Monitoring of roof drainage systems

M Escarameia

Report SR 500
February 1998

HR Wallingford

Address and Registered Office: **HR Wallingford Ltd.** Howbery Park, Wallingford, OXON OX10 8BA
Tel: +44 (0) 1491 835381 Fax: +44 (0) 1491 832233

Registered in England No. 2562099. HR Wallingford is a wholly owned subsidiary of HR Wallingford Group Ltd.

Contract

This report describes work funded by the Construction Directorate of the Department of the Environment, Transport and Regions, DETR, under research contract CI 39/5/107 for which the DETR nominated officer was Mr PB Woodhead and the HR Wallingford nominated officer was Dr SW Huntington. The HR job number was RTS 0067. The report is published on behalf of DETR, but any opinions expressed in this report are not necessarily those of the funding department. The work was carried out by M Escarameia in RWP May's section of the Rivers Group.

Prepared by Manuela Escarameia (name) Senior Research Engineer (Title)

Approved by RWP. May Principal Engineer

Date 26 February 1998

Summary

Monitoring of roof drainage systems

M Escarameia

SR 500
February 1998

Guidance on design of conventional roof drainage systems is given in BS6367:1983 "Drainage of roofs and paved areas", a document which was based on experimental data, sound theoretical considerations but also on some unverified assumptions. The present study was carried out to collect more information on rainwater systems and to investigate the importance of those assumptions on the actual performance of existing drainage systems.

An extensive monitoring programme was set up, which recorded more than 2000 storms during the period of September 1996 to October 1997. The flow conditions monitored were essentially the rainfall on the roofs and water depths at upstream and downstream sections of the roof gutters. Standard tipping bucket rain gauges were used to collect rainfall data, whereas purpose made probes were developed at HR for the measurement of water depths and subsequent calculation of flow rates in the gutters. Data, supplied by the Met. Office and the Institute of Hydrology, were also obtained on wind speed and direction for the major storms recorded.

The analysis of the data involved the investigation, amongst others, of the following aspects: typical duration of storms, time of concentration (i.e. the time required by rain falling on the most upstream part of the roof to reach the gutter outlet), percentage runoff (i.e. the ratio of runoff to the volume of rainfall producing the runoff), depression storage (i.e. the amount of rainfall before runoff is produced), effect on runoff of wind speed and direction. Further analysis was carried out with the aid of an unsteady flow numerical model developed at Heriot Watt University for the study of flows in channels with lateral inflow. Comparisons were made between the site measurements, the results of numerical simulations and the application of the design formulae given in BS6367. These led to a number of conclusions for later inclusion in the new European Norm, which has recently been prepared in draft form.

The work described in this report was partly funded by the Construction Directorate of the Department of the Environment, Transport and Regions.

Contents

Figures

Contents continued

1 Introduction

Good performance of roof drainage systems in buildings is essential to ensure the structural integrity of the building, its habitability and/or the safety of its content. Performance depends on three major factors: accurate design of the system, careful construction and adequate maintenance. This report is concerned with improving the first of these factors, the design of roof drainage systems.

Guidance on design of roof drainage is given in British Standard BS 6367:1983 "Drainage of roofs and paved areas". This document provides some accurate formulae and recommendations based on theoretical analysis and on results of laboratory work. However, some of the recommendations in the Standard were derived from unverified assumptions, and design could benefit from establishing the validity of such assumptions. A new European Norm has recently been prepared in draft form, which will contain much of the guidance given in BS 6367. It is also likely to include an annex with meteorological and other data specific to the UK, where there is scope to introduce the conclusions from the present study.

Examples of the factors that require investigation are:

- Typical duration of storms that produce heavy rainfall;
- Effect of time-varying rainfall intensity;
- Effect of storage on roofs and gutters;
- Effect of wind on run-off.

Since most of the above parameters are directly dependent on meteorological conditions, the most effective way to assess their influence is to monitor the response of roof drainage systems to such factors. The approach selected for the study was therefore to monitor existing drainage systems for sufficiently long periods of time in order to cover a wide range of weather conditions.

The objectives of the present study can be summarised as follows:

- To measure the performance of existing roof drainage systems;
- To compare the site data with predictions based on BS 6367;
- To give recommendations to improve the design guidance given in BS 6367 and in the new European Standard that is currently being produced.

In addition to the above, the study also involved the collaboration of Prof JA Swaffield of Heriot-Watt University, Edinburgh, who adapted an existing computer model for the simulation of unsteady flows in roof gutters. This program, was used to extend the range of conditions studied.

HR Wallingford was commissioned by the Construction Directorate of the Department of the Environment (now Department of the Environment, Transport and Regions) to carry out the study. The project took place between April 1996 and March 1998.

This report is divided into seven main chapters. Following the Introduction (in Chapter 1), Chapter 2 explains the criteria for selection of the sites and presents the characteristics of the sites that were monitored in the study. Chapter 3 describes the equipment used for the collection of data, while the data obtained are presented in Chapter 4. The analysis carried out on the site data is described and discussed in Chapter 5. The computer program developed by Heriot-Watt University for the study of unsteady flows in gutters is briefly described in Chapter 6. Comparison between the numerical simulations and the recorded measurements and the recommendations given in BS 6367 are also made in this chapter. Conclusions from the study and design recommendations to introduce in new standards are summarised in Chapter 7.

2 Sites monitored

2.1 Criteria for choice of sites

The choice of suitable sites for installation of the monitoring equipment required considerable time and effort. The criteria for selection were quite stringent, as the sites needed to provide conditions that met both technical and practical requirements. These latter proved to be as important as the former and more difficult to accommodate in some respects. A summary of the criteria is presented below:

Technical requirements

- In order to obtain data for different situations, it was decided to monitor two different types of roof: a sloping roof and a flat roof. These two types are very distinct in the way they are normally drained. Flat roofs tend to be drained by outlets placed directly in the centre of locally sloping areas or by outlets installed in fairly shallow gutters. Sloping roofs, on the other hand, are generally drained by outlets installed in gutters, which can be placed on the edge of the roof (eaves or parapet gutter) or between two sloping sections (valley gutter).

- Since the study involved the assessment of a number of factors, it was important to minimise the number of variables and this meant that only conventional roof drainage systems were monitored. Siphonic systems were therefore excluded so that complex issues, such as the time and effect on the flow of the priming of the systems, would not need to be addressed.

- One of the major objectives of the study was to investigate the response of roof drainage systems to the rates of rainfall typically used for design. BS 6367:1983 recommends that rainfall intensities of 75mm/hr or higher (depending on the category of the building) are used for design. The value of intensity to choose for design depends on the geographical location of the building in the UK. The areas of highest rainfall are East Anglia and the South East of England, and therefore it was decided to choose sites in these regions. To minimise travelling distances, the two sites were located in the South East, as described later in Section 2.2.

- The sites also needed to have sufficiently large drained areas to produce significant rates of flow in the gutters and outlets. This requirement was important to guarantee that the instrumentation would record data accurately.

Practical requirements:

- The roofs needed to provide safe access for installation of the instrumentation and for the regular inspections that were envisaged. This requirement meant that sloping roofs with very large pitches would not be suitable from a safety point of view.

- It was also important to guarantee the security of the equipment (and particularly of the logging equipment) against vandalism and extreme weather conditions. Sites with a room nearby, where the logging devices could be kept secure, were therefore given preference.

- The existence of an adequate power supply for powering the equipment in the vicinity of the monitored section of roof was another practical aspect that was taken into consideration.

Once the above criteria were elaborated, contacts were established with roofing contractors, the industrial partners for the present research study, to try to identify suitable sites. The contractors suggested a number of different roofs, some of which were visited to assess their conditions. Following careful inspection, two sites were chosen for the monitoring programme: a sloping roof and a flat one. The limitation of the number of sites to two was mainly due to budget restrictions in view of the non-standard nature of the equipment needed (see Chapter 3).

2.2 Description of sites

The sites monitored were: Site 1, a sloping roof in one of the buildings of HR Wallingford, Wallingford, Oxfordshire, and Site 2, a flat roof at the Tower Bridge Business Complex, in Southwark, south east London. A description of these sites is presented next.

Site 1 – Sloping roof

The roof selected for the study (see Plates 1 and 2) was made of profiled metal sheeting and had a pitch of 4.4° followed by a section that curved down vertically. It was drained by a parapet gutter, 4.5m below the curved edge of the roof, as shown schematically in Figure 1. To avoid uncertainties due to non-uniformity of rainfall and wind conditions, it was decided to monitor a section of gutter away from the edge of the building. The effective area of roof monitored (the effective catchment area) was calculated according to BS 6367:1983. This standard states that the effective catchment area for a freely exposed roof draining to a parapet wall gutter is equal to the plan area of the roof, plus half its maximum area in elevation. In the present case, the effective area, A_e, was calculated as follows (refer to Figure 1):

$$A_e = A_h + 0.5\,(A_{v1} + A_{v2})$$

$$= (23.5 + 0.26) \times 2.66 + 0.5(4.5 + 1.8) \times 2.66 = 71.6\text{m}^2$$

Although the roof was not sheltered by any buildings of similar height, there were some large trees in the proximity of the roof, which may have an effect on the catchment characteristics of the roof, particularly for winds blowing from the south. This aspect is discussed later in Section 4.6. Apart from this, the presence of the trees posed another problem to the site measurements: how to avoid small leaves and needles falling in the gutter and affecting the readings of the instrumentation. A few months after the monitoring programme had started, it was realised that regular cleaning of the gutter was not sufficient. A fairly tight net was therefore placed over the monitored gutter, which protected it from most falling leaves but it could not entirely prevent the smaller leaves from dropping into the gutter. This meant that frequent cleaning was still necessary to remove these leaves and other small debris, such as rust particles and small twigs.

The section of gutter monitored was 2.66m long and approximately rectangular in shape: 260mm sole width by 290mm depth. It widened slightly upwards from the sole to the top where the width varied between 270mm and 287mm along the length of the gutter. The gutter was made of metal, the inside of which showed signs of earlier rusting due to the combination of standing rainwater and the rotting of leaves from nearby trees.

The gutter section was drained by a 3m long vertical downpipe with a square cross-section approximately 100mm x 100mm. Being connected directly to the sole of the gutter, the outlet was also square, 100mm x 100mm, and was not protected by a leafguard. The downpipe discharged freely into a 1.3m deep concrete chamber below ground, which made the connection to the site drainage.

Site 2 – Flat roof

This roof was nominally flat, with slopes of the order of 1°, and was drained by a series of very shallow gutters (a few centimetres deep), as shown in Plate 3. It was made of a textured and slightly flexible material. Following a careful survey of the roof, it was decided to select a section of gutter with a constant, though negligible, gradient rather than one with a series of positive and negative gradients that would cause ponding of water after storm events. It was also important that the gutter section was far from the boundaries of the roof.

The gutter that was chosen for the monitoring programme is depicted in Figure 2, where it can be seen that it drained an area of 147m^2 (shown enveloped by a dashed line). The 6.1m long gutter was quite exposed, being several tens of metres away from any obstructions (the closest were two buildings, some low walls and a railway bridge). In spite of a fairly constant width of about 0.5m, the survey of the gutter showed that the shape of the cross-section and depth varied considerably along the length of the gutter. This variation is schematically represented in Figure 3, where it can be seen that the boundaries of the gutter were not very well defined, particularly at its upstream end.

The flow collected by the gutter was drained through a 200mm diameter Fulbora outlet, which included a domed leafguard, and had a 50mm diameter spigot. The outlet was installed in a small sump (0.51m x 0.50m), 50mm below the level of the sole of the gutter (see Plate 4).

3 Monitoring equipment

3.1 General considerations

The investigation of roof drainage is primarily a question of determining the amount of rain that is expected to fall on a roof and what proportion of that amount is actually collected by the drainage system. Also important is the determination of water profiles along gutters because these levels (and the necessary freeboard allowances) will dictate the overall depth of the gutters. A number of different parameters are known (or likely) to influence the relationship between rainfall and runoff: 1. The geometric characteristics of the roof and drainage system; 2. The surface material of the roof; 3. The hydrological conditions, which are basically dependent on the geographic location of the roof and on the time of the year; and 4. Whether the roof drainage system is correctly designed according to the relevant standards.

In view of the above, data needed to be collected to determine the role of each parameter. Information on some of these parameters, such as the geometry of the roof and drainage system, was obtained by surveying and by consultation of technical drawings. Parameters such as the wind speed and direction were considered to be better dealt with by using data recorded by the Institute of Hydrology (for Site 1) and the Met. Office (for Site 2). In the case of Site 1, the Institute of Hydrology was ideally located to provide such data, being only a few hundred metres away from the monitored roof. More information on wind data is given later in Section 4.6.

The parameters that required monitoring were the rainfall, the water depth and the flow in the roof gutters. Standard rain gauges are commercially available for the measurement of rainfall and were suitable for the purposes of this study. The measurement of water depths and flow in the roof gutters was more problematic as "off-the-shelf " instrumentation was not available and therefore required the development of purpose-built sets of instrumentation. Consideration of practical as well as technical aspects led to the decision to determine the flow in the gutters indirectly, by measuring water depths at certain locations and later converting them into flow rates. On Site 1, the flow at the exit from the downpipe was also monitored by a second instrument, a flowmeter, which also converted water depths into flow rates. Detailed description of the equipment used in the study is presented next.

3.2 Instrumentation

Rain gauges

Two rain gauges of similar specification were chosen for the monitoring of the rainfall on the two sites. They were tipping bucket rain gauges, a well-known and proven method, manufactured by Casella (see Plates 5 and 6). These devices consisted of the outer body of the gauge, which was basically a removable aluminium drum featuring a funnel on the top, and the tipping mechanism inside the casing. It also featured three levelling screws and a spirit level to ensure correct levelling of the gauge. This feature was particularly useful for the positioning of the gauge on the sloping roof of Site 1.

The principle of operation can be briefly described as follows. The tipping mechanism is formed by a divided bucket, which is pivoted at the centre like a seesaw. The rain falling through the funnel is collected in the half of the tipping bucket that is at a higher level, until its weight makes the bucket tilt and discharge the water. At the same time the other half of the bucket is repositioned under the funnel nozzle, ready for receiving the rainfall. Each tip of the bucket is monitored by means of a magnet and a voltage signal is sent to the data collecting device (this will be described separately).

The bucket size chosen was 0.2mm, which is particularly suitable for moderate rates of rainfall. During the study this size proved suitable for the objectives and the rain gauges were found to be very reliable.

Water depth probes

As mentioned earlier, the measurement of water depth in the roof gutters (and the determination of flow rates) was carried out using instrumentation purpose-built for this study. The water depth probes worked according to the capacitance principle, where two conductive materials are separated by a non-conductor. The probes were essentially formed by: a weather-resistant electric circuit box, an insulated wire and a wire that made the earth connection. With this arrangement, the water in the gutter was one of the electrical conductors. The capacitance of the probes varies linearly with the depth of water in contact with the insulated wire.

A number of experiments were necessary to find a suitable configuration for the probes, particularly in what concerned the insulation of the wire and the accuracy of the measurements. Plate 7 shows an earlier version of the probes installed in the gutter of Site 1. The shape of the insulated wire was later changed so that it doubled on itself to reduce the risk of water infiltrating between the wire and the isolator. It was also set at an angle of 45° with the sole of the gutter to improve accuracy in the measurement of small water depths. The final shape (adopted for both sites) can be seen on the left-hand side of Plate 8 (which corresponds to Site 2).

In order to measure the water depths in the gutter, it was decided to position, in both sites, a probe at the upstream end (where the depths are highest) and another at the downstream end, near the outlet. The location of this latter probe was determined so that it would be close to the section where critical flow was likely to occur for the range of flow depths expected in the gutters. Because of the variation in levels, this position was necessarily only approximate. On Site 2, a third probe was installed in the outlet sump in an attempt to have an alternative means of determining the flow into the outlet (see Plate 8, at the right-hand side). All the five probes installed on both sites were slightly different, as they needed to match the variable depth of the gutter cross-sections where they were installed.

The probes were clamped on to the side of the gutter (Site 1) or on to cross beams well secured to the roof by means of lead weights (Site 2) so that no damage was done to the gutters or to the flat roof. Adequate fixing of the instrumentation was of paramount importance due to the exposed nature of the sites. It was not only necessary to guarantee that no movement of the instruments would occur that could affect the readings, but also the safety of passers-by.

Flowmeter

The flowmeter used on Site 1 was installed in a below-ground chamber that collected the water from the downpipe before discharging into the site sewerage system (see Plate 9). The device consisted of a 200mm diameter pipe section, 1.05m long. This pipe section, which was fixed vertically onto a wooden support, was blocked at the bottom end by a plate with a 50mm diameter orifice. The size of this orifice was designed to allow the discharge of up to 5l/s through it. The discharge rate through the orifice could be obtained by measuring the water depth above the orifice. A metal rod with a float was fixed vertically inside the pipe: as the flow from the downpipe discharged into the pipe, the float would move upwards and give the water level above the orifice. This generated a voltage signal that was captured by the data logger. Since special attention was needed to prevent clogging of the orifice by leaves and other debris, mesh was placed at the downstream end of the downpipe and over the pipe. In spite of the mesh that was in place to cover the roof gutter, regular cleaning at the downstream end was still required.

Data logger

The readings from the rain gauge and water depth probes (and also from the flowmeter on Site 1) were collected at each site by data loggers "Datataker" type DT 50 supplied by Data Electronics Ltd. These devices allowed the acquisition and logging of the data, which later needed to be downloaded onto a computer for further processing. Regular downloading was however necessary because of memory limitations. The frequency for downloading depended on the amount of rainfall as will be explained later. Due to the distance to Site 2, and in order to reduce the frequency of the visits to download the data, a 512 kbyte memory card was fitted to the data logger on Site 2. This enabled the frequency of the visits to the site to be around once a month. At Site 1, it was usually necessary to download data every week. Failing to download before the data logger's memory became exhausted meant that subsequent rainfall events would be missed since the data logger would stop collecting data.

The data loggers were kept indoors, connected by cables to the other instrumentation. Personal computers were also permanently installed at each site to allow downloading and preliminary data processing using a spreadsheet (Lotus 123 or Microsoft Excel). Two different programs (one for each site) were written to instruct the data logger how to collect the data. This is described below.

Data acquisition program

Since it was not practical to be continuously collecting data, it was necessary to define a way of triggering the data collection. It was decided that the triggering should be done by the tipping of the rain gauge: the first tip of the gauge would send a signal to the data logger to start recording the data not only from the rain gauge, but also from the water depth probes (and from the flowmeter, in the case of Site 1). A program was written in the data logger to instruct it to take readings every 10s. Similarly to the start of the data collection, it was necessary also to decide when to stop collecting data so that the memory of the data logger would not become full with irrelevant data. This required considerable thought because it was also important to make sure not to truncate storm events and thereby miss significant data. A decision was made to stop the data collection if no more tips of the rain gauge occurred during a period of four minutes. Four minutes is a fairly arbitrary duration but it was chosen after some preliminary tests with two minutes, which revealed that the water in the gutters had not always had time to flow into the outlet.

3.3 Calibrations

The rain gauges were standard pieces of equipment that were purchased with the manufacturer's calibration. No further calibration was therefore required but nonetheless some checks were carried out to compare the rainfall measured at Site 1 with that recorded at the nearby Institute of Hydrology (IOH). It must be noted that a perfect agreement between the two measurements was not expected mainly because the rain gauges were in quite different locations: one on the roof of a building and the other closer to ground level (as is standard for the usual recording of rainfall data). The following table shows the comparison of daily rainfall (in mm) from 9am to 9am GMT:

Date	Daily Rainfall (mm)	
	Site 1	IOH
09/10/96	0.2	0.1
10/10/96	0	0
14/10/96	0.8	0.9
15/10/96	0.8	1.0
16/10/96	0	0

As can be seen, the agreement is quite satisfactory.

Considerable time and effort was spent with the calibration of the water depth probes and the flowmeter device to ensure that correct readings were taken during the monitoring programme. All the instruments were first calibrated in the laboratory but further checks were considered necessary after they were installed in situ. For example, the water depth probes of Site 1 were positioned in the gutter and water was pumped at different constant rates into the section of gutter being monitored. This was carried out using a submersible pump, which pumped water from a sump in one of HR's nearby physical model facilities. The calibration of these probes was regularly checked, in particular the values corresponding to zero water depth (i.e. the "zeros" of the probes).

During the monitoring period it was found that these zeros tended to vary for a number of different reasons. Although it was difficult to separate the effect of the various parameters, it is believed that the main reason was the change in temperature that the probes experienced at the transition between a "dry" state and a "wet" state at the beginning of a storm. Other reasons included, in spite of all the efforts to prevent leaves from falling into the gutter and the regular cleaning, the accumulation of leaves, mulch and rust particles around the wires of the probes during the periods between storm events. This variation in the zeros was taken into account in the data analysis, as mentioned later in Section 4.3.

The calibration of the flowmeter used at Site 1 was carried out by introducing known flow rates and comparing the values of discharge computed from the readings of water depth given by the instrument using the equations for flow through orifices. The agreement was very satisfactory.

4 Data collected

After completion of the on-site calibrations, a number of preliminary tests were carried out to ensure the good functioning of the instrumentation before the actual data collection started. The monitoring took place in the periods between September 1996 and October 1997 for Site 1 and between December 1996 and October 1997 for Site 2.

It was unfortunate that the Winter and Spring of 1997 were amongst the driest on record in the South East of England and therefore the amount of storms recorded and the rainfall intensity associated with these storms were relatively low. However, late Spring and Summer proved much wetter and produced some interesting records.

For this study a "storm" was defined as a period of continuous rainfall, which started with a tipping of the rain gauge and ended when no more tips occurred in a period of four minutes. This definition was adopted in the data collection program, as mentioned earlier in Section 3.2. The period of four minutes at the end of a storm was chosen so as to allow sufficient time for all the water in the gutter, including its most upstream section, to flow into the outlet. Preliminary tests were carried out using two minutes (which is considered in BS 6367 to correspond to the time taken for rain falling on the most upstream part of the roof to reach the outlet), but it was found that this time should be increased.

The storms recorded are presented in Tables 1 (for Site 1) and 2 (for Site 2) making a total of 2166 storms. They are shown as the total number of storms in each month and are also arranged in classes with different amounts of rainfall. These classes were arbitrarily chosen but are useful to illustrate the distribution of heavier and lighter storms during the year and during the period recorded.

It can be seen that the great majority of storms recorded were very light, with less than 0.4mm of rainfall. These storms are not interesting from the view point of the present study as they are too small to be considered for the design of rainwater systems. The heavier storms occurred in November 1996 and, as expected, during the summer months of June and August 1997.

Figures 4 and 5 show two examples of the raw data recorded. The first two columns give the date and time of the storm; the next column is a coefficient defined by the data acquisition program but with no relevance to the data analysis. The fourth, fifth and sixth columns are voltage readings from the instruments: two water depth probes and the flowmeter in Figure 4 and three water depth probes in Figure 5. The last column lists the number of tips of the rain gauge that occurred during the storm.

5 Data analysis

5.1 Analysis method

In order to produce recommendations for the design of roof drainage systems the analysis concentrated on the heaviest storms since these are the ones that are most likely to produce the greatest rates of runoff and the higher risks of flooding. Therefore, from all the storms listed in Tables 1 and 2, a few of the major ones were selected for analysis. This selection was based on the maximum rainfall intensity registered during each storm, which was calculated from the amount of rainfall (given by the rain gauge tips) by the time that elapsed between them. The maximum value obtained was 144 mm/hr, only observed rarely at Site 2, but several storms were identified that had maximum rainfall intensities of 72mm/hr.

The processing of the raw data involved the following steps for each of the storms:

1. the determination of the storm duration;
2. the variation in time of the rainfall intensity (in mm/hr);
3. the calculation of water depths in the gutter from the voltage readings using the calibration equations;
4. the calculation of the flow in the gutter;
5. the determination of the return period associated with the storm.

Steps 1 and 2 were straightforward but steps 3 and 4 require some explanation. It was mentioned earlier that the value of zero depth given by the water depth probes was sensitive to sharp changes in temperature such as those occurring at the start of a storm that followed a dry period. These zeros would also be affected by the presence of leaves and other debris in the gutter (a problem difficult to eliminate at Site 1). For these reasons, the zeros needed to be defined for each of the storms analysed. This was done by studying the conditions at the beginning of the storm to see whether or not storms had occurred previously and wetted the probes and/or washed away any debris in the gutter.

A number of different methods were used to determine the flow rates in the gutters: using the readings of the water depth probes; using the flowmeter readings (at Site 1); and using the data from the water depth probe at the outlet (at Site 2). The first method computed the flow rates on the upstream and downstream ends of the gutter directly from the readings of water depth at those locations, using the calibration equations. Although this method was satisfactory for most storms, it gave some inconsistent results in terms of the amount of runoff generated by a number of storms. Close study of the data revealed that the problem lay with the flow rates given by the downstream probes, in spite of the two sets of calibration undertaken (in the laboratory and in-situ) at the start of the monitoring period.

The flowmeter installed at the discharge point from the downpipe at Site 1 was found to give reliable readings for the heaviest storms but failed to be sufficiently accurate for most of the less intense storms, which formed the bulk of the data collected. It is thought that the jet discharging from the downpipe into the flowmeter sometimes imposed too strong a force on the float and restrained its upward movement. For larger flows the amount of water above the orifice was usually sufficient to "cushion" the jet and allow the float completely free movement. The readings from the flowmeter were used essentially to crosscheck the other flow data for the heavier storms, and were therefore useful. The readings of the water depth probe positioned in the outlet sump at Site 2 were used in conjunction with the rating equation for Fulbora outlets determined by HR in a previous research study of flat roof outlets (Escarameia and May, 1996). The flow rates obtained were, however, not ultimately used in the analysis of the data. They were only used for comparison purposes because the following method proved to be more reliable.

It was decided to calculate the flow rates in the gutter according to the recommendations in the draft European Standard for rectangular gutters. The method in this Standard uses the water depth at the most upstream section and requires the determination of a factor to account for the frictional resistance in the gutter. Since this coefficient depends on the ratio of the water depth to the gutter length, it was necessary to calculate its value for the variable water depths that occurred during the storms. This method produced plausible rates of runoff in the gutter for most of the storms, i.e. the rates of runoff were generally similar to or smaller than the volume of rainfall, since the method eliminated the uncertainties associated with the readings of the downstream probes.

Once the flow rates were calculated with the chosen and most reliable method, it was possible to summarise in Tables 3 and 4 the main defining parameters. These were: the storm duration; the rainfall intensity (both the maximum that occurred during the storm and the maximum average rainfall intensity that occurred in any 2 minute period of the storm); the return period associated with the 2 minute rainfall intensity; and the average 2 minute flow rate. A period of two minutes was chosen for the analysis since this is the basis for the design recommendations in BS 6367:1983. It is intended to correspond to the worst design conditions, when the duration of the storm is equal to the time required for all the rain falling on the catchment area of the roof to reach the gutter outlet. The calculation of return periods was carried out according to Appendix A2 of BS6367:1983, and was also based on the 2 minute rainfall intensity. It can be seen that all the storms recorded had small return periods, of less than one year, and therefore were quite common occurrences in the south east of England. As well as listing the heaviest storms, less intense storms recorded at Site 2 were also investigated and are summarised in Table 5.

Graphs showing the evolution of the rainfall intensity, the water depths in the gutter and the flow rates were produced and are presented in Figures 6 to 42.

5.2 Storm duration

The duration of the major storms recorded is presented in Tables 3 and 4. It can be seen that all the storms lasted more than 7 minutes and less than about 30 minutes. The less intense storms listed on Table 5 and are also within that band of values, which indicates that there is no strong relationship between storm duration and the intensity of the rainfall.

This can be more easily appreciated in Figure 43, where the storm duration is plotted against the maximum rainfall intensity occurring during the storm (top graph), and against the average rainfall intensity measured during the 2 minute interval with the highest rainfall (bottom graph). A medium intensity storm (6.5mm/hr) recorded at Site 1 on 2 July 1997 was also included in this graph to illustrate that, in spite of its lower intensity, its duration (8.3 minutes) was similar to that of the much heavier storm of 25 August 1997.

The scatter in these graphs is considerable and there appears to be no correlation between duration and rainfall intensity. Nevertheless, it can be seen that most storms are within the band of 10 to 20 minute duration. With regard to the very low intensity storms (less than 4mm/hr) also recorded in the present study, the duration was also variable but many were found to be of the order of 4 to 8 minutes. However, these storms are of little significance for the design of roof drainage systems.

5.3 Time of concentration

The time of concentration, T_c, is defined as the time taken for rain falling on the most upstream part of the roof to reach the gutter outlet. It depends on the characteristics of the roof, particularly the size (smaller roofs are likely to have shorter times of concentration) and layout (roofs with big pitches are likely to have shorter time of concentration than flat roofs). The nature of the roof material, as well as its wetness at the start of a storm, may also influence the value of T_c. In the present Standard, BS6367, it is recommended to assume that the time of concentration is normally 2 minutes. This recommendation derived from calculations based on flow formulae suitable for typical roofs (May, 1996).

The two roofs in the present study were different in terms of their layout, the roofing material, the pitch and the distance the rain had to travel to reach the outlet (see Figures 1 and 2, and

Section 2.2). At Site 1 the distance between the most upstream point on the roof draining to the monitored gutter and the outlet was 30.73m, whereas at Site 2 this distance was 18.3m.

The times of concentration were determined for all the storms listed in Tables 3 to 5. They were calculated by the difference between the time of occurrence of the beginning of the maximum 2 minute rainfall intensity window and the beginning of the maximum 2 minute flow window. This analysis (and the determination of the percentage runoff described in Section 5.4) showed that a few of the storms had unreliable data and were not considered for future analysis.

Tables 6 and 7 present the 2 minute rainfall intensity, the wetness condition of the roofs prior to the start of the storms and the time of concentration for each of the major storms of Sites 1 and 2. It can be seen that the time of concentration for both roofs is generally less than two minutes (120s). The longer times were associated with the flat roof of Site 2, in spite of the shorter length of travel for the water. This is more apparent in Figure 44 where, for similar values of the 2 minute rainfall intensity, the flat roof had bigger values of T_c than the sloping roof. It can also be seen that no relationship was found between the two variables. There is however some indication that high 2 min rainfall intensities correspond to shorter values of the time of concentrations. Similar analyses were carried out in an attempt to relate T_c to the maximum rainfall intensity and the antecedent conditions but no strong correlation was found.

Figure 44 also includes a graph of the variation of T_c with the 2min rainfall intensity for medium intensity storms recorded at Site 2 (see also Table 8, where the values are listed). As before, the time of concentration is generally under two minutes and again no relationship was found.

5.4 Percentage runoff

The percentage runoff can be defined as the ratio of the runoff to the volume of rainfall that produced the runoff and is therefore an important parameter in design. It is implicit in BS 6367:1983 that the design of roof drainage systems should be carried out assuming 100% runoff. This means that all the rain that falls on a roof should be considered to reach the drainage system, which therefore needs to be able to cope with the corresponding flow.

There is more than one way to determine the percentage runoff, and various approaches were tried before satisfactory results were obtained. One of the rejected approaches, which considered the volume of runoff during the whole storm, gave inconsistent values of percentage runoff for most of the storms, in many cases above 100%. The chosen method involved calculating the ratio of the runoff (as described in Section 5.1) and the volume of the rainfall that produced it in the highest-intensity two minute interval.

The values of percentage runoff for the major storms of Sites 1 and 2 are listed in Tables 6 and 7, where it can be seen that they range from 5 to 100% (some of the storms listed as having 100% runoff were marginally over that value). For the less intense storms listed in Table 8, the amount of runoff generated was found to be substantially smaller (with the exception of the storm of 9 Oct 97).

Similar to the analysis carried out to determine the time of concentration, attempts were made to relate the percentage runoff to various other parameters (such as the maximum and 2 minute rainfall intensities and the antecedent conditions). Figure 45 plots the percentage runoff against the 2 minute rainfall intensity. It highlights the fact that, for storms heavier than about 20mm/hr, the runoff does not depend strongly on the rainfall intensity or on the type of roof (sloping or flat). The wetness of the roof prior to the occurrence of the storm and seasonal factors such as temperature and evaporation also appear to have little significance. This confirms the results of a monitoring study carried out by Hollis and Ovenden (1988) on a total of eight different residential and factory roofs. It is interesting to note that these authors also found percentage runoffs higher than 100%, particularly for the heavier storms. The apparently illogical result could not be explained but was thought to be due to the different locations of the roofs and the rain gauges. This explanation is not valid for the present study, as the rain gauges were positioned on the roofs they were monitoring, which only highlights the complex and highly variable response of impervious surfaces. However, in the present case, higher than 100% percentage runoffs can be partly attributed to non uniform rainfall due to complex three-dimensional wind patterns on the roofs.

The Hollis and Ovenden study also showed that the percentage runoff averaged about 57% for all the storms recorded. For rainfalls above 5mm the average was about 90%. This finding cannot easily be compared with the results of the present study since the amounts of rainfall monitored by HR were almost always lower than 5mm. However, it appears that a greater variation in the percentage runoff was found in the present study.

5.5 Depression storage

The percentage runoff is linked with the depression storage of the roof, which is defined as the amount of rainfall necessary before runoff is generated. Higher depression storage is in principle more likely to be associated with flat roofs rather than roofs with significant pitches. Due to the small, nominal slopes present in flat roofs, there is more potential for areas where water can pond after a storm. This potential for ponding is usually a result of bad workmanship during the construction stage or is caused by slight distortions of the roof. The roofing material is another parameter which can affect the depression storage of a roof. Materials that are flexible will be more prone to sagging and therefore may tend to store water in certain places. Furthermore, some smooth materials are more likely than rougher materials to cause bouncing off the edges of the roof of a small percentage of the total rainfall.

The original Wallingford Procedure, a method widely used in the design of urban drainage systems, recommended a value of 0.4mm for the depression storage of pitched roofs. Further experimental studies showed that the initial losses due to depression storage, D, depended both on the slope and on the nature of the surface of the catchment (Kidd and Lowing, 1979, and Makismovic and Rdojkovic, 1986). The equation recommended for the calculation of D in software based on the revised Wallingford Procedure is:

$$D = k / (S)^{0.5}$$

where

D is given in mm
k is a numerical coefficient
    k = 0.071mm is suggested for all paved areas and roofs;

S is the slope of the roof in m/m.

Applying the above equation to the two sites monitored gives

D = 0.3mm for Site 1
D = 0.5mm for Site 2

In order to check these recommendations, the records collated for the smaller intensity storms were examined to see whether the rainfall had produced measurable runoff. All storms with rainfall greater than or equal to 0.4mm (for Site 1) and 0.8mm (for Site 2) were found to produce some runoff, although not all runoff was significant for design purposes. It should be noted that these values are approximate and were based on increments of 0.2mm. Although not in complete agreement with the values suggested by the above equations, these values confirm that there is a significant difference between the depression storage of sloping and of flat roofs.

5.6 Effect on runoff of wind speed and direction

The current British Standard, BS 6367:1983, makes allowance for the effect of wind blowing against sloping roofs or vertical walls by defining the catchment area as the sum of the plan roof area and a term for the exposed areas in elevation. The amount of rainfall caught by the exposed areas depends on the angle of descent of the rain. Limited information from the Met

Office led to the recommendation in BS 6367:1983 to assume for design the most severe wind direction and an angle of descent of 2V:1H from the vertical.

The measurement of angles of descent of rain during storm events, which are likely to depend on the rain drop sizes, the speed of the wind and the intensity of the rainfall, was outside the scope of the present study. However, it was possible to investigate effects such as exposure to the wind or sheltering on the amount of runoff generated. For this purpose, data on wind speed and direction were obtained for the major storms analysed. Data for Site 1 were supplied by the Institute of Hydrology due the proximity of the wind stations to the site. Data for Site 2 were supplied by the London Weather Centre of the Met. Office: the weather station that collected the data (and the closest to the site) was situated on a roof in Whitehall, central London. Both sources provided hourly averaged wind speeds and directions; the values closest to the time of the events (which had durations always shorter than one hour) were chosen as representative of the average wind conditions.

The wind data are listed in Tables 9 (for Site 1) and 10 (for Site 2), where the wind direction is the direction from which the wind is blowing and the wind strength follows the Beaufort classification (a scale ranging from Calm, less than 1.85km/hr, to Storm, up to 101.9km/hr). As can be seen, at the time when the storms occurred, the wind was never very strong, being in most cases light. Although the sample is fairly small and limited to two not very disparate geographical situations, this tends to confirm the idea that heavy storms may be associated with low wind speeds. The tables also show that, as expected in the south east of England, the predominant wind direction during the major storm events was south west.

The section of gutter monitored at Site 1 faced south and ran from east (upstream end) to west (downstream end). On the south side of the building, some sheltering was possible due to the presence of a few tall trees about 15m from the gutter. These could have had a sheltering effect for winds blowing from a southerly direction when compared with winds blowing from the north. In order to investigate this aspect, storms with similar hydraulic characteristics but different wind directions were listed in Table 11. The 2minute flow rate in the gutter, the 2minute rainfall intensity and the percentage runoff, as well as the wind strength and the antecedent conditions, are shown in this table. Storms with similar 2minute flow rate (or rainfall intensity) and different wind direction (for example the storms of 6Jun97 or 26Jul97 (16:39:30) with a southerly wind, and the storm of 22Jun97 with a northerly wind) have comparable values of percentage runoff. The same applies to the storms of 26Jul97 (15:40:50) and 24Aug97. If the wind direction had a strong effect, one would expect to find lower rates of runoff in storms associated with southerly winds. The table also lists the storm of 2Jul97, which was the storm with the lowest percentage runoff of the whole set of major storms recorded. In view of the comparison between the other storms, it can be concluded that the low percentage runoff is in this case due to low rainfall rates and to the antecedent conditions rather than the direction of the wind.

Conclusions regarding the effect of wind on the drainage of the flat roof of Site 2 are more difficult to draw, since there are no significant areas in elevation exposed to the wind. The section of gutter monitored ran in a south west (upstream end) to a north east (downstream end) direction. It is possible that wind blowing from the north east during a storm, i.e. against the flow in the gutter, may reduce the runoff in the very shallow gutter. Table 11 presents two storms: 11Oct97 (13:26:00) with a wind direction from the north east quadrant and 15Oct97, with an opposite wind direction. In spite of a potentially opposing wind direction, the percentage runoff of the first storm was greater than that of the latter storm.

From the limited information gathered, it appears that the wind speed and direction are parameters that have small, if any, effect on the runoff in roof gutters. This conclusion is, of course, not general but for design purposes other parameters are likely to play a much more important role.

5.7 Comparisons with BS 6367:1983

The values of runoff produced by the major storms recorded at the two sites were included in Tables 6 to 8, and their determination was described in Section 5.4. As mentioned then, for most of the storms, the percentage runoff assumed in BS 6367:1983 (100%) was bigger than the values obtained for the measured storms. Nevertheless, in 42% of the storms analysed for Site 1 and 31% of storms for Site 2, the measured runoff was within 10% of the value assumed in the Standard. In view of the wide range of results, the 100% runoff assumption in BS 6367:1983 is considered to be valid because the data show that there is a reasonable probability of it occurring in practice.

Comparisons were also made between the maximum water depths measured in the gutter and those predicted by the British Standard. These comparisons were carried out for two of the major storms collected at Site 1: the storms of 24 Feb 97 and 24 Aug97. Calculations using BS 6367 showed that the outlet restricted the flow in the gutter of Site 1, i.e. that critical flow conditions were not achieved at the outlet. Water depths at the upstream end of the gutter were calculated according to the Standard. It was found that these values were between 6 and 13% higher than the maximum water depths measured on site. This indicates that the recommendations in the BS lead to safe design but do not excessively overestimate the required water depths.

6 Numerical simulations

Numerical simulations of flow in roof gutters were carried out using a computer program developed by Prof. JA Swaffield of Heriot-Watt University, Edinburgh, for the simulation of unsteady free surface flows in pipes and channels. The program was originally written for the study and design of internal building drainage systems but was adapted by Prof. Swaffield's team for application to the study of roof drainage flows. This new program version, named GUTTER was, as the original one, written in FORTRAN and was based on the method of characteristics.

GUTTER calculates flow rates, depths and velocities in roof gutters of different shapes (half round, rectangular and trapezoidal) and various longitudinal slopes. The program offers the option of steady state and unsteady state calculations, this latter option being adopted in the present simulations. The flow into the gutter can be given directly by the user as a lateral inflow rate or be calculated by the program from the input values of rainfall intensity and the catchment area of the roof in question. Being an unsteady state model, the input rainfall intensity (and inflow rates) can vary with time. It is also necessary to specify the conditions at the outlet from the gutter, whether or not the flow is critical at the outlet. Friction losses along the gutter are calculated using Manning's equation, for which the roughness coefficient, n, needs to be specified.

The program was used to investigate the following aspects:

1. Comparison between site measurements and program results;
2. Comparison between the runoff produced by a whole storm and by the two minute block of the maximum average rainfall intensity;
3. Effect of varying the rainfall intensity in the 2 minute interval;
4. Simulation of a storm with heavier rainfall intensity than those recorded during the monitoring study, and comparison with corresponding predictions from BS 6367.

For the analysis of items 1 and 2 it was decided to select two major storms recorded at Site 1. The reason for choosing Site 1 was the nature of its drainage system, which was formed by a well defined rectangular gutter rather than by a shallow gutter with somewhat "diffuse" boundaries as in Site 2. The storms analysed were the storms of 24 February 1997 and 24 August 1997, both with percentage runoffs of 100%. Item 3 was addressed by using the storm of 24 February 1997.

All the computer simulations in the following Sections 6.1 to 6.3 were carried out with a roughness coefficient, n, of 0.011. This value was adopted because it was representative of the hydraulic roughness in the gutter, which depended on the roughness of the gutter and the turbulence caused by the lateral inflow, and corresponded to the roughness assumed in the formulae recommended in BS6367. Formulae in BS6367 were also used to determine whether critical flow conditions could be assumed at the outlet. These calculations showed that, for the gutter and outlet considered, the outlet would restrict the flow in the gutter. The computer program was therefore run for outlet control, an option in GUTTER which is represented by a power law between the head and the flow though the outlet.

6.1 Comparison between site measurements and program results

The results of the computer simulations (using the measured rainfall intensities) for the two storms were plotted in Figures 46 and 47 together with the measured values. Each figure shows the variation in time of the water depth at the most upstream section of the gutter, and of the flow rate. It can be seen that there is good agreement for both storms between measurements and computed values for the two variables. In terms of the shape of the plots, the agreement is better for the storm of 24 Aug 97 than for the storm of 24 Feb 97. The less good agreement for the February storm seems to be linked with its long period of constant rainfall (see Figure 9). At the upstream section of the gutter the rainfall appears to be directly translated by the program into water depths and flows. However, it is also possible that the differences between measured and calculated values could be partly due to the passage of debris, which may be registered as spurious peaks by the water depth probes. This may also explain why the maximum depths and flows appear to be underestimated by the program by between 12 and 23%. Although several runs were produced to achieve satisfactory simulations, it is also possible that further refinement of the input parameters to the computer model (such as the roughness coefficient) could lead to closer agreement.

6.2 Comparison between whole storm and 2 min block

The program was used to investigate the effect on water depths and flow rates of representing a storm by a two minute isolated block rainfall having a constant intensity equal to the maximum value that occurred in any 2 minute interval during the storm. Previous analysis (see Table 3) showed that the storms of 24 Feb97 and 24 Aug97 had 2min rainfall intensities of 38.8mm/hr and 34mm/hr, respectively.

The graphs of Figures 48 and 49 show a comparison between computer simulations carried out with rainfall intensities varying during the storm (as recorded on site) and blocks of constant rainfall intensity during a two minute interval preceded and followed by negligible rainfall. It is apparent in the figures that steady flow conditions were reached in the gutter when the variable rainfall was simulated by a 2min rainfall block. During the steady state condition the water depths and flow rates obtained with the two methods were very similar. However, it is also noticeable that the 2min block method did not reproduce the peak water depths and flow rates accurately, underestimating them by as much as 60%, for the particular case analysed.

6.3 Effect of varying the rainfall intensity in the 2min interval

The computer model was also used to investigate the effect of the rainfall intensity varying during the 2minute block and to compare the results with the flow conditions resulting from constant rainfall during the same interval. This comparison was carried out for the storm of 24 Feb 97, which had a 2 min rainfall intensity of 38.8mm/hr.

Three series of runs were carried out:

- Series 1, where the 2min block was divided into four sub-blocks of 30s each. The first and third blocks had rainfall intensity of 50mm/hr, the second and the fourth of 27.6mm/hr, so that the average rainfall intensity in the 2minute block was 38.8mm/hr.
- Series 2, similar to the above but where the first and the third sub-blocks had intensities of 27.6mm/hr and the second and fourth of 50mm/hr.
- Series 3, divided into two sub-blocks of 60s duration and 50mm/hr and 26.7mm/hr rainfall intensity.

The results of the simulations for the three series (values of water depth at the upstream section and flow rates in the gutter), as well as the results of simulations with uniform rainfall intensity, are plotted in Figure 50. This figure shows that steady state was not reached in Series 1 and 2 but was achieved in Series 3, where the sub-blocks were 60 seconds long. This indicates that, if the rainfall intensity changed in shorter intervals than one minute, the resulting runoff into the roof gutter and water depths might be considerably different from the case where the rainfall intensity was uniform during the two minute period. Although steady state was reached for the one minute block, it is however also apparent in the figure that flow rates and water depths can exceed those obtained for the two minute block.

6.4 Simulation of heavier rainfall

Due to the meteorological conditions during the period of site monitoring, the data collected on the two sites did not reach the high values of rainfall intensity recommended for design in BS6367. These correspond to a 2 min rainfall intensity of 75mm/hr or more. It was therefore decided to use the computer program to simulate a higher rate of rainfall intensity, 150mm/hr and compare the results with the predictions based on BS6367.

The simulations were carried out for critical flow conditions and unrestricted flow in a rectangular gutter 2.6m long. The storm simulated had a constant rainfall intensity of 150mm/hr, which lasted for 200 seconds.

In the first set of simulations it was decided to compare the results of the program for smooth gutter (a value of Manning's n of 0.001was adopted to simulate no friction along the gutter) with theoretical predictions of water depth and flow rates. As expected, the program results fully agreed with the theoretical predictions from which the recommendations in BS6367 were derived (but with an addition of a safety factor).

The program was next run for the same flow conditions but with a value of Manning's n expected for flows in roofs gutters, i.e. for n=0.011 (as described earlier in this chapter), which was the value considered in the formulae of BS6367. It was found that this value of roughness was insufficient to produce the upstream water levels predicted by BS6367. A difference of about 10% was found between the computer results and the British Standard, this latter giving higher values. Further computer simulations were carried out to investigate the value of n which would produce upstream depths similar to those of BS6367. It was found that values of n of the order of 0.02 would reduce the difference to 5%. A perfect match was not achieved since the program could not cope with higher values of Manning's n.

From the above, it can be concluded that the differences between the British Standard and the program can be accounted for by the safety factors incorporated in BS6367, which are not included in the computer program. In order to obtain close agreement, it is necessary to adopt unrealistically high values of roughness in the program. Apart from this aspect, the program appears to be an adequate tool for the simulation of unsteady flows in roof gutters.

7 *Conclusions*

A. Conclusions based on the analysis of the site data

1. A monitoring programme was carried out between September 1996 and October 1997 to measure rainfall on existing roofs and rates of runoff to the site drainage systems. Two sites were monitored, both of them in the South East of England: a sloping roof in Oxfordshire and a flat roof in London. A total number of 2166 storms were recorded (1229 in the first site and 937 in the second).

2. Standard rain gauges positioned on the monitored roofs were used to measure rainfall but it was necessary to develop special instrumentation to measure the variable water depths in the roof gutters. The data were collected by data loggers and analysed in personal computers also installed on the sites.

3. Based on the analysis of the heaviest storms recorded (with design rainfall intensities between 16 and 60 mm/hr), the typical duration of storms that produced heavy rainfall was between 10 and 30 minutes, and particularly in the band of 10 to 20 minutes. The observed storms had return periods of between just over one month and approximately 8 months. The duration of less intense storms also appeared to be within that range, although very low intensity storms were found to have shorter durations, of the order of 4 to 8 minutes.

4. The analysis of the major storms recorded at the two sites revealed that the time of concentration was generally shorter than two minutes, which is the value recommended for design in BS 6367:1983 "Drainage of roofs and paved areas". The time of concentration is defined as the time taken for rain falling on the most upstream part of the roof to reach the point of discharge, the gutter outlet. For the same rainfall intensity, the storms collected at Site 2 (a flat roof) had longer times of concentration than the sloping roof of Site 1, in spite of a shorter length of travel for the rainfall. This is likely to be essentially due to the gentle slope of the roof of Site 2, but can also be attributed to other reasons (such as the rougher nature of the roofing material). Contrary to what was expected, the condition of the roof at the start of the storm, whether it was dry or wet, appeared to have no relevance to the value of the time of concentration.

5. The percentage runoff, i.e. the ratio between runoff volume and rainfall volume, was calculated for all the storms analysed. The analysis revealed a large variation in the values for the heavier storms, from 5 to 100%; for less intense storms the runoff was found to be only a small percentage of the volume of rainfall (typically less than 10%). The great variability of the percentage runoff for the heavier storms also meant that no correlation was found between this parameter and other parameters such as the maximum and 2 minute rainfall intensities, the antecedent condition of the roof or the type of roof.

6. The depression storage associated with the roofs monitored was found to be of the order of 0.4mm for the sloping roof and 0.8mm for the flat roof. This is in fairly close agreement with the current recommendations of the Wallingford Procedure, which suggested values of 0.3mm and 0.5mm, respectively for the two sites.

7. No significant effect of wind direction on percentage runoff was detected within the overall variability of the data collected. This conclusion was based on comparisons between storms of similar rainfall intensity and opposite wind direction.

B. Conclusions regarding BS 6367:1983

1. Comparisons were also made between the site measurements and the recommendations given in BS 6367:1983 "Drainage of roofs and paved areas". With regard to the amount of runoff from roofs, it was found that the British Standard generally predicts bigger values of flow rate than those measured on site, which would be expected in view of the safety factors incorporated in the Standard. In 42% of the storms analysed for Site 1 and 31% of storms for Site 2, the measured runoff was within 10% of the value assumed in BS 6367, 100%.

2. With regard to the maximum water depths in the gutter, the present study indicated that the Standard slightly overestimated these depths, by about 10%, when compared with the site data.

3. From the above it can therefore be concluded that the recommendations in BS 6367:1983 should ensure safe design whilst not excessively overestimating the relevant design parameters. However, the results presented in this report also indicate that the time of concentration can be significantly shorter than the two minutes assumed in the Standard. There is also some evidence (see following Conclusions C) that short gutters can respond to rapid variations in rainfall, which can lead to peak water depths and flow rates greater than those based on the 2 minute rainfall intensity. The amount of the increase is likely to depend on the length of the gutters.

4. Conclusion 3 suggests that further work should be carried out on the recommended duration of design storm so that the British BSI Committee can form a view about possible changes to the European Norm when it comes up for review, three or four years after first publication.

C. Conclusions from application of numerical model

1. An unsteady flow program, GUTTER, written by Prof JA Swaffield of Heriot Watt University, Edinburgh, was used to investigate flow conditions in roof gutters that did not occur during the monitoring study. Comparisons with site measurements, for two storms collected at Site 1, showed that the program can predict water depths and flows in gutters correctly, provided a suitable value of the friction coefficient (a Manning's coefficient of about 0.02) is chosen.

2. Simulations were also carried out with the above computer program to investigate the effect of considering a 2 minute block of uniform rainfall when compared to the whole storm. This block was determined by scanning the whole storm with a 2 minute window to detect the block of maximum average rainfall. The numerical simulations showed that maximum water depths and flow rates can be significantly underestimated (by as much as 60% for the present simulations) when the 2 minute approach is chosen since account is not taken of the peak values. This indicates that the gutters can have very rapid response times (of less than two minutes) to variations of rainfall. For changes in rainfall intensity of less than 60 seconds it was found that steady state conditions are unlikely to be reached in the gutter.

3. It should be noted that the above conclusions referring to the measurements at Site 1 and the numerical simulations were drawn from quite short gutter length (2.7m) and limited catchment area. Since many gutter lengths can be greater than 10m, their response times to sudden peaks in rainfall can be considerably longer.

8 Acknowledgements

This project would not have been possible without the helpful and kind collaboration of Mr. M Harper of Briggs Roofing & Cladding Ltd and of Mr. K Brown and other staff of the Tower Bridge Business Complex, which was one of the sites monitored.

Acknowledgement is also due to Mr. J O'Reilly of Briggs and Forrester and to Rover Group Ltd for their help during the selection of the monitoring sites.

Mr LJ Smith and Mr IR Payne in the HR electronics section developed the water depth probes and wrote the program for data collection, respectively. The analysis of the data was carried out with the assistance of Ms Ruth Cano and Mr Francesco Schilliro', during their training placement at HR Wallingford

The contribution of Prof. J A Swaffield of Heriot-Watt University, Edinburgh is also gratefully acknowledged. Numerical simulations were made possible by Prof. Swaffield, who adapted a previously developed computer program for the calculation of unsteady flow conditions in open channel flow to the specific purpose of studying of roof drainage systems.

9 References

BS 6367:1983. “Drainage of roofs and paved areas”. British Standards Institution, 1983.

Escarameia M and May RWP (1996). “Performance of flat roof outlets”. HR Report SR 473. August 1996.

European Standard “Gravity Drainage Systems Inside Buildings: Part 3 – Roof Drainage, Layout and Calculation”, pr EN 12056-3. Draft version of 30.9.96.

Hollis GE and Ovenden JC (1988). “ The quantity of stormwater runoff from ten stretches of road, a car park and eight roofs in Hertfordshire, England during 1983". John Wiley & Sons, Ltd.

Kidd, CHR and Lowing MJ (1979). “The Wallingford urban subcatchment model”. IoH Report 60.

Makismovic C and Rdojkovic M (1986). “Urban drainage catchment. Selected worldwide rainfall-runoff data from experimental catchments”. Pergamon, 374pp.

May RWP (1996). “Manual for the hydraulic design of roof drainage systems. A guide to the use of British Standard BS 6367:1983”. HR Report SR 485, October 1996.

Tables

Table 1 Storms recorded at Site 1

Date	Total number of storms	Rainfall (mm)											
		<0.4	0.4< <1.0	1.0< <1.5	1.5< <2.0	2.0< <2.5	2.5< <3.0	3.0< <3.5	3.5< <4.0	4.0< <4.5	4.5< <5.0	5.0< <5.5	5.5< <6.0
1996													
Sept	22	22	-	-		-	-	-	-	-	-	-	-
Oct	69	67	1	-	-	-	-	1	-	-	-	-	-
Nov	175	149	18	3	-	2	1	-	1	-	-	-	1
Dec	77	75	2	-	-	-	-	-	-	-	-	-	-
1997													
Jan	42	41	-	-	1	-	-	-	-	-	-	-	-
Feb	168	144	18	3	2	1	-	-	-	-	-	-	-
Mar	45	44	-	1	-	-	-	-	-	-	-	-	-
Apr	51	46	5	-	-	-	-	-	-	-	-	-	-
May	75	69	4	-	1	1	-	-	-	-	-	-	-
Jun	140	121	9	3	2	3	-	1	1	-	-	-	-
Jul	59	46	5	4	3	-	1	-	-	-	-	-	-
Aug	157	141	10	3	1	2	-	-	-	-	-	-	-
Sept	39	36	1	2	-	-	-	-	-	-	-	-	-
Oct until 17	110	88	19	2	1	-	-	-	-	-	-	-	-

Table 2 Storms recorded at Site 2

Date	Total number of storms	Rainfall (mm)												
		<0.4	0.4< <1.0	1.0< <1.5	1.5< <2.0	2.0< <2.5	2.5< <3.0	3.0< <3.5	3.5< <4.0	4.0< <4.5	4.5< <5.0	5.0< <5.5	5.5< <6.0	6.0< <6.5
1996														
Dec 13 to 20	26	26	-	-	-	-	-	-	-	-	-	-	-	-
1997														
Jan*	1	1	-	-	-	-	-	-	-	-	-	-	-	-
Feb	179	166	7	4	1	-	-	-	-	1	-	-	-	-
Mar	39	37	1	1	-	-	-	-	-	-	-	-	-	-
Apr	48	47	1	-	-	-	-	-	-	-	-	-	-	-
May	109	99	7	1	-	1	-	1	-	-	-	-	-	-
Jun	162	117	27	5	2	4	-	-	1	3	1	1	1	-
Jul*	68	57	9	1	-	1	-	-	-	-	-	-	-	-
Aug	122	97	15	5	-	2	1	-	-	1	-	-	-	1
Sept	21	19	1	1	-	-	-	-	-	-	-	-	-	-
Oct (until 29)	162	141	13	2	3	-	2	1	-	-	-	-	-	-

* Not all storms were recorded due to malfunctioning of the data logger

Table 3 Major storms recorded at Site 1

Storm (Date) (Time)	Duration	Max Rainfall Intensity (mm/hr)	2 min Rainfall Intensity (mm/hr)	Return Period (2 min) (years)	Q 2 min (l/s)
4 Nov 96 04:44:10	1430s = 23.8min	72	23.5	0.12	0.67
4 Nov 96 05:22:50	1650s = 27.5min	36	23	0.12	0.90
18 Feb 97 05:32:10	880s = 14.7min	72	23.5	0.12	0.82
24 Feb 97 20:52:30	710s = 11.8min	72	38.8	0.30	0.94
26 Feb 97 01:28:30	720s = 12min	24	18	0.12	0.56
6 Jun 97 19:28:00	910s = 15.1min	24	20	0.12	0.36
21 Jun 97 13:49:00	550s = 9.1min	72	34	0.15	0.47
22 Jun 97 08:46:00	950s = 15.8min	72	18	0.12	0.21
22 Jun97 15:50:00	640s = 10.6min	36	20	0.12	0.32
26 Jul 97 15:40:50	1730s = 28.8min	72	36	0.30	0.73
26 Jul 97 16:39:30	820s = 13.6min	72	22.3	0.13	0.33
24 Aug 97 17:32:50	1080s = 18min	72	34	0.15	0.76
25 Aug 97 11:25:10	520s = 8.6min	72	28.5	0.14	0.40
30 Aug 97 03:09:20	1820s = 30.3min	72	27	0.14	0.28
9 Oct 97 21:50:40	660s = 11min	72	25.5	0.14	0.24

Table 4 Major storms recorded at Site 2

Storm (Date) (Time)	*Duration*	*Max Rainfall Intensity (mm/hr)*	*2 min Rainfall Intensity (mm/hr)*	*Return Period (2 min) (years)*	*Q 2 min (l/s)*
10 Feb 97 13:23:30	770s = 12.8min	72	18.5	0.12	0.14
18 Feb 97 06:32:40	1580s = 26.3min	72	60	0.50	0.85
24 Feb 97 02:02:40	1130s = 18.8min	72	35	0.15	0.07
5 May 97 20:14:00	880s = 14.6min	18	16.6	0.12	0.83
9 May 97 16:05:00	970s = 16.1min	36	19.5	0.12	0.56
6 Jun 97 20:53:00	1010s = 16.8min	72	38	0.25	1.94
7 Jun 97 00:36:30	1790s = 29.8min	36	22.5	0.13	0.28
16 Jun 97 14:42:10	1180s = 19.6min	72	36	0.24	1.81
19 Jun 97 08:54:00	620s = 10.3min	72	25	0.14	0.30
22 Jun 97 09:02:20	440s = 7.3min	72	42.7	0.30	0.41
22 Jun 97 15:28:30	570s = 9.5min	144	69	0.65	2.46
28 Aug 97 04:22:30	1070s 17.8min	72	42	0.30	0.96
12 Sept 97 12:18:00	800s = 13.3min	24	15.8	0.11	0.72
7 Oct 97 03:52:40	1060s = 17.7min	36	25.5	0.13	0.87
7 Oct 97 04:11:40	1240s = 20.7min	36	24	0.13	0.17

Table 5 Medium intensity storms recorded at Site 2

Storm (Date) (Time)	*Duration*	*Max rainfall Intensity (mm/hr)*	*2 min Rainfall Intensity (mm/hr)*	*Q 2 min (l/s)*
7 Oct 97 08:49:50	1010s = 16.8min	10.3	9.8	0.014
9 Oct 97 21:38:50	1220s = 20.3min	4	4	0.17
9 Oct 97 22:12:00	820s = 13.7min	4.5	4.5	0.01
9 Oct 97 23:43:40	920s = 15.3min	4.5	4.5	0.007
11 Oct 97 13:26:00	930s = 15.5min	10.3	9.3	0.023
11 Oct 97 23:35:10	1260s = 21min	5.1	5.1	0.006
15 Oct 97 03:57:10	1660s = 27.7min	14.4	12.9	0.025

Table 6 Time of concentration and % runoff of major storms at Site 1

Storm (Date) (Time)	2 min Rainfall Intensity (mm/hr)	Antecedent conditions	Time of concentration (s)	% runoff
4 Nov 96 04:44:10	23.5	wet	30	100*
24 Feb 97 20:52:30	38.8	wet	40	100*
6 Jun 97 19:28:00	20	wet	90	91
21 Jun 97 13:49:00	34	dry	40	66
22 Jun 97 08:46:00	18	dry	70	59
22 Jun 97 15:50:00	20	dry	40	68
26 Jul 97 15:40:50	36	dry	0	100*
26 Jul 97 16:39:30	22.3	wet	10	69
24 Aug 97 17:32:50	34	wet	50	100*
25 Aug 97 11:25:10	28.5	wet	30	67
30 Aug 97 03:09:20	27	wet	60	47
9 Oct 97 21:50:40	25.5	wet	30	40

* These values were rounded to 100% but were marginally higher:

Storm	4 Nov 96	104%
	24 Feb 97	113%
	26 Jul 97	102%
	24 Aug 97	107%

Table 7 Time of concentration and % runoff of major storms at Site 2

Storm (Date) (Time)	*2 min Rainfall Intensity (mm/hr)*	*Antecedent conditions*	*Time of concentration (s)*	*% runoff*
10 Feb 97 13:23:30	18.5	wet	120	19
18 Feb 97 06:32:40	60	dry	40	35
24 Feb 97 02:02:40	35	wet	50	5
5 May 97 20:14:00	16.6	dry	90	100*
9 May 97 16:05:00	19.5	~ wet	240	57
6 Jun 97 20:53:00	38	~ wet	60	100*
19 Jun 97 08:54:00	25	wet	100	24
22 Jun 97 09:02:20	42.7	wet	70	21
22 Jun 97 15:28:30	69	dry	80	91
28 Aug 97 04:22:30	42	dry	10	73
12 Sept 97 12:18:00	15.8	wet	70	98
7 Oct 97 03:52:40	25.5	dry	⊗	71
7 Oct 97 04:11:40	24	wet	60	16

⊗ Not determined

* These values were rounded to 100% but were slightly higher, 113%

Table 8 Time of concentration and % runoff of medium intensity storms at Site 2

Storm (Date) (Time)	*2 min Rainfall Intensity (mm/hr)*	*Antecedent conditions*	*Time of concentration (s)*	*% runoff*
7 Oct 97 08:49:50	9.8	wet	80	3
9 Oct 97 21:38:50	4.0	wet	40	69
9 Oct 97 22:12:00	4.5	wet	200	4
9 Oct 97 23:43:40	4.5	wet	✇	3
11 Oct 97 13:26:00	9.3	wet	100	5
11 Oct 97 23:35:10	5.1	wet	✇	~ 0
15 Oct 97 03:57:10	12.9	wet	70	3

✇ Not determined

Table 9 Wind speed and direction during major storms at Site 1

Storm	*Time*	*Wind direction*	*Wind speed (km/hr)*	*Wind strength*
4 Nov 96	04:44:10	SW	12.6	Light
24 Feb 97	20:52:30	SW	27.0	Moderate
6 Jun 97	19:28:00	SE-S	8.28	Light
21 Jun 97	13:49:00	SW	13.7	Light
22 Jun 97	08:46:00	W	7.2	Light
22 Jun 97	15:50:00	NW	7.2	Light
2 Jul 97	18:02:10	S	4.86	Light
26 Jul 97	15:40:50	S-SW	7.90	Light
26 Jul 97	16:39:30	S-SW	7.90	Light
24 Aug 97	17:32:50	N	2.66	Light
25 Aug 97	11:25:10	S-SW	4.68	Light
30 Aug 97	03:09:20	SE	7.02	Light
9 Oct 97	21:50:40	SW	14.9	Light

Notes: Wind direction measured as direction from which wind is blowing

N – north; E – east; S – south; W – west
SW – south-west; SE – south-east; NW – north-west

Table 10 Wind speed and direction during major storms at Site 2

Storm	*Time*	*Wind direction*	*Wind speed (km/hr)*	*Wind strength*
10 Feb 97	13:23:30	SW-W	25.9	Moderate
18 Feb 97	06:32:40	SW	32.4	Fresh
24 Feb 97	02:02:40	SW	12.5	Light
5 May 97	20:14:00	SW to N	19.4	Moderate
9 May 97	16:05:00	W-SW	8.33	Light
6 Jun 97	20:53:00	E-SW	19.4	Moderate
7 Jun 97	00:36:30	SE	10.2	Light
19 Jun 97	08:54:00	SW	8.33	Light
22 Jun 97	09:02:20	SW-W	13.0	Light
22 Jun 97	15:28:30	W	18.5	Light
28 Aug 97	04:22:30	E-SW	9.26	Light
12 Sept 97	12:18:00	SW	18.5	Light
7 Oct 97	03:52:40	SW	15.7	Light
7 Oct 97	04:11:40	SW-W	15.7	Light
7 Oct 97	08:49:50	SW	13.0	Light
11 Oct 97	13:26:00	E	11.1	Light
15 Oct 97	03:57:10	SW	8.33	Light

Notes: Wind direction measured as direction from which wind is blowing

N – north; E – east; S – south; W – west
SW – south-west; SE – south-east

Table 11 Comparison of wind data for Sites 1 and 2

Storm	*Wind direction*		*Wind strength*	*Q 2 min (l/s)*	*Rainfall int 2min (mm/hr)*	*% runoff*	*Antecedent conditions*
	North quadrant	*South quadrant*					
Site 1							
6 Jun 97		✔	Light	0.36	20	91	wet
26 Jul 97 16:39:30		✔	Light	0.33	22.3	69	wet
22 Jun 97	✔		Light	0.32	20	68	dry
26 Jul 97 15:40:50		✔	Light	0.73	36	100	dry
24 Aug 97	✔		Light	0.76	34	100	wet
2 Jul 97		✔	Light	0.06	6.4	25	dry
Site 2	*North-East quadrant*	*South-West quadrant*					
11 Oct 97 13:26:00	✔		Light	0.023	9.3	5	wet
15 Oct 97		✔	Light	0.025	12.9	3	wet

Figures

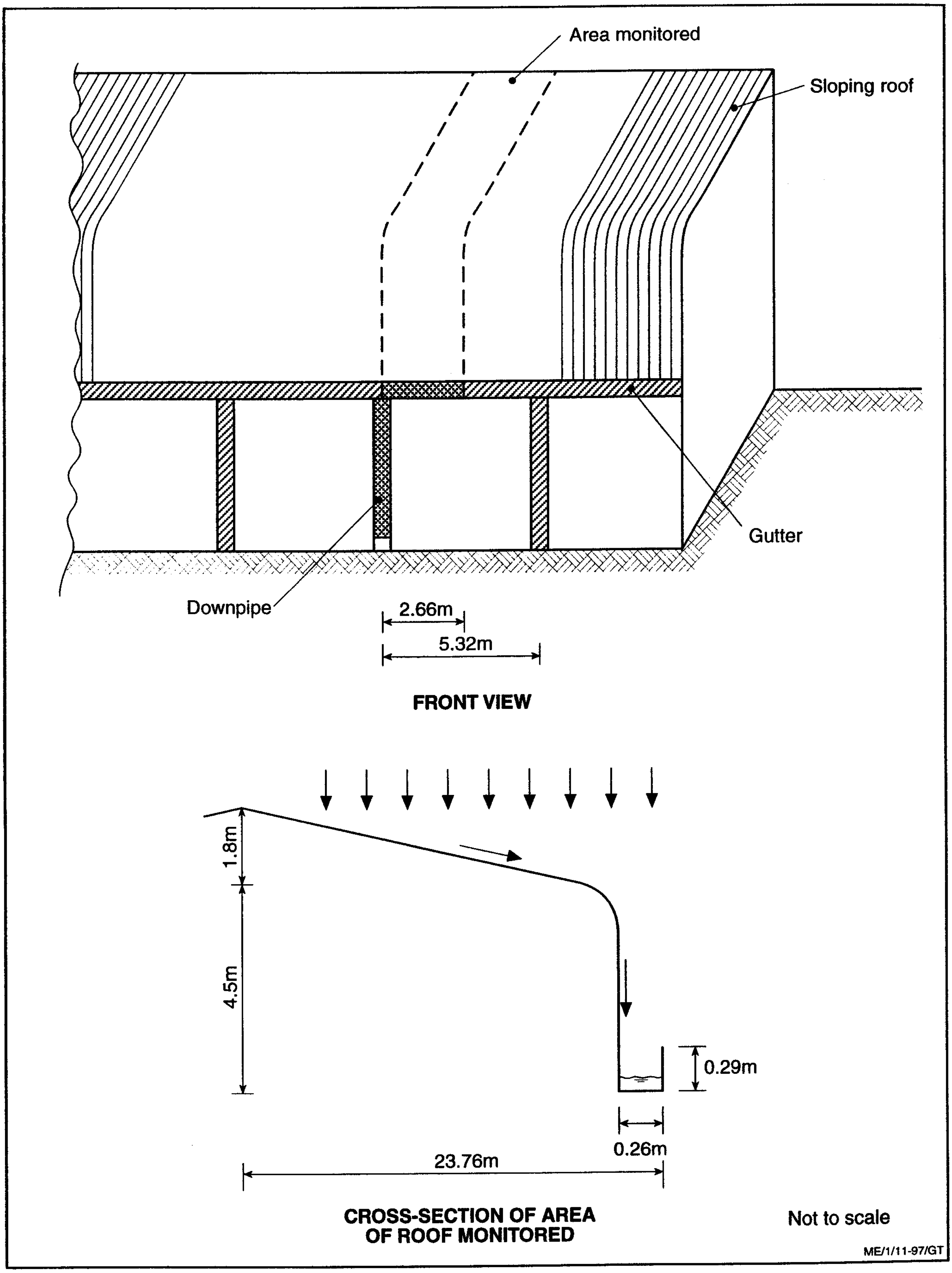


Figure 1 Site 1 - sloping roof.
Geometric characteristics of roof and area monitored

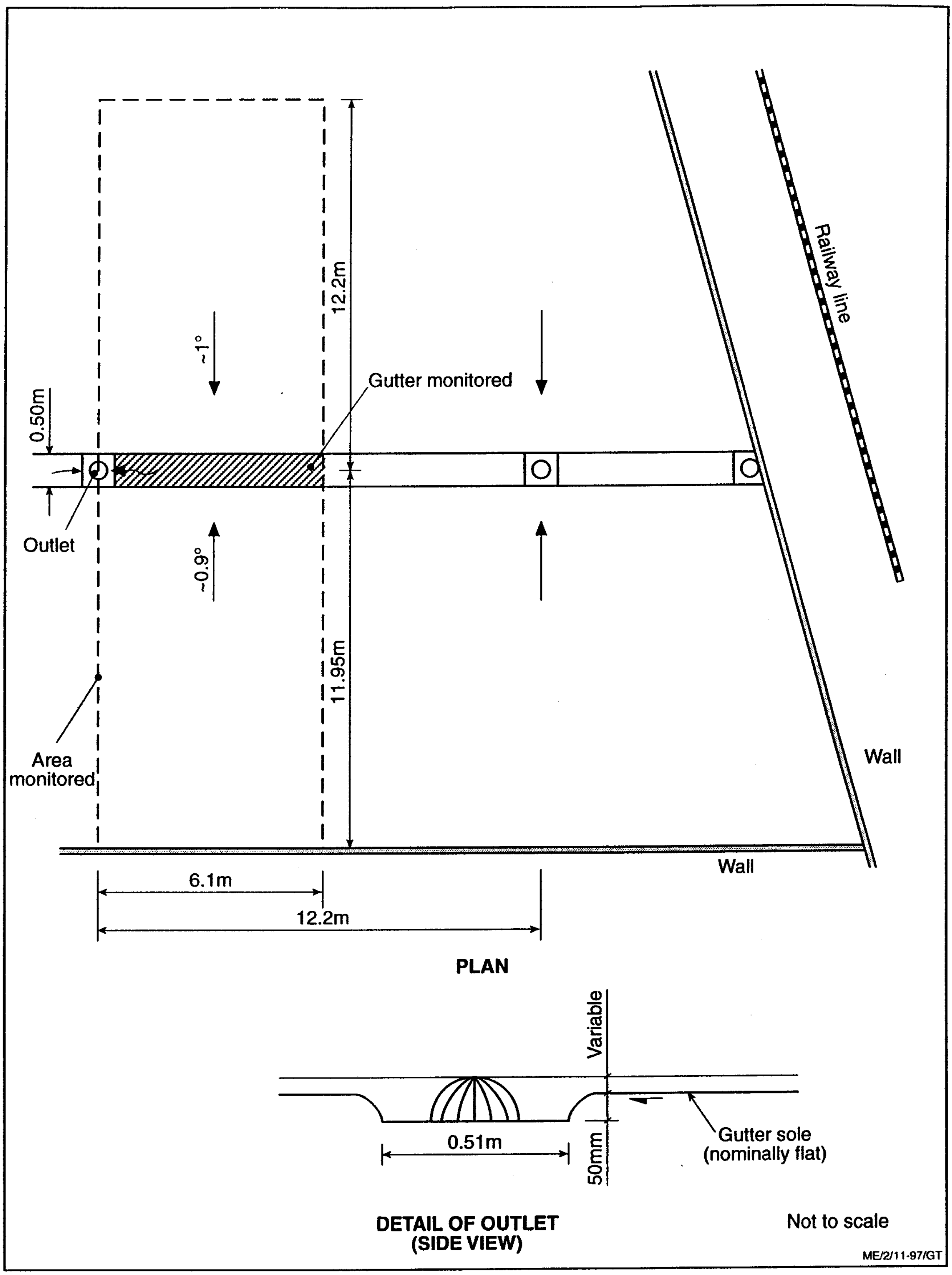
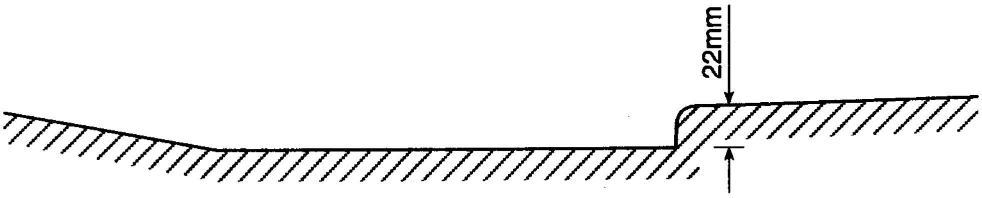
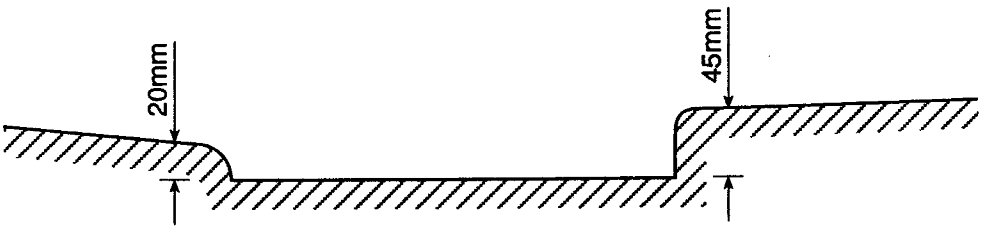


Figure 2 Site 2 - flat roof. Geometric characteristics of area monitored



a) Typical cross-section of gutter at upstream end (viewing upstream)



b) Typical cross-section of gutter at downstream end (viewing upstream)

ME/3/11-97/GT

Figure 3 Schematic examples of gutter cross-sections at Site 2

Storm 22 June 1997 15:50:00

06/22/97	15:50:00	A	101.16	101.79	2386.6	1
06/22/97	15:50:10	A	101.41	102.79	2389.4	0
06/22/97	15:50:20	A	102.02	103.84	2383.1	0
06/22/97	15:50:30	A	103.16	106.65	2386.9	0
06/22/97	15:50:40	A	105.65	108.53	2386.7	1
06/22/97	15:50:50	A	109.09	112	2385.9	0
06/22/97	15:51:00	A	110.76	116.43	2386.6	0
06/22/97	15:51:10	A	114.04	121.85	2388.9	0
06/22/97	15:51:20	A	115.47	119.47	2385.8	0
06/22/97	15:51:30	A	114	122.4	2384.8	1
06/22/97	15:51:40	A	112.07	124.05	2384.6	0
06/22/97	15:51:50	A	114.99	125.27	2384.8	1
06/22/97	15:52:00	A	118.33	123.89	2383.1	0
06/22/97	15:52:10	A	118.85	130.07	2370.6	0
06/22/97	15:52:20	A	121.77	127.69	2368.1	1
06/22/97	15:52:30	A	117.82	128.09	2366.1	0
06/22/97	15:52:40	A	115.74	126.07	2374.3	0
06/22/97	15:52:50	A	116.59	125.48	2381.3	0
06/22/97	15:53:00	A	115.31	124.3	2377.5	0
06/22/97	15:53:10	A	114.18	123.48	2380.9	0
06/22/97	15:53:20	A	112.53	120.62	2391.3	1
06/22/97	15:53:30	A	111.66	119.24	2391.3	0
06/22/97	15:53:40	A	108.23	117.51	2390.9	0
06/22/97	15:53:50	A	107.51	115.87	2391.1	0
06/22/97	15:54:00	A	106.56	115.58	2391.5	0
06/22/97	15:54:10	A	106.97	112.79	2391.3	0
06/22/97	15:54:20	A	104.81	112.43	2391.3	0
06/22/97	15:54:30	A	104.68	111.27	2392	0
06/22/97	15:54:40	A	104.13	109.92	2391	0
06/22/97	15:54:50	A	102.88	109.93	2390.5	0
06/22/97	15:55:00	A	103.11	108.88	2391	0
06/22/97	15:55:10	A	102.11	108.79	2391.6	0
06/22/97	15:55:20	A	101.71	108.84	2391.7	0
06/22/97	15:55:30	A	101.39	108.25	2388.6	0
06/22/97	15:55:40	A	101.35	108.78	2385.3	0
06/22/97	15:55:50	A	101.55	106.63	2385.7	0
06/22/97	15:56:00	A	101.3	107.3	2385.1	0
06/22/97	15:56:10	A	100.18	106.81	2385.2	0
06/22/97	15:56:20	A	101.2	107.13	2385.3	0
06/22/97	15:56:30	A	100.91	106.52	2385.8	0
06/22/97	15:56:40	A	100.59	105.56	2384.9	1
06/22/97	15:56:50	A	99.676	105.72	2384.8	0
06/22/97	15:57:00	A	99.35	104.91	2384.8	0
06/22/97	15:57:10	A	99.148	105.97	2385.1	0
06/22/97	15:57:20	A	99.561	104.62	2384.8	0
06/22/97	15:57:30	A	99.002	104.92	2385.5	0
06/22/97	15:57:40	A	99.18	104.76	2385.3	0
06/22/97	15:57:50	A	99.918	104.62	2391.3	0
06/22/97	15:58:00	A	98.473	104.56	2390.9	0
06/22/97	15:58:10	A	99.191	104.16	2391.6	0
06/22/97	15:58:20	A	98.367	103.78	2390.7	0
06/22/97	15:58:30	A	98.178	104.03	2388.8	0
06/22/97	15:58:40	A	98.199	102.79	2391.1	0
06/22/97	15:58:50	A	98.516	103.63	2390.6	0
06/22/97	15:59:00	A	98.559	102.66	2390.9	0
06/22/97	15:59:10	A	98.41	102.66	2391.9	0
06/22/97	15:59:20	A	98.398	102.98	2390.8	0
06/22/97	15:59:30	A	97.461	103.05	2391.9	0
06/22/97	15:59:40	A	97.818	102.47	2391.7	0
06/22/97	15:59:50	A	96.807	102.2	2391.4	0
06/22/97	16:00:00	A	97.123	102	2391.9	0
06/22/97	16:00:10	A	97.135	102.06	2391.1	0
06/22/97	16:00:20	A	96.648	101.42	2391.3	0
06/22/97	16:00:30	A	96.701	101.52	2390.4	0
06/22/97	16:00:40	A	96.541	101.34	2390.1	0

Figure 4 Example of data collected at Site 1

Tower Bridge 12 sept 97
12:18:00

12/09/97	12:18:00 A	81.807	30.813	35.119	1
12/09/97	12:18:10 A	83.111	34.418	36.106	0
12/09/97	12:18:20 A	87.732	36.019	36.563	0
12/09/97	12:18:30 A	90.229	37.018	36.996	1
12/09/97	12:18:40 A	96.586	35.83	37.584	0
12/09/97	12:18:50 A	102.54	37.317	37.916	0
12/09/97	12:19:00 A	106.87	37.584	37.694	0
12/09/97	12:19:10 A	125.15	38.115	36.896	1
12/09/97	12:19:20 A	123.6	41.308	37.971	0
12/09/97	12:19:30 A	124.32	39.962	38.026	0
12/09/97	12:19:40 A	126.47	40.249	37.517	0
12/09/97	12:19:50 A	126.22	38.568	37.805	0
12/09/97	12:20:00 A	121.4	37.251	37.417	0
12/09/97	12:20:10 A	119.54	36.207	36.384	0
12/09/97	12:20:20 A	119.34	35.341	36.974	0
12/09/97	12:20:30 A	116.02	34.708	36.607	1
12/09/97	12:20:40 A	115.35	34.44	35.563	0
12/09/97	12:20:50 A	111.5	34.964	36.073	0
12/09/97	12:21:00 A	110.11	33.805	35.907	0
12/09/97	12:21:10 A	109.14	33.314	34.307	0
12/09/97	12:21:20 A	106.73	32.278	33.816	0
12/09/97	12:21:30 A	105.46	31.541	33.626	0
12/09/97	12:21:40 A	101.57	30.315	33.236	0
12/09/97	12:21:50 A	100.43	29.252	33.191	0
12/09/97	12:22:00 A	99.539	27.562	32.98	0
12/09/97	12:22:10 A	97.92	27.632	32.813	0
12/09/97	12:22:20 A	98.895	26.725	33.515	1
12/09/97	12:22:30 A	97.719	25.756	32.97	0
12/09/97	12:22:40 A	95.775	26.76	32.857	0
12/09/97	12:22:50 A	94.74	26.245	32.624	0
12/09/97	12:23:00 A	95.246	25.01	32.11	0
12/09/97	12:23:10 A	94.07	24.4	33.014	0
12/09/97	12:23:20 A	93.461	24.898	33.081	0
12/09/97	12:23:30 A	91.076	24.158	33.069	0
12/09/97	12:23:40 A	90.73	23.503	32.657	0
12/09/97	12:23:50 A	90.516	23.449	32.857	0
12/09/97	12:24:00 A	91.221	22.718	32.779	0
12/09/97	12:24:10 A	89.127	22.534	32.913	0
12/09/97	12:24:20 A	88.82	22.203	32.813	0
12/09/97	12:24:30 A	90.852	22.502	33.437	0
12/09/97	12:24:40 A	91.025	22.163	32.256	0
12/09/97	12:24:50 A	89.383	21.458	32.813	0
12/09/97	12:25:00 A	87.836	22.606	32.69	0
12/09/97	12:25:10 A	88.646	21.575	32.412	0
12/09/97	12:25:20 A	86.998	21.603	32.378	1
12/09/97	12:25:30 A	86.967	21.579	33.292	0
12/09/97	12:25:40 A	91.199	21.831	32.925	0
12/09/97	12:25:50 A	90.842	22.498	34.084	0
12/09/97	12:26:00 A	91.689	22.526	32.69	0
12/09/97	12:26:10 A	90.617	23.474	33.648	0
12/09/97	12:26:20 A	88.871	22.394	33.236	0
12/09/97	12:26:30 A	88.031	22.271	32.435	0
12/09/97	12:26:40 A	87.65	21.724	32.624	0
12/09/97	12:26:50 A	87.537	21.931	32.713	0
12/09/97	12:27:00 A	87.131	21.357	32.166	0
12/09/97	12:27:10 A	86.125	21.967	32.612	0
12/09/97	12:27:20 A	87.162	21.665	32.144	1
12/09/97	12:27:30 A	86.125	21.828	32.077	0
12/09/97	12:27:40 A	86.094	22.498	32.412	0
12/09/97	12:27:50 A	85.641	22.536	32.4	0
12/09/97	12:28:00 A	85.59	21.99	32.49	0
12/09/97	12:28:10 A	85.92	21.357	32.668	0
12/09/97	12:28:20 A	85.98	21.029	32.188	0
12/09/97	12:28:30 A	85.498	20.855	32.267	0
12/09/97	12:28:40 A	84.982	21.004	31.865	0
12/09/97	12:28:50 A	84.754	20.761	31.731	0
12/09/97	12:29:00 A	84.713	20.756	31.965	0
12/09/97	12:29:10 A	84.275	20.56	32.032	0
12/09/97	12:29:20 A	84.951	19.558	30.847	0
12/09/97	12:29:30 A	83.916	19.803	31.574	0
12/09/97	12:29:40 A	83.307	19.825	30.947	0
12/09/97	12:29:50 A	82.719	19.453	32.032	0
12/09/97	12:30:00 A	82.449	18.976	31.395	0
12/09/97	12:30:10 A	82.521	18.873	31.608	0
12/09/97	12:30:20 A	82.625	18.858	31.216	0
12/09/97	12:30:30 A	83.627	18.056	30.824	0
12/09/97	12:30:40 A	82.531	17.962	30.813	0
12/09/97	12:30:50 A	81.723	18.189	31.171	0
12/09/97	12:31:00 A	81.588	18.185	31.395	0
12/09/97	12:31:10 A	81.318	17.7	31.474	0
12/09/97	12:31:20 A	82.854	17.111	30.181	0

Figure 5 Example of data collected at Site 2

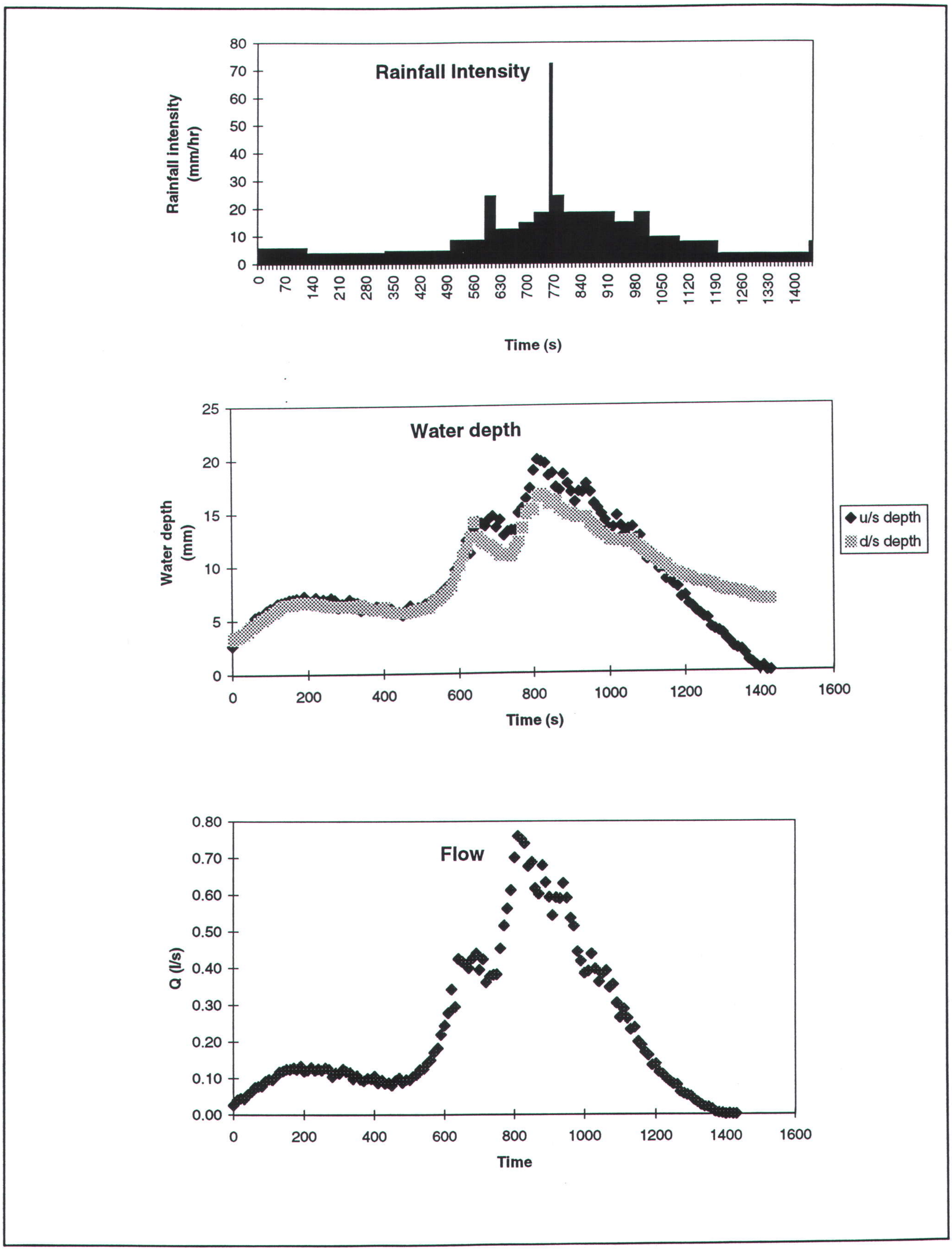
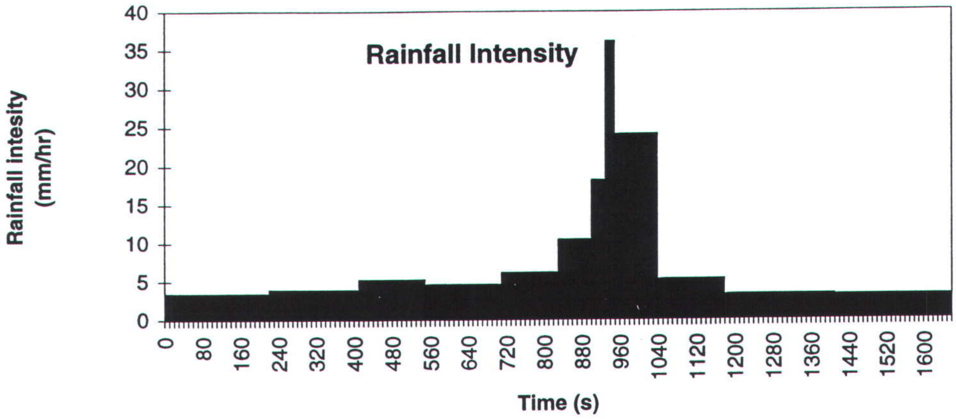
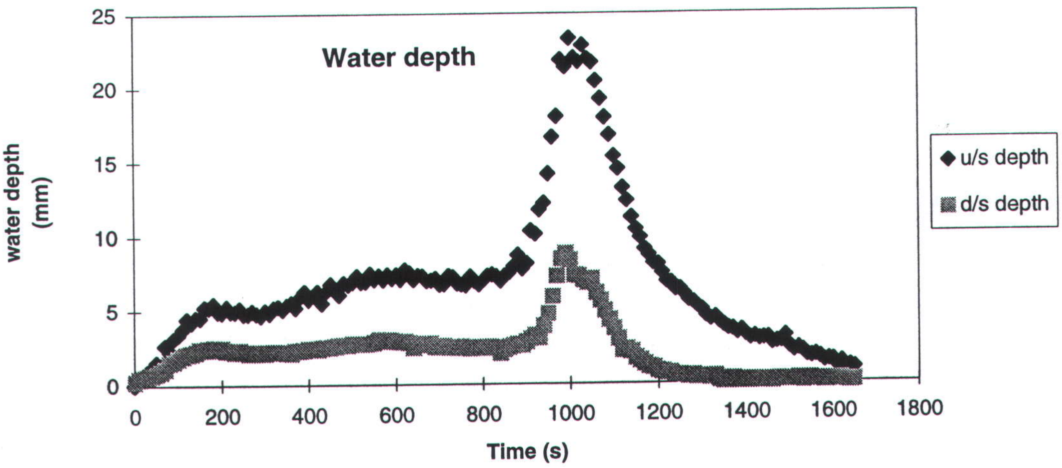


Figure 6 Site 1
Storm of 4 Nov 96, 04:44:10





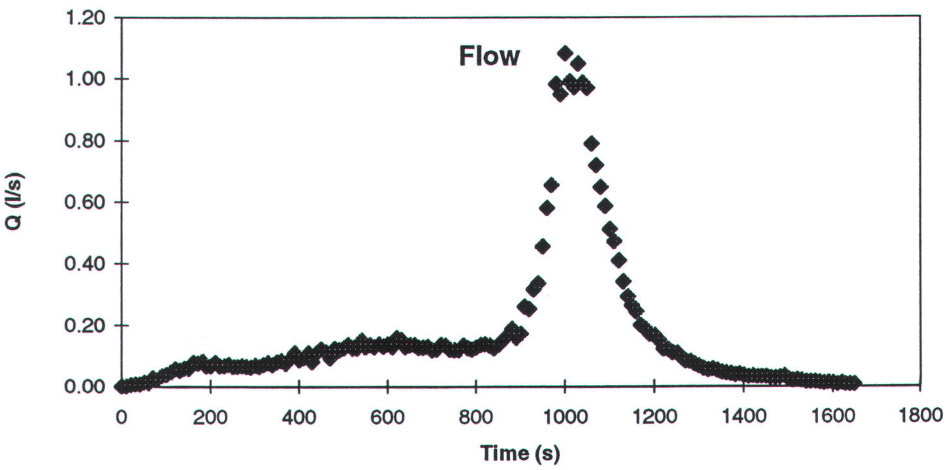


Figure 7 **Site 1**
Storm of 4 Nov 96, 05:22:50

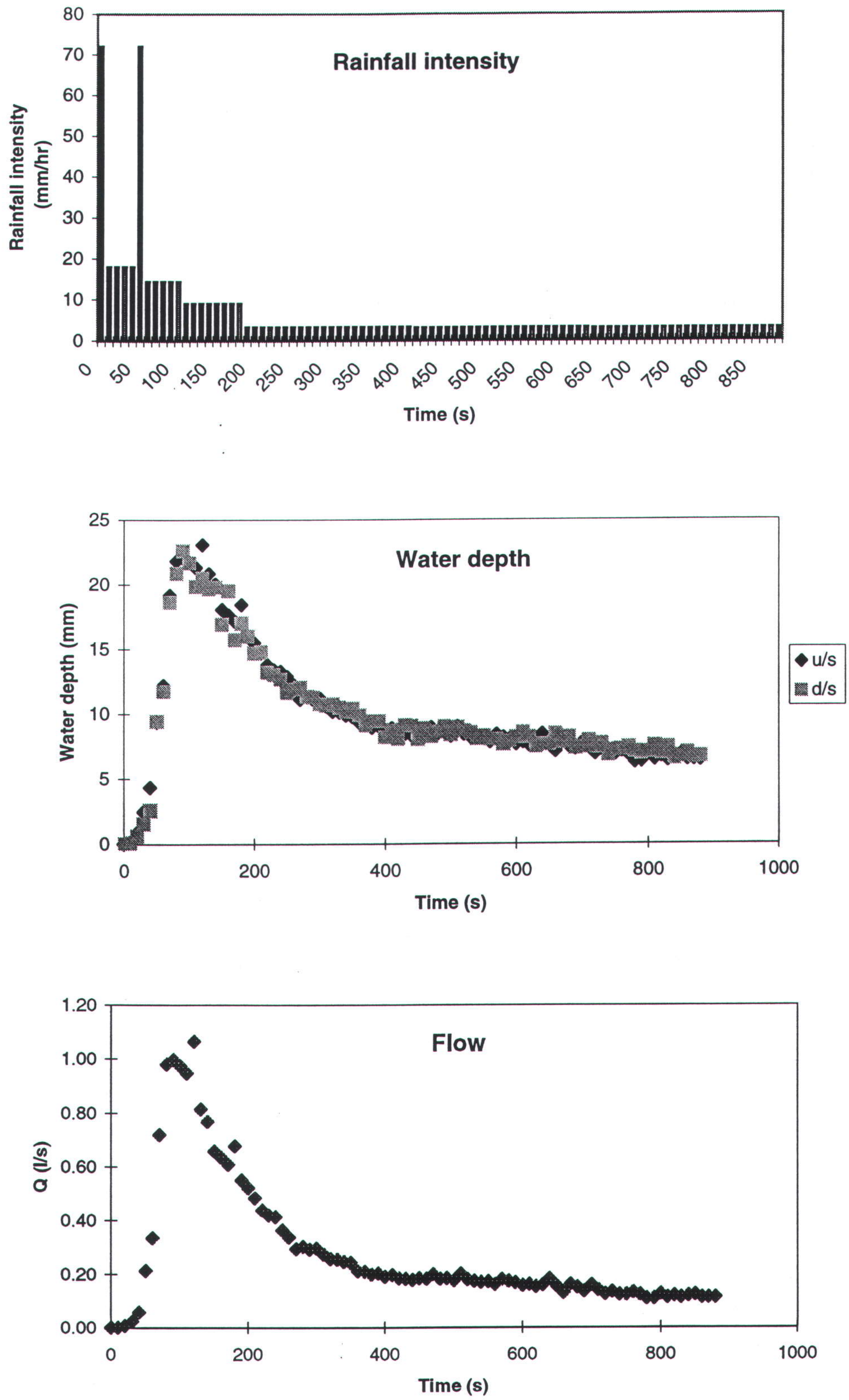


Figure 8 **Site 1**
Storm of 18 Feb 97, 05:32:10

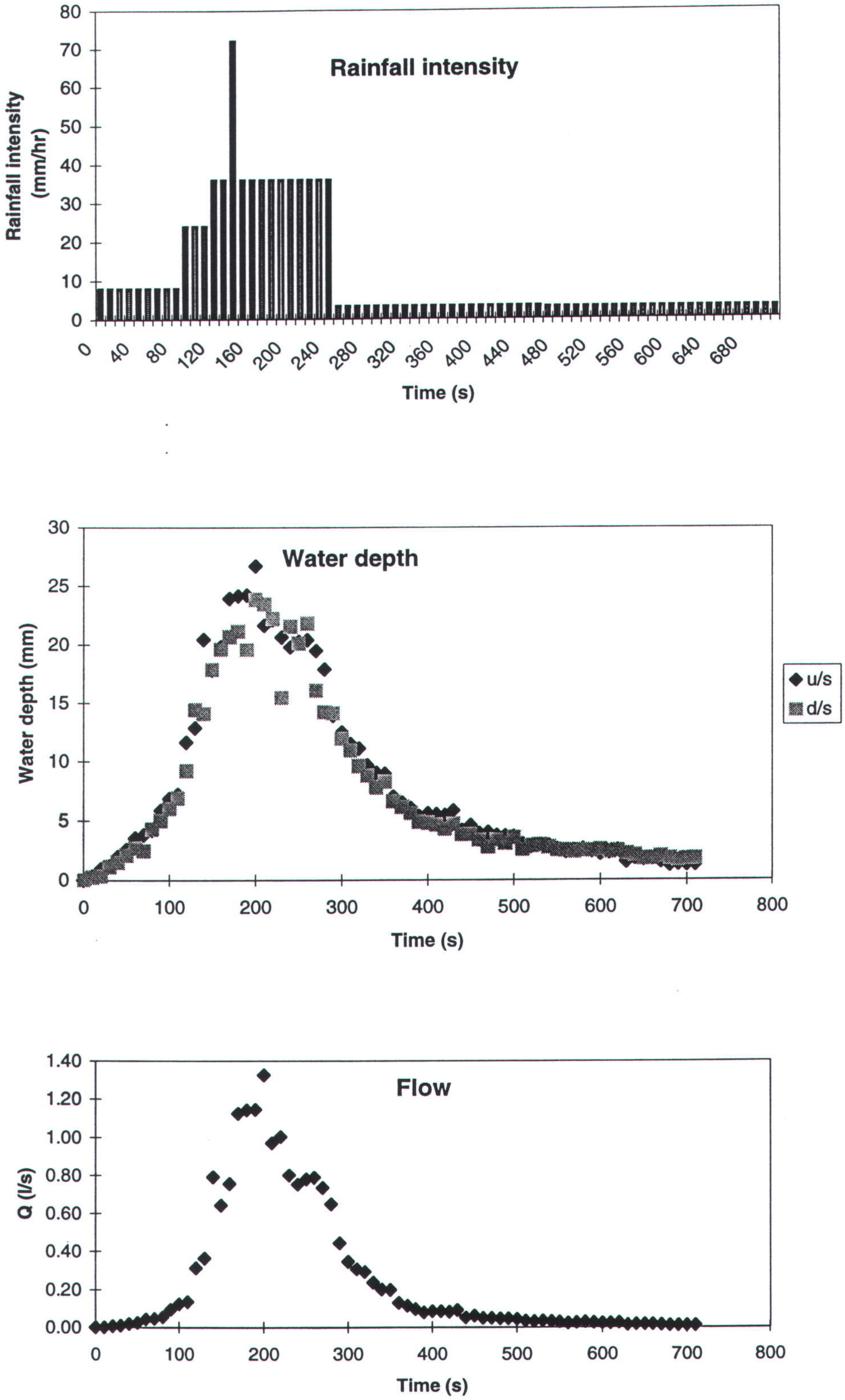


Figure 9 **Site 1**
Storm of 24 Feb 97, 20:52:30

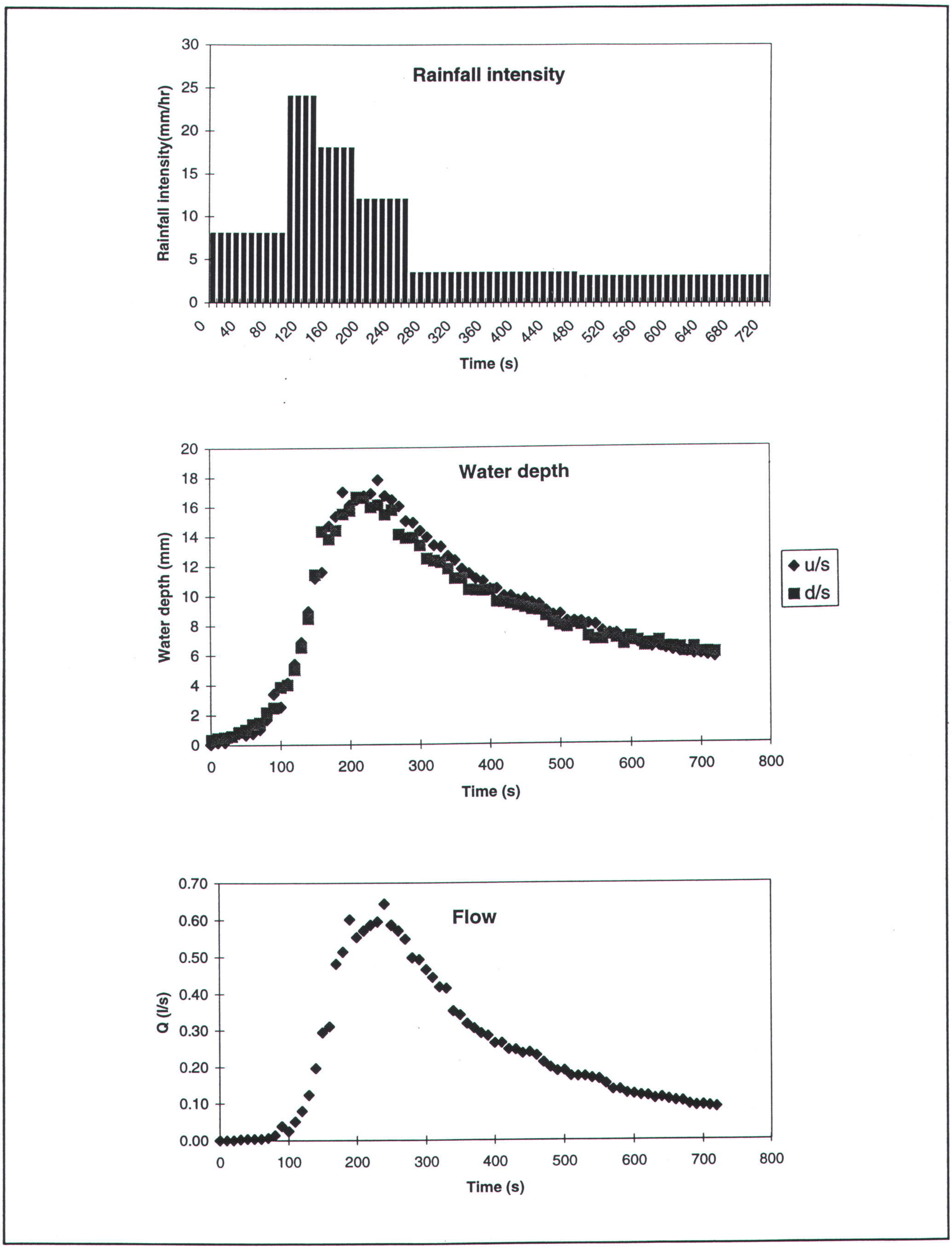


Figure 10 Site 1
Storm of 26 Feb 97, 01:28:30

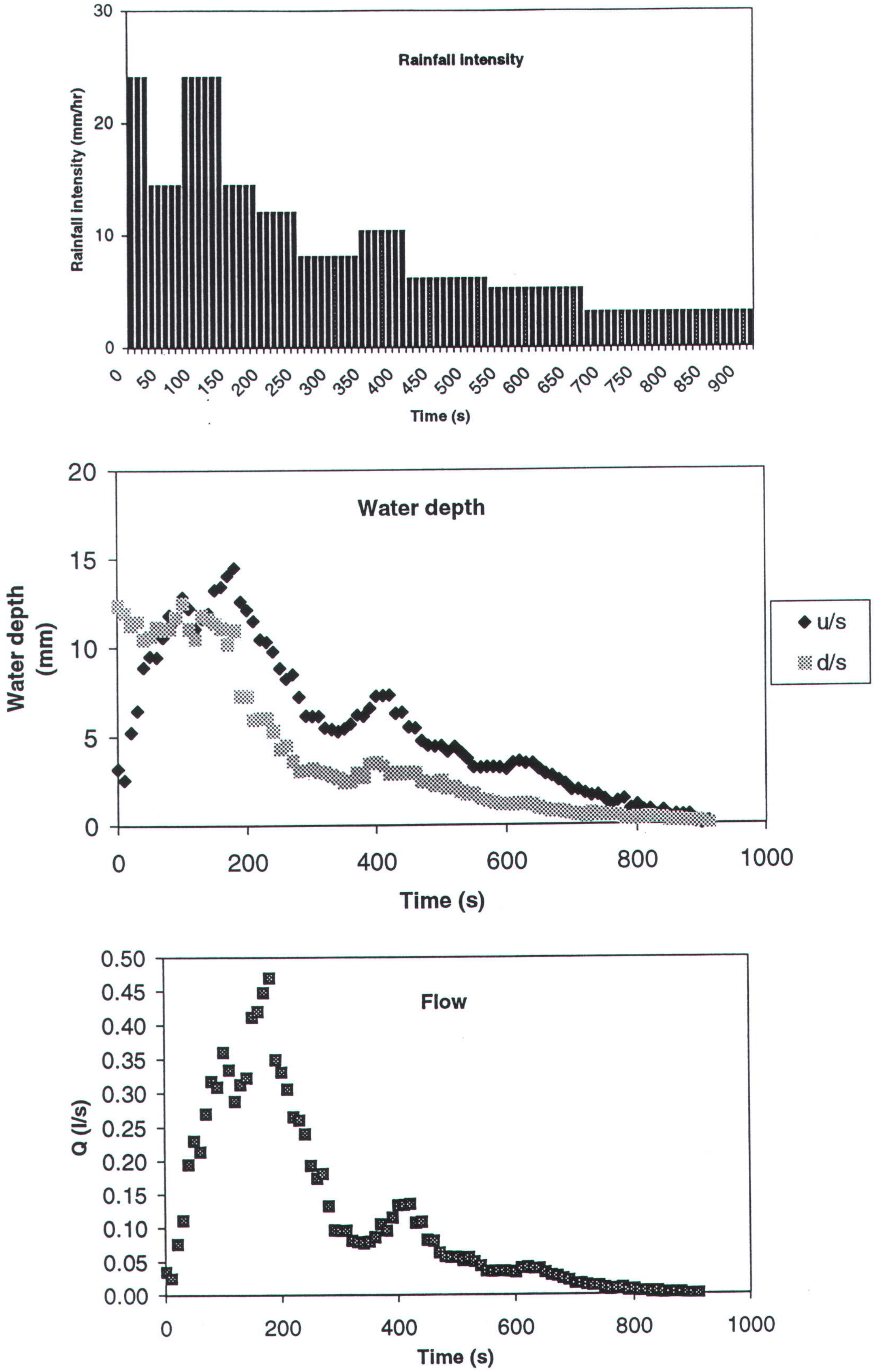


Figure 11 Site 1
Storm of 6 Jun 97, 19:28:00

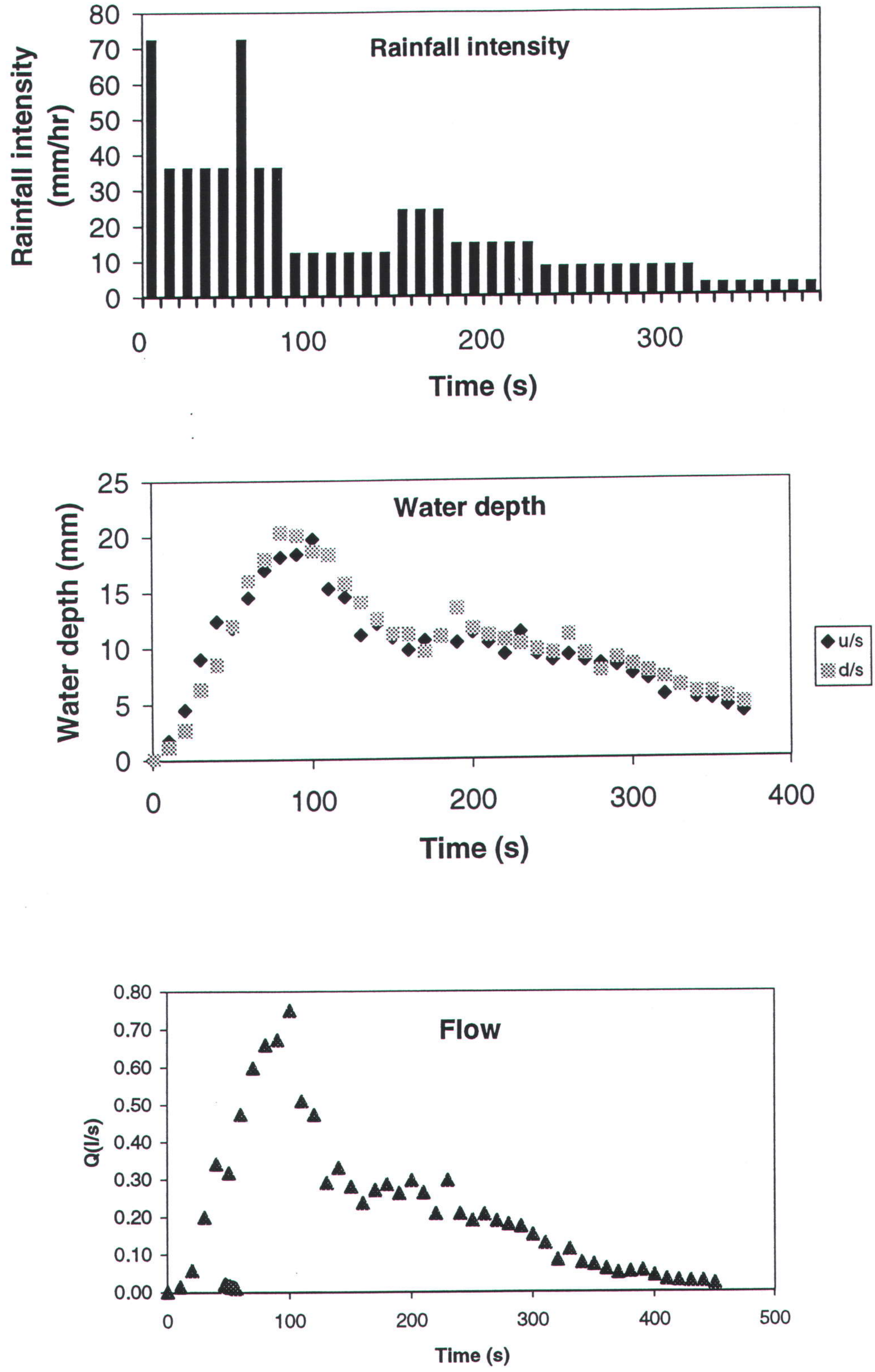


Figure 12 **Site 1**
Storm of 21 Jun 97, 13:49:00

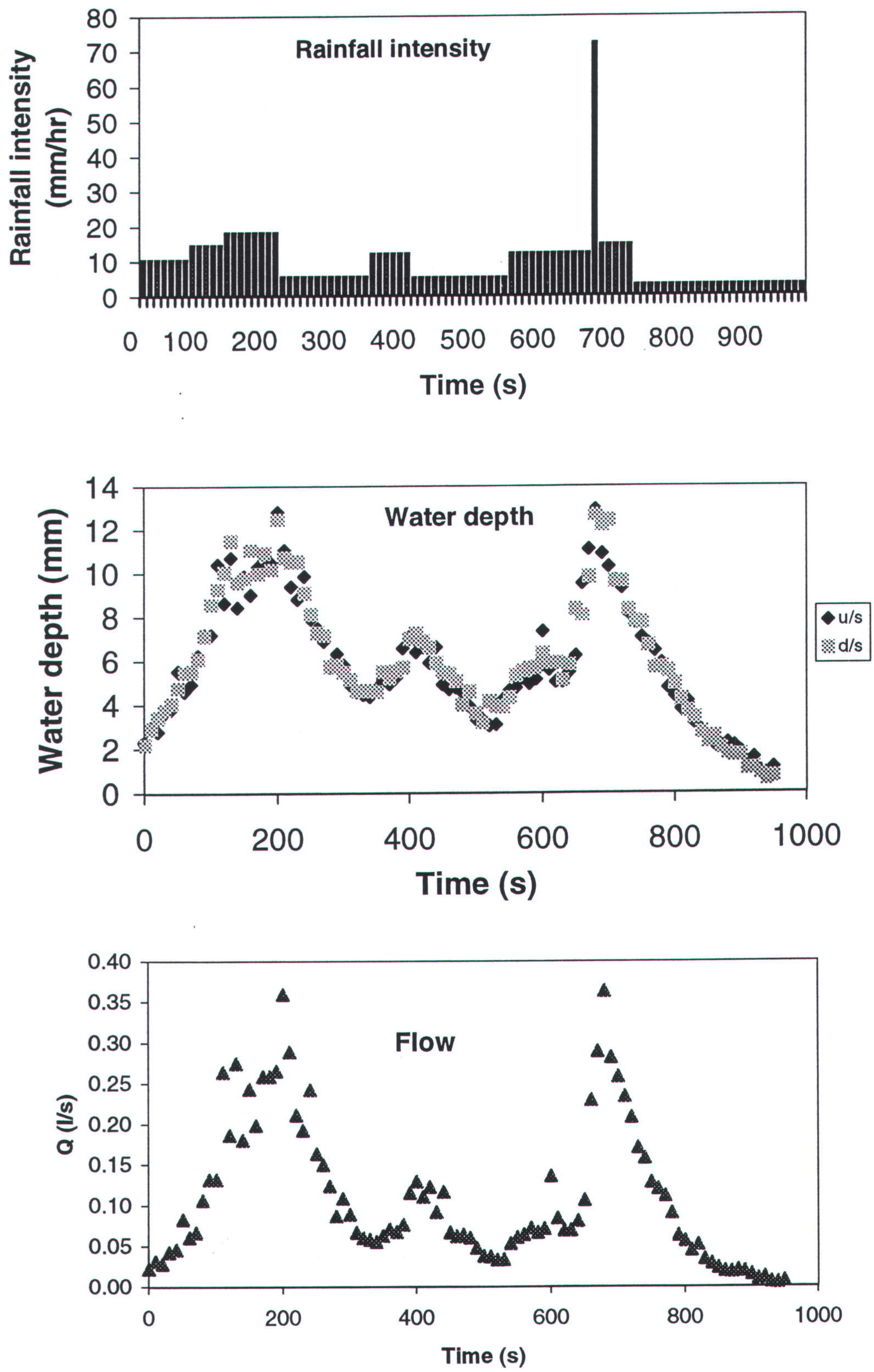


Figure 13 **Site 1**
Storm of 22 Jun 97, 08:46:00

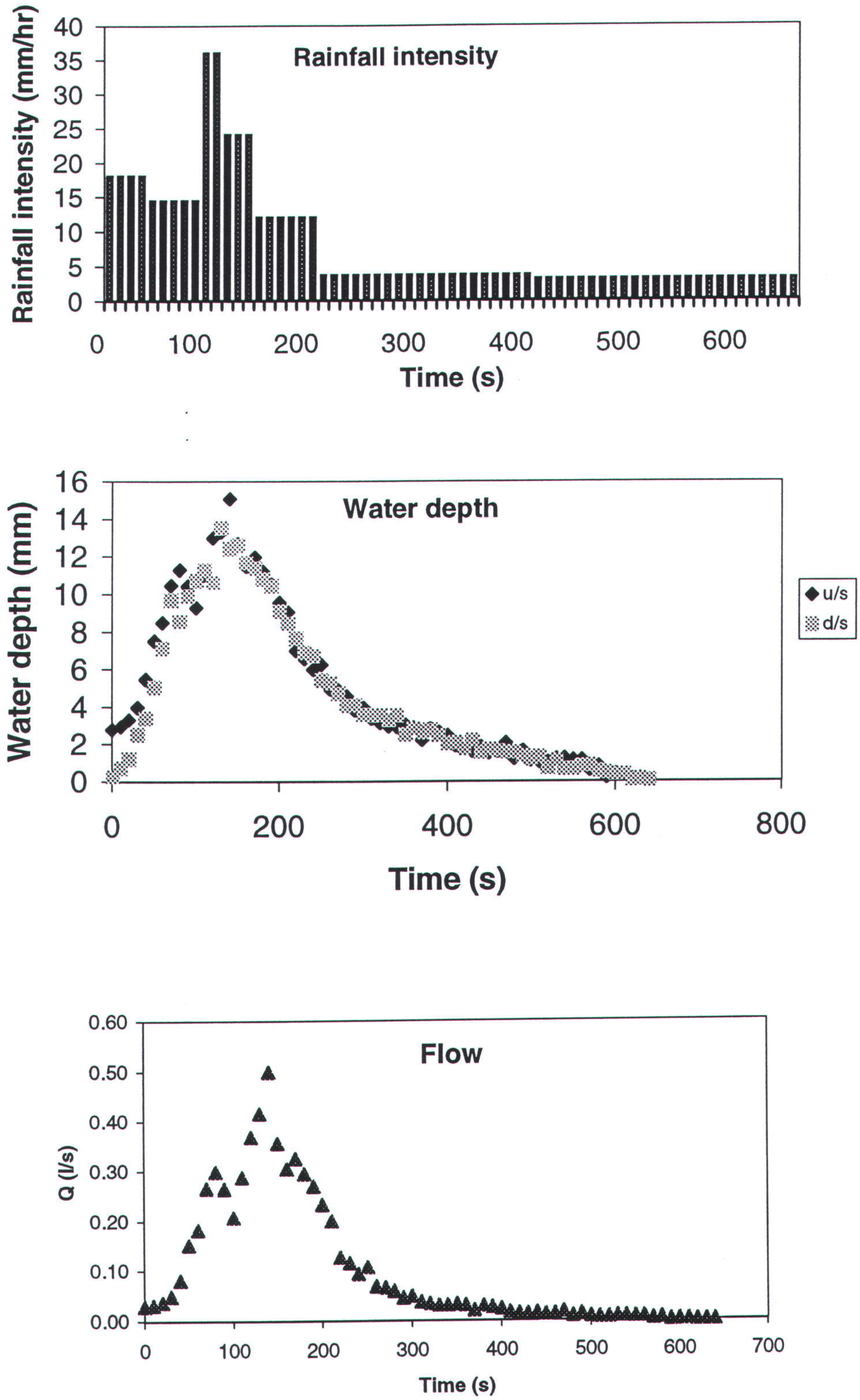


Figure 14 **Site 1**
Storm of 22 Jun 97, 15:50:00

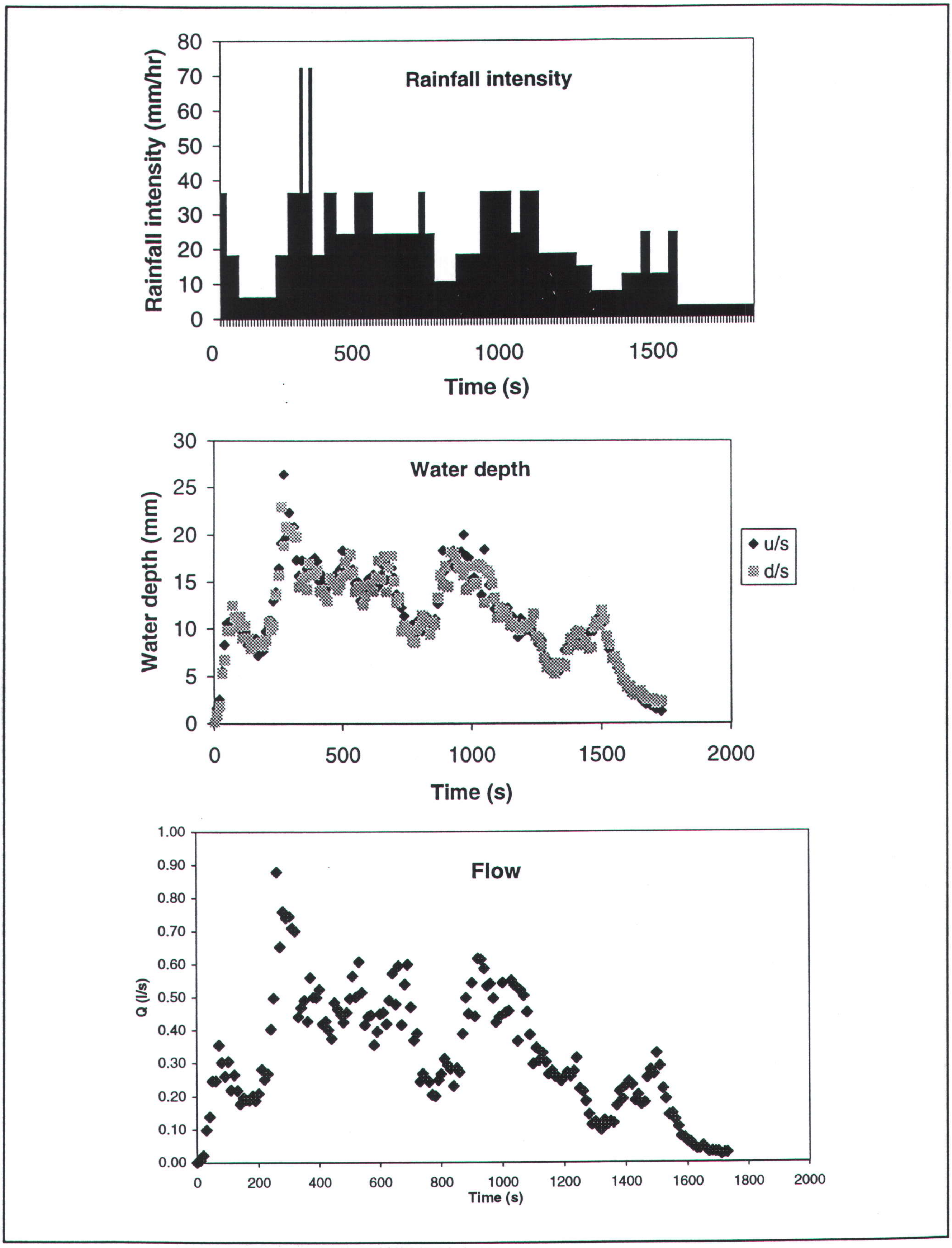


Figure 15 **Site 1**
Storm of 26 Jul 97, 15:40:50

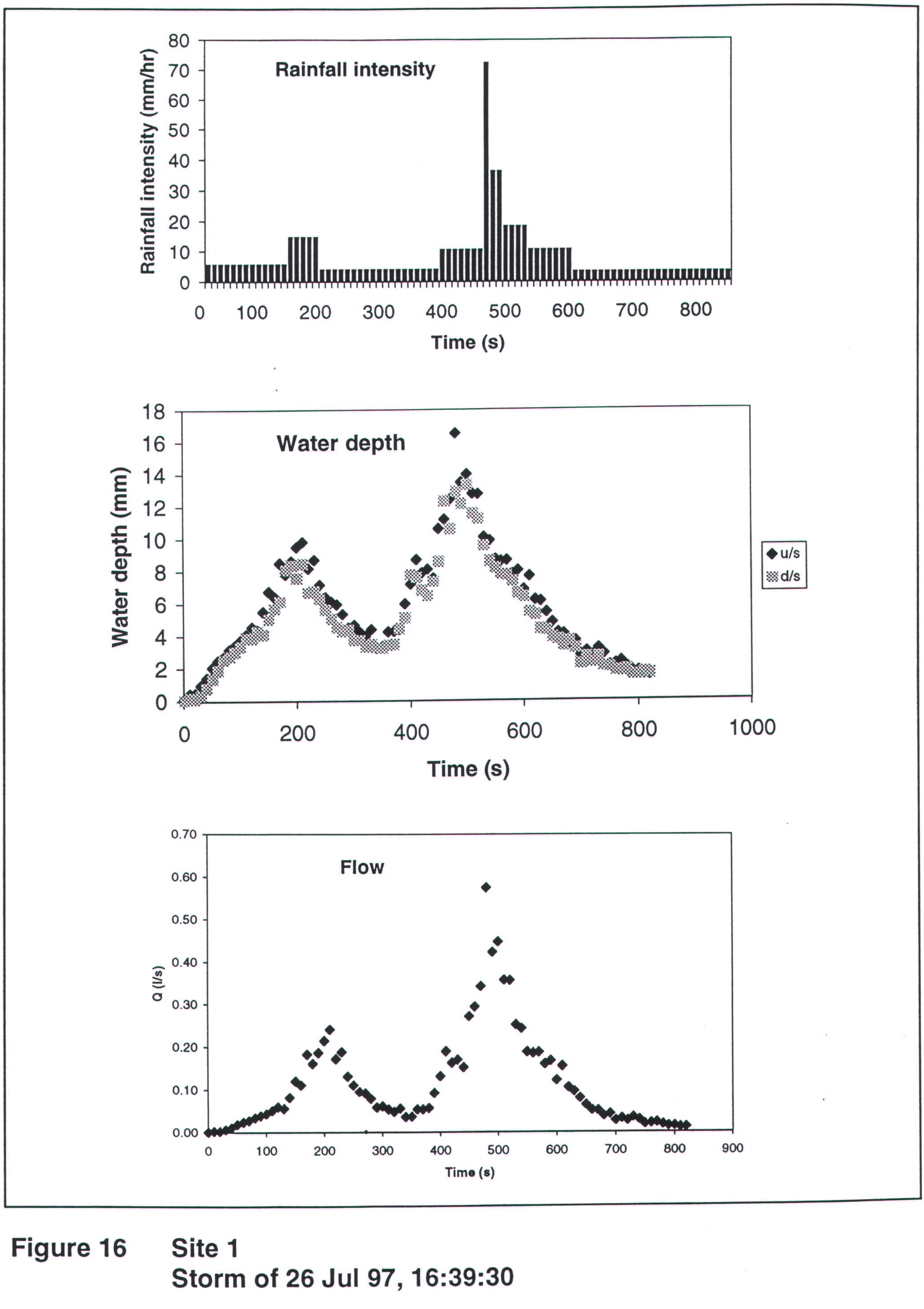


Figure 16 **Site 1**
Storm of 26 Jul 97, 16:39:30

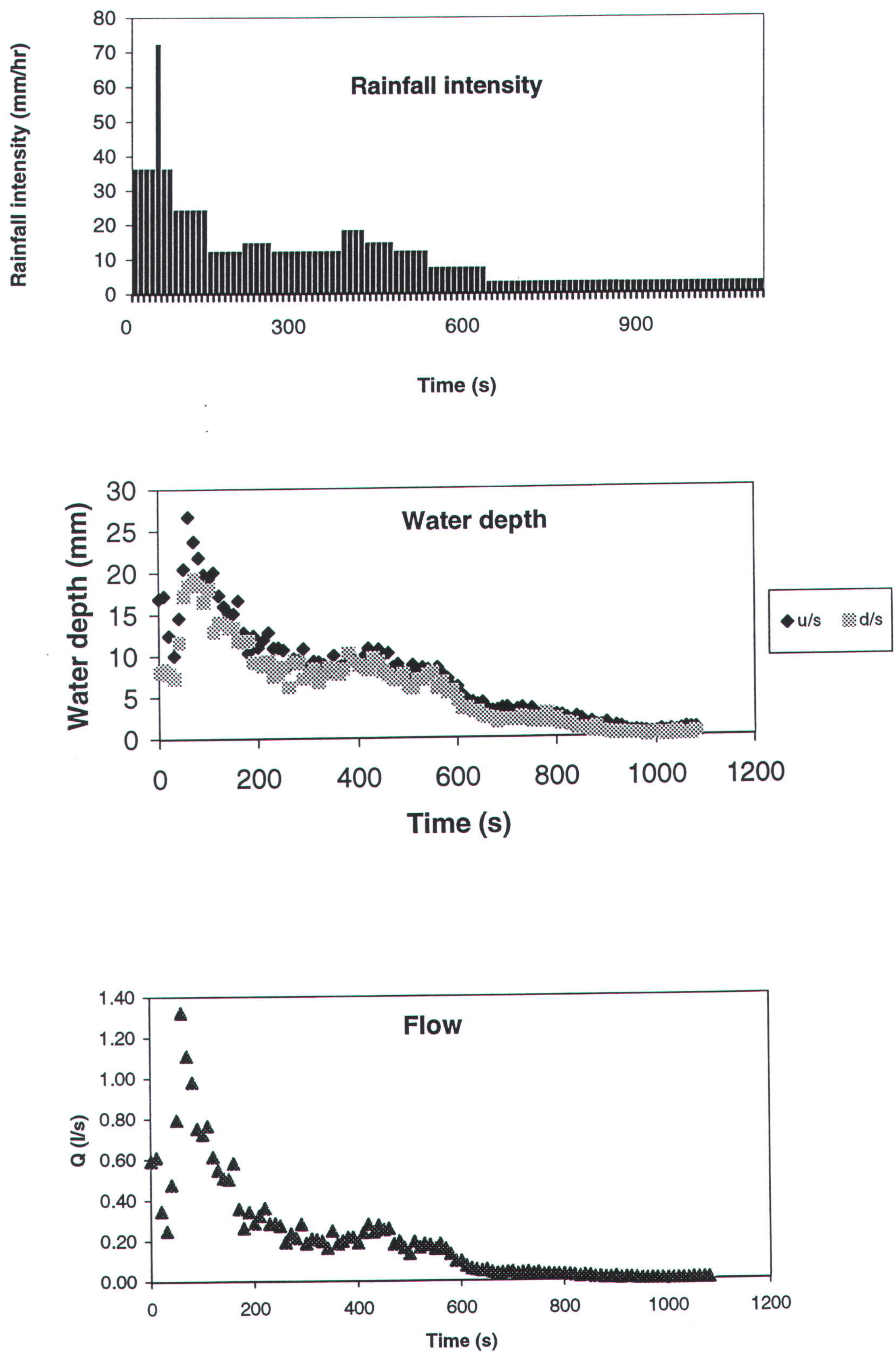


Figure 17 **Site 1**
Storm of 24 Aug 97, 17:32:50

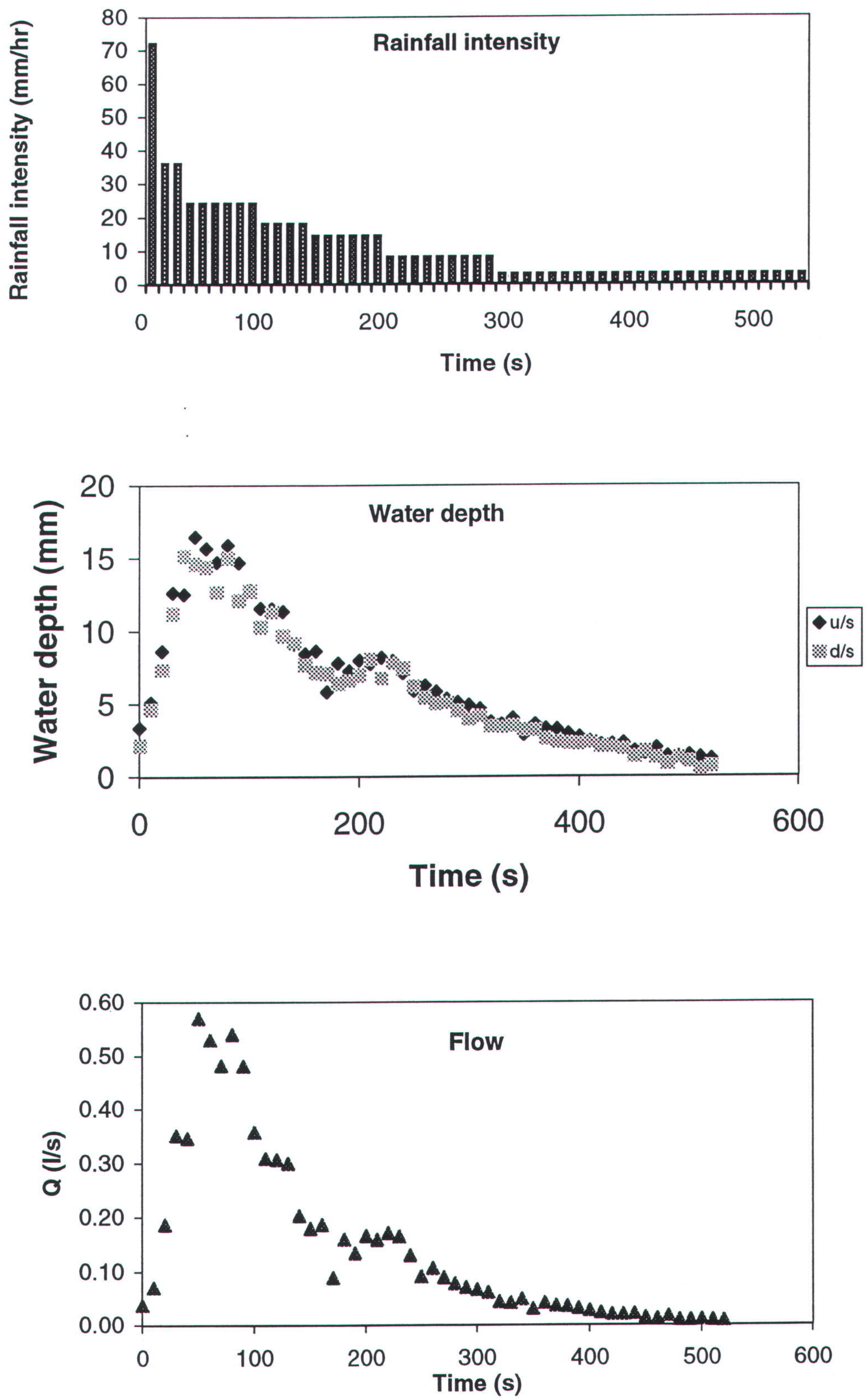


Figure 18 Site 1
Storm of 25 Aug 97, 11:25:10

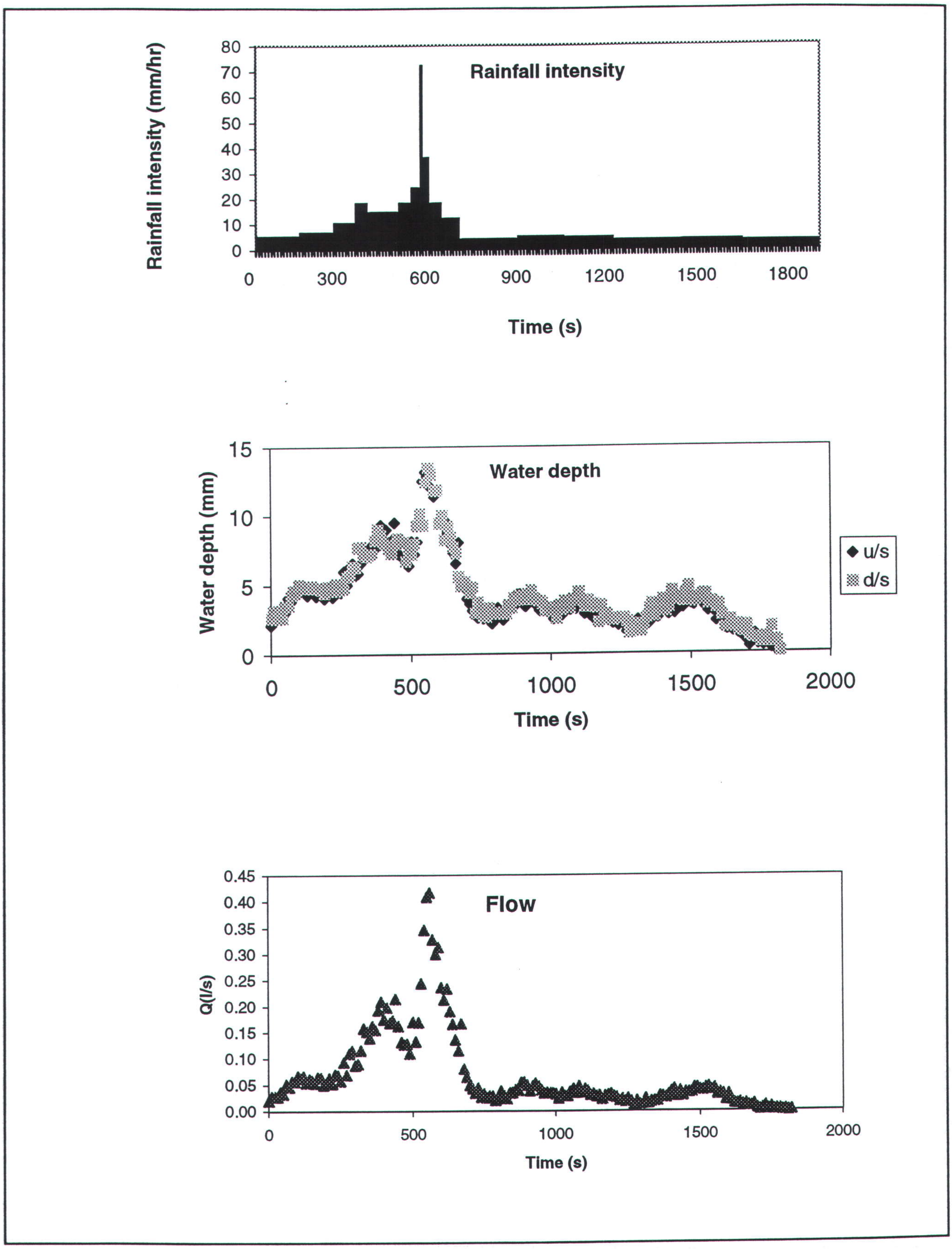


Figure 19 Site 1
Storm of 30 Aug 97, 03:09:20

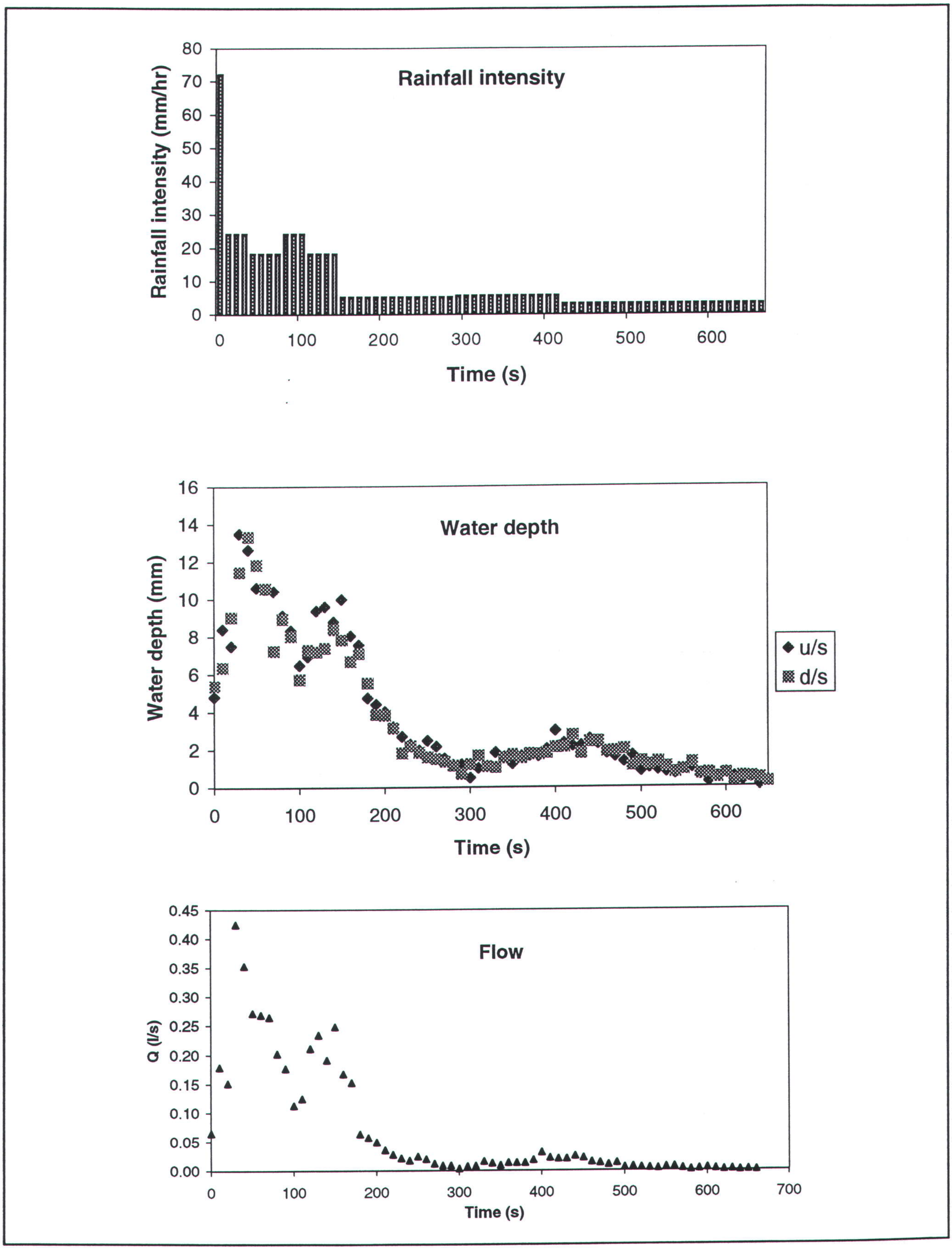
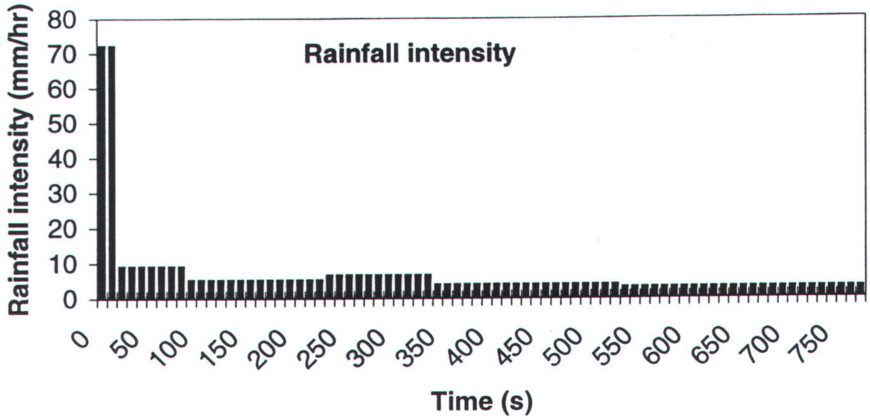
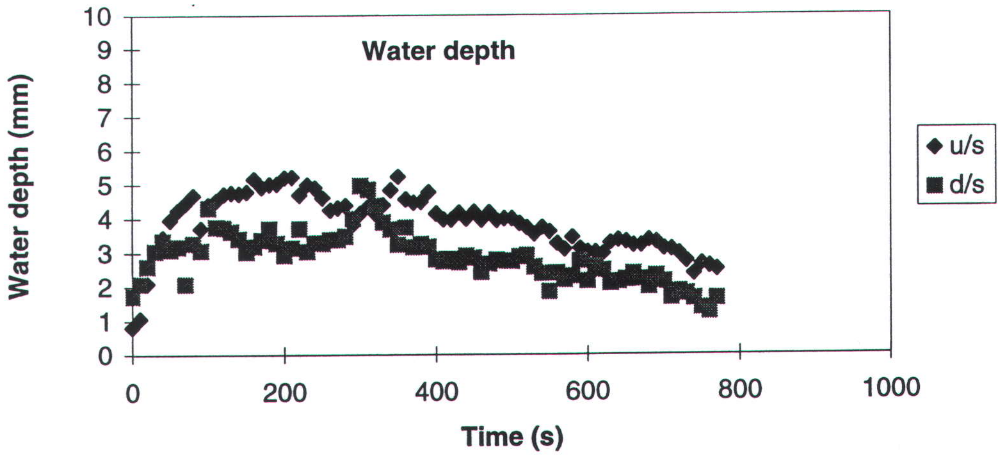


Figure 20 Site 1
Storm of 9 Oct 97, 21:50:40





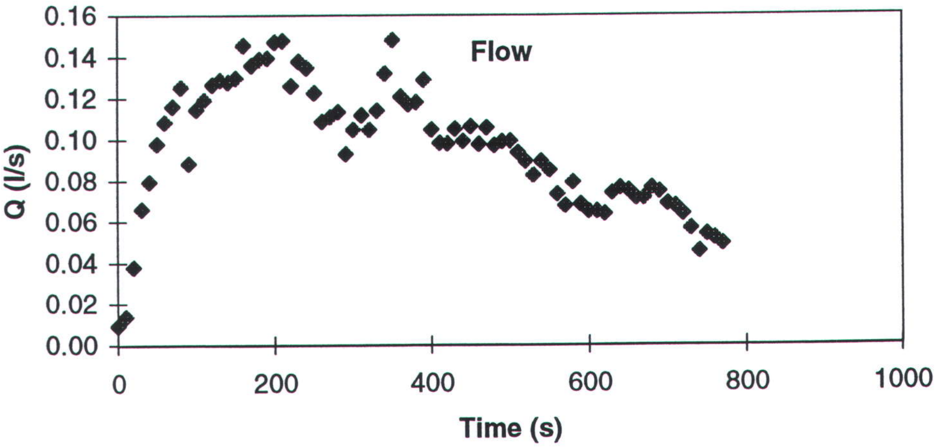


Figure 21 **Site 2**
Storm of 10 Feb 97, 13:23:30

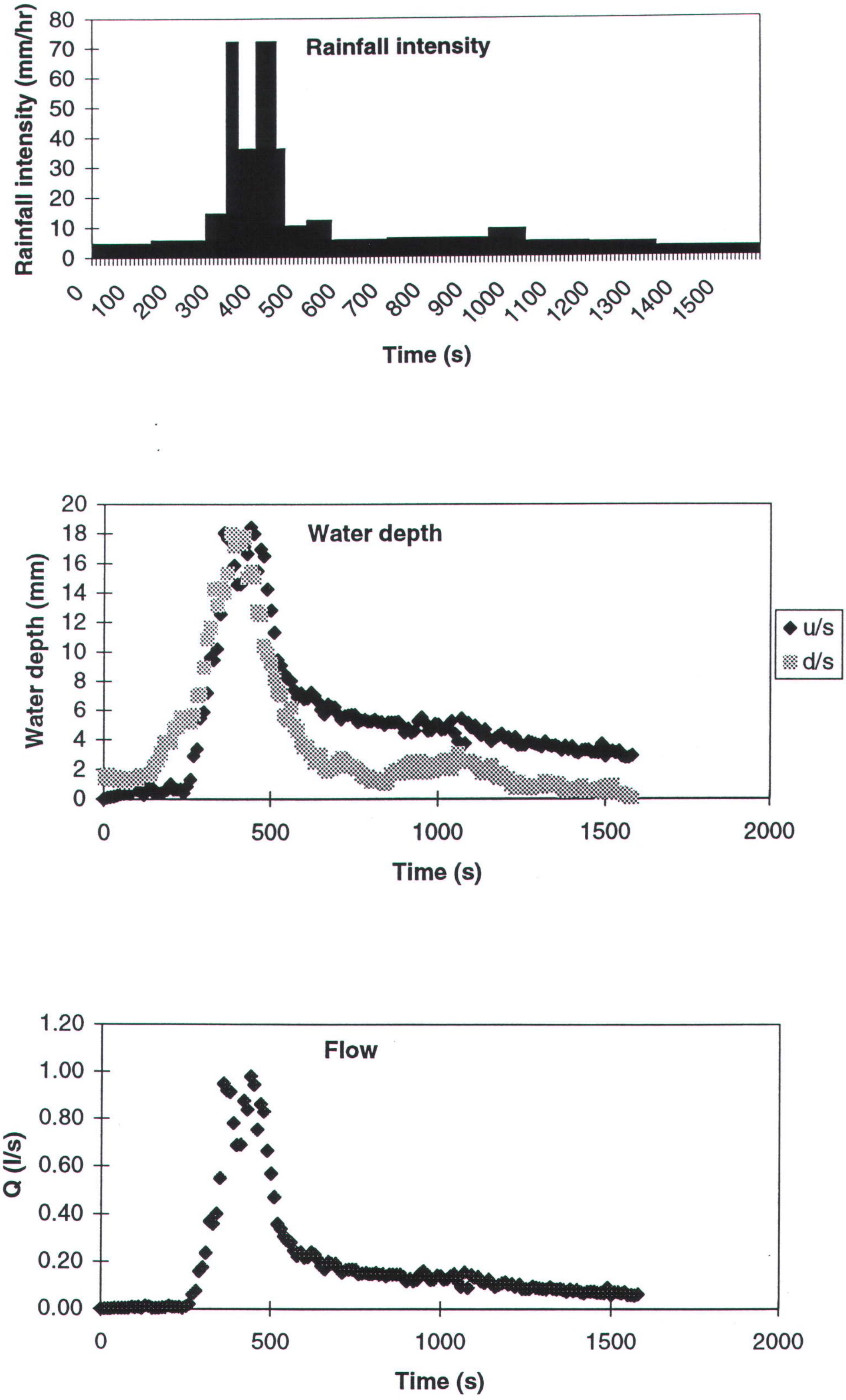


Figure 22 Site 2
Storm of 18 Feb 97, 06:32:40

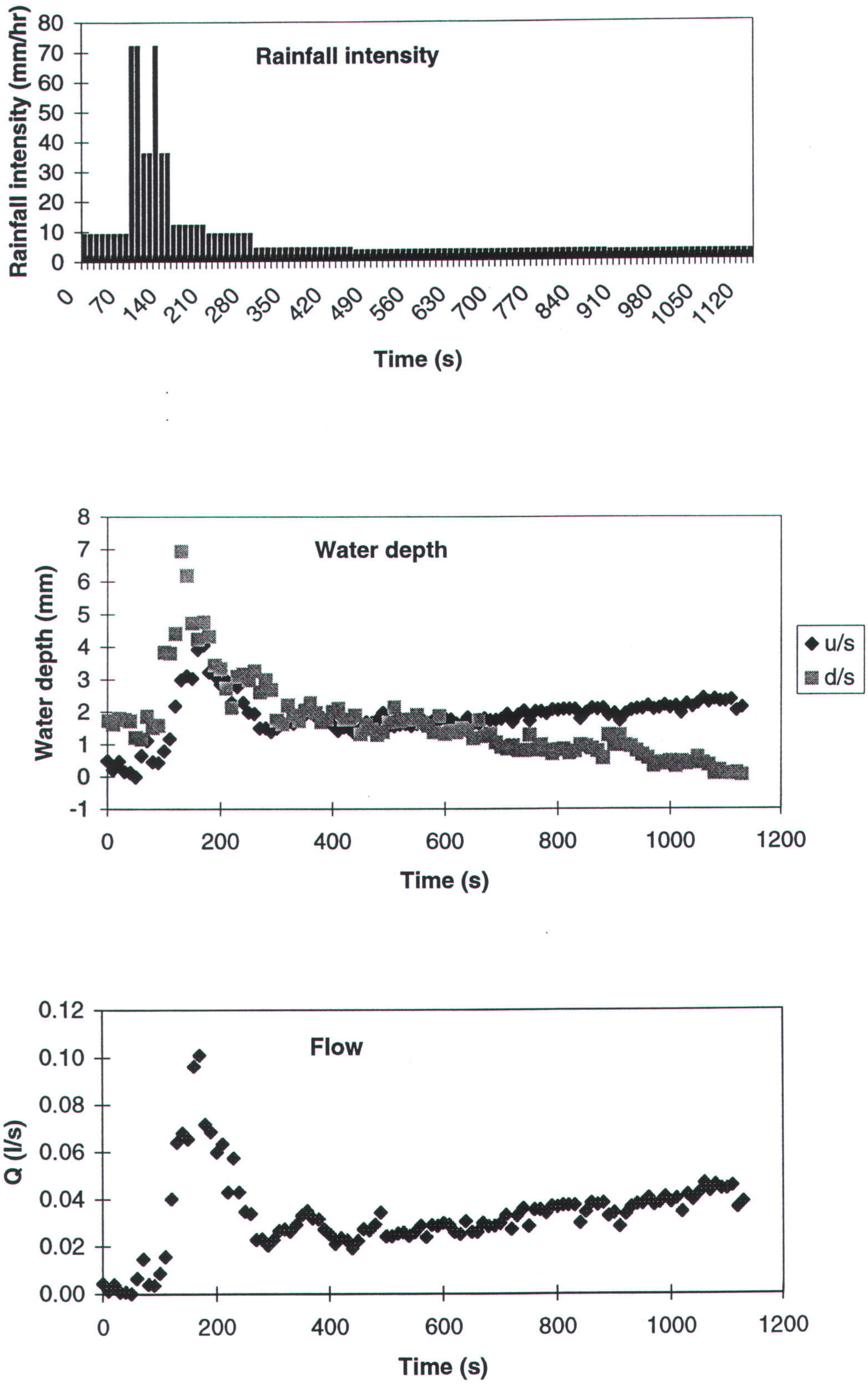


Figure 23 Site 2
Storm of 24 Feb 97, 02:02:40

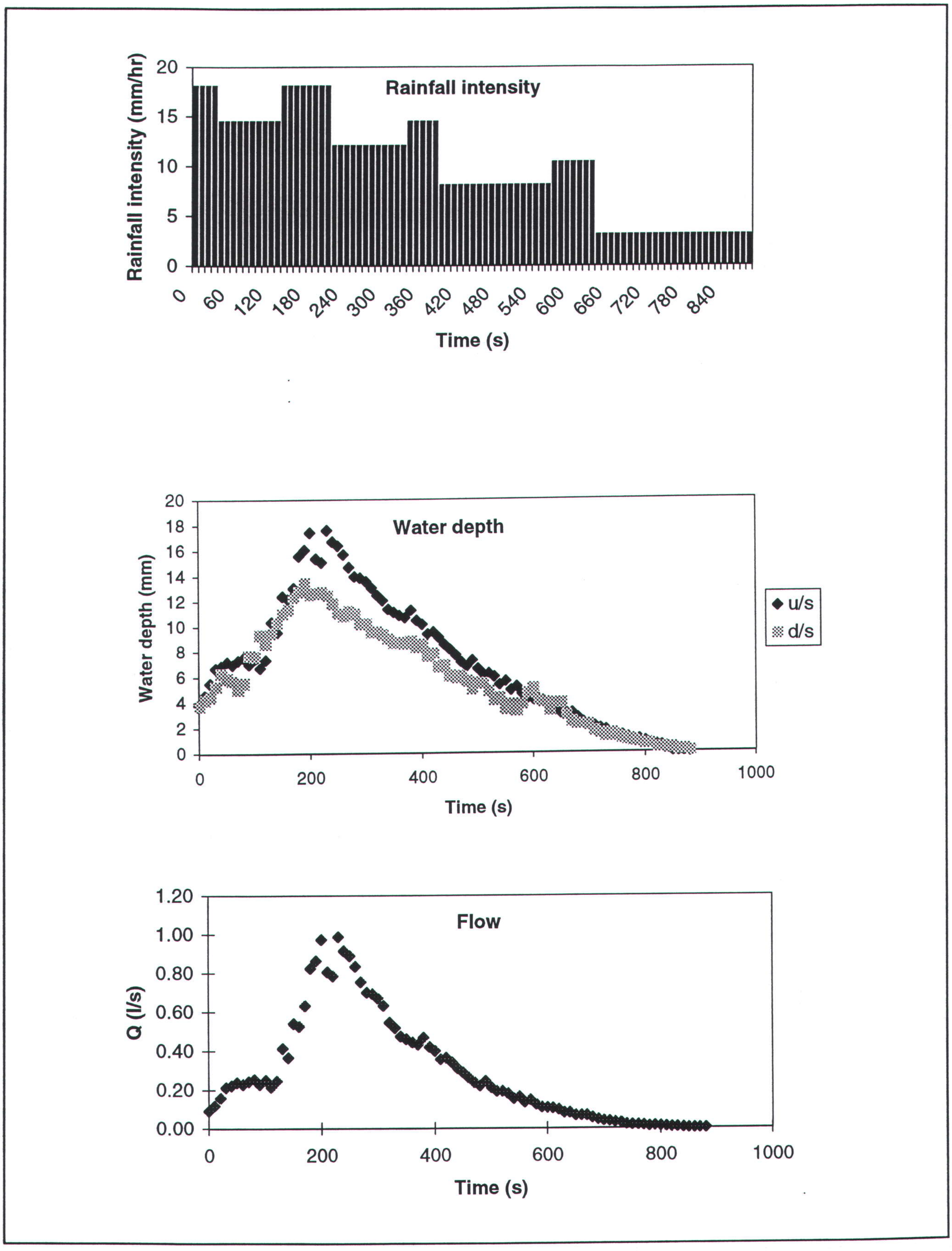


Figure 24 Site 2
Storm of 5 May 97, 20:14:00

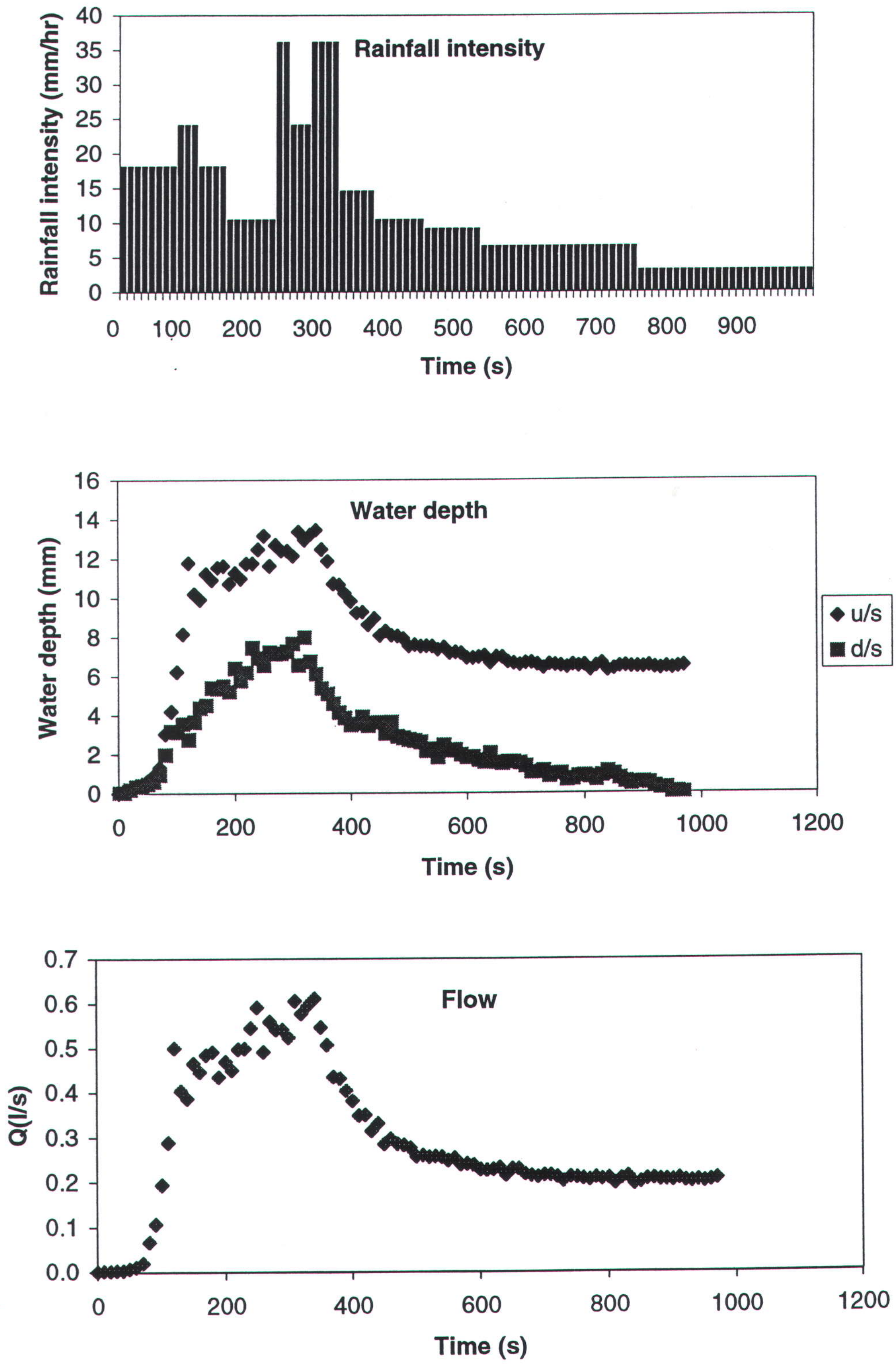


Figure 25 Site 2
Storm of 9 May 97, 16:05:00

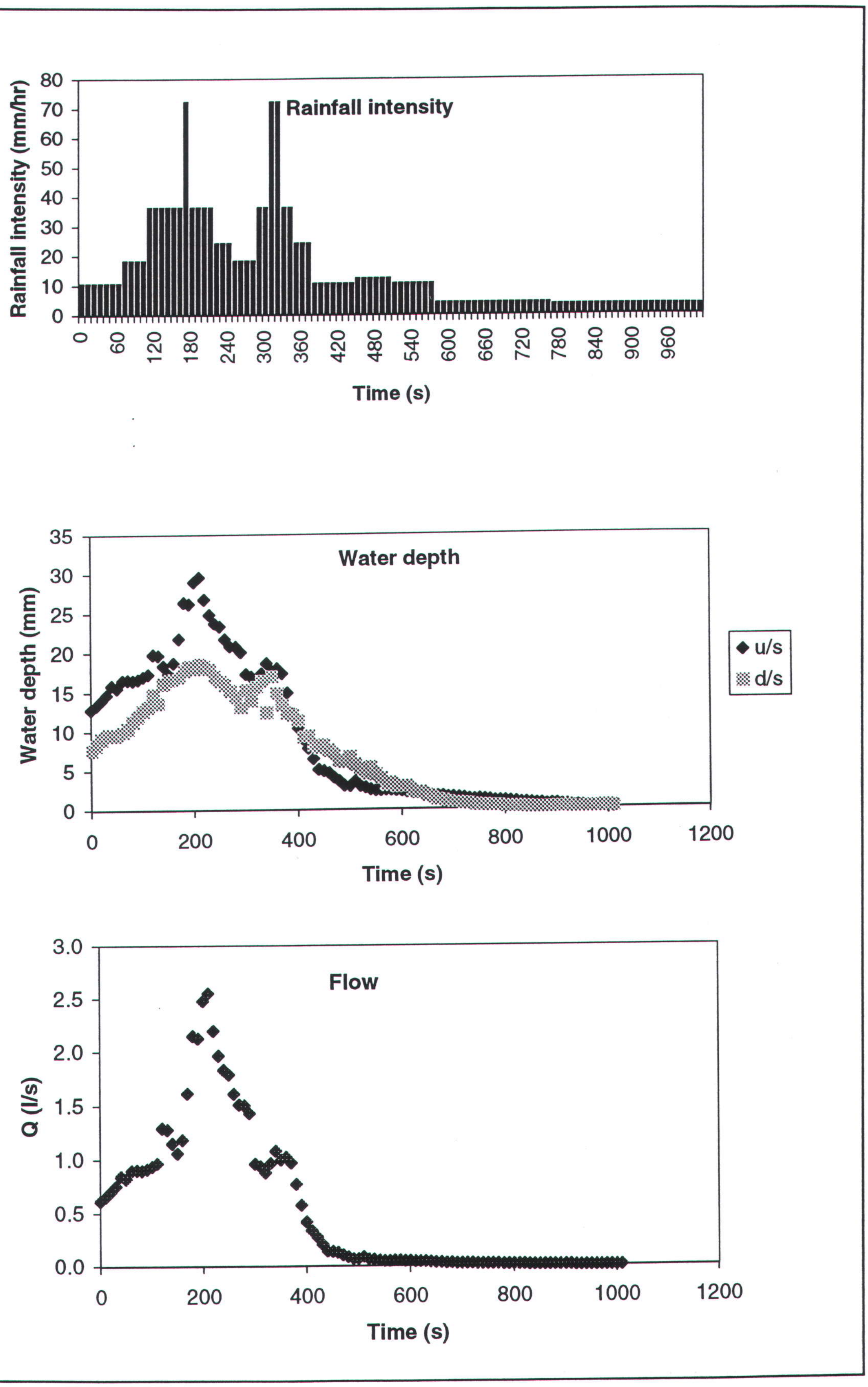


Figure 26 Site 2
Storm of 6 Jun 97, 20:53:00

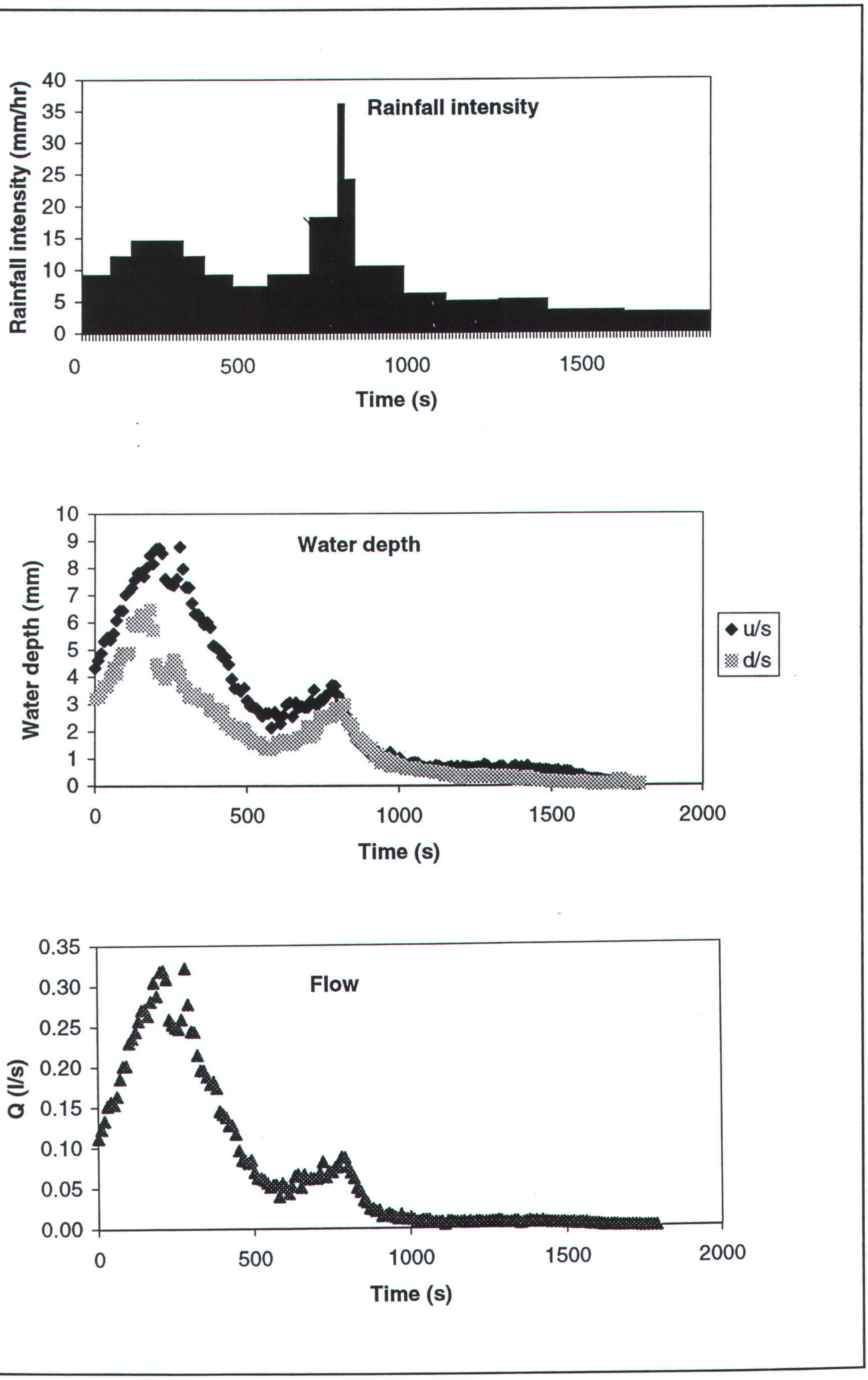
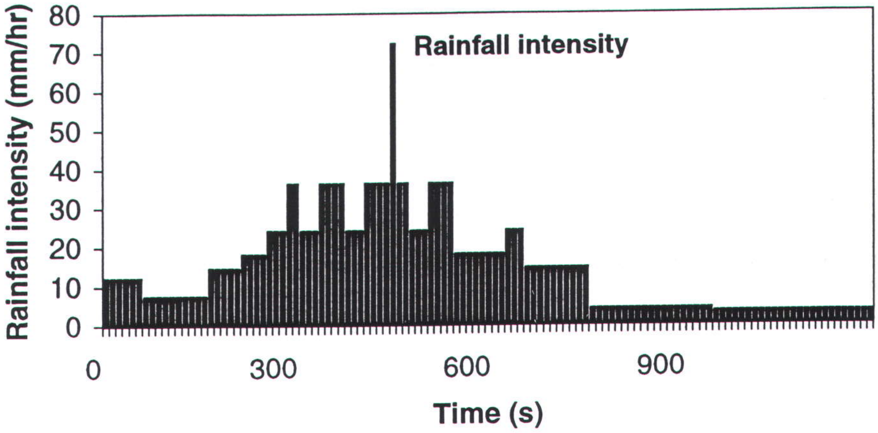
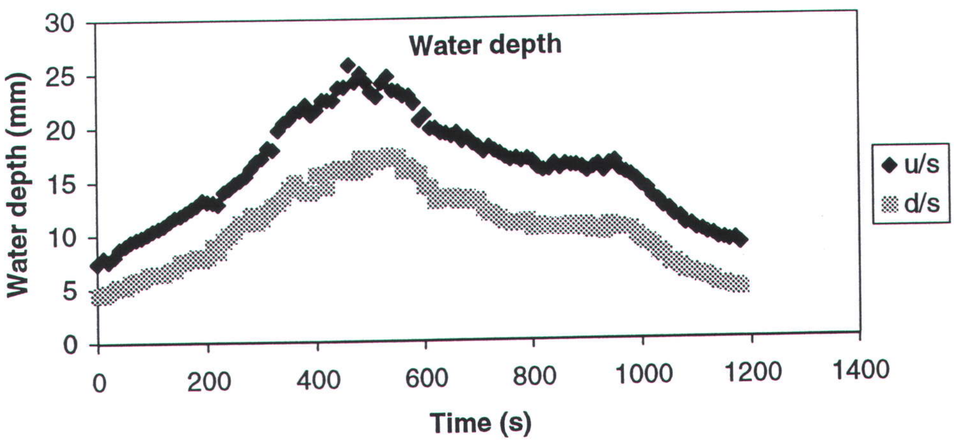


Figure 27 Site 2
Storm of 7 Jun 97, 00:36:30





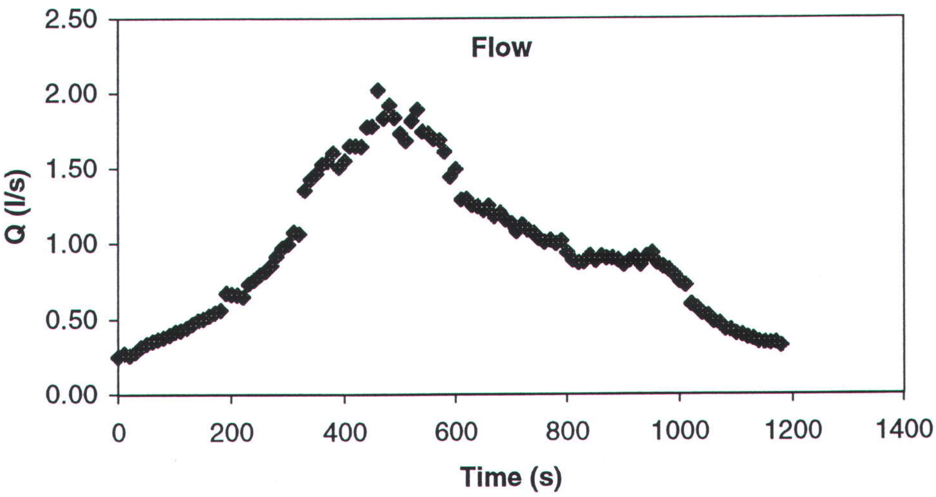


Figure 28 **Site 2**
Storm of 16 Jun 97, 14:42:10

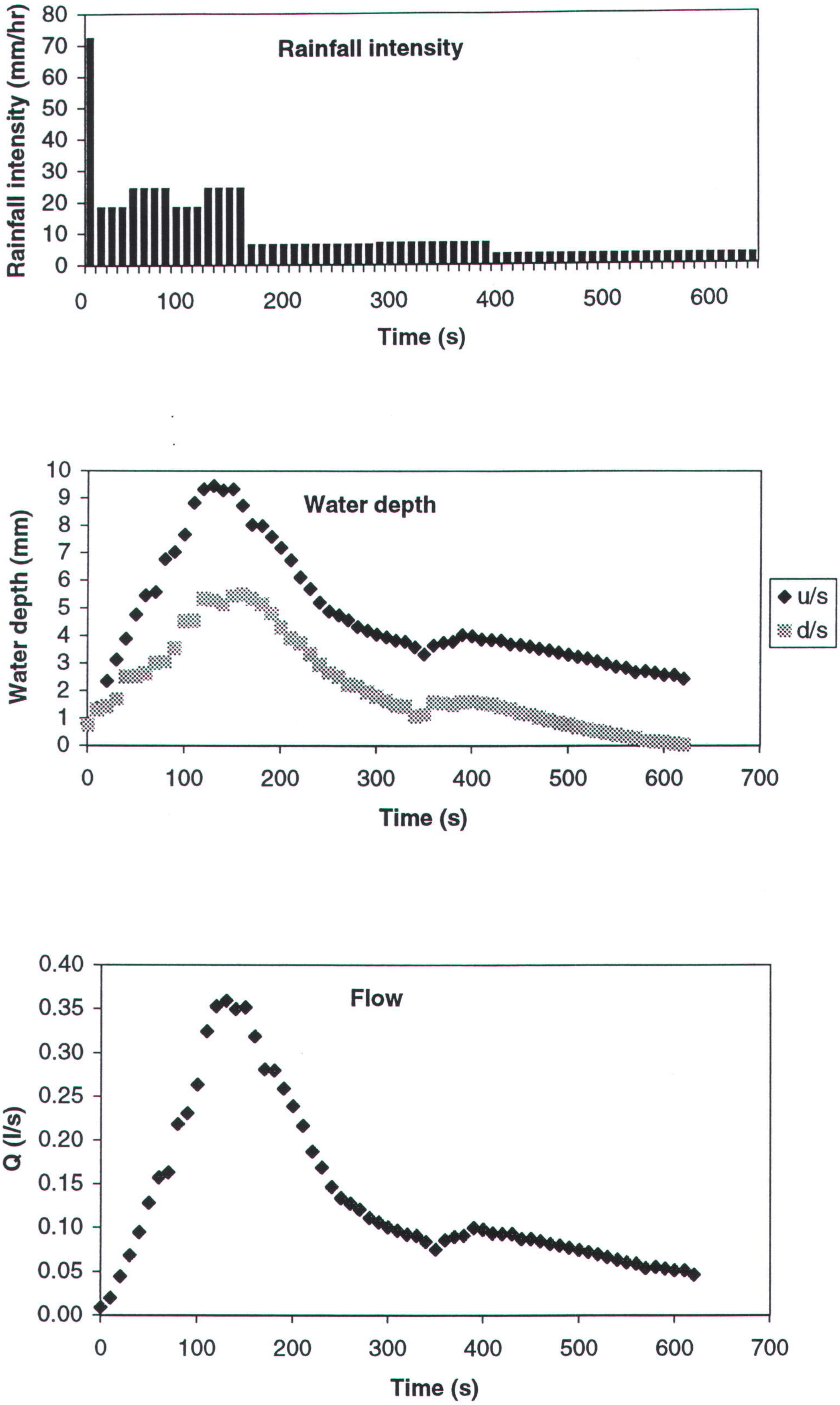


Figure 29 **Site 2**
Storm of 19 Jun 97, 08:54:00

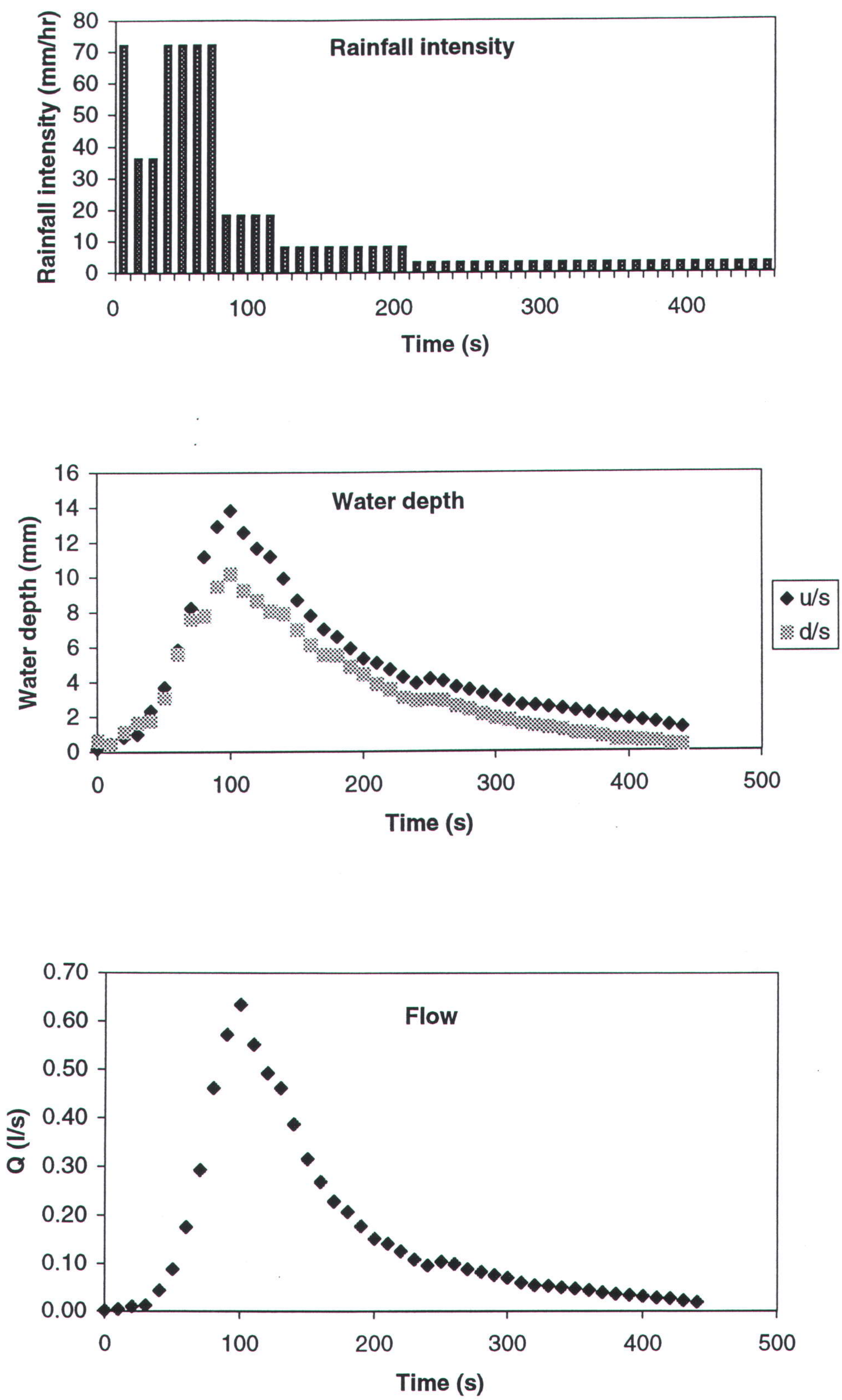


Figure 30 **Site 2**
Storm of 22 Jun 97, 09:02:20

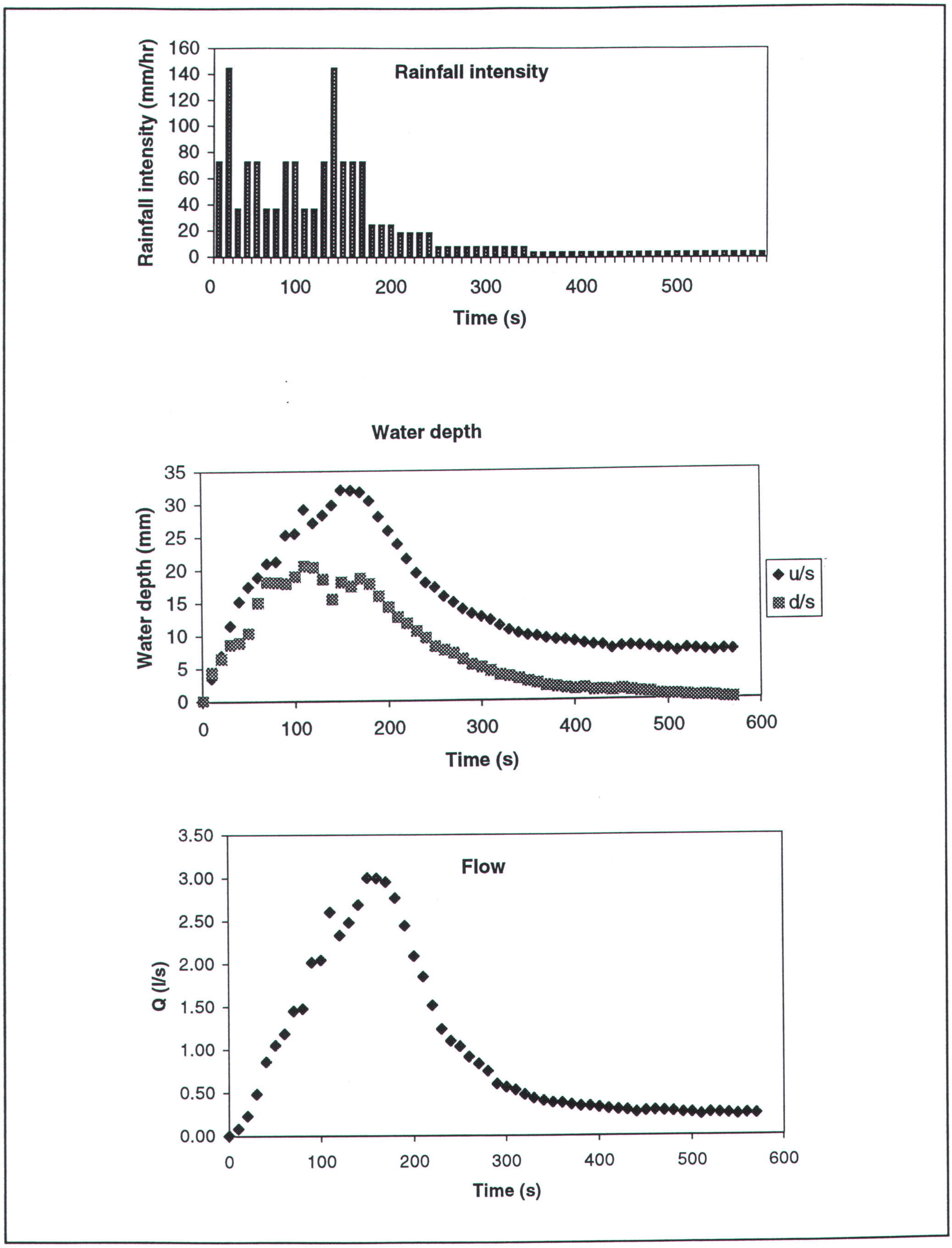


Figure 31 Site 2
Storm of 22 Jun 97, 15:28:30

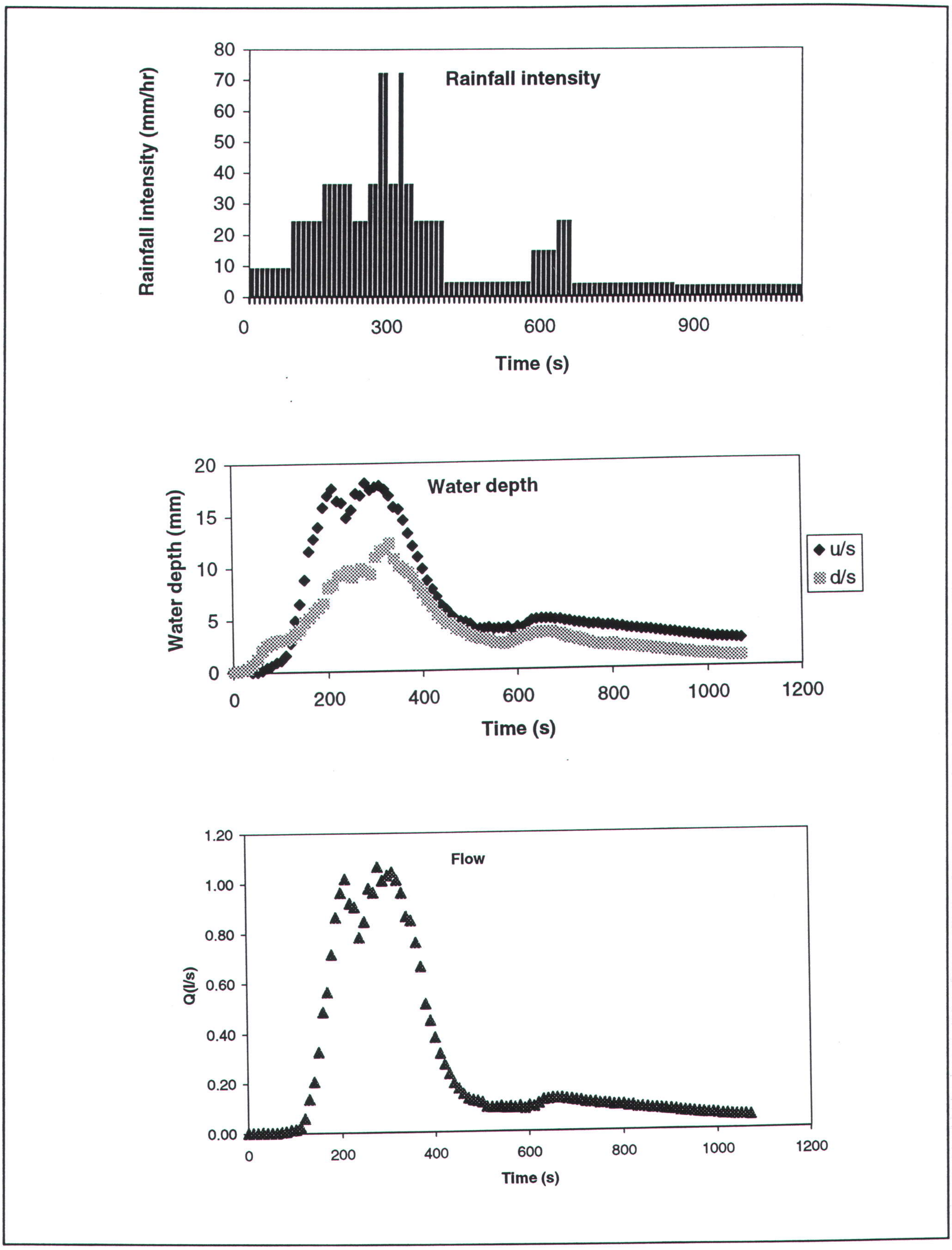


Figure 32 Site 2
Storm of 28 Aug 97, 04:22:30

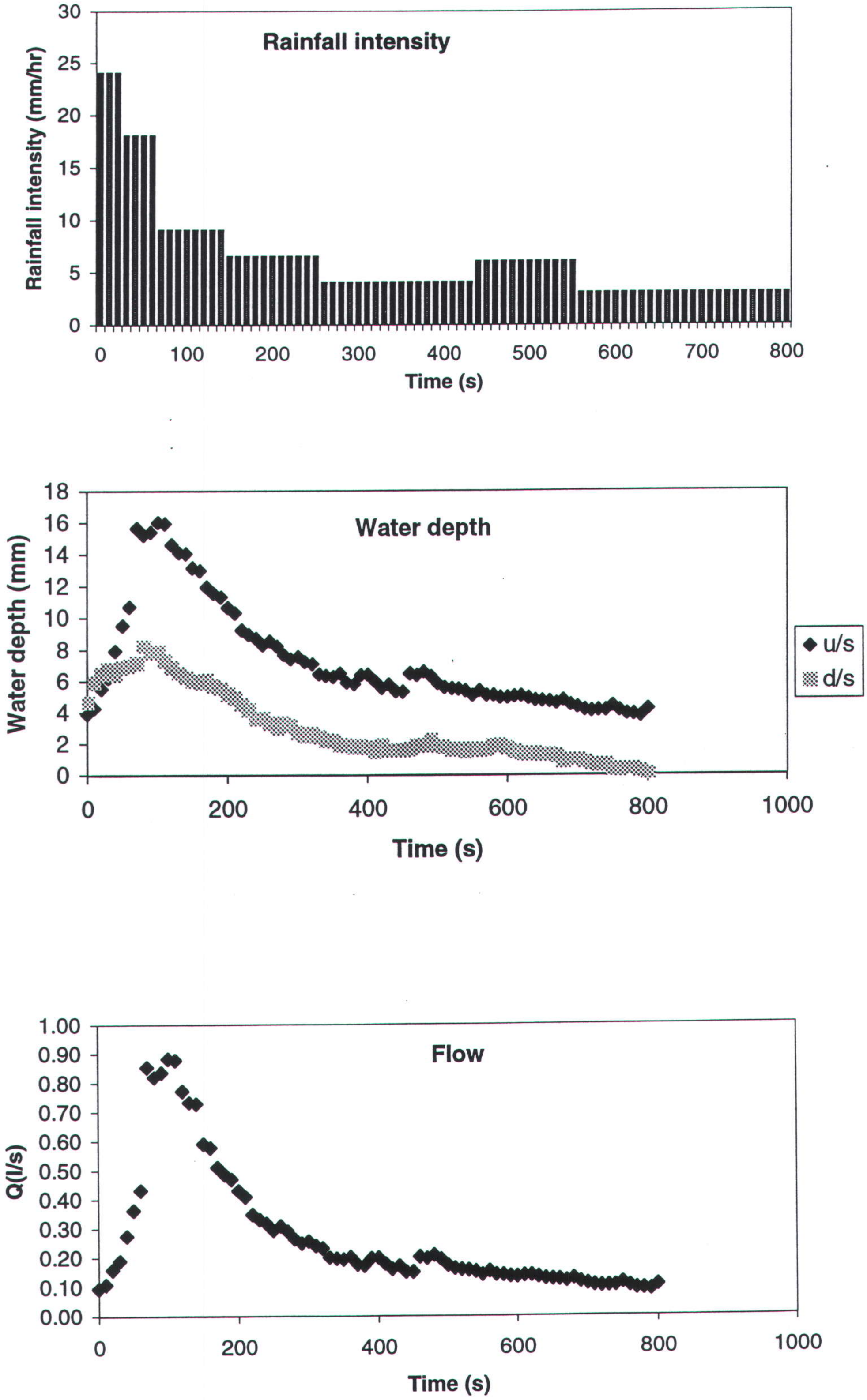


Figure 33 Site 2
Storm of 12 Sept 97, 12:18:00

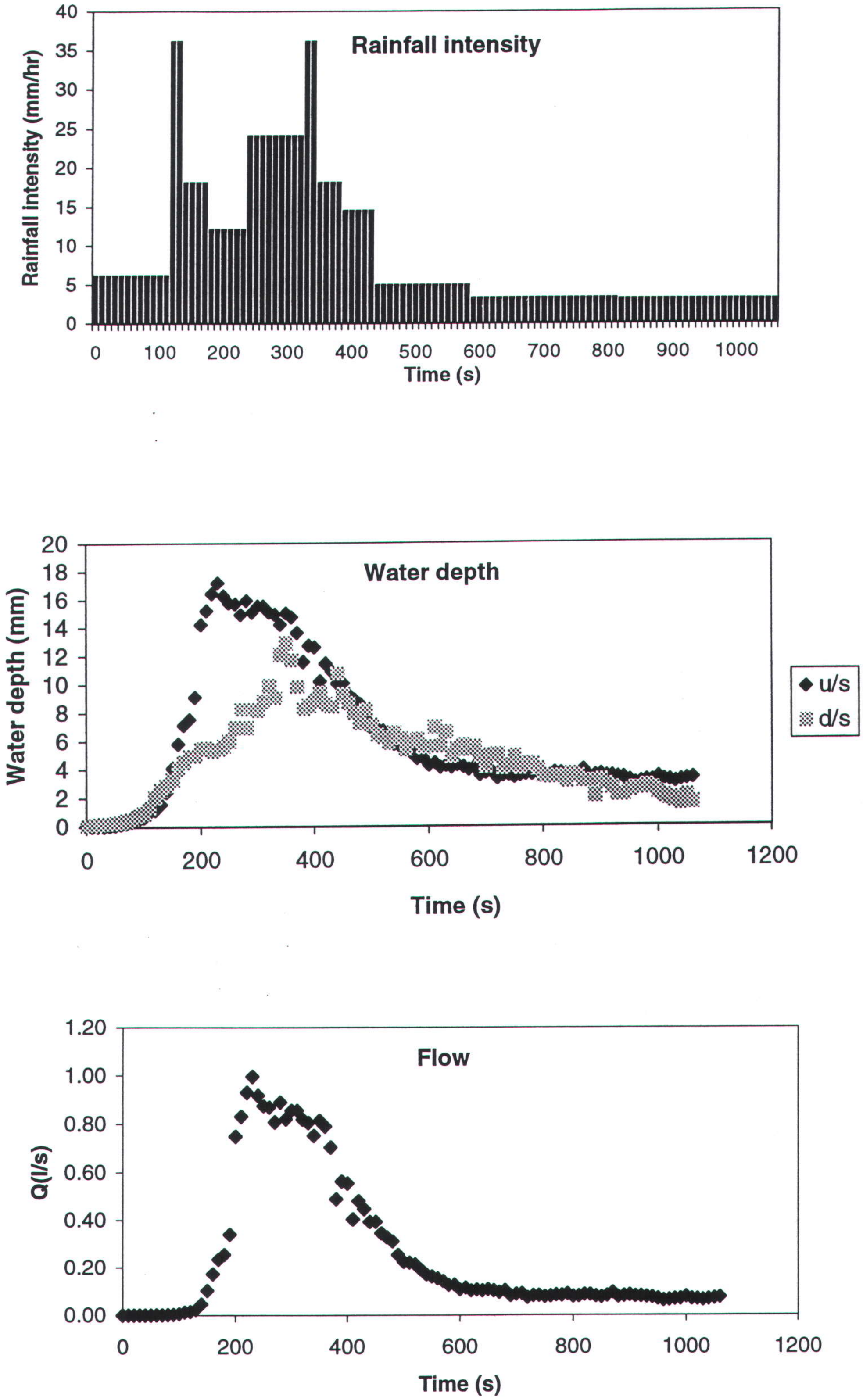


Figure 34 **Site 2**
Storm of 7 Oct, 03:52:40

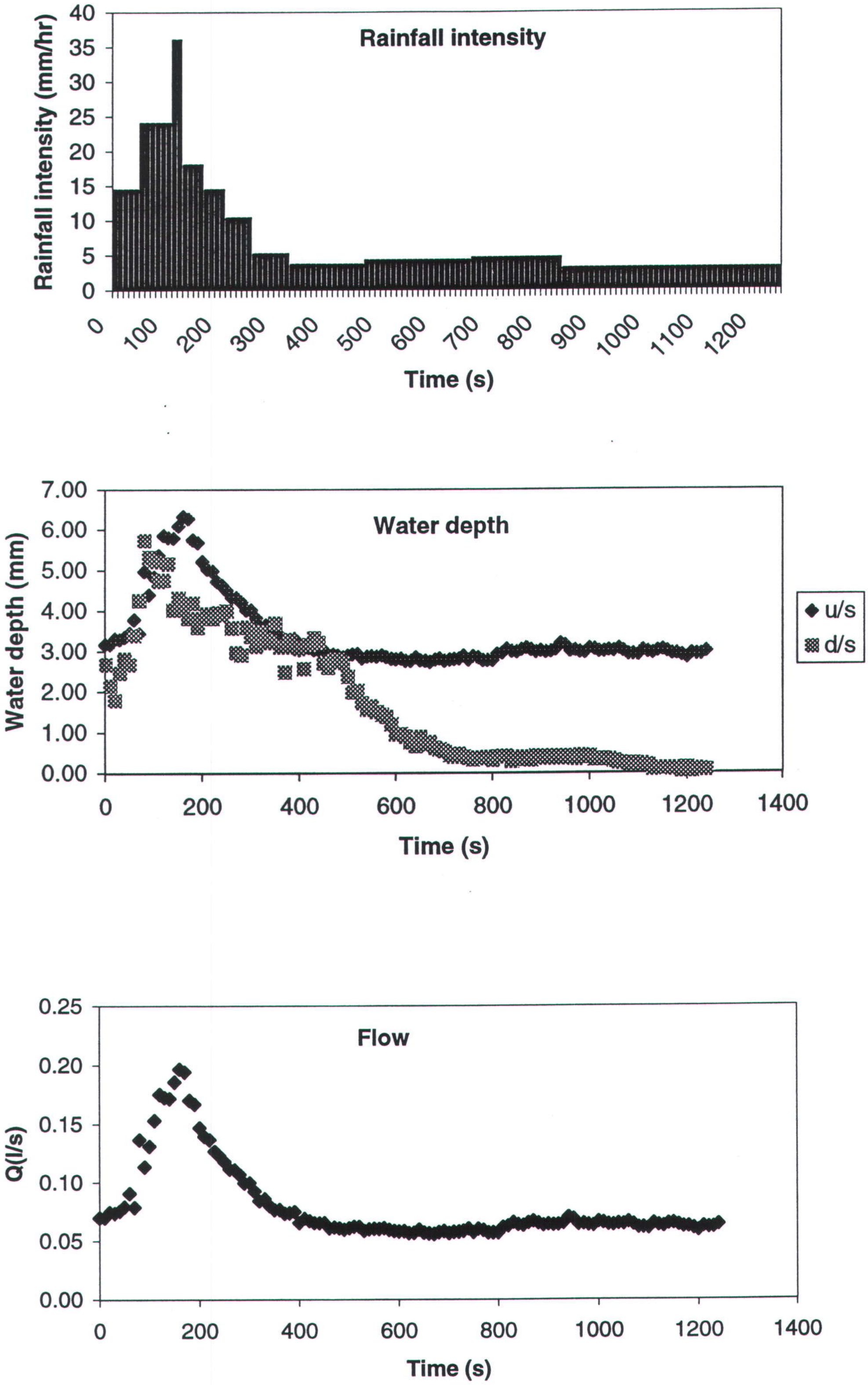


Figure 35 Site 2
Storm of 7 Oct 97, 04:11:40

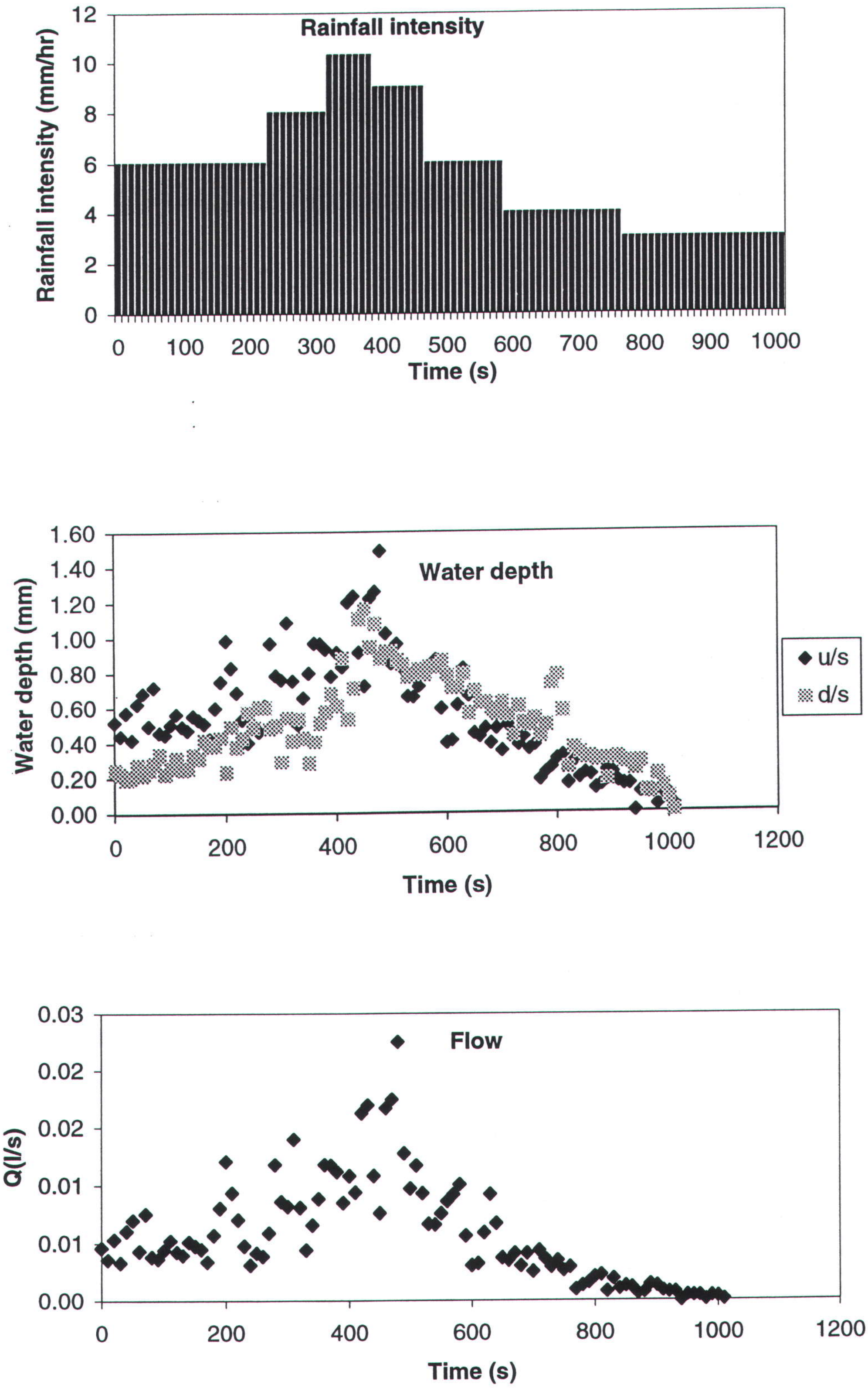


Figure 36 **Site 2**
Storm of 7 Oct 97, 08:49:50

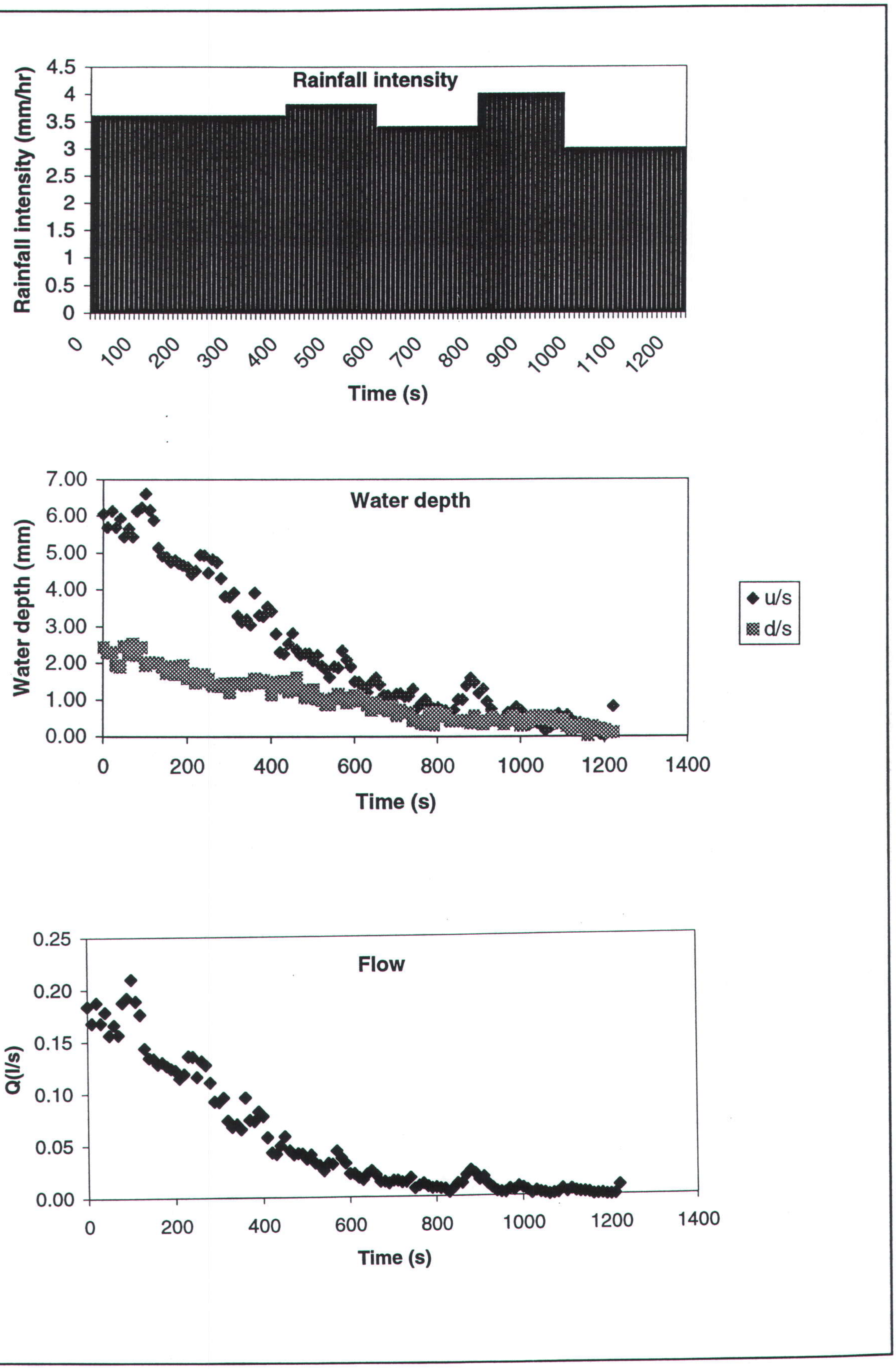


Figure 37 **Site 2**
Storm of 9 Oct 97, 21:38:50

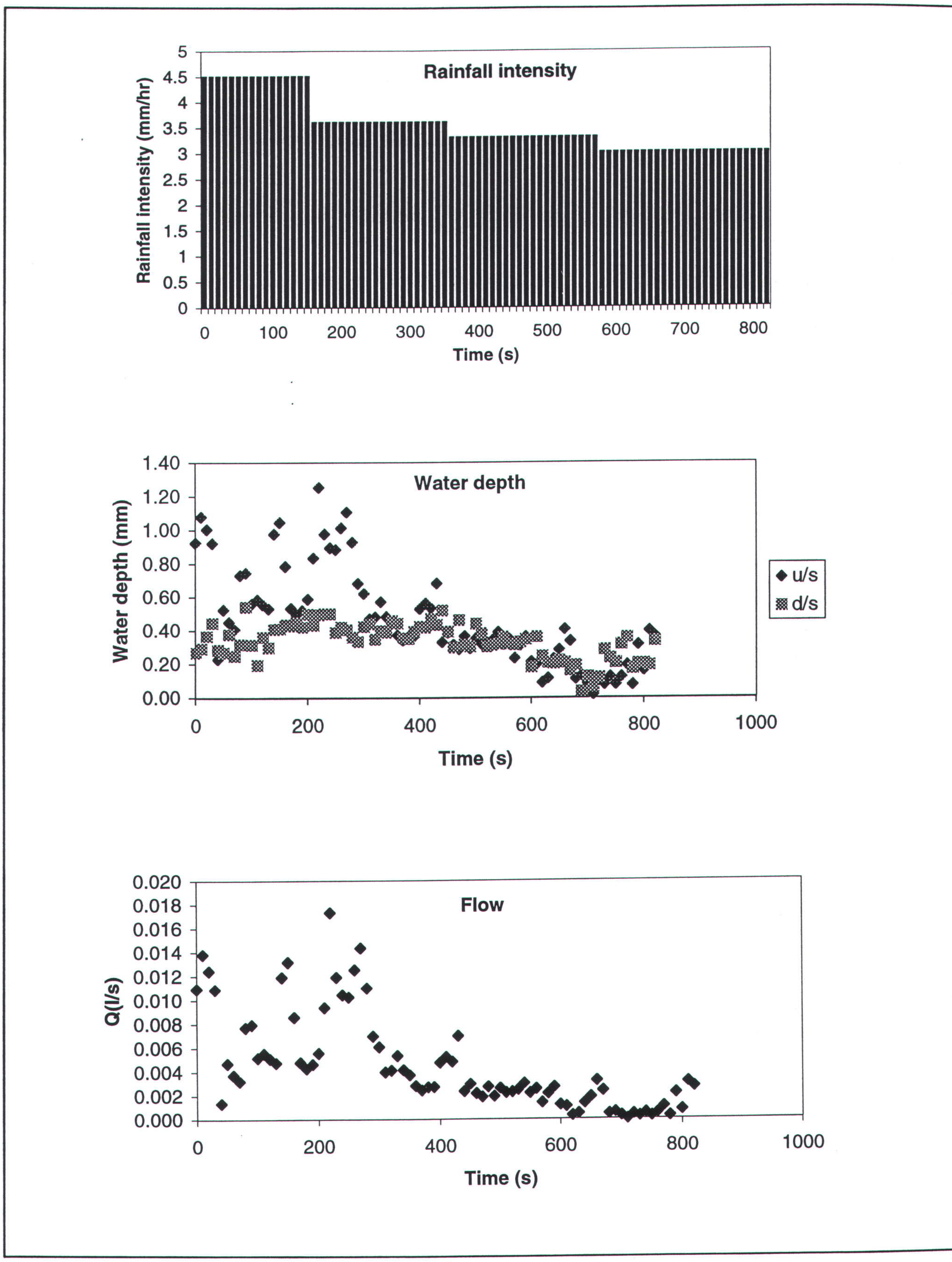


Figure 38 Site 2
Storm of 9 Oct 97, 22:12:00

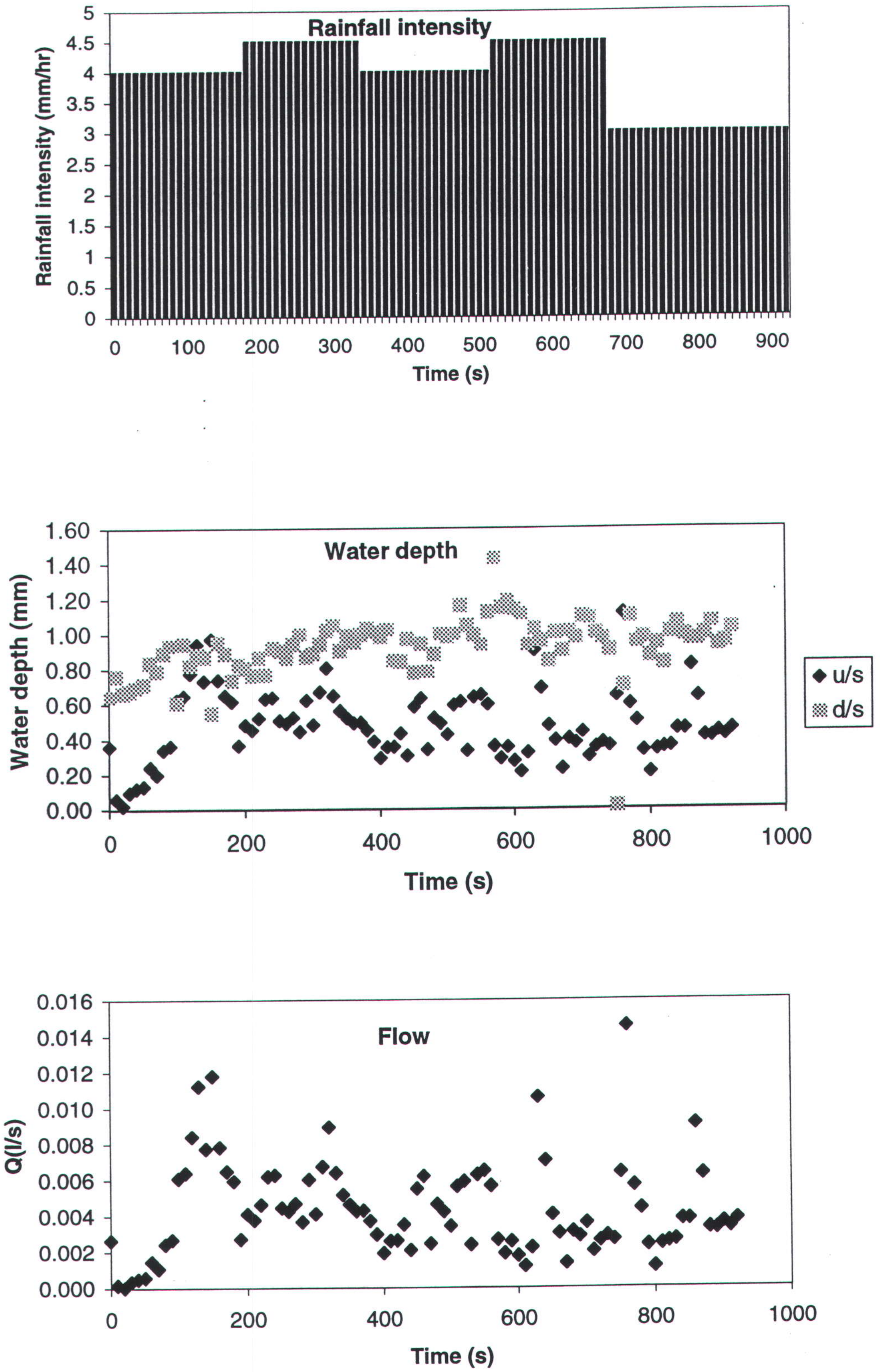


Figure 39 Site 2
Storm of 9 Oct 97, 23:43:40

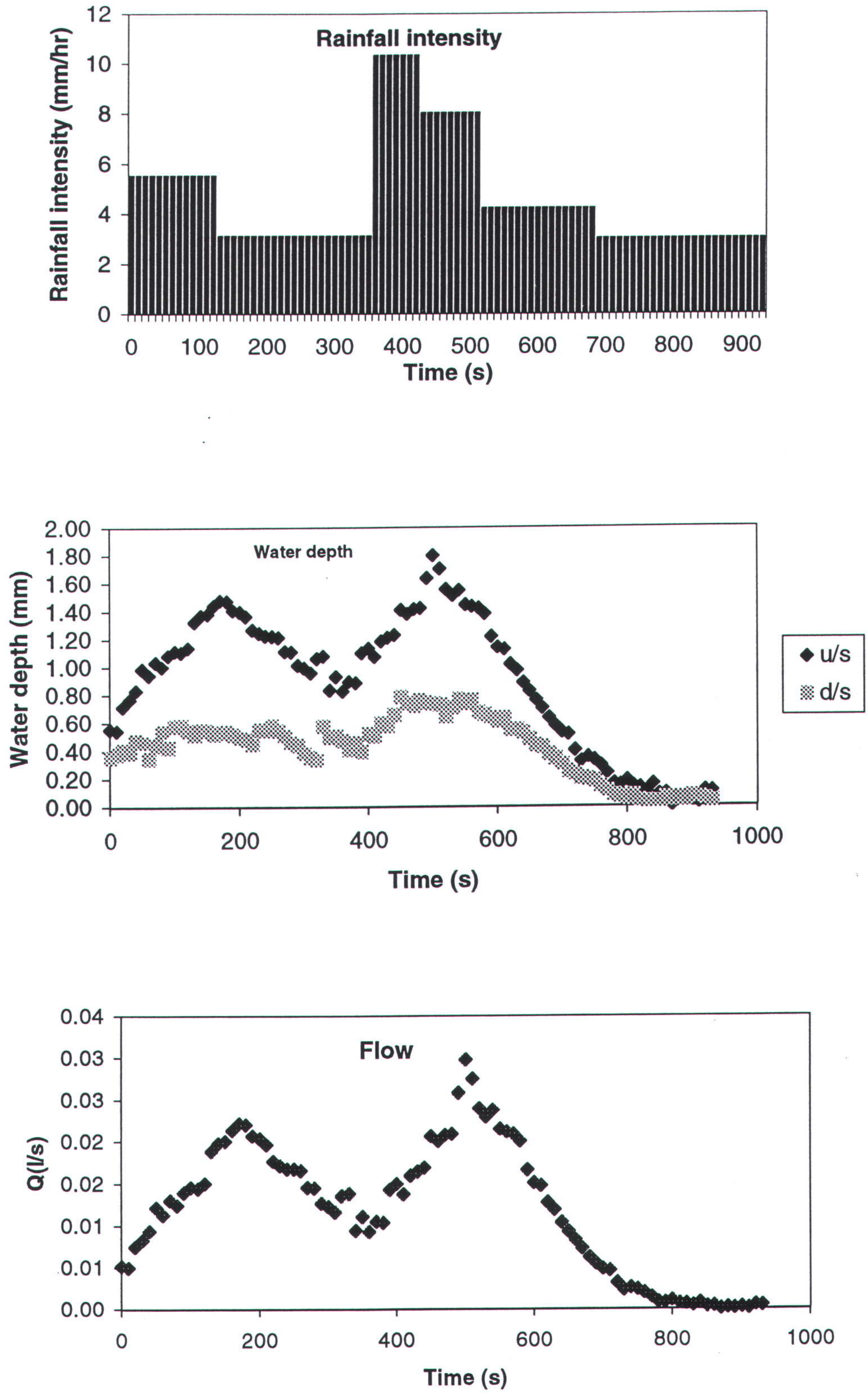


Figure 40 **Site 2**
Storm of 11 Oct 97, 13:26:00

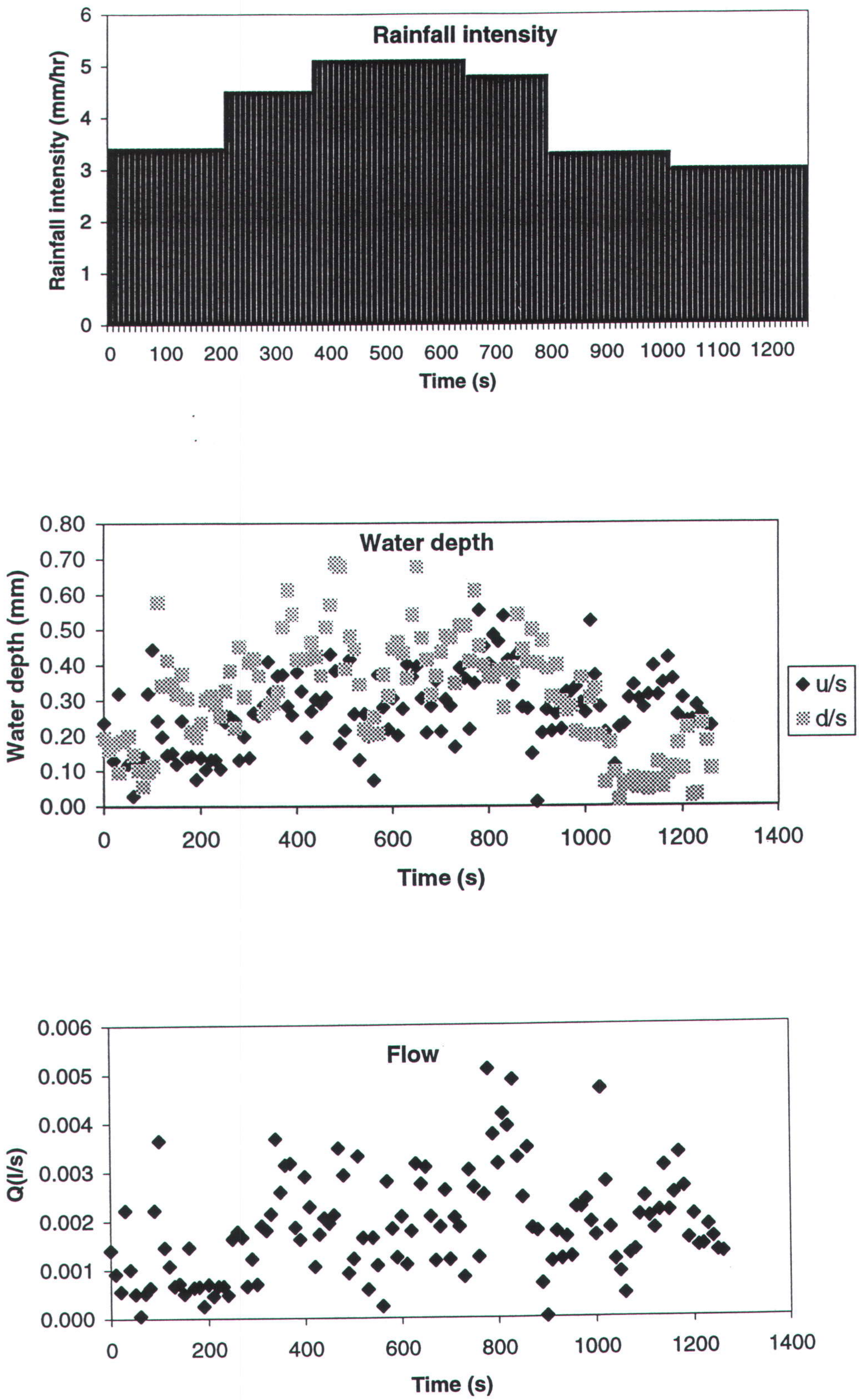


Figure 41 Site 2
Storm of 11 Oct 97, 23:35:10

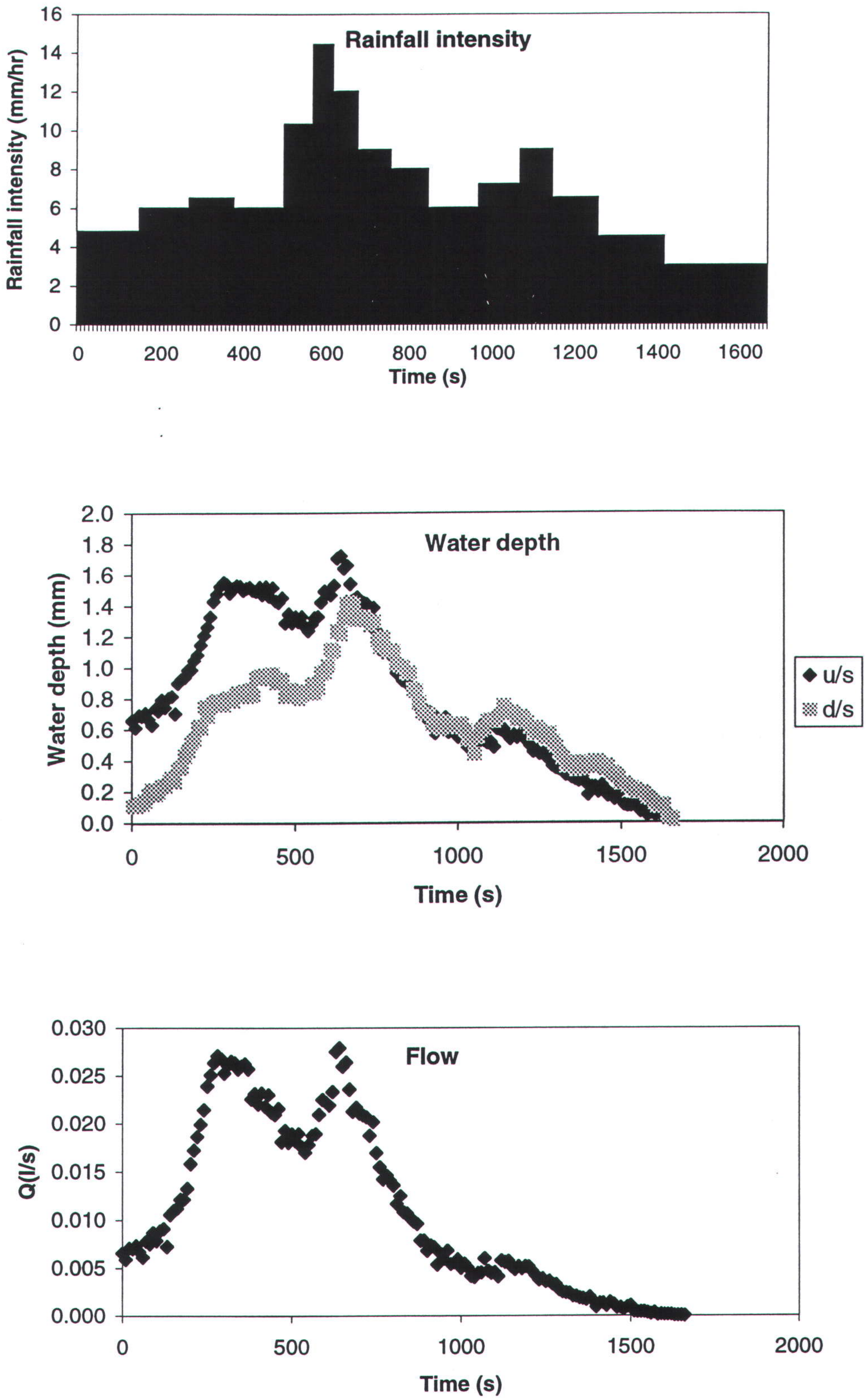


Figure 42 Site 2
Storm of 15 Oct 97, 03:57:10

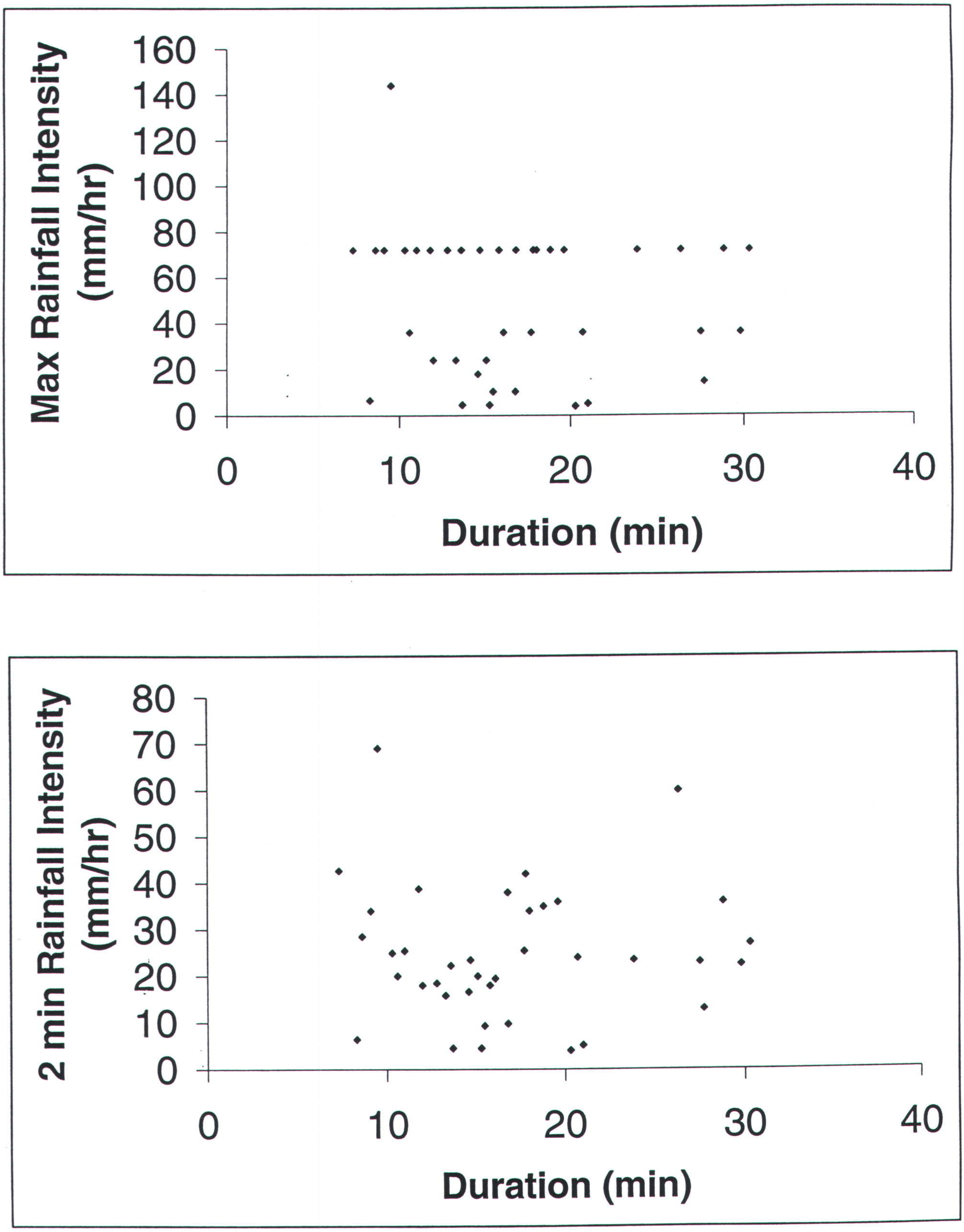
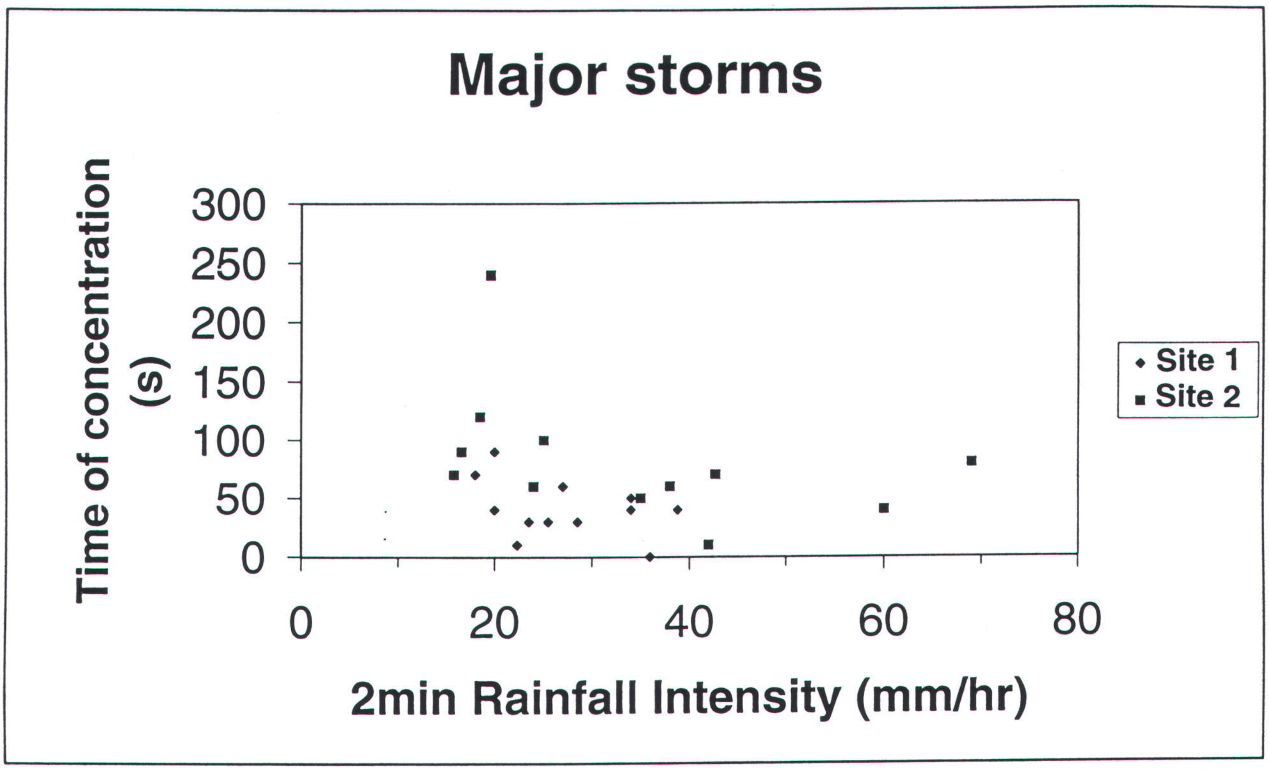


Figure 43 Relationship between rainfall intensity and storm duration



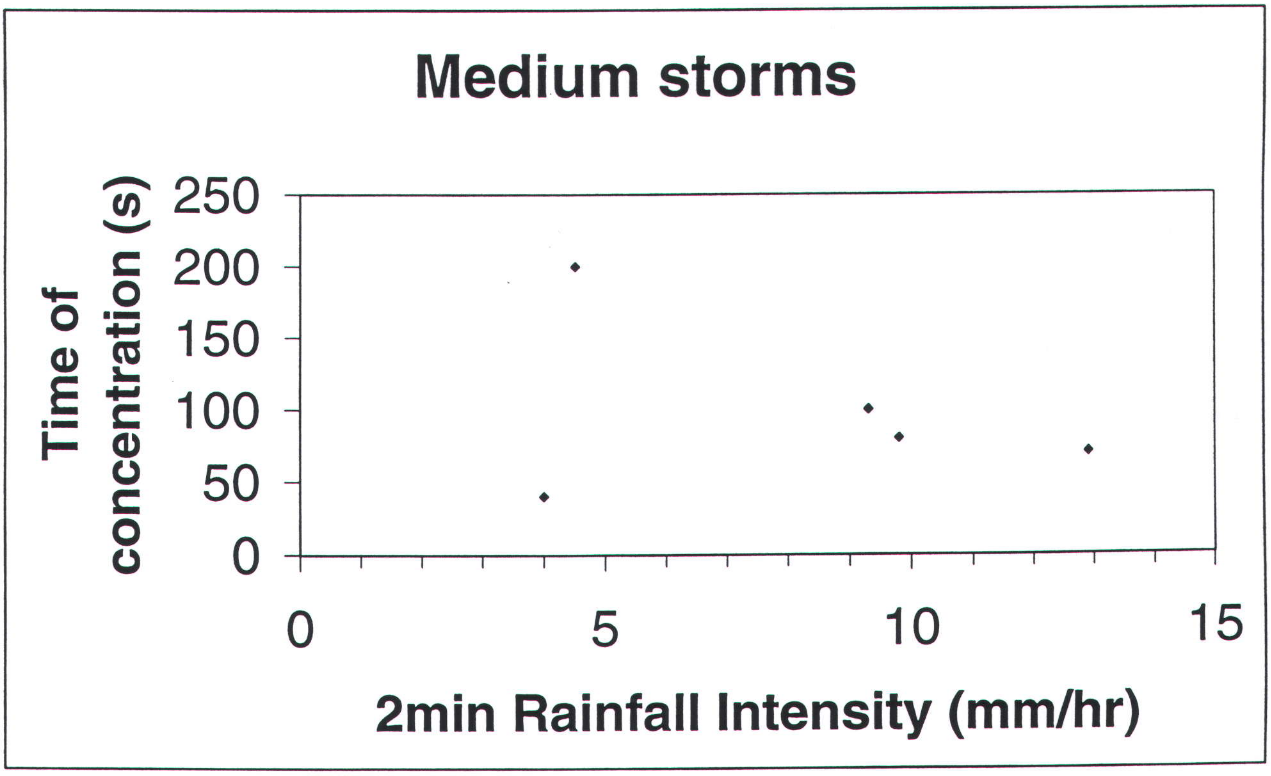
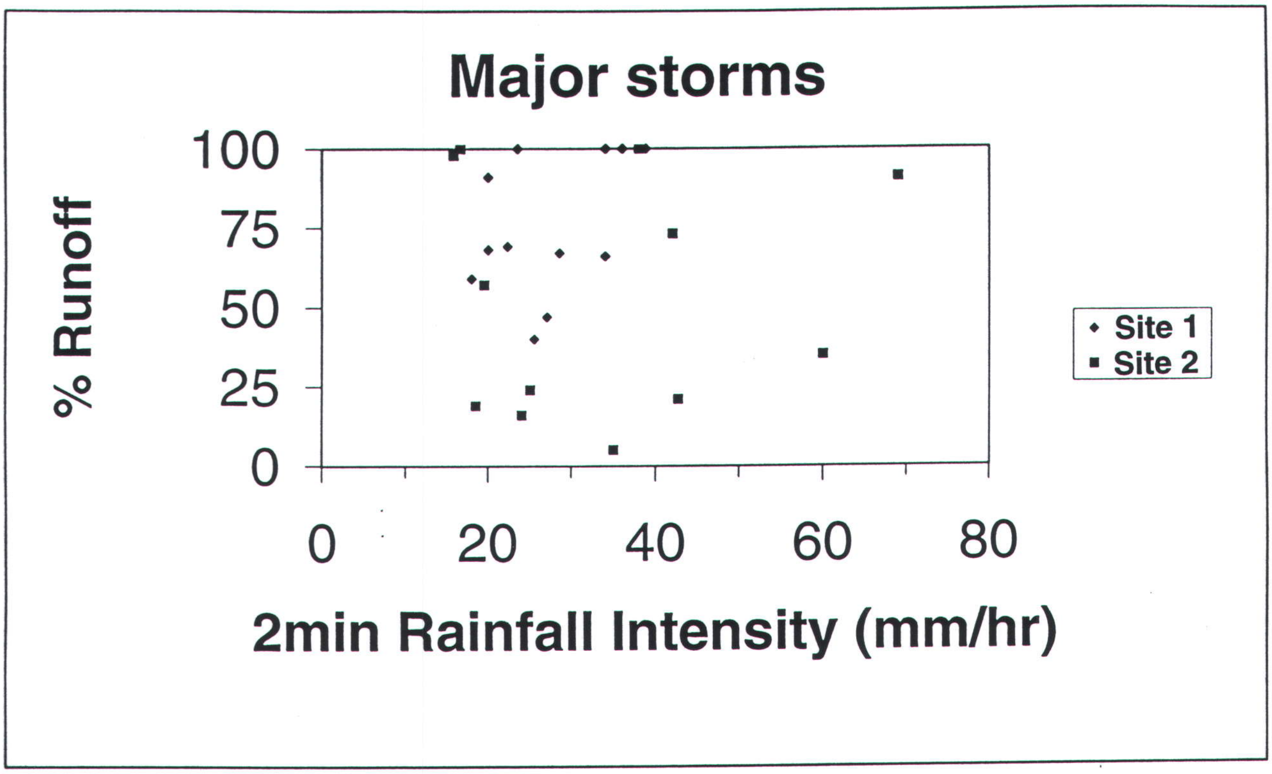


Figure 44 **Relationship between rainfall intensity and time of concentration**



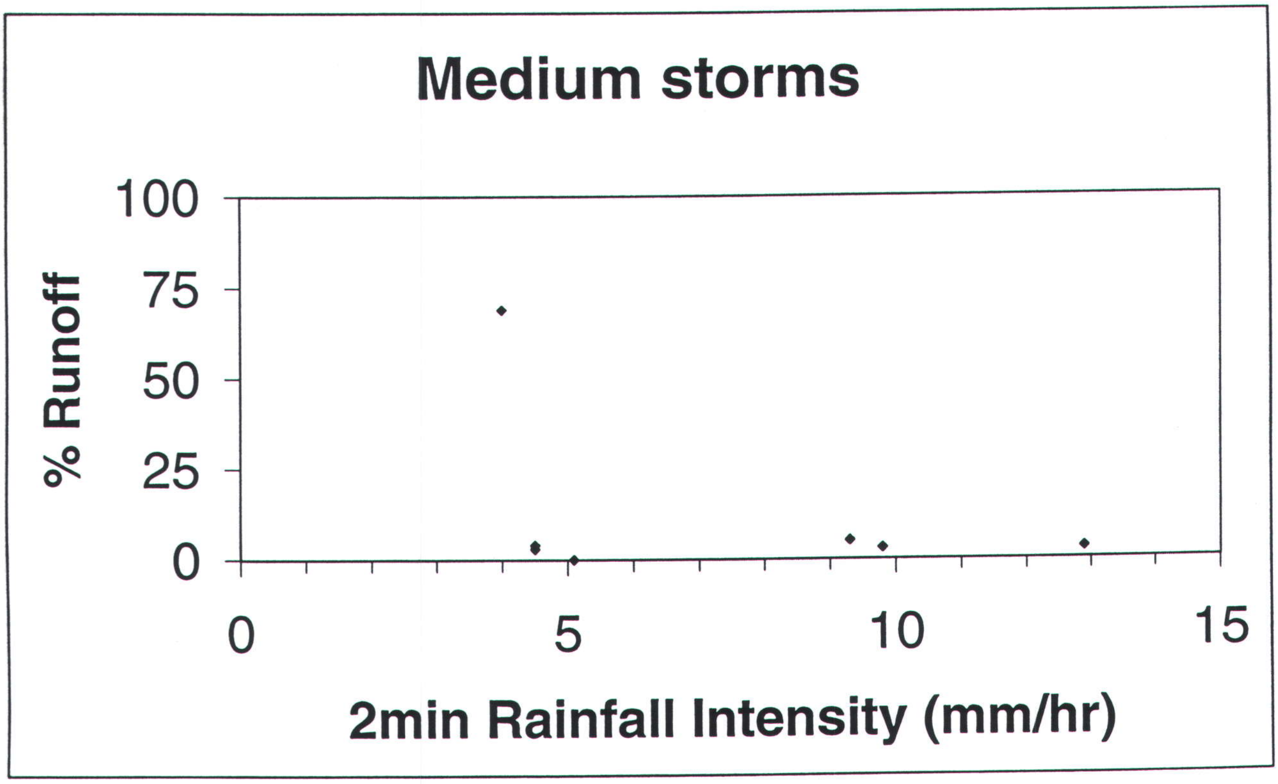
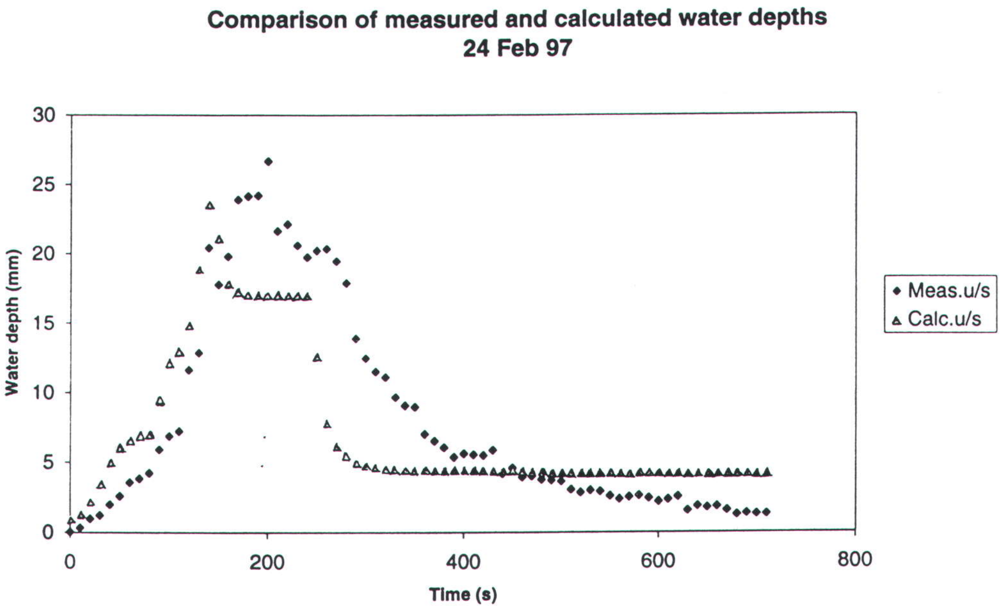


Figure 45 Relationship between rainfall intensity and percentage runoff



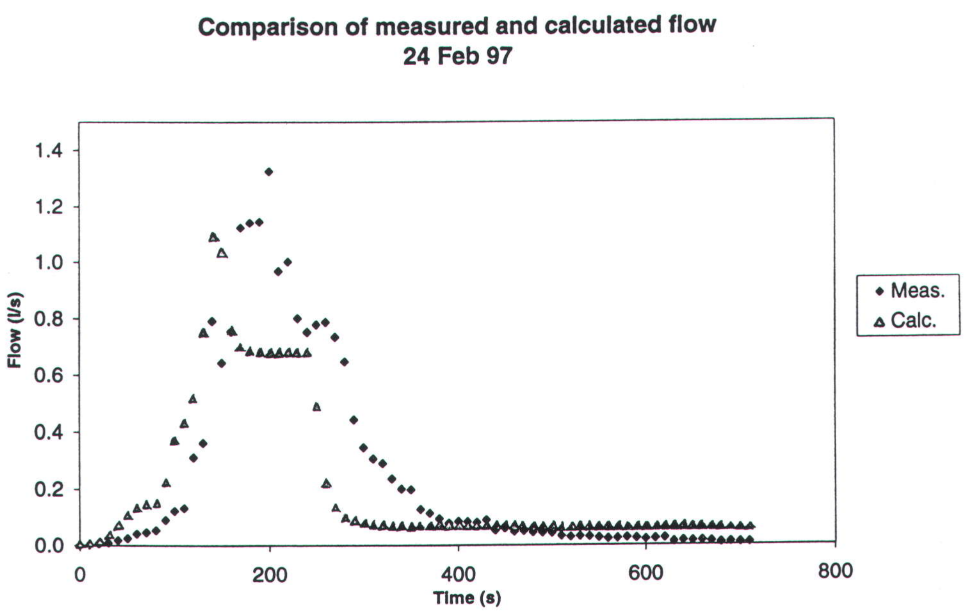


Figure 46 **Comparison of measured values and computer simulations for storm 24 Feb 97**

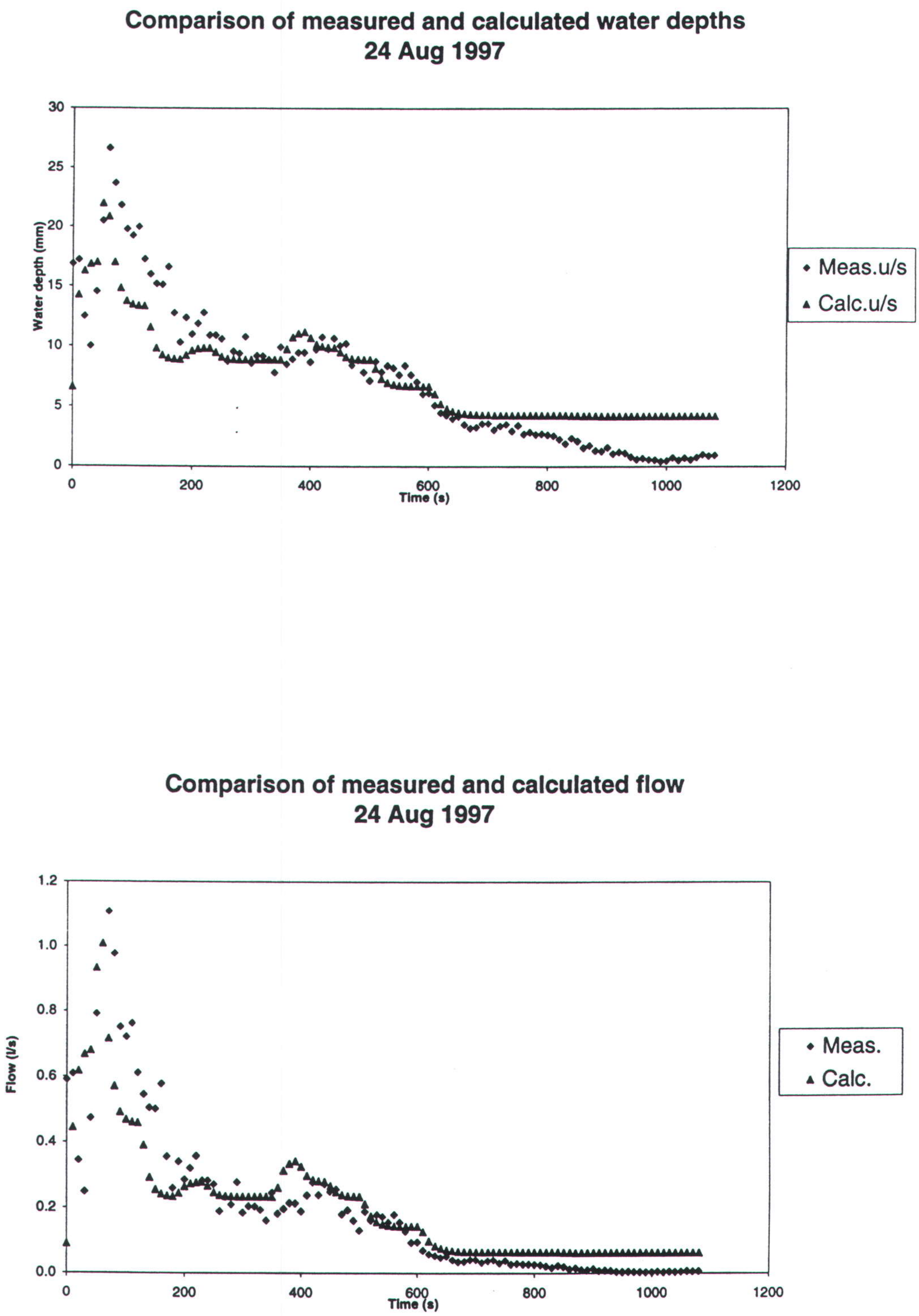
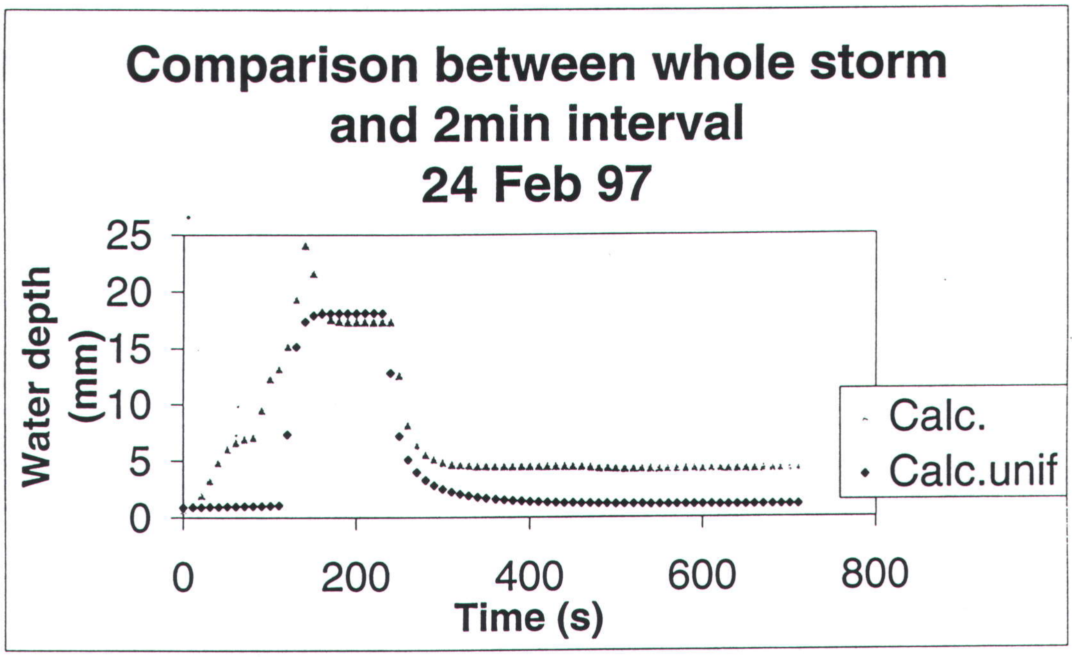


Figure 47 Comparison of measured values and computer simulations for storm 24 Aug 97



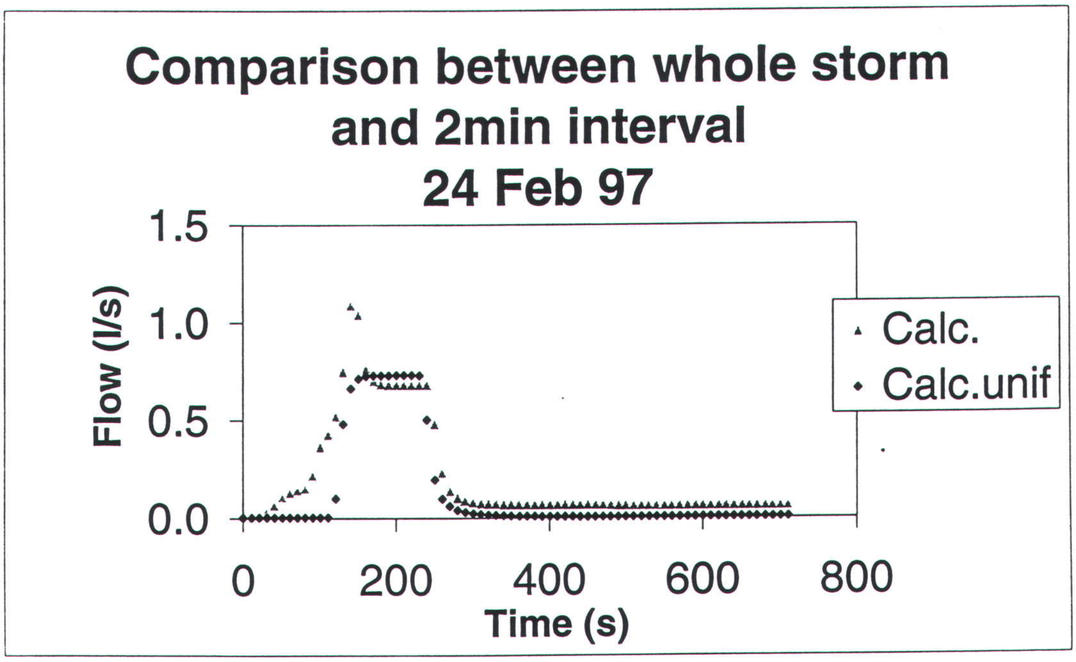
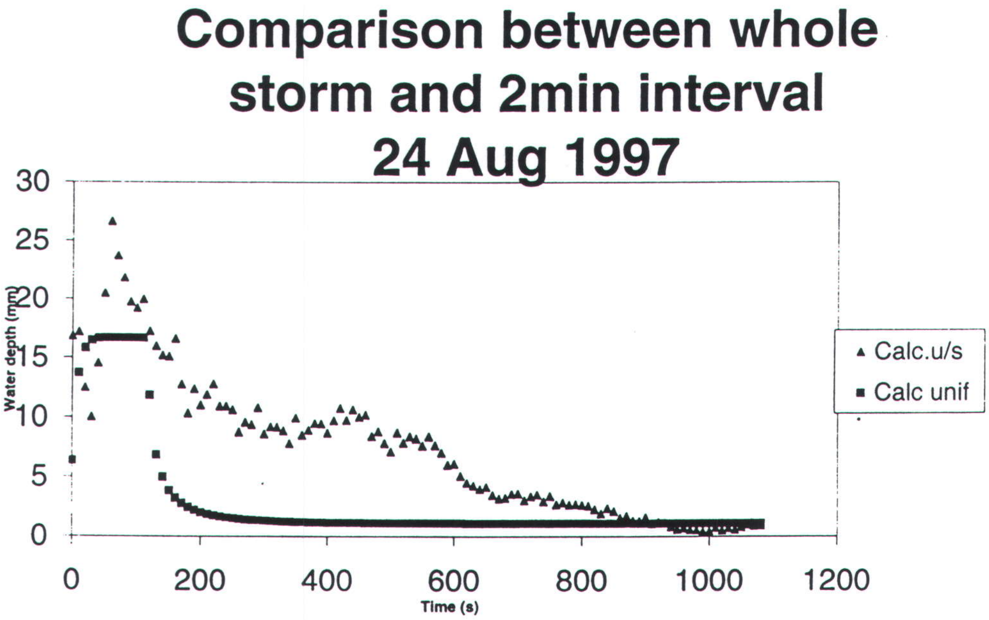


Figure 48 **Comparison between whole storm and 2 min block for storm 24 Feb 97**



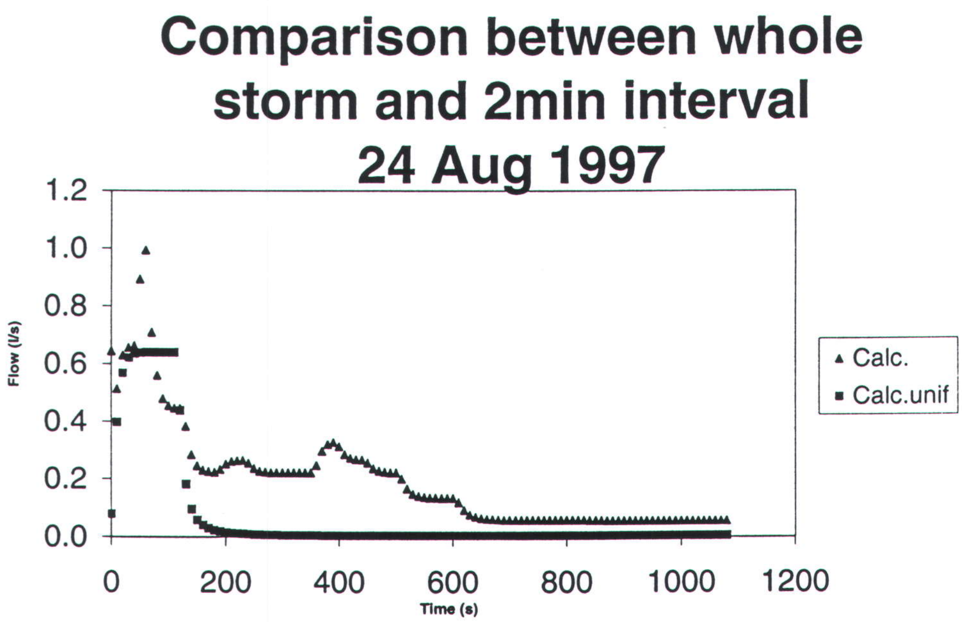


Figure 49 **Comparison between whole storm and 2 min block for storm 24 Aug 97**

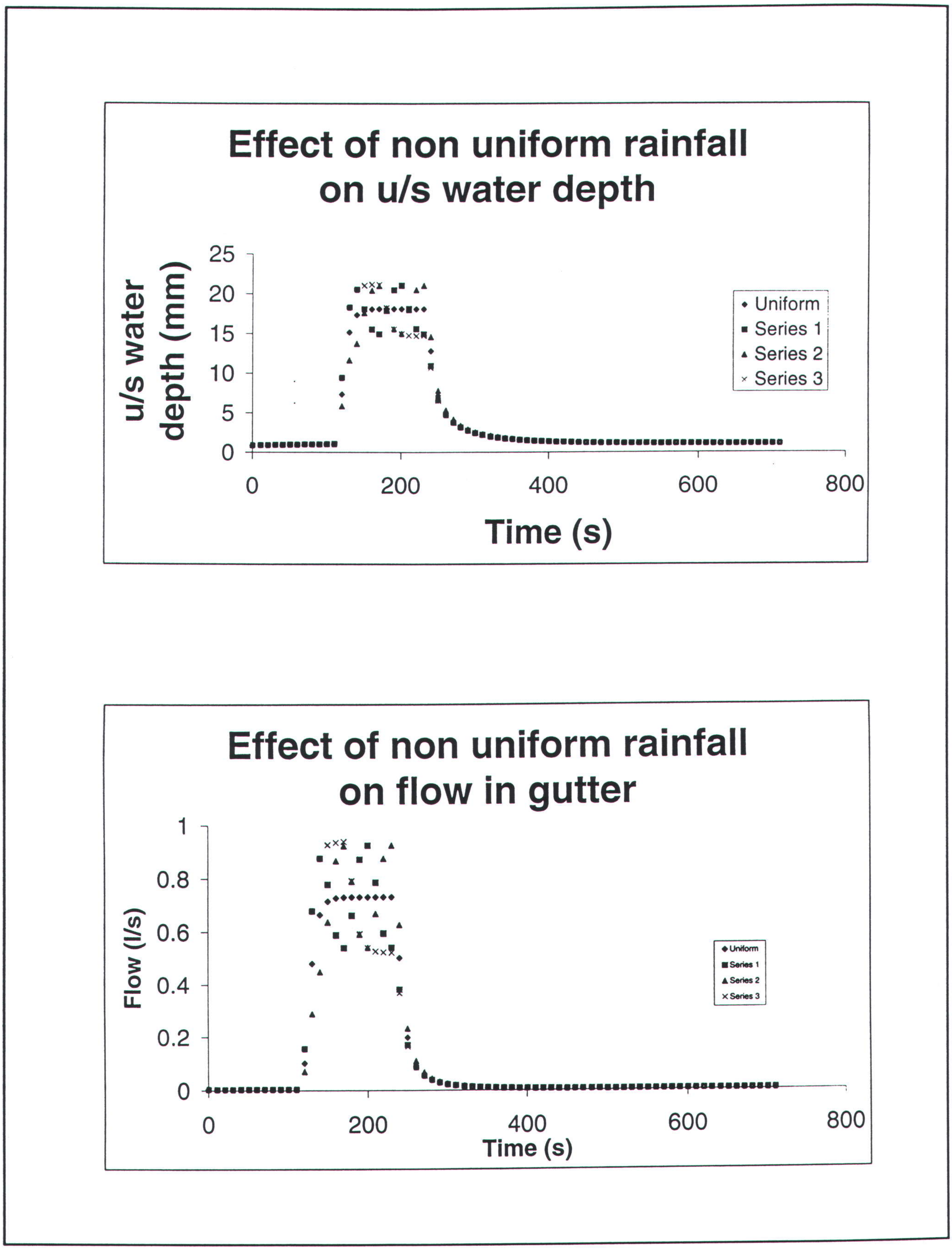


Figure 50 Effect of variable rainfall intensity during a 2 min block

Plates

Plate 1 View of Site 1
[Area monitored on the left hand side of the photograph]

Plate 2 Site 1
Gutters and downpipes

Plate 3 General view of Site 2

Plate 4 Site 2
Close-up of outlet

Plate 5 Site 2
Raingauge installed on the roof

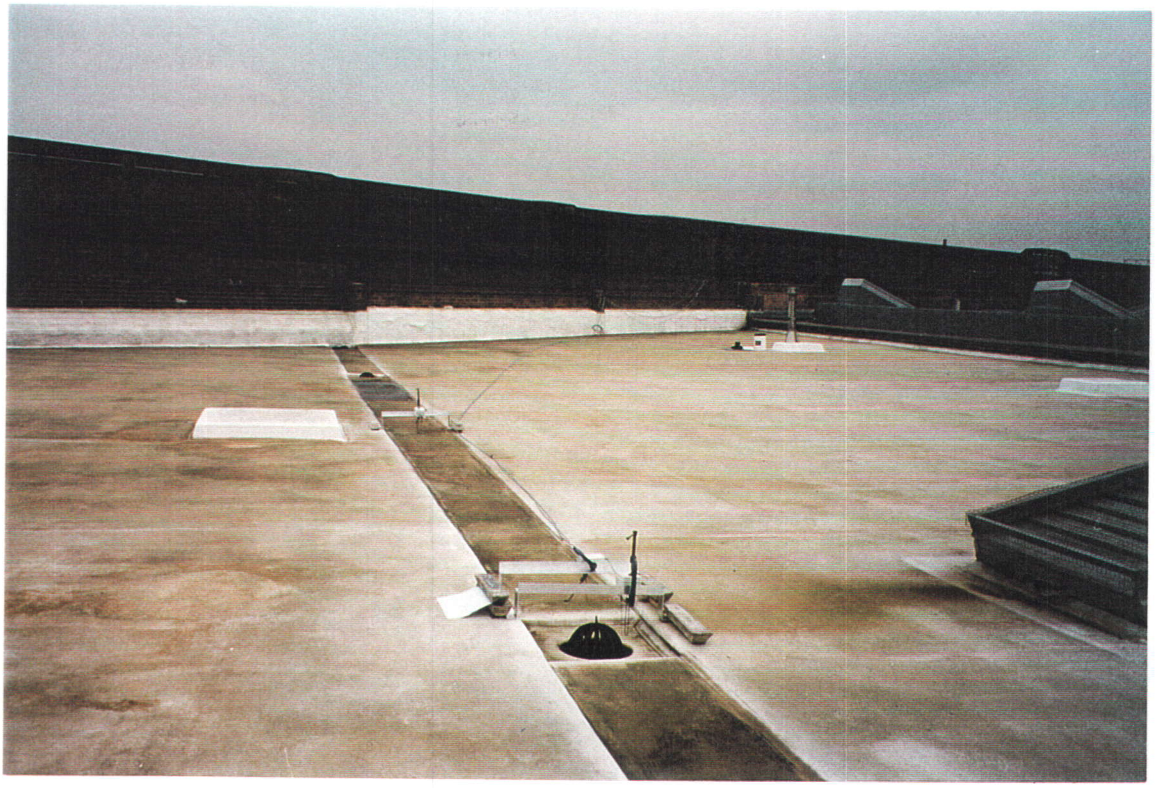


Plate 6 Site 2 - overall view of instrumentation

Plate 7 Site 1 - water depth probes installed in the gutter

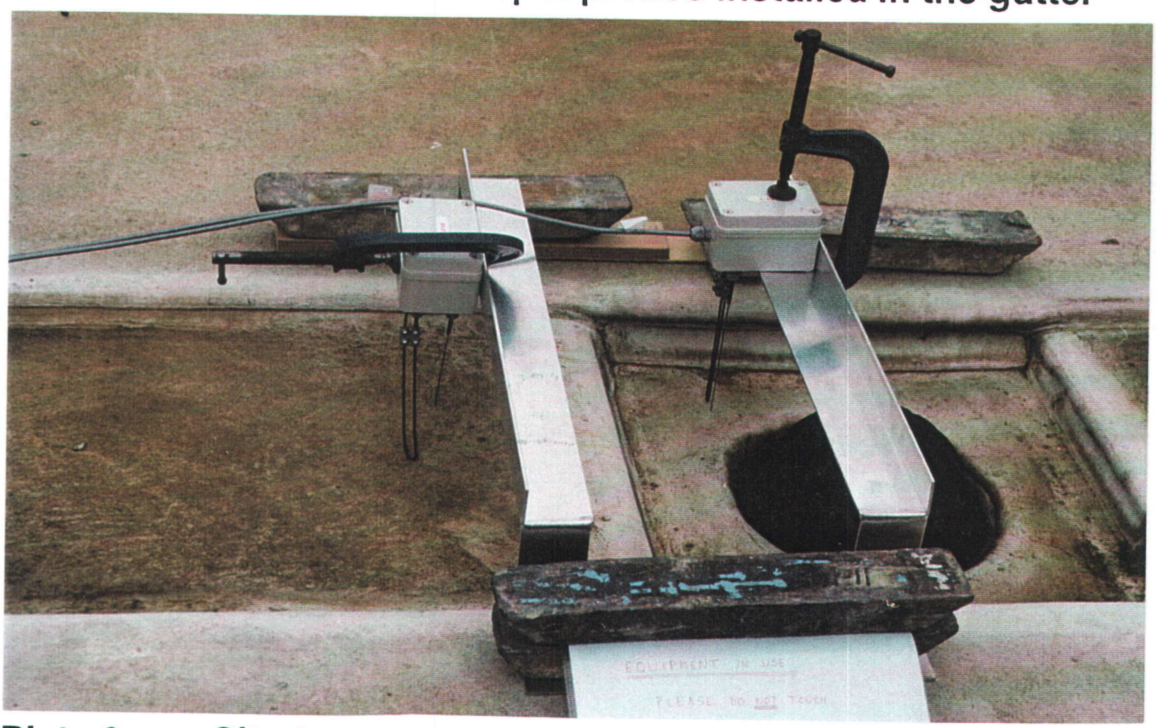


Plate 8 Site 2
Close-up of water depth probes at the outlet

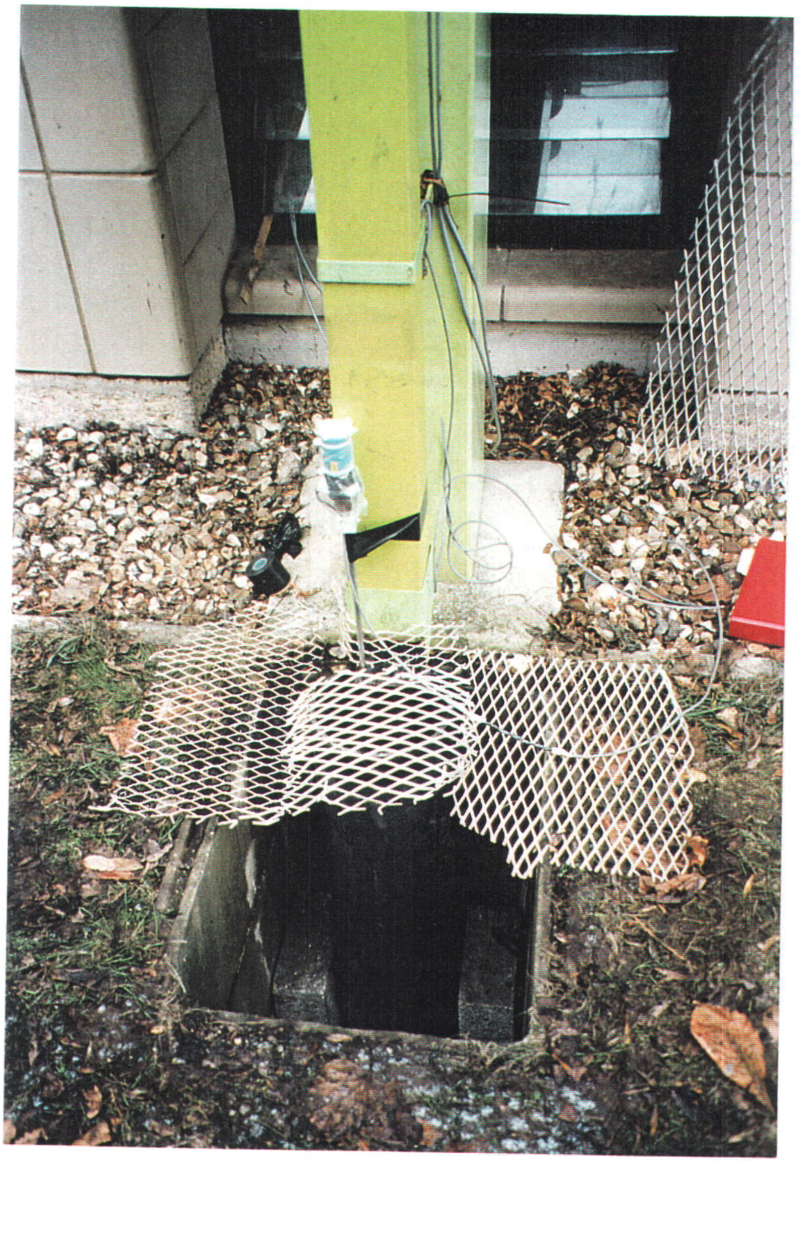


Plate 9 **Site 1 – flowmetering device**