EARTH SURFACE PROCESSES AND LANDFORMS, VOL. 7, 53–61 (1982)

AUTOMATIC SAMPLING OF STREAM WATER DURING STORM EVENTS IN SMALL REMOTE CATCHMENTS

R. P. MARTIN AND R. E. WHITE

Department of Agricultural Science, University of Oxford, OX1 3PF, England

Received 29 May 1980
Revised 23 October 1980

ABSTRACT

In order to study the relationship between water composition and stream flow rate, it is desirable to sample at a frequency related to flow rate, especially during storm events. In a rural catchment of 18 ha near Oxford, the rate of rainfall was found to be linearly related to discharge on the rising limb of the stream hydrograph. A sampling system was therefore designed in which electrical pulses from a tipping-bucket raingauge were used to initiate and control the action of an automatic water sampler. A threshold rainfall intensity is set above which sampling commences. Sampling then continues at regular increments of rainfall until the intensity drops below the threshold, after which sampling occurs at regular intervals during the period that the stream flow reverts to normal.

The CMOS electrical circuits which control the sampling also operate a cassette tape recorder which records the time of each tip of the raingauge and operation of the sampler. Since the sytem is designed to impose very little additional load on the battery which powers the water sampler, and can operate unattended for at least a fortnight, it is ideal for use in small, remote catchments. The system has been extended to include measurements of water temperature and could provide other measurements as well.

KEY WORDS Water sampling Stream flow Recorder Raingauge

INTRODUCTION

It is now widely recognized that the concentration of many soluble and particulate constituents of stream water varies with the flow rate or discharge. In small catchments, stream response to rainfall and the corresponding changes in solute and sediment concentrations can be extremely rapid (Gregory and Walling (1973, p. 172)) and can occur at any time of the day or night. Detection of these rapid changes usually requires some form of automatic sampling of the stream water before, during, and after a storm event. Many of the sampling systems described in the literature operate at a fixed time interval varying between 2 min and 24 h (Doty (1970); Walling (1974); Foster and Walling (1978))—some run continuously while others only function when the discharge reaches a preset value (Walling and Teed (1971)). Disadvantages of the latter approach are: (a) the stream water is not sampled immediately before the discharge begins to rise to give the 'background' solute and sediment concentrations, and (b) in catchments where the base flow varies appreciably with the season, the discharge level which triggers the sampier has to be reset from time to time. Moreover, in catchments exhibiting 'flashy' hydrographs, sampling at fixed time intervals may not give adequate detail of the rapid changes in solute and sediment that occur during an event.

In order to monitor these changes and thus calculate accurately the solute and sediment loads, it is essential that the frequency of sampling varies with the discharge. This has been achieved by sampling at a preset increment in volume, which requires continuous integration of the flow rate (Claridge (1975)) or by subdivision of the maximum expected discharge into classes and progressively increasing the number of samples taken as the discharge increases from one class to another (Fredrickson (1969)). Samplers operating on either of these systems usually run continuously, in which case, to keep the samples to a manageable number, a large volume increment is chosen and rapid changes that occur over small increments in discharge remain undetected. But if set to operate only when a threshold level of discharge is attained, the sampler does not provide a measure of the 'background' stream conditions.

0197–9337/82/010053–09$01.00

In this paper we describe a technique of water sampling which makes use of the relationship between stream discharge and intensity of rainfall in a small catchment. An assembly of tipping-bucket raingauge, sampler and recorder was designed to operate automatically on a 12 V d.c. power supply, and when used in conjunction with a simple weir or flume and stage recorder, provides individual water samples that can be correlated with the rainfall intensity and stream discharge before, during, and after a storm event.

DESIGN AND CONSTRUCTION OF THE RECORDING–SAMPLING SYSTEM

Our system was designed to monitor short-term variations in the solute and sediment concentration of a stream draining an 18 ha catchment on the University Field Station at Wytham (Nat. Grid. Ref. SP 447 209). The average annual rainfall is 628 mm which is uniformly distributed throughout the year. Details of the geology, soils and vegetation will be given elsewhere (White, Wellings and Bell (unpublished)) but one should note that the soils were predominantly sandy clay loam to clay loam over silty clay loam and silty clay in texture, grading into silty clay loam over silty clay in the lower part of the catchment where a small area (1·6 ha) of underdrainage occurred. Site X in Figure 1 shows the position of the installations to be described.

The system consists of four units: (1) a V-notch weir, stilling pond and stage recorder; (2) a Rock and Taylor multipurpose liquid sampler; (3) a Rimco raingauge; and (4) a sampler control and information storage system. Power is supplied by a 12 V, 72 Ah battery.

The V-notch weir and stage recorder

The 90° partially contracted V-notch weir (Figure 2) was designed according to BS 3680 Part 4A (1965). The height h of water passing through the V-notch is recorded by a Munro IH 89 vertical water level

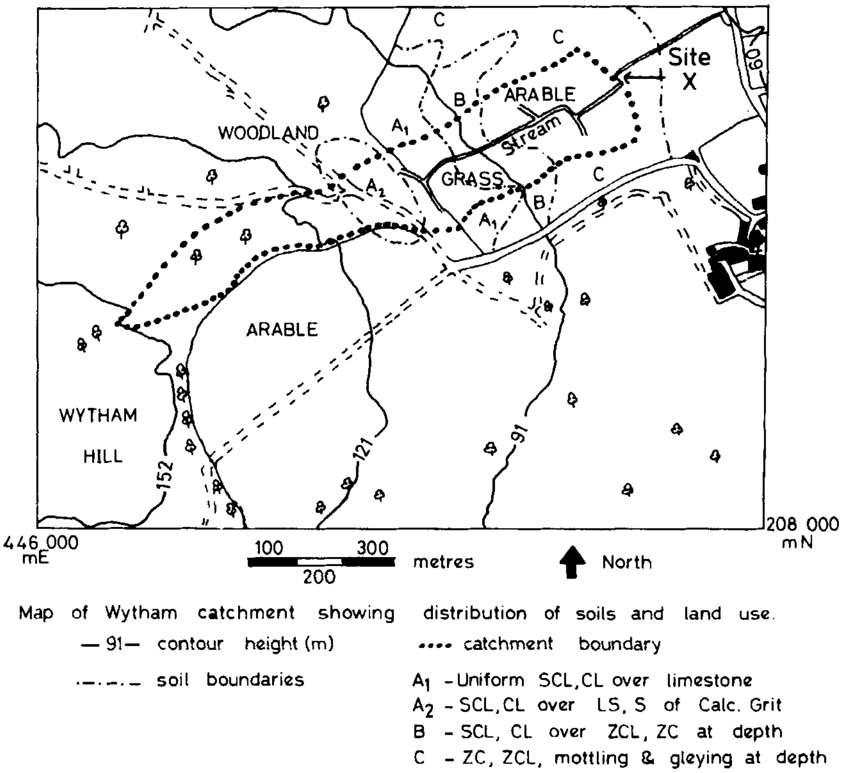


Figure 1. Map of Wytham catchment showing distribution of soils and land use (Legend as on figure)

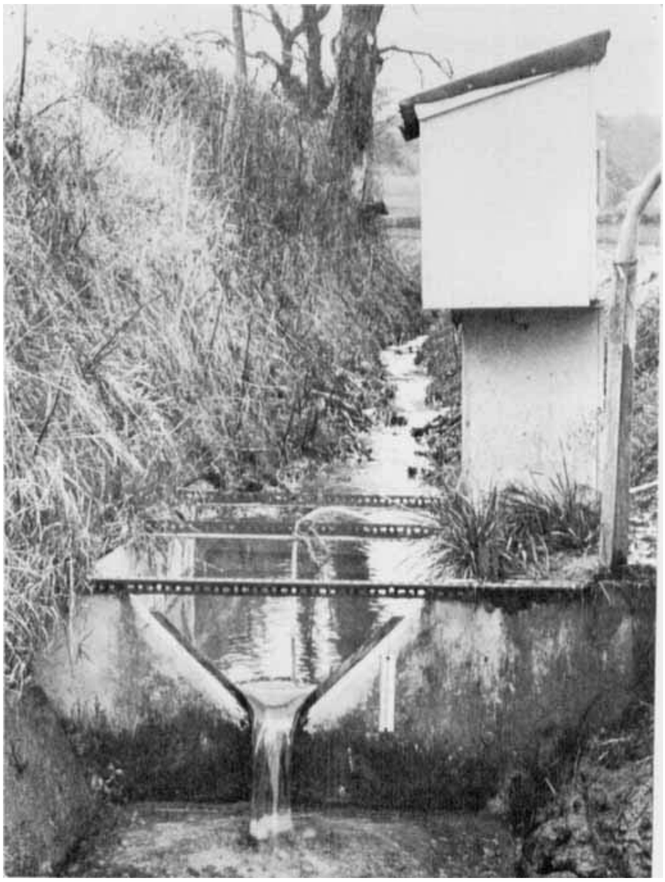


Figure 2. The 90° partially contracted V-notch weir and stage recorder housing

recorder using a 15 cm diameter float and a tape wheel to scroll wheel ratio of 1 : 11 to 1. The chart on the clock-driven chart drum is changed once weekly. The calibration was checked regularly and the value of h found to be accurate to $\pm 0{\cdot}25$ cm (maximum range 25 cm). Discharge Q in $m^3\ h^{-1}$ is calculated from the formula:

$$Q = 0{\cdot}04932\ h_e^{5/2}$$

where $h_e = h + 0{\cdot}08$ (cm).

The water sampler

The Rock and Taylor multipurpose liquid sampler (A in Figure 3) takes a maximum of 48 samples of up to $0{\cdot}55\ dm^3$ by means of a rotating arm that delivers water to a single bottle during the forward cycle of the peristaltic pump B. The pump intake tube is placed in the weir stilling pond. The volume of sample is varied by altering the forward pumping time, the maximum time required in our system being 2·5 min. After each sampling, the connecting PVC tubes are flushed out by reversal of the pumping action for 1 min. The sampler offers a choice of 7 sampling programmes—we set it to operate on external impulse, cycle 3, which pumps one sample into each bottle. When the sampler is switched on, the initiation and frequency of sampling is governed by predetermined rainfall criteria, as described below.

There were no significant or consistent differences in conductivity, NO_3-N and PO_4-P concentrations between pumped and manual samples collected at the same time. Sediment concentrations in the pumped samples were 90 to 94 per cent of those in the manual samples.

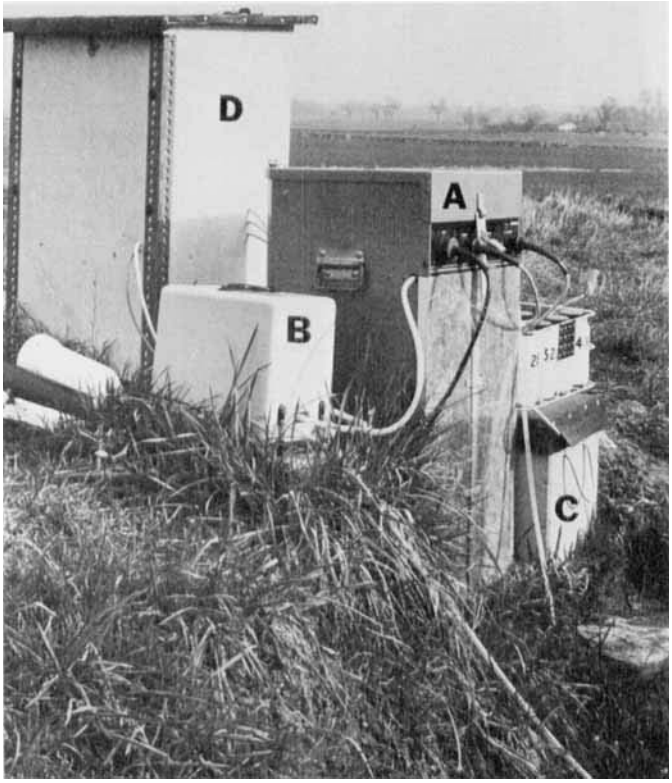


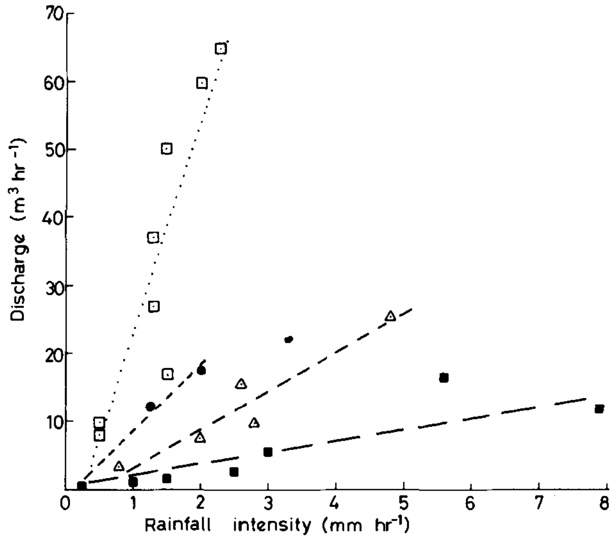
Figure 3. A. Multipurpose liquid sampler; B. Peristaltic pump; C. 12 V lead accumulator; and D. Housing for recording system

The recording raingauge

The relationship between discharge and rainfall intensity. Many years ago Childs (1943) observed a very close relationship between rainfall rate and the flow rate of mole drains in a clay soil at Cambridge. Similarly, our observations on the small clay soil catchment at Wytham over four years from 1 September 1976 indicated that the rise in stream discharge from the base flow level during a storm was closely correlated with the intensity of rainfall. The stream responded quickly to rainfall and, depending on the antecedent soil moisture deficit (SMD), peak discharge occurred within 30 min to 2 h of peak rainfall, which was comparable to Childs' estimate of 27 min (with a standard deviation of 35 min) for the period between rainfall pause and the decline in drain discharge.

The graphs in Figure 4 exemplify the catchment response to moderate intensities of rain falling on different occasions when the estimated SMD ranged from 0 to 80 mm. By matching the peak discharge to peak rainfall for each event and proceeding back along the rising limb of the stream hydrograph, the observed relationships between discharge ($m^3 h^{-1}$) and rainfall intensity ($mm h^{-1}$) were obtained. The correlation coefficients of the fitted linear regressions lay between 0·89 and 0·99. (Prior to 25 May 1978, the SMD values were obtained from Meteorological Office records for mixed land use in the Thames Conservancy; subsequently they were calculated directly from changes in soil moisture measured by the Wallingford neutron probe (Bell (1976)). Certainly the relationship between discharge and rainfall intensity during the rising hydrograph is not always linear and can be disturbed by rapid and erratic fluctuations in rainfall during a storm, but it was consistent enough to warrant an attempt at controlling the sampling of stream water by linking the Rock and Taylor sampler to a recording raingauge.

Raingauge and sampler operation. The Rimco Type R/TBR raingauge is designed to operate unattended for long periods. It has a 280 mm diameter funnel and is fitted with a syphon of 0·2 mm capacity which discharges into a tipping-bucket assembly. Each tip of a bucket closes a mercury microswitch and allows a



Symbol	Date	SMD (mm)	Regression equation	r value
●	3.10.76	55	$Q = -1{\cdot}54 + 9{\cdot}96\,P$	0·99
■	16.8.77	80	$Q = 0{\cdot}66 + 1{\cdot}60\,P$	0·93
□	27.1.78	0	$Q = -8{\cdot}71 + 31{\cdot}41\,P$	0·89
△	10.5.79	15	$Q = -2{\cdot}43 + 5{\cdot}68\,P$	0·96

Figure 4. Relationship between stream discharge Q and rainfall intensity P during storm events

pulse of current to pass to the control and recording system. This system also includes a quartz crystal timer and cassette tape recorder so that the time interval (to the nearest minute) during which each 0·2 mm of rain that falls is recorded. The number of pulses received from the start of rainfall is stored and used in the control of the water sampler's operation.

With the sampler on, pumping commences whenever rainfall reaches a preset threshold intensity. From our experience of the catchment, we set the threshold intensity at 1 mm (5 pulses) in 20 min—this enables a sample to be taken at the onset of heavy rain before there is a surge of stream flow, but does not initiate sampling when the rainfall is too light to cause a significant raise in the hydrograph. Once started, sampling continues on the rising hydrograph at the rate of 1 sample/1 mm of rain but there is a 'dead' period of 5 min after the start of each pumping sequence to allow the forward and reverse cycles of the pump to be completed and the sampler distribution arm to move to the next position.

When the rain stops, or the intensity falls below 1 mm in 20 min, sampling continues at fixed time intervals until a further 9 samples are collected, or sample No. 48 is collected, when the sampler stops. Originally we chose an interval of approximately 90 min; but subsequent inspection of the hydrographs and an assessment of the time taken for the 'quickflow' response to subside (Hibbert and Cunningham (1967)) suggested that a 2 h interval was more appropriate, giving a total sampling period of 18 h for the recession limb of the hydrograph, which is therefore the minimum sampling period for any event which attains the threshold intensity. The recession limb routine may be interrupted and a new sequence initiated if rainfall intensity again increases above the threshold. The intensity and time criteria imposed on sampling during a storm event may of course be varied to suit the response characteristics of individual catchments.

If there is a short storm in which rain ceases before the stream responds the sampling rate will be low (1 sample/2 h) during the whole of the hydrograph, but this is not an event of much hydrological interest. In keeping with Childs (1943) we have found that most of the rainfall which produces a significant stream response consists of intense showers of variable duration separated by periods of relative quiescence. Our system works well under these conditions, with frequent samples being collected when discharge is changing most rapidly. Clearly the system does not give strictly proportional sampling over the whole hydrograph, but if further observations confirm the need, it would be possible to combine the use of rainfall measurements on the rising hydrograph with the sensing of water level change on the falling hydrograph, to initiate and control the water sampling. We could then also record water level and time to give additional detail while sampling is in progress.

The recorder circuit

This was originally designed to record operation of the raingauge and sampler; temperature measurements were added later. The system was specifically arranged so that data could be read from the tape directly into an electro-mechanical printer (ADDO-X) which was available as part of other equipment. This dictated the rate of data recording. Furthermore, with a view to the possible use of semiconductor memories, a simple binary coding system was used and decoding was carried out by the University computer into which data was fed manually.

In future, the data will be processed by a micro-computer which can read directly from the tape. The rate of data flow can then be increased and additional data recorded if desired. Alternatively, if semiconductor memories are used these can be read directly by the computer although cost may limit the size of memory available. The main limitation in the use of high speed tape recording is that time must be allowed for the recorder to run up to speed under the worst conditions of temperature and voltage.

Our recording system has advantages for operating in remote areas because of its robustness, low cost, low power consumption and ability to function for long periods without attention. The electronic components are made from CMOS integrated circuits which have extremely low power consumption. The tape recorder runs for only 2–3 s at a time to record the operation of the raingauge or sampler. Pumping the water samples consumes most of the power, the additional consumption due to the recorder not exceeding 1 Ah per week. During dry periods, one tape will last for many weeks but even during wet weather we have not needed to change the tape more than once fortnightly. The tape recorder and all the electronic components are enclosed in a polythene freezer-storage box which is housed in a wooden cabinet (D in Figure 3). This has proved very effective in keeping the equipment in good order during varied weather conditions. In addition, operations to be carried out on site are kept to a minimum so that bad weather does not interfere with data retrieval.

A block diagram of the components is given in Figure 5. A crystal-controlled timebase provides an output at 100 Hz. This is fed into a 16-stage divider which controls the timing of all operations. The data bit rate is

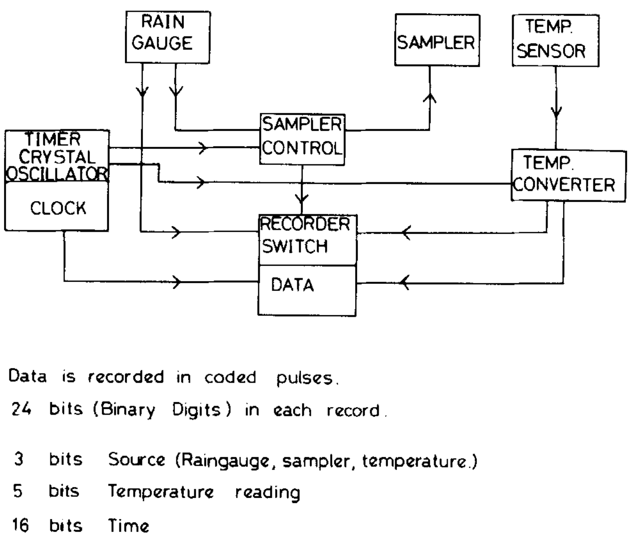


Figure 5. Block diagram showing the components of the recorder circuit

$12 \cdot 5/s^{-1}$ and the recorded time interval is 40·96 s. A further 16-stage divider and shift register timer allow periods of approximately one month to be measured. Since the equipment is subject to considerable temperature change and also to possible fluctuations in battery voltage, a system of recording which is insensitive to fairly wide variations in speed of the tape recorder was selected. This also permitted the use of a cheap tape recorder. Pulse length modulation is used, each data bit consisting of 10 ms (0) or 40 ms (1) of a 2 kHz signal with a 40 ms space between data bits. The playback system has to select between two widely different pulse lengths which allows considerable tolerance in speed and this has proved very reliable in practice. The timer is set to zero whenever the tape is changed and Greenwich Mean Time is recorded. After a run of one month the accuracy of timing has always been within 2 min as checked by a test pulse applied at the end of the tape. Even when the battery voltage has been too low to operate the sampler, the timer has functioned accurately.

As indicated in Figure 5, the recording system can also accept inputs from other sensing devices. As part of a study of calcium and bicarbonate equilibria in the Wytham stream water, we are measuring water temperature at approximately 90 min intervals using a semiconductor sensor encapsulated in epoxy resin. The sensor is connected to an analogue-to-digital converter and the digital output is fed to the tape recorder together with the time pulse code. The temperature is checked with a mercury thermometer when the tape is changed and agrees with the recorded data within the 0·5°C step output of the sensor.

Current costs of system

The cost of the components of the control and recording system are as follows:

Sampler control	£24
Recorder	£15
Visual display (if required) *c.*	£20

RESULTS OF FIELD OPERATION

The recording equipment was installed in the catchment (site X, Figure 1) in December 1978 after laboratory testing. It has functioned satisfactorily during very cold weather (January–February, 1979) and during heavy rainfall (December, 1979). However, in areas which regularly experience prolonged and very cold winters, we suggest the use of a Rimco Type R/TBR-8HG raingauge which has a thermostatically-controlled heater fuelled by liquified petroleum gas.

An example of the data provided by the whole system—raingauge, weir, stage recorder and sampler—is presented in Figure 6 for a storm of 20 mm on the 10–11 May, 1979. The SMD at the onset of rain was $\approx$15 mm. The water samples, each of 0·5 dm^3, were filtered through 0·5 μm 'Nuclepore' polycarbonate filter papers which were subsequently dried and weighed to determine the quantity of suspended sediment in the sample. Nitrate in the filtered water was determined by the distillation procedure of Bremner (1965).

As expected, the peak in sediment concentration was virtually coincident with peak discharge; there was also a close correlation between NO_3^- concentration and discharge on the recession limb of the hydrograph. The initial rise and subsequent fall in NO_3^- concentration on the rising hydrograph has been observed consistently in the nitrate 'chemographs' of other events of moderate rainfall intensity, when there has been no evidence of significant surface runoff. However, these and other interesting features of the solute 'chemographs' will be discussed more fully elsewhere in terms of solute retention and release processes occurring in the soil (White, Macduff and Kneale (unpublished)).

CONCLUSION

We have described the current state of development of our integrated rainfall recording–water sampling system which is providing useful data for the study of water movement and solute processes in the Wytham catchment. Its performance is being continuously evaluated with a view to identifying weaknesses and making improvements, as indicated in the second section. In future it is likely that semiconductor memories will become cheap enough to replace the tape recorder as an information store—our system can be easily

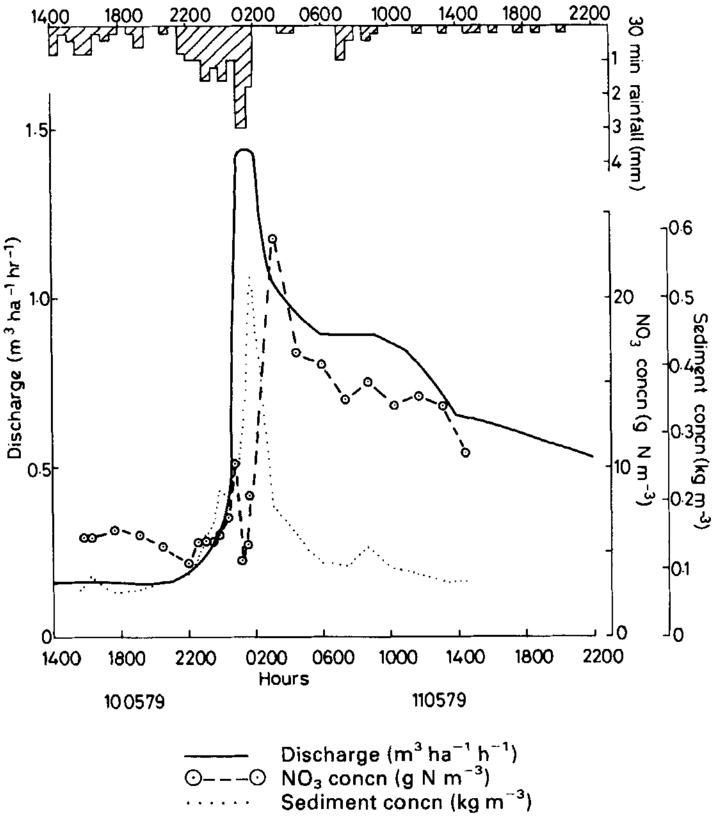


Figure 6. Rainfall, discharge and water quality records for a storm event of 10–11 May 1979

modified to that end. Furthermore, if the power consumption of readily available microprocessors were to be markedly reduced, such devices could be used with advantage to replace many of the integrated circuits in the system.

Further information on the design and construction of this rainfall recording–water sampling system is available from the authors on request.

ACKNOWLEDGEMENTS

We are pleased to acknowledge the contributions of Mr. F. Honey, Mrs. J. Hughes, Mr. A. Probitts, Mr. E. Rhymes, Mrs. J. Inglis, and the late Mr. C. Donaldson to this project, and to Professor G. W. Thomas of the University of Kentucky who drew our attention to the work of Childs (1943).

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