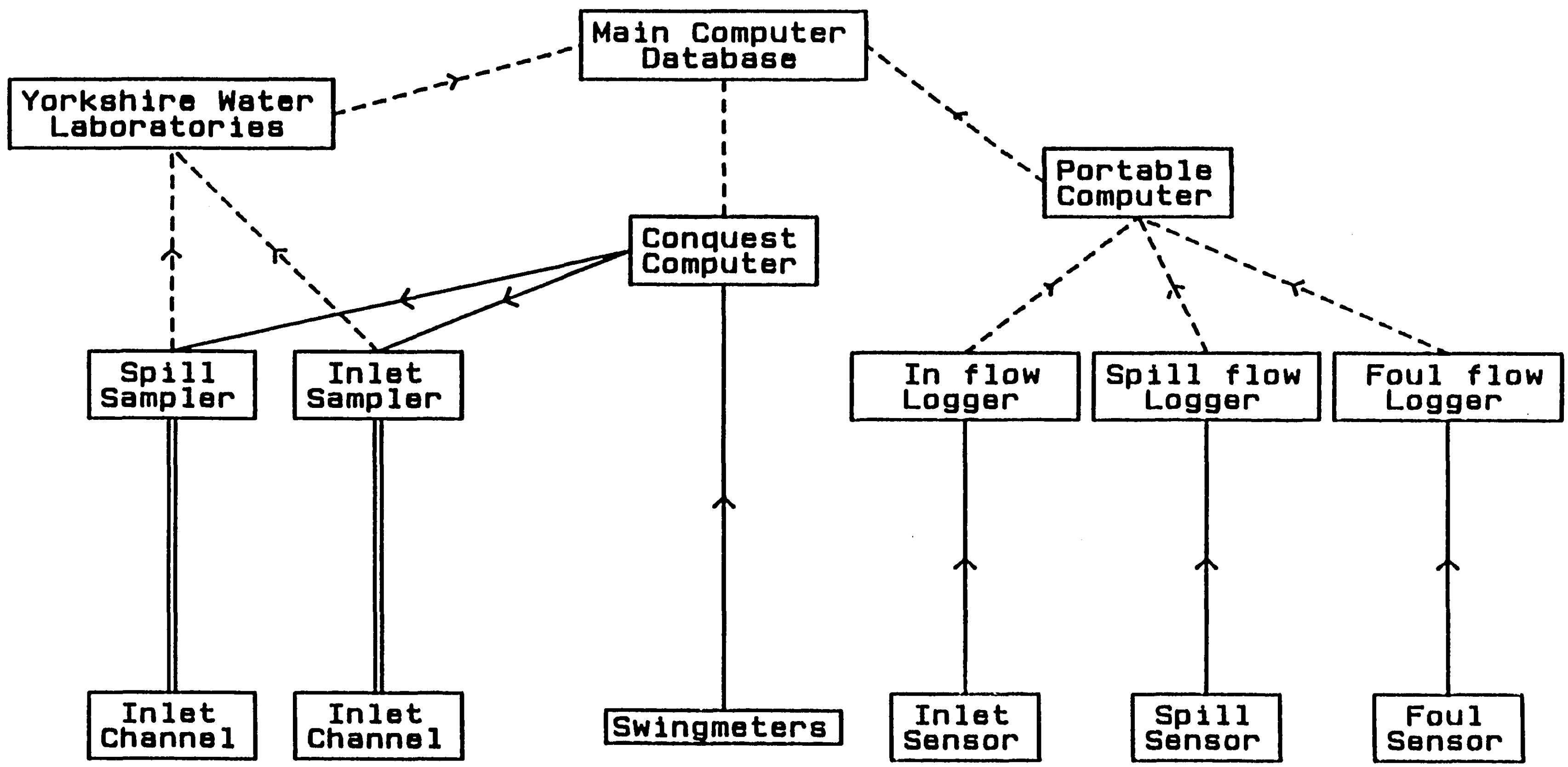
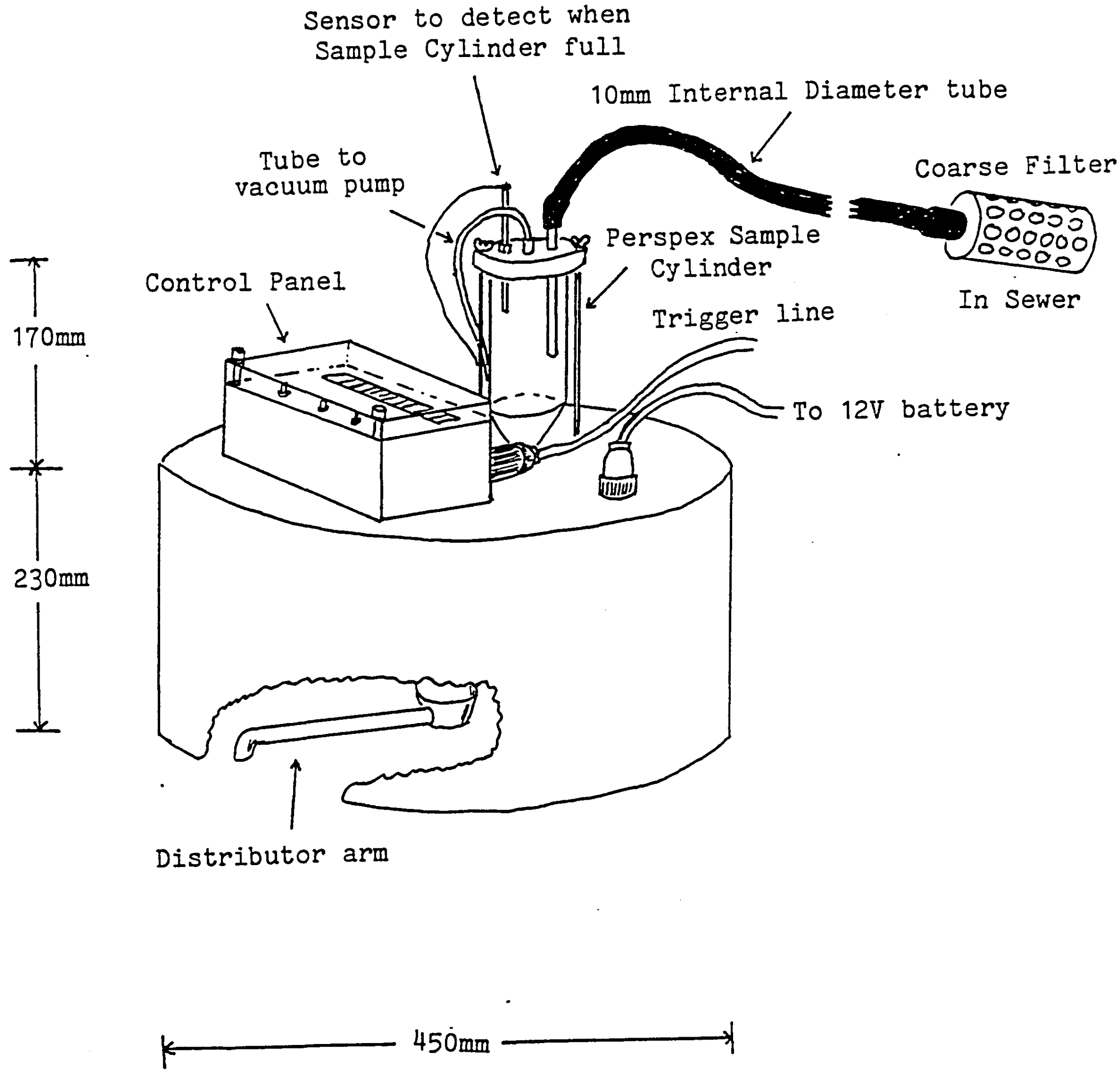


Figure 4.2 Samplers and Flow Monitors at the Bacon Lane Overflow



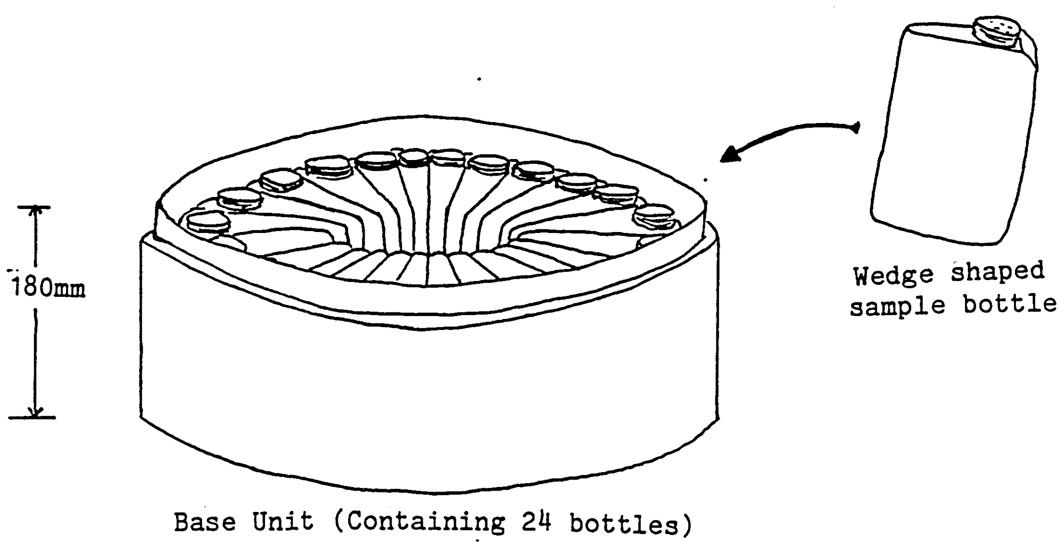


Figure 4.3 Sirco Bottle Sampler

Gross Solids Monitoring Equipment

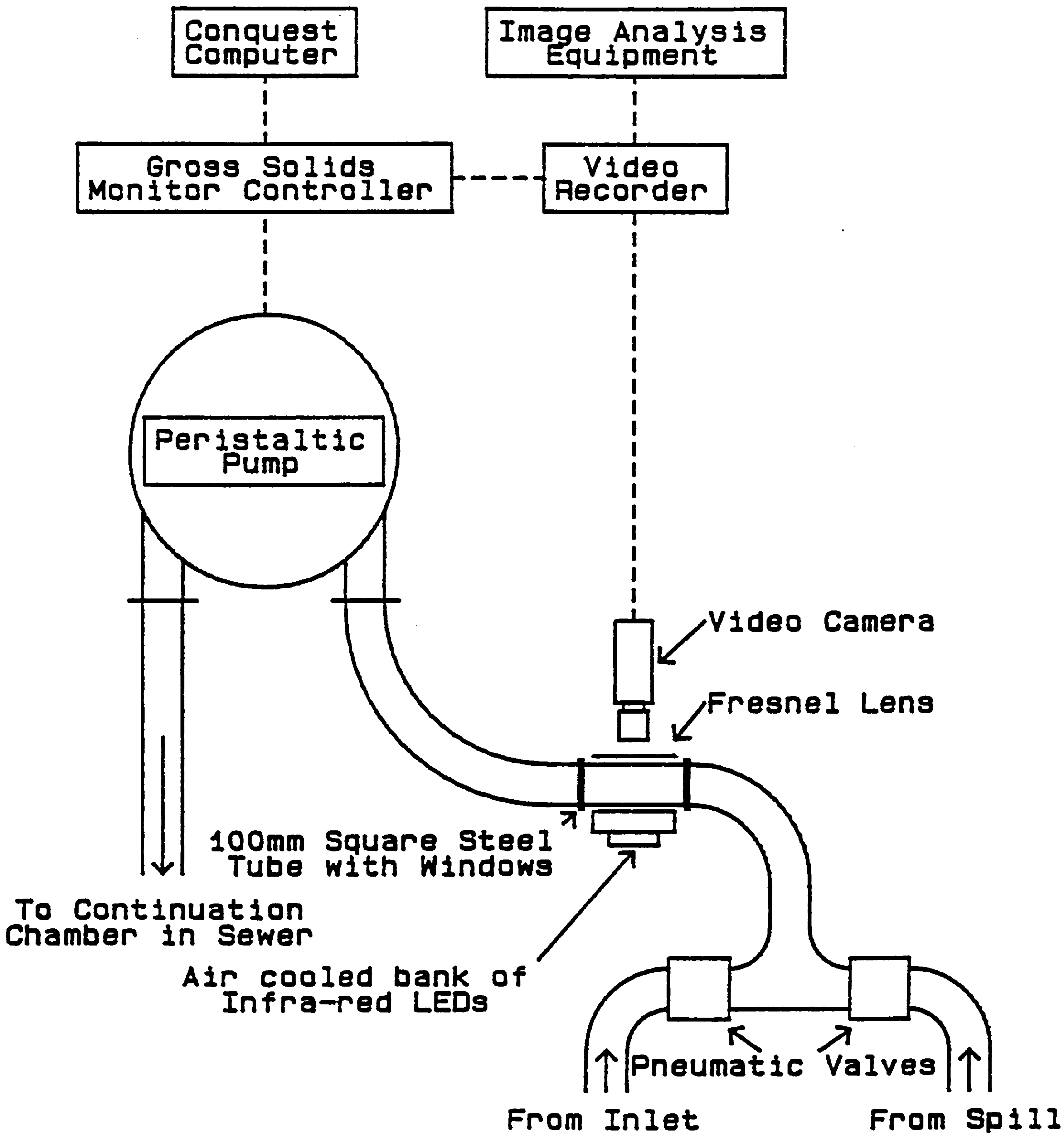


Figure 4.4 The Gross Solids Monitor

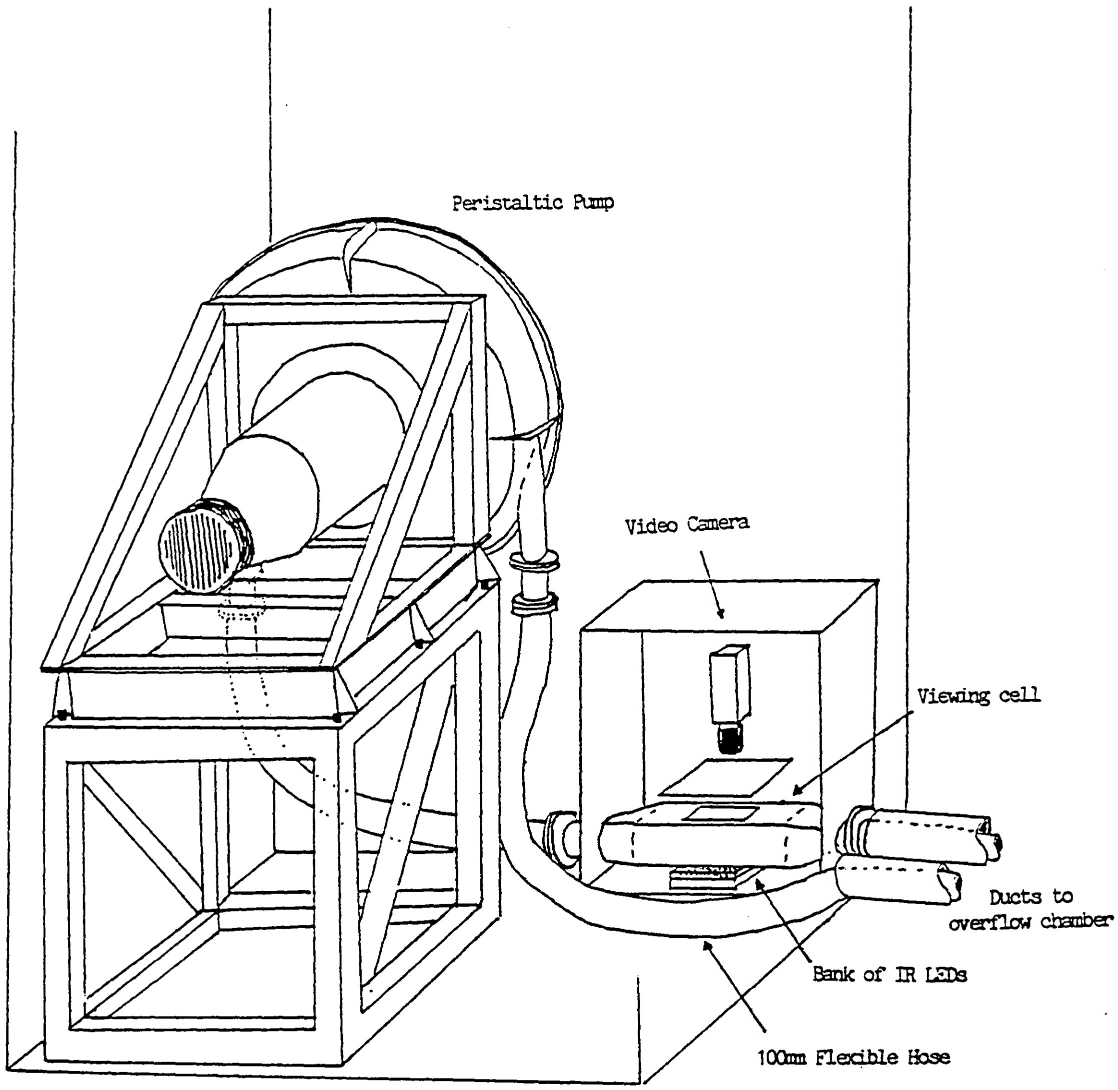


Figure 4.5 Gross Solids Monitoring Equipment in Monitoring Station

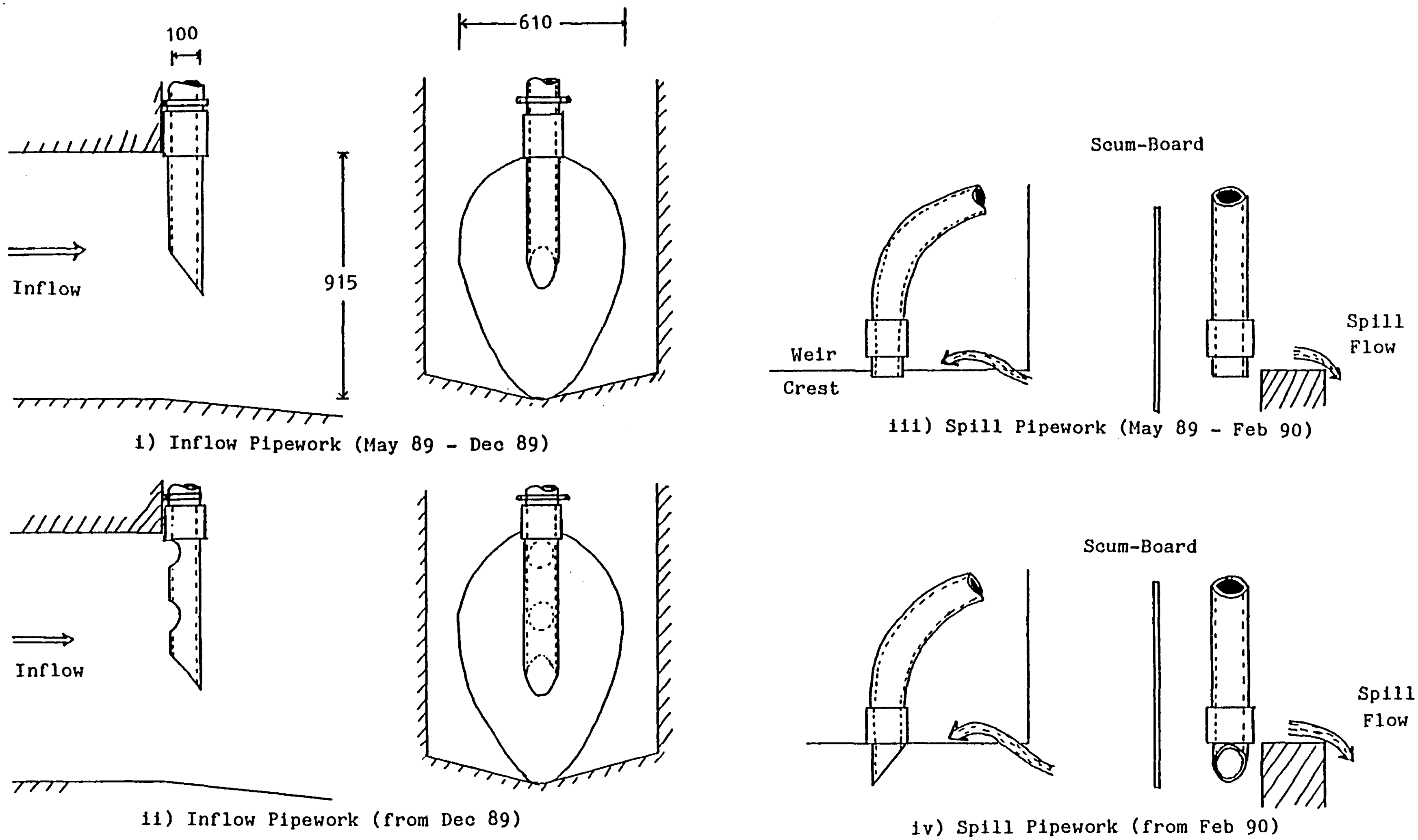


Fig.4.6 Arrangements of Gross Solids Monitor Inlet Pipework

Chapter 5 Results and Interpretation

5.1 Introduction

The overflow performed well during the three years since its construction. It proved to be self cleansing, the only signs of use being small deposits of floating matter clinging to the walls at the top of the inlet channel, and rags on the chains in the spill channel. This latter indicates that the overflow certainly isn't retaining all the gross solids.

The automatic penstock was disabled due to electrical and mechanical problems for some time, but on the one occasion that the orifice became blocked (by a car tyre and a 10 gallon plastic drum), the system was working. Since there was no rain at the time, the flow in the trunk sewer was relatively low, and the penstock was open. The blockage eventually caused the chamber to fill with raw sewage, which began spilling over the weir. The open penstock allowed the sewage back into the continuation chamber, preventing it from spilling into the River Don. When the problem was discovered, the chamber was drained by opening a manual bypass penstock beside the inlet, allowing the blockage to be reached. Unfortunately the project coincided with some of the hottest summers and mildest winters for some considerable time, and was hampered by the scarcity of notable rainstorms. This prompted a six month extension to the three year project, which bore some fruit in allowing several more events to be recorded by the Gross Solids Monitor.

5.2 Hydraulic Characteristics of the Vortex Overflow.

5.2.1 Introduction

The flows into the overflow from almost all storms occuring between September 1988 and May 1990 were recorded.

There were about 20 storms large enough to cause the overflow to spill in this time, for nine of which all three flows (in, continuation and spill) were recorded.

A typical storm had an initial rapid rise in flow rate to a peak, then a gradual decline (eg Figure 5.1).

5.2.2 Comparison of Flow Monitor Measurements

When all three monitors recorded data it was possible to compare their results to assess the consistancy of the equipment. By adding the continuation flow to the spilled flow and plotting the sum against the inflow, it was possible to see if the results were consistant (Fig.5.2). It was found that the curves had the same general form suggesting the spill and foul monitors were fairly consistant, but that the inflow unit seemed to be underestimating by about 10% on average.

When the spill flow (Q_s) is plotted against the inflow, for instance Fig.5.3, the points roughly follow the line

$$Q_s = R_s \times Q_{in} - Q_0 \qquad \text{(Equation 5.1)}$$

where Q_0 was the inflow when the spill flow has just subsided to zero (the intercept of the line with $Q_s = 0$), and R_s is the gradient of the straight line. The value of Q_0 gives an estimate of the measured steady state flow required to just begin spilling. Table 5.1 gives the values for this parameter for each storm with spill recorded.

Date	Q_0 (l/s) (= Q_{in} when Q_s=0)	$k_i = 175/Q_0$
30-Jun-89	160	1.10
7-Jul-89	135	1.30
8-Jul-89	150	1.15
8-Jul-89	140	1.25
8-Jul-89	150	1.15
9-Jul-89	160	1.10
8-Nov-89	(170)	1.03
7-Feb-90	190	0.92
13-Feb-90	190	0.92

Mean: 160

Standard Deviation: 17

Table 5.1 Summary of results from plotting the spill flow against the inflow to the chamber.

The results in brackets were dubious due to either large scatter or an unusual form to the graph suggesting problems with the monitors. If the monitors became ragged up or silted over they could misread.

The majority of the points which go to make up each line on the graphs are gathered when the inflow is declining slowly. It seems reasonable to assume that the flow when it stops spilling will be the same for each storm, and that the differences in the measured values are due to discrepancies in the monitor. The average value of Q_0 from the recorded data was 160l/s. The inflow monitor tended to underestimate by 10% on average, so the best estimate of Q_0 is 175l/s. This figure was used to scale the inflow monitor results by taking

$$\text{Inflow, } Q_{in} = k_i \times Q_{in}(m) \qquad \text{(Equation 5.2)}$$

$Q_{in}(m)$ = Measured inflow

and

$$\text{Inflow Coefficient, } k_i = 175/Q_0 \qquad \text{(Equation 5.3)}$$

The values of k_i for each storm are shown in Table 5.1.

For storms where the spill flow was not recorded, k_i was taken as 1.1.

Plotting the scaled inflow against the sum of the spill and continuation flows gave a better fit, but it could be improved further by calculating the sum

$$QT = (k_c \times Q_c(m)) + (k_s \times Q_s(m)), \qquad \text{(Eq.5.3)}$$

$Q_c(m)$ = Measured Continuation Flow

$Q_s(m)$ = Measured Spill Flow

k_c, k_s : Flow coefficients

With suitably chosen flow coefficients.

This was best achieved by first plotting the inflow and $k_cQ_c(m)$ on the same graph and varying k_c until a good fit was achieved for the lower flows. For instance, for the 7-Feb-90 storm k_c = 0.74 (Figure 5.4).

If $k_s Q_s(m)$ was added, plotting QT (Eqn.5.3) and the inflow, k_s could be varied until the best overall fit was obtained. For 7-Feb-89 the best $k_s = 0.74$ (Fig.5.5).

This was repeated for the other eight storms to get the coefficients k_c and k_s for each (Table 5.2). The closer k_c & k_s are to 1, the more consistent are the results from the monitors.

Storm Start Time	Recorded Volume (m^3)			Flow Coefficients	
	In	Cont.	Spill	k_c	k_s
30-Jun-89 22:50	770	650	60	1.20	1.20
7-Jul-89 15:30	1340	990	610	1.10	1.10
8-Jul-89 11:00	640	1000	20	1.05	0.75
8-Jul-89 16:45	1000	930	420	1.05	0.95
8-Jul-89 19:30	1020	1220	100	1.10	0.95
9-Jul-89 0:30	1090	960	120	1.10	1.00
8-Nov-89 8:00	(4440)	4110	370	0.80	0.95
7-Feb-90 13:30	3500	4300	120	0.75	0.75
13-Feb-90 16:30	650	730	50	0.70	0.75

Mean Value : 1.00 0.95

Table 5.2 Volumes and estimates for Continuation (k_c) and Spill (k_s) Coefficients for the best correlation between inflow and outflows.

It is usually accepted that monitors can be inaccurate by as much as 20%, because of the difficulty measuring the mean velocity of the flow.

It was felt that the mean values of k_c and k_s being close to 1.0 justified the earlier assumption that the inflow monitor was underestimating. Had it this not been allowed for the means would be 0.9 and 0.85, showing that the spill and continuation flows would have to be reduced by 15% to get them to fit the inflow results.

In some cases a simple scaling of measurements was insufficient to give a good approximation to the inflow measurement. An equation of the form

$$QT' = (A1 + A2 \times Q_c(m)) + (B1 + B2 \times Q_s(m))$$

(Eq.5.4)

would give a better fit. This would be necessary when the measurement was offset for some reason, such as a build up of silt in the pipe. This occured during the summer when a number of bent metal plates became lodged in the continuation pipe a little downstream of the sensor. However, it was felt that the errors in the data would be too large to justify a much more accurate attempt to fit.

By assuming the continuation flow, Q_c, to be

$$Q_c = k_c \times Q_c(m), \quad \text{(Equation 5.5)}$$

and the spill flow, Q_s, to be

$$Q_s = k_s \times Q_s(m), \quad \text{(Equation 5.6)}$$

it was possible to make some adjustments for the variability of the performance of the flow monitors between storms.

If the continuation flow is plotted against the inflow it is possible to examine the relationship between the two (Fig.5.6). The general form of these graphs seemed to be a line parallel to $Q_c = Q_{in}$ at low flows, intersecting a line with a much lower gradient at higher flows. The latter indicated the change to the spilling flow regime, where an increase in inflow only causes a small increase in continuation flow, the rest spilling over the weir.

Estimates of the transition point, the point where the spilling flow regime begins, are given in Table 5.3 (Overleaf), along with the peak values of the inflow and scaled continuation flow. These estimates are not very accurate, since there tends to be a good deal of scatter on the graphs.

The results in brackets were dubious due to either large scatter or an unusual form to the graph suggesting problems with the monitors. If the monitors became ragged up or silted over they could misread.

The points above the transition to the spilling regime tended to lie around a line of the form

$$Q_c = (Q_t) + R_c \times (Q_{in} - Q_t) \qquad \text{(Equation 5.7)}$$

Q_t = Inflow at transition point

where R_c is the gradient of the line, and lies between 0 - 0.15. Again, it was difficult to obtain an accurate value because of the scatter on the data. This meant that when the inflow increased by 100l/s, the continuation flow appeared to increase by no more than 15l/s.

Date	From Q_c vs Q_{in} graphs				Max rise above transition	
	Transition Point		Q_c Peak	Q_{in} Peak		
	Q_c (l/s)	Q_{in} (l/s)	(l/s)	(l/s)	Q_c (l/s)	Q_{in} (l/s)
30-Jun-89	175	175	200	300	25	100
30-Jun-89	175	175	180	270	5	95
31-Jun-89	200	200	220	300	20	100
7-Jul-89	170	185	260	500	90	310
8-Jul-89	175	175	180	260	5	85
8-Jul-89	(200)	(300)	225	425	(25)	(125)
8-Jul-89	195	175	200	220	5	45
9-Jul-89	170	175	175	265	5	90
30-Oct-89	165	165	175	255	10	90
8-Nov-89	(185)	(205)	(205)	360	(20)	(155)
7-Feb-90	155	155	195	250	30	95
13-Feb-90	165	175	185	230	20	55

Table 5.3 Summary of results from plotting the continuation flow and spill flow against the inflow to the chamber.

The scaled spill flow (Q_s) was again plotted against the inflow, for example Fig.5.7. The points roughly followed the line

$$Q_s = R_s \times Q_{in} - Q_0 \qquad \text{(Equation 5.1)}$$

where Q_0 was the inflow when the spill flow has just subsided to zero (the intercept of the line with Q_s = 0), and R_s is the gradient of the curve. R_s was slightly less than unity on average, allowing for the slight increase in continuation flow with increase in inflow.

The flow out of the spill pipe remained free surface, even during extreme storms. During a storm on 24-May-89 the spill flow rose to about 1000l/s, but the depth in the pipe was no more than 810mm (the pipe is 915mm high).

It was apparent that the curves formed by sequential points on the Continuation flow vs Inflow and the Spill flow vs Inflow graphs looped around the average lines estimated for them. During rising flows the curve tended to have higher values of inflow than those at the same foul/spill flow when falling. This was caused by the storage in the chamber and the spill channel. Both have similar volumes, of about 9000 litres. In both cases the outflow was dependent upon the depth. If the inflow suddenly rose, the outflow could only rise to match it when the depth had been augmented sufficiently by the excess of inflow over outflow. This caused a delay during which time the inflow might rise further. Of course the situation was complicated by the fact that the inflow was rarely steady for any length of time. The effect was that during sharp rises in inflow the outflow would lag behind, showing as a bias toward higher inflows on the Inflow - Outflow plot. The size of the bias was be dependent on the rate of increase. For instance if the chamber were to be filled from empty by a sharp initial storm peak in 8 minutes, the net continuation flow volume during this time would be 9000 litres less than the inflow, so the continuation flow would be 9000/(60 x 8) = 20 l/s less than the inflow over the period. If the rise was less sharp, say over 15 minutes, the difference would be correspondingly smaller, about 10 l/s.

Similarly, if the inflow were to fall rapidly, the outflow would remain higher for a while. However, in practice the inflow usually declined relatively slowly compared to its increase, so there tended to be less deviation from the average.

A similar effect would occur if there were a mistiming fault, with the clocks on the spill or foul flow monitors being a little ahead of the clock on the inflow monitor. Periodic checks were made to try to prevent this.

5.2.3 Comparing Flows with the Depth in the Chamber

The depth measured by the inflow monitor could be used as an estimate of the maximum sewage depth above the inlet pipe invert in the chamber. The inflow was plotted against this depth, (eg Fig.5.8). This showed that the flow rose slowly with the depth as the chamber fills, the relationship between the two being governed by the properties of the vortex formed in the chamber. When spilling, the flow down the continuation pipe did not increase greatly (5.2.3). The gradient of the flow-depth relationship was thus governed more by the hydraulics of the weir than the orifice. The point of intersection between the lines relating to sub-spill and spilling conditions gave the measured steady flow and depth required for the chamber to just spill.

These values were calculated for each storm with sufficient data available (see Table 5.4 overleaf). (Note : The flows shown include the correction factor k_i from Table 5.1 where available.)

The measured depth at the transition started around 1400mm during the last three months in 1988, but suddenly leapt up to 1550 $\pm$ 50mm during February - July 1989, suggesting something happened to it over Christmas 1988. Its internal battery ran out in early December, and required recharging, but this is the only unusual incident and doesn't seem likely to have affected previous results.

The weir level was 1550mm above the invert of the incoming sewer, so the later results are all within 4%. This suggests that the calibration could be checked to a few percent by finding the transition to the spilling flow regime on a graph, and comparing it with the weir level.

The old depth transducer broke down in August '89, before there was a chance to recheck its calibration. It was replaced and the logger recalibrated. This was done at the manufacturers, without the extension cable between the logger and sensor, as it would have been difficult to remove the latter from the ducting between sewer and monitoring station. The subsequent results for storms in October and November are on average a little higher than those before the recalibration. At the time it was felt that the extension cable might be causing problems, perhaps due to condensation in the narrow air line to the pressure transducer. From December '89 the logger was installed in the sewer chamber, bypassing the extension cable. However

Date of Storm	Intercept of sub-spill and spill lines		
	Depth (mm)	Velocity (cm/s)	Flow (l/s)
6-Oct-88	1400	47	200
12-Oct-88	1400	49	210
20-Oct-88	1410	49	210
30-Nov-88	1390	46	200
3-Dec-88	1400	44	195
24-Feb-89	1530	44	185
2-Apr-89	1600	48	200
10-Apr-89	1510	44	185
1-May-89	1550	42	180
30-Jun-89	1550	44	185
30-Jun-89	1550	44	185
7-Jul-89	1550	40	200
8-Jul-89	1550	43	185
8-Jul-89	1540	39	165
8-Jul-89	1580	42	180
9-Jul-89	1550	42	180
30-Oct-89	1580	40	170
8-Nov-89	1580	43	190
30-Jan-90	1590	43	175
31-Jan-90	1590	39	175
7-Feb-90	1600	46	190
13-Feb-90	1600	46	190

Mean : 44cm/s 185l/s

Standard Deviation : 4cm/s 15l/s

Table 5.4 Measured values of depth, inlet velocity and flow required for spill.

the unit seemed to continue to slightly overestimate the weir depth. To check further, during March 1990 the orifice was deliberately blocked with a plug (See 4.2.3). While the chamber was spilling the depth reading on the monitor could be checked. It read between 1560-1575mm, showing that it is fairly accurate (to with 2%). When the extension cable was fitted the logger gave a result of 1578mm, but gave a velocity reading of 0.28m/s (without the cable the reading was

0.01m/s). Subsequently the cable was not used, since it appeared to be causing problems.

The flow was calculated from the measured velocity and depth, and so may be biased by the drift in the early depth readings. Plotting measured velocity against depth produced a similar shape to the flow-depth graph (Fig.5.9), with the sub-spill and spilling lines intersecting at the same depth.

The values of velocity were all within about 10% of the mean (44cm/s), which is within the error range of the equipment. The flow results were also within 10% of the mean of 185 l/s. This result was slightly higher than that of 175l/s obtained in section 5.2.2. in part because of higher estimates from earlier storms for which no foul or spill data was available, and in part because of the scatter of the data. However, the differences were still within the accuracy range of the monitors.

By plotting the spill flow against the measured depth ($D_{in}(m)$) it was possible to estimate D_0, the minimum inflow depth necessary for the chamber to spill (Figure 5.10). Thus D_0 was the depth measured when the sewage is just at the level of the weir. A power law relationship was assumed between the spill flow and the height above the weir ($h = D_{in}(m) - D_0$);

$$Q_{in} = b1 \times h^{b2} \qquad \text{(Equation 5.9)}$$

To estimate the coefficients b1 & b2, graphs were plotted of $\ln(Q_s)$ against $\ln(h)$ (Fig.5.11). The index, b2, can be found from the gradient of the line formed by the points, and the coefficient, b1, found from the intercept with the $\ln(h) = 0$ line.

The values obtained are set out in Table 5.5 (Overleaf)

Date of Storm	D_0 (mm)	b1	b2
30-Jun-89 23:20	1550	3.4	1.25
7-Jul-89	1500	5.7	1.75
8-Jul-89 11:00	1540	1.0	1.13
8-Jul-89 16:45	1540	2.9	1.25
8-Jul-89 19:30	1540	1.4	1.25
9-Jul-89	1550	3.4	1.25
8-Nov-89	1590	5.7	1.67
7-Feb-90	1620	2.8	1.33
13-Feb-90	1620	2.8	1.33

Table 5.5 Estimates of the minimum depth required to spill and the coefficients of the equation $Q_s = b1\ h^{b2}$.

Figure 5.12 shows all the data plotted on one graph. The lines shown are the regression of ln(Q) against ln(h) and the regression of ln(h) against ln(Q), and have a correlation coefficient of 0.86. The average of these lines gives the best overall fit, which corresponds to

$$Q_s = 3.9\ h^{1.5} \qquad \text{(Equation 5.10)}$$

Q_s = spill flow in cumecs,
h = height above weir in metres.

There was a lot of scatter on the graph, making the values of a and b a little uncertain. The gradient of the line, which was equal to b, could vary by about 10%.

If it is assumed that the intercept has a similar error range, then because of the exponential nature of the function, the coefficient of $h^{1.5}$ derived from a, 3.9, has an error of about $\pm$ 20%.

When Equation 5.10 was compared with the standard weir equation;

$$Q = 2/3\ C_d \sqrt{2g}\ \times \text{(Weir Length)} \times h^{1.5} \qquad \text{(Eqn.5.11)}$$

it was seen that the two correspond, with the discharge coefficient, C_d = 0.6 ($\pm$20%).

Figure 5.12, showing all the data on a $\ln(Q_s)$ against $\ln(h)$ graph appears to have three branches at low values of flow (<10 l/s). Examination of the data has shown that the branches below and above the regression lines are predominantly due to storms on 8-Jul-89 (18:30) and 9-Jul-89 respectively. During both these events the spill flow was low (rarely above 70 l/s), and the head above the weir small. In such cases a small error in the estimation of D_0 would have a proportionally much larger effect upon $h = (D - D_0)$. Similarly timing discrepancies between the monitors would give an inaccurate value of D for a given Q_s, the effect of which would also be amplified. Such errors appear to cause the results to diverge from the average line at low flows.

The estimates of the minimum depth required for spill were close to those made by examining the $Q_{in} - D_{in}$ graphs, though not identical. The differences were likely to be due to the delay in the effects of the inflow caused by the storage in the system, and the scatter in the results.

Looking at the graphs of the continuation flow against the depth when the chamber is spilling, (ie $D_{in} > D_0$), such as Fig.5.13, it was apparent that the foul flow rose little as the depth increased above D_0. There was too much scatter for an accurate fit, but a rough one was given by

$$Q_c = (Q_c \text{ at transition}) + 0.1\ (D_{in}(m) - D_0)\ \text{l/s} \qquad \text{(Eqn 5.12)}$$

Depths D_{in}, D_0 in mm

Although perhaps not shown clearly by Fig.5.13 the continuation flow rises slowly with increasing depth above D_0 giving a greater than zero value for the coefficient of $(D_{in} - D_0)$. A power law relationship may have been more appropriate, but there was too much scatter to fit one.

5.3 Bottle Sampler Results

The bottle samplers were set up in October 1988, and produced results for 20 storms before they were removed in April 1990.

In order to examine how the analysis results vary, one set of six samples was made up from a mixture of sewage from the spill (The distributor arm on the sampler had jammed, providing a ready made mix in the bottom of the sampler). These were taken to the Laboratories for analysis, and the results shown in Table 5.6.

	BOD (mg/l)	COD (mg/l)	pH	SS (mg/l)	Ash (mg/l)	Amm (mg/l)	Con (uS/cm)
	150	718	6.8	721	415	1.73	765
	148	708	6.8	726	404	1.59	760
	158	765	6.9	776	472	1.61	765
	124	645	6.9	582	352	1.64	760
	152	663	6.9	664	383	1.59	765
	168	871	6.9	864	513	1.58	765
Mean :	150	728	6.9	722	424	1.62	763
S.D. :	13	73	0	66	54	0.05	3

Table 5.6 Results from six subsample of one mixed sample showing mean and standard deviation.

For all but the ash, the standard deviation was 10% or less of the mean.

Twenty four samples were taken at hourly intervals in August 1989, in order to assess the quality of the dry weather flow (Figs.5.14,5.15). The levels of COD and suspended solids were generally between 400-1200 mg/l, although they were higher at 1 and 2 pm. This may have been due to an increase in cooking, washing and defacating at lunchtime, or it may be that there was a discharge from a factory or the abbatoir at around this time. The ammonia peaked at 1am, 8-10am and appeared to peak at 1 - 2 pm at the start of recording. It was thought that this latter lunchtime peak was larger than the others because of the concentration of people working during the day in the industrial areas.

In several of the recorded storms, there was indication of a 'first foul flush', with a peak level of pollutant concentrations at the beginning of the storm, coinciding with, and sometimes preceding, the peak in flow rate. The flushes could have peak COD concentrations of up to five times the typical dry weather maxima, and last up to 20 minutes before returning to levels comparable with those of dry weather. The time since the last rainfall varied between less than an hour to 12 days. In general, the longer since the last storm, the higher the peak in pollutants, and the longer the duration of the flush. This suggested that the flushes contained sediment built up since the previous storm. These results were similar to those of Saul et al[5,6,7], corresponding to 'Type B' storms. In these pollutant levels are greater than those of the DWF, the peak arrives at the same time as that of flow and is affected mainly by the time since the last rain and the rainfall intensity.

In only 7 of the storms were sufficient samples collected to compare the quality of the incoming sewage to that of the outgoing sewage. There did not appear to be any significant difference between the two for any of the seven parameters measured (Suspended Solids, COD, BOD, pH, Ammonia, Non-Volatile Suspended Solids and Conductivity) (Fig.5.16-17).

Because of the method of sampling, it was thought that only particles with relatively low settling/rising velocities were being gathered. There was little sign of any floating material in the samples when they were collected, and some simple tests suggested that only slowly settling material was present. The inlet sample was taken from the middle of the flow. Although there was a drop of 5.6m about 65m upstream, where the sewer runs beneath a canal, it may have been that the flow down to the overflow was insufficiently turbulent to retain complete mixing. Since the samples were drawn up 4-6m into the monitoring station, it is possible that the flow up the tube, being quite slow, did not entrain denser particles.

It was the rapidly rising and sinking particles which model tests suggested are most effectively concentrated in the foul flow. Material with a low settling velocity remains largely unaffected, with concentrations in the foul and spilled flow being close to that of the inflow.

5.4 Gross Solids Monitor Results.

5.4.1 Introduction

The GSM was installed during the Summer of 1988, and produced videos of the flowing sewage with few problems. An over-sensitive pressure sensor caused it to cut out a number of times in the Spring of 1989, but this was replaced. The new sensor continued to trip out occasionally, so it is suspected that pulses in the power supply may be responsible. The pump power supply was rendered inoperative once when a fuse blew.

After the spill sample pipe was repositioned to the weir seven storms of note were recorded and analysed by eye.

The films produced were usually of reasonable quality, with a number of objects being clearly visible as shadows gliding across the image. The pulsing in the flow caused by the action of the peristaltic pump was noticable.

Occasionally the recorded image went dark, at times almost black. This was thought to be because of an increase in sewage turbidity, perhaps caused by the blood etc from the abattoir, which flushed out quite regularly. This had been observed to turn the dry weather flow a deep crimson. The turbidity was often high at the beginning of a storm, most probably associated with the first flush.

There was a gradual build up of scum on the window, which was visible when there was no flow through the cell. However, when even fairly clear sewage was flowing the variance in brightness due to the scum was negligible compared to the turbidity of the sewage, resulting in an almost uniform background. Occasional cleaning of the windows was sufficient to ensure the build up did not become significant. This cleaning was not easy, requiring the removal of numerous fixing screws which held the top window down with a tight seal.

5.4.2 Comparison between computer analysis and human counting.

Attempts to analyse the videos using the image analysis software were eventually abandoned in favour of counting by eye. The main reasons for this were :

i) The image-analyser was inefficient at picking out objects. Often shadows clearly visible to the eye were ignored. In order to avoid too much noise from the background, which could be misinterpreted as objects, quite a narrow intensity threshhold was required, which missed some lighter shadows.

ii) Quite often bubbles appeared on the screen. These usually had one edge sufficiently dark to appear as a crescent shaped object when the frame was threshholded. These were then counted. The number of bubbles could vary enormously from one minute to the next. Tipping the cell at a slight angle to the vertical ensured that the bubbles remain on one side of the window, but at times they could cover half the area, sometimes with a few large bubbles, sometimes with gradually growing rafts of small ones.

iii) Counting by eye suggested there were rarely more than 80-90 visible objects larger than about 3mm passing through the cell in one minute. The image analysis system could take roughly 3-5 secs (depending on how many objects it found) to examine one frame. In order to count a large proportion of the objects passing, one ought to check at least one frame per second. This could be done by repeatedly pausing the video, or by running through it several times, neither very satisfactory. Some objects clung to the window, and gradually crawled across the screen, nudged onward by each peak in flow from the peristaltic pump. They could take 10 seconds or more, to cross the screen, and would thus be counted many times.

The most effective method of using the image-analysis software was found to be by capturing 3 frames in rapid succession. The first and last were averaged to provide a background, which was subtracted from the middle frame, and the result threshholded. This had obvious drawbacks, such as any objects in the middle frame whose position corresponds with objects in the first or last would be lost in the darker background. This would erase slow moving objects, and would be significant when there were many objects. The method coped well with changes in background brightness. However as mentioned above, the software misinterpreted some bubbles, missed objects visible to the eye, and was not quick enough.

Counting by eye has proved quite effective. This involved watching each minute of video identified by the tones and counting objects larger than about 3mm which pass. Depending upon the number of objects and clarity of the image, between 2 and 5 counts were done on each minute. The counts generally varied by $\pm$ 10% from the mean. The errors came from not counting fast enough during dense periods, indecision as to whether certain objects were large enough to be counted and lapses of concentration.

Often objects were made visible by their motion - the eye is very sensitive to relative motion. These would be harder to spot on a still image. The eye has no trouble distinguishing between objects and bubbles, using clues such as their shapes, positions and motions. It usually took about one to two hours to go through each hour of useful video (only one minute in four was identified with tones).

5.4.3 The Reliabitity of Human Counting

The results of two pairs of people counting objects in several sections of film of sewage are set out in Tables 5.7,8.

Mean Object Count/Minute		Ratio
Kate (OC_K)	Tim (OC_T)	(OC_T/OC_K)
25	41	1.65
39	58	1.49
45	64	1.44

Table 5.7 Comparison of numbers of objects counted by different people (I).

Film Section	Mean Object Count/Minute			Ratios		
	Li (OC_L)	Tim (OC_{T1})	Tim one week earlier (OC_{T2})	$\left(\frac{OC_{T1}}{OC_L}\right)$	$\left(\frac{OC_{T1}}{OC_{T2}}\right)$	$\left(\frac{OC_{T2}}{OC_L}\right)$
a	62	46	70	0.74	0.66	1.13
b	39	27	44	0.69	0.61	1.13
c	48	52	55	1.08	0.94	1.15
d	37	28	50	0.76	0.56	1.35
e	71	58	82	0.81	0.71	1.15
			Mean (excluding (c)) :	0.75		
			Standard Deviation :	0.04		
			Mean (excluding (d)) :			1.14
			Standard Deviation :			0.01
			Mean (excluding c&d) :		0.66	
			Standard Deviation :		0.04	

Table 5.8 Comparison of numbers of objects counted by different people (II).

The mean counts were taken from between two and four examinations of each section of film. The individual counts were almost all within 10% of the mean, except for occasional outliers.

The tables suggest that two people would give results when counting that were in a fairly constant ratio. However, it is apparent from Table 5.8 that occasionally one result would be unusually high or low, for example Tim's count for section c of 52 gave much higher ratios (OC_{T1}/OC_L, OC_{T1}/OC_{T2}) than the other results. Similarly Tim's result for section d from the previous week gives a substantially higher value for OC_{T2}/OC_L (and lower OC_{T1}/OC_{T2}). When these two results were ignored standard deviations in the ratios of 6% and less were obtained, though admittedly for a small sample.

The results also suggested that the same person may give different, though consistantly different, counts when examining a sections at different times and under different conditions. It seemed reasonable to propose that during a given session, each person counted a fairly constant proportion of the total number of objects which were actually visible. The proportion depended on the various criteria the person used for judging whether to include a particular object (ie was it sufficiently large), how carefully they watched the screen (some objects hid near the edge, or became obscured near bubbles) the brightness and contrast of the monitor used to show the film and the illumination in the room. These factors may vary from person to person and from day to day. Occasionally after going through a storm, its first few minutes were returned to and recounted. The numbers obtained were close to those counted the first time, which suggested that the results for one session were likely to be consistant, and that it was reasonable to compare the results from the spill with those from the inlet in the same storm.

It was considered that the method used was reasonably reliable in estimating the relative concentrations of objects during different parts of a storm, as long as all the sections were counted under the same conditions, preferably with only short breaks between sections.

5.4.4 Results from Gross Solids Monitor.

Examining the seven recorded storms by eye suggested a significant (about 25-40%) decrease in the number of objects visible in the flow drawn from the spill compared with those in the inlet sample (Fig.5.18-23, Table 5.9). The flow through the cell is fixed at about 3 l/s, so the number of objects counted in a minute is a measure of the concentration of such objects in the storm sewage.

Start Date	Duration (mins)	Number of mins of data		Mean count (objects/min)		Reduction in spill objects counted
		Inlet	Spill	Inlet	Spill	
30-Jun-89	55	4	3	21	10	53%
20-Oct-89	45	4	2	46	39	15%
22-Oct-89	55	6	6	9	6	33%
8-Nov-89	300	12	11	56	34	39%
14-Dec-89	240	17	19	34	24	29%
16-Dec-89	150	14	13	39	29	26%
21-Dec-89	90	2	2	71	55	23%

Table 5.9 Summary of results from GSM recordings. The mean count is a measure of the concentration of visible objects in the storm sewage.

The number of objects could vary considerable during a storm (Fig.s 5.18-23). Typically it was high initially, decreasing as time went on. Secondary peaks in storm flow could produce increases, and there also seemed to be occasional jumps in numbers, perhaps as a result of discharges into the sewer from the abattoir etc.

The results during 1989 (except on 21-Dec) were all produced with the inflow inlet pipe halfway up the incoming pipe, with its end cut at an angle (Fig.4.6i). The spilling sewage was sampled with a pipe cut off horizontally (Fig.4.6iii). This may have caused differences in the types of object drawn up, and may have been one reason for the apparent reduction in spilling object concentration compared with that of sewage entering the chamber. On 18 December 1989 a new inlet was fitted (Fig.4.6ii) but only one short storm was recorded with the new configuration, this giving insufficient results to draw any conclusions. In February 1990 the spill sample pipe was adjusted with an angled cut-off (Fig.4.6iv). The equipment was maintained until the end of May 1990 in the hope of catching a storm, but it was not to be. No heavy rainfall occurred in the period.

5.5 The Nature of the Gross Solids

5.5.1 Introduction

It proved difficult to assess the settling velocities of particles of material in the sewage, even to obtain a crude estimate of the values.

The samples taken by the bottle sampler contained almost no floating material at all, and what little sinking material tended to be only fine particles.

The samples taken in bottles directly from the dry weather flow contained more material, but again very little floating particles. The settling material contained small (<1mm) objects and much fibrous matter. When this was in the tube, it tended to become clumped up, the denser particles being bound up by the loose fibres. These clumps made their way gently to the bottom at low speed (less than 10mm/s).

Although this might have happened in the sewage, it was suspected that these clumps would be less likely to form, with the turbulence of the flow ensuring a less concentrated mixture of matter than would be obtained if it were allowed to settle.

Samples taken with the Copasacs produced more material to work with, but it was not known how being collected in a net affected the settling characteristics of the matter.

5.5.2 Results of Tests on Gross Solids

Unfortunately the Copasacs did not arrive early enough for many tests to be done using them. They seemed to prove quite effective at trapping material in the flow. Typically they gathered bits of tissue and hand towels, blood clots (from the abbatoir, it was assumed) lumps of the more sturdy faecal matter, vegetable matter (leaves, twigs and occasional bits of salad) and many unidentifiable objects.

Table 5.10 shows the quantities of material gathered, and an estimate of the concentration. The concentration of suspended solids in a bottle sample collected mid-morning was about 1000mg/l.

Day & Time	Time in flow	Estimated Volume passed through sack	Weight whilst wet	Estimate of concentration (Wet weight)	Estimate of concentration (Dry weight)
2-May 10am	60s	900l	310g	340mg/l	40mg/l
9-May 11am	100s	1500l	250g	170mg/l	20mg/l
15-May 10am	100s	1500l	850g	560mg/l	75mg/l
15-May 10am	100s	1500l	650g	430mg/l	45mg/l
22-May 10am	90s	1350l	870g	640mg/l	80mg/l

Table 5.10 Weight of Material Caught from Dry Weather Flow by Copasacs

The dry weight of the material gathered on 15 May 90 was found by drying and weighing a subsample. It was found that the dry weight is about 1/8 of the wet weight. This figure was used to estimate the dry weight of the other results.

The figures given for the concentration suggest gross solids account for about 2-8% of the material in the flow. This is likely to be an underestimate, since some material will have been washed through the sack. Finer matter that may have been caught by the fibres of the rags could have been scoured off, but equally the semi-clogged sack may have acted as a coarse filter to trap more material later in the sampling period.

The breakdown into Floaters and Non-Floaters (strictly that not on surface - this figure will include the material which neither floats nor sinks) is shown in Table 5.11. The result for the non-floaters on 9-May-90 was produced while the method was being developed, before the plankton net was used to capture material, and an unknown amount of matter escaped down the sink.

Sample	Wet weight conc. (mg/l)	Dry Weight (mg/l)	
		Floaters	Non-Floaters
9-May-90	170	3.5	(6)
15-May-90 (a)	560	2.5	73
15-May-90 (b)	430	2.5	44

Table 5.11 Dry weight concentrations of floating and sinking material.

The examination of the velocity distribution proved quite difficult. As with earlier tests, fibrous matter, of which there was a great deal, entangled everything together if there was too much in a given subsample. The floating material was less hindered by this problem, since except for small shreds, the tissue and towel waste seemed to sink slowly. The samples gathered from the bottom were badly affected, several runs having to be aborted due to the sample forming one slowly sinking clump, even with quite small samples.

One factor that was noticed when counting the floaters was that some of them had trapped small air bubbles which were giving them buoyancy.

Some of the material that was floating on the surface of the bucket promptly sank when put in the tube, and similarly some of the samples from the bottom of the bucket floated. It was assumed that floaters and sinkers had become loosely bound together, some clumps floating, some sinking. Disturbing the clumps broke some of them up.

The tests typically ran for 80 seconds, sufficient for all the material with a sinking/rising velocity of greater than 15mm/s to reach the bottom or top of the tube. It was estimated that between one quarter and one third of all the material was counted in this time. This suggested that about 75% of the solids in the flow have settling velocities of less than 15mm/s.

Summaries of the results for the particles counted are shown in Tables 5.12,13 (See following two pages).

Velocity Range (mm/s)	Percentage of Measured Sinkers in Range		
	15-May-90 (342 objects)	22-May-90 (625 objects)	Overall Result
15 - 19	11.5	15.0	13.5
20 - 24	20.5	22.5	22.0
25 - 29	14.0	17.5	17.0
30 - 34	11.5	13.0	12.5
35 - 39	12.0	11.0	11.0
40 - 44	6.5	7.5	7.5
45 - 49	3.5	4.5	4.0
50 - 54	3.0	1.5	2.0
55 - 59	3.0	1.5	2.0
60 - 64	2.5	1.0	1.5
65 - 69	2.5	1.0	1.5
70 - 74	2.5	1.0	1.5
75 - 79	2.5	1.0	1.5
> 80	4.5	2.0	2.5

Table 5.12 Distributions of Settling Velocities of the Approx. 25% of Sinking Material in the DWF with V_s>15mm/s.

Some of the samples of sinking matter were perhaps biased toward the faster sinking end by the technique of removing slowly settling tissue waste by repeatedly diluting and decanting off the top layers of mixture. This was done on some samples in order to remove the fibrous matter which tends to form webs which clump the whole sample together, preventing the distribution from being assessed.

The tables above show the results for a series of samples taken on two days. It can be seen that there are differences between results from different days. These are of similar order to differences between samples on the same day, and are not surprising, sewage being such an inhomogeneous mixture. It would require the average of many samples to get a reasonably repeatable result, if it is possible at all.

Velocity Range (mm/s)	Percentage of Measured Floaters in Range		
	9-May-90 (45 objects)	15-May-90 (162 objects)	Overall Result
15 - 19	29.0	16.0	18.5
20 - 24	29.0	11.5	16.0
25 - 29	5.0	6.0	6.5
30 - 34	8.5	10.0	10.0
35 - 39	11.0	9.5	9.0
40 - 44	6.0	12.0	11.5
45 - 49	5.0	7.5	6.5
50 - 54	3.0	4.0	3.5
55 - 59	3.0	4.0	3.5
60 - 64	1.5	2.5	2.5
65 - 69	0	2.5	2.5
70 - 74	0	2.5	2.0
75 - 79	0	2.5	2.0
> 80	0	7.5	6.5

Table 5.13 Distributions of Settling Velocities of the Approx. 25% of Floating Material in the DWF with V_s>15mm/s.

The crude method chosen, that of counting the number of objects reaching the top or bottom of the pipe during given time intervals, gave a rough estimate of the distribution of particles with given velocities. However it may be misleading to use this distribution as if it were one of mass. The greater tendancy a particle has to sink, the denser it is likely to be. Thus a distribution of percentage mass with a given settling velocity is likely to be accentuated more toward the fast sinking end of the spectrum than the equivalent distribution of numbers of particles. This assumes that the particles are of approximately similar size, which is rarely true.

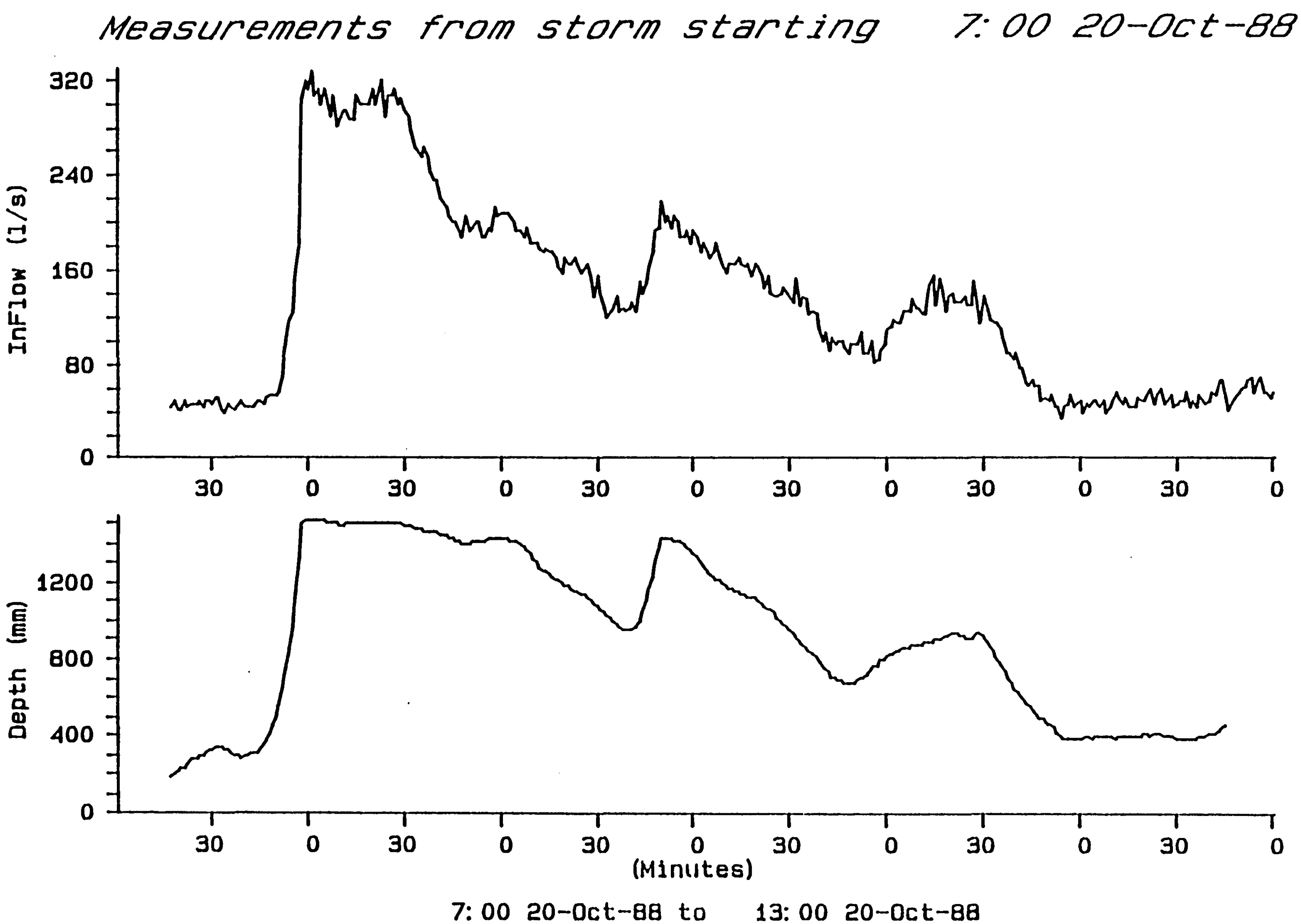


Figure 5.1 Typical Flow and Depth Measurements from the Monitor at the Inlet

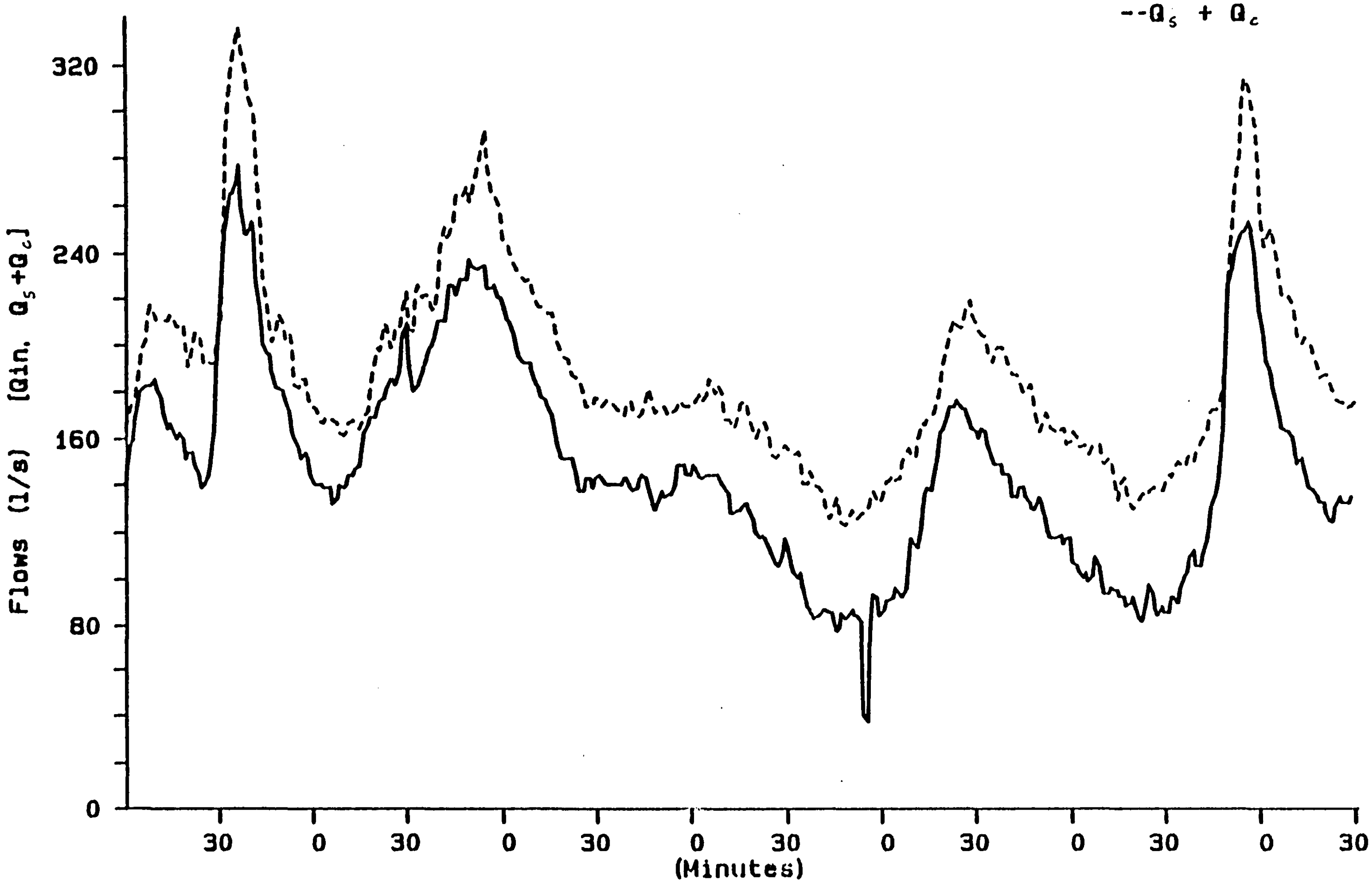


Figure 5.2 Comparison Between the Measured Inflow and the sum of the Measured Continuation Flow and Spill Flow

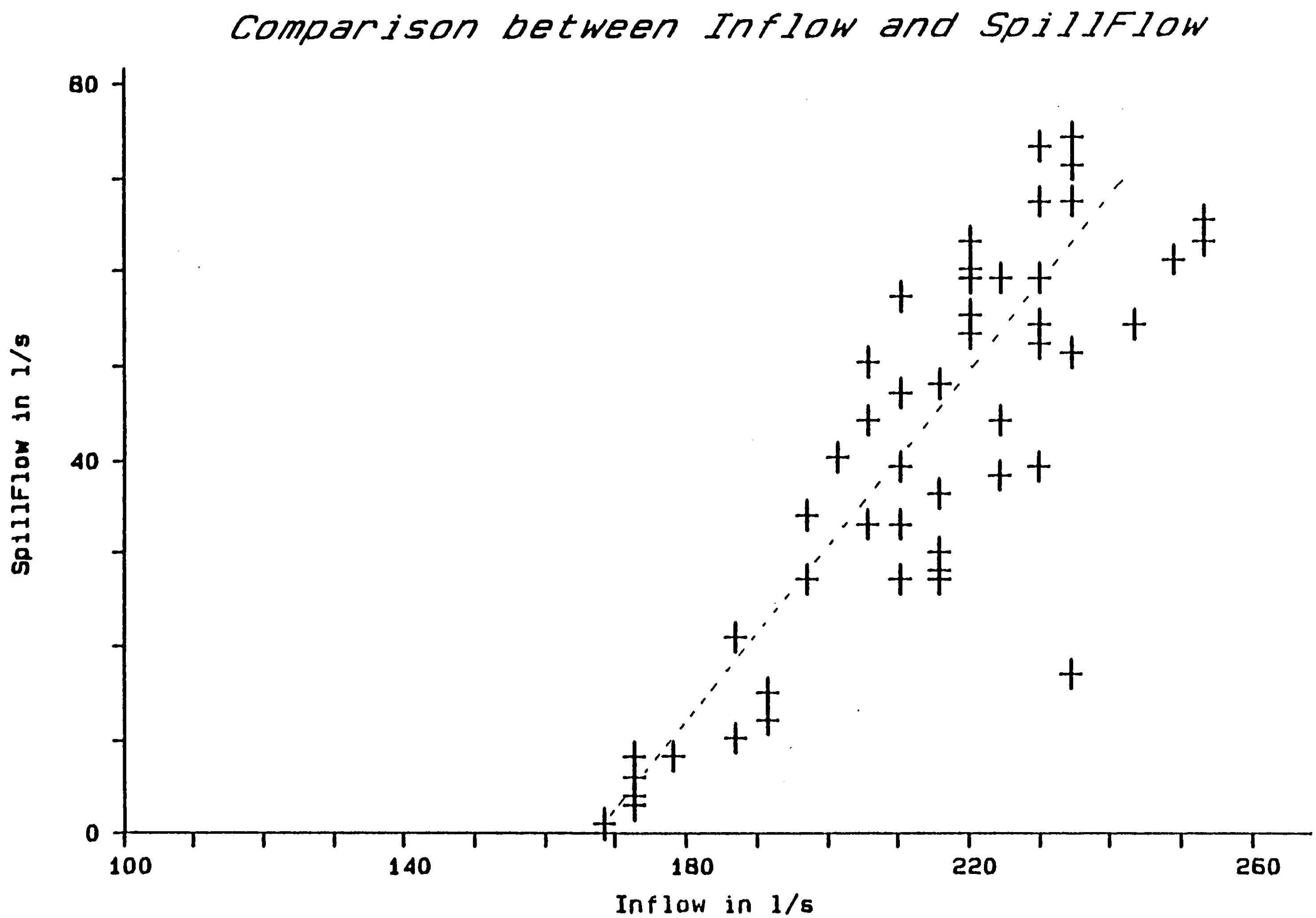


Figure 5.3 A Plot of the Spill Flow against the Inflow for a Storm on 9-July-89 0:30 - 2:30

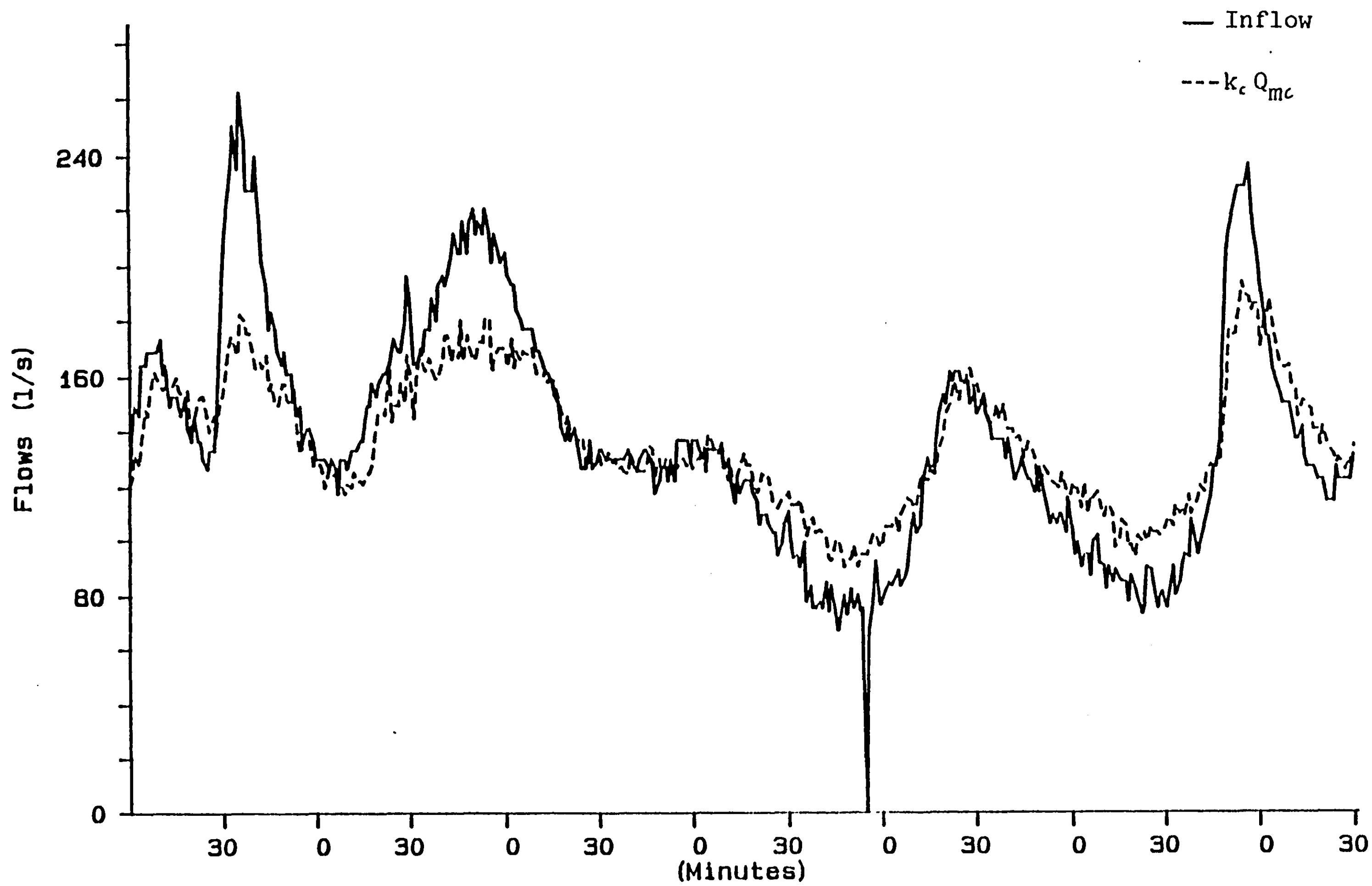


Figure 5.4 Comparison Between the Inflow and k_c x (Measured Continuation Flow) (k_c = 0.75) (7-Feb-90)

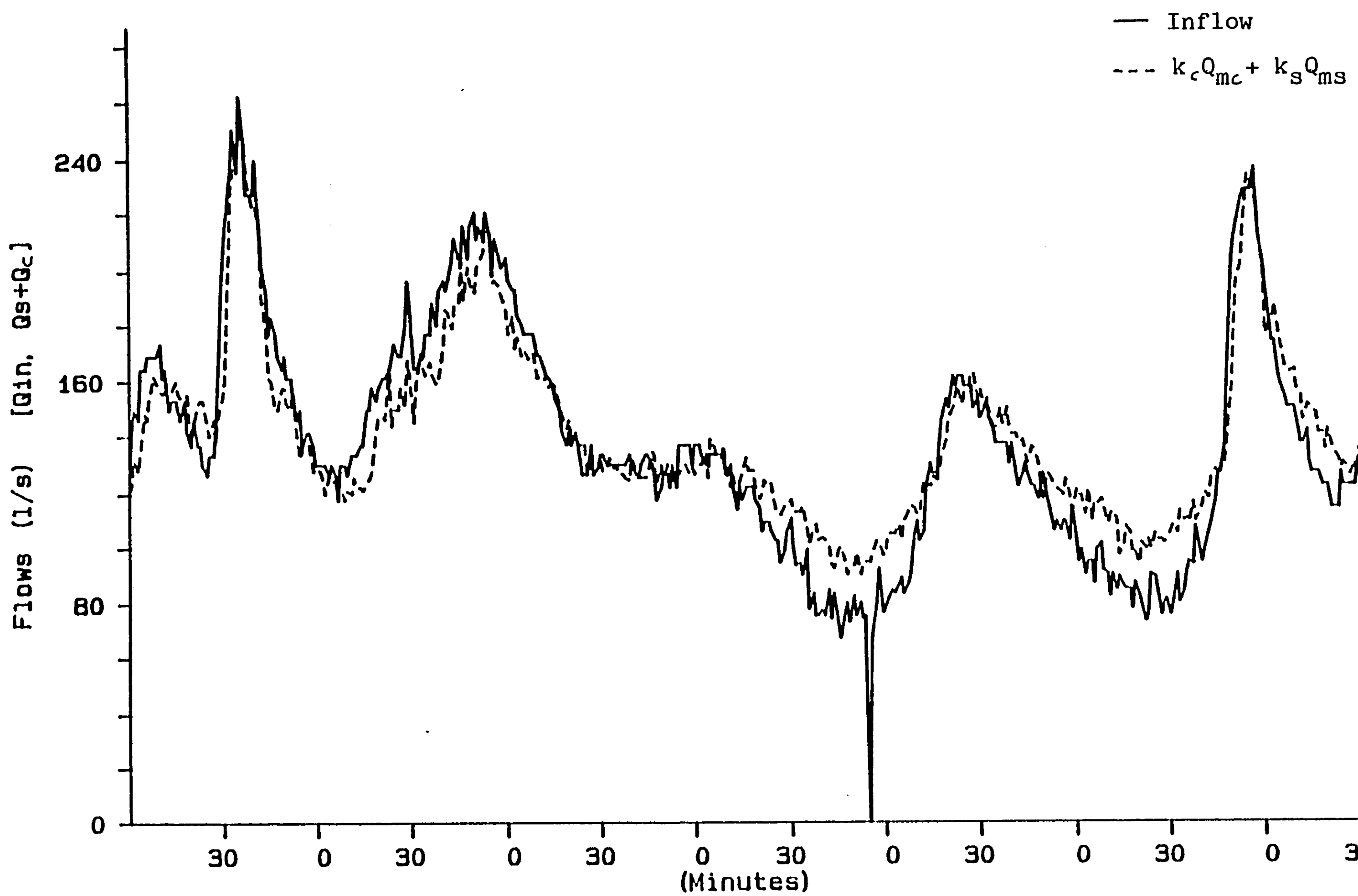


Figure 5.5 Comparison Between the Inflow and the sum k_c x (Measured Continuation Flow) + k_s x (Measured Spill Flow) ($k_c = k_s = 0.75$)

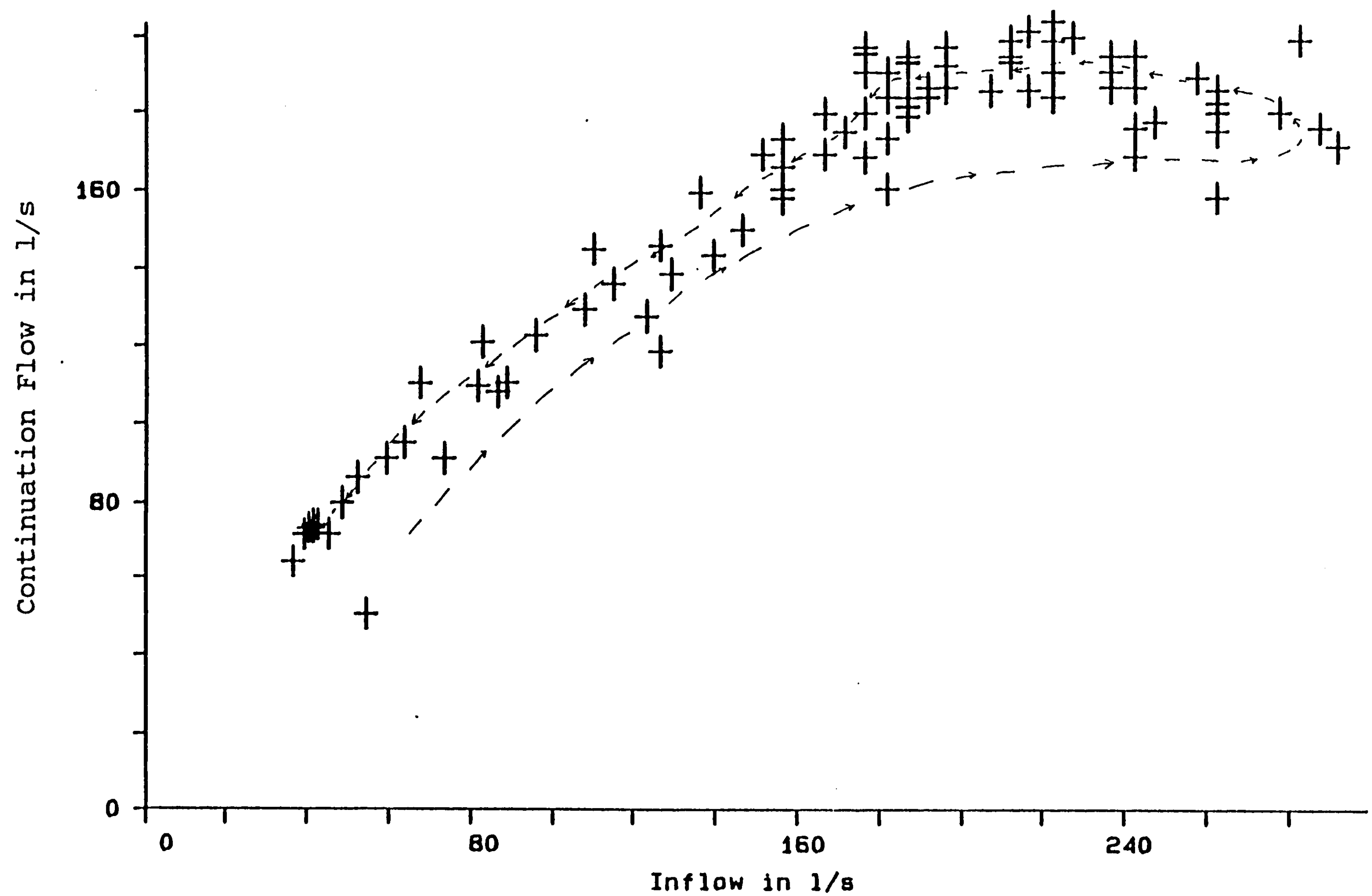


Figure 5.6 A Plot of the Continuation Flow against the Inflow for a Storm on 30-Jun-89 22:50 - 1:00

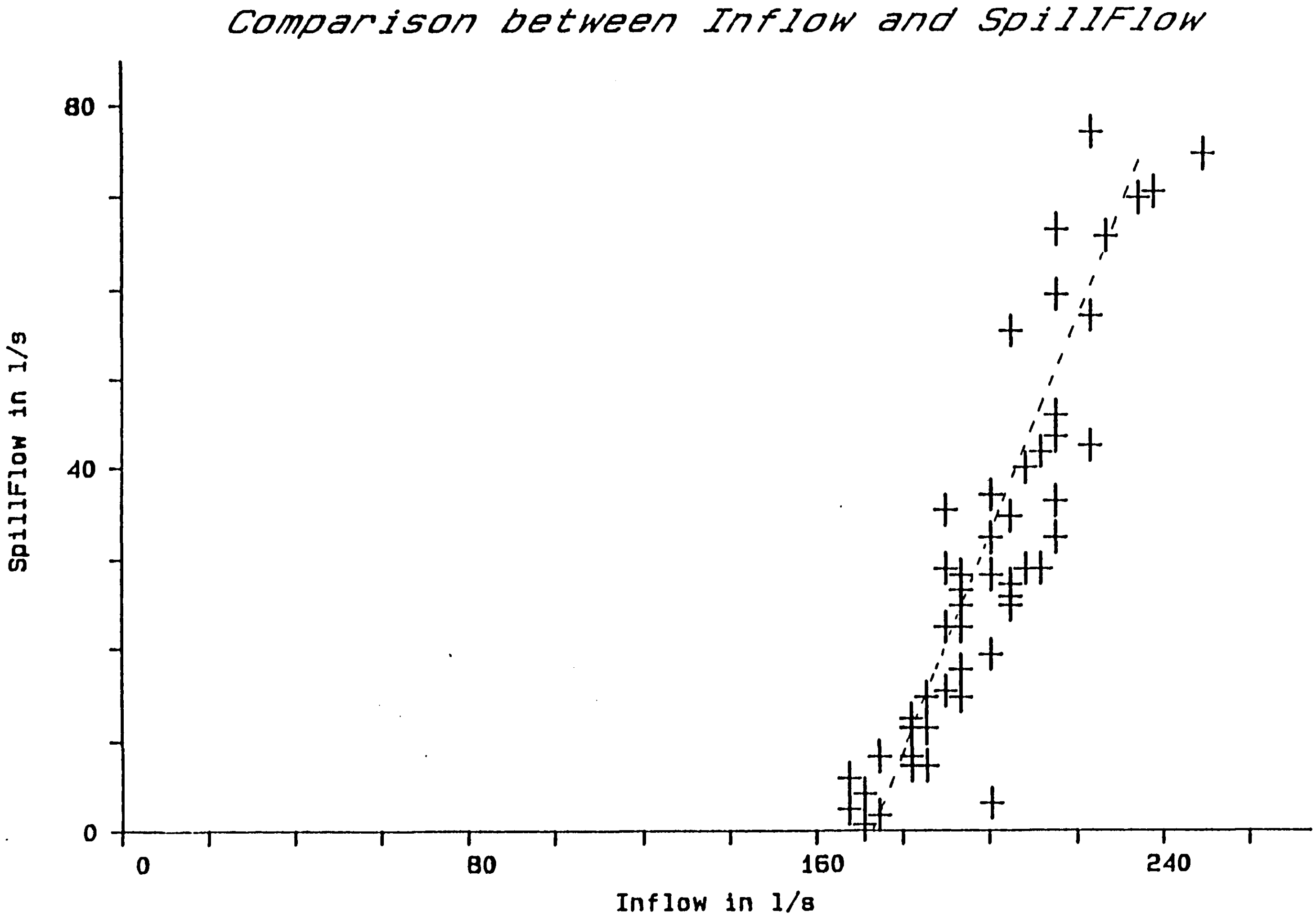


Figure 5.7 A Plot of the Spill Flow against the Inflow for a Storm on 7-Feb-90

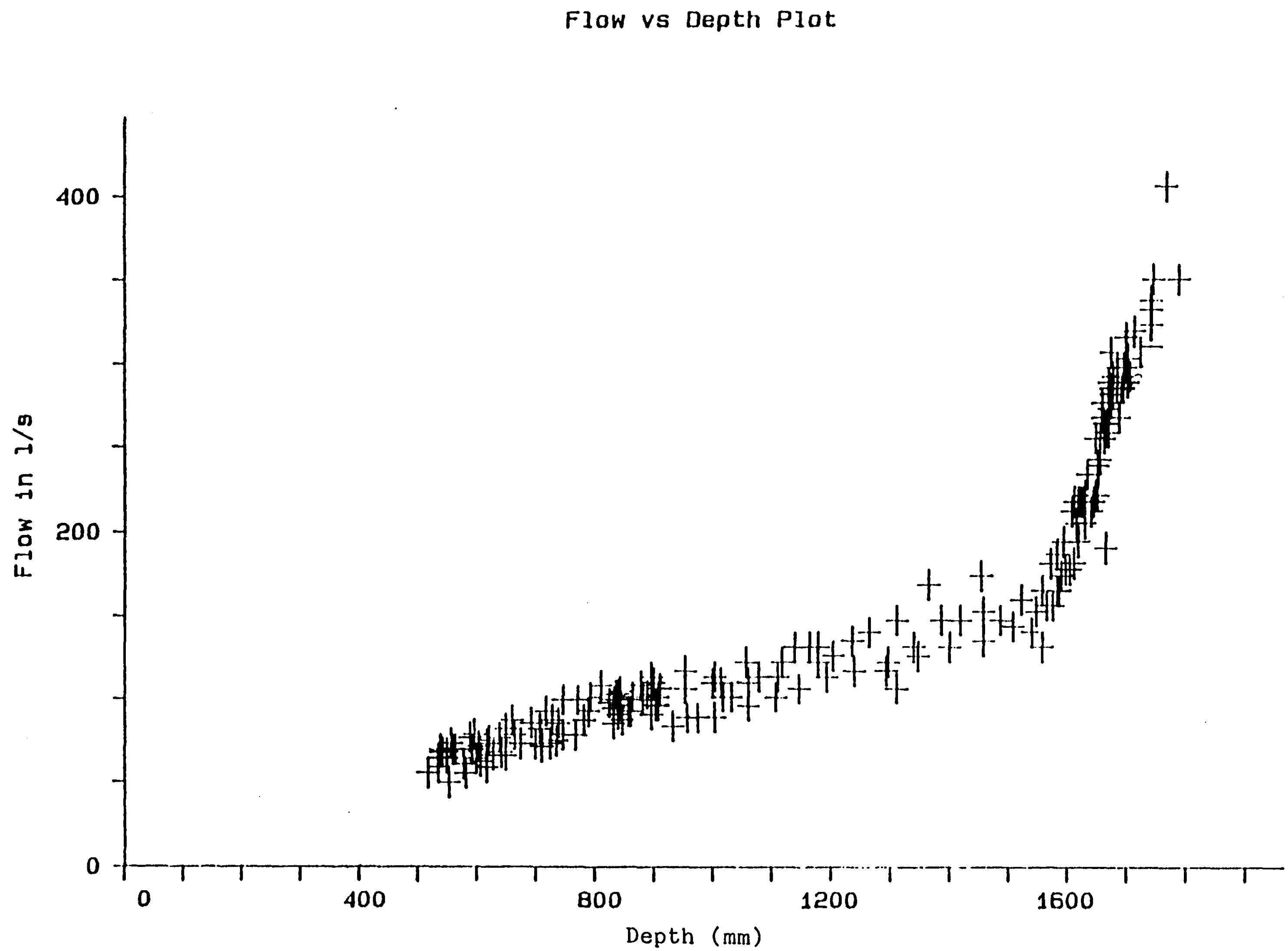


Figure 5.8 A Graph Showing the Relationship Between Measured Depth and Inflow for Storms on 7&8 July 89.

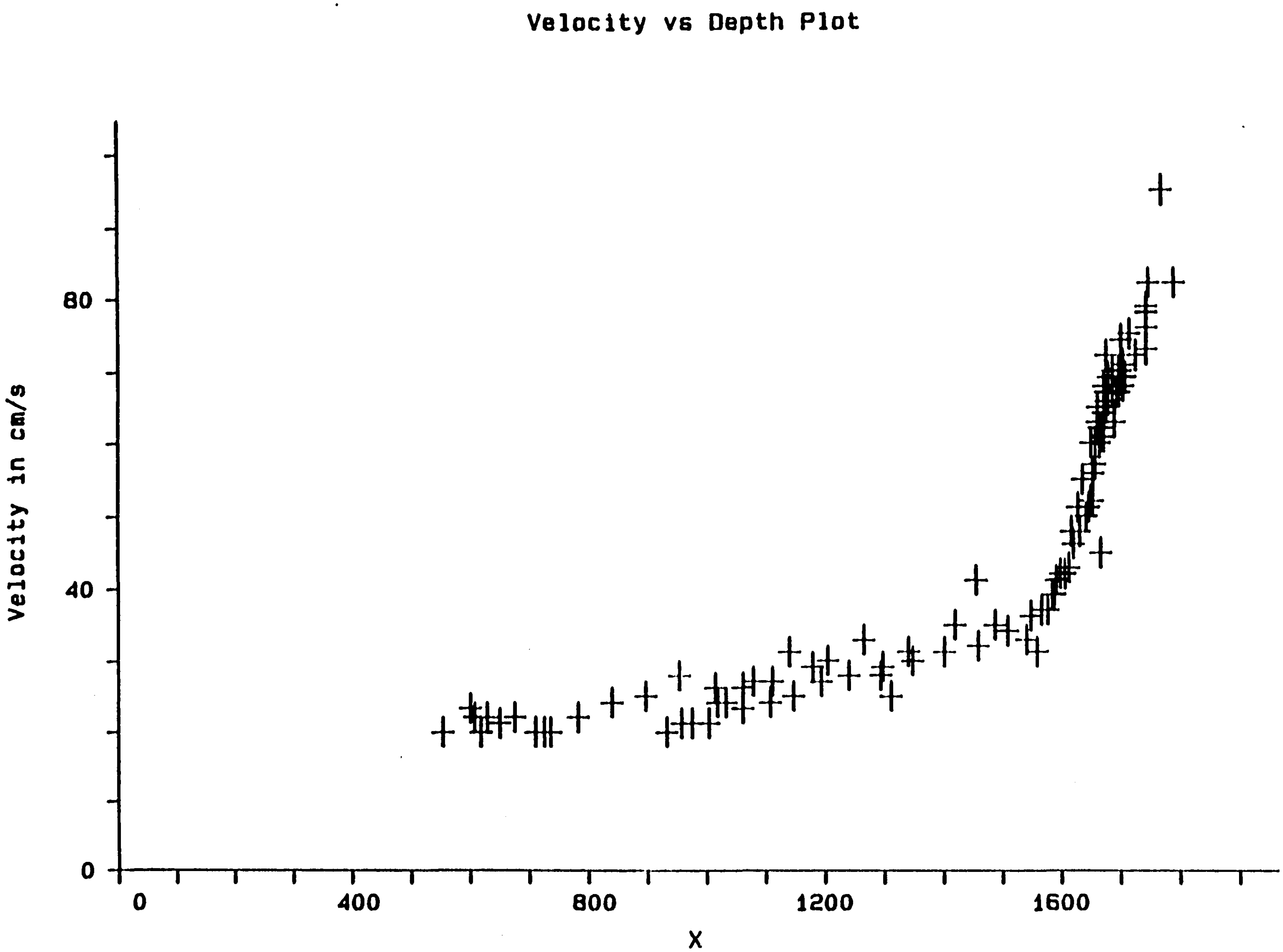


Figure 5.9 A Graph Showing the Relationship Between Velocity and Measured Depth for a Storm on 7 July 89.

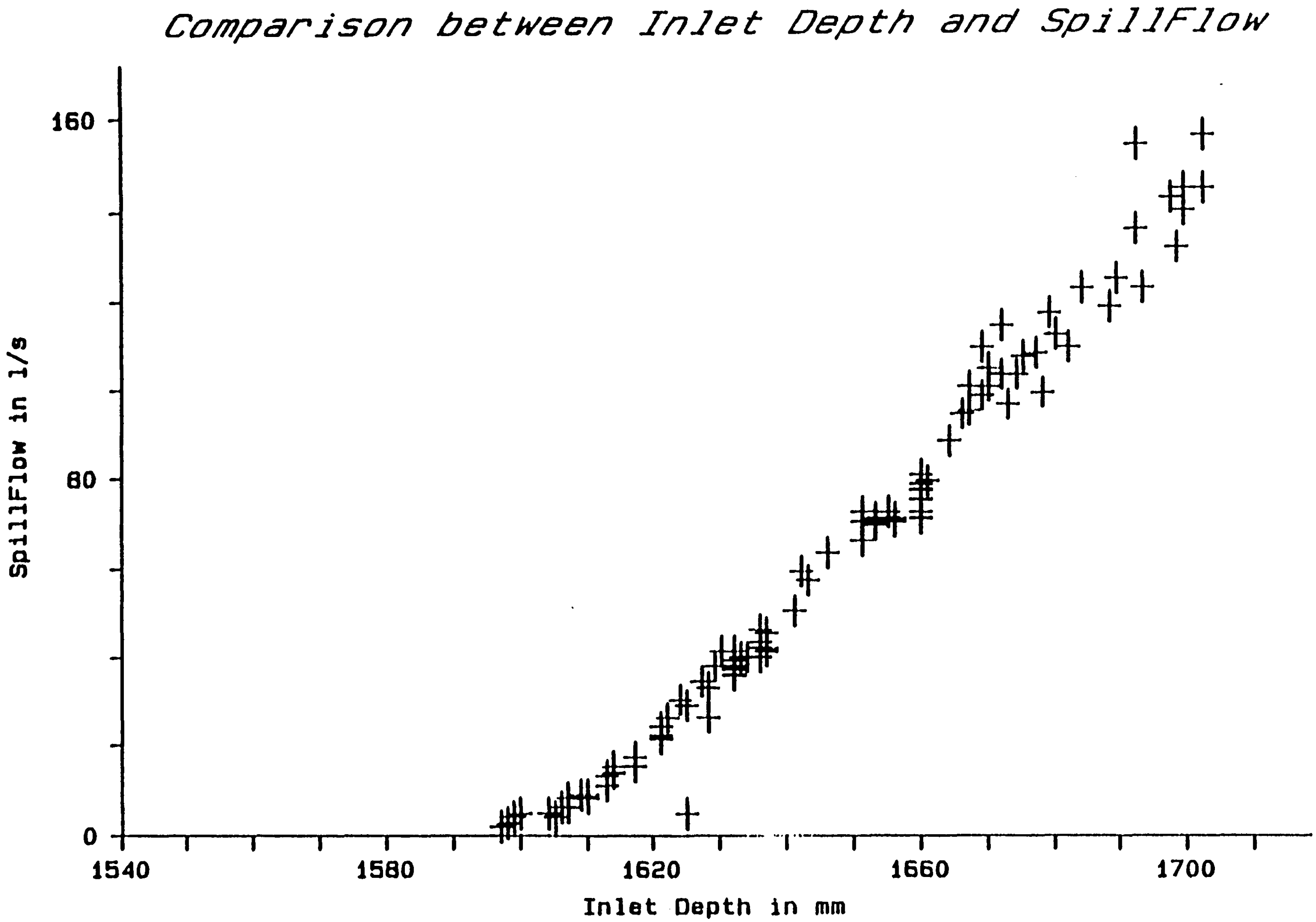


Figure 5.10 A Graph Showing the Relationship Between Spill Flow and Measured Depth for a Storm on 8-Nov-89.

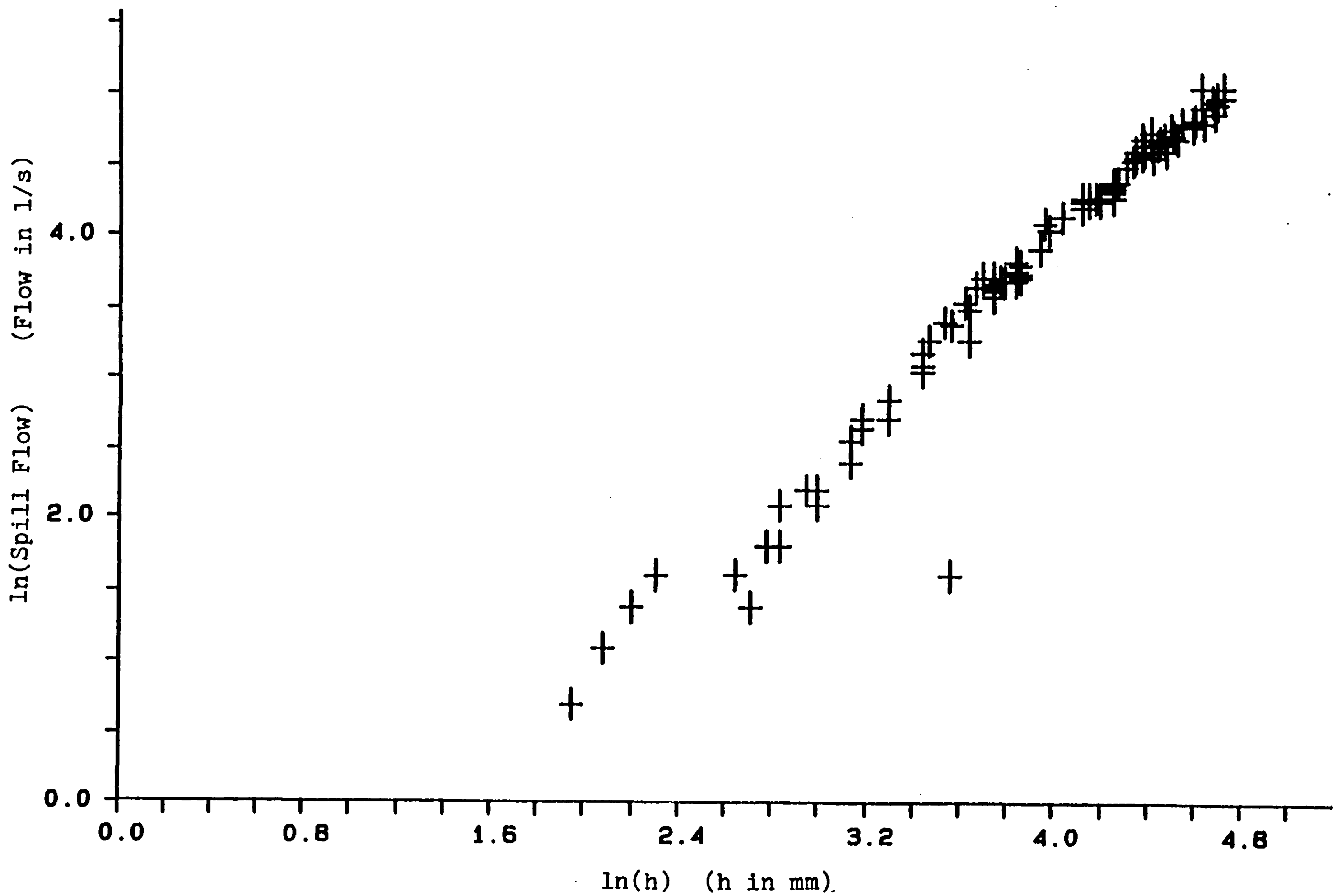


Figure 5.11 A Graph Showing the Relationship Between ln(Spill Flow) and ln(Head above Weir) for a Storm on 8-Nov-89

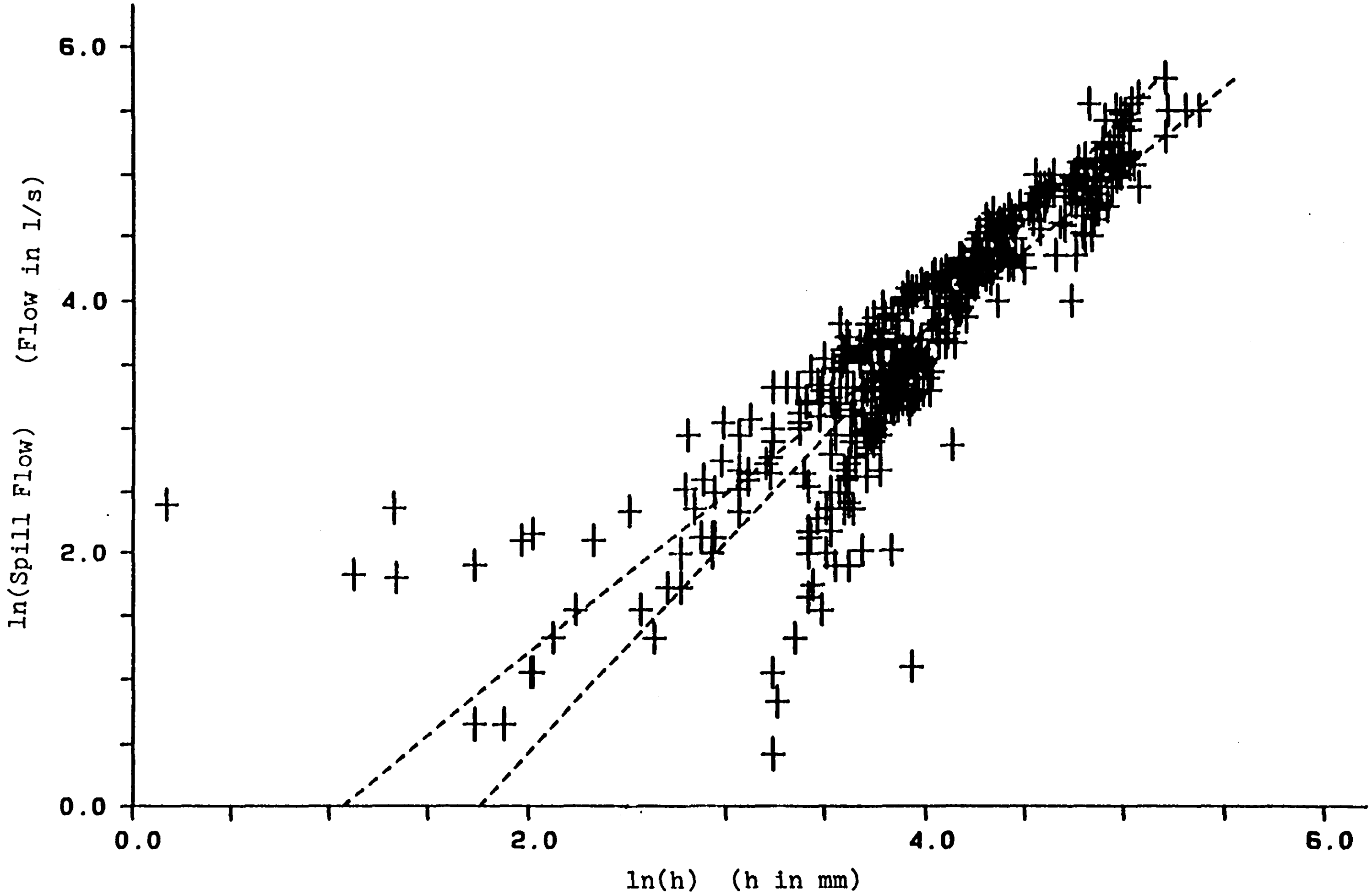


Figure 5.12 A Graph Showing the Relationship Between ln(Spill Flow) and ln(Head above Weir) for all available data.

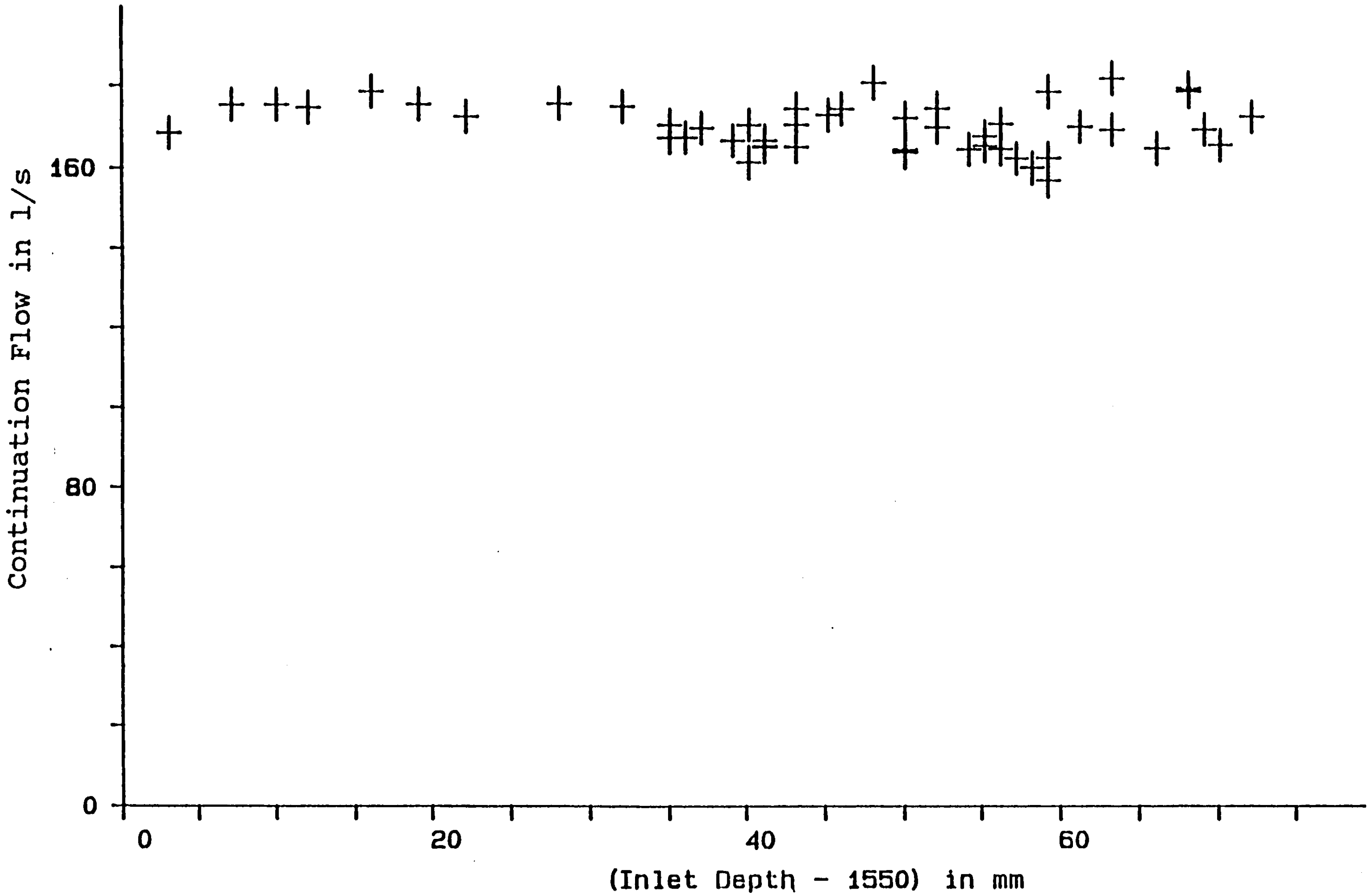


Figure 5.13 A Graph Showing the Relationship Between Continuation Flow and Measured Inlet Depth for a Storm on 9-Jul-89.

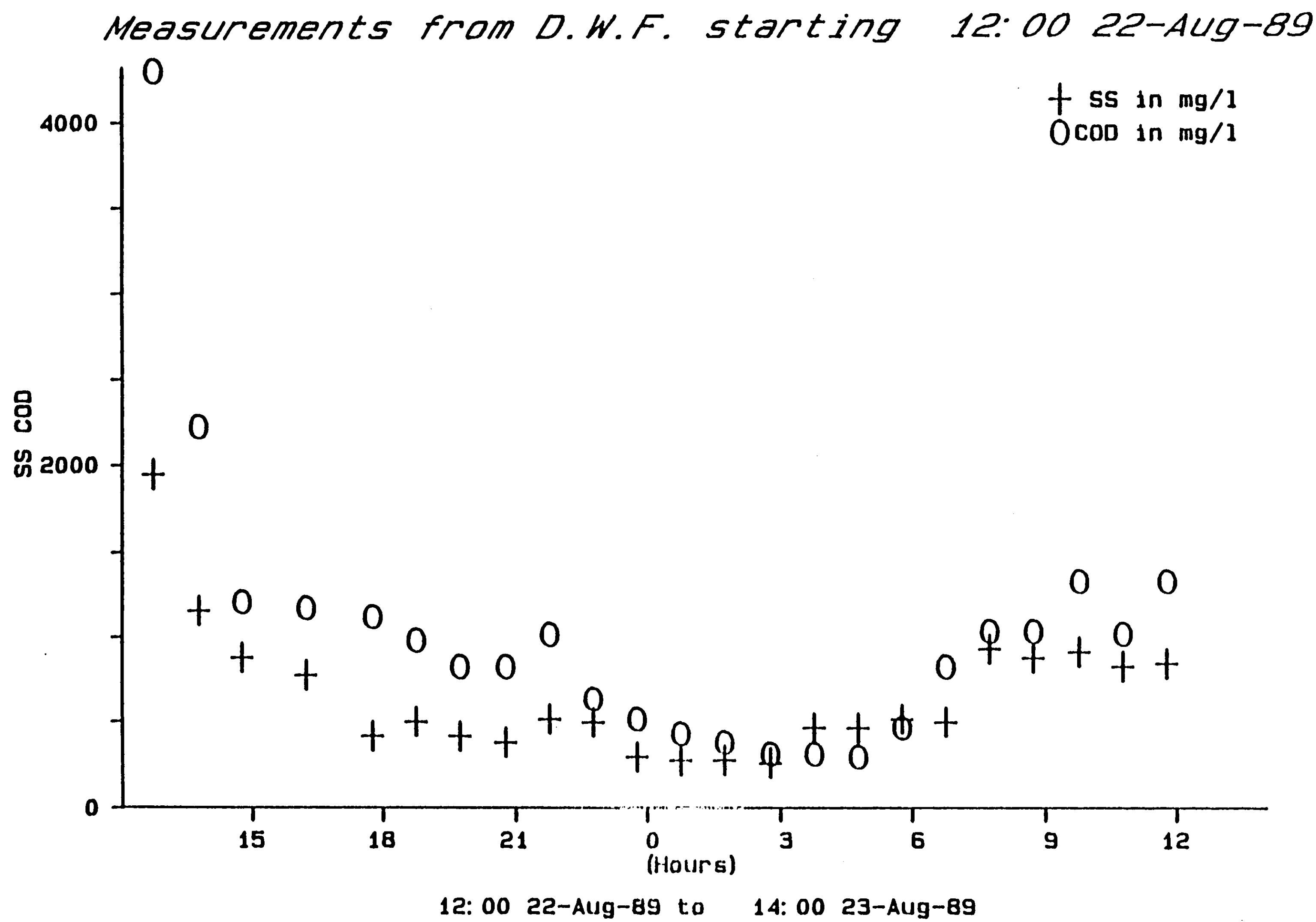


Figure 5.14 Suspended Solids & COD from Samples of Dry Weather Flow 22-23 August 1989

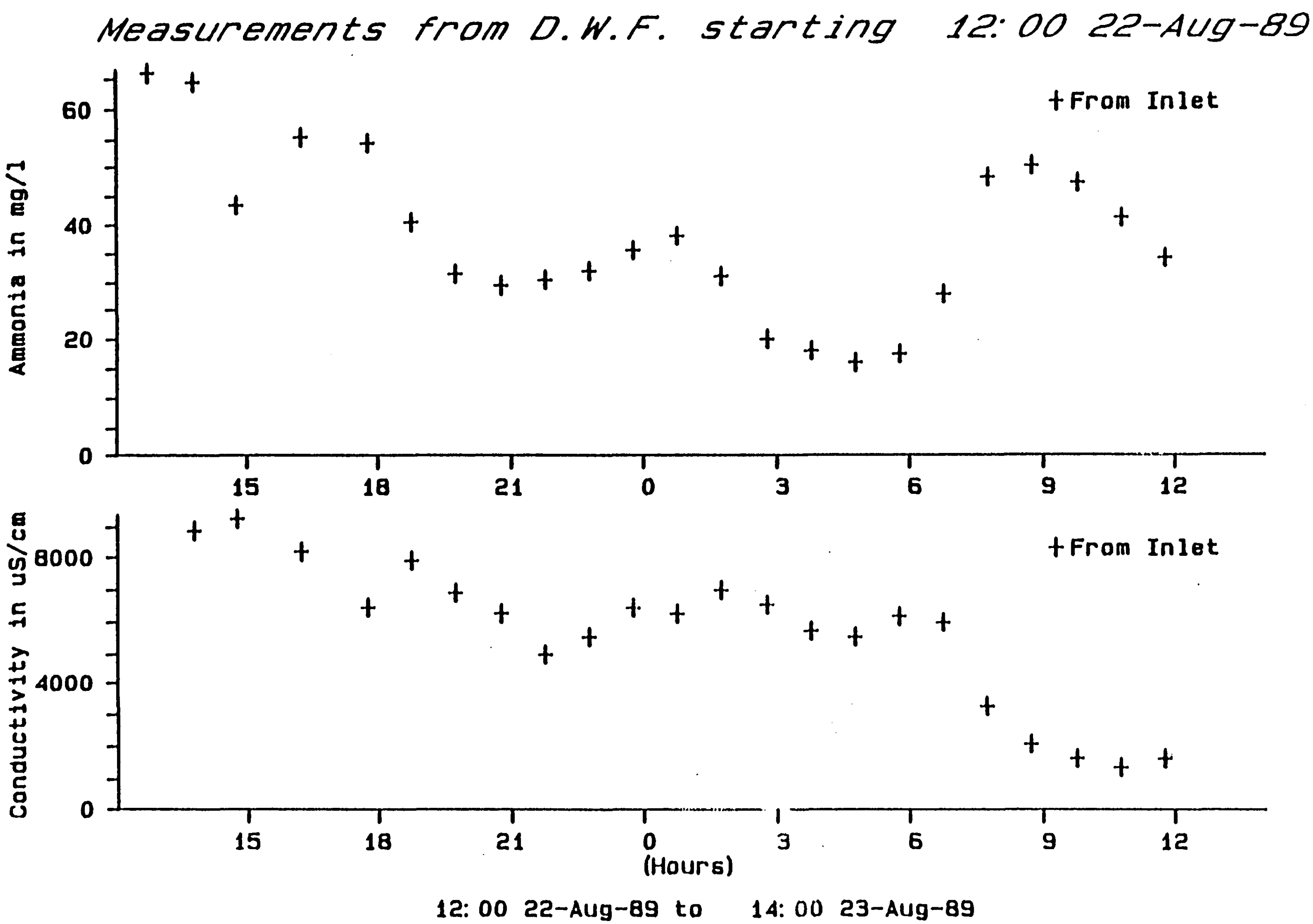


Figure 5.15 Ammonia and Conductivity from Samples of Dry Weather Flow 22-23 August 1989

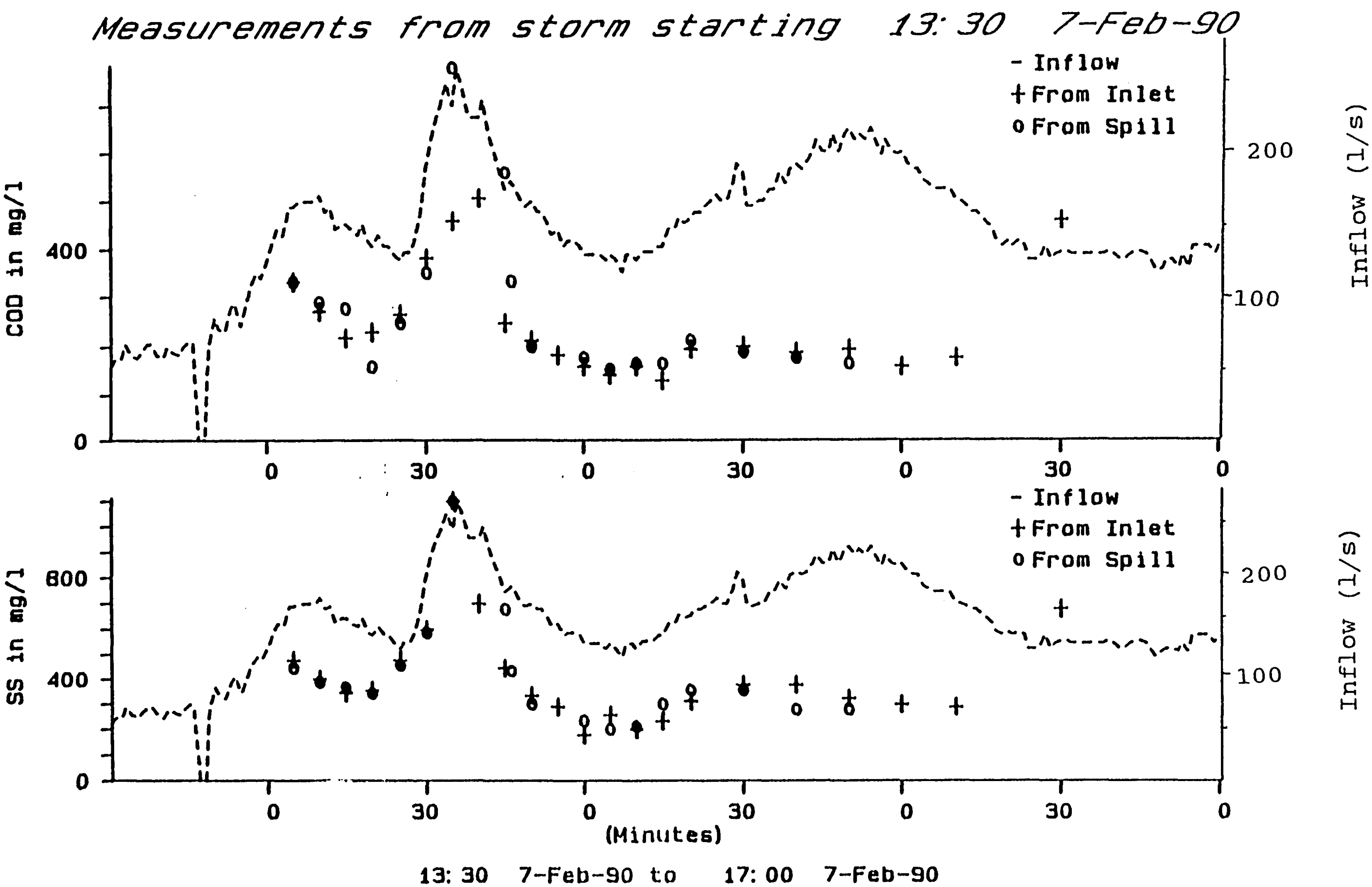


Figure 5.16 Comparison Between Bottle Samples from Inflow and Spill Flow Taken on 7-Feb-90. (Suspended Solids & COD).

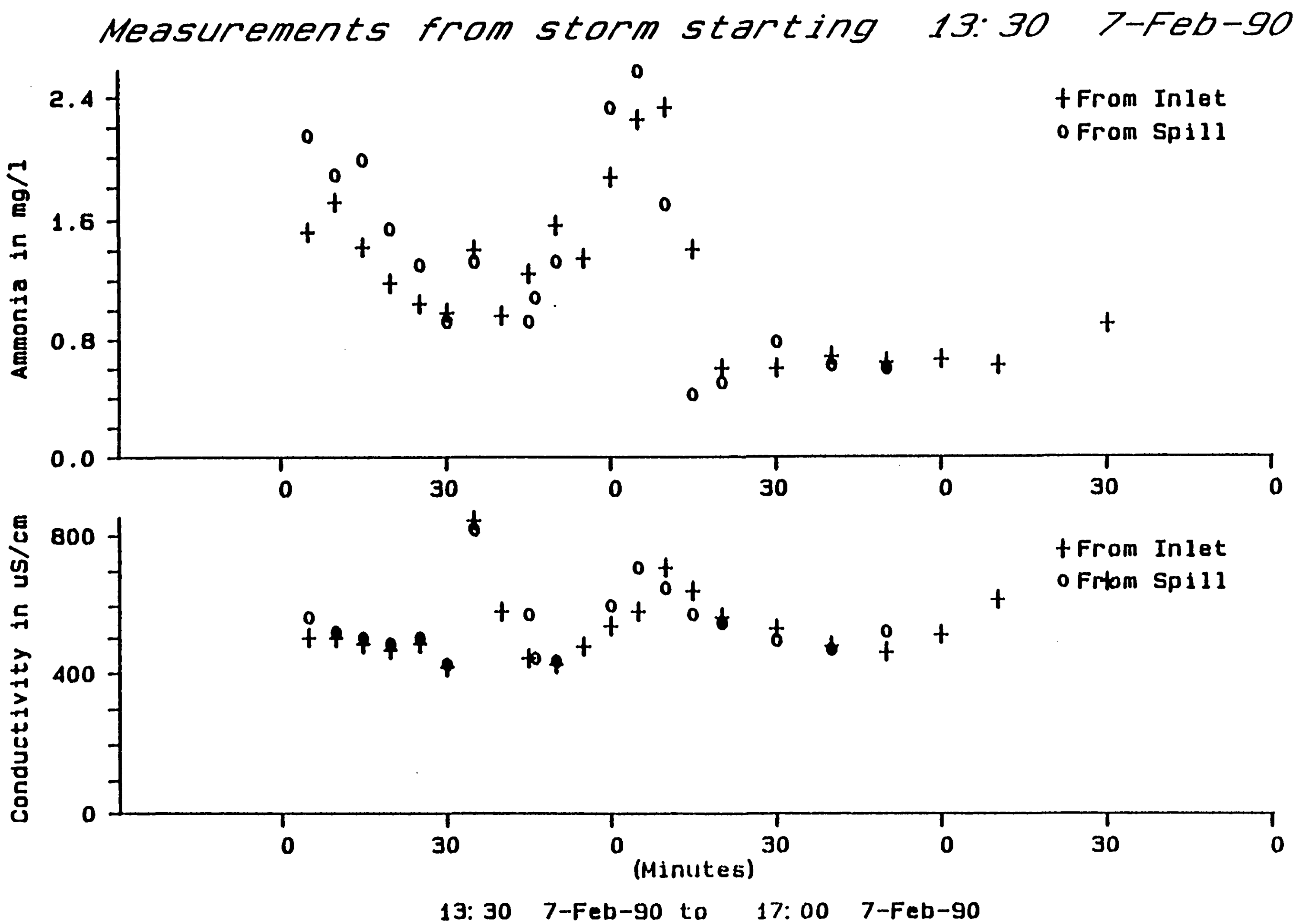


Figure 5.17 Comparison Between Bottle Samples from Inflow and Spill Flow Taken on 7-Feb-90. (Ammonia and Conductivity).

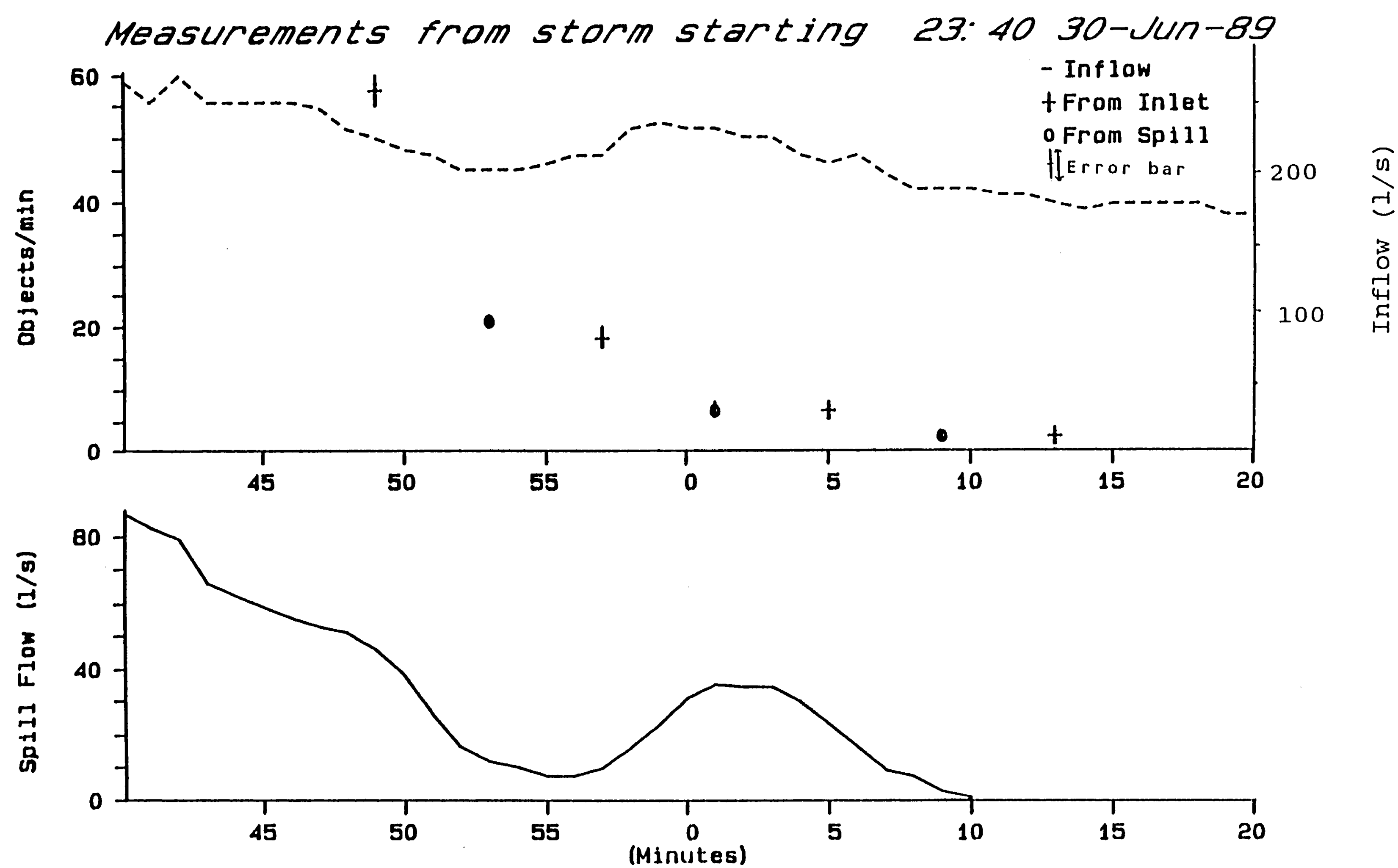


Figure 5.18 Objects Counted on Film from Gross Solids Monitor with Inflow Superimposed (30-Jun-89)

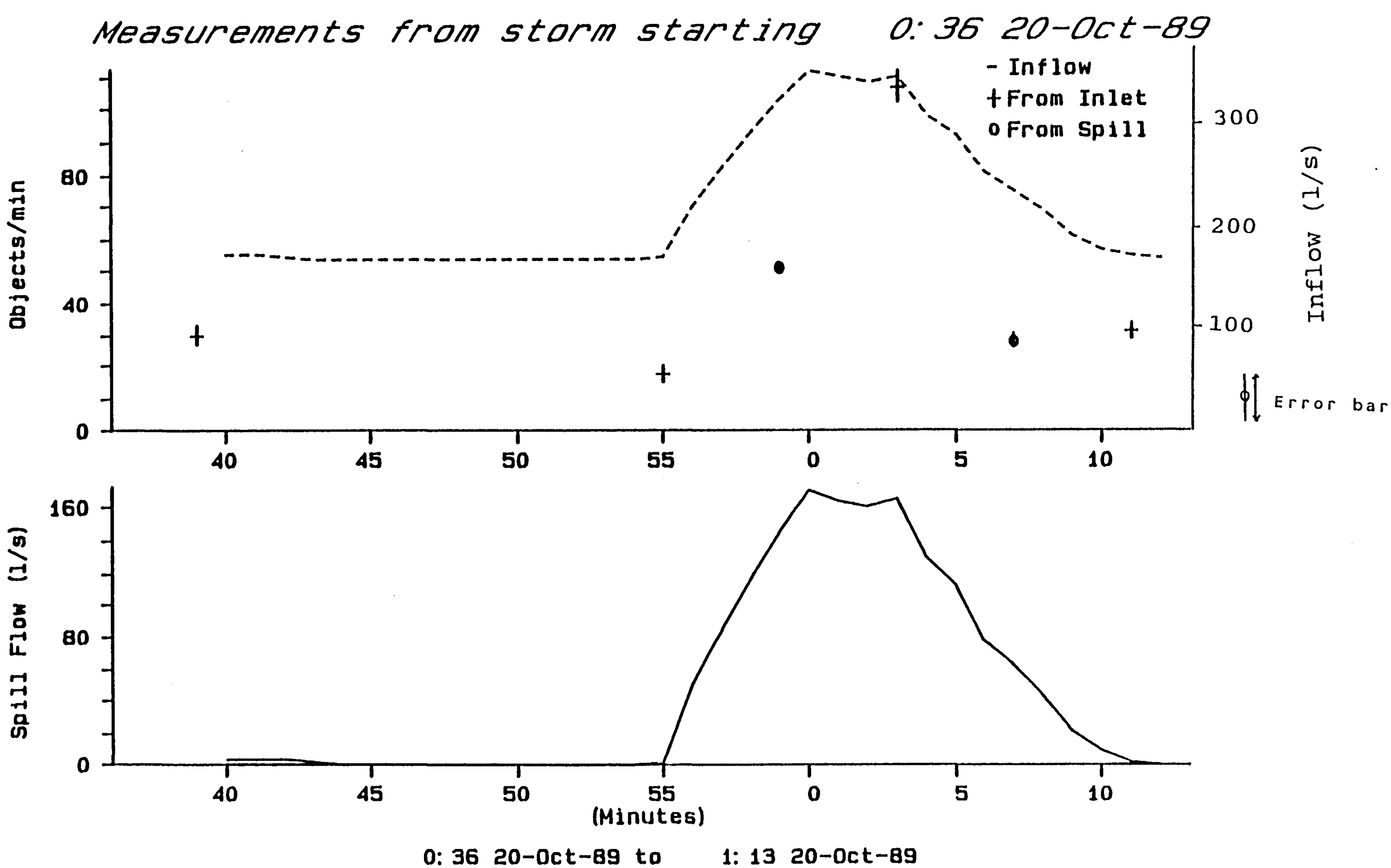


Figure 5.19 Objects Counted on Film from Gross Solids Monitor with Inflow Superimposed (20-Oct-89)

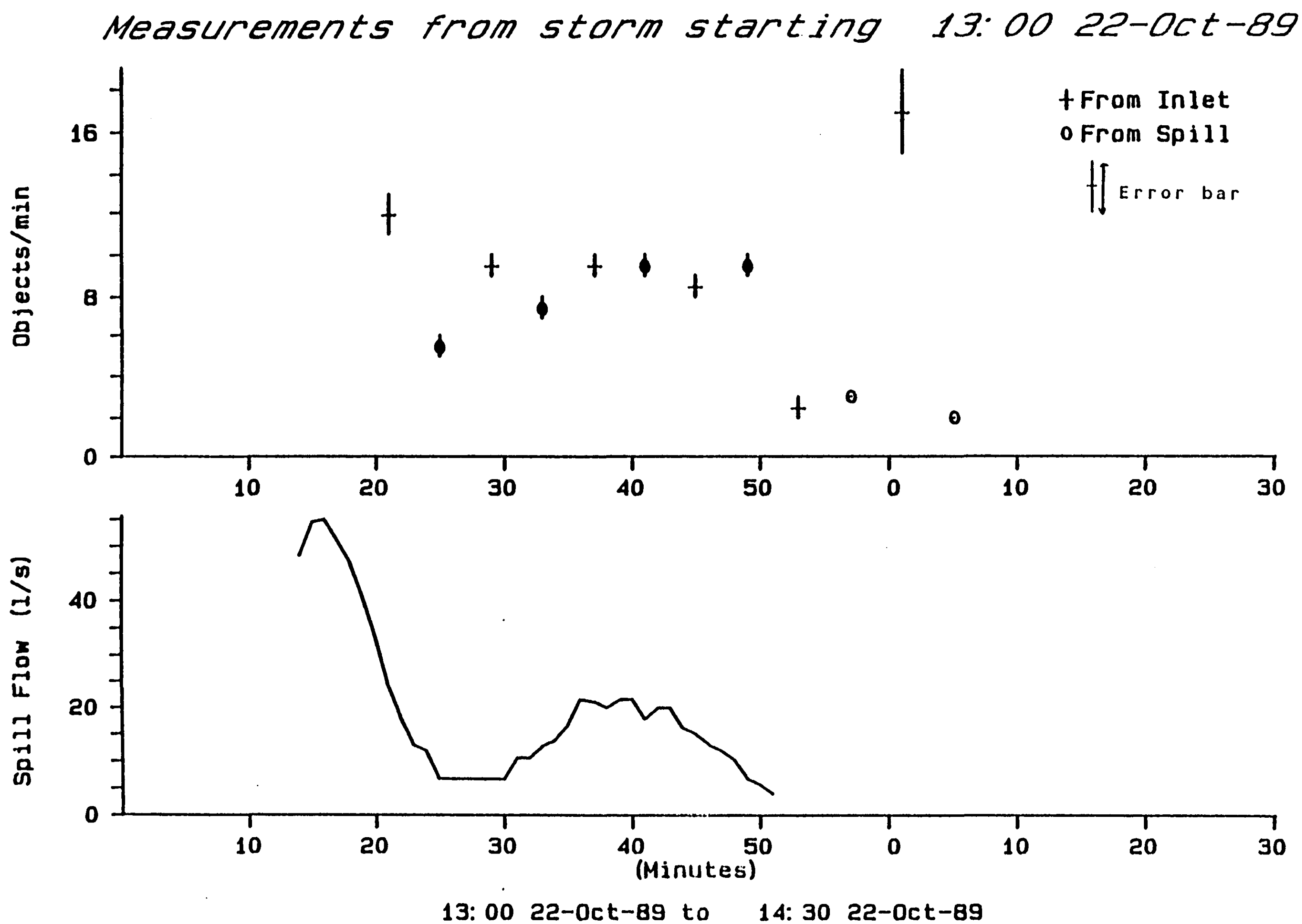


Figure 5.20 Objects Counted on Film from Gross Solids Monitor

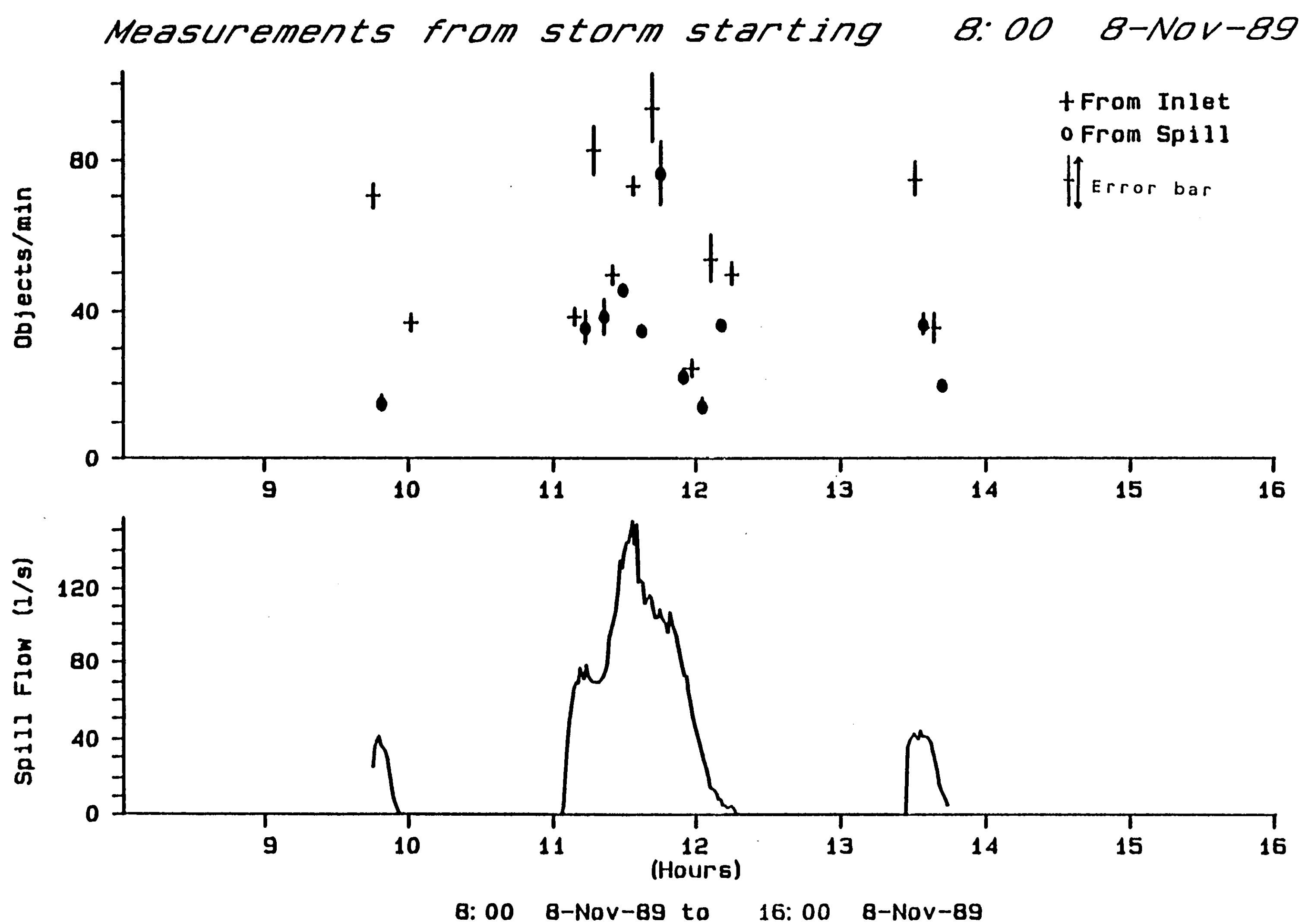


Figure 5.21 Objects Counted on Film from Gross Solids Monitor

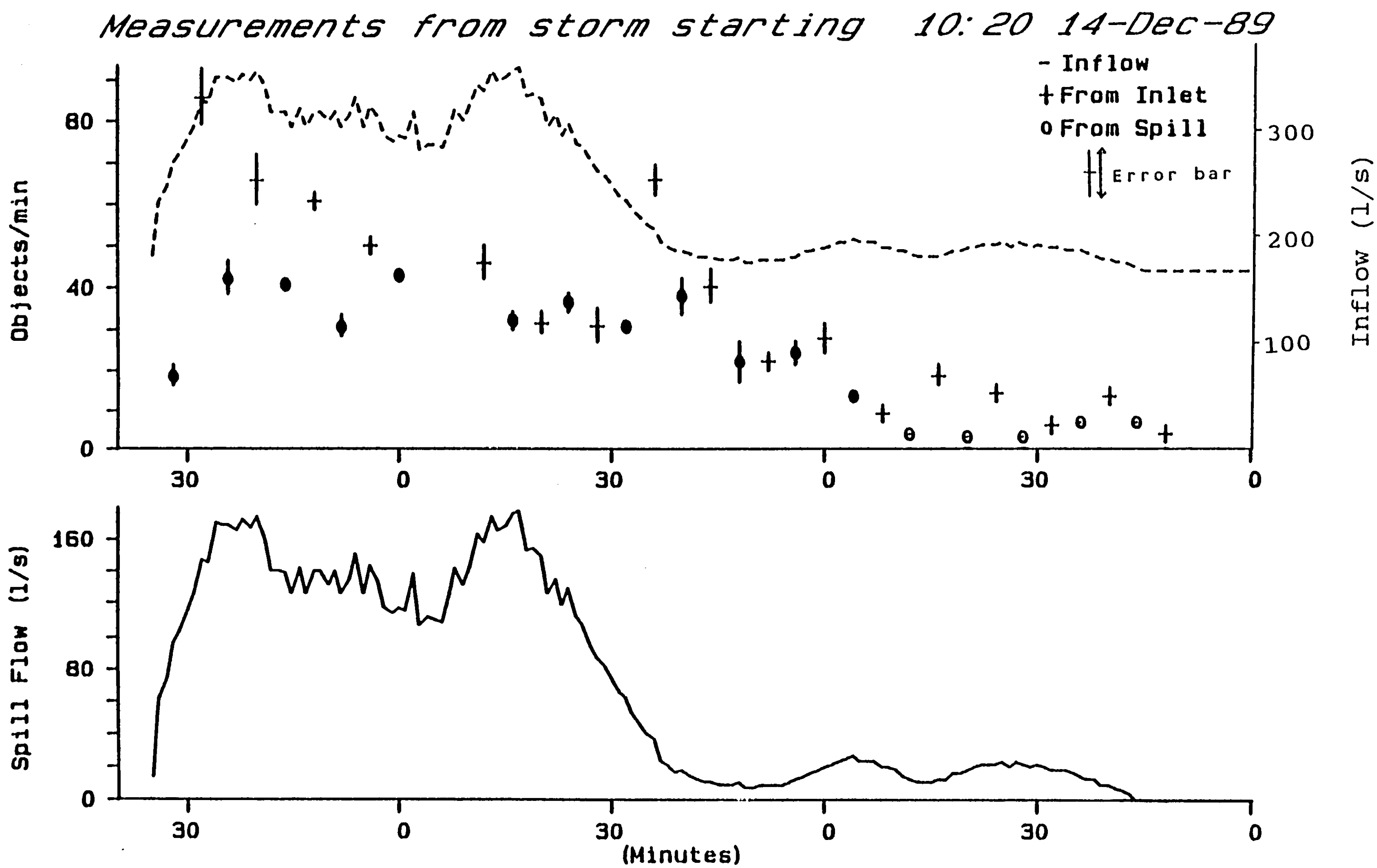


Figure 5.22 Objects Counted on Film from Gross Solids Monitor with Inflow Superimposed (14-Dec-89)

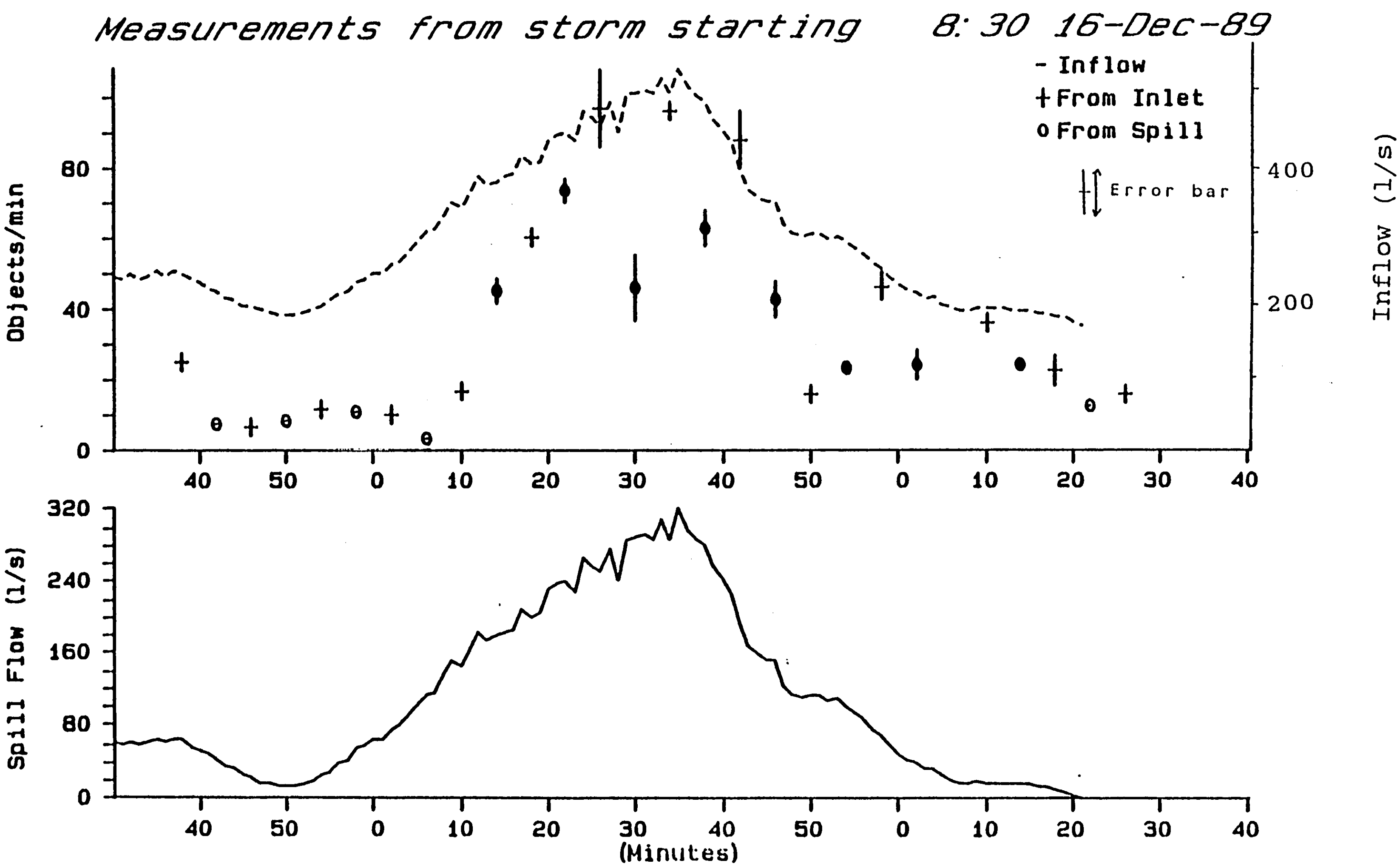


Figure 5.23 Objects Counted on Film from Gross Solids Monitor with Inflow Superimposed (16-Dec-89).

Chapter 6 Computer Simulation of the Drainage Area

6.1 Introduction

Advances in computer technology over the years have made feasible computer models of the flows in sewer networks which are detailed enough and will run swiftly enough to be a useful tool in sewerage analysis.

It was decided to build a model of the catchment upstream of Bacon Lane using one such program, known as WASSP (The Wallingford Storm Sewer Package). This would allow the examination of flows through the system, and would prove useful to test a more advanced version of the program (known as MOSQITO) which predicts the quality of the storm sewage as well as its quantity.

The WASSP software[34] allows the user to build up a file describing a network, indicating such information as the lengths, shape, diameter, roughness and contributing area of each pipe, the levels at either end, and to which other pipes it is connected. There is also accomodation for storm overflows and tanks to be modelled.

The program includes a rainfall input model, surface runoff and overland flow simulations, and algorithms to model the hydraulic routing of flow through channels and sewers.

The user is able to specify a rainfall event on the catchment of the sewer network, either by supplying a rainfall hyetograph or by giving a return frequency and duration. The program simulates the effect of the rainfall, calculating flows at given time intervals, and giving flow hydrographs of any requested pipe.

Such a model can be of considerable value if rehabilitation works are being contemplated. It allows designers to try out various schemes and choose the most appropriate.

To be used in such a situation, it is important that the model gives a good approximation of flows in real events. Once a model has been built up from sewer records, maps and inspections of the catchment, it is necessary to verify its validity.

Historical data about the effects of known rainfall events, such as details of flooding or flows in pipes, can be used to see how well the model predicts the consequences of the events.

Also a 'sewer flow survey' can be used. This involves placing flow monitors and raingauges at critical points in the system, and recording the flows and rainfalls over a period of weeks.

The rainfall hyetograph can then be fed into the computer, and the model predictions compared with the measured flows.

A model is usually deemed acceptable if it predicts flooding and surcharging locations, predicts values of runoff and peak flow rates to within about +20% to - 10% of measured values, and surcharge levels to within 0.5m to -0.1m. Overprediction is more tolerated than underprediction to allow a safety factor.

6.2 Building the WASSP model.

The approximate boundaries of the catchment were found from maps in the Main Drainage Department of Sheffield City Council. Some time ago a TRRL computer model (a less sophisticated sewer flow model) had been made of the area, and the data used was obtained. By comparing the old map from the TRRL model with current sewer maps, the catchment boundary was more clearly defined. All the sewers in the area were traced from seven 1:1250 maps onto one large sheet, and invert and cover levels were put on where known.

The system contained some 250 pipes, and simplification was appropriate. Consecutive pipes were grouped together, with nodes chosen

i) at end points,

ii) at branches,

iii) at large changes of gradient (where known),

iv) at manholes whose levels were known.

The last proved useful where levels were known for only a few manholes in a long series of pipes.

Driving round the system it was discovered that an area marked as terraced housing on the maps had been demolished and landscaped. Appropriate changes were made to the catchment map.

Using notes from the TRRL model, the latest sewer maps and visual examination of the catchment, runoff areas were ascribed to each defined pipe length. Areas were measured with a planimeter. The percentage impermeable and roofed areas were estimated from the maps and from site visits where appropriate.

The data on levels and areas was written onto standard WASSP data entry sheets, and a Sewer System Data (SSD) file made up from this.

The area contained two storm sewer overflows, which had to be included. The details concerning these in the card index were limited to sketches of their layout, one without any dimensions at all. It was necessary to visit these structures.

With the assistance of the Polytechnic's sewer entry team the undimensioned overflow was surveyed. This was found to be an oddly shaped stucture perhaps best described as a low side weir (Fig.6.1b). It was found to contain a 2 meter steel bar and a crumpled up 'Keep Left' sign, which cannot have helped its hydraulic characteristics. Measurements were made, and used to estimate parameters for the overflow ancillary data in the SSD file.

Both overflows seemed to spill into a surface water system, which was assumed to drain into either a canal or the nearby River Don.

When all the data was entered, the SSD file was run through WASSP-CHK, a subprogram of WASSP used to check that the data was consistant.

6.3 Equipment used to verify the WASSP model.

Five flow monitors were obtained to help verify the model, four from WRC, one from Thames Water Authority.

Two tipping bucket raingauges and 'Newlog' data recorders were acquired to gather rainfall data. The buckets of the gauges tip each time they are filled by the equivalent of 0.2mm of rainfall. Each tip closes a contact, and the time is stored by the data recorder. The time between tips can be calculated and the intensity of the rainfall deduced.

The portable Epson HX-20 computer, with suitable programs was used to collect data from the flow monitors and raingauges.

6.4 Verifying the WASSP Model

The model was run with a number of simulated storms of varying durations and return periods, to look for obvious problems, such as the prediction of excessive flooding.

A pipe running from an industrial area seemed to be spilling large volumes. The area it drained was entirely impermeable macadam and roofs. Closer inspection of the site suggested that the macadam drained into neighbouring low lying wasteland. Adjustments were made to the impermeable areas used in the model.

It was decided to conduct a flow survey to compare the model predictions with measured flows during storm events.

Five monitor sites were chosen. These were selected so as to measure the flows coming from the 3 major sections of the catchment and to allow deduction of the flows into and out of the storm overflows (Fig.3.2).

The sites were

1) At the downstream end of the catchment,
2) Just upstream of where the Eastern area sewer joins the main trunk,
3) Just upstream of Storm Overflow (A)
4) On the downstream end of the pipe joining the SE area to the main trunk,
5) On the pipe joining the SW area to the main trunk, upstream of Storm Overflow (B).

To get the best results a flow monitor should be placed at the downstream end of a staight section with subcritical flow, minimum turbulence and little silting[4]. In practise installation is often limited to those sewers which are accessible. A number of possible manholes were selected in the region of the desired sites, using the maps of the sewer network. Each of these were visited to choose the most suitable. In some cases manholes marked on the map were inspection covers, too small for access to the sewer. Some covers had not been lifted for a long time and were difficult to remove.

Site 3 proved to have a manhole ideal except that the sewer was more than 7m below the surface. As such it is defined as a deep sewer and required a 'Permit to Work' to enter. At that time there were only two technicians fully trained to work in sewers, which was too few to enter such a potentially dangerous sewer. The Sheffield Main Drainage Sewer Entry Team assisted in installing and removing the sensor at this site.

The monitors were visited once a week to replace batteries, collect data and clean the sensor heads, which in some cases were prone to become 'ragged up'. Fortunately the sensor in the deep sewer remained fairly clean, so it was not necessary to call out the Main Drainage Team too often - it was possible to maintain the logging unit which was hung at the top of the ladder, easily accessible from the surface. The calibration of each unit was checked by measuring the depth of flow and comparing it with the value displayed by the logger. Where necessary loggers and sensors were removed to be repaired.

Data was collected using an Epson HX20 Portable Computer, and transferred to an IBM PC in the office (Fig.6.2). Rainfall data was collected by the two tipping bucket raingauges which were placed on flat-roofed buildings in the catchment. The 'Newlog' data recorders were placed nearby, hidden from general view but accessible. These were visited regularly to collect their data, again using the Epson computer.

The rainfall, depth and velocity data so gathered was processed using WRc's Sewer Survey Analysis Software (SSAS). This package allows data to be transferred from a variety of computers and data collection devices. The size and shape of each pipe with a sensor in it is entered into the program, and any calibration data required for the FSU's. The program then calculates the flows and depths from the raw depth and velocity readings. It converts rainfall data into rainfall hyetographs, and allows the display and output of rainfall, flows, depths and so on for events which can be defined.

The most suitable storms for verification can be chosen by inspecting the graphs.

A program was written to convert the output from the SSAS package into files to simulate the recorded storm with WASSP. These were transferred to the Polytechnic's IBM mainframe and run on WASSP. The results were plotted against the measured results using a Calcomp plotter.

6.5 Results of WASSP Model Verification

Monitors were placed in all five sites for three months from mid-September till mid-December 1988. However during this time problems occurred with some of the monitors, particularly those at sites 4 and 5 (Fig.3.2) toward the top of the catchment. Difficulties were experienced transferring data from the Golden River logging unit - this had to be brought into the Polytechnic to be connected to an IBM compatable machine once a week, since a suitable portable computer wasn't available. In addition, battery failures plagued the project resulting in no significant storms being recorded at sites 4 and 5.

However monitors at sites 1,2 and 3 worked well, providing data from 9 storms.

The hyetographs generated from the raingauge results were run through the WASSP model and good correlation was found between predicted flows and those measured (Fig.6.3, 6.4, 6.5).

During the first five months of 1989 a spare monitor was placed in the sewer at site 5, but again was hampered by breakdowns and an unseasonable absence of rain. One sizable storm was recorded during this time by the unit. The predictions of the WASSP Model correlated well in this case.

The Flow Monitor units were needed at the vortex overflow, so further verification could not be done. The results gathered seem to suggest that the model works well for the sizes of storms recorded and would be suitable for testing the MOSQITO package of programs.

6.6 Attempts at Quality Modelling using MOSQITO

MOSQITO is a software package produced by Hydraulics Research Ltd which models both the flows and the quality of the sewage in a system. The flows are modelled by a more advanced version of WASSP called WALLRUS, which is included in the MOSQITO package.

In addition the package includes models of pollutant washoff from catchment surfaces and foul water inflow. The soluble pollutants are assumed to be dissolved in the flow, and the behaviour of other pollutants is simulated by a sediment transport model. Should the user choose, the package can produce graphs of how pollution levels for a variety of substances vary throughout a chosen storm.

The package works by estimating the pollutants washed off the catchment surfaces, estimating the amount re-suspended from the sediment in the sewer by the storm flows and then calculating how the pollutants are washed down the system.

Although it is preferable if data for the various parameters which will affect pollutant concentration, such as the nature of dry weather flows and sediment deposits, is gathered for the catchment being examined, the MOSQITO package includes default values which can be used if local results are not available.

Since the flows and the quality of sewage entering the Bacon Lane Overflow were recorded during the project (See following sections), results were available which could be used to test the MOSQITO programs, which at the time were still being developed. A copy of the package, suitable for running on a microcomputer, was kindly given by Hydraulics Research Ltd for this purpose.

The existing WASSP model was adjusted to be used with this program, and various tests done to compare the predicted results with those measured by the flow monitors and the samplers.

6.7 Results of MOSQITO Model Tests

The WASSP model built and verified on the mainframe computer contained about 100 pipes. The microcomputer version of MOSQITO used for the tests was only able to deal with at most 40 pipes, so it was necessary to simplify the model. Groups of three or four sequential pipes without branches were replaced by single pipes with the same cross-section and the same total contributing area. The reduced model was run with several storms on the mainframe using WASSP, and the results compared with those from the original. The differences were small, much less than those between the model and the measured flows. The simplified model was thus considered acceptable to attempt to run with MOSQITO.

The sewer system data file was transfered to a microcomputer, and a few adjustments were made to the format to make it suitable for use by MOSQITO.

Several storms were run using the flow model only, in order to check that this worked acceptably, which it appeared to do.

To examine the performance of the pollution model in MOSQITO, it was necessary to choose storms for which there were complete records of rainfall, flow and samples. Seven such storms were initially chosen, each of which was run estimating flows only. Two of these, from the 3rd December '88 and the 13th December '89, were used for the pollution tests. These gave the best fits with the measured flow data, and were not too long in duration.

A Pascal program was written to take the measured flow and sample results from the database and plot them on the same graph as the calculated results produced by the MOSQITO package.

The constraints of the microcomputers memory meant that only one or two pollutant parameters could be calculated during each run. If too many were chosen the program either failed or occasionally overwrote some files on the disc.

When the program was run on the chosen storms with default values of sediment composition and no dry weather flow, there was no correlation between calculated and measured results.

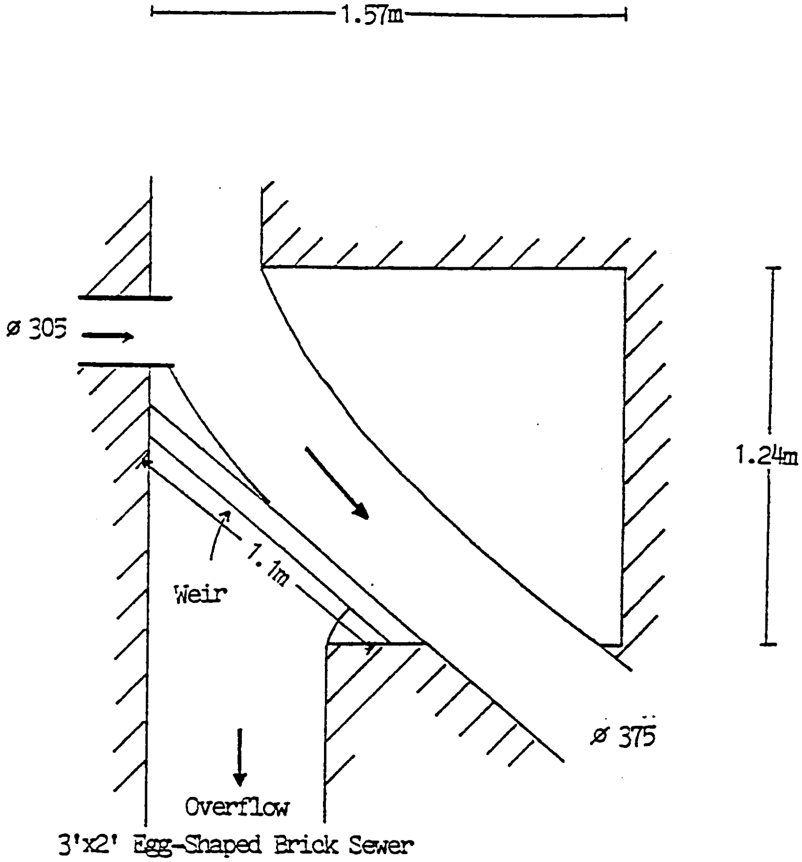
The results from the sampling of dry weather flow in August 89 were used to generate dry weather flow files for the two storms. Although it would have been preferable to use data taken during December, as the quality may vary throughout the year, none was available.

When using such files, the program first used the data to estimate sediment deposits in the pipes, running the dry weather flow for a time defined by the user (the Antecedent Dry Weather Period). Unfortunately it was discovered that in the version of the program used, there were errors which caused large amounts of sediment to be artificially created, making the results meaningless.

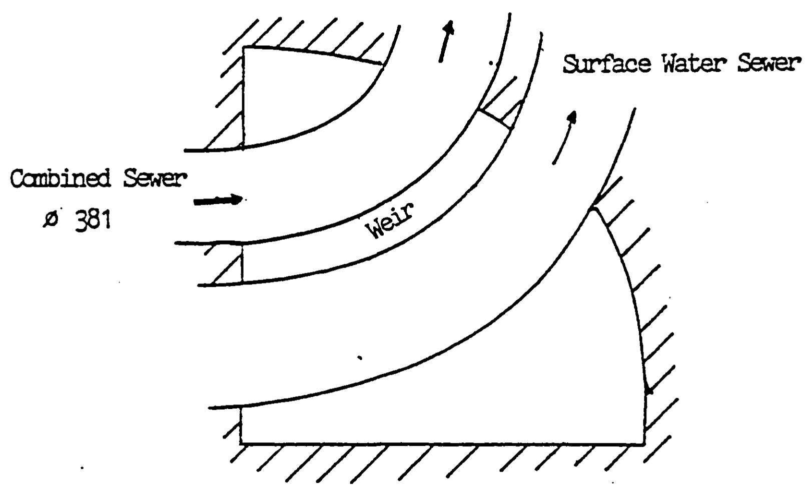
Hydraulics Research Ltd was made aware of the problems, and was able to suggest ways round some of them.

They recommended artificially increasing the volume of the two SSOs in the system by lowering the base level, leaving the initial water level unchanged. This had no effect on the hydraulic performance, but could eliminate errors which sometimes occur in the pollutant model. The latter assumes complete mixing at overflows, but the algorithm to calculate this may have given poor results if the volume was too small.

This was done, and the sediment deposited by the initial dry weather flow was found to be more reasonable. However it did not stop excessively high pollutant concentrations occuring at the outfall shortly after the storm starts, even with very low flows which cause no change in the sediment deposition. Work at HR comparing the micro version of the program with that running on their workstations showed that there was a significant difference, which is put down to compilation errors. The whole program is to be upgraded and recompiled. This will not happen in time for an assessment of the new program to be



a) Woodburn Road Bifurcation



b) Cricket Inn Crescent SSO

Figure 6.1 Storm Sewage Overflows Upstream of Bacon Lane

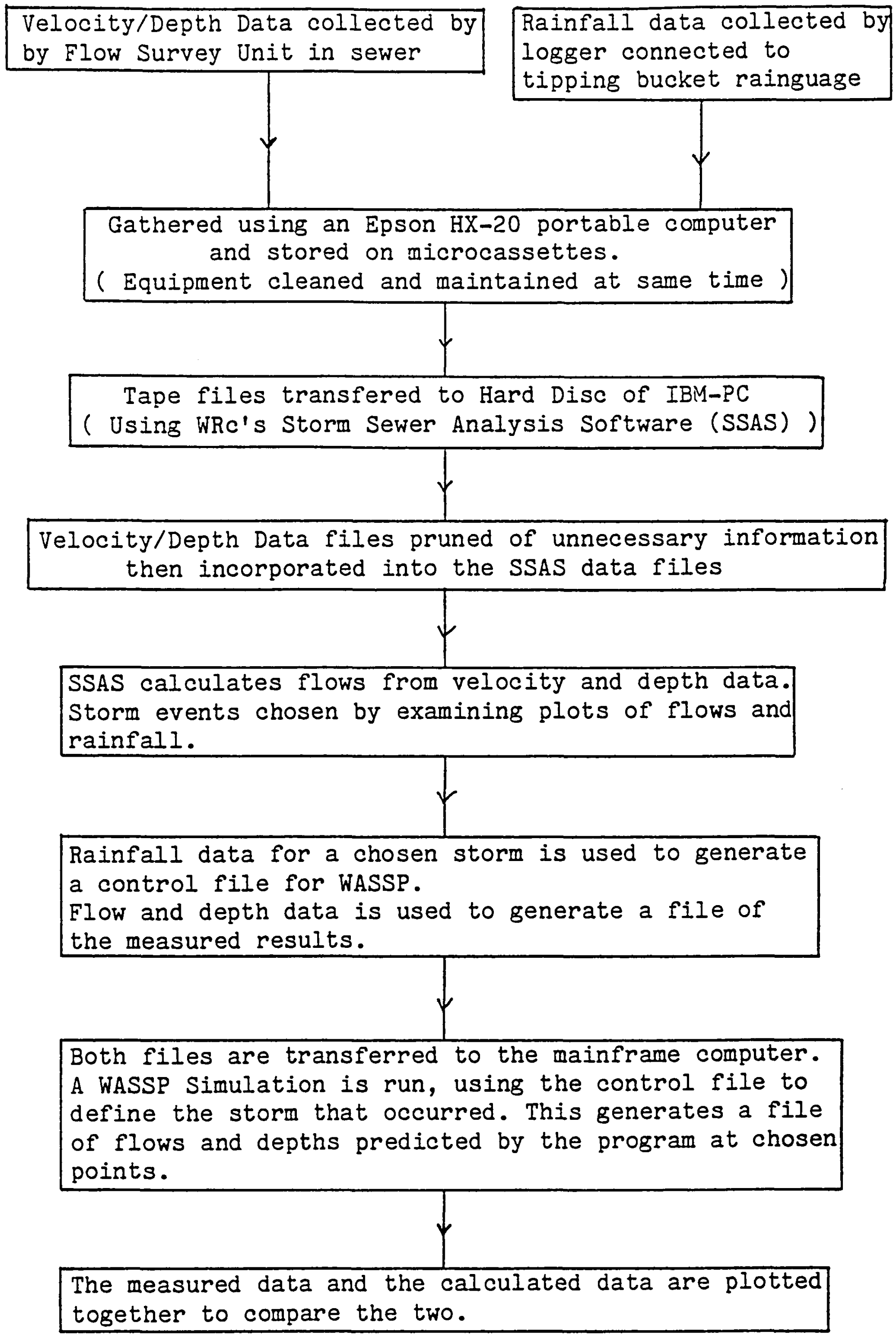


Figure 6.2 Path of Data from Monitors Used In Verifying The WASSP Model

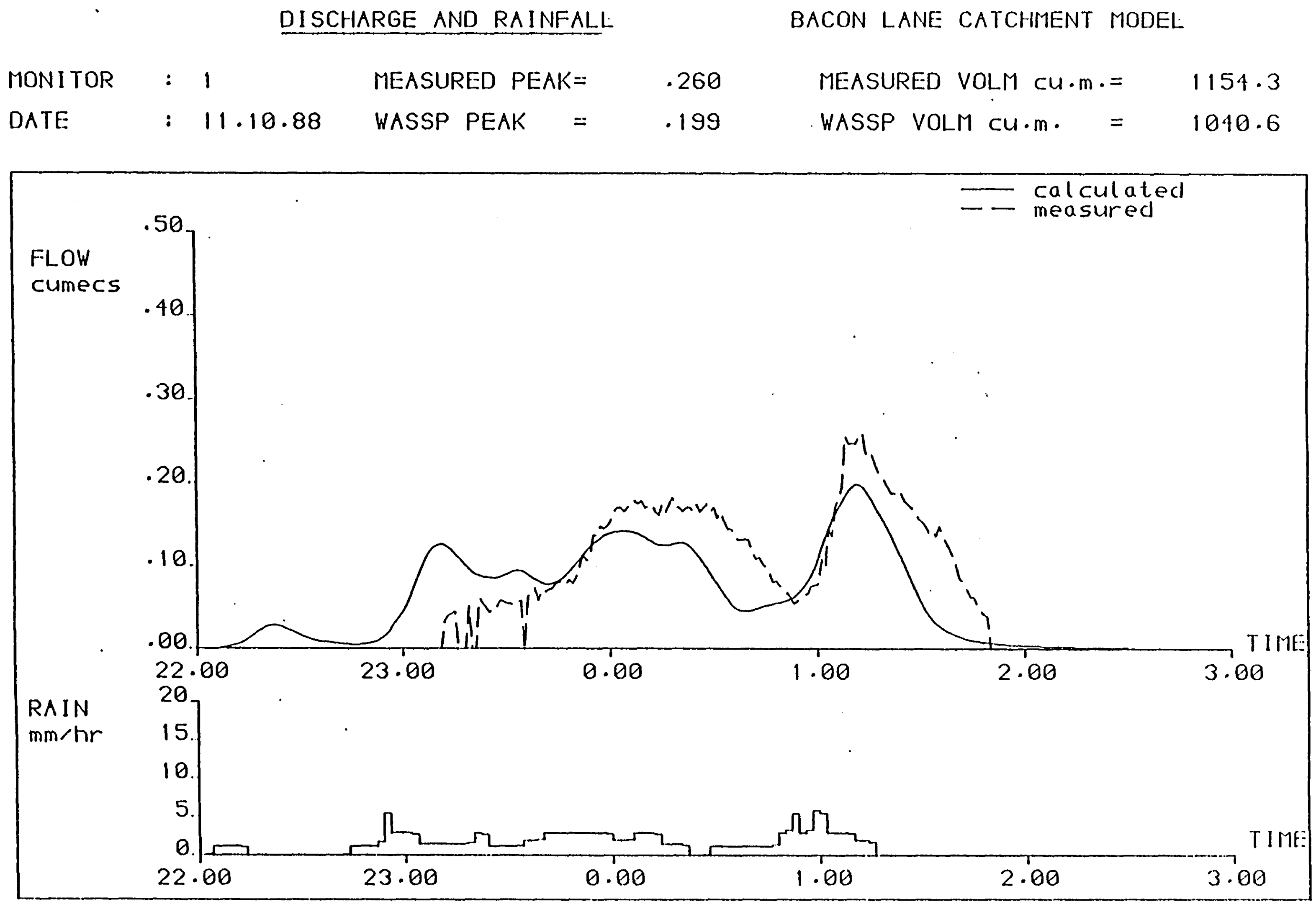


Figure 6.3 Comparison of WASSP prediction with measured flow at inlet to Bacon Lane Vortex Storm Sewer Overflow

DISCHARGE AND RAINFALL BACON LANE CATCHMENT MODEL

MONITOR	: 2	MEASURED PEAK=	.118	MEASURED VOLM cu.m.=	624.0
DATE	: 11.10.88	WASSP PEAK =	.128	WASSP VOLM cu.m. =	641.2

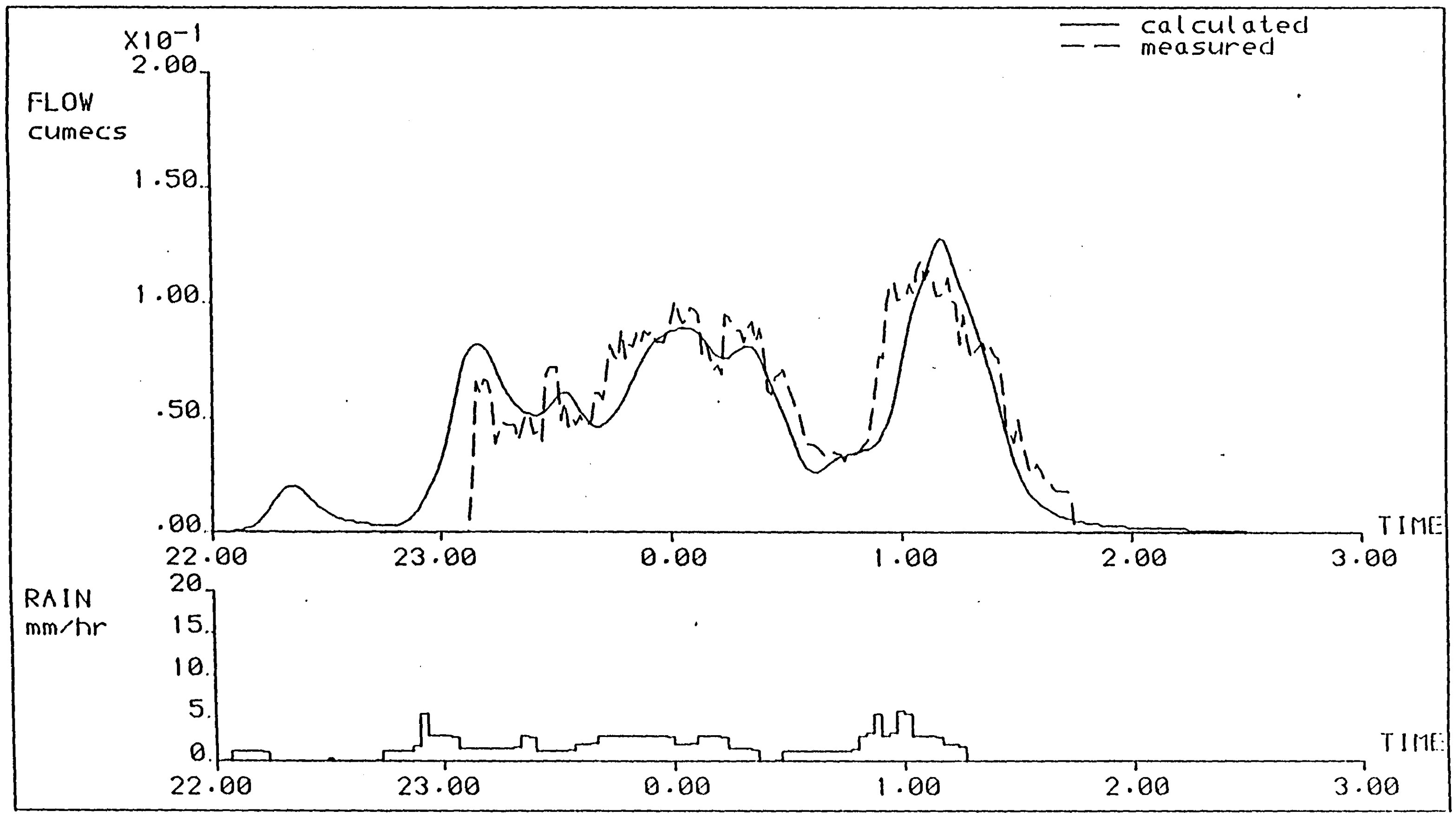


Figure 6.4 Comparison of WASSP prediction with measured flow at Lovetot Road monitoring site

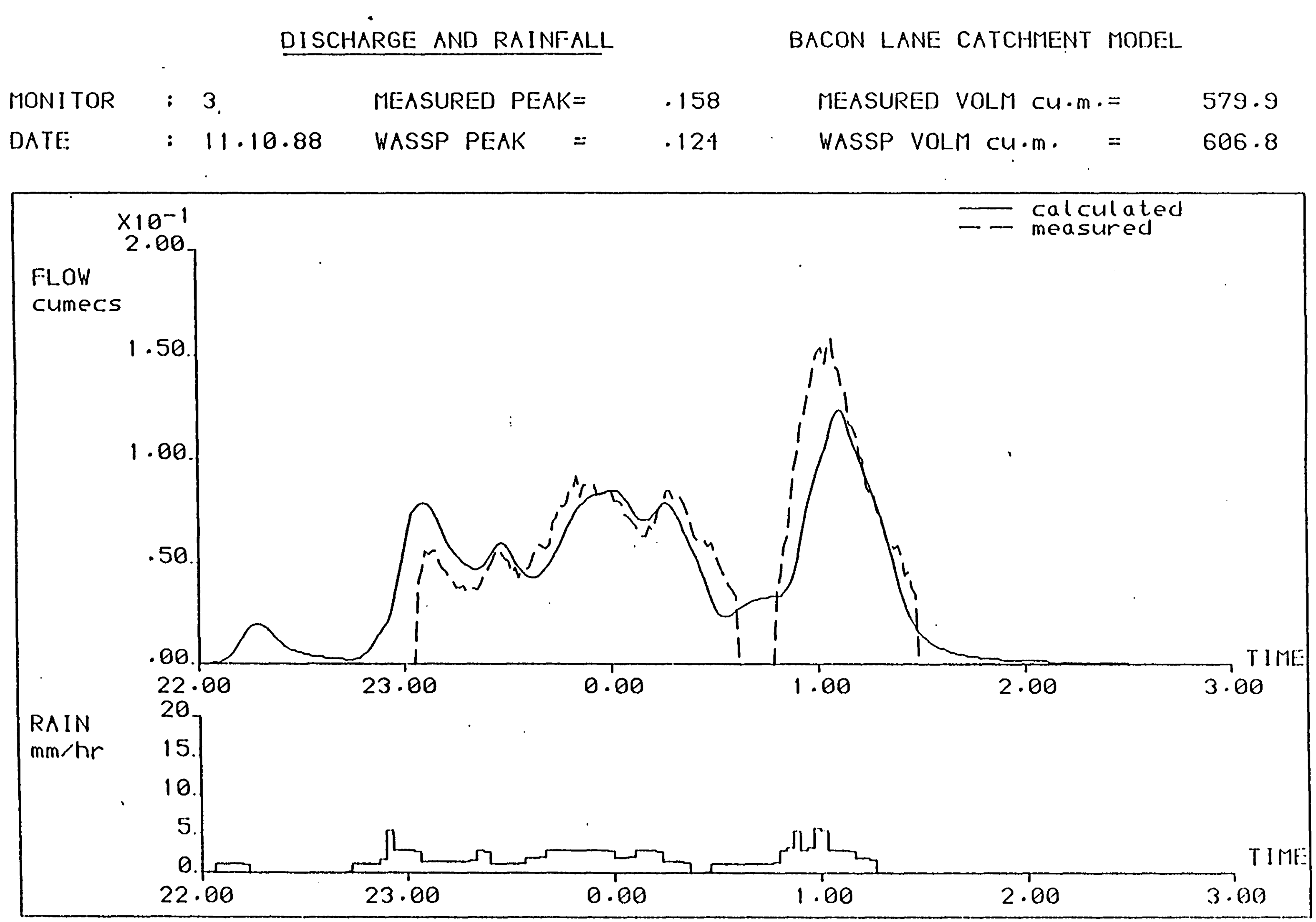


Figure 6.5 Comparison of WASSP prediction with measured flow at Woodburn Road monitoring site

Chapter 7 Discussion

7.1 Hydraulic Performance of Vortex Storm Sewage Overflow

7.1.1 Flow Relationships

The various methods of assessing the flow at the transition between spilling and non-spilling regimes suggested a value of 175 l/s with a standard deviation of around 10%. This could be taken as the flow at which the chamber would begin spilling if there was a gradual increase in inflow from the dry weather flow.

Flow monitors were known to be accurate to within only about 20%, so the error range was not considered unreasonable. The variation was mainly due to the errors in velocity measurements. Velocity was estimated by looking at the echo from an ultrasonic pulse and calculating the doppler shift of the main component of the echo. The pulse was reflected from particles in the flow, which would be moving at different velocities depending upon their nature and position in the flow cross-section (those closest to the middle of a surcharged pipe moving fastest). Thus the form of the echo, and its interpretation, depended upon the type of particles in the sewage, which could vary significantly from one storm to another, and even over the length of a single storm.

It was found that by simply scaling the flows up or down by suitable factors, it was possible to get a good fit between the inflow and the sum of the continuation and spill flows. This gave some confidence in the results, although it led to uncertainty as to which monitor was likely to be most accurate.

The sum of the spill and continuation flow tended to be around 10% more than the measured inflow on average, so the latter was increased by 10%.

The inflow when the spill flow just dropped to zero averaged 175 l/s, so this was taken as the flow required to begin spilling in a steady state situation. The flows were then scaled accordingly.

The graphs of continuation or spill flow plotted against the inflow showed the effect of storage in the chamber and spill channel, which serves to damp down peaks and smooth troughs in the flow. Sudden rises in inflow first fill up storage before being passed on to continuation or spill flows.

Because of this initial peak flows could be considerably more than 175 l/s without causing spilling if they were of sufficiently short duration. Clearly the effect is not so great as in larger tank overflows, but may prove useful in reducing the total volume spilling to the river.

The graphs of spill and continuation flow against inflow when the chamber was spilling suggested equations of the form,

$$Q_c = R_c(Q_{in} - Q_t) + Q_t \qquad \text{(Equation 5.3)}$$

$$Q_s = R_s(Q_{in} - Q_0) \qquad \text{(Equation 5.4)}$$

Q_{in}, Q_c, Q_s = In, Continuation & Spill flows,

R_c = Rate of change of continuation flow with inflow when spilling (0 - 0.15),

R_s = Rate of change of spill flow with inflow (0.8 - 1.1),

Q_t = Point of transition to spilling regime on Qf-Qin graph (175l/s),

Q_0 = Minimum inflow required to cause spill (175l/s).

Considering the flow balance, (ignoring temporary storage effects),

$$Q_{in} = Q_c + Q_s \qquad \text{(Equation 5.1)}$$

which gives

$$Q_t = Q_0 \qquad \text{(Equation 7.1)}$$

and

$$R_c + R_s = 1 \qquad \text{(Equation 7.2)}$$

Equation 7.1 is true, with $Q_t = Q_0 = 175$ l/s.

Equation 7.2 is harder to assess, but the crude results gathered would appear to confirm it.

Taking $R_c = 0.1$ gave $R_s = 0.9$. Assuming that the inlet monitor was indeed underestimating by 10%, then the equations governing the flow through the overflow when it is spilling were

$$\text{Continuation Flow} = 175 + 0.1(\text{Inflow} - 175) \;\; \text{l/s} \qquad \text{(Equation 7.3)}$$

$$\text{Spill Flow} = 0.9(\text{Inflow} - 175) \;\; \text{l/s} \qquad \text{(Equation 7.4)}$$

to within 20%.

7.1.2 Depth Relationships

By comparing the apparent depth at which spilling begins on plots of flow against depth the calibration of the depth monitor could be checked. It was found to be accurate to within 4% using this method and within 2% when the chamber was filled slowly with dry weather flow.

The results from examining the plots of spill flow against inlet depth graph gave an approximate equation

$$\text{Spill Flow} = 2/3\ C_d\sqrt{2g} \times (\text{Weir Length}) \times (D_{in} - H_w)^{1.5} \text{ cumecs} \qquad \text{(Eqn.7.5)}$$

D_{in} = Depth at inlet (m),
H_w = Height of weir above inlet invert,
Weir Length = 2.12m,
C_d = 0.6. (± 20%)

This equation could be used to estimate the head above a weir for a given flow. The largest recorded spill flow was about 1000 l/s, occurring on 24 May 1989. The equation predicted that the depth in the chamber rose to 410mm above the level of the weir. Unfortunately the inflow monitor was not operational at the time, so this prediction could not be tested.

Since the sides of the chamber rose 865mm above the weir level, the chamber would only become drowned if the flow was above 3000 l/s, which would require a very heavy rainstorm indeed.

During the May '89 storm the measured depth in the spill channel rose to 804mm above the invert. The pipe had a height of 915mm, so the flow was free surface. Some 670mm downstream the pipe enters a trough in the next manhole (Fig.7.1). This is a side entry manhole allowing access to both the continuation sewer, whose invert is about 560mm below the floor level of the manhole, and the spill sewer, which runs in a trough directly above the continuation sewer. The side of the trough rises 770mm above its bed. This means that during the May '89 storm the spill flow would be about 30mm above the level of the side, and would be spilling over the edge like a high side weir, returning a portion of the flow to the continuation sewer below. This was in effect short circuiting the vortex overflow during heavy storms. The problem has been described to the Main Drainage Department for their consideration. It only occurs during very high flows, and will not have affected any of the results taken for this project.

7.1.3 Attempts to Fit Theoretical Flow-Depth Relationship to that Measured.

Work was done to find the best mathematical model of the hydraulics of the vortex by comparing the derived flow - depth relationships with the measured results. Such a model would be useful to choose the weir setting or orifice size for a new overflow.

Ackers & Crump's work on the Vortex Drop was used as a base (see section 2.1.2) guided by recommendations made by Balmforth and Lea.

By combining the hydraulic properties of a free vortex with the Bernoulli Equation, and applying the principle of maximum discharge, Ackers & Crump obtained a relationship between head and discharge (See Fig.2.1).

The equations they derived are;

$F_1 = f^2 /(4(1+f))$ $\qquad$ f = fractional air core = a^2/d^2

$F_2 = 0.25\ (1/f - 1)(2(1-f))^{0.5}$

$G_1 = \log_e (r_2/r_1)$

r_1 = Minimum radii of helical side,

r_2 = Maximum radii of helical side.

$$G_2 = \frac{d^2}{r_2^2} \left(\frac{r_2^2}{r_1^2} - 1 \right)$$

$$\frac{E}{d} (G_1 - F_1 G_2) = F_2 + (t/_d)\, F_1 G_2 \qquad \text{(Equation 2.1)}$$

E = Energy Head,

d = Diameter of orifice,

t = Depth of minimum air core area below orifice, approx. 2d/3.

$$\frac{C^2}{gd^3} = 4F_1 \,(\, E + t\,)_{/d} \qquad \text{(Equation 2.2)}$$

C = Circulation in the chamber.

$$\frac{Q}{g^{1/2} d^{5/2}} = F_2 \, (4F_1 (E+t)/d)^{0.5} \qquad \text{(Equation 2.3)}$$

Q = Inflow.

For a variety of values of the fractional air core, f, the head and the inflow can be calculated to obtain the discharge-head relationship.

However, these equations are for a chamber as depicted in Fig.2.1, with a helical circumference and a flat bottom.

There are obvious differences with the prototype, namely;

i) The prototype chamber has a circular cross section,

ii) The prototype has a conical floor sloping down to the orifice,

iii) The prototype has an egg shaped entry pipe into a short inlet channel.

These must be accounted for if the model is to give reasonable estimates of the depth for a given flow.

A computer program was written to estimate the flow at different depths based on Ackers and Crump's theory. This uses;

r_2 = Chamber radii = 1.35m

d = orifice diameter = 0.225m

A theoretical inlet channel is assumed, whose width, W, was derived in two ways;

i) It is set to the width of the short existing inlet channel, 1.020m,

ii) It is set so that the cross section of flow through it has the same area as the inlet pipe ($0.415m^2$),

$$W = 0.415 / h$$

h = Height of liquid above invert

The inner helical radii for Ackers & Crump's equations is then

$$r_1 = r_2 - W$$

Ackers & Crump use the parameter t to denote the depth below the orifice of the point where the air core has minimum cross section, and suggest a value of t = 2d/3. In the program the parameter t was replaced by t1, where

$$t1 = t + S, \qquad S = \text{Depth of orifice below invert.}$$

Two techniques were then tried to allow for the floor;

i) It was assumed flat, at the level of the invert, ie S = 0,

ii) Its slope was allowed for by choosing S = 0.480m

Applying these give four different flow-depth relationships, shown on the same graph as typical measured results in Figure 7.2.

Assuming the inlet channel cross section to be equal to the inlet pipe area gives lines which are clearly unsuitable. The closest fit is given by assuming the inlet channel width of 1020mm and that S = 0, though this overestimates by perhaps 5-10%. Setting S = 0.480 causes overprediction by 30-40l/s. It must be remembered, however, that the measured flow could be up to 20% out, in which case the latter might give a better estimate.

If the flow values are assumed to be reasonably reliable, it can be concluded that an approximate value for the flow required to just spill for a standard vortex overflow with peripheral spill can be found using Ackers & Crump's method, assuming $r_1 = r_2 - W$, where W is the width of the short inlet channel, and that a sloping floor can be modelled as if it were flat, with the orifice assumed to be at the same level as the invert of the incoming pipe. These recommendations have been used to draw up the design chart in Appendix A.

Given the knowledge of the flow depth relationships it would be possible to assess the performance of the chamber by solving the continuity equation for inflow, spill flow, continuation flow and storage. Preliminary analysis (5.2.2) suggests that the effects of storage would be likely to affect results with a rapid rise in flow rate by a difference of about 20 l/s between inflow and continuation flow, which is within the error range of the flow monitors.

7.2 Bottle Samples

The results from the tests on several samples from the same mixture (Table 5.5) had a standard deviation from the mean of 10% or less for all the parameters except Ash (the non-volatile suspended solids), so, assuming a normal distribution, 60% or more of actual values will lie within 10% of the measured value for a sample.

The samples show no significant difference between inflow and spill flow, which means the overflow has little or no effect upon the pollutants gathered by the samplers. These will be the dissolved material and the fine suspended matter with densities close to that of water. Very little floating matter was observed in the samples, and only small quantities of fine settled material. Other matter in the storm sewage is perhaps filtered out by the coarse inlet filters on the sample pipes, or does not reach the sampler since it floats near the soffit or runs along the floor of the sewer (samples were taken from the middle of the flow). The lack of floating matter ties in with the results from analysing the gross solids caught in a sack from the dry weather flow. These suggested only about 5% of the material floated.

The sample tube in the inflow was suspended about halfway up the inlet pipe, and as a result it is unlikely that the heavier material, such as grit, with high settling velocities will have been collected, for this was likely to be moving along the bed of the sewer. Model tests suggested that such material remains close to the floor of the chamber and almost all of it goes down the orifice into the continuation flow. Since this material was not sampled it is not possible to confirm this prediction.

Routines were written into the analysis program to examine the correlation between various parameters and with the flow rate. The only significant relationships found are between COD, BOD and SS;

$$BOD = 0.19\ COD \qquad \text{(Eqn.7.6)}$$

(From 299 samples with COD<1500mg/l, 89% fit)

$$COD = 40 + 0.75\ SS \quad mg/l \qquad \text{(Eqn.7.7a)}$$

$$SS = 95 + 0.87\ COD \quad mg/l \qquad \text{(Eqn.7.7b)}$$

(From 333 samples with COD,SS < 1500)

(65% fit)

That between BOD and COD could be used to estimate the former from the latter for the sewage at Bacon Lane. Such a relationship is of use because of the difficulty and length of time it takes to assess the BOD of a sample. The relationships between SS and COD, having only a 65% fit, are not as good, and are perhaps only useful for a crude estimate of one from the other.

7.3 The Gross Solid Monitor

7.3.1 Consideration of the Method

The method of attempting to sample Gross Solids, that of filming images of storm sewage sucked from inlet and spill, seemed to work, though further refinement could be done. Difficulties were caused by the size of the equipment compared to that of the pit into which it was to fit. This required careful arranging of the pipework, pump and monitoring cell. With more preplanning the pit would have been dug much larger, making installation and maintainance considerably easier.

The equipment produced reasonably clear images most of the time, though during some periods the sewage became too dark to see through. It is possible that a stronger back illumination source and more sensitive camera would improve the quality of the image and allow examination even during these dark sections. The bubbles which appeared on the image could obscure objects which were to be counted, and made analysis with computers difficult. It may be possible to fit a bubble trap to reduce their numbers, or a small channel at the edge to allow them to pass across the window in a controlled manner. Putting the cell on its side, so the camera looks horizontally through the sewage may be useful. The bubbles would remain out of the way at the top of the image. However rapid floaters and sinkers would also tend to stick to the top and bottom of the tube, and may be missed.

The windows gradually became clouded up with deposits. These never became sufficiently opaque to affect the image when the sewage was flowing through. They were cleaned twice during the 20 months of operation. However if the equipment was used with sewage which left more scum on the windows, it may become a problem. In this case it would be wise to include some method of cleaning them automatically, perhaps by fitting a nozzle inside the cell to allow them to be sprayed with tapwater. There would be the danger that such a device would get ragged up during operation unless it was carefully designed.

As explained in section 5.4.2 it was decided not to use computer image analysis to examine the films produced, as it was considered unreliable. Although examining films by eye could be tedious, there was more confidence in the results and a better idea was gained of what was in the sewage. The repeatabitity tests suggested that human counting is consistant as long as each section of tape is assessed under the same conditions and a storm is examined in one session, with the minimum of breaks necessary to remain alert.

More accurate results may be possible if the facility to play the films in slow motion were available. This would certainly be useful for those sections with more than 70 or 80 particles visible per minute.

7.3.2 Nature of Results From Gross Solids Monitor

The results from the seven storms with sufficient data to be useful suggested that the concentration of objects in the sample from the spill was lower than that of samples from the inflow, with an average reduction of about 20-40%.

It is unfortunate that no storms were recorded with the new spill sample pipe, as it would have been interesting to discover whether the change in shape had any effect upon the relative proportions of objects drawn up. It is possible that the horizontal cut-off may have more ragging round the leading edge than the angled cut-off, and this may act to filter the sewage sucked up, so contributing to the apparent difference in concentrations between inlet (which had an angled cut-off) and spill (which didn't during the storms measured).

Figures 7.3,4 show the comparison between the suspended solids measured in the bottle samples and the gross solids concentration measured by the GSM. There is little correlation, with the suspended solids tending to decline as the storm progresses much quicker than the gross solids. For instance on the 8-Nov-89 the suspended solids dropped to one third their peak concentration after three hours, whereas the gross solids concentration remains undiminished.

When the object/minutes concentrations at given times were compared with the inflow (Fig.s 5.18 - 5.23) there appeared to be a rough correlation between them.

The fact that the concentration seems to increase with increase in flow suggests that the objects counted aren't just those in the dry weather flow, for the concentration of such objects drops as the dilution increases. The flow must contain sediment scoured from the pipes and material washed in by the rainfall, such as leaves, twigs, seeds and so on, all of which have been identified on the video images.

When the square of the flow was plotted on the same graph as the object counts (Fig.s 7.5,7.6) a similar form was apparent, which suggested that the amount of gross solid material scoured might be proportional to the square of the flow rate.

To examine the relationship further ln(GSM count) was plotted against ln(Flow) for each point in the storms recorded (Fig.7.7). A linear regression was done on each graph. If a line could be fitted it would suggest a relationship of the form

$$\text{GSM Count} = Y_0 \times Q_{in}^{Y_1} \qquad \text{(Equation 7.8)}$$

Where Y_0 could derived from the Q = 0 line intercept and Y_1 would be the gradient of the line. Estimates for these from the regression lines for various storms are given in Table 7.1, as well as the correlation coefficients for the lines.

Storm Date	Number of Points	Y_0	Y_1	Corr. Coef.
20-Oct-89	3	1100	2.3	0.94
22-Oct-89	6	4100	3.6	0.55
8-Nov-89	9	1800	4.2	0.46
14-Dec-89	17	2400	3.2	0.72
16-Dec-89	13	800	2.7	0.73

Table 7.1 Estimates of the coefficients Y_0 and Y_1 in Equation 7.8.

Taking the average from the latter four storms (the earlier one having too few points) give approximate values of Y_0 = 3800, Y_1 = 3.5, giving

$$\text{GSM Count} = 3600 \times Q_{in}^{3.5} \qquad \text{(Equation 7.9)}$$

It is to be remembered that this relationship has been derived from small amounts of data with much scatter, so the coefficients could vary considerably from those given, with the index (Y_1) most likely lying in the range 2 - 4.5.

The apparent improvement of 20-40% may be caused by the different shape of sample pipe inlet, or possibly be affected by the velocity of the sewage passed the pipe, which is different for inlet and spill. Assuming that the different sample pipe inlet shapes and positions have only a small effect on the gross solids drawn up the tube, ie that the samples drawn passed the video cell were reasonable representative, and that the larger rags and objects behave in a similar manner to the smaller ones observed, then there was a 20-40% improvement in the concentration of the spilled sewage compared to that entering the chamber for the storms recorded. This was much better than spilling unseparated sewage and may go some way to reducing the aesthetic dissatisfaction caused by the discharges from the overflow into the Don.

7.3.3 Gross Solid Loading Estimates

During sampling the pump draws about 3 l/s. Knowing the flow in the sewer allows us to estimate the gross solids loading, using

$$\text{Object Loading (Obj/min)} = \text{Count} \times (\text{Flow Rate})/3 \quad (\text{Flow in l/s})$$

(Equation 7.10)

Unfortunately, for most of the storms with GSM data, the inflow was not recorded since the monitor was either faulty or temporarily inoperative. However the spill flow monitor collected data on all the relevant storms. In order to avoid the complications of flow coefficients the measured spill flow was assumed to be accurate, and the inflow was derived from it, regardless of whether there is any inflow data available. Equation 7.4 was rearranged to

$$\text{Inflow, } Q_{in} = 175 + Q_s/0.9; \qquad (\text{Equation 7.10})$$

The loadings for several storms are displayed in Figs.7.8, 7.9, 7.10 and 7.11.

The average loading for each storm was calculated by summing the loadings at each point of GSM data and dividing by the number of points. This was done for both inflow and spill flow.

$$\text{Mean Loading} = \sum \frac{\text{Count x Flow/3}}{\text{Number of samples}} \qquad (\text{Equation 7.12})$$

When the mean spill loading was divided by the mean inflow loading, an estimate of the proportion of objects spilling was obtained. Subtracting this from 100% gave the proportion retained in the continuation flow;

$$\text{Proportion Retained in Sewer} = 100\% - 100 \times \frac{\text{Mean Spill Load}}{\text{Mean Inflow Load}}$$

(Equation 7.13)

For instance during a storm on 14-Dec-89 the mean inlet load was 3300 particles/min, the mean spill load 660 particles/min, so 80% of particles were retained in the continuation flow.

The proportion of the particles retained in the continuation flow during a given storm was dependant on the hydraulic performance of the overflow during a storm, and the separating effect it exerted to concentrate pollutants in the continuation flow. In heavy storms, where a large proportion of the flow is spilt, fewer particles were be retained. However, if the overflow was effective at concentrating particles in the continuation flow, this would improve its performance.

If there were no separating effect in the chamber the concentration of particles per unit volume in the spill and continuation flows would be the same as that in the inflow. The proportion of particles spilling would then depend only on the hydraulic characteristics of the chamber and the way the particle concentration in the inflow changes.

The average spill loading assuming no separation of particles in the chamber was calculated by multiplying the inlet count by one third of the spill flow at that time, and taking the mean over all the inlet data points;

$$\text{Mean Spill Load (No Sep.)} = \sum \frac{\text{(Inflow Count)} \times \text{(Spill Flow)}/3}{\text{No. Inflow GSM Samples}} \qquad \text{(Equation 7.14)}$$

This was used in Equation 7.13 to calculate the proportion that would be retained in the continuation flow if the chamber has no effect on the object concentration. For instance on the 14-Dec-89 only 65% of particles would have been retained if the spill flow had the same particle concentration as the inflow.

This value gave the proportion of particles retained as a result of the hydraulic properties of the overflow. When it was compared with the measured results it was possible to assess the improvement in the concentration of particles in the spill flow caused by the separating effects.

$$\text{Percentage improvement} = 100\% - 100 \times \frac{\text{Mean Spill Load (Measured)}}{\text{Mean Spill Load (No sep.)}} \qquad \text{(Equation 7.15)}$$

On the 14-Dec-89 20% of the particles were spilt. If the chamber had not concentrated the particles in the continuation flow, 35% would have been spilt, so there was a 45% improvement in the measured results over that predicted for no separation.

The mean loadings for each of 6 storms are shown in Table 7.2 (overleaf), with the mean proportion of objects continuing in the sewer.

Depending upon the nature of the storm, the vortex overflow seemed to retain between 60-95% of the incoming gross solids in the sewer. Clearly during heavy storms with high flows, where a larger proportion of the sewage was spilled to the river, a larger proportion of the solids would go too. In addition model tests suggested that the higher the flow, the less efficient the structure was at reducing the concentration of objects in the spill flow compared to that in the inflow.

The loadings estimated from the GSM spill results were 20-45% less than the loadings produced assuming the spill flow has the same particle concentration as the inflow (ignoring those with only a few GSM results), which compared well with the estimations of improvement in spill concentrations.

Start Date	Number mins of data		Mean object loading (objects/min)		Percentage of objects continuing in sewer.		Percent improv. over no sep.
	In	Sp.	Inlet	Spill	Using spill results	Assuming no separation	
30-Jun-89	4	3	1400	55	95%	80%	80%
20-Oct-89	4	2	4000	1500	60%	60%	-5%
22-Oct-89	6	6	430	20	95%	90%	45%
8-Nov-89	12	11	5400	870	80%	75%	30%
14-Dec-89	17	19	3300	660	80%	65%	45%
16-Dec-89	14	13	4700	1800	60%	55%	20%

Table 7.2 Summary of estimates of average gross solid loadings during storms, the percentages of objects continuing in the continuation flow and the improvement of the measured results compared to those assuming no separation.

It must be remembered, however, that the gross solids only account for about 2-8% of the total suspended solids in the dry weather flow. The majority of the material is in fine suspension or is dissolved. The separating performance of the overflow will only have a noticable effect on the total mass of material spilt if a significant proportion of the polluting material in the storm sewage is in the form of gross solids. Otherwise it is more the overflows hydraulic performance in reducing the overall volumes of sewage spilt in order to prevent street flooding which can help to improve river quality, were a vortex with peripheral spill used to replace older, less efficient overflows.

7.4 The Analysis of Gross Solids

The method used to get an assessment of the settling velocities of sewage particles was very crude. By capturing them in a net it is possible that their properties were affected, certainly they tended to clump together, held by the more fibrous material such as tissue paper. This prevented many particles from contributing to the distribution. Without using a net it was difficult to get a large enough sample to examine.

If it was assumed that 75% of material has a settling velocity less than 15mm/s, and that only 5% of the material floated (as was suggested by the dry weights of material in Table 5.9) the results from sinking and floating particles in Tables 5.10 & 5.11 could be used to generate the distribution shown in Table 7.3 (Overleaf).

It was a pity that the figure for material in the range Vs<15 was the least accurate, since it was here that the majority of particles lie.

The above is, of course, a distribution for dry weather flow only. The GSM results (7.3.2) suggested that only a small proportion of the particles in storm sewage are contributed from the DWF. The rest come from sediment and from material washed in. However, the sediment will be primarily formed from settled DWF material. Unless it had changed its nature significantly its settling velocity distribution would be similar to that of the dry weather flow material, though perhaps biased somewhat toward the faster sinking end of the spectrum, for they would be the ones to settle out.

Velocity Range (mm/s)	Proportion of Particles in this range.
> (40)	0.5%
(40) -(15)	1.0%
(15) - 0	3.5%
0 - 15	71.0%
15 - 25	8.5%
25 - 35	7.0%
35 - 45	4.5%
45 - 60	2.0%
> 60	2.0%

Table 7.3 Proportions of particles in given ranges of settling velocities. (Figures in brackets indicate floaters).

This distribution was compared with the distributions obtained for sites described in the ARD 6 report[40] (Fig.7.12). The distributions in that report are by mass whereas the one from this work is by number of particles, so the two are not strictly comparable. Those from Bacon Lane show a lower proportion of material with high rise or sink velocity, though the curves are similar in shape. The differences could arise from the sewage being different in nature, the estimate of proportion of material with low settling velocity (V_s<15 mm/s) being too high (see 5.5) or that the faster sinking particles would tend to be heavier than the slower ones so would bias a distribution by mass toward the faster sinkers. The latter would not account for the apparent low level of floaters though.

7.5 Comparison Between Laboratory Model Tests and Prototype Results

7.5.1 Hydraulic Comparison

Results from tests of vortex overflow models by Balmforth and Lea have been used to compare with the prototype measurements. A better comparison would require more detailed tests on accurate scale models of the Bacon Lane vortex overflow.

For Bacon Lane the measured flows suggest

Continuation Flow = 175 + R_c(Inflow - 175)

where R_c is in range 0 - 0.15.

The results from a model of a vortex to be built at Calderdale(37) give R_c as 0.04, and Lea's result suggest R_c = 0.03 - 0.06 depending upon the geometry. These figures all lie in the admittedly broad range of 0 - 0.15 suggested by the prototype. More accurate flow monitoring would be required to get a better figure for R_c for the prototype. It is likely that the fluctuations of inflow produce pulses of continuation flow which blur any exact relationship that might be visible in steady state tests.

The model tests suggest that the value of R_c of 0.1 chosen to allow estimation of flows not recorded may be a little high.

The head-discharge relationship at the weir is

$$\text{Spill Flow} = 2/3\ C_d \sqrt{2g} \times (\text{Weir Length}) \times (\text{Head above weir})^{1.5} \text{ cumecs} \quad \text{(Eqn.5.5)}$$

The measured results suggest a discharge coefficient C_d of 0.6, with an error range of about ± 20%.

The results from the Calderdale model give a similar relationship with a value of C_d = 0.46, which is 25% lower. This may be because the model had a weir which was relatively lower than that in the prototype, which may affect the flow regime when spilling.

Within the range of experimental error the model tests seem to predict the hydraulic performance of the prototype.

7.5.2 Comparison Between Estimated Efficiencies from Models and Prototype.

The results from tests on model vortex overflows were used to estimate the proportion of load which would be passed on to the continuation flow by the prototype, and the result compared with the measured results.

Tests on the Calderdale model were used as a basis for the calculation. Although the model was proportioned slightly differently (with a lower weir for instance), the results were the best available at the time of writing.

In order to model a particle of sewage with settling velocity V_s, two conditions must hold;

a) The ratio of continuation flow to inflow (Q_c/Q_{in}) must be the same for both the model and prototype, and

b) The ratio of the settling velocity of model particle to inflow velocity must be the same as that in the prototype.

ie $$(Q_c/Q_{in})\text{model} = (Q_c/Q_{in})\text{prototype} \qquad \text{(Eqn.7.16)}$$

and

$$(V_s/V_{in})\text{model} = (V_s/V_{in})\text{prototype} \qquad \text{(Eqn.7.17)}$$

The first of these conditions posed a problem. The highest value of (Q_c/Q_{in}) modeled was 0.32. During the events recorded this ratio only occasionally fell below 0.40 for the prototype.

The results from the model test were displayed on a graph of separating efficiency against the settling velocity ratio, (V_s/V_{in}), where in this case separating efficiency was described as the proportion of particles entering the chamber which were carried out the continuation pipe. Curves had been fitted for the various flow ratios (Q_c/Q_{in}) between 0.14 and 0.32. The separating efficiency at $V_s/V_{in} = 0$ was equal to the flow ratio.

This graph was copied, and curves were estimated for flow ratios between 0.4 and 0.9 based on those from the tests for lower values (Fig.7.13).

Estimates of the flow and inlet velocity for given flow ratios were needed. Equation 7.3,

$$Q_c = 175 + 0.1(Q_{in} - 175)$$

was rearranged to obtain

$$Q_{in} = \frac{160}{(Q_c/Q_{in}) - 0.1} \quad \text{l/s} \qquad \text{(Equation 7.18)}$$

When the chamber was just spilling there was an estimate of the inflow velocity measurement of 44cm/s (Section 5.2.4). The flow was directly proportional to the inlet velocity when the pipe was surcharged, giving,

$$V_{in} = 440 \times Q_{in}/175 \quad mm/s \quad (Q_{in} \text{ in l/s}) \qquad \text{(Equation 7.19)}$$

For a given flow ratio Q_c/Q_{in} these equations were be used to calculate V_{in} and Q_{in}. From the value of V_{in} were derived velocity ratios in the settling velocity distribution. For example, for Q_c/Q_{in} = 90%, V_{in} = 500mm/s. Looking at the slowest sinkers (V_s = 0 - 15mm/s) in Table 7.3) it was deduced that 71% of particles had a settling velocity of between 0 and 15/500, ie 0 - 0.03 times the inlet velocity for a flow ratio of 90%. Looking at the curve for Q_c/Q_{in} = 90% on Figure 7.13, it was estimated that about 92% of these particles were retained in the continuation flow, so this range contributed 92% of 71% = 65% of all particles to the continuation flow. When this calculation was done for each velocity range, an overall estimate of the proportion of particles retained could be deduced, as shown in Table 7.4.

Velocity Range (mm/s)	Proportion of Particles in this range	Q_c/Q_{in} = 90%	V_{in} = 460mm/s	
		V_s/V_{in} Range	Average retention in sewer	Proportion of total in sewer
> (40)	0.5%	>(0.080)	99%	0.5%
(40) -(15)	1.0%	(0.080)-(0.030)	96%	1.0%
(15) - 0	3.5%	(0.030)- 0	92%	3.0%
0 - 15	71.0%	0 - 0.030	92%	65.0%
15 - 25	8.5%	0.030 - 0.050	95%	8.0%
25 - 35	7.0%	0.050 - 0.070	98%	7.0%
35 - 45	4.5%	0.070 - 0.090	100%	4.5%
45 - 60	2.0%	0.090 - 0.120	100%	2.0%
> 60	2.0%	> 0.120	100%	2.0%

Net Proportion of Particles Retained in Continuation Flow : 93.0%

Table 7.4 Calculations of overall proportion of particles entering overflow which are retained in continuation flow, assuming the given particle distribution, at Q_c/Q_{in} = 90%.

If there was a concentration of C_p particles per unit volume in the inflow, then the total number entering per unit time,

$$Nin = C_p \times Q_{in}. \qquad \text{(Equation 7.20)}$$

If the proportion of these retained in the continuation flow was P_c, then the total in the continuation flow was

$$N_c = N_{in} \times P_c \quad \text{(per unit time)} \qquad \text{(Equation 7.21)}$$

and the total in the spill flow was

$$N_s = N_{in} \times (1-P_c) \quad \text{(per unit time).} \qquad \text{(Equation 7.22)}$$

The concentration of objects in the spill flow was then

$$C_s = N_s/Q_s = (1-P_c) \times C_p \times Q_{in}/Q_s \qquad \text{(Equation 7.23)}$$

and the relative concentration of spill flow compared to inflow was

$$C_s/C_p = \frac{(1 - P_c)}{(1 - Q_c/Q_{in})} \qquad \text{(Equation 7.24)}$$

similarly the relative concentration of objects in the continuation flow compared to that in the inflow was

$$C_c/C_p = \frac{P_c}{(Q_c/Q_{in})} \qquad \text{(Equation 7.25)}$$

For (Q_c/Q_{in}) = 90%, P_c = 93%, so the relative concentration C_s/C_p is thus 70% - the spill flow contains 30% fewer particles per unit volume than the inflow. For this flow ratio C_c/C_p = 103% - the continuation flow contains 3% more particles per unit volume than the inflow.

These calculations were repeated for different flow ratios, each of which had a different V_{in}, thus different velocity ratio ranges and different average retention proportions. The results of such calculations are shown in Table 7.5.

Q_{in} (l/s)	Q_c/Q_{in}	V_{in} (mm/s)	Overall Proportion Retained	Relative Spill Conc. (C_s/C_p)	Relative Cont.Conc. (C_c/C_p)
530	40%	1340	43.5%	96%	109%
400	50%	1010	55.0%	90%	110%
320	60%	810	66.0%	85%	110%
270	70%	680	75.5%	82%	108%
230	80%	580	86.0%	70%	108%
200	90%	500	93.0%	70%	103%
(175)	(100%)	(440)	(100.0%)	-	100%

Table 7.5 Values of inflow, inlet velocity and overall proportion of sewage particles estimated to be retained in continuation flow for given flow ratios (Q_c/Q_{in}).

As the flow increases the relative concentration of the spill flow increases. The model predicted that the overflow will perform better at low flows, providing up to a 30% reduction in concentration. This compared well with the the GSM prediction of 20-40% improvement, which was based on storms with flows predominantly less than 350 l/s.

The relationship between Q_c/Q_{in} and the overall retention was programmed into the computer, using a linear interpolation algorithm This allowed the percentage of particles spilled and retained during each time step of a hydrograph to be calculated, simply by calculating the flow ratio at that timestep and using the algorithm. The concentration of particles per litre at the inflow was estimated, and multiplied by the inflow to get the total number of particles entering the chamber during a timestep.

$$\text{No. Particles in Inflow} = Q_{in} \times C_p \times \Delta t \qquad \text{(Equation 7.26)}$$

where C_p = Particle concentration (particles/litre)
Δt = length of timestep

Multiplying this by the proportion retained, P_c (Deduced from Table 7.5), gave the number retained in the continuation flow.

$$\text{No. Particles in Continuation flow} = Q_{in} \times C_p \times P_c \times \Delta t$$

(Equation 7.27)

By repeating this calculation for every timestep and summing over the time during which the chamber is spilling, estimates of the total number of particles entering the chamber and the total number leaving in the continuation flow were obtained. Dividing the latter by the former gave a value for the percentage load retained which could be compared with estimates from the Gross Solids Monitor results (Section 5.4.4).

$$\text{Percentage Load Retained} = \frac{\text{Total Particles in Continuation Flow}}{\text{Total Particles in Inflow}}$$

(Eqn.7.28)

This was done for the six storms with both gross solids results and flows available. Again the flows were deduced from the recorded spill flow using equation 7.11.

The results depended upon how the concentration of particles in the inflow was estimated. Three methods were tried;

(a) The concentration was assumed to be constant throughout the storm,
(b) The concentration was assumed to be proportional to the inflow,
(c) The concentration was assumed to be proportional to the square of the inflow.

The predicted retentions are shown in Table 7.6 (overleaf) along with the estimated result from the GSM work, and the proportion of particles which would be retained assuming the chamber has no separating effect at all (ie the sewage spilled has the same particle concentration as that entering). The estimated improvement in the particle loading of the spill flow was calculated in the same way as for the GSM results using Equation 7.15.

The retention results for the constant concentration were consistantly higher than for concentration proportional to inflow, which in turn were higher than the results for concentration proportional to the square of inflow. This was because the latter two give more weight to times of high flow, when the chamber is less efficient at preventing material from spilling.

The calculated values for (c) when no separation effects were assumed were quite similar to the estimates from the GSM with no separation (though the former are on average a few percent higher).

	Total Particles Retained/ Total in Inflow for storms during 1989					
	30-Jun	20-Oct	22-Oct	8-Nov	14-Dec	16-Dec
Model Test Predictions						
(a) C_p = Constant						
Estimated Retention	88%	81%	93%	90%	78%	70%
No Separation	84%	78%	90%	87%	74%	66%
Spill Load Reduction	30%	15%	30%	25%	15%	10%
(b) $C_p = k\ Q_{in}$						
Estimated Retention	87%	76%	92%	87%	74%	64%
No Separation	83%	72%	89%	84%	69%	60%
Spill Load Reduction	25%	15%	25%	20%	15%	10%
(c) $C_p = k\ (Q_{in})^2$						
Estimated Retention	86%	72%	92%	83%	70%	59%
No Separation	82%	67%	89%	80%	65%	56%
Spill Load Reduction	25%	15%	25%	15%	15%	5%
Measured Results						
GSM Estimate	95%	60%	95%	80%	80%	60%
GSM (No separation)	80%	60%	90%	75%	65%	55%
GSM Spill Load Reduction	80%	-5%	45%	30%	45%	20%

Table 7.6 Comparison between retentions of particles measured by GSM and those predicted by model, and the reduction in spilled load caused by the particle separation and concentration in the continuation flow.

The estimated improvement in the concentration of particles in the spill flows for (a) are better than those for (b) which are better than those for (c). Again, this is because the latter two give more weight to the less efficient high flows. Except for one storm (where there were only a small number of GSM points) the GSM estimates of spill load reduction are better than those predicted by the model, roughly twice as good as those predicted by (c).

There are a number of possible explainations for the differences between model predictions and measured results;

- The GSM may not be sampling the spill in the same way that it is sampling the inflow due to the shape, position and flow around the sample pipe entry.

- The settling velocity distribution may not be representative. The one used is fairly crude, and based on dry weather flow samples. The storm sewage is likely to contain more sediment, with a higher proportion of material at the faster sinking end of the spectrum. The overflow is very efficient at dealing with such particles, and were they included in the model, the estimated retention would improve.

- The estimated retentions of particles with given settling velocities have been poorly extrapolated from the model tests (Fig.7.13).

- Errors in measuring the flow and the particle concentration were significant.

In order to investigate the second point in more detail, that the particles in the storm sewage are more likely to be sinkers if they are re-entrained from the sediment, two settling velocity distributions (SVDs) for storm sewage were derived from the existing dry weather one;

SVDi) In which twice as many particles are assumed to have settling velocities >15mm/s as in the DWF distribution.

SVDii) In which twice as many particles are assumed to be in the range $15<V_s<25$, and three times as many with $V_s>25$mm/s, compared to the DWF distribution.

These are detailed in Table 7.7.

Velocity Range (mm/s)	Proportion of Particles in this Range		
	In DWF	SVDi	SVDii
> (40)	0.5%	0.5%	0.5%
(40) -(15)	1.0%	1.0%	1.0%
(15) - 0	3.5%	3.5%	3.5%
0 - 15	71.0%	47.0%	31.5%
15 - 25	8.5%	17.0%	17.0%
25 - 35	7.0%	14.0%	21.0%
35 - 45	4.5%	9.0%	13.5%
45 - 60	2.0%	4.0%	6.0%
> 60	2.0%	4.0%	6.0%

Table 7.7 Proportions of particles in given ranges of settling velocities. (Figures in brackets indicate floaters).

These two distributions were be used to estimate the total proportion of particles retained and the relative concentration of spill flow to inflow for different flow ratios (Q_{in}/Q_c) in the same way as was described above. The results are displayed in Table 7.8.

Q_c/Q_{in}	Q_{in} (l/s)	DWF		SVDi		SVDii	
		%age ret-ained	Conc. Ratio (C_s/C_p)	%age ret-ained	Conc. Ratio (C_s/C_p)	%age ret-ained	Conc. Ratio (C_c/C_p)
40%	530	43.5%	96%	46.0%	90%	48.5%	86%
50%	400	55.0%	90%	58.0%	84%	60.5%	79%
60%	320	66.0%	85%	69.0%	77%	72.5%	69%
70%	270	75.5%	82%	80.0%	67%	82.0%	60%
80%	230	86.0%	70%	88.5%	57%	90.0%	50%
90%	200	93.0%	70%	94.0%	60%	95.5%	45%
(100%)	(175)	(100%)	-	(100%)	-	(100%)	-

Table 7.8 Values of overall proportion of sewage particles estimated to be retained in continuation flow for given flow ratios (Q_c/Q_{in}).

In the flow range up to about 350l/s SVDi gave improvements in spill concentrations of 20-40%, SVDii gave improvements of 25-55%. The former compares well with the predictions from the GSM, the latter is perhaps a little high.

When these figures were used to predict total loadings over the storms recorded (modelling the particle concentration at the inlet as proportional to the square of the inflow) the results in Table 7.9 were obtained.

	Percentage Load Retained for storms during 1989					
	30-Jun	20-Oct	22-Oct	8-Nov	14-Dec	16-Dec
Model Result if no Separation	82%	67%	89%	80%	65%	56%
Original DWF SVD						
Estimated Retention	86%	72%	92%	83%	70%	59%
Spill Load Reduction	20%	15%	25%	15%	15%	5%
SVDi						
Estimated Retention	89%	75%	93%	85%	73%	62%
Spill Load Reduction	40%	20%	35%	25%	25%	15%
SVDii						
Estimated Retention	90%	77%	95%	87%	76%	64%
Spill Load Reduction	45%	30%	55%	35%	30%	20%
GSM Estimate	95%	60%	95%	80%	80%	60%
GSM Spill Load Reduction	80%	-5%	45%	30%	45%	20%

Table 7.9 Comparison between retentions of particles measured by GSM and those predicted by model using different settling velocity distributions.

For the later four storms, for which there were more data than the 6 GSM readings for each of the earlier two, there appears to be a broad correlation between the GSM figures and those calculated.

The estimated retentions from the GSM results were all within 10 percentage points of the values predicted by the model. The reductions in spill loadings due to the separating effects of the chamber predicted using the DWF distribution and SVDi were all too low. Those using SVDii were in two cases two high and in two too low, but were all within 15 percentage points. These values were quite sensitive to variation in the estimated retention percentage.

Bearing in mind the margins of error in the experimental procedures, the results suggest that it is possible to predict the separating performance of an overflow by doing model tests on particles with appropriately scaled settling velocities. Were more detailed model test results available, particularly at lower flow ratios, and if there was better knowledge of the settling velocity distribution of the storm sewage, it seems likely that good predictions of the loadings in a full scale overflow could be made.

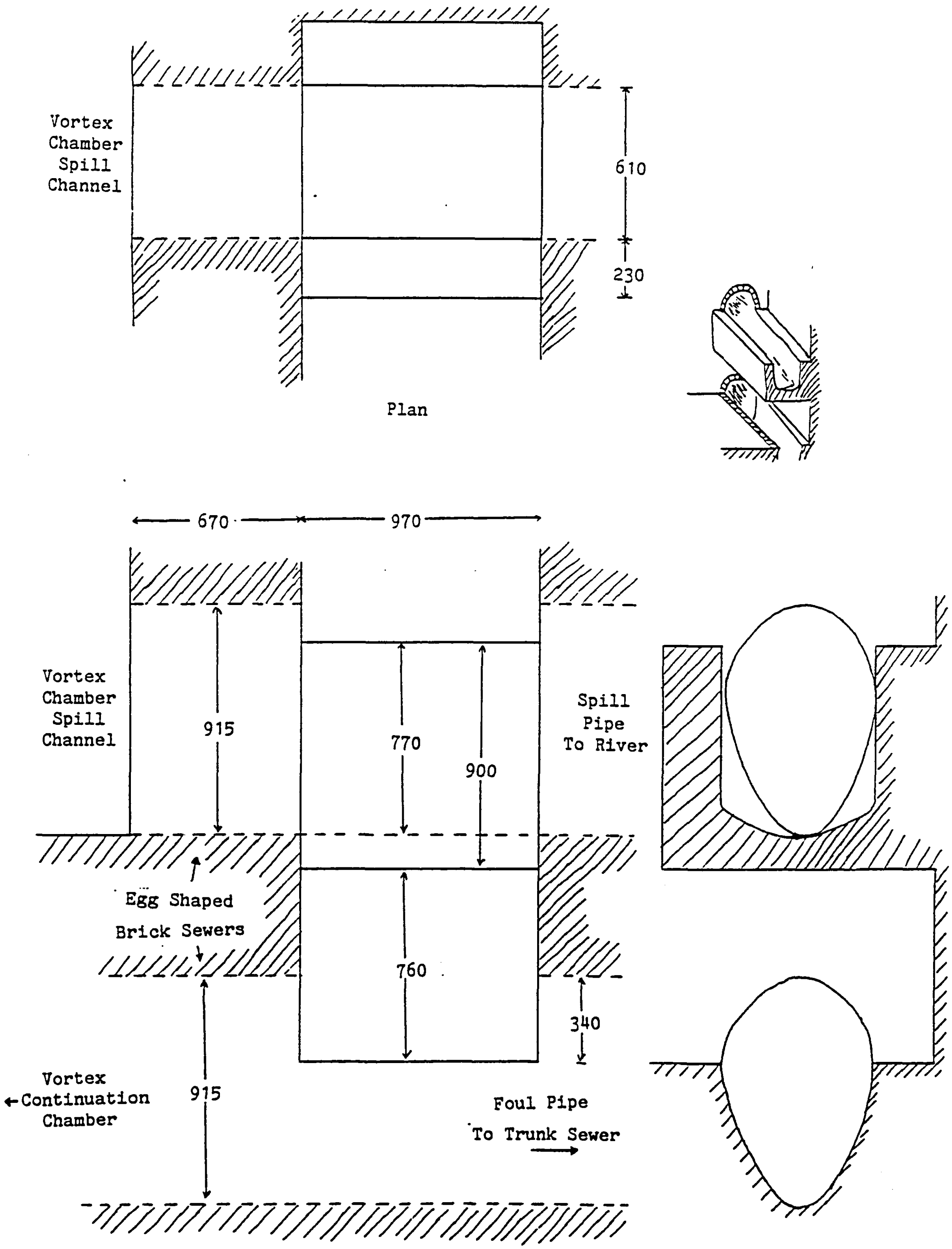


Figure 7.1 Manhole Downstream of Vortex Overflow

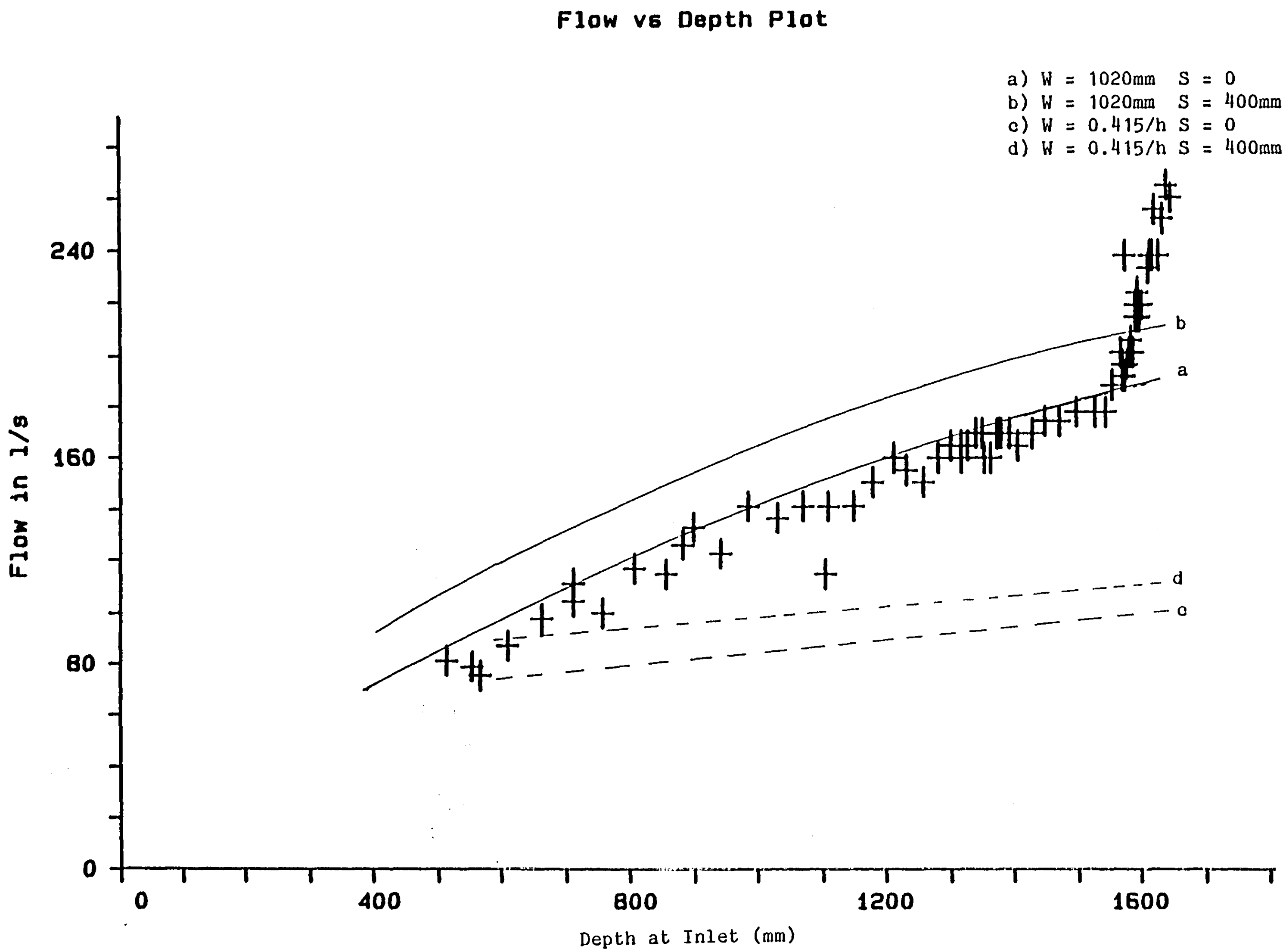


Figure 7.2 Comparison of Mathematical Model Predictions of Flow -Depth Relationship in Vortex with Measured Results.

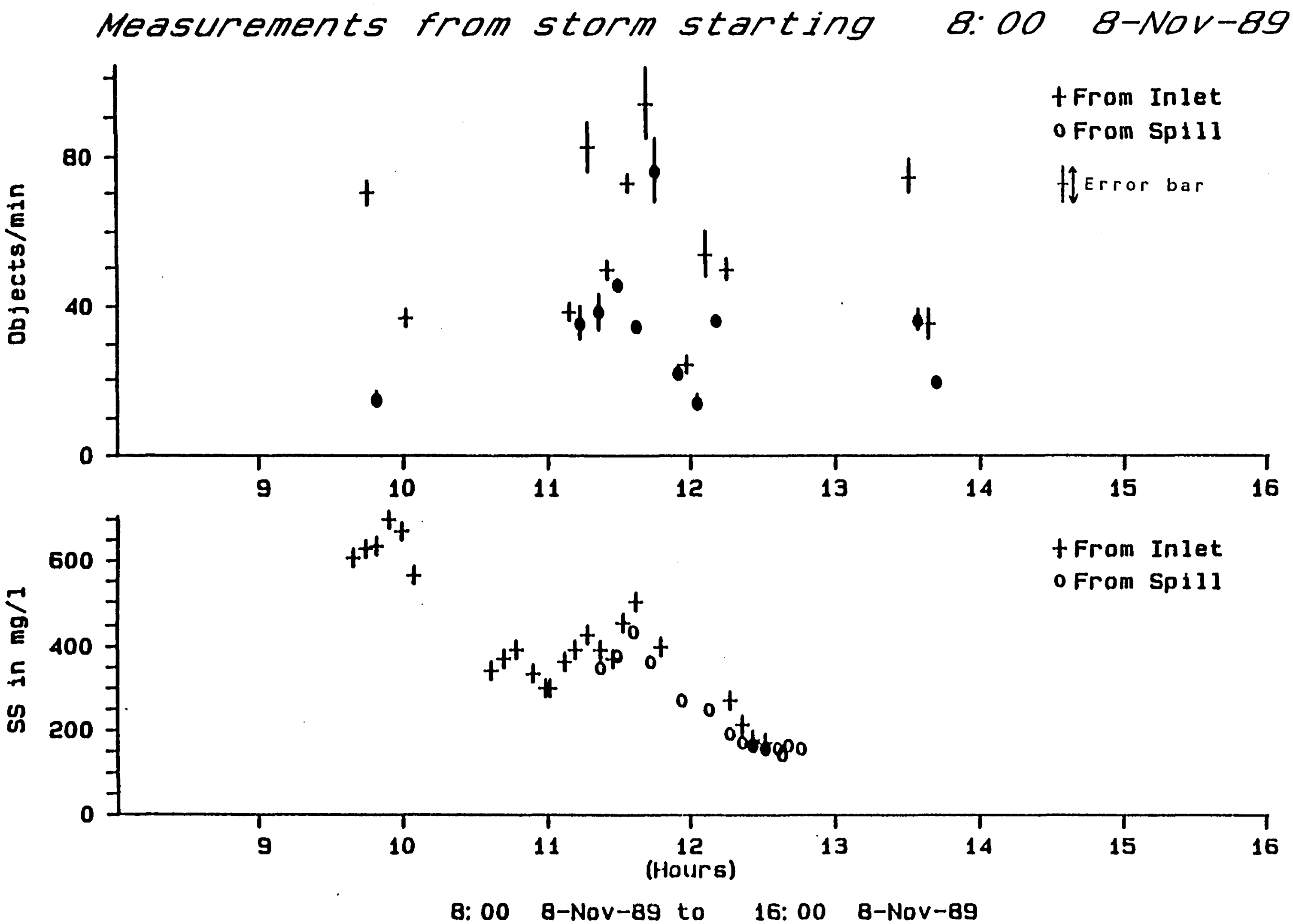


Figure 7.3 Comparison Between Gross Solids Counts/Minute and Suspended Solids in Samples on 8-Nov-89.

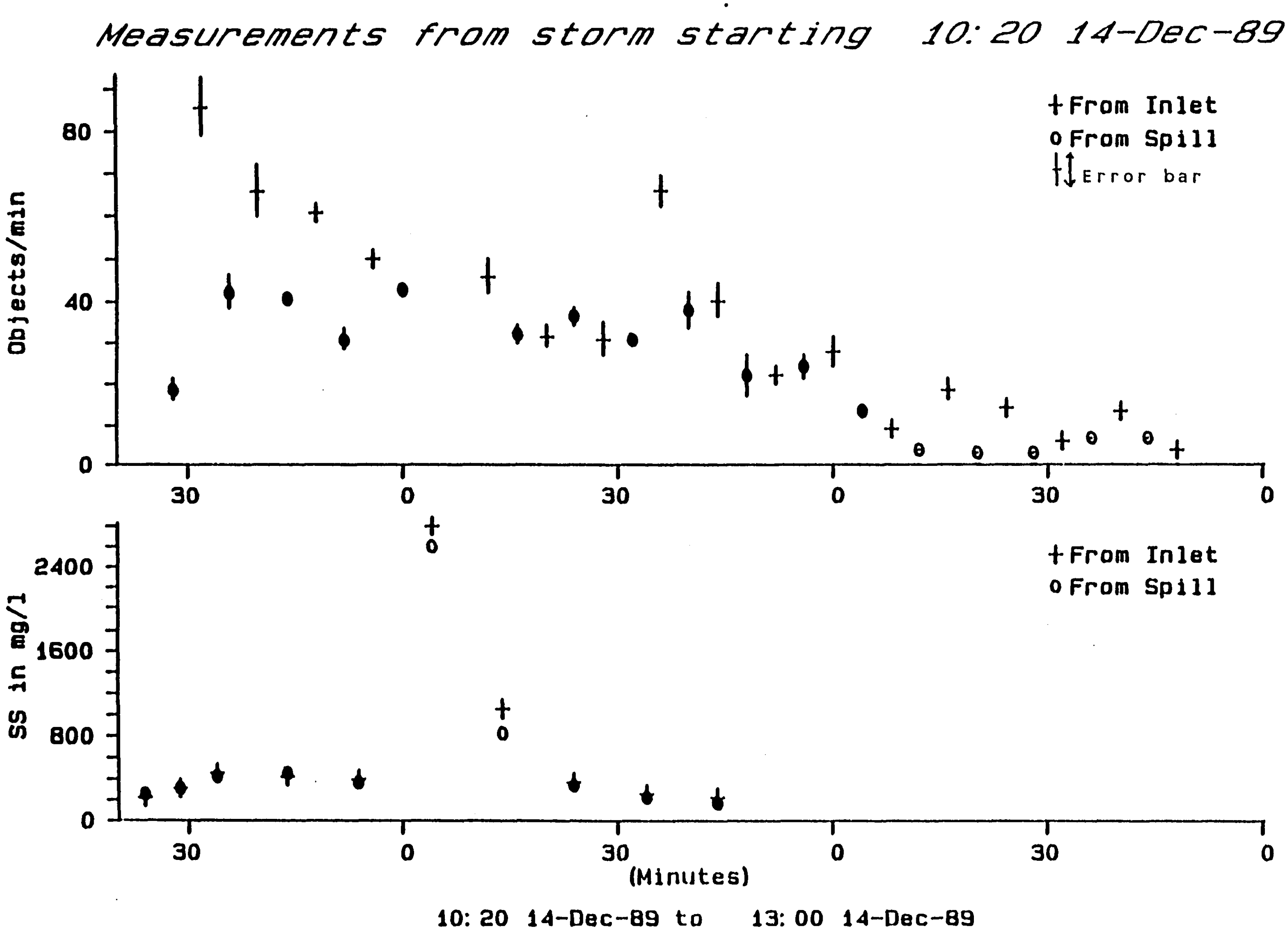


Figure 7.4 Comparison Between Gross Solids Counts/Minute and Suspended Solids in Samples on 14-Dec-89.

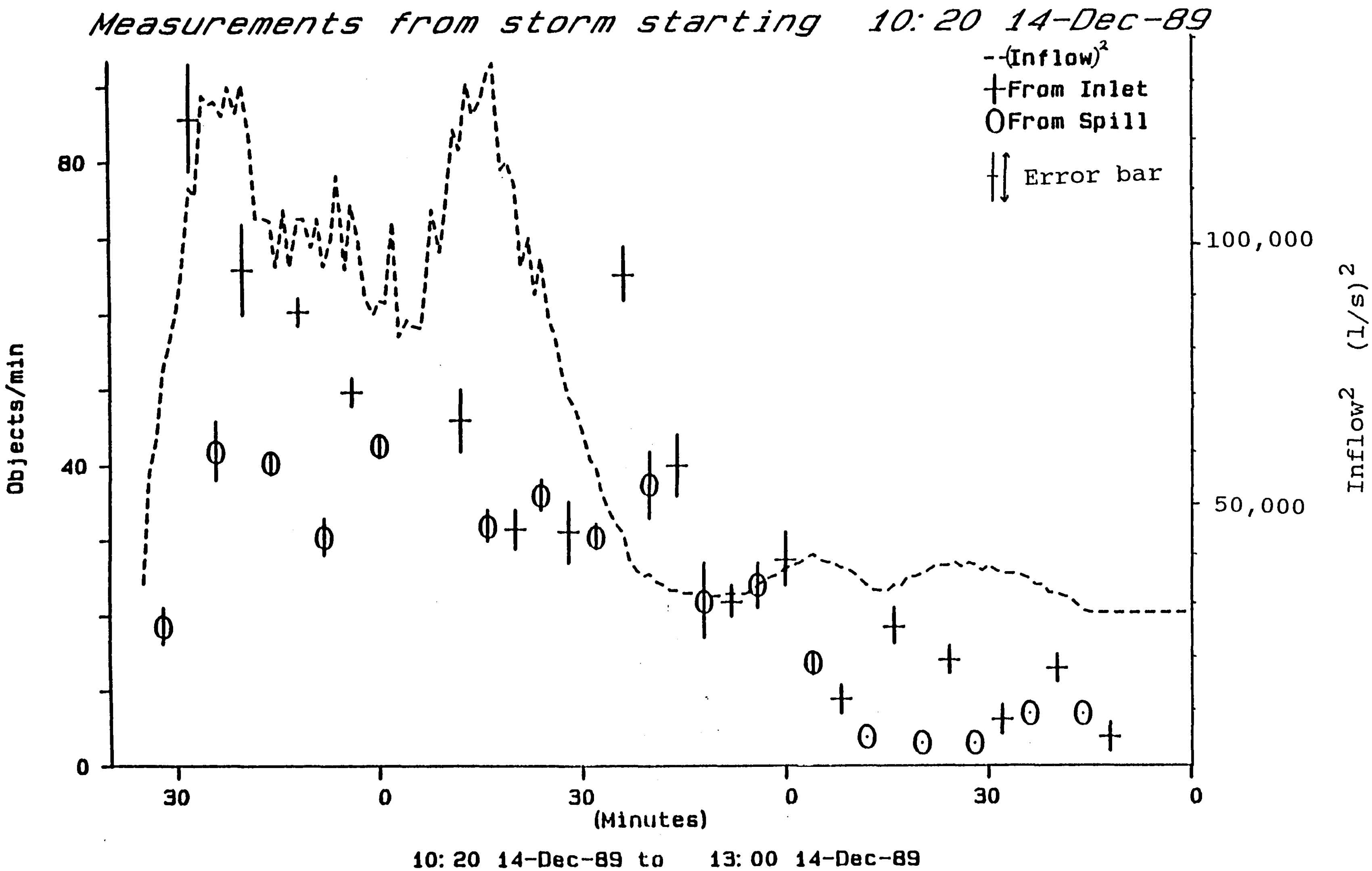


Figure 7.5 Comparison Between Gross Solids Counts/Min. Profile and $(\text{Inflow})^2$ on 14-Dec-89

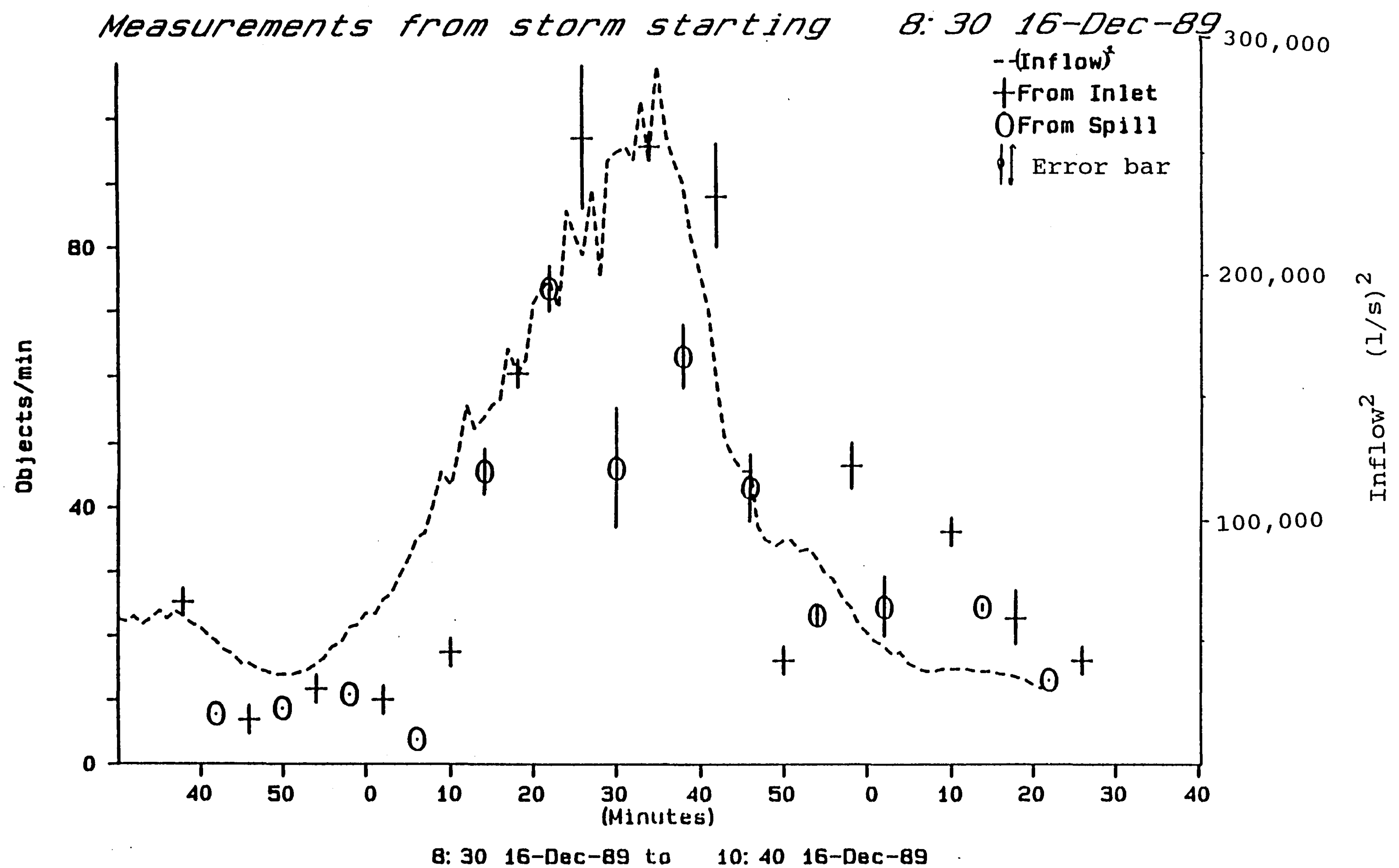


Figure 7.6 Comparison Between Gross Solids Counts/Min. Profile and $(\text{Inflow})^2$ on 16-Dec-89

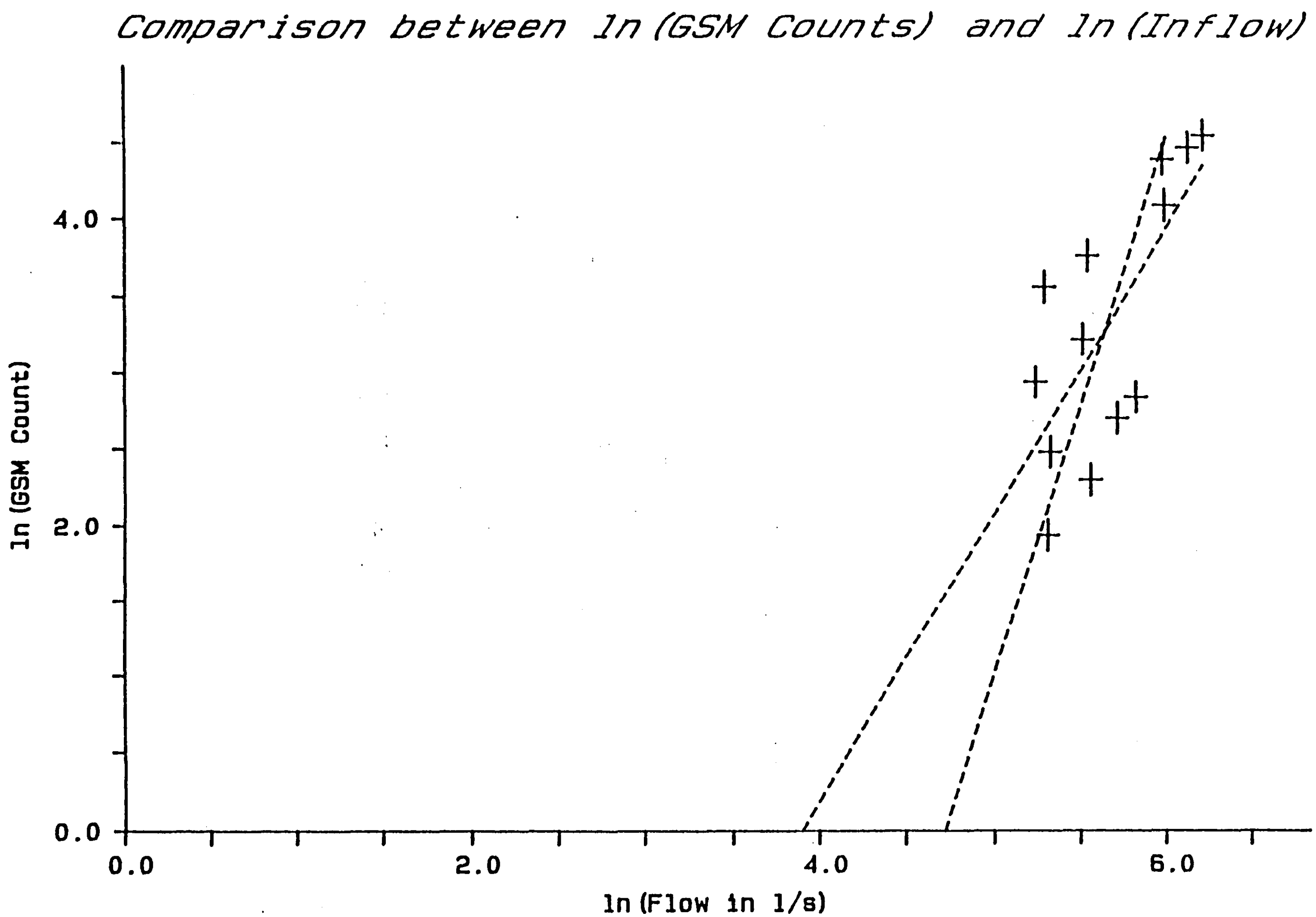


Figure 7.7 Comparison Between ln(GSM Counts) and ln(Flow in l/s) for a Storm on 16-Dec-89

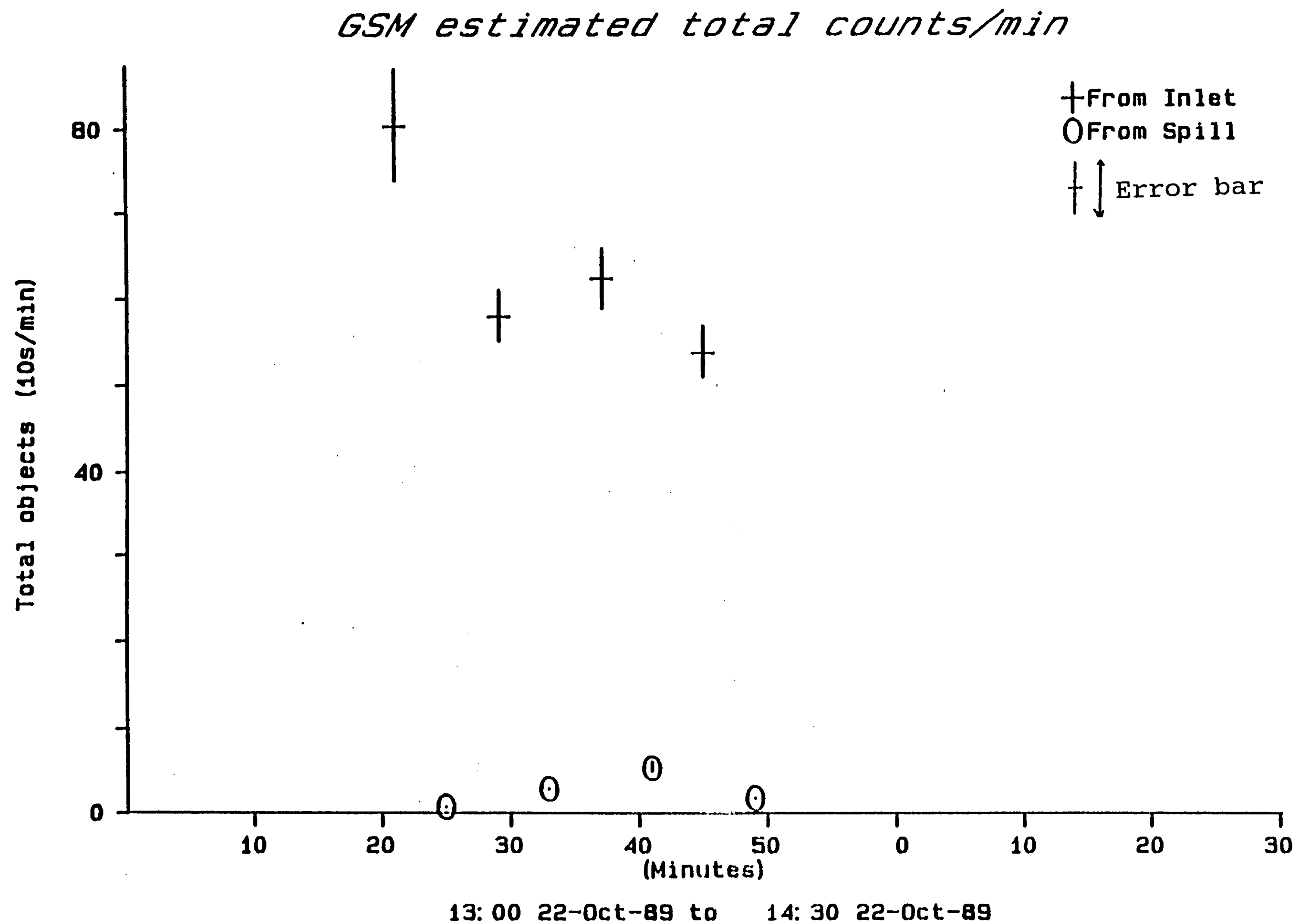


Figure 7.8 Estimates of Numbers of Gross Solids Entering and Spilling on 22-Oct-89

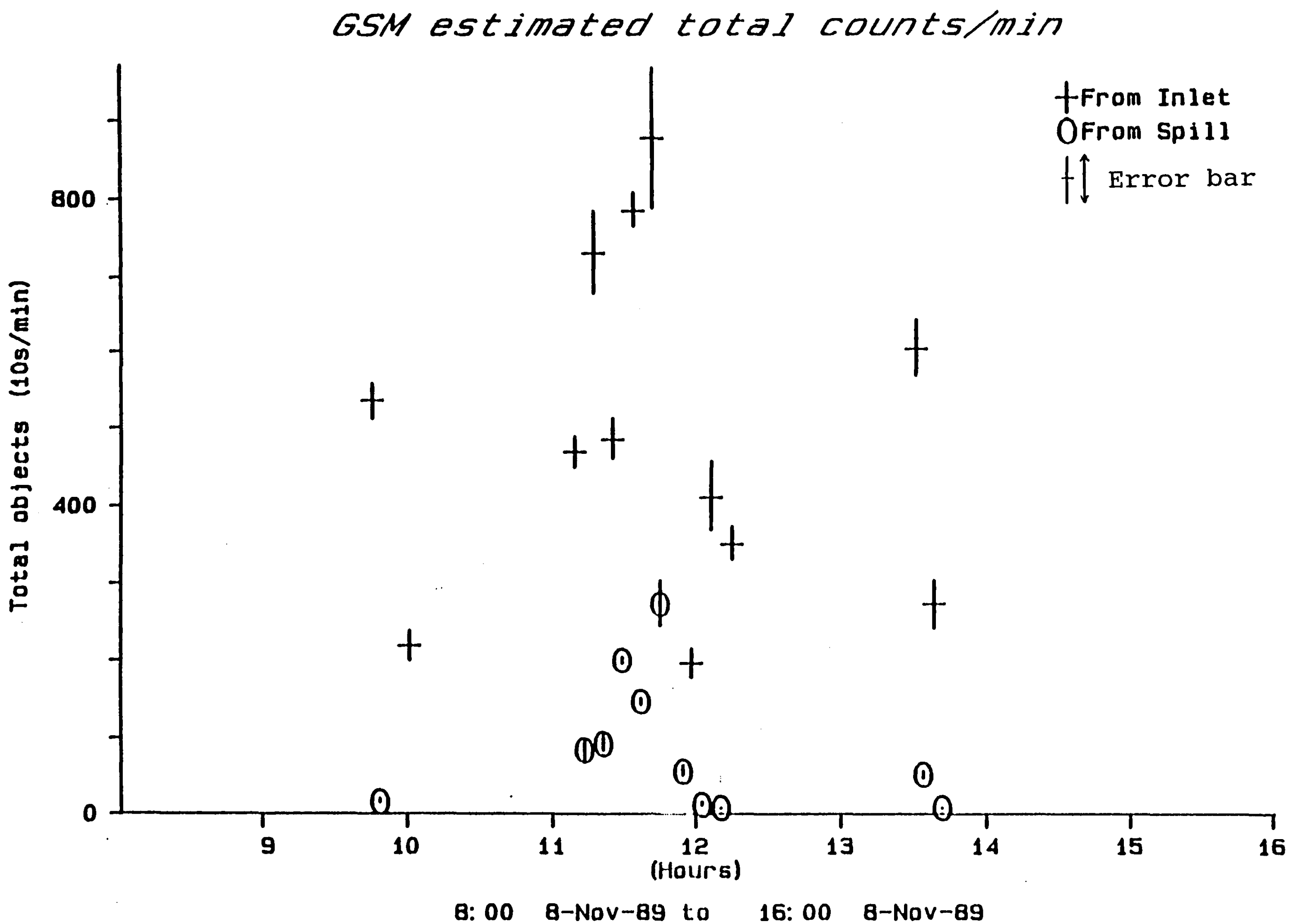


Figure 7.9 Estimates of Numbers of Gross Solids Entering and Spilling on 8-Nov-89

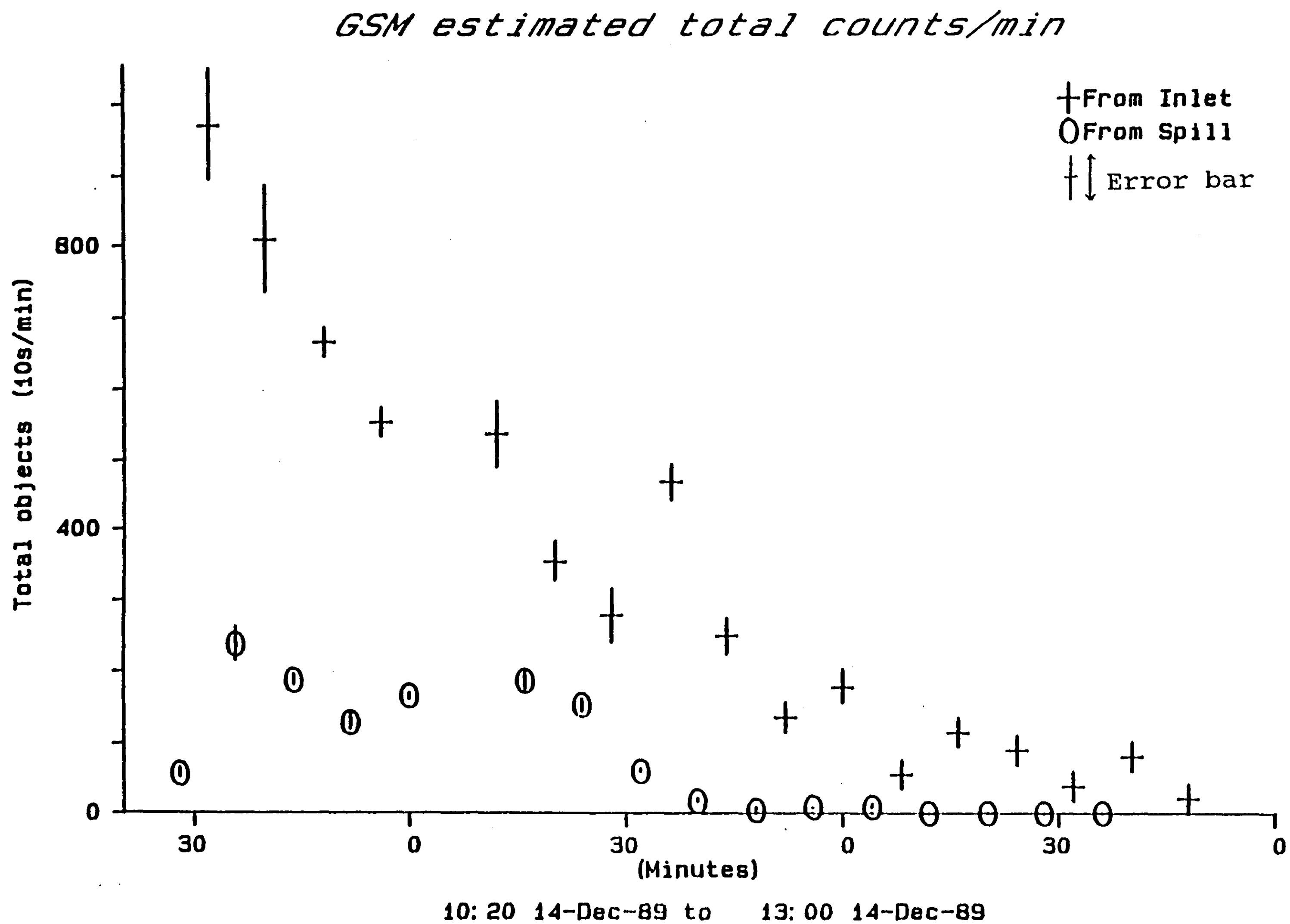


Figure 7.10 Estimates of Numbers of Gross Solids Entering and Spilling on 14-Dec-89

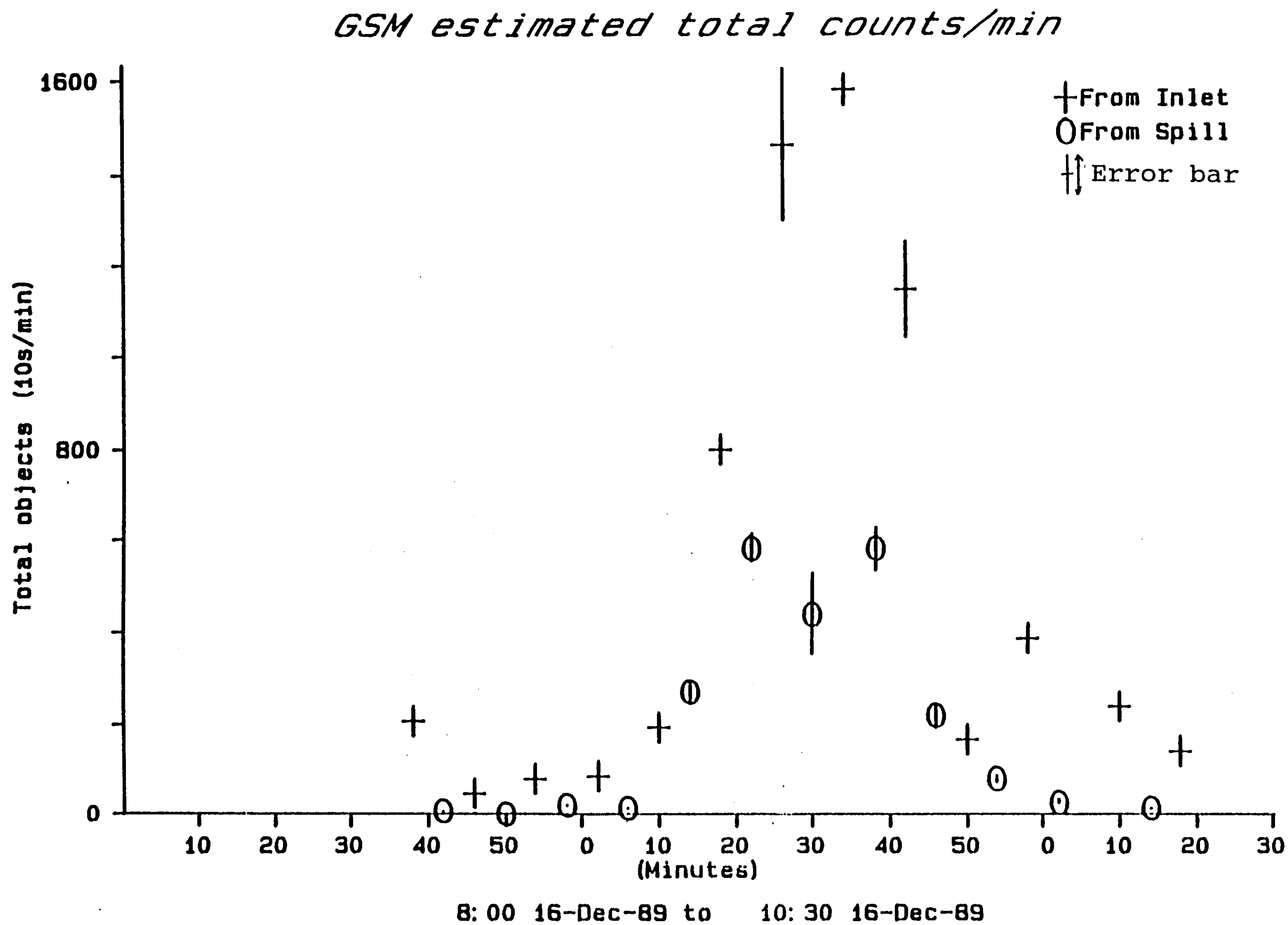


Figure 7.11 Estimates of Numbers of Gross Solids Entering and Spilling on 16-Dec-89

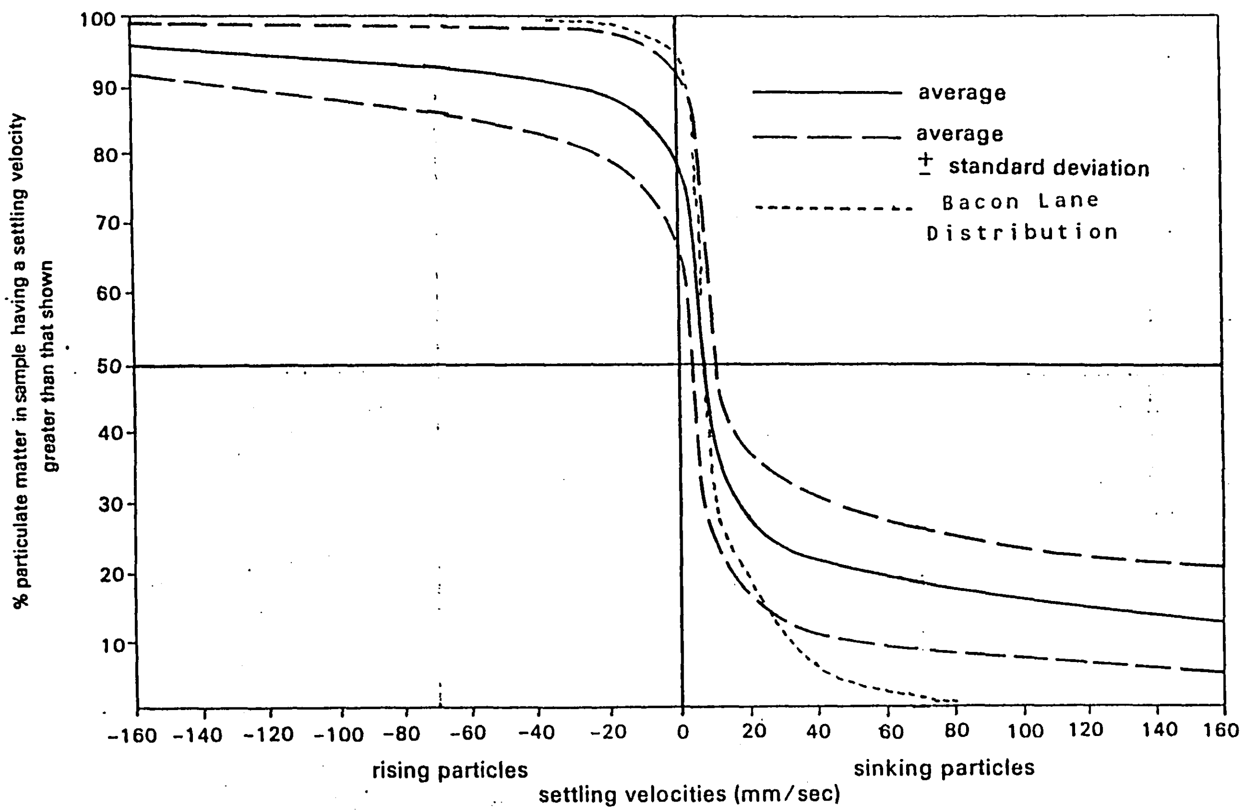


Figure 7.12 Settling Velocity Distribution Results from ARD6 Report with Bacon Lane Distribution Superimposed.

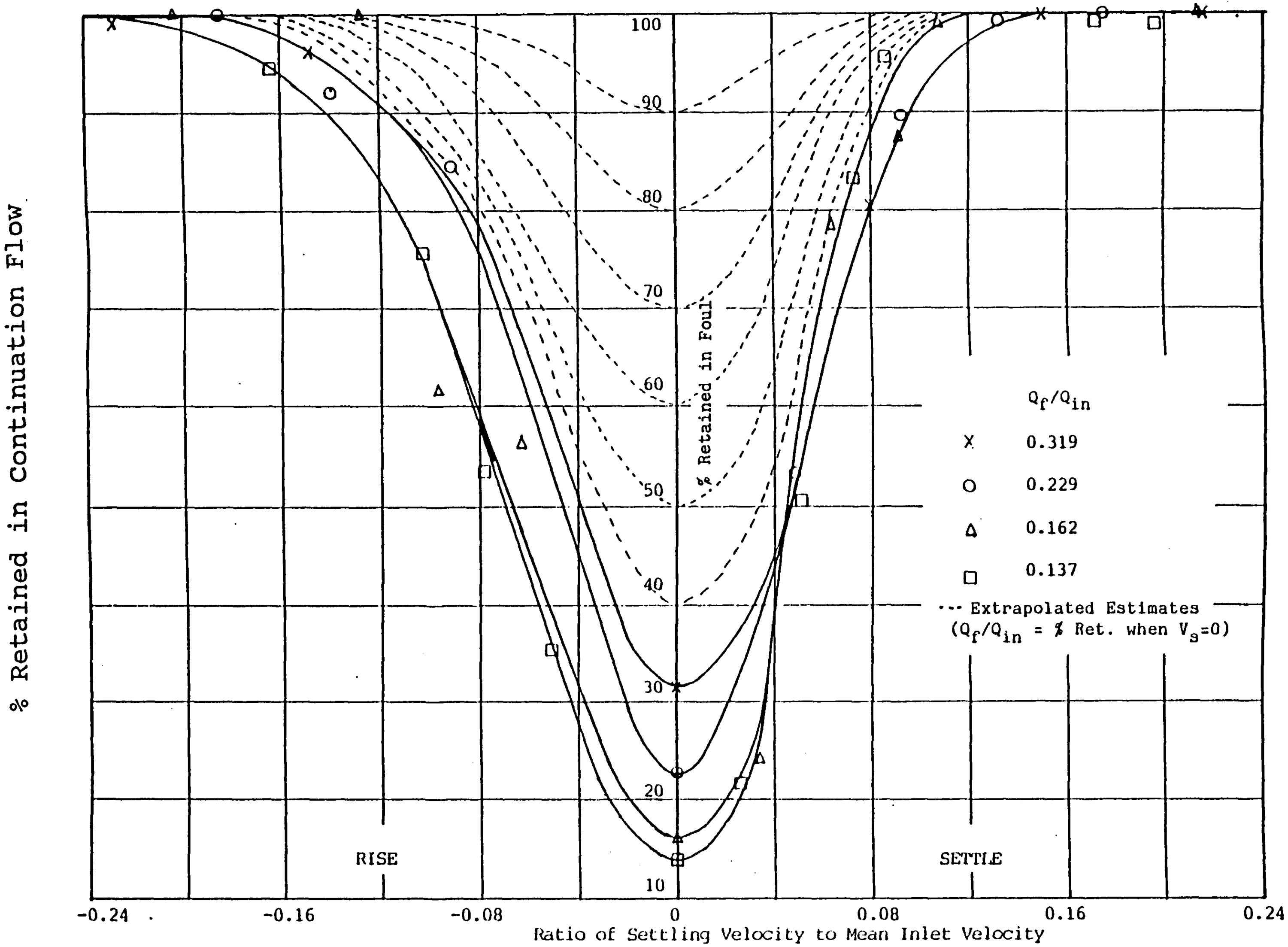


Figure 7.13 Curves of the Proportion of Particles Retained in Foul Flow at Different Vs/Vin Ratios and Various Qf/Qin Ratios Predicted by Calderdale Model Tests. (Based on Fig. by Balmforth).

Chapter 8 Conclusions

8.1 The Performance of the Prototype

- The chamber is self cleansing, apart from with small amounts of matter that cling to the sides of the inlet channel above the inlet pipe.

- During almost three years of operation the chamber only became blocked once.

- The vortex overflow with peripheral spill performs well hydraulically, with the continuation flow rising little above the 175 l/s just required to spill. This minimum flow required to spill can be estimated using a variant of Ackers & Crump's theory.

- The overflow has little or no effect on the concentrations of dissolved or fine suspended solids collected by bottle samplers. However certain heavier material, such as grit, is likely to be retained.

- If the results of the Gross Solids Monitor are assumed to be representative, the chamber concentrates gross solids, such as rags, tissues, sticks etc in the foul flow, reducing the concentration of such objects in the spill flow by 20-40% compared to that in the inflow during storms with flows up to twice that required to spill.

- During such storms the Gross Solids Monitor suggested that the load retained is between 60-95% of that entering the chamber. The separating effects of the chamber reduce the load spilled by 20-45% compared to what it would be were there to be no separation, when the concentration of particles in the spill flow would be the same as that in the inflow.

8.2 The Gross Solids Monitor

- The equipment installed to monitor the gross solids worked well, only hampered occasionally by oversensitive sensors.

- The system produces fairly clear videos on which shadows of objects can usually be seen clearly. They are only obscured when the sewage becomes very turbid, which sometimes happens early on in the storm, or when a large number of bubbles appear in the pipe.

- These videos can be analysed by counting by eye the numbers of particles visible in each minute of useful film. If done under the right conditions this produces repeatable internal ratios (such as the average spill count/average inflow count), although the actual numbers counted at different times by different people may vary.

- Using a computer image analysis system proved difficult mainly owing to its slowness and the difficulty in isolating valid particles and distinguishing them from the edges of bubbles. More advanced computer systems and the improvements to the image which may be possible with better cameras and light sources, bubble traps and so on may allow the automatic analysis of the video recordings.

8.3 Comparison of the Prototype to Model Tests

- Within the practical constraints of the experiments, the hydraulic performance of the prototype compares well with model predictions.

- The results suggest that if synthetic gross solid particles are used with suitably scaled settling velocities in models of storm overflows, predictions can be made of the performance of the full scale chamber.

8.4 Suggestions for Further Work

- More results from the Gross Solids Monitor would be useful, particulary from storms with higher flow rates.

- Tests to examine the affect of different Gross Solids Monitor sample pipe inlet arrangements on the results, and how representative the measured results are would allow the performance of the overflow to examined with greater accuracy.

- Sampling from the continuation flow for gross solids would give an additional check on how the monitor and the chamber perform.

- The GSM system may be improved with a better camera, a more powerful light source, window washing facilities and bubble traps, amongst other things. The closer the measurement cell can be put to the pipe inlets, the shorter the time needed to flush the system and the more useful sections of film could be obtained for a storm. The ability to play back films in slow motion would allow more accurate counting by eye, should this method be continued.

- Judicious use of Copasacs in the inlet channel and on the weir may allow estimation of the gross solid loadings into and out of the chamber. These results could be used to check the GSM predictions. If such a method were attempted the sacks would have to be well secured and provision made in case they came loose.

- A more accurate distribution of the settling velocities of material in the storm sewage could be derived, either using a similar technique to that used in the project, based on samples from Copasacs, or using large samples of storm sewage.

- Additional model tests and more results from the prototype would be useful to reinforce the conclusions.

Appendix A Design Method for a Vortex Overflow with Peripheral Spill

(Based on the work of Balmforth and Lea)

If an overflow is to be designed for a system with a design flow of Q_{max}, (in m^3/s), then for best inlet velocity conditions, the diameter of the upstream pipe, D_{min}, should be

$$D_{min} = 0.815\, Q_{max}^{0.4} \qquad (m)$$

However a vortex overflow is less affected by increased inlet velocities than other overflows, so the equivalent diameter of the actual upstream pipe, D, can be as much as 25% smaller than D_{min}. This may prove useful when the vortex chamber is replacing an older inadequate overflow, since it may avoid the need to replace the existing pipe network.

The chamber should be dimensioned as shown in Figure A1, based on the theoretical pipe diameter D_{min}, or the actual inlet pipe diameter, D, if this is larger.

Thus the chamber radius, $R = 2D_{min}$ (or 2D if $D > D_{min}$).

The weir crest should be at the level of the soffit of the inlet pipe.

The central outlet can be a round edged orifice plate or a short vertical throttle pipe with rounded entry. If an orifice plate is used it is easy to replace with a different size should it be necessary. Its diameter, d, will determine the continuation flow to be passed on downstream before the chamber begins spilling (ie the setting of the overflow, Q).

The setting should be chosen with careful regard to the nature of the receiving watercourse and the hydraulic requirements of the sewer system. For a given setting and chamber radius, R, the diameter of the orifice in a plate can be found from the dimensionless design chart (Fig.A2). Note: The chart is based on theoretical calculations by Ackers & Crump[23] (See section 7.1.3) Measured results on the prototype suggested actual flows at first spill were 5 - 10% lower than those predicted by the theory.

The discharge over the weir may be calculated from

$$Q_s = 0.45\ L_W\ g^{0.5} h_W^{\ 1.5}$$

Q_s = Weir discharge (m^3/s)
L_W = Length of weir (m)
h_W = Head above weir (m)

If it is not possible to discharge sufficient flow within the confines of head, the chamber may be enlarged overall. The chamber size should not be increased by increasing diameter alone.

Vortex overflows require a significant drop between inlet and continuation pipes, so are not usually suited to catchments with slack gradients. However they work well at high inlet velocities, so are well suited to steep catchments.

As shown in the figure they can easily be constructed in circular shafts, so making them a good option in bad ground.

Example

It is desired to replace a leaping weir overflow with a vortex SSO with peripheral spill.

The leaping weir is in a 915x610 egg-shaped sewer with a gradient of 1 in 22.

The continuation and overflow pipes are also 915x610 sewers at the same gradient.

Inlet sewer invert level = 42.400m AOD
Overflow sewer invert level = 42.400m AOD
Continuation sewer invert level = 40.150m AOD

The 2 year design discharge = 1200 l/s.
The setting is to be 180 l/s.

i) Upstream Sewer

$$D_{min} = 0.815 \times 1.2^{0.4} = 0.877m$$

Equivalent diameter of existing sewer, D = 0.738m

$D/D_{min} = 0.84$

This is above 0.75 so the upstream sewer will not need resizing.

ii) Chamber Dimensions

Base on D_{min}=0.877m (See Figure).

Chamber Diameter = 4 x 0.877 = 3.51m

Level if throttle pipe throat = 42.200 - 0.8x0.877 = 41.690m AOD

Level of weir crest (invert soffit) = 42.40 + 0.915 = 43.315m AOD

Length of inlet channel = 1.2 x 0.877 = 1.05m

Width of inlet channel = 1.15 x 0.877 = 1.01m

Opening of scumboard at weir = 0.5 x 0.877 = 0.44m

Opening of scumboard at inlet = 0.9 x 0.877 = 0.79m

Depth of scumboard below weir = 0.36 x 0.877 = 0.32m (42.995m AOD)

Floor slopes at 1 in 4 towards throttle pipe.

Entrance to throttle pipe rounded at radius d/2 (d = throttle pipe diameter).

iii) Design of Throttle

Chamber radius, R = 2 x 0.877 = 1.754m

Ordinate on design chart = $\dfrac{0.180}{9.81^{0.5} \times 1.754^{2.5}}$ = 0.0141

Interpolating from the design chart, d/R = 0.175

Thus the throttle diameter, d = 0.175 x 1.754 = 0.307m

So use 300mm.

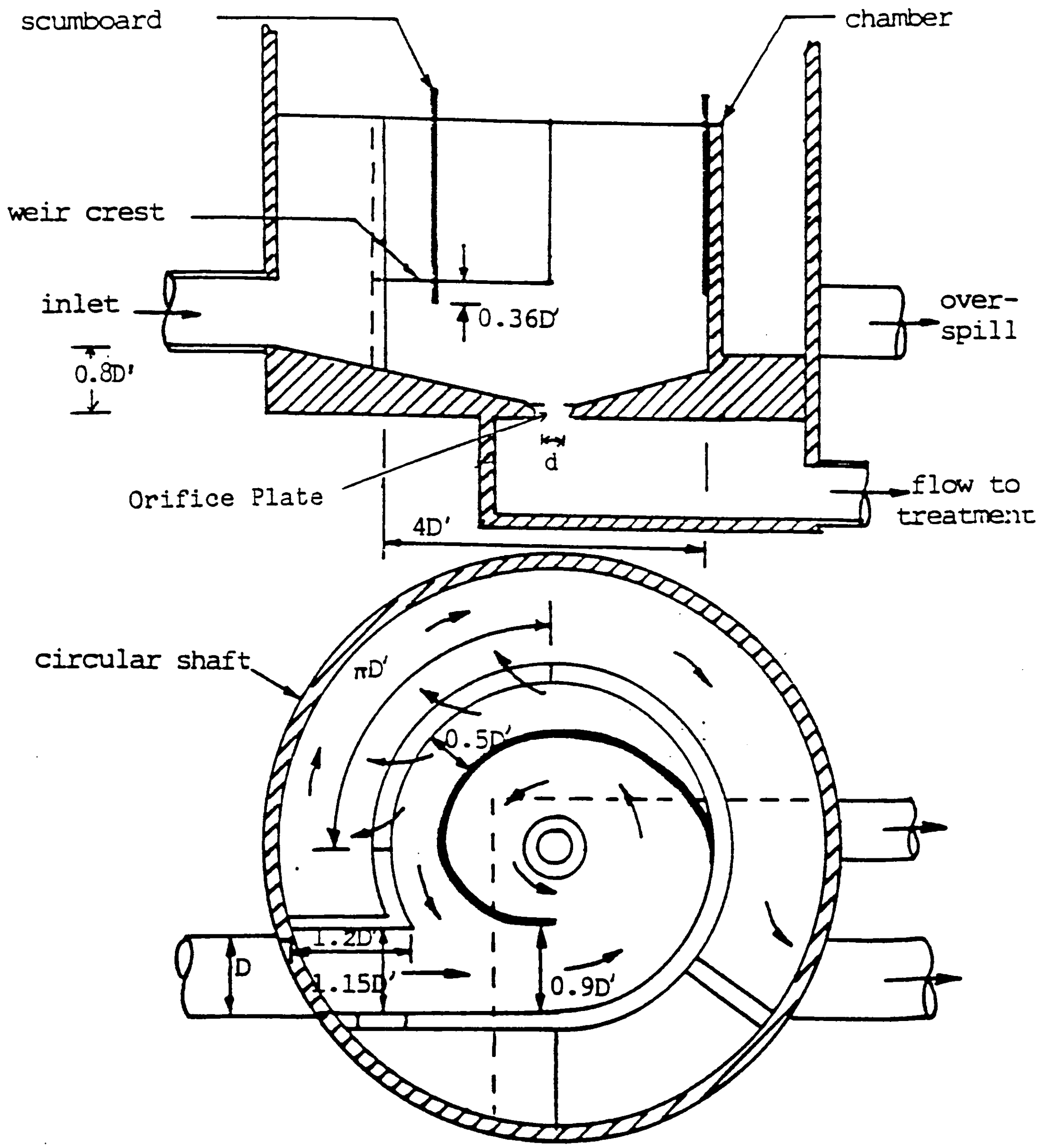


Figure A1 Recommended Design of Vortex Storm Sewer Overflow ($D' = D_{min}$ or D if larger)

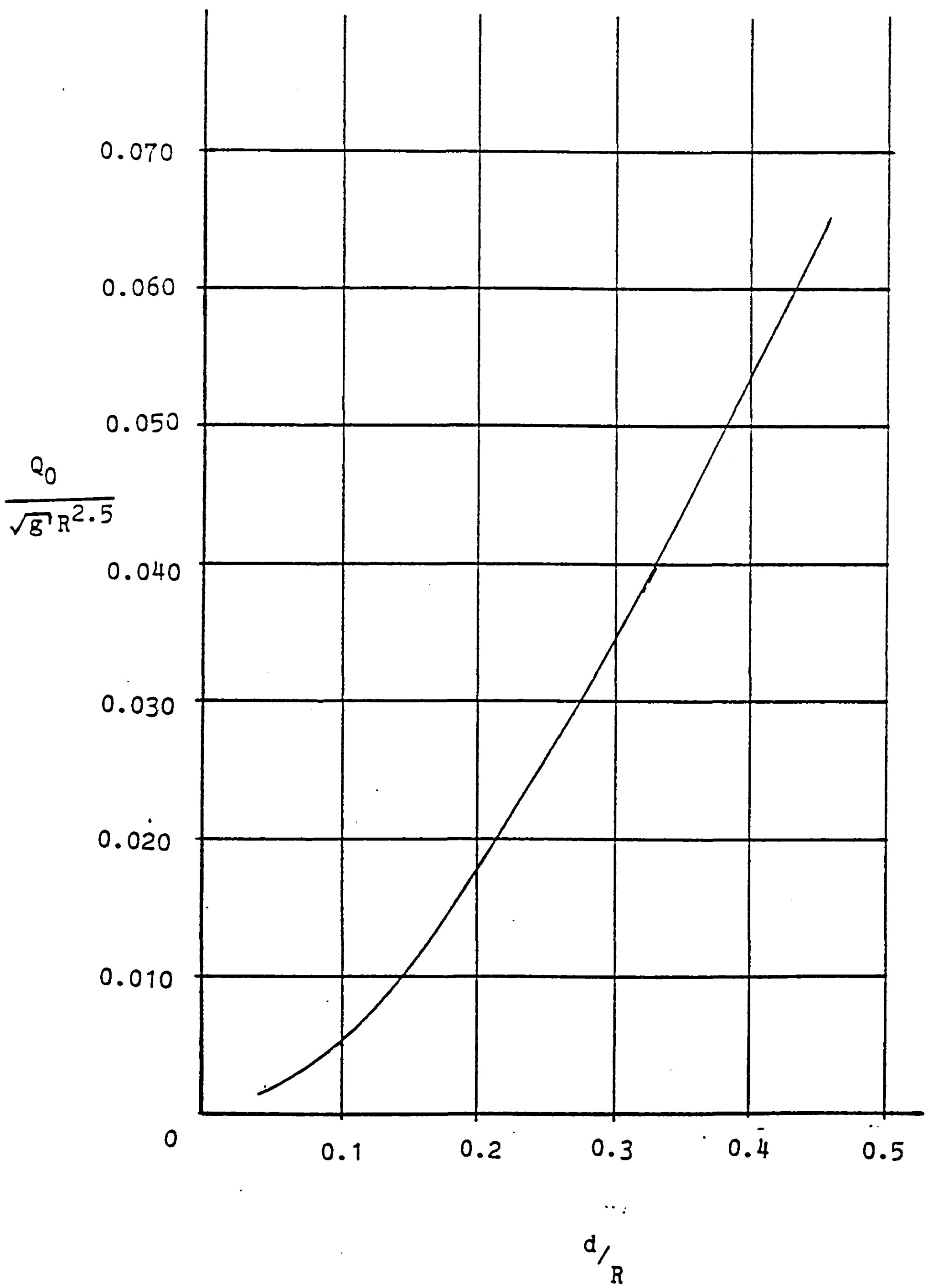


Figure A2 Dimensionless Design Chart for Vortex Throttle Diameter

DATAPROG - A program for storing, displaying and analysing results from flow monitors, jar samples and GSM equipment

1 Introduction

DATAPROG is a program originally written for a project to monitor a vortex storm sewage overflow. It can accept data on flows (in the inlet, spill and continuation (foul) pipes), the depth and velocity at the inlet, results from bottle sample analysis from inlet and spill (BOD, COD,SS,Ash,pH,Conductivity & Ammonia) and results from the gross solids monitor (counts of objects from inlet and spill samples).

It comes in two parts;

DATAPROG - Which allows entry and display of data
DATAANAL - Which allows analysis and display of the data.

The programs are stored in directory '\MONITOR' and are run simply by typing in their name and when in this directory.

The data files are stored in the directory '\MONDATA', and any files for the plotter are in a subdirectory of this called '\PICFILES'.

The programs were originally written to deal with the data gathered by the author, and it wasn't expected that it would be used by others. Consequently some parts may be a little ideosyncratic. It is hoped that the programs use is mostly self explainatory, or can be understood with a little experimentation. It isn't totally 'idiot proof' and may occasionally crash if unexpected responses are given to the questions.

The programs were written using Turbo PASCAL version 4.0 on an IBM-AT.

B2 Outline of Facilities

The DATAPROG section contains the following

1) Index of data files
2) Data Entry Routines
3) Display routines

4) Events definition & adjustment

The DATAANAL section contains

1) Index of data files
2) Data Analysis Routines
3) Display routines
4) Events definition & adjustment

The Index, Display and Events routines are common to both and are explained below.

Index Routines

These list the files of data, and is perhaps only useful for debugging. Usually it's not necessary to use this.

Events Definition & Adjustment

In order to make life easier it is possible to define the start and end times of various storm events.

Using the menu one can

1) List existing events,
2) Add an event,
3) Erase an event,
4) Adjust an event.

The events are saved in a file called 'EVENTS.DAT' in the data directory (\MONDATA).

Display Routines

These allow one to look at the data either by showing lists of results or by plotting graphs. These graphs can be plotted on the HP7475 plotter if one wishes. To do this one replies with a Y (for Yes, of course) to the inquiry in the routine about plotting. The routine will then produce a file of text in the 'PICFILES' subdirectory. One can plot this out on the HP7475 by selectin option 7 (see below).

The following are available;

1) Display and Manipulate Index
2) Display contents of swingo levels file
3) Display Sample times file
4) List Sample Analysis data in month file
5) Plot analysed sample parameters
6) Plot Samples/Flow/Rainfall
7) Plot a Pic File on external plotter
8) Turn on/off grids on screen plots

2) Display contents of swingo levels file

- Displays the swingmeter readings sent by a special CONQUEST program, either in a list or a plot.
- Not terribly useful if you don't record swingmeter readings.

3) Display Sample times file

- Another specialist routine for displaying sampler times recorded by Conquest.

4) List Sample Analysis Data in Month File

- The results from sample analysis are stored chronologically in files, one for each month.
- The files are labelled 'SAMyymmm.VAL' where yy is the year and mmm are three letters for the month (eg SAM89JUN.VAL)
- The routine allows the selection of one month file, which it will then list the results from.

5) Plot analysed sample parameters

- Allows choice of start and end times (one can use an event), and then plots out the chosen parameters (eg SS or COD etc).

6) Plot Samples/Flow/Rainfall

- A general routine which allows plotting of just about any data stored.
- One or two graphs can be produced in any combination of

Flow In
Overflow (Spill flow)
Continuation Flow
Rainfall
Velocity
Depth
Sample value
GSM values
Dry Weather inflow
Dry Weather outflow

- If one chooses two graphs but no data is available for one, only one will be plotted.
- The shape of the spill flow can be superimposed on sample results, scaled so the peak reaches the top of the graph.
- One can smooth the flows by averaging over more than one point. If one chooses to average over N points, each point plotted will be the mean of the N points nearest in time to the point in the database.

7) Plot a Pic File on external plotter
   - Displays the plotter data files in \PICFILES and allows a choice which it sends to the HP7475 plotter.
     (Note the Baud Rate settings at the back of the plotter should be set to 000100111)

8) Turn on/off grids on screen plots
   - Allows one to put grids on the screen plots (not on paper plots) for easier examination of results graphs.

B3 Data Entry

Function two in the DATAPROG program allows the incorporation of flow data, sampler results and so on into the database. They can then be plotted and analysed with the other routines.

The options are :

1) Display and Manipulate Index
2) Read in raw data from Conquest

3) Convert raw swingo data into individual storm files
4) Add raw sampler times to files
5) Incorporate data files from Monitors (via SSAS)
6) Incorporate GSM object data files
7) Read in Sample Values from YWA file

2) Read in raw data from Conquest
- This reads the swingo data and sample trigger times from the CONQUEST computer. They are sent by the FORTH program which monitors the swingos and triggers the samplers and GSMs.

3) Convert raw swingo data into individual storm files
- Decodes the swingo data read from CONQUEST

4) Add raw sampler times to files
- Decodes the sample times read from CONQUEST

5) Incorporate data files from Monitors (via SSAS)
- A much more useful routine allowing one to get at the data read by flow monitors.
- The procedure for getting the data is as follows;
  a) Collect data from the flow monitor and enter into SSAS package.
  b) Use SSAS to decode and choose interesting events.
  c) Use the 'Data Transfer' function in the Final Analysis menu of SSAS to create files of Flow,Depth or Velocity, one per monitor for each event. (The filename must have 'F','D' or 'V' appended as appropriate, eg 'datafile.V').
  d) Select this function in DATAPROG
  e) Choose what type of data you have selected (InFlow,Spill Flow, Foul Flow,Depth,Velocity, Dry Weather Inflow or Dry Weather Foul Flow)
  f) The program should list the files available, hopefully including the one you just generated with SSAS. Choose the appropriate one. It will then be read in and added to the database.

6) Incorporate GSM object data files

(Not yet implemented)

- GSM results are entered by editing the file 'GSMDATA.TXT' in directory '\MONDATA'.
  This contains one line per data point in the following format;

```
'SSSSS dd-mon-yy hh:mm    XX  YY'
```

where SSSSS = 'INLET' or 'SPILL'

dd-mon-yy is the date eg 17-Jun-90

hh:mm is the time eg 15:24

XX is the minimum objects/minute

YY is the maximum objects/minute

So a typical line might be :

```
INLET 30-Jun-89 23:49    55  60
```

- All the inlet results for a given storm or event should be written chronologically, followed by all the spill results. (Followed in turn by all the inlet results for the next event, then its spill events and so on).

7) Read in Sample Values from YWA file

- The sample data is first put into files with one line per sample, all the inlet samples preceding the spill ones. Each line contains the sample origin (INLET or SPILL) ,the date (in form dd.mm.yy), the BOD,COD,pH,SS,Ash,Ammonia & Conductivity in that order. For example:

```
'INLET  8.11.89 1037  80     312    7.4   344    198    3.16   560'
( Sample  Date   Time  BOD    COD    pH    SS     ash    amm    cond )
                       mg/l   mg/l         mg/l   mg/l   mg/l   uS/cm
```

- This was the format of the files produced by Yorkshire Water Authority
- All the inlet results for a given storm or event should be written chronologically, followed by all the spill results.

- The file should be named filename.YWA, eg 10Aug90.YWA.
- This routine will then allow the choice of files to read in, and will add the data to the relevant database files.

B4 Data Analysis Routines

The following routines are available from the Analysis menu in the DATAANAL program;

1) Correlation of Sample Data
2) Pollutographs
3) Flow or Velocity vs Depth Graphs
4) Compare incoming flow with flows out
5) Plot Foul/Spill flow against inlet flow/depth
6) Plot GSM counts weighted by flow
7) Estimate overall efficiency during a storm

1) Correlation of Sample Data
   - This allows plotting of one parameter (flow or the sample analysis parameters - COD,SS etc) against another, and the calculation of the best fit lines using regression analysis. It gives the correlation coefficient and the percentage fit.
   - The points are the samples from any number of chosen events.

2) Pollutographs
   - This allows one to plot the mass loading of one pollutant, ie the (concentration) x (flow) for a given event

3) Flow or Velocity vs Depth Graphs
   - This allows the plotting of flow or velocity against a function of depth.
   - The function of depth can be;
     a) Depth
     b) Depth - Offset
     c) Weir Length x $(\text{Depth} - \text{Offset})^{1.5}$

     Where one can choose the weir length and offset.
   - Data points from several storms can be combined.
   - The X scale on the graph if option c is chosen has been multiplied by 1000 to be comparable with the flow in litres/s.

- It can either plot with crosses or with a line joining the sequential points.

4) Compare incoming flow with flows out
   - For a given storm this can plot the function

     Total Flow = A x (Foul Flow) + B x (Spill Flow)

     on the same graph as the inflow, so one can compare the two.
   - It gives recommendations for A & B to make the volumes match, but these may be out if the monitor was inoperative for any stretches of time.
   - The best way to choose A & B so as to get a good fit is to set B to 0 first and adjust A till a good fit is obtained for the lower (sub-spill) values. Then set B to 1.0 and adjust till the best fit is found.

5) Plot Foul/Spill flow against inlet flow/depth
   - For a chosen event it will plot either the foul flow or the spill flow against the inlet flow or a function of depth (as in (3) above).

   - It can either plot with crosses or with a line joining the sequential points.

6) Plot GSM counts weighted by flow
   - This takes the GSM data points (objects/min in sample) for a given event and multiplies by the inflow or spill flow as appropriate, to get the total number of objects entering or leaving. It then plots these out.

   - In addition it calculates the average loading per minute, and calculates the average spill loading that there would be if the spill flow has the same object concentration as the inflow. It then calculates the percentage of objects retained in the foul, and the percentage that would be retained were the spill object conc. equal to that in the inflow.

7) Estimate overall efficiency during a storm

- This is a routine to predict the performance of an overflow in dealing with gross solids during a chosen event, based on separating efficiencies derived from model tests and examination of the sewage.
- From model tests one can predict the performance of the overflow in dealing with particles of given settling velocities at given flow ratio Qs/Qf (see Discussion section of Thesis). From this one can estimate the total percentage of particles retained in the foul flow at different values of Qf/Qin (40%,50%,...,90%,100%). These values are entered asked for by the routine.
- One then chooses an event, and the program calculates the total percentage of particles spilled during the storm, the total percentage that would be spilled if the spill flow was the same quality as the inflow and the relative improvement in quality of the spill flow in the former compared to the latter (See Discussion section for a better explaination). It does this using three different assumptions as to the concentration of objects in the inflow;

  i) Conc. is constant

  ii) Conc. is proportional to flow

  iii) Conc. is proportional to the square of the flow.

Results From Bottle Sample Analysis

Sample	Date	Time	BOD (mg/l)	COD (mg/l)	pH	SS (mg/l)	ash (mg/l)	amm (mg/l)	cond (uS/cm)
SPILL	20.10.88	0755	94	352	7.4	350	212	3.40	587
SPILL	20.10.88	0759		484	7.4	616	250	3.76	455
SPILL	20.10.88	0804		378	7.5	456	408	3.01	356
SPILL	20.10.88	0809		325	7.3	292	234	2.31	313
SPILL	20.10.88	0814		266	7.3	312	232	2.04	321
SPILL	20.10.88	0819		210	7.4	272	184	2.31	315
SPILL	20.10.88	0822		219	7.4	268	134	2.07	304
SPILL	20.10.88	0829		220	7.4	292	108	1.63	297
SPILL	20.10.88	0834		238	7.4	278	160	1.76	295
SPILL	20.10.88	0839		181	7.3	228	226	1.73	307
SPILL	20.10.88	0844		237	7.3	240	114	1.77	314
SPILL	20.10.88	0849	34	209	7.3	238	152	1.91	325
SPILL	20.10.88	0854		262	7.2	240	198	1.58	348
SPILL	20.10.88	0859		219	7.2	240	122	1.20	362
SPILL	20.10.88	0904		205	7.3	238	96	1.53	368
SPILL	20.10.88	0909		230	7.3	226	168	1.45	368
SPILL	20.10.88	0946		202	7.2	210	104	1.61	370
SPILL	20.10.88	0950		219	7.2	256	256	1.93	423
SPILL	20.10.88	0955		234	7.2	268	98	1.93	438
SPILL	20.10.88	1000	48	210	7.2	274	142	1.82	436
INLET	20.10.88	0755	114	401	7.3	426	180	2.88	535
INLET	20.10.88	0759	96	387	7.4	412	284	2.84	370
INLET	20.10.88	0804	84	353	7.4	390	220	2.15	332
SPILL	9.11.88	0106	150	718	6.8	721	415	1.73	765
SPILL	9.11.88	0115	148	708	6.8	726	404	1.59	760
SPILL	9.11.88	0125	158	765	6.9	776	472	1.61	765
SPILL	9.11.88	0135	124	645	6.9	582	352	1.64	760
SPILL	9.11.88	0145	152	663	6.9	664	383	1.59	765
SPILL	9.11.88	0155	168	871	6.9	864	513	1.58	765
INLET	9.11.88	0106		1730	6.7	1720	756	4.00	1290
INLET	9.11.88	0110	409	1780	6.7	1540	628	3.90	1270
INLET	9.11.88	0115		768	6.8	756	364	2.03	1090
INLET	9.11.88	0120		469	6.8	508	237	1.38	930
INLET	9.11.88	0125		424	6.9	428	229	0.98	785
INLET	9.11.88	0130	148	742	6.9	894	602	0.65	640
INLET	9.11.88	0135		641	6.9	748	510	0.57	530
INLET	9.11.88	0140		522	6.9	728	459	0.39	420
INLET	9.11.88	0145		537	7.0	596	363	0.29	380
INLET	9.11.88	0150		141	6.9	416	268	0.29	380
INLET	9.11.88	0155	48	374	6.9	303	196	0.35	400
INLET	29.11.88	1754	461	2970	7.1	4790	3360	12.70	3100
INLET	29.11.88	1758		1860	7.2	2960	1950	5.80	2430
INLET	29.11.88	1803		1720	7.5	1930	1240	2.65	2040
INLET	29.11.88	1808		482	7.3	764	488	1.27	1370
INLET	29.11.88	1935		343	7.3	444	276	1.28	1090
INLET	29.11.88	1939		277	7.3	382	240	1.30	1010
INLET	29.11.88	1944		224	7.1	254	142	1.02	853
INLET	29.11.88	2111	32	194	7.0	248	146	0.23	780
INLET	29.11.88	2116		214	7.0	222	146	0.22	718

Sample	Date	Time	BOD (mg/l)	COD (mg/l)	pH	SS (mg/l)	ash (mg/l)	amm (mg/l)	cond (uS/cm)
INLET	29.11.88	2121		196	7.2	204	126	0.57	691
INLET	29.11.88	2126		198	7.1	188	116	0.38	687
INLET	29.11.88	2131		158	7.0	172	106	1.17	720
INLET	29.11.88	2136		163	7.1	164	90	1.03	932
INLET	29.11.88	2141		250	7.0	250	110	1.30	828
INLET	29.11.88	2146		160	7.0	170	98	1.01	671
INLET	29.11.88	2151	20	135	7.1	158	84	0.89	606
INLET	29.11.88	2156		153	7.1	154	88	0.87	619
INLET	29.11.88	2206		144	7.2	146	78	0.36	584
INLET	30.11.88	0328		141	7.3	188	106	0.37	535
INLET	30.11.88	0332		129	7.3	152	90	0.31	493
INLET	30.11.88	0337		117	7.3	142	78	0.26	493
INLET	30.11.88	0342		174	7.4	176	116	0.33	568
INLET	30.11.88	0416		231	7.4	304	190	0.33	501
INLET	30.11.88	0421	565	2780	7.2	5430	3730	13.30	4520
INLET	3.12.88	1637	213	1090	7.2	1180	688	1.97	800
INLET	3.12.88	1641	129	891	7.4	830	640	1.88	706
INLET	3.12.88	1646	97	623	7.4	852	542	1.06	640
INLET	3.12.88	1651	97	552	7.4	736	504	0.83	578
INLET	3.12.88	1656	64	565	7.4	646	438	0.69	520
INLET	3.12.88	1701	72	496	7.2	532	350	0.47	502
SPILL	3.12.88	1641	105	617	7.4	742	500	0.53	618
SPILL	3.12.88	1646	65	546	7.4	730	486	0.89	593
INLET	12.01.89	0800	542	2860	7.4	4540		6.50	1390
INLET	12.01.89	0805	422	2490	7.5	3140		5.80	977
INLET	12.01.89	0810	238	1160	7.6	1720		4.40	698
INLET	12.01.89	0815	158	729	7.6	976		4.46	701
INLET	12.01.89	0820	126	549	7.6	912		3.92	738
SPILL	12.01.89	0800	506	2980	7.3	3650		8.20	1700
SPILL	12.01.89	0805	446	2300	7.3	4460		5.90	1050
INLET	13.02.89	1041	101	636	7.5	740	366	3.94	2900
INLET	13.02.89	1045	99	668	7.5	794	466	4.16	2500
INLET	13.02.89	1050	25	706	7.6	1000	634	2.77	
INLET	13.02.89	1055	114	767	7.7	998	608	2.10	1110
INLET	13.02.89	1100	84	813	7.6	792	442	2.50	9470
INLET	24.02.89	1814	51	270	7.2	292	108	1.27	1198
INLET	24.02.89	1818		2158	7.2	230	92	1.98	949
INLET	24.02.89	1823		244	7.3	250	134	1.64	874
INLET	24.02.89	1828		206	7.3	246	132	1.40	762
INLET	24.02.89	1833		219	7.4	234	126	1.28	726
INLET	24.02.89	1833		197	7.5	212	112	1.24	738
INLET	24.02.89	1843		197	7.5	256	82	1.08	681
INLET	24.02.89	1848		193	7.4	270	138	0.97	652
INLET	24.02.89	1853		203	7.5	282	142	0.85	628
INLET	24.02.89	1858		208	7.5	264	96	0.74	597
INLET	24.02.89	1903	27	195	7.6	248	118	0.88	585
INLET	24.02.89	1908		200	7.5	260	170	0.62	575
INLET	24.02.89	1913		219	7.2	224	144	0.78	611
INLET	24.02.89	1918		206	7.4	292	162	1.00	617
INLET	24.02.89	1923		155	7.5	170	116	1.05	628

Sample	Date	Time	BOD (mg/l)	COD (mg/l)	pH	SS (mg/l)	ash (mg/l)	amm (mg/l)	cond (uS/cm)
INLET	24.02.89	1928		151	7.5	184	116	1.21	621
INLET	24.02.89	1933		140	7.4	178	110	1.08	598
INLET	24.02.89	1943		182	7.4	152	86	1.31	685
INLET	24.02.89	1953		208	7.4	168	100	1.20	640
INLET	24.02.89	2003		146	7.3	152	88	0.96	658
INLET	24.02.89	2013	20	146	7.5	184	136	0.86	596
INLET	24.02.89	2023		287	7.5	412	234	0.48	483
INLET	24.02.89	2033		317	7.4	404	378	0.36	432
INLET	24.02.89	2043		245	7.3	322	220	0.32	429
SPILL	24.02.89	1820		188	7.3	230	128	0.98	614
SPILL	24.02.89	1850		182	7.3	208	148	1.00	611
SPILL	24.02.89	1930		157	7.3	190	116	0.93	611
SPILL	24.02.89	2010		153	7.3	190	118	0.89	611
SPILL	24.02.89	2040	27	173	7.3	212	148	0.96	612
INLET	20.03.89	1826	68	323	7.3	230	148	2.44	684
INLET	20.03.89	1830	49	274	7.3	270	160	1.75	611
INLET	20.03.89	1835	41	252	7.4	236	178	1.72	558
INLET	20.03.89	1840	38	222	7.4	262	156	1.53	544
INLET	20.03.89	1845	32	246	7.4	230	148	1.22	516
INLET	20.03.89	1850	37	229	7.4	202	116	0.98	501
INLET	20.03.89	1855	28	193	7.3	184	118	1.41	510
INLET	20.03.89	1900	23	169	7.3	160	106	1.22	502
INLET	20.03.89	1905	21	139	7.3	146	92	1.29	524
INLET	20.03.89	1910	21	143	7.2	138	84	1.01	537
SPILL	20.03.89	1830	68	325	7.3	328	212	1.43	548
SPILL	20.03.89	1835	39	223	7.3	256	184	1.57	546
INLET	2.04.89	1804		138	6.9	118	68	0.80	366
INLET	2.04.89	1809	23	119	6.9	130	62	0.97	336
INLET	2.04.89	1814		125	6.9	118	74	0.77	320
INLET	2.04.89	1819		123	6.8	104	42	0.80	322
INLET	2.04.89	1824		116	6.9	122	48	1.47	329
INLET	2.04.89	1829	28	165	6.9	136	68	1.33	315
INLET	2.04.89	1834		128	6.9	158	66	0.86	313
INLET	2.04.89	1839		120	7.0	150	34	0.83	309
INLET	2.04.89	1844		111	7.0	128	58	0.94	312
INLET	2.04.89	1849		105	6.9	90	38	1.02	318
INLET	2.04.89	1854	11	83	7.0	82	24	1.25	320
INLET	2.04.89	1859		89	6.9	254	52	1.19	324
INLET	10.04.89	0551	17	152	7.3	150	64	0.49	375
INLET	10.04.89	0555		147	7.4	156	86	0.54	323
INLET	10.04.89	0600		169	7.2	174	94	0.68	302
INLET	10.04.89	0605		168	7.3	158	86	0.55	289
INLET	10.04.89	0610		202	7.7	158	88	0.51	281
INLET	10.04.89	0615		159	7.3	134	72	0.55	287
INLET	10.04.89	0620	15	129	7.4	154	100	0.84	298
INLET	10.04.89	0625		101	7.5	108	64	0.69	306
INLET	10.04.89	0630		109	7.4	102	60	0.69	305
INLET	10.04.89	0635		90	7.4	120	78	0.61	303
INLET	10.04.89	0640		125	7.4	112	72	0.67	313
INLET	10.04.89	0645		95	7.3	106	58	0.79	319

Sample	Date	Time	BOD (mg/l)	COD (mg/l)	pH	SS (mg/l)	ash (mg/l)	amm (mg/l)	cond (uS/cm)
INLET	10.04.89	0650	15	97	7.4	96	48	0.76	326
INLET	10.04.89	0655		85	7.3	114	58	1.11	338
INLET	10.04.89	0732		148	7.3	166	92	2.11	296
INLET	10.04.89	0737		153	7.3	150	86	1.83	333
INLET	10.04.89	0742		125	7.2	140	76	1.35	329
INLET	10.04.89	0745	22	139	7.2	124	64	1.32	340
INLET	1.05.89	0113	76	438	7.2	474	280	0.41	500
INLET	1.05.89	0117		402	7.1	482	298	0.37	350
INLET	1.05.89	0122		364	7.1	400	234	0.39	290
INLET	1.05.89	0127	48	264	7.1	298	174	0.48	270
INLET	1.05.89	0132		189	7.1	202	106	0.50	260
SPILL	1.05.89	0113		454	7.1	446	266	0.33	480
SPILL	1.05.89	0117		364	7.1	422	260	0.39	350
SPILL	1.05.89	0122	52	316	7.2	362	230	0.43	300
SPILL	1.05.89	0127		284	7.2	306	196	0.52	280
SPILL	1.05.89	0132		206	7.2	196	120	0.65	265
INLET	24.05.89	2001		276	7.1	490	350	1.07	386
INLET	24.05.89	2056		146	6.8	76	28	1.05	716
INLET	24.05.89	2031		231	7.0	242	152	1.41	990
INLET	24.05.89	1941		2490	7.0	3100	2100	3.68	555
INLET	24.05.89	1946		714	7.1	1598	1144	2.08	366
INLET	24.05.89	2146		97	7.1	88	48	0.72	543
INLET	24.05.89	2006		245	7.1	420	304	1.02	469
INLET	24.05.89	2036		188	6.9	168	90	1.37	968
INLET	24.05.89	2156		105	7.0	76	32	0.61	706
INLET	24.05.89	2011		235	7.0	308	202	1.15	557
INLET	24.05.89	2136		116	7.1	64	30	0.64	505
INLET	24.05.89	2046		161	6.9	98	58	1.23	775
INLET	24.05.89	2021	42	226	7.0	270	172	0.94	781
INLET	24.05.89	1951		637	7.3	1064	784	1.39	335
INLET	24.05.89	2126	20	119	7.1	96	48	0.77	560
INLET	24.05.89	1937	275	1450	7.2	2878	2092	1.57	486
INLET	24.05.89	2026		269	7.0	292	170	1.48	933
INLET	24.05.89	2051		181	6.8	132	64	1.06	721
INLET	24.05.89	1956		384	7.2	698	512	1.13	371
INLET	24.05.89	2106		142	6.9	98	46	1.22	641
INLET	24.05.89	2116		190	7.0	90	44	1.10	588
INLET	24.05.89	2041		161	6.9	130	62	1.29	899
INLET	24.05.89	2016		217	7.0	226	144	0.93	680
INLET	24.05.89	2206		120	7.0	88	38	0.79	843
SPILL	24.05.89	1941		2010	7.2	2666	1998	2.73	474
SPILL	24.05.89	2106		235	7.0	104	64	0.85	587
SPILL	24.05.89	1951		587	7.3	1036	812	1.25	350
SPILL	24.05.89	1946		836	7.2	1634	1262	1.79	365
SPILL	24.05.89	2116	26	102	7.0	112	74	0.62	549
SPILL	24.05.89	2006		209	7.3	410	308	1.03	486
SPILL	24.05.89	2001	30	240	7.3	484	374	1.01	413
SPILL	24.05.89	1956		365	7.3	674	534	1.09	376
SPILL	24.05.89	2011		239	7.0	298	224	1.08	571
SPILL	24.05.89	2016		268	7.0	438	332	1.06	700
SPILL	24.05.89	2031		220	7.0	288	200	1.11	962
SPILL	24.05.89	2036		181	7.0	198	134	1.25	837
SPILL	24.05.89	2046		129	6.8	104	64	1.01	649

Sample	Date	Time	BOD (mg/l)	COD (mg/l)	pH	SS (mg/l)	ash (mg/l)	amm (mg/l)	cond (uS/cm)
SPILL	24.05.89	2041		154	6.9	184	118	1.15	724
SPILL	24.05.89	1936		2220	7.2	3478	2562	1.88	492
INLET	27.06.89	1215	67	370	7.2	390	232	2.27	712
INLET	27.06.89	1219		351	7.1	330	190	2.24	602
INLET	27.06.89	1224		276	7.1	290	160	2.03	493
INLET	27.06.89	1234		263	7.2	290	174	1.77	454
INLET	27.06.89	1229		242	7.2	230	132	2.29	456
INLET	27.06.89	1314		203	7.1	192	96	3.61	639
INLET	27.06.89	1254		354	7.0	252	136	0.96	357
INLET	27.06.89	1319		229	7.2	188	92	3.40	661
INLET	27.06.89	1324		195	7.1	154	78	2.74	570
INLET	27.06.89	1244		296	7.1	346	210	0.74	380
INLET	27.06.89	1334	40	188	7.2	146	76	3.10	478
INLET	27.06.89	1304		312	7.2	228	104	1.91	495
INLET	27.06.89	1249		289	7.1	310	186	1.03	352
INLET	27.06.89	1309		260	7.1	294	118	3.15	612
INLET	27.06.89	1239		272	7.2	328	208	0.85	390
INLET	27.06.89	1329		206	7.1	222	88	2.43	502
INLET	27.06.89	1259	70	260	7.2	250	122	1.33	396
SPILL	27.06.89	1219		317	7.1	370	218	2.06	678
SPILL	27.06.89	1229		251	7.2	320	194	2.43	487
SPILL	27.06.89	1224		327	7.2	354	216	2.13	455
SPILL	27.06.89	1244		278	7.2	350	234	2.08	392
SPILL	27.06.89	1239		257	7.3	354	232	1.51	415
SPILL	27.06.89	1234		264	7.2	340	208	2.23	460
SPILL	27.06.89	1249	44	264	7.2	316	208	1.96	374
SPILL	27.06.89	1254	36	249	7.2	332	200	1.12	359
INLET	22.08.89	1245		4310	7.0	1960		66.30	****
INLET	22.08.89	1945		838	7.2	420		31.20	6900
INLET	22.08.89	2045		843	7.2	388		29.40	6280
INLET	22.08.89	2145		1020	7.1	532		30.30	4960
INLET	22.08.89	2245		647	7.3	504		31.70	5510
INLET	22.08.89	2345		518	7.4	296		35.40	6460
INLET	22.08.89	1615		1174	7.5	788		55.10	8170
INLET	22.08.89	1745		1130	7.4	424		54.20	6481
INLET	22.08.89	1845		986	7.2	512		40.60	7930
INLET	22.08.89	1445		1220	7.6	888		43.50	9280
INLET	22.08.89	1345	631	2230	7.5	1172		64.70	8850
INLET	23.08.89	0145		385	7.5	276		31.10	6990
INLET	23.08.89	1145		1330	7.4	856	476	34.00	1584
INLET	23.08.89	0545	146	481	7.5	532	348	17.50	6150
INLET	23.08.89	0345		320	7.6	468		18.20	5710
INLET	23.08.89	0745		1050	7.3	936	432	48.10	3320
INLET	23.08.89	0245		324	7.5	268		20.20	6500
INLET	23.08.89	0645		834	5.1	508	252	27.80	6030
INLET	23.08.89	1045		1020	7.4	832	436	41.00	1341
INLET	23.08.89	0945		1330	7.1	916	428	47.40	1624
INLET	23.08.89	0445		303	7.6	476	336	16.00	5550
INLET	23.08.89	0845		1050	7.9	892	436	50.00	2060
INLET	23.08.89	0045		437	7.7	288		38.10	6230
INLET	8.11.89	1037		312	7.4	344	198	3.16	560
INLET	8.11.89	1132		328	7.6	456	326	0.83	327

Sample	Date	Time	BOD (mg/l)	COD (mg/l)	pH	SS (mg/l)	ash (mg/l)	amm (mg/l)	cond (uS/cm)
INLET	8.11.89	1107		271	7.5	360	226	1.06	451
INLET	8.11.89	0949		474	7.5	636	420	1.45	513
INLET	8.11.89	1226		222	7.2	180	122	1.13	442
INLET	8.11.89	1042		654	7.5	372	210	3.23	545
INLET	8.11.89	1112		295	7.4	392	278	1.25	401
INLET	8.11.89	1231		178	7.3	172	110	1.23	457
INLET	8.11.89	1047		416	7.5	392	258	2.77	604
INLET	8.11.89	1221		199	7.2	216	144	1.15	430
INLET	8.11.89	0939	104	554	7.4	612	370	4.60	525
INLET	8.11.89	1122		300	7.5	388	310	1.35	351
INLET	8.11.89	1059	49	273	7.5	296	226	1.77	484
INLET	8.11.89	0959		554	7.5	672	372	1.11	476
INLET	8.11.89	1216	40	206	7.3	268	178	0.96	396
INLET	8.11.89	0944		530	7.4	632	384	1.28	503
INLET	8.11.89	1101		243	7.6	296	224	1.34	474
INLET	8.11.89	1127		283	7.5	372	272	0.88	325
INLET	8.11.89	1004		424	7.5	568	270	1.16	472
INLET	8.11.89	1137		443	7.7	500	368	0.92	318
INLET	8.11.89	1147		271	7.6	400	294	0.85	322
INLET	8.11.89	1117		329	7.5	424	312	1.17	350
INLET	8.11.89	1054		331	7.5	332	250	2.24	526
INLET	8.11.89	0954		733	7.5	704	476	1.15	500
SPILL	8.11.89	1129		490	7.5	376	252	0.90	339
SPILL	8.11.89	1246	38	168	7.4	156	196	1.11	490
SPILL	8.11.89	1143		280	7.7	364	276	0.73	309
SPILL	8.11.89	1136		308	7.6	432	304	0.71	327
SPILL	8.11.89	1216	40	204	7.4	196	140	1.27	430
SPILL	8.11.89	1207		213	7.5	248	144	1.36	433
SPILL	8.11.89	1156		224	7.5	272	196	0.78	345
SPILL	8.11.89	1122		309	7.4	348	220	1.18	350
SPILL	8.11.89	1221		189	7.5	176	122	1.12	445
SPILL	8.11.89	1226		171	7.5	168	112	1.11	435
SPILL	8.11.89	1231		165	7.5	156	104	1.20	450
SPILL	8.11.89	1238		193	7.5	144	102	1.08	456
SPILL	8.11.89	1241		173	7.4	168	106	1.06	534
SPILL	8.11.89	1236		170	7.4	160	110	1.31	499
SPILL	13.12.89	1004	125	708	7.9	1232	828	0.60	447
SPILL	13.12.89	1009	133	848	7.9	1128	708	0.60	433
SPILL	13.12.89	1014	169	757	7.6	988	528	0.75	427
SPILL	13.12.89	1019	91	460	7.7	660	428	1.05	413
SPILL	13.12.89	1029	56	342	7.7	496	336	1.25	436
SPILL	13.12.89	1024	76	373	7.7	548	364	0.65	402
SPILL	13.12.89	1129	41	275	7.7	336	208	1.10	410
SPILL	13.12.89	1049	51	291	7.8	444	308	0.75	375
SPILL	13.12.89	0949	101	719	7.8	1100	760	1.10	547
SPILL	13.12.89	1218	43	255	7.6	272	160	1.10	455
SPILL	13.12.89	0954	85	792	8.1	1064	736	0.90	496
SPILL	13.12.89	1223	42	246	7.6	232	132	1.35	474
SPILL	13.12.89	0959	133	746	7.9	1276	864	0.80	479
SPILL	13.12.89	0939	155	1670	7.8	1372	924	1.95	635
SPILL	13.12.89	1039	51	328	7.7	448	304	0.95	373
SPILL	13.12.89	1109	40	299	7.6	352	228	0.80	377
SPILL	13.12.89	0944	113	755	7.8	1148	780	1.65	575
SPILL	13.12.89	1044	53	383	7.8	416	280	0.40	368

Sample	Date	Time	BOD (mg/l)	COD (mg/l)	pH	SS (mg/l)	ash (mg/l)	amm (mg/l)	cond (uS/cm)
SPILL	13.12.89	1119	54	336	7.5	384	224	1.15	412
SPILL	13.12.89	0934	137	1530	7.7	1228	832	2.00	660
SPILL	13.12.89	1034	56	357	7.7	440	280	1.25	385
SPILL	13.12.89	1228	44	258	7.7	264	164	1.25	450
SPILL	13.12.89	1059	58	365	7.7	440	288	0.90	363
INLET	14.12.89	1004		208	7.4	200	84	1.15	553
INLET	14.12.89	0944		220	7.3	192	80	0.90	448
INLET	14.12.89	1114		210	7.7	1056	880	0.04	345
INLET	14.12.89	0924		329	7.2	368	164	1.70	441
INLET	14.12.89	1124		178	7.7	384	260	0.03	363
INLET	14.12.89	1009	47	220	7.4	232	120	1.15	551
INLET	14.12.89	0954		257	7.4	212	92	1.10	500
INLET	14.12.89	1144	45	191	7.7	228	136	0.06	454
INLET	14.12.89	1019		220	7.5	252	140	1.15	511
INLET	14.12.89	0929		265	7.3	272	144	0.90	410
INLET	14.12.89	0949		220	7.3	200	84	0.90	470
INLET	14.12.89	1134		187	7.6	264	152	0.04	391
INLET	14.12.89	1014		189	7.4	208	100	1.15	534
INLET	14.12.89	1034		294	7.6	456	188	0.65	360
INLET	14.12.89	0959		215	7.4	184	72	1.10	533
INLET	14.12.89	0939		248	7.4	264	140	0.90	448
INLET	14.12.89	1029		447	7.7	320	276	0.85	437
INLET	14.12.89	0934		214	7.3	244	128	0.70	427
INLET	14.12.89	1024		213	7.6	248	136	1.05	478
INLET	14.12.89	0915	76	327	7.4	300	112	0.45	516
INLET	14.12.89	1104		233	7.7	2816	2520	0.55	336
INLET	14.12.89	1054		234	7.7	408	252	0.55	317
INLET	14.12.89	1044		312	7.7	436	268	0.04	321
INLET	14.12.89	0919		300	7.4	324	168	0.75	461
SPILL	14.12.89	1029		230	7.5	312	200	0.90	440
SPILL	14.12.89	1124		183	7.7	356	248	0.04	365
SPILL	14.12.89	1134		174	7.6	232	148	0.50	395
SPILL	14.12.89	1144	45	195	7.7	188	100	0.55	455
SPILL	14.12.89	1054		248	7.7	392	264	0.40	321
SPILL	14.12.89	1104		276	7.7	2604	2340	0.55	345
SPILL	14.12.89	1024	68	219	7.5	268	160	1.15	520
SPILL	14.12.89	0924		311	7.4	304	156	1.80	440
SPILL	14.12.89	1114		235	7.7	836	704	0.35	346
SPILL	14.12.89	0929		221	7.4	284	156	1.00	420
SPILL	14.12.89	0939		207	7.5	252	144	1.00	449
SPILL	14.12.89	0914	102	355	7.5	320	152	0.10	504
SPILL	14.12.89	1044		348	7.6	472	296	0.45	339
SPILL	14.12.89	0919		277	7.5	296	156	1.15	463
SPILL	14.12.89	0959		269	7.5	324	180	1.15	519
SPILL	14.12.89	1034		282	7.6	432	292	0.70	385
SPILL	14.12.89	0934		209	7.4	236	124	0.90	425
INLET	16.01.90	2226		508	7.7	628	348	2.33	585
INLET	16.01.90	2231		347	7.7	428	256	1.78	576
INLET	16.01.90	2236		269	7.7	348	200	2.37	590
INLET	16.01.90	2241		255	7.6	272	152	2.73	714
INLET	16.01.90	2251		191	7.7	212	124	2.64	624
INLET	16.01.90	2246		227	7.5	228	128	3.00	709
INLET	16.01.90	2212	170	890	8.1	1632	740	3.41	1180

Sample	Date	Time	BOD (mg/l)	COD (mg/l)	pH	SS (mg/l)	ash (mg/l)	amm (mg/l)	cond (uS/cm)
INLET	16.01.90	2216		822	7.6	1508	804	3.31	940
INLET	16.01.90	2221		628	7.7	852	496	2.18	646
INLET	16.01.90	2301	29	201	7.7	204	92	3.55	634
INLET	16.01.90	2256	34	194	7.6	220	120	2.92	597
SPILL	16.01.90	2216		937	7.6	1212	756	3.13	945
SPILL	16.01.90	2221		718	7.6	880	520	2.46	650
SPILL	16.01.90	2226		487	7.7	616	344	2.53	585
SPILL	16.01.90	2212	191	940	7.4	1308	784	3.42	1350
INLET	7.02.90	1600	24	157	9.0	302	208	0.66	512
INLET	7.02.90	1610		174	9.3	296	210	0.63	612
INLET	7.02.90	1630		461	7.6	674	358	0.90	667
INLET	7.02.90	1050		354	7.6	502	322	1.30	690
INLET	7.02.90	1410		274	7.6	401	256	1.71	501
INLET	7.02.90	1505		139	7.5	254	150	2.24	582
INLET	7.02.90	1440		509	7.7	704	436	0.95	576
INLET	7.02.90	1540		191	8.4	384	274	0.69	479
INLET	7.02.90	1415		218	7.7	352	236	1.41	488
INLET	7.02.90	1445		249	7.6	450	300	1.23	446
INLET	7.02.90	1550		194	8.2	326	234	0.65	459
INLET	7.02.90	1420		230	7.6	354	248	1.18	468
INLET	7.02.90	1530		200	9.3	384	268	0.61	532
INLET	7.02.90	1455		181	7.9	290	198	1.33	480
INLET	7.02.90	1430		378	7.7	598	422	0.98	416
INLET	7.02.90	1049	75	326	7.6	508	304	1.60	545
INLET	7.02.90	1520		195	9.3	314	222	0.60	560
INLET	7.02.90	1435		460	8.1	1100	750	1.40	846
INLET	7.02.90	1500		158	7.6	186	120	1.86	540
INLET	7.02.90	1405		330	7.8	480	312	1.52	504
INLET	7.02.90	1510		159	7.5	208	132	2.33	703
INLET	7.02.90	1515		126	7.7	234	160	1.40	635
INLET	7.02.90	1450	27	214	7.6	334	216	1.55	430
INLET	7.02.90	1425		269	7.7	484	346	1.03	488
SPILL	7.02.90	1410		292	7.6	386	252	1.89	520
SPILL	7.02.90	1515		165	8.4	304	228	0.43	571
SPILL	7.02.90	1550	20	162	8.3	286	210	0.61	524
SPILL	7.02.90	1420		160	7.5	350	244	1.53	483
SPILL	7.02.90	1530		191	8.0	358	272	0.78	495
SPILL	7.02.90	1415		278	7.6	374	246	1.99	504
SPILL	7.02.90	1520		214	8.5	362	276	0.50	545
SPILL	7.02.90	1435		779	7.9	1100	754	1.31	817
SPILL	7.02.90	1430		350	7.7	590	414	0.92	427
SPILL	7.02.90	1540		178	7.9	286	214	0.62	469
SPILL	7.02.90	1425		251	7.7	458	316	1.29	500
SPILL	7.02.90	1500	22	178	7.6	240	154	2.33	594
SPILL	7.02.90	1510		166	7.6	216	150	1.70	650
SPILL	7.02.90	1505		152	7.4	202	130	2.57	705
SPILL	7.02.90	1450		200	7.5	306	216	1.32	435
SPILL	7.02.90	1446		332	7.6	436	290	1.08	442
SPILL	7.02.90	1445		563	7.6	682	416	0.92	571
SPILL	7.02.90	1405	43	333	7.6	450	290	2.14	559

Counts from Gross Solids Monitor Films

Where there are apparent gaps in the data, this is because the film was either too dark or there were too many bubbles obscuring the image.

Sample Origin	Date	Time	Objects/Minute Lowest Count	Highest Count
INLET	30-Jun-89	23:49	55	60
INLET	30-Jun-89	23:57	17	20
INLET	01-Jul-89	00:05	6	8
INLET	01-Jul-89	00:13	2	3
SPILL	30-Jun-89	23:53	20	22
SPILL	01-Jul-89	00:01	6	8
SPILL	01-Jul-89	00:09	2	3
INLET	20-Oct-89	0:39	27	33
INLET	20-Oct-89	0:55	16	20
INLET	20-Oct-89	1:03	102	112
INLET	20-Oct-89	1:11	31	33
SPILL	20-Oct-89	0:59	50	52
SPILL	20-Oct-89	1:07	26	31
INLET	22-Oct-89	13:21	11	13
INLET	22-Oct-89	13:29	9	10
INLET	22-Oct-89	13:37	9	10
INLET	22-Oct-89	13:45	8	9
INLET	22-Oct-89	13:53	2	3
INLET	22-Oct-89	14:01	15	19
SPILL	22-Oct-89	13:25	5	6
SPILL	22-Oct-89	13:33	7	8
SPILL	22-Oct-89	13:41	9	10
SPILL	22-Oct-89	13:49	9	10
SPILL	22-Oct-89	13:57	3	3
SPILL	22-Oct-89	14:05	2	2
INLET	8-Nov-89	9:45	67	73
INLET	8-Nov-89	10:01	36	38
INLET	8-Nov-89	11:09	38	40
INLET	8-Nov-89	11:17	76	88
INLET	8-Nov-89	11:25	47	52
INLET	8-Nov-89	11:33	71	75
INLET	8-Nov-89	11:41	84	103
INLET	8-Nov-89	11:58	23	25
INLET	8-Nov-89	12:06	48	60
INLET	8-Nov-89	12:14	47	53
INLET	8-Nov-89	13:30	70	79
INLET	8-Nov-89	13:38	31	39
SPILL	8-Nov-89	9:49	13	17
SPILL	8-Nov-89	11:13	31	40
SPILL	8-Nov-89	11:21	34	43
SPILL	8-Nov-89	11:29	45	47
SPILL	8-Nov-89	11:37	34	36
SPILL	8-Nov-89	11:45	68	84
SPILL	8-Nov-89	11:54	20	24
SPILL	8-Nov-89	12:02	12	16
SPILL	8-Nov-89	12:10	35	37
SPILL	8-Nov-89	13:34	34	39
SPILL	8-Nov-89	13:42	19	21
INLET	14-Dec-89	9:18	42	46

Sample Origin	Date	Time	Objects/Minute Lowest Count	Highest Count
INLET	14-Dec-89	9:25	76	86
INLET	14-Dec-89	10:32	79	93
INLET	14-Dec-89	10:40	60	72
INLET	14-Dec-89	10:48	60	61
INLET	14-Dec-89	10:56	48	51
INLET	14-Dec-89	11:12	42	50
INLET	14-Dec-89	11:20	29	34
INLET	14-Dec-89	11:28	27	35
INLET	14-Dec-89	11:36	62	69
INLET	14-Dec-89	11:44	36	44
INLET	14-Dec-89	11:52	20	24
INLET	14-Dec-89	12:00	24	31
INLET	14-Dec-89	12:08	8	10
INLET	14-Dec-89	12:16	16	21
INLET	14-Dec-89	12:24	13	15
INLET	14-Dec-89	12:32	6	6
INLET	14-Dec-89	12:40	13	13
INLET	14-Dec-89	12:48	4	4
SPILL	14-Dec-89	9:22	34	48
SPILL	14-Dec-89	9:30	20	30
SPILL	14-Dec-89	10:28	16	21
SPILL	14-Dec-89	10:36	38	46
SPILL	14-Dec-89	10:44	39	42
SPILL	14-Dec-89	10:52	28	33
SPILL	14-Dec-89	11:00	41	44
SPILL	14-Dec-89	11:16	30	34
SPILL	14-Dec-89	11:24	34	38
SPILL	14-Dec-89	11:32	29	32
SPILL	14-Dec-89	11:40	33	42
SPILL	14-Dec-89	11:48	17	27
SPILL	14-Dec-89	11:56	21	27
SPILL	14-Dec-89	12:04	12	15
SPILL	14-Dec-89	12:12	4	4
SPILL	14-Dec-89	12:20	3	3
SPILL	14-Dec-89	12:28	3	3
SPILL	14-Dec-89	12:36	7	7
SPILL	14-Dec-89	12:44	7	7
INLET	16-Dec-89	8:38	25	26
INLET	16-Dec-89	8:46	7	7
INLET	16-Dec-89	8:54	12	12
INLET	16-Dec-89	9:02	10	10
INLET	16-Dec-89	9:10	17	18
INLET	16-Dec-89	9:18	59	62
INLET	16-Dec-89	9:26	86	108
INLET	16-Dec-89	9:34	94	98
INLET	16-Dec-89	9:42	80	96
INLET	16-Dec-89	9:50	15	18
INLET	16-Dec-89	9:58	43	50
INLET	16-Dec-89	10:10	35	37
INLET	16-Dec-89	10:18	19	27
INLET	16-Dec-89	10:26	16	16
SPILL	16-Dec-89	8:42	8	8
SPILL	16-Dec-89	8:50	9	9
SPILL	16-Dec-89	8:58	11	11

Sample Origin	Date	Time	Objects/Minute Lowest Count	Highest Count
SPILL	16-Dec-89	9:06	4	4
SPILL	16-Dec-89	9:14	42	49
SPILL	16-Dec-89	9:22	70	77
SPILL	16-Dec-89	9:30	37	55
SPILL	16-Dec-89	9:38	58	68
SPILL	16-Dec-89	9:46	38	48
SPILL	16-Dec-89	9:54	22	25
SPILL	16-Dec-89	10:02	20	29
SPILL	16-Dec-89	10:14	24	25
SPILL	16-Dec-89	10:22	13	13

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