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GAUGING OF THE RIVERS DULAS AND VYRNWY USING THE CHEMICAL TRACER DILUTION METHOD

Report To National Rivers Authority (Severn-Trent Region)

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BACKGROUND

Gauging of steep streams in the uplands presents many problems, not least the large-scale turbulence and irregular channel form that makes conventional current metering difficult and unreliable. Dilution methods, using a suitable tracer, offer an alternative means of coping with these difficult sites and obtaining the points necessary for the construction of the rating curve.

The Institute of Hydrology (IH), which has experience of using dilution methods with chemical tracers since the early 1970's, was approached by the Severn-Trent Division of the NRA to provide gaugings of the Dulas at Rhos-y-Pentre (a trapezoidal flume) and the Vyrnwy at Pontrobert (a velocity-area station) at high flows. Each gauging was to consist of an extended constant rate injection of sodium iodide tracer, timed to catch as high a flow as possible and if possible to obtain several points on the recession limb of the hydrograph. The decision to mount each gauging operation was to be made on the basis of stage data acquired from the gauging stations through a modem, using the ODIN software package kindly provided for this project by the NRA. The gaugings were carried out in March 1994.

The British Standard (BS3680 Part 2) relating to dilution methods is undergoing a thorough and overdue revision: the recently published International Standard ISO 9555-1 (1994) will be published shortly as the new BS, and will describe the field techniques and analysis of results. The work described by this report followed the procedures laid down in the ISO Standard.

LOCATIONS OF GAUGING SITES

The technique of dilution gauging requires the selection of two cross-sections with reasonably easy access to the water. At the upstream cross-section a suitable tracer is injected as a solution, making use of natural turbulence and features such as channel constrictions to obtain as good as possible a mix with the stream waters. It is advantageous to be able to inject at a point near the centre of the flow, as lateral injections require a greater downstream distance to achieve full mixing with the water in the stream. At the downstream site, samples are taken from a number of fixed stations across the channel, so that an assessment can be made of the quality of the mixing. The total discharge at the downstream cross-section is determined from the quantity of tracer solution injected and the dilution of this solution with the river water.

The required distance between the two cross-sections can be estimated according to a number of criteria, but ultimately the choice of cross-sections will be a compromise between the needs of access and technical suitability. While too short a gauging reach could not provide sufficient mixing, too great a distance would involve long travel times and a larger quantity of tracer, and would therefore increase the expense of the gauging. Longer gauging reaches also allow increased adsorption losses, and increase the likelihood of influence from tributaries, abstractions and changing storage volume within the reach.

Where the measurement of discharge is required at a fixed cross-section, for example a gauging station, it is preferable to take the samples at or near this section, with no significant intervening tributaries. Lateral inputs upstream, between injection and sampling cross-sections, will be at least partially mixed into the flow.

At Rhos-y-Pentre (Figure 1), there is no suitable injection cross-section offering access to the centre of the channel, and the nearest available sampling cross-section to the gauging station is at Pentre-Dulas Bridge, about 100 m upstream of the gauging station. The channel is between 5 and 6 m wide. For a side injection of tracer, the length required for mixing would be of the order of 100 times the width, i.e. 600 m, but it was expected that steep reaches and bends between the Wern and the bridge would improve mixing, and the selected injection point, 255 m upstream of the bridge, proved to be satisfactory.

At Pontrobert (Figure 2), a bridge immediately upstream of the gauging station provided a suitable sampling site, but there were problems in selecting an injection cross-section. The river is of the order of 20 m wide, which suggests a 2000 m gauging reach from a side injection, or a 500 m reach using a centre injection. There is no suitable upstream cross-section with access to the centre of the channel, and it was decided that 2000 m could be too long on the grounds of excessive time-of-travel. A tributary enters from the north (left) bank opposite Doladron, about 910 m upstream of the bridge, and it was decided to inject tracer from a road bridge into this stream, on the assumption that a significant flow entering at right angles to the main flow of the river would carry tracer across the flow and help it to mix. However, on analysis of the river samples, transverse mixing was found to have been less than satisfactory.

At each sampling cross-section, four equally-spaced sampling stations were marked on the bridge parapet: at Pontrobert two samples were taken from each of the two arches of the bridge.

METHOD

To obtain several flow gaugings on the same day, the constant-rate injection method (BS 3680 Part 2A, ISO 9555-1) was chosen. A constant discharge of tracer solution was provided by a Mariotte vessel, which is a constant-head vessel holding up to about 50 litres. Tracer discharge rates of a few ml/sec can be provided over a period of several hours. Although the injection rate is set by the choice of a jet, it is determined in the field for each gauging by timed readings of a calibrated sight tube on the Mariotte vessel. The constant-rate injection method can be used to measure slowly varying flow, for example on the recession limb of a hydrograph: in this case the downstream concentration, after a steep rise as the tracer reaches the sampling cross-section, continues to increase slowly over the period of the gauging, as the dilution decreases. With the alternative integration (sudden injection or gulp) method, it is necessary to wait for the passage of all the tracer from a previous injection before the next can be carried out.

In the gaugings described here, the limitations on the duration of tracer injection and sampling were partly logistical. At Rhos-y-Pentre, which is closer to IH's office at

Staylittle, two separate injections were made, with a break in sampling around midday while the tracer flow at the sampling cross-section re-established its constant rate. At Pontrobert the single long injection started around midday.

IH has been using the iodide ion as a tracer for many years: iodide is non-toxic and highly soluble, is not adsorbed strongly by materials normally found in rivers, and can be analysed at very low levels. The usual aim is to produce levels of around 50 μg/litre in the river, which is sufficiently elevated above the normal background level of around 2 μg/litre, while remaining undetectable without specialised instrumentation, and not requiring large inputs of tracer substance for each gauging. Even so, for large flows the dilution factor can be around 5 million, and kilogram quantities of tracer (in solid form) will be necessary. The practical limitations on the flow that can be measured are the difficulty of dissolving large quantities of tracer effectively, and the handling of large volumes of quite dense solutions (the solubility of iodide is of the order of 1.5 kg/litre).

Three injections were carried out for this study. The existing rating was used as a guide to the quantity of tracer required, and the jet for the Mariotte vessel, which controls the injection rate of tracer solution, was chosen so as to ensure the longest injection time possible within daylight hours. Tracer was added to the injection vessel in solid form, and made up to the required volume of around 40 litres.

Dulas at Rhos-y-Pentre No.1 - 9 March 1994

3 kg of sodium iodide dissolved in stream water and injected by Mariotte vessel between 12:12 and 14:32 GMT.

Samples of concentrated tracer solution taken from outlet from Mariotte vessel at start and finish of injection.

Background samples taken from the river upstream of injection point before start and after finish of injection.

Stream samples taken from upstream side of Pentre-Dulas Bridge at 15-minute intervals, at four stations across the river, using a weighted sampler on a rope.

Dulas at Rhos-y-Pentre No.2 - 9 March 1994

2 kg of sodium iodide added to about 11 litres of tracer solution remaining in Mariotte vessel and made up to full volume with stream water. Injected between 14:47 and 17:00 GMT.

Samples: as for No.1.

Vyrnwy at Pontrobert - 22 March 1994

8 kg of sodium iodide dissolved in stream water and injected by Mariotte vessel between 12:15 and 16:55 GMT.

Injected tracer solution and background samples: as for Rhos-y-Pentre.

Stream samples taken from downstream side of Pontrobert bridge at 15-minute intervals from four stations across the river, using a weighted sampler on a rope.

For each gauging, the tracer injection rate was determined by regression analysis of sight tube readings (taken every 10 mm and timed to the nearest second) against time. Sight tube calibration, of level against volume remaining in the vessel, was carried out in the laboratory. All stream and background samples were analysed by catalytic spectrophotometry in the IH laboratories in Wallingford. Injection solution samples were diluted by the estimated dilution factor, to bring them to approximately the same concentrations as the river samples, before analysis.

RESULTS

Dulas at Rhos-y-Pentre No.1

Injection rate: 2.538 ml/sec
Concentration of injected tracer: 35.6 μg/litre x Dilution factor of 2000000
Background concentration: 2.6 μg/litre

River samples:

Time	Concentrations corrected for background, μg/litre			
GMT	Left bank			Right bank
1224	21.7	16.8	18.1	17.1
1237	37.7	44.9	40.3	41.8
1252	44.9	45.7	39.3	42.7
1307	45.2	42.8	48.5	47.3
1322	43.0	46.2	43.0	44.5
1336	44.9	41.7	49.3	49.3
1352	49.3	49.2	50.6	51.2
1407	52.3	53.9	52.3	51.5
1422	51.8	54.2	52.0	51.5

Samples taken at 12:24 and 12:37 show signs of the increase towards the final "steady" concentrations. Discharge was calculated from samples 12:52 to 13:22, 13:22 to 13:52 and 13:52 to 14:22.

For these samples, the degree of mixing, calculated according to the method of ISO 9555-1 and giving equal weight to each sampling station, was 99.7%.

12:52 to 13:22

Stage (from telemetry): 0.819 m at 13:00 GMT, 0.809 m at 13:15 GMT
Estimated stage: 0.814 m at 13:07 GMT

Discharge from rating: 3.53 cumecs
Discharge (dilution): 4.07 ± 0.15 cumecs (95% conf. limits)

13:22 to 13:52

Stage (from telemetry): 0.800 m at 13:30 GMT, 0.790 m at 13:45 GMT
Estimated stage: 0.795 m at 13:37 GMT

Discharge from rating: 3.35 cumecs
Discharge (dilution): 3.86 ± 0.17 cumecs

13:52 to 14:22

Stage (from telemetry): 0.781 m at 14:00 GMT, 0.773 m at 14:15 GMT
Estimated stage: 0.777 m at 14:07 GMT

Discharge from rating: 3.17 cumecs
Discharge (dilution): 3.50 ± 0.08 cumecs

Dulas at Rhos-y-Pentre No.2

Injection rate: 2.827 ml/sec
Concentration of injected tracer: 45.63 µg/litre x Dilution factor of 2000000
Background concentration: 2.6 µg/litre

River samples:

Time	Concentrations corrected for background, µg/litre			
GMT	Left bank			Right bank
1502	76.3	80.7	79.7	80.7
1516	80.2	86.4	86.4	81.3
1532	75.8	92.1	93.3	89.4
1547	90.3	87.9	87.1	84.3
1602	87.1	91.2	94.1	91.2
1616	91.2	93.1	91.9	92.1
1632	91.2	92.1	92.1	83.3
1646	88.7	87.0	88.7	87.8
1702	88.7	89.6	94.1	95.1

Samples taken at 15:02, 15:16 and 15:32 show signs of the increase towards the final "steady" concentrations. Discharge was calculated from samples 15:47 to 16:32 and 16:16 to 17:02.

The degree of mixing, calculated according to the approximate "equal weighting" method of the British and International Standards, was 99.6%.

15:47 to 16:32

Stage (from telemetry):	0.724 m at 16:00 GMT, 0.719 m at 16:15 GMT
Estimated stage:	0.721 m at 16:09 GMT
Discharge from rating:	2.68 cumecs
Discharge (dilution):	2.87 ± 0.05 cumecs (95% conf. limits)

16:16 to 17:02

Stage (from telemetry):	0.714 m at 16:30 GMT, 0.709 m at 16:45 GMT
Estimated stage:	0.711 m at 16:39 GMT
Discharge from rating:	2.59 cumecs
Discharge (dilution):	2.85 ± 0.05 cumecs

Vyrnwy at Pontrobert

Injection rate: 2.292 ml/sec
Concentration of injected tracer: 32.32 µg/litre x Dilution factor of 5000000
Background concentration: 2.0 µg/litre

River samples:

Time	Concentrations corrected for background, µg/litre			
	Left bank			Right bank
1332	9.1	13.1	30.4	39.5
1348	9.4	11.7	30.3	44.0
1402	10.3	13.8	32.1	41.3
1416	12.5	14.1	30.3	43.8
1432	7.6	16.8	30.9	44.1
1446	9.3	13.7	32.5	42.4
1502	9.1	12.9	30.2	47.5
1516	15.9	19.8	36.3	38.2
1533	9.5	15.8	33.8	40.7
1546	9.0	13.5	37.5	46.4
1602	14.6	17.7	40.0	47.5
1616	17.0	16.9	36.9	42.1
1632	15.2	15.3	37.8	37.8
1646	15.7	34.9	34.6	42.8
1702	11.6	14.9	33.2	48.2
1716	9.6	9.5	17.6	0.6
1732	0.2	0.6	0.5	0.6
1746	1.1	0.4	1.3	0.3

Transverse mixing of the tracer was not achieved fully at the sampling cross-section, though it appears that the tracer had crossed the river to appear in greatest concentrations on the right bank, and calculation of the discharge from these figures proceeds on the assumption that there is no serious interaction between the distributions of concentration and velocity (integrated over depth) across the sampling cross-section. Reference will be made to this assumption in the next section.

Samples taken after 17:16 show the rapid decline towards background after the cessation of tracer injection, while one sample taken at 16:46 shows an unaccountably high concentration compared with its predecessors from that station. Discharge was calculated from samples taken 13:32 to 14:32, 14:32 to 15:33 and 15:33 to 16:32.

For these samples, the degree of mixing, calculated according to the approximate "equal weighting" method of the International Standard was 75%.

13:32 to 14:32

Stage (from telemetry):	1.448 m at 14:00 GMT, 1.447 m at 14:15 GMT
Estimated stage:	1.448 m at 14:02 GMT
Discharge from rating:	8.47 cumecs
Discharge (dilution):	15.27 ± 3.84 cumecs

14:32 to 15:33

Stage (from telemetry):	1.445 m at 15:00 GMT, 1.443 m at 15:15 GMT
Estimated stage:	1.445 m at 15:02 GMT
Discharge from rating:	8.38 cumecs
Discharge (dilution):	14.61 ± 3.51 cumecs

15:33 to 16:32

Stage (from telemetry):	1.430 m at 16:00 GMT, 1.427 m at 16:15 GMT
Estimated stage:	1.430 m at 16:02 GMT
Discharge from rating:	7.95 cumecs
Discharge (dilution):	13.60 ± 3.05 cumecs

DISCUSSION

At both sites, the estimate of flow by dilution methods exceeds that given by the rating curve, and for the Vyrnwy at Pontrobert the difference is considerable, of the order of 70 to 80%.

Clearly, without further field measurements, it is not possible to go into great detail over the likely reasons for such a discrepancy. However, in view of the fact that systematic errors in the dilution method generally lean towards over-estimation, it would be useful here to consider the range of possible errors in the dilution measurement, in addition to the random uncertainties contained in the confidence limits quoted above.

In the Standard, attention is given to several sources of systematic error arising from loss of tracer, failure to sample fully, poor mixing and changes in the flow during the gauging.

Adsorption of tracer is avoided by careful choice of the tracer substance. It is believed that adsorption of the iodide ion by the bed, banks and sediment of the river during the gauging was negligible, and samples were filtered on reaching the laboratory, and refrigerated to prevent losses in storage.

Failure to achieve a "steady" downstream concentration is a feature of short injection and sampling periods, and it is believed that this condition did not apply to the gaugings described here. The evidence from river samples at both sites suggests that the "steady" concentrations were achieved after between 40 minutes and one hour after the start of injection at Rhos-y-Pentre, and that the river concentrations were down to background levels about the same time after cessation of injection at Pontrobert.There is little doubt that the majority of river samples, and all of those actually used in the calculations, were taken while "steady" conditions obtained.

The discharge was changing during the gaugings, and the steady conditions required ideally by dilution gauging (and most other gauging methods) did not obtain. Nevertheless, the change in discharge over the mean time of travel through the gauging reach (between about 10 and 15 minutes at each site) was 1.7 to 2.5% (Rhos-y-Pentre No. 1), 1.0 to 1.6% (Rhos-y-Pentre No. 2) and 0.5 to 0.8% (Pontrobert). The systematic error for these gaugings, arising from this source, would be +1.7 to +2.5%, +1.0% to +1.6% and +0.5% to +0.8% respectively.

Mixing was very good in the Rhos-y-Pentre gaugings, and the values obtained would suggest a systematic error of less than 0.8%. This systematic error could be of either sign, as nothing is known about the distribution of velocities in the sampling cross-section. At Pontrobert, the gauging reach was clearly insufficient to provide good mixing for a side injection, and there could be a systematic error related to the distribution of discharge across the sampling cross-section. If the majority of the discharge were through the right-hand arch of the bridge, this would place most weight on the right-hand pair of samples, and would imply that the total discharge was over-estimated by taking the overall mean river concentration. In an extreme case, the true value of the discharge could approximate that given by the rating curve, but this would be the case only if the velocity were distributed in an extremely asymmetric way. It is the opinion of the author, based on visual examination of the flow under the bridge at Pontrobert, that flow through the right-hand arch could not exceed double that through the left-hand arch. In this case, the discharge estimates from the dilution method would be modified to

13.14 ± 3.30 cumecs at a stage of 1.448 m

12.57 ± 3.02 cumecs at a stage of 1.445 m

and 11.70 ± 2.62 cumecs at a stage of 1.430 m.

These figures exceed the rating curve discharges by between 47 and 55%. At the other extreme the flow could be uniformly distributed. It is considered that the true values lie somewhere between the "flow-weighted" estimates and the values calculated on an "equal-weight" basis.

In view of the mixing problems encountered at Pontrobert, it is recommended that in any future dilution exercise at this station, consideration should be given to moving the injection cross-section upstream as far as the next tributary at Coed Lletty'r-aderyn, at grid reference SJ 097138, to provide a mixing reach of about 1800 m. Alternatively a pump could be used to carry out an injection on the centre-line of the channel.

FINAL RESULTS

The ISO Standard recommends a procedure for combining uncertainties from all sources, including systematic errors. Analysis of the first gauging is presented in full as an example:

Dulas at Rhos-y-Pentre No.1 (12:52 to 13:22)

Random uncertainty only:

Discharge 4.07 ± 0.15 cumecs

Systematic uncertainties:

From changing flow: +1.7% to +2.5% = +0.07 to +0.11 cumecs

From mixing: ±0.8% = ±0.03 cumecs

Following ISO 9555-1, largest value Q_2 is

$$4.07 - 0.07 + 0.03 = 4.03 \text{ cumecs}$$

and smallest value Q_1 is

$$4.07 - 0.11 - 0.03 = 3.93 \text{ cumecs}$$

and the mid-point value, $(Q_1+Q_2)/2$, is

$$(4.03 + 3.93)/2 = 3.98 \text{ cumecs}$$

with a remaining uncertainty of $\pm(Q_1-Q_2)/2$

±0.05 cumecs

On combination with the random uncertainty this becomes

$$\pm\sqrt{(0.15^2 + 0.05^2)} = \pm 0.16 \text{ cumecs}$$

So for a stage of 0.814 m the final discharge estimate is

3.98 ± 0.16 cumecs (13% above rating)

Using the above method, the compete set of results (see Figures 3 & 4) is:

Dulas at Rhos-y-Pentre - 9 March 1994

Sample times	Stage, m	Discharge, cumecs		Dilution result exceeds rating by
		Dilution gauging	Rating	
12:52 to 13:22	0.814	3.98 ± 0.16	3.53	13%
13:22 to 13:52	0.795	3.78 ± 0.18	3.35	13%
13:52 to 14:22	0.781	3.42 ± 0.09	3.17	8%
15:47 to 16:32	0.721	2.83 ± 0.06	2.68	6%
16:16 to 17:02	0.711	2.81 ± 0.06	2.59	8%

Vyrnwy at Pontrobert - 22 March 1994

Sample times	Stage, m	Discharge, cumecs		Dilution result exceeds rating by
		Dilution gauging	Rating	
13:32 to 14:32	1.448	14.11 ± 3.73	8.47	67%
14:32 to 15:33	1.445	13.51 ± 3.43	8.38	61%
15:33 to 16:32	1.430	12.57 ± 3.42	7.95	58%

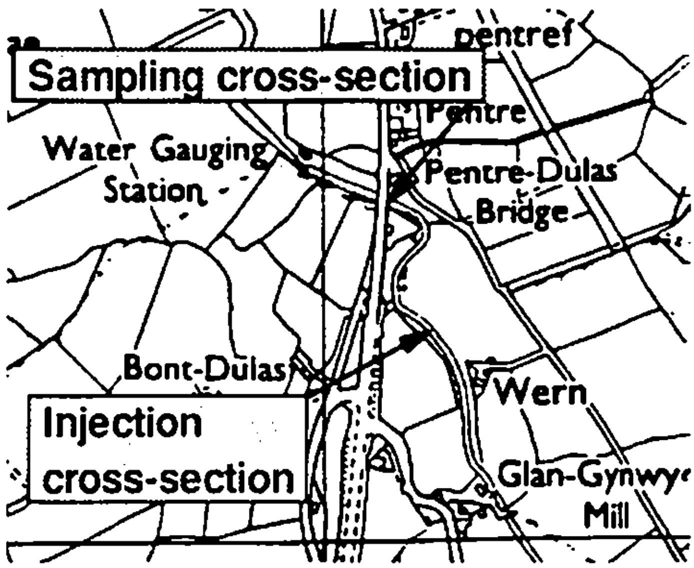

Figure 1 *Location of injection and sampling sites for Dulas at Rhos-y-Pentre, 9 March 1994. The sampling cross-section (Pentre-Dulas Bridge) was 255 m downstream of the injection cross-section, and tracer was injected from the right bank of the river.*

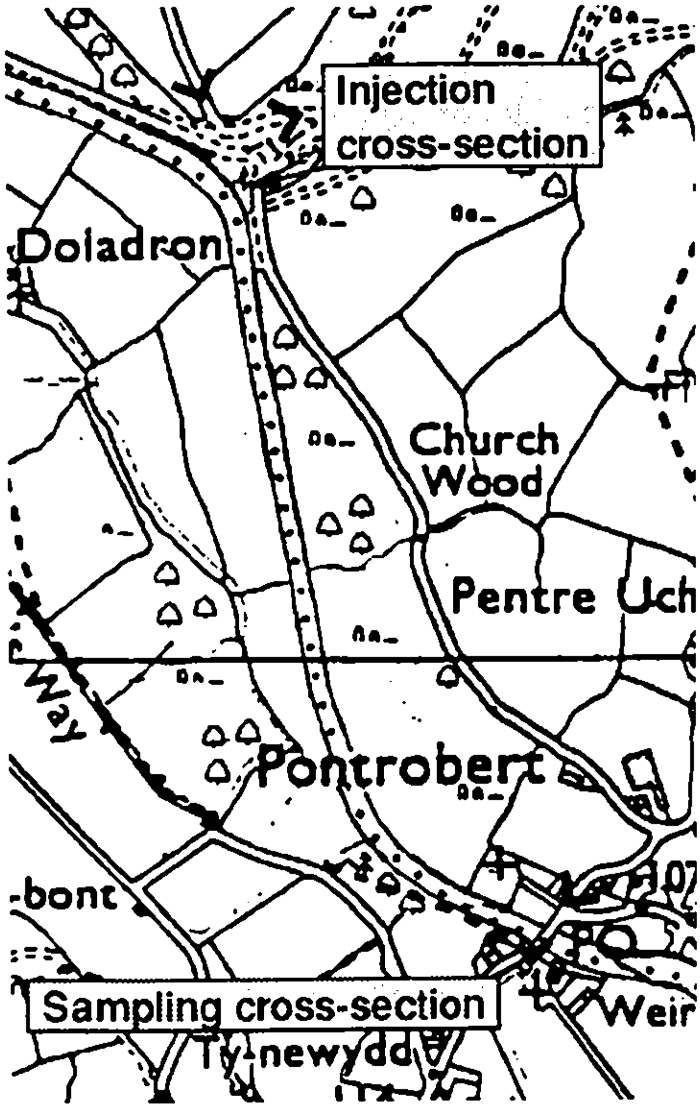

Figure 2 *Location of sampling and injection sites for Vyrnwy at Pontrobert, 22 March 1994. Injection and sampling cross-sections were 910 m apart, and tracer was injected into a tributary entering the river from the left bank. Samples were taken from the downstream side of the Pontrobert bridge.*

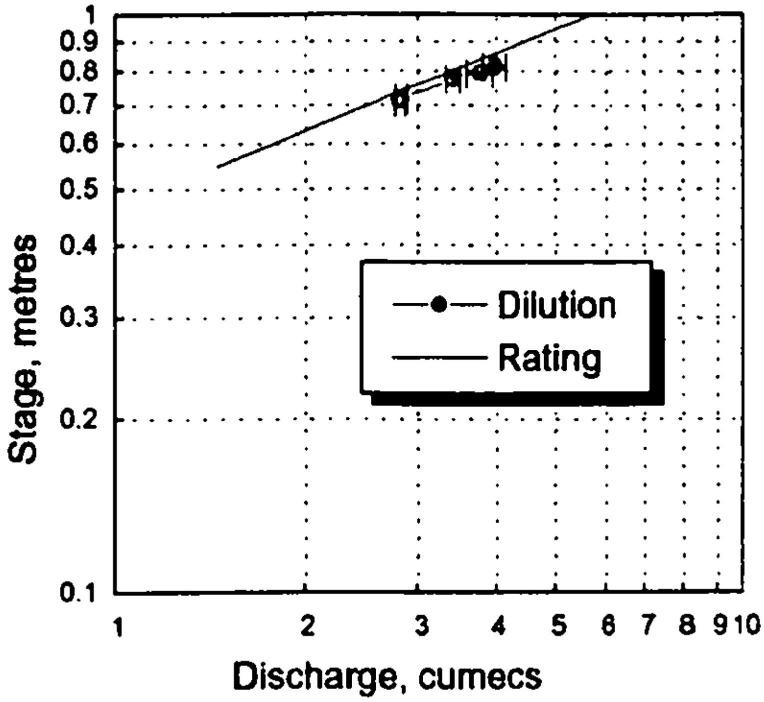

Figure 3 Dulas at Rhos-y-Pentre - 9 March 1994

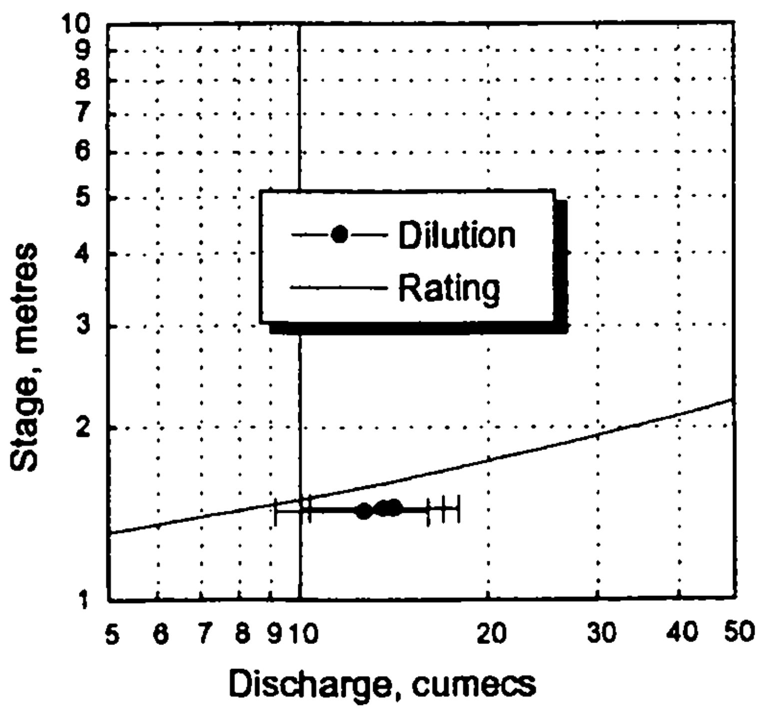

Figure 4 Vyrnwy at Pontrobert - 22 March 1994