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MEASURING THE FLOW OF THE RIVER AVON USING THE CONSTANT RATE DILUTION GAUGING METHOD

by

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ABSTRACT

This report describes the methods and results of a constant rate dilution gauging exercise to measure the discharge of the River Avon at Christchurch, Dorset. The objective was to provide a calibration point for an ultrasonic gauging station then being operated by the Water Research Centre. A team from WRC was present at the time of the dilution gauging work and carried out gaugings by the velocity/area method. Comparing the three methods, the dilution gauging result was significantly higher then the other two. It is thought that this was because steady conditions, essential for the correct determination of flow by the constant rate injection method, had not been attained. However, it is argued that the knowledge gained in developing the techniques, both technical and analytical, offset to some extent the less than satisfactory nature of the result, and that slow-moving rivers such as the Avon represent the limit of applicability of the method.

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1. INTRODUCTION

When a permanent river gauging structure is installed, all possible effort should be expended at the outset to obtain a reliable calibration. The methods available comprise theoretical analysis, laboratory calibration and field calibration (White 1975). Field calibration, although it is the most direct method, is difficult and expensive, and is usually not justified for conventional structures. However, in some cases, direct discharge measurement by the velocity/area method or dilution gauging is the best means of checking the theoretical rating of a structure.

The Knapp Mill ultrasonic gauging station on the River Avon at Christchurch was installed in July 1974, and was ready for field calibration in October 1974. At the request of the Water Research Centre, the flow of the Avon was measured by dilution gauging, using constant rate injection of sodium iodide tracer. Gauging by the velocity area method using multiple-rod mounted current meters was carried out simultaneously by a team from the Water Research Centre (Green and Ellis 1974).

In the dilution gauging method normally used by the Institute, tracer solution is injected into the stream at a single point. This single-point injection is appropriate for rapid, turbulent mountain streams where good mixing of the tracer can be assured. However, the Avon at Knapp Mill is 24 m wide and 2 m deep and has a mean velocity of approximately 0.5 m s^{-1}; a single-point injection would thus necessitate an impracticably long mixing distance. It was therefore necessary to develop a multipoint injection method which could distribute the tracer across the river at the injection cross-section and so reduce the distance between injection and sampling sites. A preliminary measurement of the flow using dilution methods was made on 11 October 1974, and the following problems were encountered:

(i) *mixing length*

An initial estimate of 400 m for the distance between injection amd sampling points was found to be insufficient. A preliminary gauging, though expensive, is the only sure method for determining the mixing length.

(ii) *sampling*

Samples were taken using bottles clipped to a rod which was lowered from a boat at intervals across the river. This method had the disadvantage that the location of each sample was not accurately known or repeatable.

Further gaugings were undertaken on 15, 16 and 17 April 1975, with modifications suggested by the preliminary gauging. The mixing length was kept at 400 m on the 15th, but was increased on the

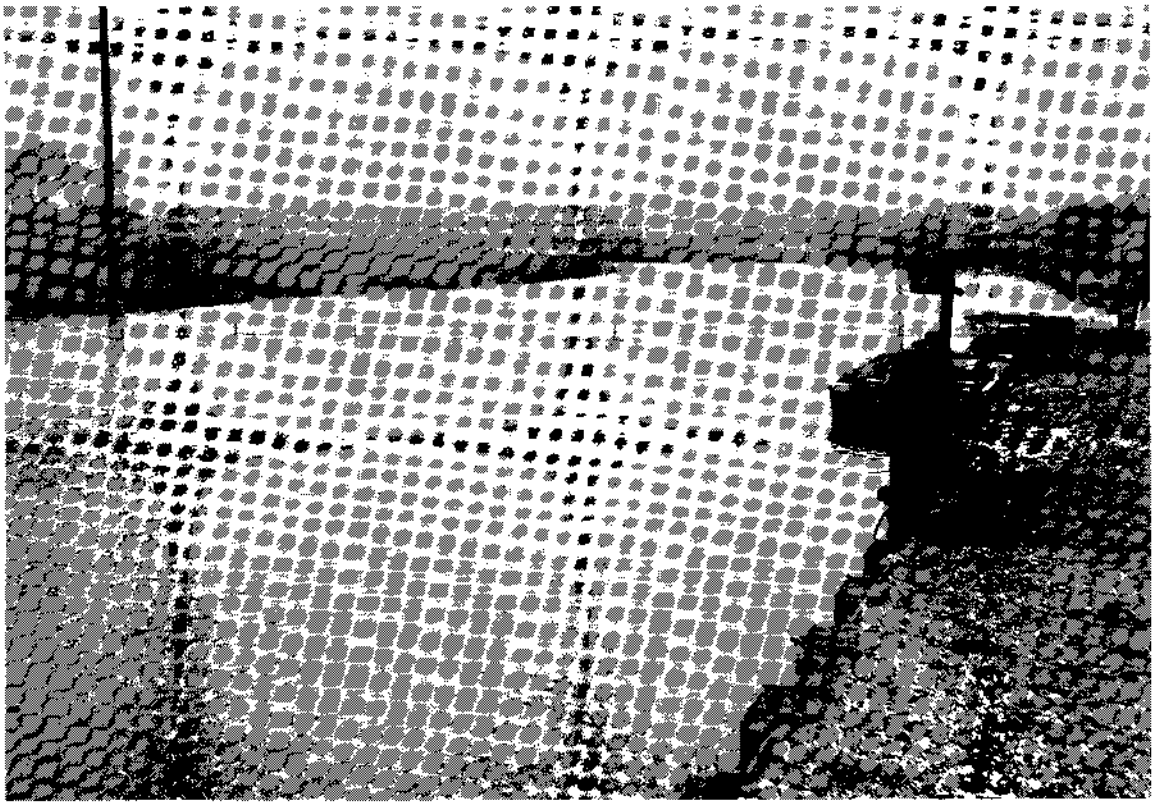


PLATE 1 Sample site looking downstream

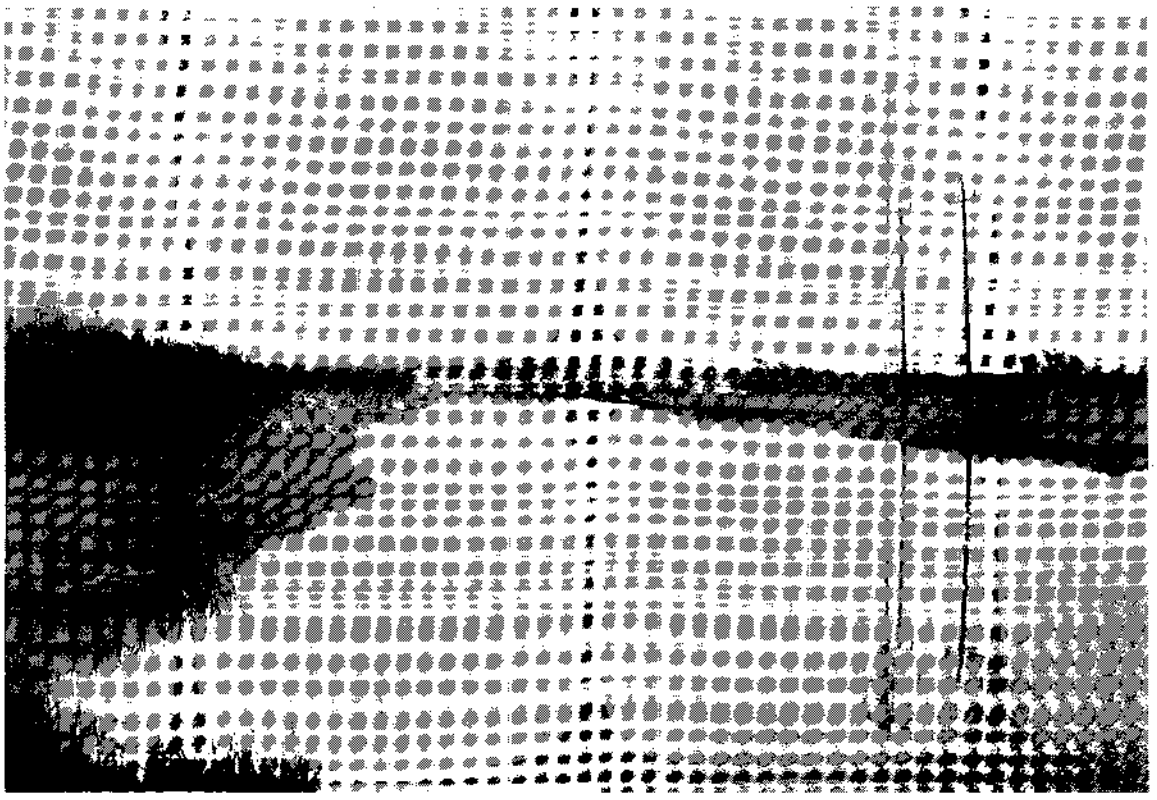


PLATE 2 Sample site looking upstream

subsequent days. Samples were taken by peristaltic pump from an array of points on a series of rods driven into the river bed.

The dilution method is best where mixing, which is central to the method, can be established without difficulty. Chemical tracers are most appropriate for small rivers, where the bulk of injected tracer is not large. Using the method on the River Avon was therefore testing the chemical gauging technique to its limit, and, as the results show, further refinement would be necessary to obtain a satisfactory conclusion. However, the value of the Avon study lies in the methods of tracer distribution, sampling and statistical analysis, which will probably prove useful in other dilution gauging exercises.

2. LOCATION OF THE GAUGING SITE

The River Avon has its source in the greensand of the Vale of Pewsey but derives the bulk of its flow from the Chalk of the Salisbury plain, as do two of its tributaries, the River Bourne and the River Wylye. These rivers, together with a further tributary, the River Nadder, join at Salisbury before flowing over the Tertiary outcrop north of Fordingbridge. Downstream of Fordingbridge there are a number of small streams flowing from the sands and gravels of the New Forest, whose normal flow is extremely small but which, after heavy rainfall, contribute an appreciable portion of the flood flow. The Avon discharges into Christchurch Harbour, which has a very small tidal range, the river itself being influenced by the tide to a point 1000 m downstream of the Wessex Water Authority's intake at Knapp Mill (Avon and Dorset River Authority 1970).

The ultrasonic gauging station (43/21) is situated approximately 500 m upstream of the water intake (gauging station map reference SZ 155943). The river at this site and for several kilometres upstream is slow moving and meanders across a gravel flood plain.

Ultrasonic river gauging is in principle a form of the velocity/area method. A change in frequency, explained by the Doppler effect, occurs when an ultrasonic beam is transmitted horizontally and diagonally across the flow. From this change in frequency, the integral of the stream velocity along the beam may be computed. The method requires that there should be a measurable component of velocity parallel with the beam; consequently the beam is usually transmitted at an angle of about 45° to the flow direction. At Knapp Mill the river banks are defined by steel sheet piling for 31 m along each side of the river, and the station is sited at the downstream end of a straight reach 250 m in length.

Figure 1 shows the location of the experimental sites. The ultrasonic station was used as a sampling site (A) for all dilution gaugings. The injection site for gaugings on 11 October and 15 April was at point B (grid reference SZ 157945), while the injection site for gaugings on 16 and 17 April was at C (grid reference SZ 158947). B is approximately 400 m upsteam of A, while C is approximately 700 m upstream of A. Plates 1 and 2 show the wide sluggish nature of the river at site A.

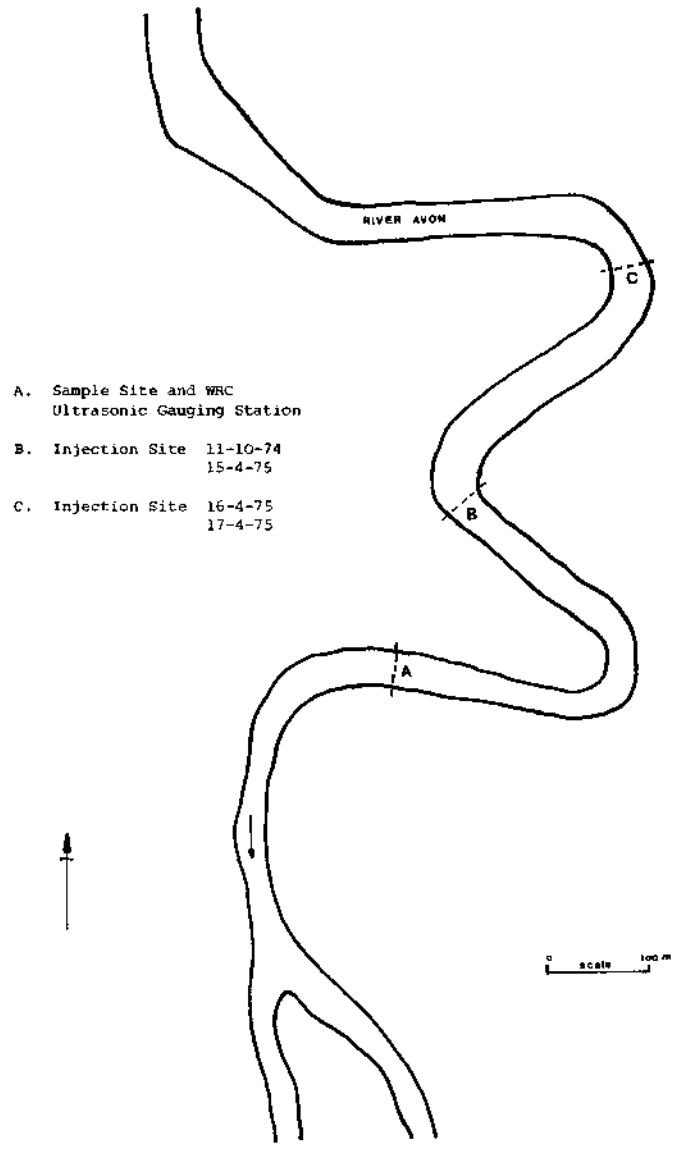


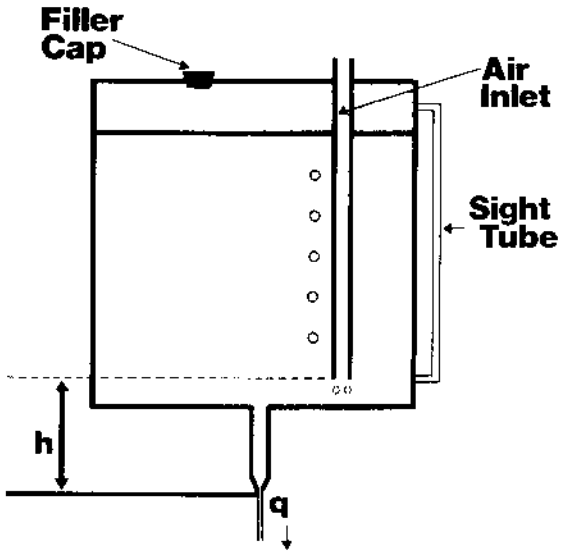
FIGURE 1 Map of dilution gauging sites on the River Avon

3. METHOD AND APPARATUS

The tracer dilution method of stream gauging is based on the principle of mixing a known amount of a tracer with the stream flow, and determining the discharge from the dilution of the tracer. Two methods are available; the constant rate injection and the sudden injection. For chemical tracers, neither technique can be said to be simpler or more precise: the constant rate method requires a careful injection of tracer, while the sudden injection (integration) method has more sampling problems. The Institute has more experience with the constant rate method, so this was selected for the Avon gaugings.

The constant rate injection method is described in publications by the British Standards Institution (1964), the International Organisation for Standardisation (1973), and in a manual by the Water Research Association (1970). Greenland (1975) described in full the methods and equipment used by the Institute for gauging mountain streams, while Truesdale and Smith (1975) presented the analytical method for the iodide ion.

The essential similarity in method between the gaugings described in this report and that of gauging mountain streams is the Mariotte vessel which ensures a constant rate of injection of tracer (Figure 2).



h - is the constant head.
q - is the constant discharge.
q - is varied by changing the orifice diameter.

FIGURE 2 Mariotte bottle

The Mariotte is an airtight vessel with a nozzle near its base. The tracer solution flows out through the nozzle, and air enters the vessel through a tube at a fixed height above the nozzle, maintaining atmospheric pressure at the lower end of the air inlet. Thus the head of tracer on the nozzle and consequently the injection rate remain constant, independently of the level in the vessel. A sight tube is fitted to the side of the vessel. This sight tube is graduated so that readings of the level in the Mariotte vessel can be made at different times during the injection. The rate at which injection of tracer occurs may be controlled by the choice of nozzle diameter, giving a range between one and ten millilitres per second.

1. Injection of tracer

Since a single-point injection, especially from the bank of the river, would need a much longer mixing distance, the tracer solution was distributed across the injection section by the multipoint injection apparatus shown in Figure 3 and Plate 3. Sodium iodide solution was injected at constant rate from a Mariotte vessel and spread across the river by centrifugal pumps. This method was used without modification for all the gaugings.

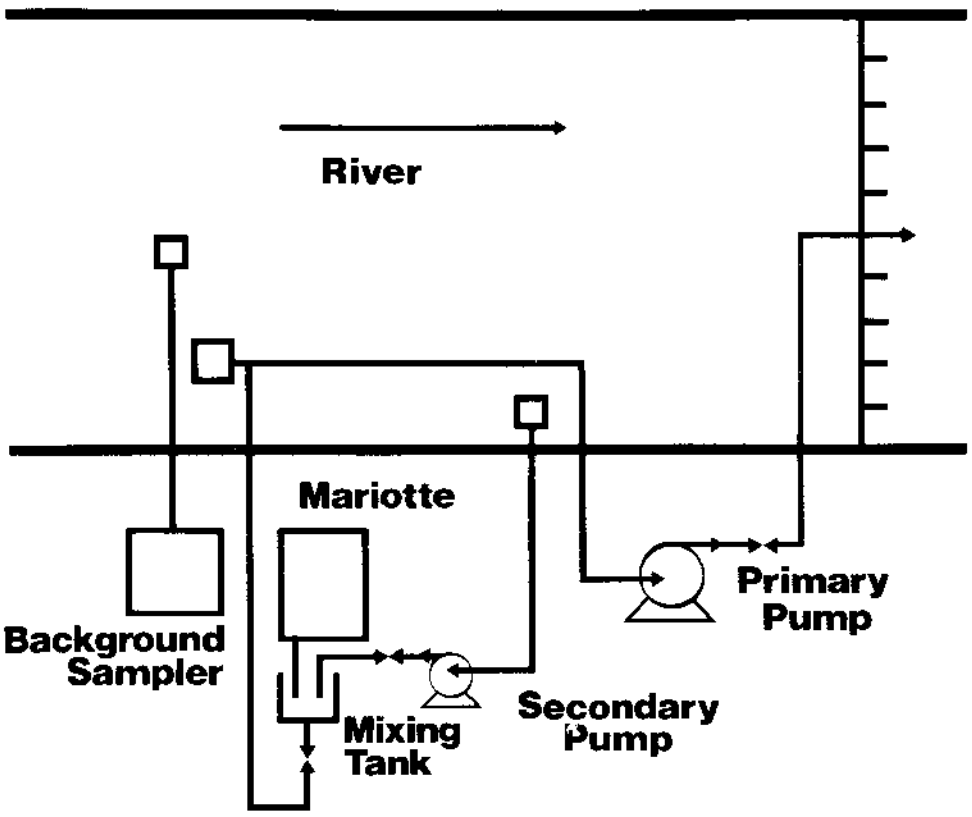


FIGURE 3 Diagram of multi-point injection apparatus

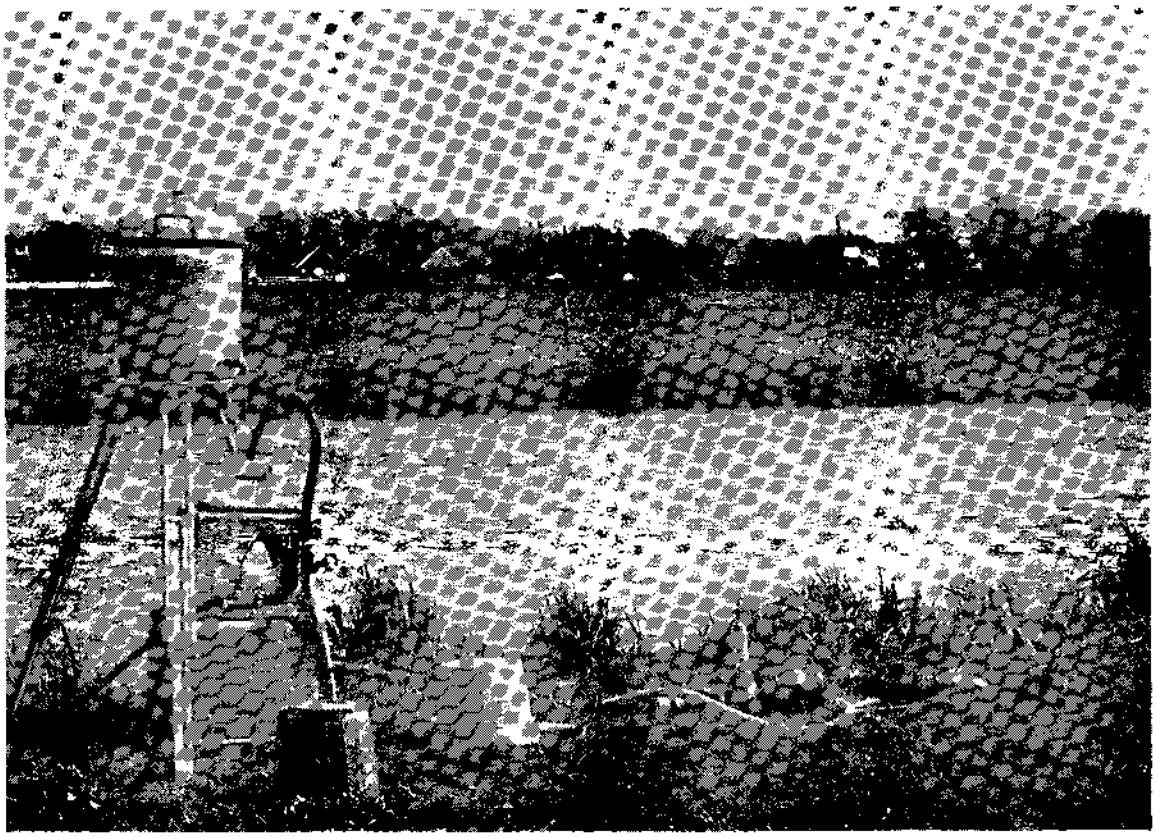


PLATE 3 Injection site C showing Mariotte and injection pumps

Injection equipment

(i) Mariotte vessel

Figure 2 and Plate 4 show the Mariotte vessel, with a volume of 50 litres, used in the Avon gaugings. The injection rate was measured in the field by taking readings of the time from the start of injection, and the sight tube reading. A nozzle was selected which would give a five-hour injection.

(ii) Pumps

The Mariotte vessel injected tracer solution into an open vessel; the solution then drains into the inlet of a large centrifugal pump. The open vessel was flushed with river water by a smaller centrifugal pump. The large pump maintained a steady flow of about 2 litres per second of river water and tracer, which was injected into the river through a perforated hose.

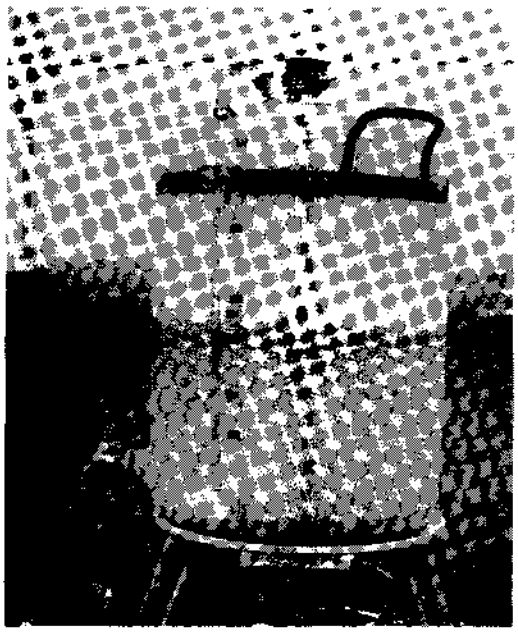


PLATE 4

Mariotte vessel at site C

Tracer

Sodium iodide (BP grade) was used as the gauging tracer. The quantity of tracer in the Mariotte vessel, and the injection rate, were chosen to give a downstream rise in iodide concentration of 40 µg/l. For each gauging 25 kg of sodium iodide was mixed with river water in the Mariotte vessel and shaken until dissolved.

Injection procedure

To maintain a constant discharge, the Mariotte vessel must inject at atmospheric pressure. For this reason a secondary pump was used, with an open vessel to receive tracer from the Mariotte. The level of solution in the open vessel was kept constant by manipulation of valves on its inlet and outlet. The outlet was led to a tapping on the inlet pipe of the large pump, above the foot valve, and the outlet from this pump was connected to the middle of a perforated hose spanning the river at the surface, ensuring that the tracer solution was spread across the river.

Both pumps were of the centrifugal type, and required priming. A 2.5 kW generator provided 240 v AC power.

Injection samples

Samples of tracer solution were taken from the Mariotte vessel after each injection. The samples were diluted to approximately 40 µg/l, and the concentrations of iodide determined by catalytic spectrophotometry.

Injection data

TABLE 1. Injection data

Date	Mariotte No.	Nozzle No.	Duration of injection (h)	Volume injected	Concentration g/l
11.10.74	7	47	2.08	41.1	168
15. 4.75	8	54	4.65	38.6	516
16. 4.75	8	54	5.17	41.1	528
17. 4.75	8	56	6.47	35.0	679

2. River sampling

When a tracer is injected at constant rate into a stream, the concentration of tracer at the sampling point downstream rises from its background level to a final steady-state or 'plateau' level. It is this plateau level which is of interest, for when the downstream concentration is at steady state, it is known that a tracer balance has been reached, and the tracer output rate of the gauging reach may be set equal to the tracer input rate. To establish the rise in concentration due to the tracer injection, two measurements are required: the natural or background level and the plateau level.

Samples are usually taken at several points across the river to check for adequate mixing of the tracer and it was decided to sample at several depths also in the Avon gauging exercise.

Preliminary gauging (11.10.74)

(i) Downstream samples for plateau concentration

A sampling rod, with four bottles attached at distances of 0.3, 0.8, 1.4 and 2.0 m from the bottom of the rod, was lowered quickly into the river from the side of a small boat. By lowering the rod at 2 m intervals a profile of 48 samples across the river was obtained. The profile samples were taken when the rise to plateau concentration was believed to be complete. Single samples were taken every five minutes from the centre of the river with a throwing bottle, to show the rise to plateau conditions.

(ii) Background samples

Background samples were taken by an automatic sampler at a rate of one sample every half-hour, so that any variation in background could be monitored. The sampler was situated 5 m upstream of the injection site.

Later gaugings (15, 16 and 17.4.75)

(i) Downstream samples for plateau concentration

An improved sampling techniques was developed for the later gaugings. Ten steel rods, 25 mm diameter and 2.7 m in length, were driven firmly into the bed of the river and secured to a rope across the river at the surface. The rods were spaced 2.5 m apart across the river (Figure 4 and Plate 5). To each of the rods five 3 mm internal diameter PVC tubes were attached, ending at distances 0.6, 1.05, 1.5, 1.95 and 2.4 m from the bottom of each rod, making a grid of 50 sample points. The 30 m long PVC tubes led to the bank, where a ten-channel peristaltic pump was used to extract samples.

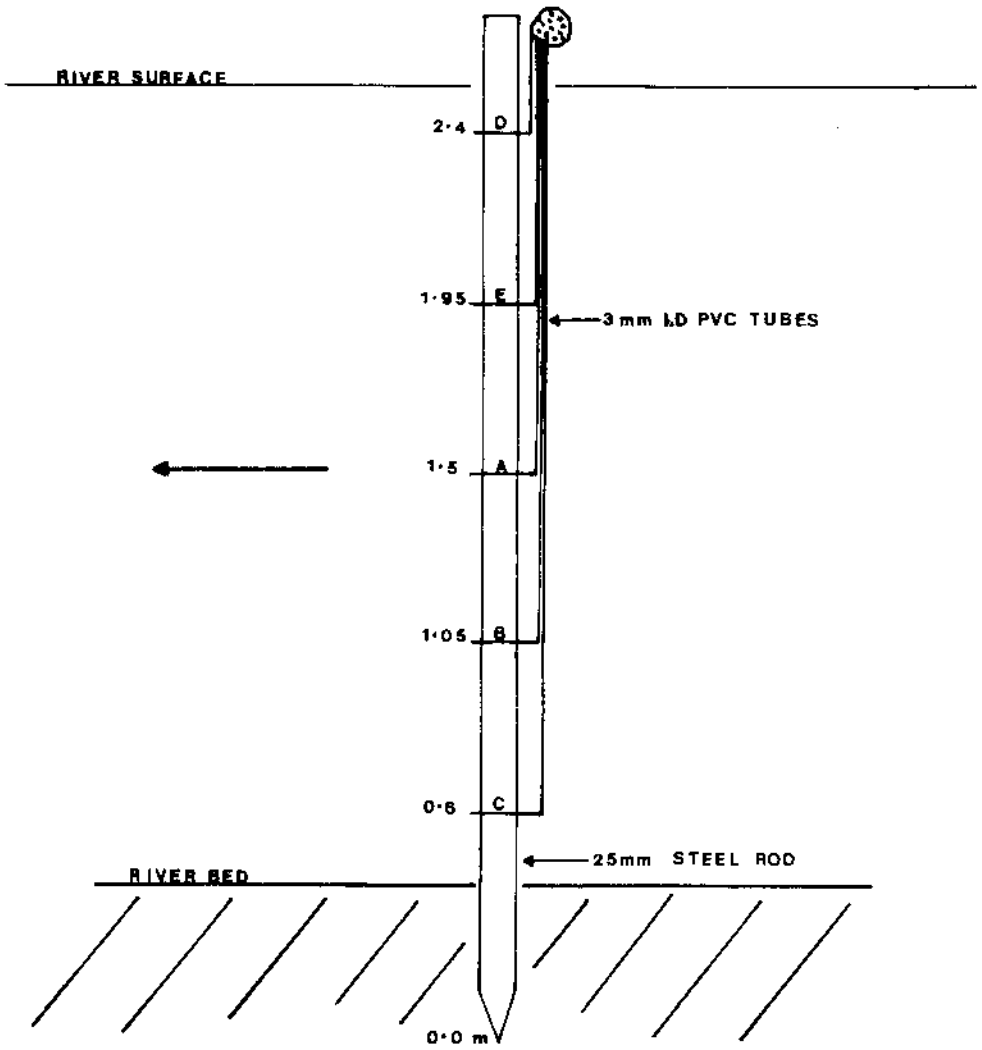


FIGURE 4 Detail of sampling rod

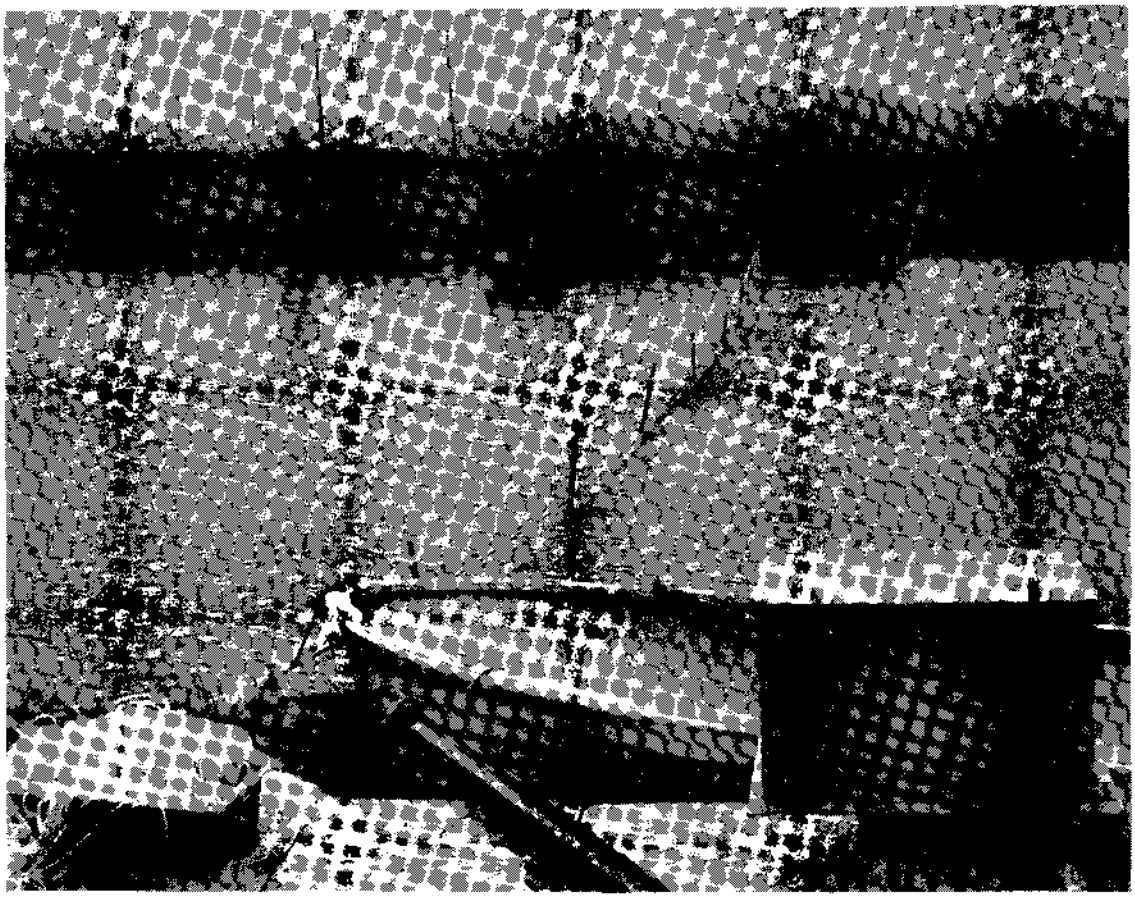


PLATE 5 Sample site looking across to the left bank

With this system ten samples could be taken simultaneously. At a pumping rate of 40 ml/min, it took ten minutes to clear the tubes and take a sample, so a complete profile of 50 samples could be taken in an hour. The sampling grid was arranged so that in each batch of ten samples one was taken from each vertical. Moreover the simultaneous sampling positions on adjacent rods were as far apart as possible. Figure 5 shows the sampling grid. The batches of ten samples were lettered from A to E. The sampling sequence started with the ten As (part profile A) and ended with the ten Es (part profile E) to make up the complete profile of 50 samples. Within the part profiles each vertical (rod), and hence each sample, was numbered between 0 and 9.

(ii) Midstream samples at the sampling site

One midstream sample was taken every five minutes at the start of the gauging and every ten minutes during the profile sampling period. The midstream sample was taken through a tube coming from the middle of the river near the surface to a single peristaltic pump. This pump sampled continuously at a rate of 100 ml/min, and each sample represented a five minute or ten minute average.

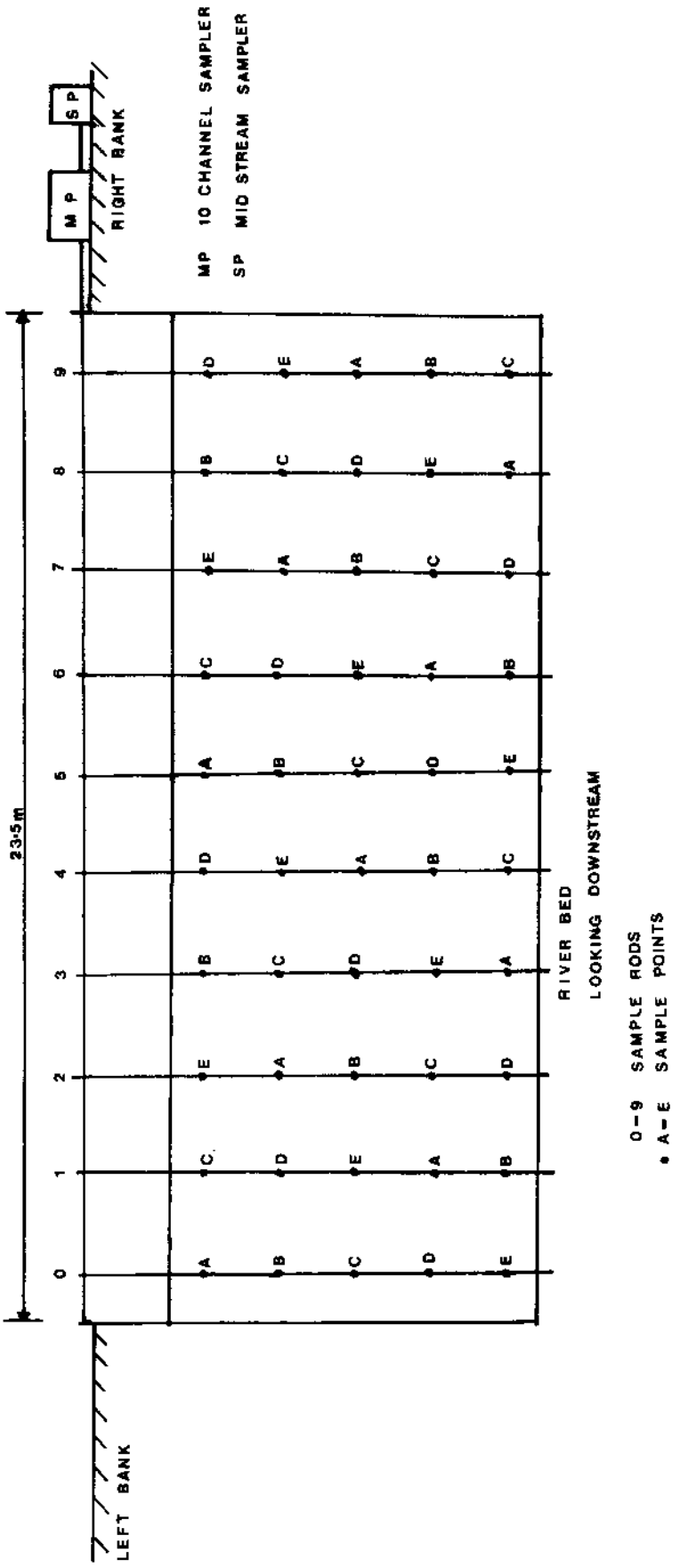


FIGURE 5 Randomised multi-point river sampling system

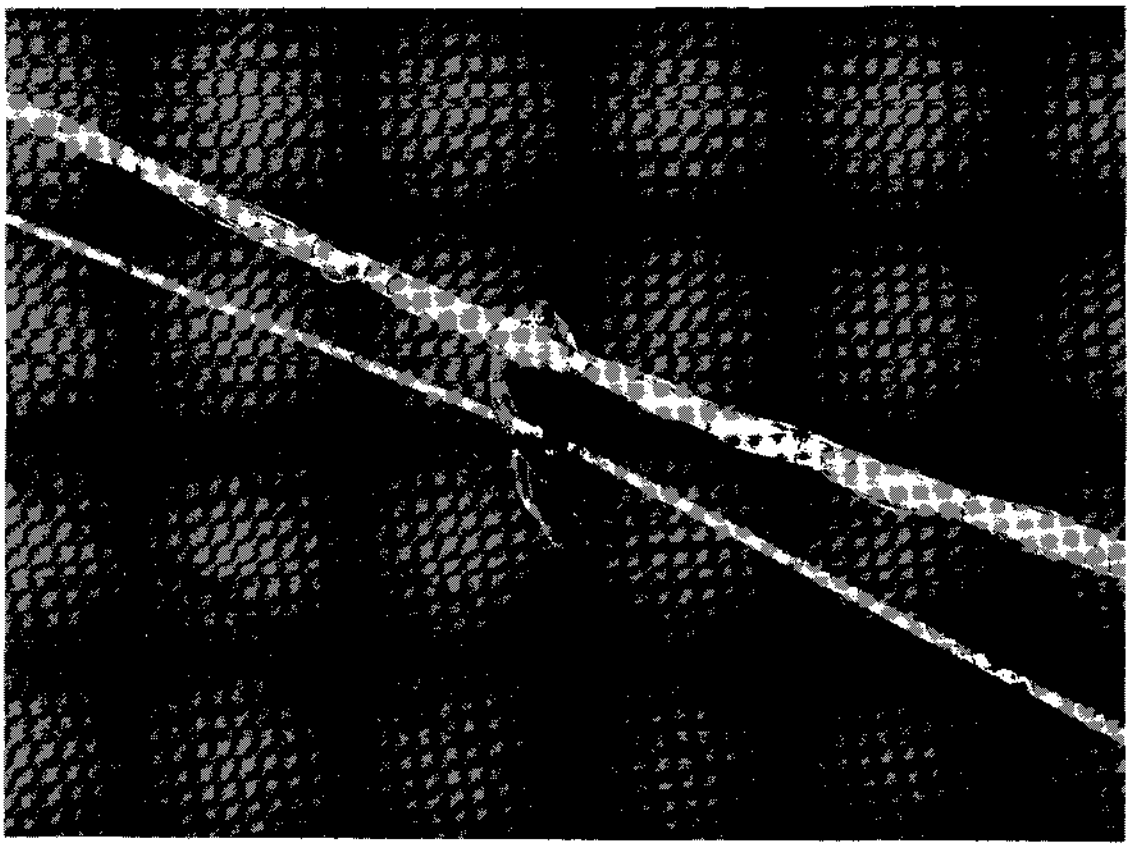


PLATE 6 Detail of Rod 8 and the sample tubing

PLATE 7 Sampling from a boat using a sampling rod. 11.10.74

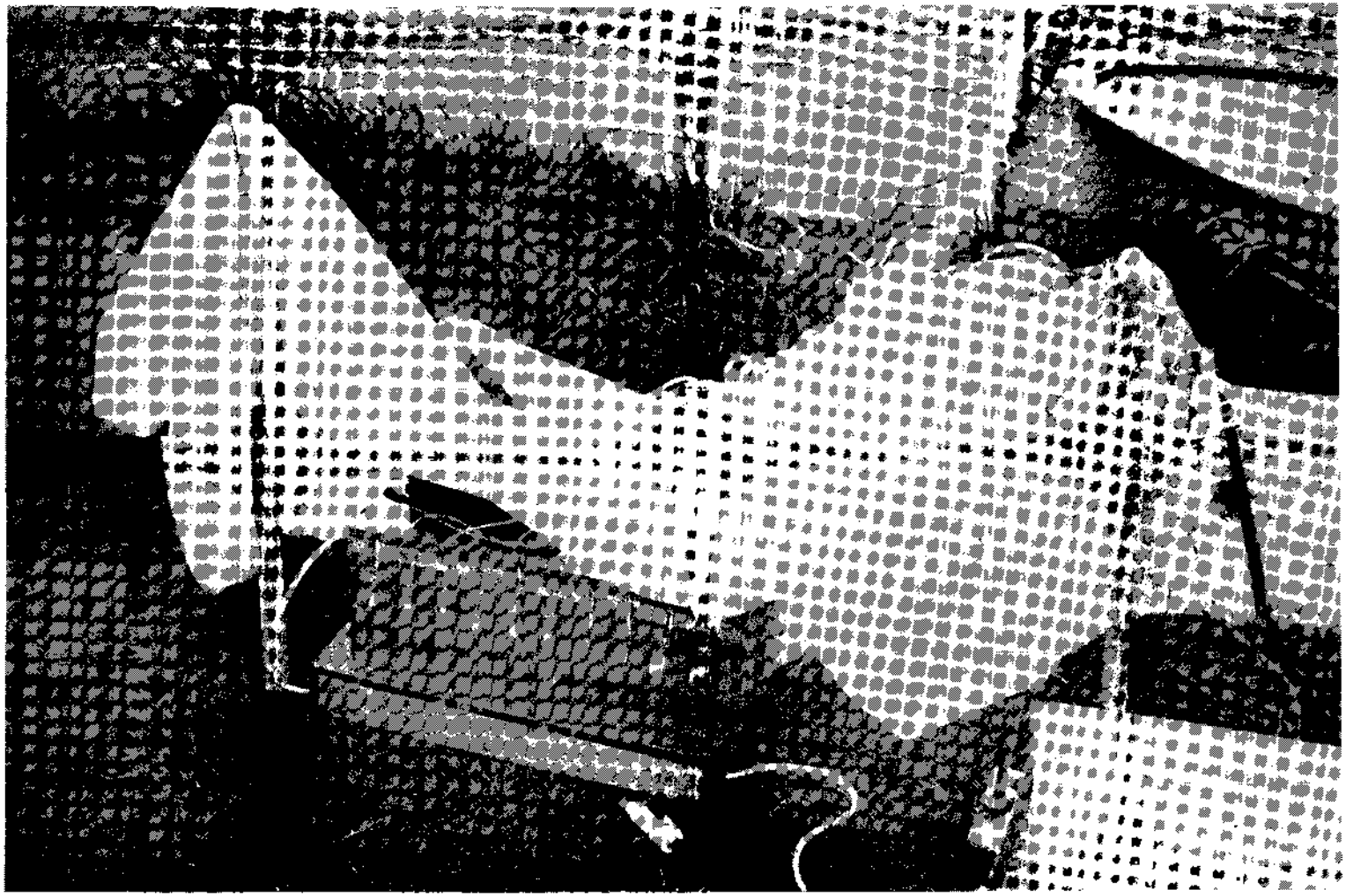


PLATE 8 During sampling ten bottles are filled at a time by a 10-channel peristaltic pump. 16.4.75

(iii) Background samples

Duplicate background samples were taken each day before gauging commenced. As background variation had been found to be insignificant for the 11 October gauging, these samples were assumed to be representative of the whole period of each gauging.

4. RESULTS AND DISCUSSION

1. Injection rate

Each Mariotte vessel used in the gaugings had been calibrated in the laboratory to ensure that readings taken from the sight tube were linearly related to the volume of liquid discharged. The calibration was performed by filling the vessel with water and taking readings of the sight tube after measured amounts had been discharged. This calibration was repeated a number of times to give the co-ordinate pairs $(S_k, M_k)_\rho$, $k = 1 \ldots, m$, $\rho = 1, \ldots, n$, where S_k are the sight tube readings, M_k is the mass of water discharged, m is the number of pairs for a particular calibration and n the number of replications of the calibration (normally n = 3). This data was then used as input into the program MARIOTTE (dilution gauging programs are described in Smith 1977) along with the density of the water at ambient temperature (enabling readings of mass to be converted to volumes). The program fits the n best straight lines to the data and computes the grouped best estimate for the slope α (ℓ/cm) and its variance var(α) (ℓ^2/cm^2).

For the particular Mariottes used in these gaugings the results were put in the form of the graphs shown in Figures 6 and 7. Having found estimates for α and var (α) it was possible to translate sight tube readings taken in the field to volumes of tracer injected.

The injection rate for each gauging was determined by taking sight tube readings S_i with time t_i from the start of injection. This data was then used as input to the program INJECT along with values of α and var (α) found by MARIOTTE. The program, in a similar way to MARIOTTE, determines the best straight line for the pairs (t_i, S_i), $i = 1, \ldots, r$ and computes the slope β (cm/s) and its variance var (β) (cm/s) and its variance var (β) (cm^2/s^2).

It is therefore possible, knowing the values of α and β, var (α) and var (β) to estimate the injection rate q(l/s) and its variance var (q) (l^2/s^2) by

$$q = \alpha.\beta \qquad (l/s)$$

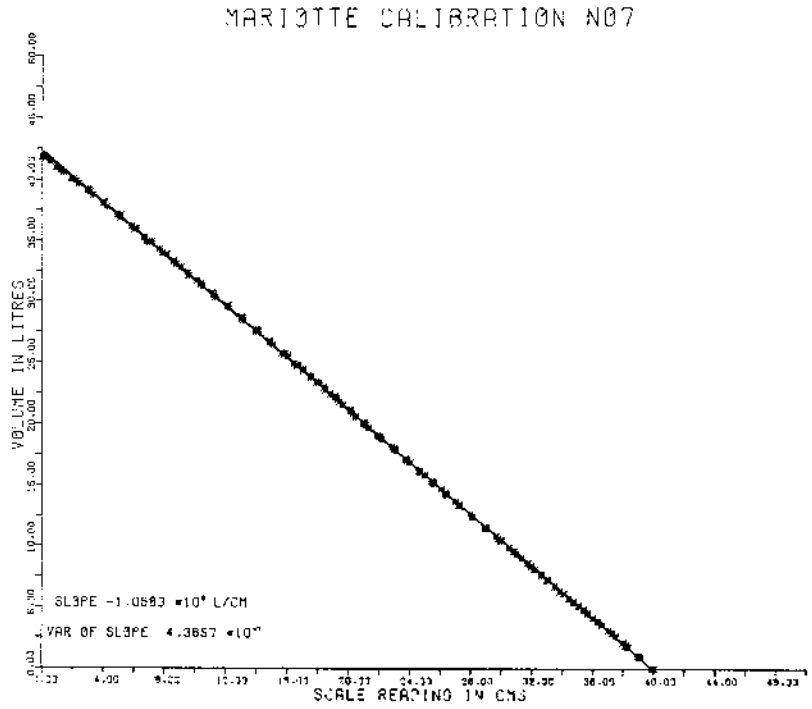


FIGURE 6 Mariotte calibration

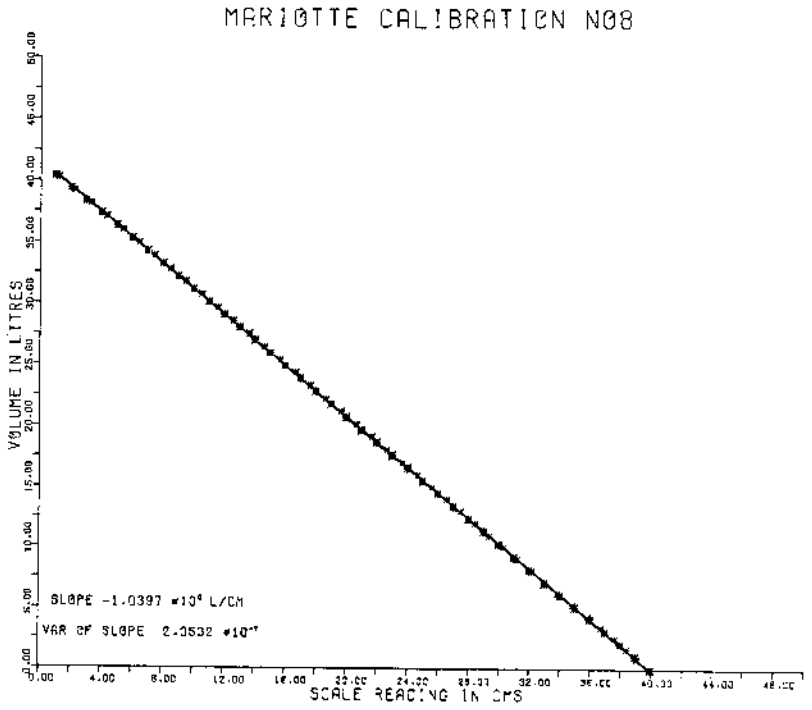


FIGURE 7 Mariotte calibration

and var (q) = β^2 var (α) + α^2 var (β) (l^2/s^2)

The program INJECT computes q and var (q) for the particular gauging and the results are put in the form of graphs as shown later in Figures 8, 9, 10 and 11.

TABLE 2. Injection rates

Date	Mariotte	α	Var (α) ($\times 10^{-7}$)	β ($\times 10^{-3}$ cm/s)	Var (β) ($\times 10^{-2}$ cm^2/s^2)	q ($\times 10^{-3}$ l/s)	Var (q) ($\times 10^{-12}$ l^2/s^2)
11 Oct 1975	7	- 1.0589	4.3857	- 4.7873	17.716	5.0692	29.915
15 Apr 1975	8	- 1.0396	2.2859	- 2.2173	5.9217	2.3051	7.5238
16 Apr 1975	8	- 1.0396	2.2859	- 2.1267	8.1497	2.2109	9.8418
17 Apr 1975	8	- 1.0396	2.2859	- 1.4444	2.4979	1.5016	3.1765

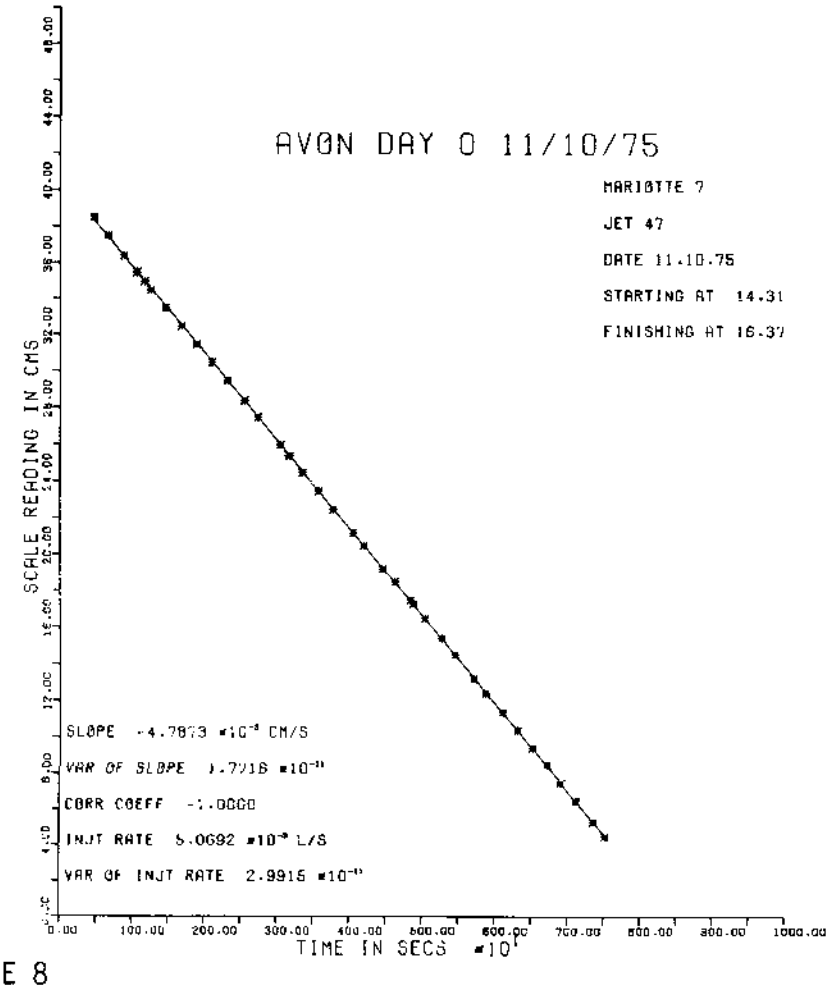


FIGURE 8

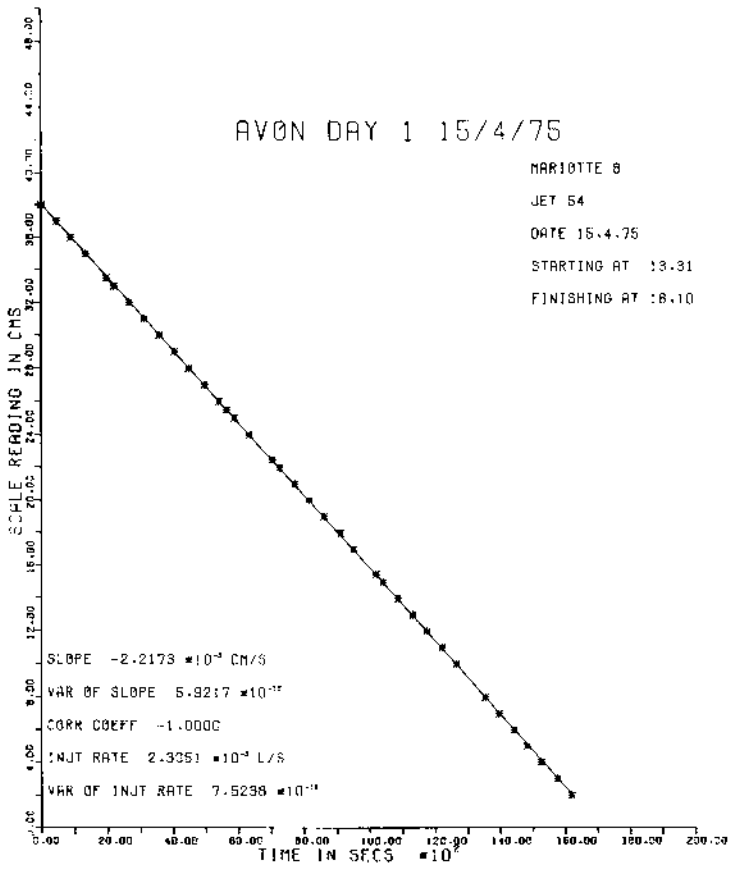


FIGURE 9

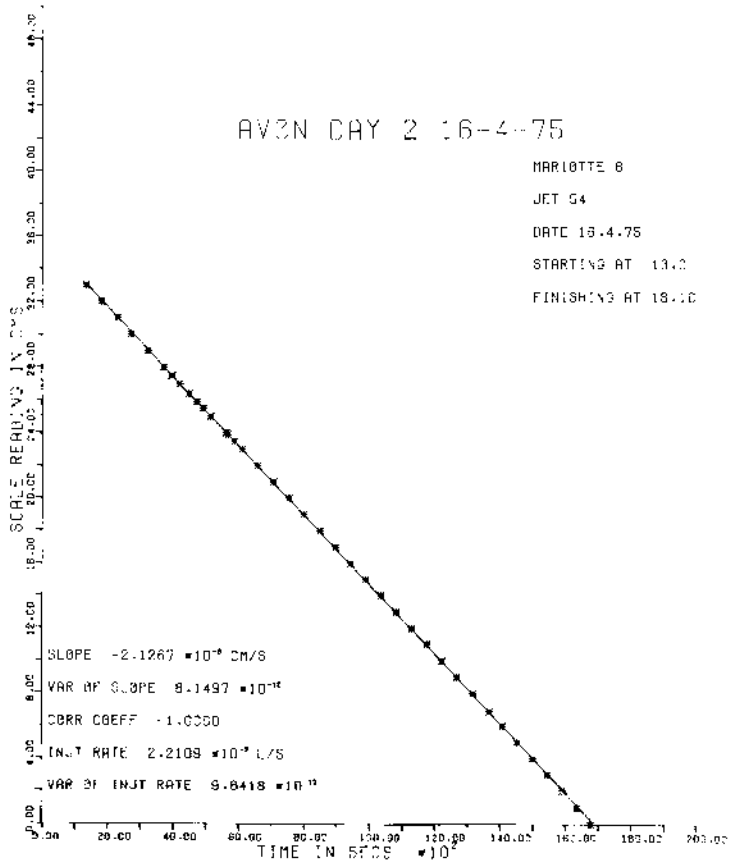


FIGURE 10

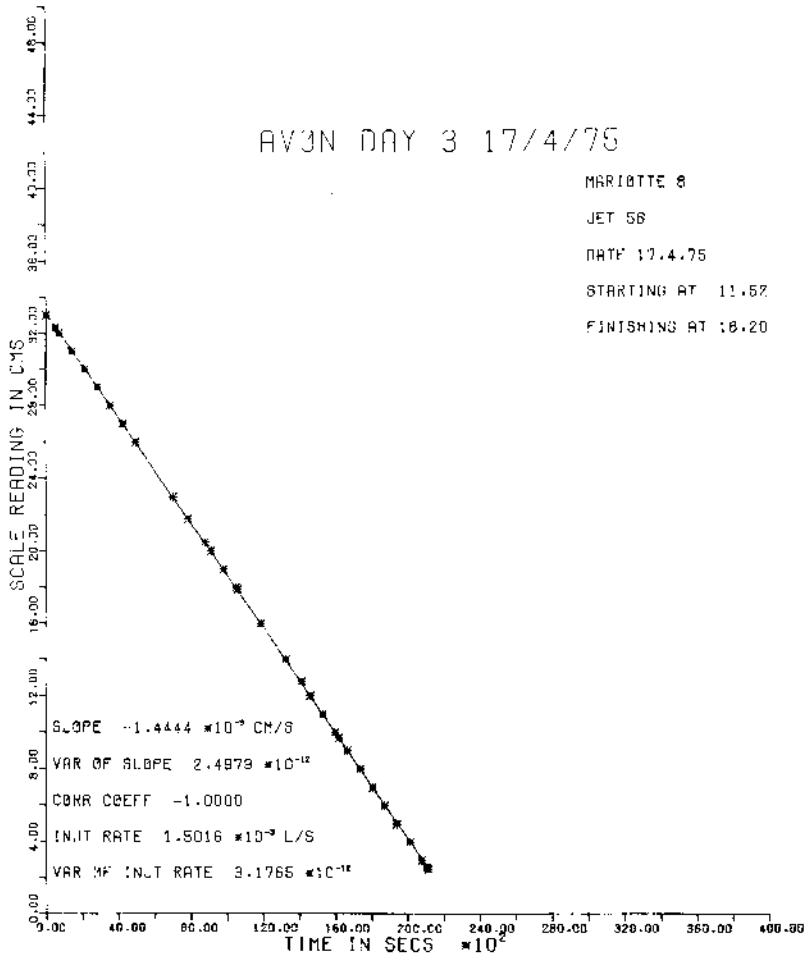


FIGURE 11

2. Calibration of the iodide analysis method

A catalytic spectrophotometric procedure using a Technicon Auto-Analyser system was used to determine the concentration of iodide in the diluted sodium iodide tracer solution and the river water samples taken before injection and at plateau.

The response of the Auto-Analyser is in the form of a transmission, which must be converted into an iodide concentration. The equation governing the relation between transmission and iodide is of the form

$$T = e^{-Ze^{-I\theta}} - e^{-Z} + D \qquad (1)$$

where T is the transmission measured

$Z = D \ln(10)$ is the transmission defining the base line

I is the concentration in µg/l

$\theta = \omega t$, a compound variable involving the sensitivity of the reaction and the reaction time

and D is a measure of the background iodide level.

The method of calibrating the Auto-analyser is to measure the transmission of iodide standards and using a non-linear least squares fitting technique estimate the parameters Z, θ and D, thus enabling iodide concentrations to be found from equation (1).

The program CALIBRATE, using the method outlined above, estimates the values of Z,θ and D for a particular set of samples and plots a calibration curve (an example is shown in Figure 12). The program also produces a look-up table so that the iodide concentration for a sample can be found, given the transmission.

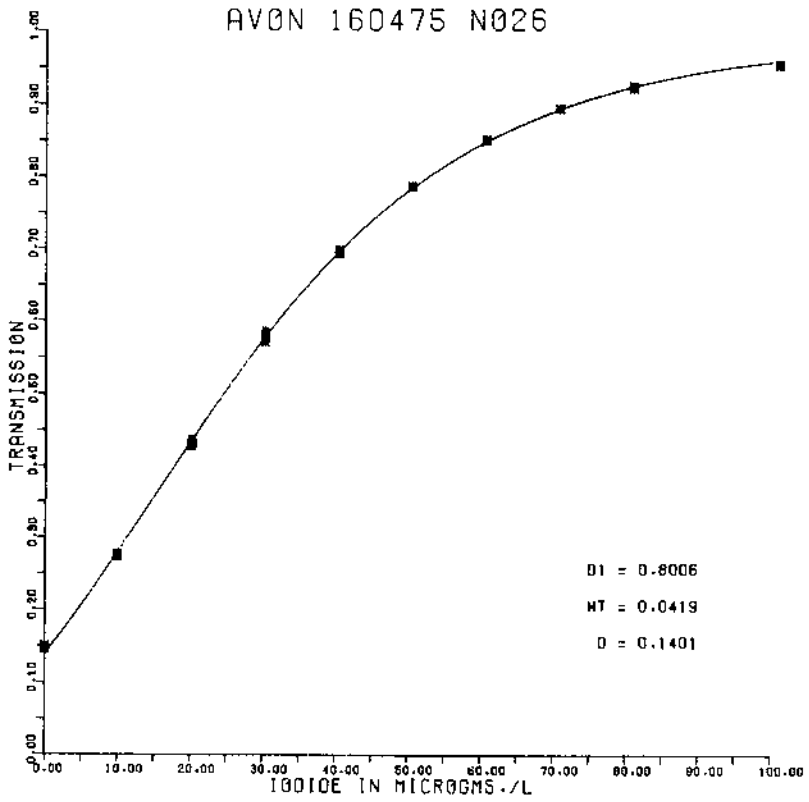


FIGURE 12 Typical iodide calibration curve

3. Background samples

During the preliminary gauging 11/10/74 an automatic sampler was used to establish whether there was any significant variation in the background level of iodide in the river. The automatic sampler took a river sample at half-hourly intervals during the gauging. These samples were analysed on the Auto-Analyser and were found to have a mean

iodide concentration of 3.5 µg/l with random variation within the reading error. Since the variation in background was small it was thought unnecessary to monitor the background level of iodide continuously in the subsequent gaugings but rather to take background samples before the gauging. These background samples were used as the diluent in all dilutions and standards, so that the background apparent iodide concentration was eliminated.

4. Samples of injected tracer solution

Samples were taken from the Mariotte vessel at the end of each gauging and were diluted by a factor F to bring them into the range of iodide concentration (40 - 60 µg/l) of the river samples, and determined by the same method at the same time as the river samples to minimize the errors. Moreover, since one full profile of 50 samples is a convenient number to analyse at any one time, the injection concentration was determined for each profile. Table 3 shows the injection concentration $\bar{C}_1$ and its variance var $(\bar{C}_1)$. The dilution factor F and its variance var (F) are also shown.

TABLE 3. Injection Concentration Data

Profile No.	Date	Injection concentration $(\bar{C}_1)$ µg/l	Variance Var $(\bar{C})$ $\mu g^2/l^2$	Dilution Factor (F) $\times 10^7$	Variance Var (F)
0	11.10.74	33.56	.378	.5	3.8
1	15. 4.75	51.39	2.958	1.0	0.7
2	"	52.47	2.739	1.0	"
3	"	50.87	2.091	1.0	"
4	"	51.52	2.43	1.0	"
5	16. 4.75	51.62	.327	1.014	"
6	"	51.85	.619	1.014	"
7	"	52.18	.236	1.014	"
8	"	52.5	.216	1.014	"
9	17. 4.75	53.81	.112	1.257	"
10	"	53.77	.114	1.257	"
11	"	54.1	.187	1.257	"
12	"	54.2	.283	1.257	"
13	"	54.0	.298	1.257	"

5. Sample storage and sorption experiments

Storage

To determine whether any loss of iodide occurred in the sample bottles between the time of sampling and analysis, 10 sample bottles were filled with a river water sample made up to a concentration of 40 µg/l of iodide. This was carried out before each gauging. 10 ml of 20 µg/l iodide solution were added to 5 litres of river water using grade A volumetric glassware, to give a concentration of 40 µg/l. Analysis of the samples was repeated with each analysis of the profile samples. The result showed that no significant loss of iodide had occurred.

A storage experiment with iodide samples has shown that filtered samples can be stored for 60 days without loss of iodide. Unfiltered samples do not keep for so long and should be analysed within 25 days of sampling.

Sorption

Sorption of iodide on to river sediments is most likely to occur on the finely divided sediment, which has a very high surface area and can travel in suspension. Six samples of bed gravels and silt from different parts of the river were used to make up solutions containing 20 g/l sediment and 40 µg/l iodide. Table 4 below shows the results after 2½ hours of storage, which is longer than the time a water sample would spend in the river (the mean residence time in the gauging reach was less than 1 hour). The results show no significant loss of iodide tracer through sorption in the river. Fuller discussion of sorption of iodide may be found in the paper by Neal and Truesdale (1976).

TABLE 4.

Sample No.	Description	% Sorption after 2½ hours
1	Silt	- 0.5
2	Gravel	0.0
3	Gravel	- 0.5
4	Silt	0.3
5	Gravel	0.0
6	Gravel	0.0

6. River samples

The river sampling method was the major change between the preliminary gauging (October 1974) and the later gaugings (April 1975). In the preliminary gauging a boat was rowed across the river along a rope and samples were taken at 2 m intervals at four depths with sample bottles clipped on to a sample rod. The disadvantages with this method of sampling are that an accurate location cannot be assigned to the sample position and the time dependent variation in concentration cannot be easily examined. In the later gaugings a multipoint sampling method (Figure 4) was used to overcome these disadvantages. With this method the locations of sampling points were known and remained constant over the three days of gauging. Moreover, since ten samples were taken every ten minutes (one from each rod across the river) the behaviour of the concentration of the samples could be studied in relation to the time the sample was taken. The sampling procedure, shown in Figure 5, was to take ten A samples (part profile A), then ten B samples (part profile B) until the ten E samples (part profile E) completed the profile of 50 samples. It was therefore possible to complete the concentration profile at all sampling positions in the river in 50 minutes, and this will be referred to as a complete profile. The concentrations of the river samples in the complete

profile give the best estimate of river concentration which is then used to evaluate the flow of the river over the period of sampling.

A computer program, PROFILE (an example data set, output and the program listing are given in Appendix A) was written to process the sample concentration data from the river samples. The program was written for several reasons. Firstly, because of the problems of assigning exact co-ordinates to each river sample, then to patch missing values resulting from blocked tubes with weighted mean estimates and presenting the data in a suitable form for subsequent analysis (for example contouring the complete profiles using the surface approximation package SACM), and statistical analysis using the statistical package ASCOP. The analysis was performed in three stages:

(a) each profile was *contoured* to exhibit any significant trend in the data in a pictorial form. (Appendix B).

(b) the profiles were *analysed statistically* to investigate the spatial and temporal variation and its significance where it occurs. (Appendix C).

(c) after significant spatial variation was found in the results of the complete profiles 0-4, the normalised sample concentrations were *weighted* with the normalised velocity distribution given by current metering carried out during the preliminary gauging. (Appendix D).

a. Contoured profiles - see Appendix B

Contour plots of the sample concentrations for the complete profiles (0-13, excluding 10) show clearly the spatial variation exhibited in the early profiles (0-4). This spatial variation is seen towards the left bank as roughly parallel vertical contours on the profiles (0-4). However, the contours show a more confused picture on the later profiles (5-13). These qualitative conclusions are confirmed statistically in Appendices C and D. Profile 10 is not included in Appendix B because an interruption in the injection gave a large range of concentrations for the samples in this profile.

b. Statistical analysis

As can be seen from Table C.1 there is a highly significant variation in the x-direction (across the stream) in the profiles 0-4. These profiles were obtained from data from the preliminary gauging (profile 0) and the gaugings on the 15 April 1975 (profiles 1-4). The variation is probably due to a lack of mixing; since the tracer was injected at the site B (Figure 1) the length of the mixing reach was not sufficient to achieve mixing. This opinion was to some extent verified on the subsequent two days' gauging by moving the injection site to C (Figure 1). The spatial variation for later profiles is non-significant in Table C.1 although owing to the interruption of injection the last two profiles 12 and 13 again show a significant variation across the stream.

Profile 6 shows a significant variation in the y direction (with depth) but this is only at the 5% level and could well be non-significant in a physical sense.

Before the flow value can be computed it is necessary not only to check for systematic spatial variation but also to check that the concentration in the stream is not changing with time in a systematic way. This type of variation is more difficult to deal with since it has two possible causes. It can be caused by a changing discharge or a failure to reach a plateau concentration, or of course a changing injection rate. It is as well in the Avon gauging that we know, from the simultaneous gauging conducted by the Water Research Centre, that the discharge did not change significantly over each day's gauging. The importance of this assumption cannot be overstressed. If there was evidence that the discharge changed on a day when the dilution gauging was conducted then a different course would have to be taken (Gilman 1977, Smith 1977).

The results in Table C.2 show a disturbing picture of significant variation in time, which may be caused by the rise of tracer concentration towards its plateau level. Figure 13 shows the concentration of tracer in the river samples taken on 16th April. The graph shows the increase in concentration of tracer with time in minutes. The concentration values are the means of the ten river samples that make up a part profile and are lettered A, B, C etc. The spiky appearance of this graph could be accounted for by a varying residence time in the tubes or by sampling error. The five-point moving average is also shown on the graph as a bold line. Figure 13 also shows the behaviour (given as a broken line) of the derivative of the concentration with respect to time. The derivative is approximated by plotting the difference between successive values of concentration with time. After an initial period the differences oscillate around the zero line: this indicates that a plateau concentration may have been reached. However, at 100 minutes after sampling commenced (A of profile 7) the differences seem to oscillate around a line of about .75 µg/l difference before dipping once more. This last dip is inexplicable: its suddeness and magnitude throw some doubt on the following interpretation. That is, that the oscillations centred on a higher value indicate that the flow of the river is such that one part of the flow arrives at the sampling site only after residing a long time in the gauging reach. This behaviour could be caused by large eddies or a sharp bend in the river: either cause may account for the behaviour of the Avon results. Be that as it may it does mean that to achieve reasonable gauging results a longer time of injection would be required to achieve plateau concentration. A standard method for prior determination of plateau time is the injection of a fluorescent dye such as fluorescein (sodium salt), and recording the time of passage. In the case of the Avon gaugings this was prevented on water quality grounds, owing to the proximity of the water supply intake.

Gilman (1976) showed that with fast-flowing turbulent mountain streams like those found in Plynlimon, Wales, the time to approach within ½% of plateau concentration might be as much as fifteen times the time of

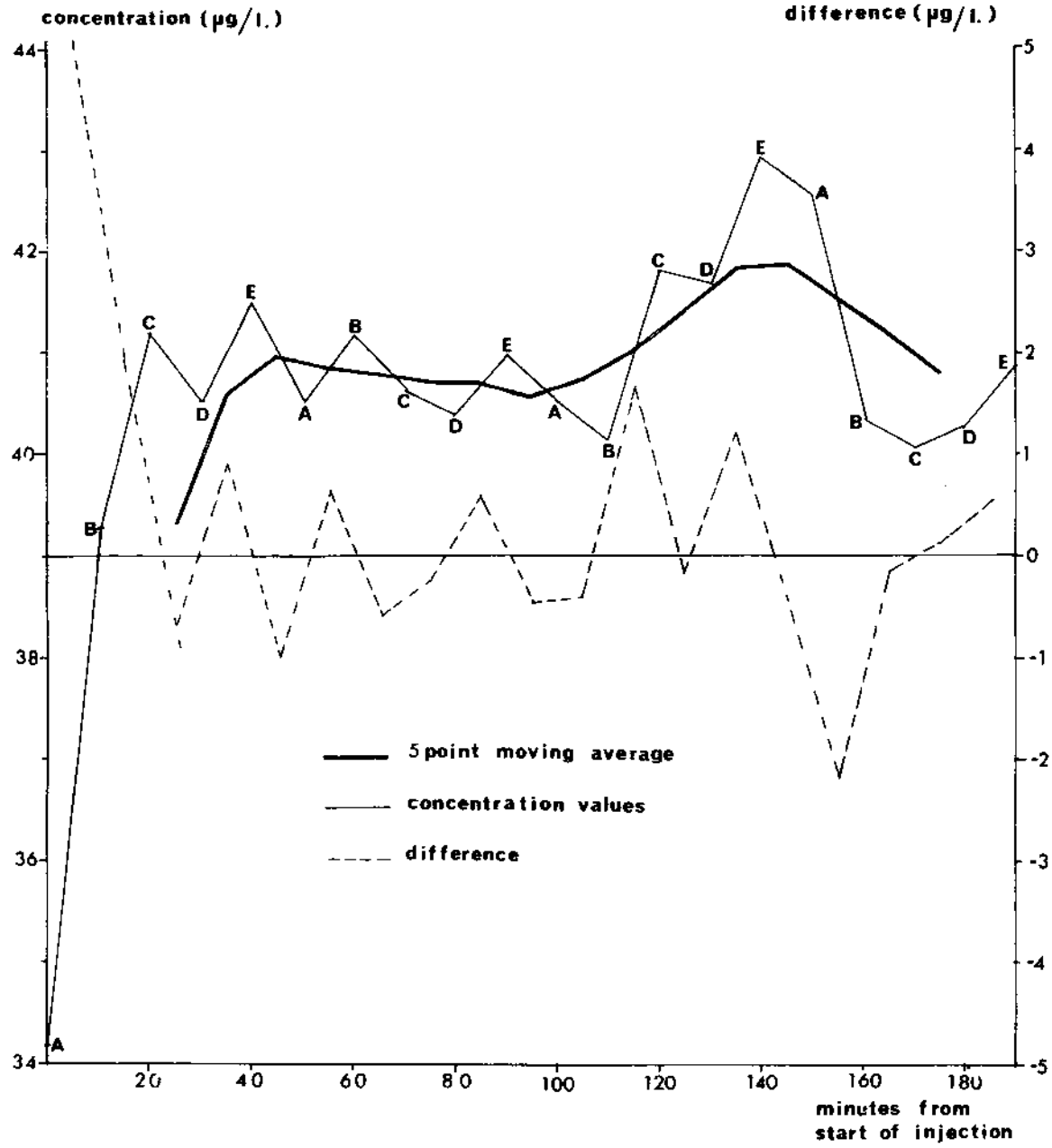


FIGURE 13 Variation of sample concentration (16.4.75)

arrival of a fluorescein slug. This result applied to gauging the River Avon would give an answer of 7½ hours to reach plateau concentration. Intuitively one would consider this time to be an underestimate when the fast flowing mountain streams of Plynlimon are compared to the sluggish flow of the River Avon.

c. Weighting the concentration profiles

For the gauging on 11 October 1974 and the first day of the later gauging on 15 April 1975, the distance between the injection and sampling sites was not sufficient to achieve mixing. Consequently the

profiles 0-4 of the distribution of iodide concentration are not random but indicate a systematic variation across the river, that is, the concentration is a function of position of the sampling cross section. To give a better estimate of the flow value, the concentration must be weighted with the velocity distribution (Gilman 1972). Thus the velocity-weighted estimate of the river concentration is

$$\hat{C}_2 = \frac{\int_S u(x,Y)\ C_2(x,y)\ dx\ dy}{\int_S u(x,y)\ dx\ dy}$$

where $C_2(x,y)$ is the measured river concentration at (x,y)

$u(x,y)$ is the measured river velocity at (x,y)

and integration is over the sampling cross-section S.

It is helpful to scale the variables x and y and functions C_2 and u in the integrals above by letting $\zeta = x/x_{max}$, $\eta = y/y_{max}$, $\tilde{C}_2 = C_2/\bar{C}_2$ and $\tilde{U} = u/\bar{U}$, where x_{max} and y_{max} are width and depth of the river (considered as a channel with rectangular section) and $\bar{C}_2$ and $\bar{u}$ are the mean river concentration and velocity calculated from the discrete data. Then

$$\hat{C}_2 = \frac{\bar{C}_2 \int_0^1 \int_0^1 \tilde{u}(\zeta,\eta)\ \tilde{C}_2(\zeta,\eta)\, d\zeta d\eta}{\int_0^1 \int_0^1 \tilde{u}(\zeta,\eta)\, d\zeta d\eta} = W\bar{C}_2$$

Thus W is the factor by which $\bar{C}_2$ must be multiplied by to find $\hat{C}_2$.

The velocity distribution used in these studies was obtained from the results of current metering conducted by the Water Research Centre about 4 m upstream of the dilution gauging sample site on the same day as the preliminary gauging. It has been assumed that the velocity distribution remains fairly constant over small ranges of flow. This assumption is based on the premise that the velocity distribution is dependent mainly on the geometry of the stream bed and banks, which does not change appreciably for small changes in stage. As a consequence of this assumption not only was the concentration profile for the preliminary gauging (profiles) weighted with this particular velocity distribution but also that of the later gaugings (profiles 1-4) scaled. The velocity distribution is

$$\tilde{u}(\zeta,\eta) = -.176 + 2.405\zeta + 2.436\eta - 2.221\zeta^2 - .377\zeta\eta - 1.368\eta^2$$

and the scaled concentration distributions are

Profile 0 $\tilde{C}_2(\zeta,\eta) = .898 + .393\zeta - .281\zeta^2$

Profile 1 $\tilde{C}_2(\zeta,\eta) = .836 + .730\zeta - .565\zeta^2$

Profile 2 $\tilde{C}_2(\zeta,\eta) = .860 + .765\zeta - .603\zeta^2$

Profile 3 $\tilde{C}_2(\zeta,\eta) = .260 + .681\zeta - .557\zeta^2$

Profile 4 $\tilde{C}_2(\zeta,\eta) = .844 + .748\zeta^2 - .609\zeta^2$

The statistical details of the distributions of $\tilde{u}(\zeta,\eta)$ and $\tilde{C}_2(\zeta,\eta)$ are given in Appendix D. The weights W and the weighted concentration estimates are given in Table 5.

TABLE 5. Weighting the River Sample Concentrations

PROFILE	W	$\bar{C}_2$	$\hat{C}_2$
0	1.004 46	41.73	41.92
1	1.019 14	41.25	42.04
2	1.020 26	39.65	40.48
3	1.020 81	37.66	38.44
4	1.021 59	37.12	37.92

Although by using this method the effect of the significant spatial variation of profiles (0-4) has been minimised, nothing has been done to reduce the effect of the significant temporal variation. There is little doubt that significant time variation exists in the results of profiles (0-4). The shorter reach of these early profiles may have reduced the time required to reach plateau, but the statistical analysis offers no obvious insight in the problem of the mixed significant variation problem, ie both spatial and temporal variation.

River sample concentrations and their variances are presented in Table 6. The variance is of the $\bar{C}_2$ and not of $\hat{C}_2$, ie the variance has been calculated from the sample concentrations for profiles 0-4 before they have been weighted. The mean river sample concentrations and variances for profile (5-13), excluding 10, have been calculated assuming the plateau concentration has been reached (ie no significant time variation). This is due to the fact that there is no way to obtain satisfactory estimates for the asymptotic plateau concentration from the data available.

TABLE 6. River Sample Concentrations and Variances

Profile No.	Date	River Sample Concentration ($\bar{C}_2$) (µg/l)	Variance Var ($\bar{C}_2$) $\mu g^2/l^2$
0	11.10.74	41.92 ($\hat{C}_2$)	5.06
1	15.4.75	42.04 ($\hat{C}_2$)	11.16
2	15.4.75	40.84 ($\hat{C}_2$)	10.13
3	15.4.75	38.44 ($\hat{C}_2$)	10.39
4	15.4.75	37.92 ($\hat{C}_2$)	10.15
5	16.4.75	40.10	2.33
6	16.4.75	40.72	.84
7	16.4.75	41.37	2.16
8	16.4.75	40.73	1.58
9	17.4.75	34.67	7.29
11	17.4.75	40.63	5.32
12	17.4.75	38.36	3.31
13	17.4.75	38.30	1.95

7. Calculation of stream discharge

The tracer balance for a constant rate injection gauging is

$$Q(C_2 - C_o) = q(C_1 - C_o)$$

where Q is the river discharge

C_2 is the downstream plateau concentration

C_o is the background concentration

q is the injection rate of tracer solution

C_1 is the concentration of the tracer solution

The tracer concentration C_1 is in fact measured as the product of a dilution factor F and a low concentration c_1. Computation of the discharge Q and its variance is performed by the program FLOVAR which has the facility of including another dilution factor f to bring the river samples into the measuring range ($C_2 = fc_2$). Including both dilution factors

$$Q = \frac{qFc_1}{fc_2}$$

and since background water was used for both dilution and the preparation of standards the background concentration C_o does not appear.

The variance of Q

$$\text{var } Q \simeq \left(\frac{\partial Q}{\partial q}\right)^2 \text{var } q + \left(\frac{\partial Q}{\partial c_1}\right)^2 \text{var } c_1 + \left(\frac{\partial Q}{\partial F}\right)^2 \text{var } F$$

$$+ \left(\frac{\partial Q}{\partial c_2}\right)^2 \text{var } c_2 + \left(\frac{\partial Q}{\partial f}\right)^2 \text{var } f$$

$$= \left(\frac{Fc_1}{fc_2}\right)^2 \text{var } q + \left(\frac{qF}{fc_2}\right)^2 \text{var } c_1 + \left(\frac{qc_1}{fc_2}\right)^2 \text{var } F$$

$$+ \left(\frac{qFc_1}{fc_2^2}\right)^2 \text{var } c_2 + \left(\frac{qFc_1}{f^2c_2}\right)^2 \text{var } f$$

The values necessary to calculate the flows and their confidence limits are given in Tables 2, 3 and 6. The river sample dilution factor f is unity in this case since no dilution was required, (hence var f = 0 and $c_2 = \bar{C}_2$). The 95% confidence limits on each gauging are given approximately by

$$\pm 2 \, (\text{var } Q)^{\frac{1}{2}}$$

and Table 7 shows the river discharges and confidence limits for profiles 0-13 (excluding 10).

TABLE 7. Dilution Gauging Results

Profile No.	Date	River Flow Q m^3/s		95% confidence interval m^3/s	
0	11.10.74	20.5	±	2.3	*
1	15. 4.75	28.2	±	5.0	*
2	15. 4.75	29.9	±	5.3	*
3	15. 4.75	30.5	±	5.6	*
4	15. 4.75	31.3	±	5.8	*
5	16. 4.75	28.9	±	2.3	
6	16. 4.75	28.6	±	1.6	
7	16. 4.75	28.3	±	2.1	
8	16. 4.75	28.9	±	1.9	
9	17. 4.75	29.3	±	4.6	
11	17. 4.75	25.1	±	2.9	
12	17. 4.75	26.7	±	2.6	
13	17. 4.75	26.6	±	2.0	

*denotes that Q was calculated using the weighted mean estimate $\hat{C}_2$

8. Comparison of Dilution Gauging with Ultrasonic and Current Metering

The Water Research Centre have kindly given the results for their ultrasonic and velocity/area gaugings conducted on the same day as the Institute's gauging of the river using the continuous injection method. The results are shown in Table 8.

TABLE 8. Comparison of Flow values (all values in m^3/s)

Date	Ultrasonic	Current metering	Dilution Gauging
11 Oct 1974	18.6	18.3	20.5
15 Apr 1975	25.4	24.2	28.2 - 31.3
16 Apr 1975	25.2	24.0	28.3 - 28.9
17 Apr 1975	24.2	23.0	25.1 - 29.3

The results show a significant difference between the flow values calculated by dilution gauging and those calculated using the ultrasonic and current metering methods. The results for dilution gauging are given as a range of values on 15, 16 and 17 April since a significant trend was found in the flow values calculated for different times during the day.

9. Continuous Monitoring of the Tracer Concentration at Mid-Stream

The build up, plateau and recession of tracer concentration, for the gaugings carried out in April, was monitored continuously by a pump sampling from the middle of the river. Samples were taken every 5 minutes up to the approximate time of plateau, every 10 minutes during plateau and then every 5 minutes after the injection had finished. These samples represent a bulked sample taken over the 5 or 10 minute period.

Figures 14, 15, 16 show the plot of tracer concentrations of these samples against time. (Values shown are of concentration rise above background level).

Calculation of flow by the Extended Gulp Method

The mid-stream samples can be used to obtain a flow figure using the extended gulp method for which the equation is:

$$Q = \frac{VC_1}{A} \quad \text{where:-}$$

Q = flow m^3/s

V = volume injected m^3

C_1 = Injection Concentration µg/l

A = Area under the curve of mid-stream sample concentration plotted against time. (µg.s/l)

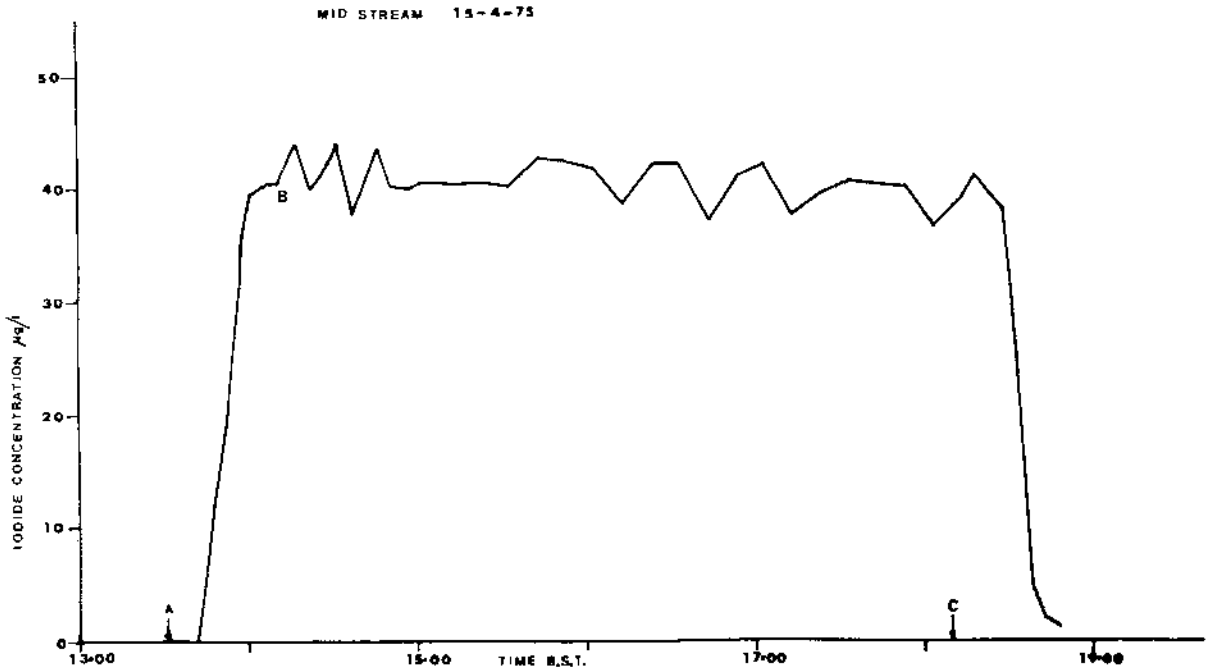


FIGURE 14 15 April 1975. The variation of tracer conentration in the plateau shows the incomplete mixing.

A = injection start time B = approximate plateau time
C = injection finish time

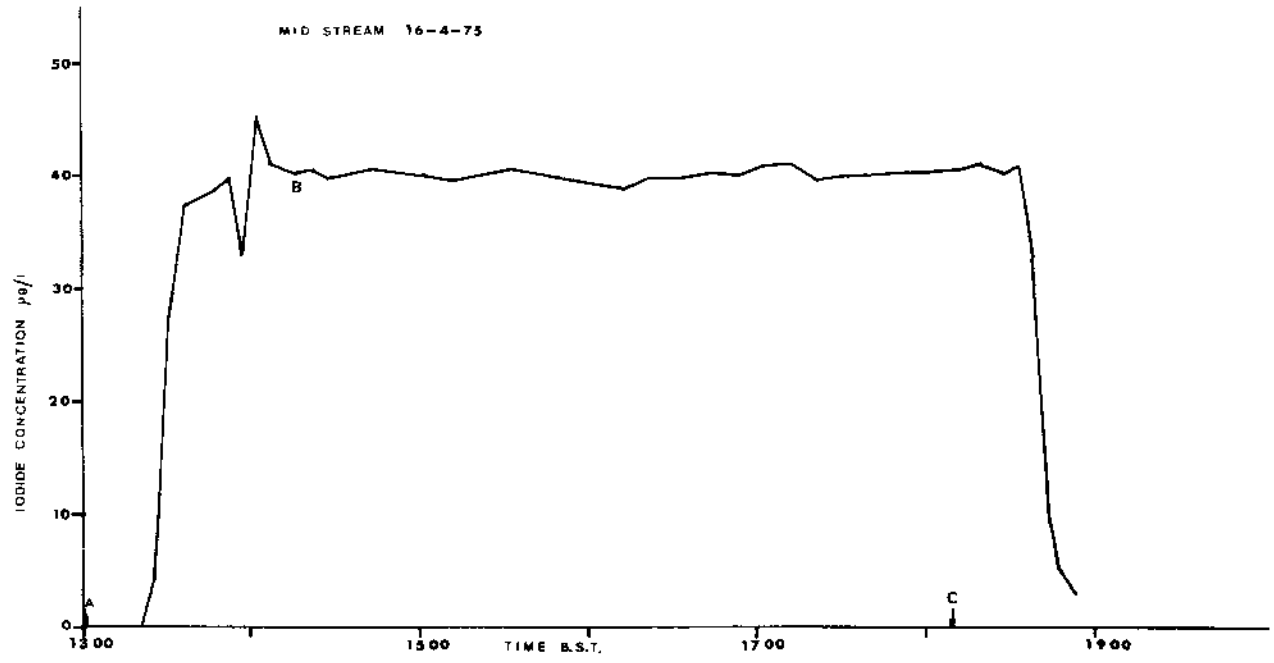


FIGURE 15 16 April 1975. The variation of tracer concentration in the plateau is much less, owing to the increased mixing length. The blip at the beginning was due to a temporary blockage in the Mariotte.

A = injection start time B = approximate plateau time
C = injection finish time

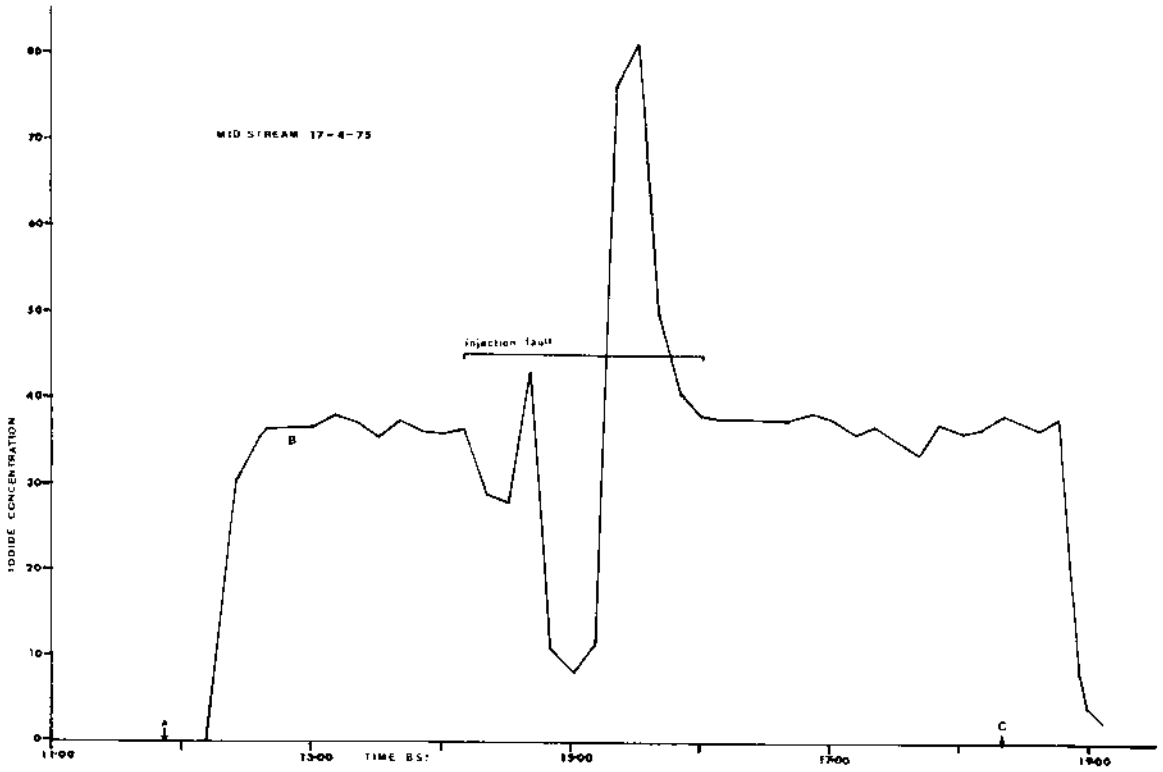


FIGURE 16 17 April 1975. This should have shown a similar curve to Fig. 14 but a blockage in the suction filter of the pump caused a cessation of tracer injection followed by a large release of tracer when the blockage was removed. This caused the large changes in tracer concentration observed. Apparently normal conditions returned by 1600 hours.

Table 9 shows the results, which compare favourably with the constant rate method.

TABLE 9. Flow Calculated by the Extended Gulp Method

Date	V l	C_1 µg/l	A µg.s/l	Q m^3/s
15. 4.75	41.1	52.7×10^7	6780	28.7
16. 4.75	38.6	50.4×10^7	7412	29.2
17. 4.75	35.0	67.7×10^7	8624	27.4

5. CONCLUSIONS

The primary objective of this study was the measurement of the discharge of the River Avon using chemical dilution gauging, for comparison with discharge measurements by the ultrasonic and velocity/area methods. This was not achieved because:

(i) in the comparison between the three gauging methods the dilution gauging results are well outside the range of the ultrasonic and velocity/area results;

(ii) there are doubts about the achievement of the steady state condition which is essential to the method.

These results raise questions about the applicability of chemical methods to larger rivers such as the Avon, as a longer injection time would have demanded a still greater quantity of tracer. The same objection could be made to the sudden injection or integration method, which uses only slightly less tracer. However, at Knapp Mill only sodium iodide could meet the water quality requirement imposed by the Water Authority, so radio-tracers, though more appropriate to large rivers, were unacceptable.

If plateau conditions were achieved in the gauging (and the evidence for very long residence times is inconclusive), then some loss of tracer is the inevitable conclusion. The possibilities of sorption and storage losses have been explored, and the only remaining sink for tracer is convection into the groundwater body of the gravel floodplain. Since the river, for much of its course, is traversing its floodplain and is moving parallel with the expected groundwater contours, there could be signficant gains and loses, which, although not important in net effect, would result in attenuation of an injected tracer. This hypothesis cannot however account for the varying magnitude of the apparent losses on the four gauging days.

In spitc of these problems important advances have been made in the technology of the constant rate method and in the analysis of results. The multipoint injection system developed for the preliminary gauging and used with only minor modifications for subsequent gaugings has worked well, and has probably been effective in making a substantial reduction in the mixing distance. In the river sampling array over 1500 m of small bore plastic tubing was used to sample the river water at 50 points in the cross-section. Out of a total of 650 samples only 45 were lost owing to blocked tubes, in spite of quite a heavy load of suspended vegetable matter in the river.

The fact that sampling points remained static and were positioned exactly in the river has made it possible to use statistical analysis to a greater degree. This is because a major cause of variation between profiles, namely the variation of river sample concentration due to sampling at different positions, was removed from the analysis.

The collection of a large number of cross-section samples has allowed us to use automatic contouring and statistical methods which are normally impossible in dilution gauging analysis. The contouring has given a useful qualitative picture of the distribution of tracer in the river and the statistical analyses have been valuable in the objective assessment of sources of variation.

Perhaps the most important conclusion is that steady-state or plateau conditions have not received the attention they should in the dilution gauging literature. The decision that plateau conditions have or have not been achieved is too often made on the slimmest of evidence, or even on a subjective basis, and more research is required into residence time distributions in river reaches before the decision can be made with confidence for any dilution gauging site.

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APPENDIX A

The program .PROFILE

A major drawback in using the multipoint sampling system shown in Figure 4 is the difficulty in positioning a sample concentration in the river. Moreover, in the case of the gaugings of the River Avon, as all thirteen profiles of fifty samples had two replicates taken of each sample, a hand method of calculating co-ordinates for each sample would be extremely laborious. With this in mind and also the fact that several values would need to be interpolated, the program .PROFILE was written. Using this program it was also possible to write files of the data in the correct format for use with statistical and contouring packages used extensively in this study.

If we consider the grid shown in Figure 4 as a (5x10) matrix G, then the method of positioning the sample tubes can be shown to be the following. Let the groups of 10 samples A, B, C..,E be numbered 1,2, ..., 5 and the poles 0, 1 ...,9 numbered 1, 2, ...,10. Then the sequence G(1,1) = 1,G (2,1) = 2..., G(1,2) = 3, G(2,2) = 4, ..., G(3,1) = 5, G(3,2) = 1, ... can be written in the form

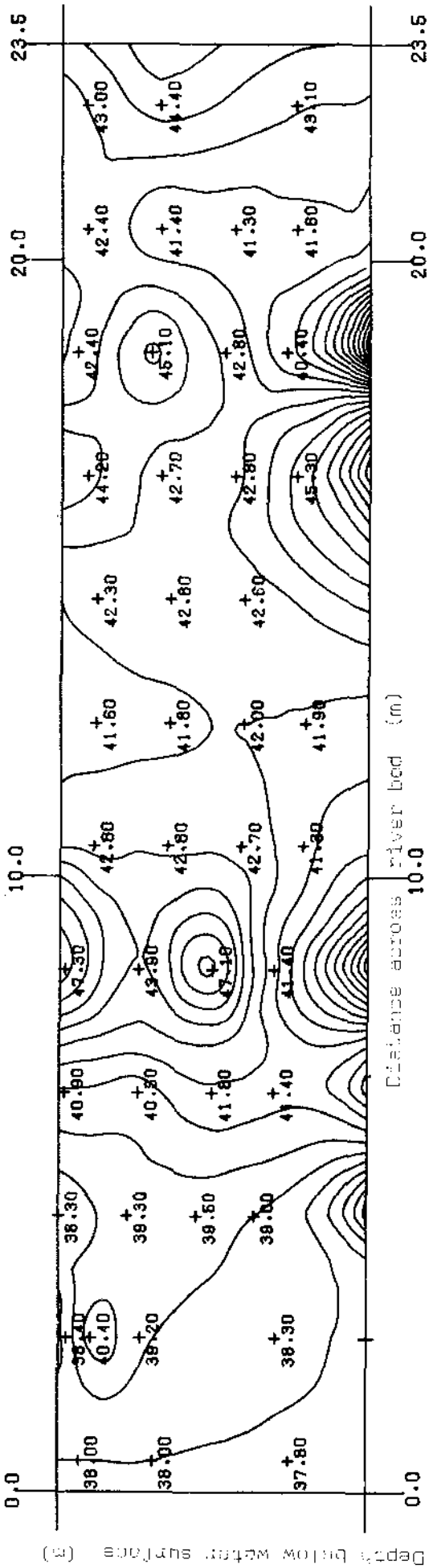
$$G(i,j) = k - 5 \left| \frac{(k-1)}{r} \right|$$

where $k = 3(j-1) + i$, $|\ |$ is the integer part of and $i = 1, \ldots, 5$ and $j = 1, \ldots, 10$. A complete profile indicates all the A, B etc groups of ten samples, with exception of a few interpolated missing values, put together on the grid. A part profile, on the other hand, means taking say the A group of samples and interpolating over the whole grid of samples.

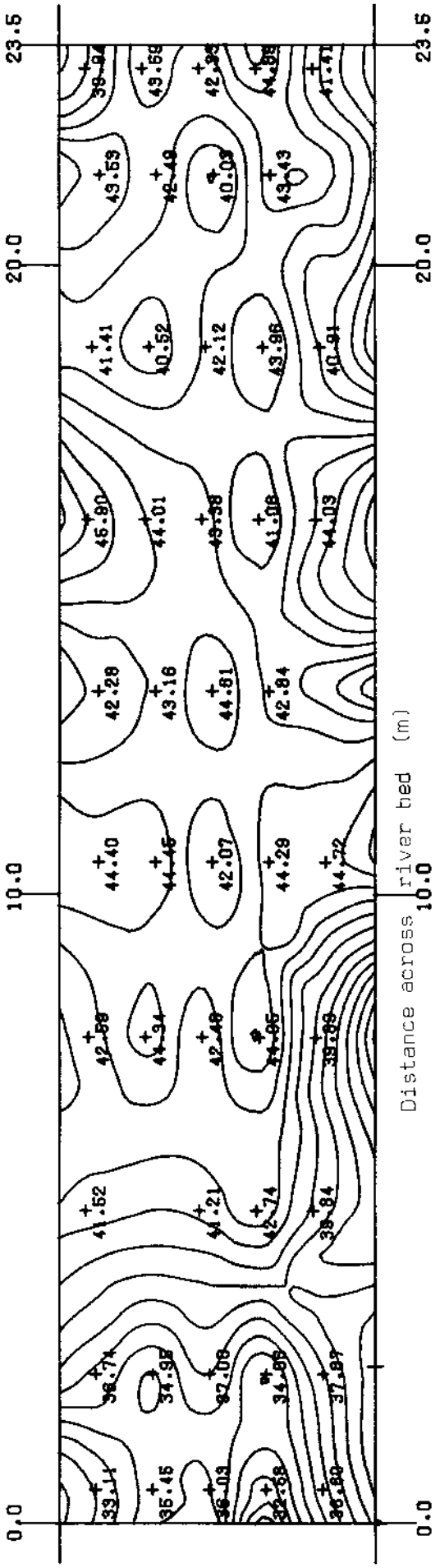
APPENDIX B

The contoured river sample concentration profiles

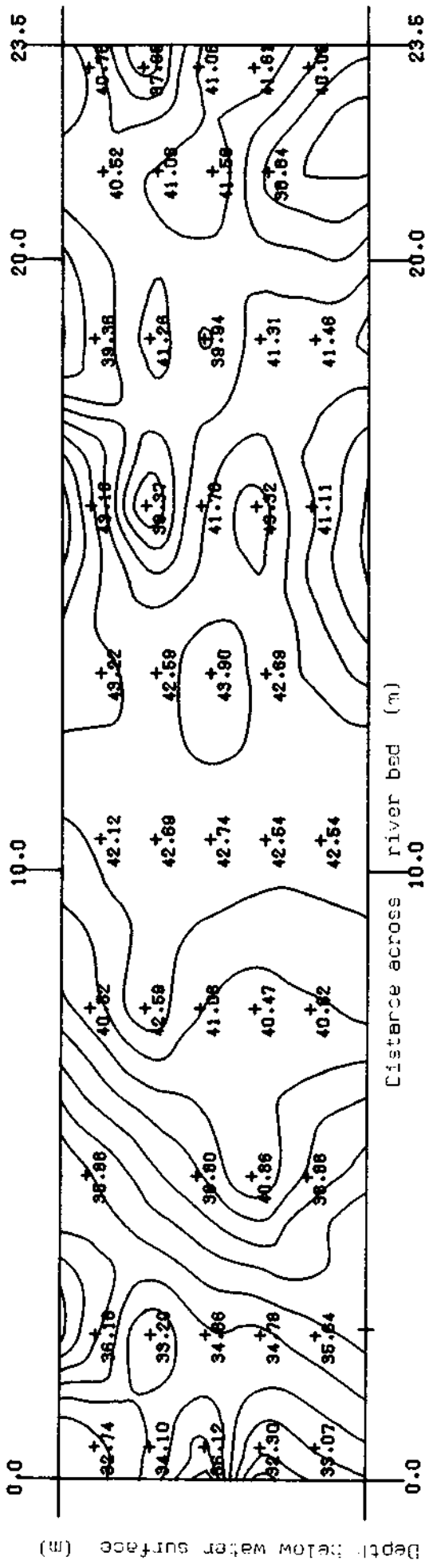
PROFILE	DATE	
0	11.10.74	The data from the preliminary gauging with four samples in depth and three missing samples.
1	15.4.75	The data from the first days gauging with five samples in depth and three missing samples. (The systematic variation across the stream can be seen on these contours).
2	15.4.75	
3	15.4.75	
4	15.4.75	
5	16.4.75	The data from the second days gauging again with five samples in depth and three missing samples.
6		
7		
8		
9	17.4.75	The data from the third days gauging. Profile 10 is missing because of the interruption in the injection. The other profiles show the effects of this interruption.
11		
12		
13		


23.5
20.0
10.0
0.0
Distance across river bed (m)
Depth below water surface (m)

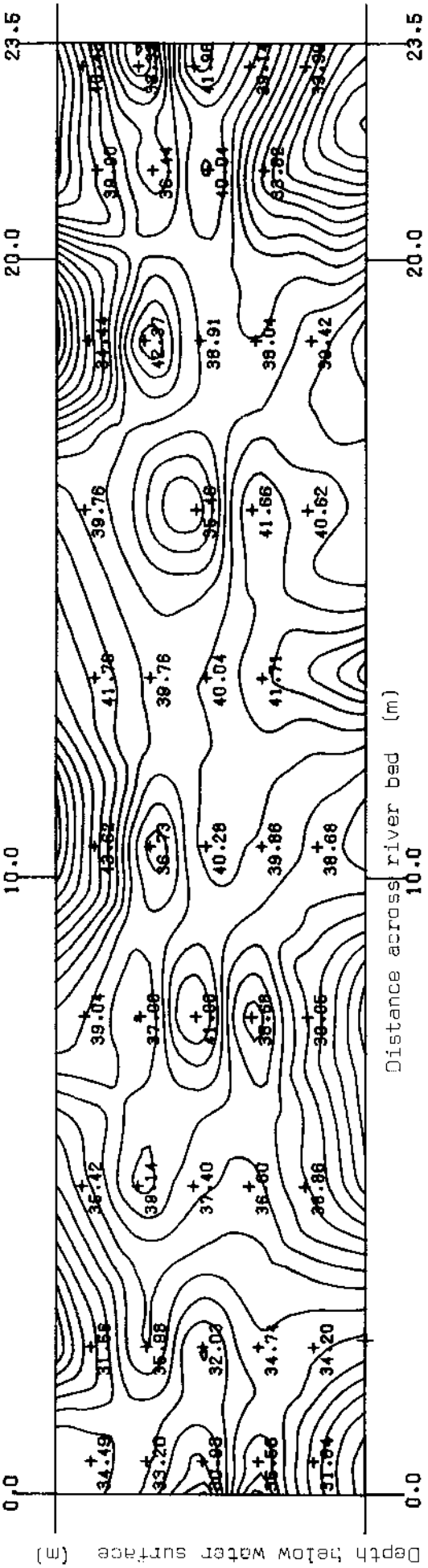
PROFILE 0


23.5
20.0
10.0
0.0
Distance across river bed (m)
Depth below water surface (m)

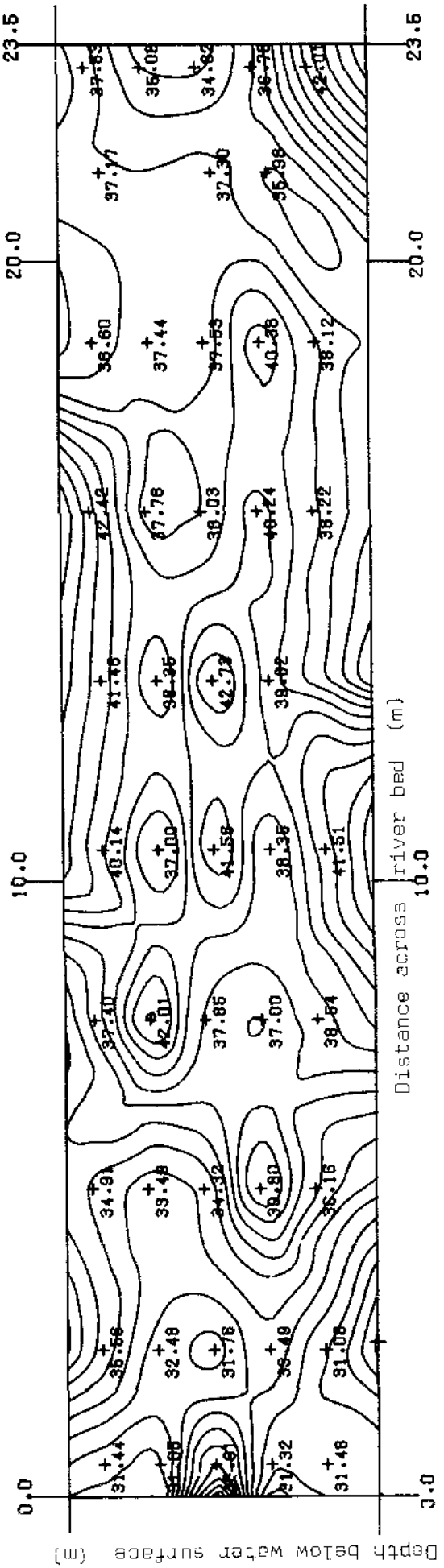
PROFILE 1


23.5
20.0
10.0
0.0
Distance across river bed (m)
Depth below water surface (m)

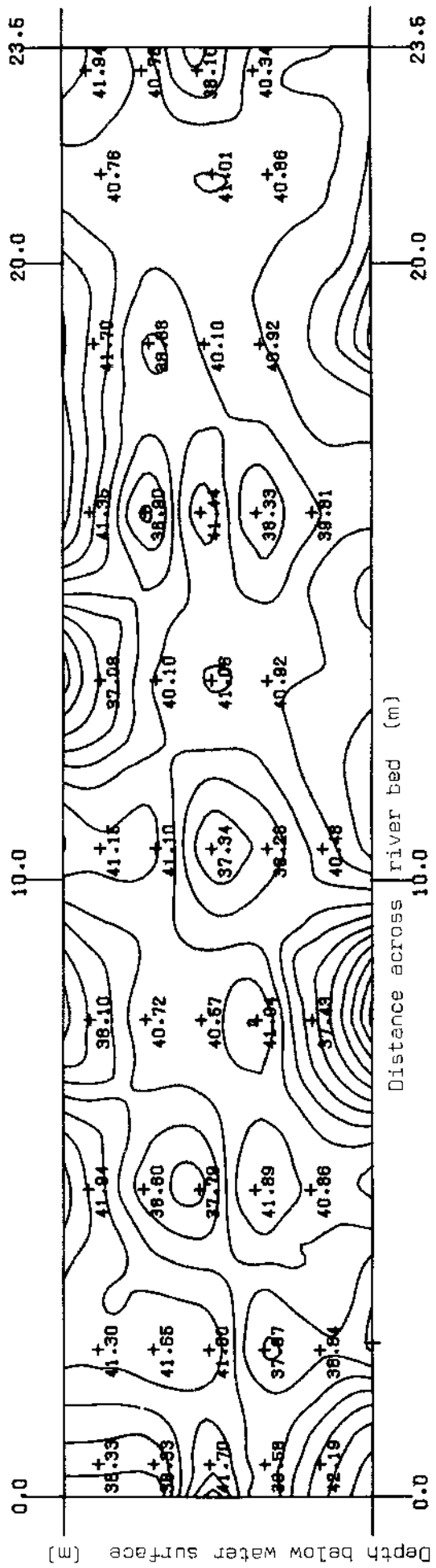
PROFILE 2


0.0
10.0
20.0
23.5
Distance across river bed (m)
Depth below water surface (m)

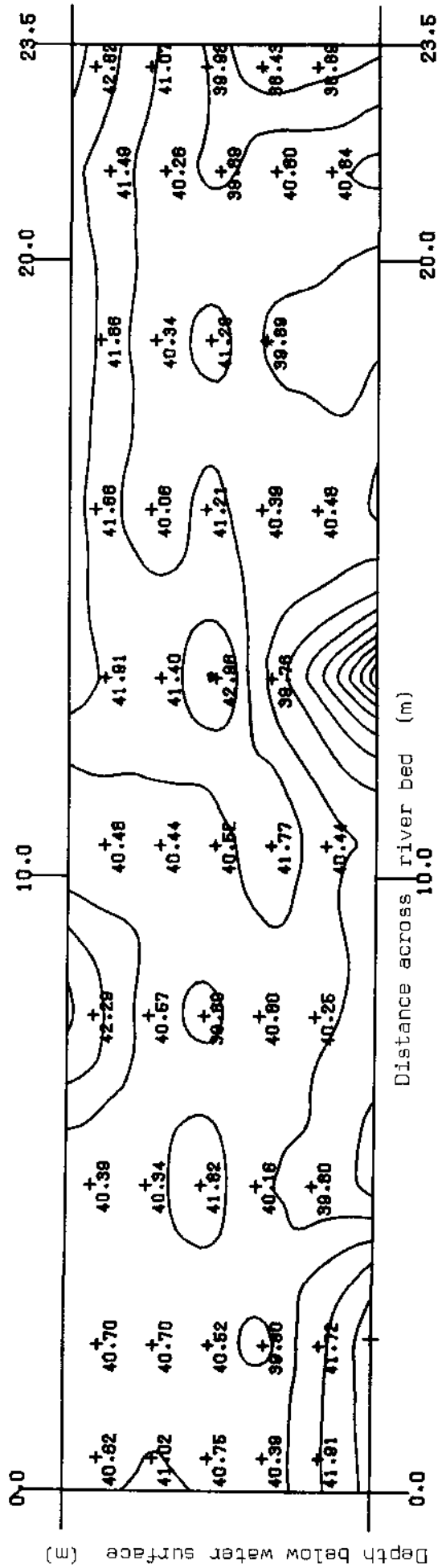
PROFILE 3


23.5
20.0
10.0
0.0
3.0
Distance across river bed (m)
Depth below water surface (m)

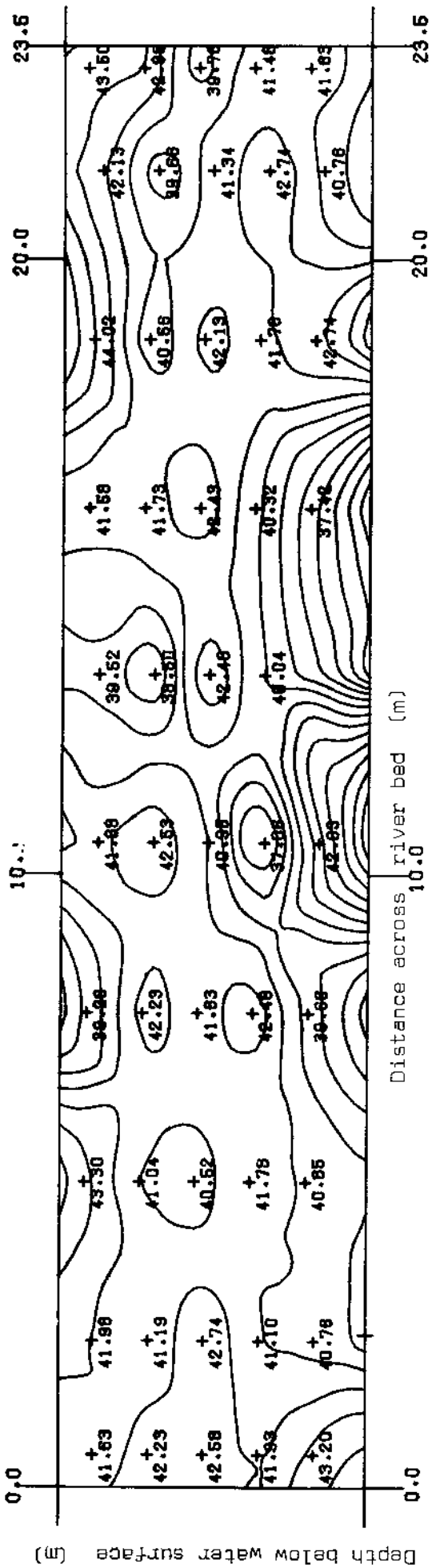
PROFILE 4


0.0
10.0
20.0
23.5
Distance across river bed (m)
Depth below water surface (m)

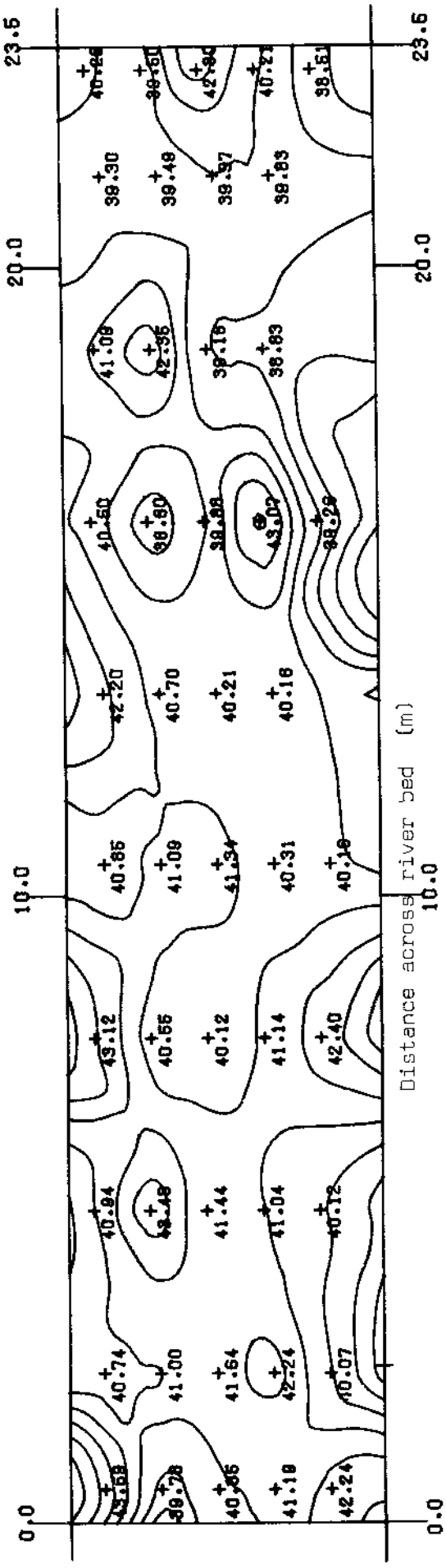
PROFILE 5


23.5
20.0
10.0
0.0
Distance across river bed (m)
Depth below water surface (m)

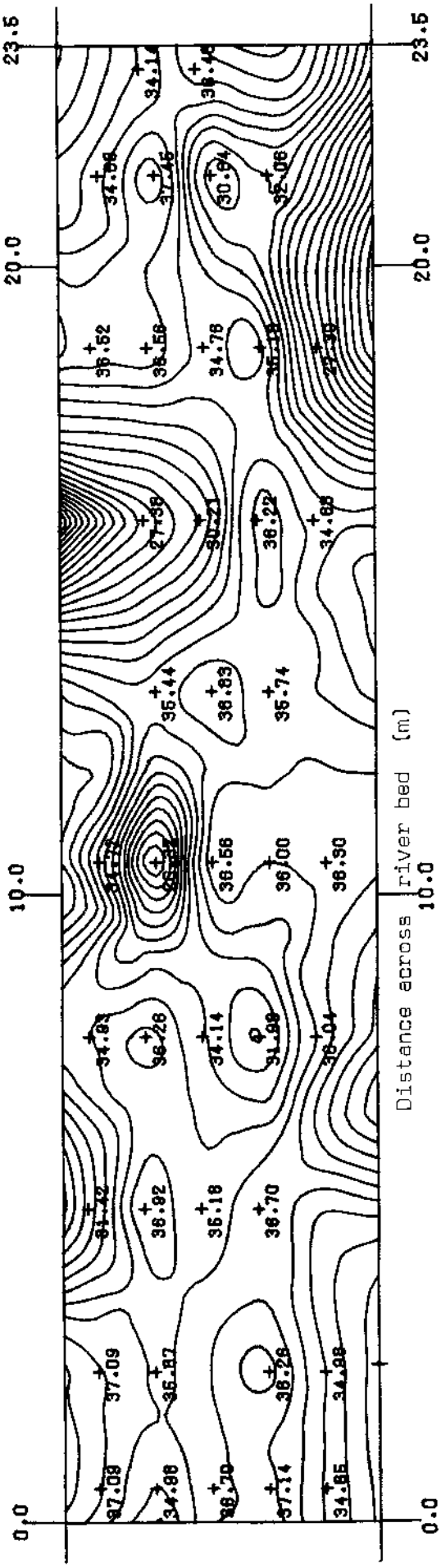
PROFILE 6


23.6
20.0
10.0
0.0
Distance across river bed (m)
Depth below water surface (m)

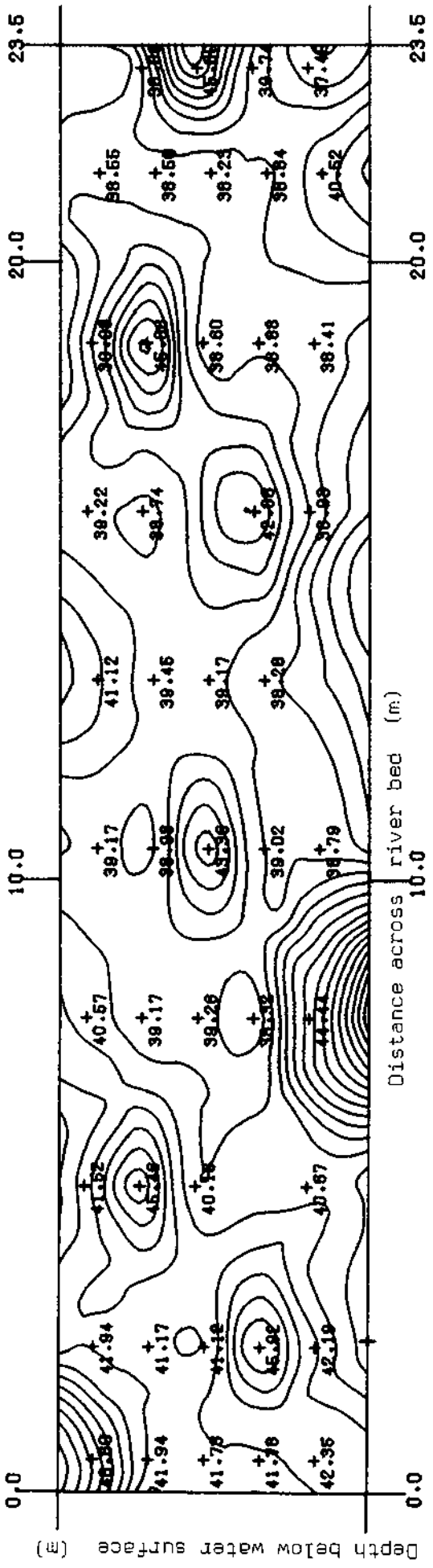
PROFILE 7


23.5
20.0
10.0
0.0
23.6
20.0
10.0
0.0
Distance across river bed (m)
Depth below water surface (m)

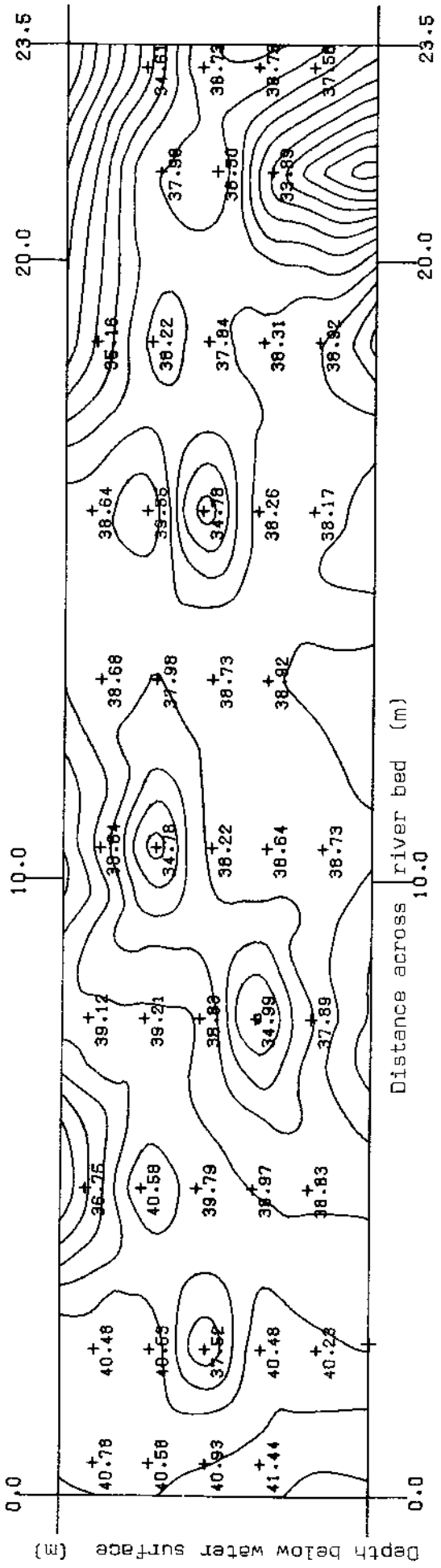
PROFILE 8

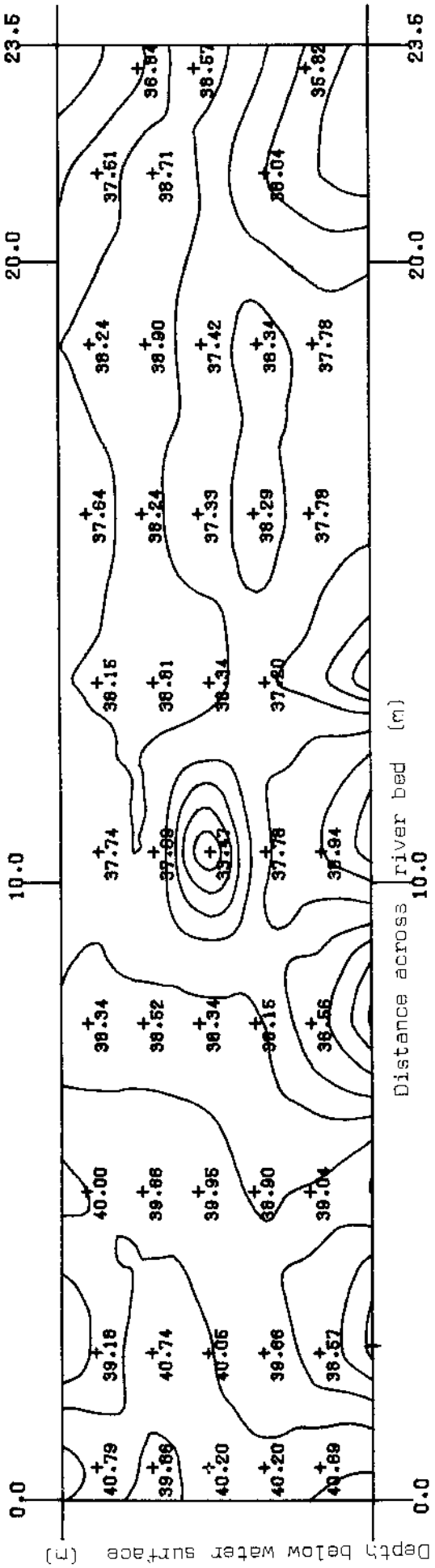

23.5
20.0
10.0
0.0
Distance across river bed (m)
Depth below water surface (m)

PROFILE 9


23.5
20.0
10.0
0.0
Distance across river bed (m)
Depth below water surface (m)

PROFILE 11


23.5
20.0
10.0
0.0
Depth below water surface (m)
Distance across river bed (m)
PROFILE 12


0.0
10.0
20.0
23.5
Depth below water surface (m)
Distance across river bed (m)
40.79
39.86
40.20
40.20
40.89
39.18
40.74
40.05
39.66
38.57
40.00
39.66
39.95
39.90
39.04
38.34
38.52
38.34
38.15
38.56
37.74
37.09
37.78
38.94
38.15
38.81
38.34
37.80
37.64
38.24
37.33
38.29
37.78
38.24
38.90
37.42
38.34
37.78
37.61
38.71
36.04
38.57
36.82

PROFILE 13

APPENDIX C

Statistical Interpretation of the concentration profiles

Using the ASCOP ( ) package available on the Univac 1108 computer at the Institute it was possible to study the components of variation within the concentration profile. There were two main objectives in this study; one was to see that spatial mixing had been achieved and the second to ensure plateau concentration conditions had been reached. The method of analysis of variance (ANOVA) is a useful way of studying significant variation.

The later gaugings in April 1975 have been analysed using ANOVA in two ways, to study both spatial and time variation. The multipoint river sampling system shown in Figure 3 has the total 50 sample positions that make a complete profile. The sampling procedure was such that 10 samples were taken at one time, defined as part profile A, B, C, D and E. Thus by analysing the concentration data in two ways we can obtain information about both the spatial and time variation; for the spatial variation rods 0-9 give the variation in the X direction (across the river) while the sample position ABCDE on rod 0, CDEAB on rod 1 etc. give the time variation in the Y direction (in depth). For time variation we can study all the As then all the Bs etc. so that the variation within the As, Bs etc. is attributable to some component spatial variation (ie. a combination of X and Y). The results of the ANOVA is given in two tables C.1 and C.2. Table C.1 shows the results of ANOVA of the complete profile with the sources of variation simply as the X and Y directions. Table C.2 shows the results of ANOVA again on the complete profile but now ordered so that the variation due to time is given by variation between part profiles and XxY, some component spatial variation within the part profiles. The results in both tables are given as the variance ratio F value with its significance denoted in the following way:

***	denotes significance at the 0.1% level
**	denotes significance at the 1% level
*	denotes significance at the 5% level
+	denotes significance at the 10% level.
N.S	denotes non-significance (ie. greater than the 10% level)

TABLE C.1 Anova Results (Spatial Variation) F-Values and Their Significance

	DATE	15.4.75					16.4.75					17.4.75		
	PROFILE	1	2	3	4	5	6	7	8	9	1Ø	11	12	13
SOURCE OF VARIATION	Y (Depth)	.125	.972	.173	.656	.152	2.711	.662	.925	.388	.2368	.125	.079	1.307
		N.S	N.S	N.S	N.S	N.S	*	N.S	N.S	N.S	N.S	N.S	N.S	N.S
	X (Across the River)	200.2	29.2	4.76	8.78	.256	.589	1.02	1.452	1.473	.155	1.741	3.264	7.378
		***	***	***	***	N.S	N.S	N.S	N.S	N.S	N.S	N.S	**	***

TABLE C.2 Anova Results (Time Variation) F-Values and Their Significance

	DATE	15.4.75					16.4.75					17.4.75		
	PROFILE	1	2	3	4	5	6	7	8	9	10	11	12	13
SOURCE OF VARIATION	TIME	10.12	49.24	17.89	22.43	16.36	1.285	9.069	12.59	4.098	39.67	49.76	3.26	.227
		***	***	***	***	***	N.S	***	***	**	***	***	*	N.S
	XxY	41.95	407.2	13.96	28.57	.71	.518	1.907	3.16	2.055	.817	11.22	.079	6.605
		***	***	***	***	N.S	N.S	+	**	+	N.S	***	N.S	***

APPENDIX D

Weighting the concentration profile with the velocity file

As has been discussed in Section 4.6, the concentration profiles of the preliminary gauging and the gauging on the 15 April 1975 (profiles 0-4) exhibited systematic variation across the river. The normalised sample concentration distributions were weighted by the velocity distribution obtained by current metering results. In this appendix we shall show how the particular distributions of sample concentration and velocity were found by multiple regression, in particular, examining the sums of squares due to fitting several different distributions (models) and comparing the sums of squares about the regression.

For the sample concentration data the models chosen were

$$\text{I} \quad \tilde{c}_2(\zeta,\eta) = a_o + a_1\zeta + a_2\eta + a_3\zeta^2 + a_4\zeta\eta + a_5\eta^2 \quad \text{(quadratic in both } \zeta \text{ and } \eta),$$

$$\text{II} \quad \tilde{c}_2(\zeta,\eta) = a_o + a_1\zeta \quad \text{(linear in } \alpha \text{ only)},$$

$$\text{III} \quad \tilde{c}_2(\zeta,\eta) = a_o + a_1\zeta + a_2\eta \quad \text{(linear in both } \zeta \text{ and } \eta),$$

and

$$\text{IV} \quad \tilde{c}_2(\zeta,\eta) = a_o + a_1\zeta + a_3\zeta^2 \quad \text{(quadratic in } \zeta \text{ only)}.$$

where $\tilde{c}_2$, ζ and η are the normalised forms of c_2, x and y respectively. The complete set of results of fitting the five profiles of normalised sample concentration data is given in Table D.1. The fittings show a remarkably consistent picture, especially when one considers the small difference between profile 0 and profiles 1-4 in the light of the difference in time and river sampling method. Examining the column labelled "sums of squares about regression" invariably model I fits the data the best, as would be expected because of the greater number of parameters. However, the parameter model IV is again invariably nearly as good a fit. The linear models II and III are consistently worse fits than the quadratic models I and IV. By combining the two analysis of variance for the fits of I and IV for all the profiles it is possible to compare them by the variance ratio test of the additional sums of squares accounted for by the η, $\zeta\eta$ and η^2 terms in model I from model IV and the residual sums of squares with (3,n) degrees of freedom where n is 39 for profile 0 and 41 for profiles 1-4. The variance ratio values are profile 0 (.670), profile 1 (.403), profile 2 (.711), profile 3 (.481) and profile 4 (.733) all of which indicate a non-significant improvement between the models I and IV. Thus in all five cases model IV was preferred.

A similar exercise was carried out on the normalised velocity profile data

$$\text{I} \quad \tilde{u}(\zeta,\eta) = b_o + b_1\zeta + b_2\eta + b_3\zeta^2 + b_4\zeta\eta + b_5\eta^2$$

TABLE D.1 Spatial Distributions Fitted to Concentration Profiles

PROFILE	MODEL	a_0	a_1	a_2	a_3	a_4	a_5	SUMS OF SQUARES DUE TO REGRESSION	df	SUMS OF SQUARES ABOUT REGRESSION	df
									ANOVA		
0	I	*** .873	*** .388	N.S .072	*** -.283	N.S .015	N.S -.046	.070	ANOVA 5	.058	39
	II	*** .946	*** .106	-	-	-	-	.045	1	.083	43
	III	*** .985	*** .108	N.S .017	-	-	-	.046	2	.032	42
	IV	*** .898	*** .393	-	*** -.281	-	-	.068	2	.060	42
1	I	*** .839	*** .724	N.S -.003	*** -.565	N.S .011	N.S -.005	.240	5	.084	42
	II	*** .922	*** .154	-	-	-	-	.121	1	.202	45
	III	*** .923	*** .155	N.S -.002	-	-	-	.121	2	.202	44
	IV	*** .836	*** .730	-	*** -.564	-	-	.239	2	.084	44
2	I	*** .821	*** .764	N.S .074	*** -.603	N.S .001	N.S -.076	.252	5	.054	41
	II	*** .923	*** .150	-	-	-	-	.115	1	.191	45
	III	*** .932	*** .151	N.S -.015	-	-	-	.116	2	.190	44
	IV	*** .832	*** .765	-	*** -.603	-	-	.250	2	.056	44
3	I	*** .869	*** .639	N.S -.009	*** -.561	N.S .077	N.S -.011	.180	5	.177	41
	II	*** .945	** .111	-	-	-	-	.064	1	.293	45
	III	*** .936	** .111	N.S -.015	-	-	-	.064	2	.292	44
	IV	*** .860	*** .681	-	*** -.557	-	-	.177	2	.180	44
4	I	*** .852	*** .805	N.S -.080	-.608	N.S -.095	N.S .092	.225	ANOVA 5	.127	41
	II	*** .936	*** .130	-	-	-	-	.084	2	.268	45
	III	*** .944	*** .130	N.S -0.13	-	-	-	.085	2	.268	44
	IV	*** .844	*** .747	-	*** -.609	-	-	.220	2	.133	44

with only one alternative model:

$$\text{II} \quad \tilde{u}(\zeta,\eta) = b_o + b_1\zeta + b_2\eta.$$

Table D.2 makes it clear why the two other alternative models concerned with just α variation were excluded; since all five parameters of I are significant to some degree, there was little reason to exclude any of them. However, it was thought that the fit of quadratic model I should be compared to the linear model II.

TABLE D.2 Spatial Distributions Fitted to Velocity Profile

MODEL	b_o	b_1	b_2	b_3	b_4	b_5	SUMS OF SQUARES DUE TO REGRESSION	df	SUMS OF SQUARES ABOUT REGRESSION	df
							ANOVA			
I	+ -.176	*** 2.405	*** 2.436	*** -2.221	* -.377	*** -1.378	7.931	5	1.875	112
II	*** .625	N.S -.11	*** .725	-	-	-	3.546	2	6.260	115

Again, comparing the fittings of models I and II the variance ratio value of the additional sums of squares accounted by the extra parameters in model I from model II against the residual sums of squares is 9.344 with (3,112) degrees of freedom. This is significant at the .1% level, and thus model I is a much better fit than model II.

```
C     PROGRAM TO PRODUCE IODIDE PROFLES
C
C     P.SMITH MAY 1975
C
      DIMENSION PROFLE(6,10,5),GRID(2,10,5),POLE(10),HOLE(5),IZERO(3,50
     1),WL(10),IITLE(5),IPE(10),DUM(3,10),RSE(6,10,5),IS(10,5),IZP(5)
      DATA POLE/.53,1.85,2.625,2.74,2.765,2.735,2.72,2.73,2.75,1.69/HOLE
     1/2.4,1.95,1.5,1.05,.6/WL/2.6746,2.6746,2.5984,2.61745,2.7,2.7,2.61
     2745,2.6492,2.7127,2.5984/IPE/0.1,2,3,4,5,6,7,8,9/IZP/3HA     B
     3  C     D     E     /
C
C     PROFLE(1,J,I) IS THE INTERPOLATED A PROFLE
C           (2,J,I)                        B PROFLE
C           (3,J,I)                        C PROFLE
C           (4,J,I)                        D PROFLE
C           (5,J,I)                        E PROFLE
C           (6,J,I) IS-THE COMPOSITE FULL PROFLE
C
      READ(5,100)(IITLE(I),I=1,5)
  100 FORMAT(5A6)
      WRITE(6,200)(IITLE(I),I=1,5)
  200 FORMAT(1H1///56X,5A6/56X,30(1H-)///)
C
C     POLE X-CO-ORDINATES
C
      DIST=0.
      DO 1 J=1,10
      DIST=DIST+POLE(J)
      DO 2 I=1,5
    2 GRID(1,J,I)=DIST
    1 CONTINUE
C
C     INPUT INCREMENT AWAY FROM 17/4/75 STAGE VALUE
C
      READ(5,102)AINCR
  102 FORMAT()
      DO 3 I=1,10
    3 WL(I)=WL(I)+AINCR
      DO 4 J=1,10
      DO 4 I=1,5
    4 GRID(2,J,I)=WL(J)-HOLE(I)
      WRITE(6,201)(IPE(I),I=1,10),(((GRID(I,J,K),I=1,2),J=1,10),K=1,5)
  201 FORMAT(  ' GRID CO-ORDINATES (LOOKING DOWNSTREAM)'/1X,39(1H-)/9X,I
     11,9(12X,I1)//1X,1HA,10(2H (,F5.2,1H,,F4.2,1H))//1X,1HB,10(2H (,F5.
     22,1H,,F4.2,1H))//1X,1HC,10(2H (,F5.2,1H,,F4.2,1H))//1X,1HD,10(2H (
     3,F5.2,1H,,F4.2,1H))//1X,1HE,10(2H (,F5.2,1H,,F4.2,1H))///)
C
C     INTERPOLATE MISSING PROFLE VALUES
C
      M=0
      DO 5 I=1,5
      READ(5,101)((DUM(K1,K2),K1=1,3),K2=1,10)
  101 FORMAT(5(F5.1,F5.2,F5.3))
      DO 5 J=1,10
```

```
      IA=(J-1)*3+I
      IB=IA-((IA-1)/5)*5
      DF=DUM(2,J)
      IF(DF.LE.99.98)GOTO 9
      M=M+1
      IZERO(1,M)=I
      IZERO(2,M)=J
      IZERO(3,M)=IB
      GOTO 20
9     X=GRID(1,J,IB)
      Y=(2.5-GRID(2,J,IB))*2.
      WRITE(11,215)X,Y,DF
215   FORMAT(3F8.2)
20    PROFLE(I,J,IB)=DF
      PROFLE(6,J,IB)=DF
      IS(J,IB)=DUM(1,J)
      RSE(I,J,IB)=DUM(3,J)
      RSE(6,J,IB)=DUM(3,J)
5     CONTINUE
      IF(M.EQ.0)GOTO 6
      DO 7 K=1,M
      IY=IZERO(2,K)
      IX=IZERO(3,K)
      AY=GRID(1,IY,IX)
      AX=GRID(2,IY,IX)
      SUM=0.
      SUMD=0.
      SUMR=0.
      DO 8 J1=1,10
      DO 8 I1=1,5
       DO 14 LK=1,M
       JY=IZERO(2,LK)
       JX=IZERO(3,LK)
      IF(JY.EQ.J1.AND.JX.EQ.I1)GOTO 8
14     CONTINUE
      Y=GRID(1,J1,I1)
      X=GRID(2,J1,I1)
      DIST=(X-AX)*(X-AX)+(Y-AY)
      SUM=SUM+PROFLE(6,J1,I1)/DIST
      SUMD=SUMD+1./DIST
      SUMR=SUMR+RSE(6,J1,I1)/DIST
8     CONTINUE
      PROFLE(6,IY,IX)=SUM/SUMD
      RSE(6,IY,IX)=SUMR/SUMD
      IZ=IZERO(1,K)
      PROFLE(IZ,IY,IX)=SUM/SUMD
      RSE(IZ,IY,IX)=SUMR/SUMD
7     CONTINUE
C
C      WRITE SAMPLE MOS RSE'S AND CONC'S FOR THE COMPLETE PROFLE
 6     WRITE(6,202)(IPE(I),I=1,10),((IS(J1,I1),J1=1,10),I1=1,5)
 202   FORMAT(1X,'COMPLETE PROFILE'/1X,16(1H-)//1X,'SAMPLE NUMBERS'/9X,I1
     1,9(12X,I1)//1X,1HA,I9,9I13//1X,1HB,I9,9I13//1X,1HC,I9,9I13//1X,1HD
```

```
     2,I9,9I13//1X,1HE,I9,9I13///)
      WRITE(6,203)
 203  FORMAT(1X,'IODIDE CONCENTRATIONS'/)
      WRITE(6,204)(IPE(I),I=1,10),((PROFLE(6,J2,I2),J2=1,10),I2=1,5)
 204  FORMAT(9X,I1,9(12X,I1)//2H A,F9.3,9F13.3//2H B,F9.3,9F13.3//2H C,F
     19.3,9F13.3//2H D,F9.3,9F13.3//2H E,F9.3,9F13.3///)
      WRITE(6,205)
 205  FORMAT('1RELATIVE STANDARD ERRORS'/)
      WRITE(6,204)(IPE(I),I=1,10),((RSE(6,J2,I2),J2=1,10),I2=1,5)
C
C     INTERPOLATE PART PROFLES
C
      DO 10 I=1,5
      DO 13 J=1,10
      IA=(J-1)*3+I
      IB=IA-((IA-1)/5)*5
      R1=PROFLE(I,J,IB)-RSE(I,J,IB)
      R2=PROFLE(I,J,IB)+RSE(I,J,IB)
      WRITE(12,210)R1,R2,J,I
 210  FORMAT(2F8.2,2I4)
      DO 11 K=1,5
      IF(K.EQ.IB)GOTO 11
      AY=GRID(1,J,K)
      AX=GRID(2,J,K)
      SUM=0.
      SUMR=0.
      SUMD=0.
      DO 12 L=1,10
      IC=(L-1)*3+I
      ID=IC-((IC-1)/5)*5
      Y=GRID(1,L,ID)
      X=GRID(2,L,ID)
      DIST=(X-AX)*(X-AX)+(Y-AY)*(Y-AY)
      SUM=SUM+PROFLE(I,L,ID)/DIST
      SUMR=SUMR+1./DIST
      SUMD=SUMD+RSE(I,L,ID)/DIST
 12   CONTINUE
      PROFLE(I,J,K)=SUM/SUMR
      RSE(I,J,K)=SUMD/SUMR
 11   CONTINUE
 13   CONTINUE
      IF(I.EQ.3)WRITE(6,207)
 207  FORMAT(1H1)
      WRITE(6,206)IZP(I)
 206  FORMAT(1X,'PART PROFILE  ',A6//)
      WRITE(6,204)(IPE(I5),I5=1,10),((PROFLE(I,J5,I6),J5=1,10),I6=1,5)
 10   CONTINUE
      DO 15 I=1,5
      DO 15 J=1,10
      DO 15 K=1,5
      R1=PROFLE(I,J,K)-RSE(I,J,K)
      R2=PROFLE(I,J,K)+RSE(I,J,K)
      WRITE(13,211)R1,R2,K,J,I
 211  FORMAT(2F8.2,3I4)
 15   CONTINUE
```

```
      DO 16 J=1,10
      DO 16 K=1,5
      R1=PROFLE(6,J,K)-RSE(6,J,K)
      R2=PROFLE(6,J,K)+RSE(6,J,K)
      WRITE(14,210)R1,R2,K,J
16    CONTINUE
      STOP
      END
```