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THE DESIGN, OPERATION AND CALIBRATION OF THE PERMANENT FLOW MEASUREMENT STRUCTURES IN THE PLYNLIMON EXPERIMENTAL CATCHMENTS

by

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ABSTRACT

Descriptions and illustrations are provided for the major flow measurement structures on the Rivers Wye and Severn (Crump weir and trapezoidal flume) and the specially designed flumes on the tributary streams. The dimensions quoted are according to design flow calculations. Both analogue and digital water-level recorders have been used. Field calibrations have been made by dilution gauging, current metering and volumetric gaugings as a check on the theoretical rating curves.

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INTRODUCTION

Accurate measurement of flow is a crucial part of the Institute's long-term hydrological investigation of the Plynlimon catchments. Eight sites were chosen, one on each of the two main streams, the Severn and Wye, and one on each of the six major tributary streams - the Hore, Hafren and Tanllwyth in the Severn catchment and the Cyff, Gwy and Iago in the Wye catchment. Continuous flow measurement was required at each site for inter-catchment comparisons of streamflow.

An existing structure on the River Severn, a sharp-crested weir, was rejected in favour of a new critical depth flume of trapezoidal cross section sited further downstream. In the Wye, an existing weir at Cefn Brwyn (built originally by the Central Electricity Generating Board in the early fifties) was modified to form a compound Crump weir. The design of both these structures followed established practice. Conventional gauging structures were unsuitable for the tributary streams due to their steep gradients and high throughput of bed load sediment. Accordingly, the Hydraulics Research Station was commissioned to design and calibrate a new form of structure suitable for the tributary streams. The resultant design* was tested as a scaled hydraulic model and accepted by the Institute.

The dimensions of the design were determined by the flow characteristics of the six minor catchments and the structures were built on site by the Wye River Authority (now the Wye Division of the Welsh National Water Development Authority). This report on the different structures describes the Institute's experience of their performance and operation as accurate flow measuring devices under difficult conditions.

1. THE FLOW MEASUREMENT STRUCTURES

1.1 Severn trapezoidal flume

The Severn flume was designed by the Hydraulics Research Station to gauge discharges from a catchment at the head of the River Severn. The design criteria were as follows:

Catchment area	8.70 km^2
Stream slope	0.011
Minimum discharge to be measured	0.023 cumecs
Maximum discharge to be measured	41.030 cumecs

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* *HRS Report No. 335 June 1966.*
Plynlimon Experimental Catchments - model investigation of a structure for flow measurement in steep streams.

Natural channel Froude number* at bank-full discharge | 0.6

The flume was designed so that the Froude number in the approach remained at 0.6 throughout the range of discharge. This ensured that depths and velocities in the approach are similar to those occurring upstream thereby minimising the risk of deposition of sediment and the consequent inaccuracies in gauging.

The flume, as built, is a critical depth flume of trapezoidal section. It has a flat invert, 457 mm wide, with a 9 mm step down into the throat achieved over a 610 mm long transition section. The side slopes in the approach are 1 : 3.90 and 1 : 3.25 in the throat. Transition from the approach to the throat section is achieved by two cylindrical surfaces, the axes of the cylinders passing through the entrance to the throat. Stage levels are measured in a stilling well connected by a pipe to the side of the flume at the invert level of the approach section. The plan dimensions and layout of the flume are shown in Appendix I.

The concrete flume was completed in 1968 with the outer surface finished with particular care. A Leupold and Stevens chart recorder and a Fischer and Porter punched tape recorder were installed to record stage. This instrument duplication provided a back-up in the case of recorder failure and has kept data retrieval at a very high level.

Performance

The flume has worked successfully since construction although the inevitable operational problems have been magnified by the need for high levels of precision and continuous records essential for research purposes.

The original design report issued by HRS recommended checks on the as-built dimensions and a field calibration, since any variation in the dimensions would cause a departure from the theoretical stage/discharge relationship. The dimensions of the constructed flume were measured on completion and found to match the design.

Sedimentation problems

It soon became apparent that large quantities of bed load were moving through the structure with a shoal in the reach immediately above the flume constantly changing its shape and dimensions. At worst, the shoal extended into the approach section (see Plate 1), thereby reducing the cross-sectional area and increasing the velocity of the water. This error reduced the stage recorded in the stilling well.

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* *Froude number : a dimensionless number expressing the ratio between influence of inertia and gravity in a fluid. It is the velocity squared divided by length times the acceleration due to gravity. When analysing hydraulic models, the ratio should be similar in both model and full-size plant.*

PLATE 1

Sediment shoal building up
in entrance to Severn trapezoidal
flume

PLATE 2

Excavation of sediment trap
in River Severn, upstream of
trapezoidal flume

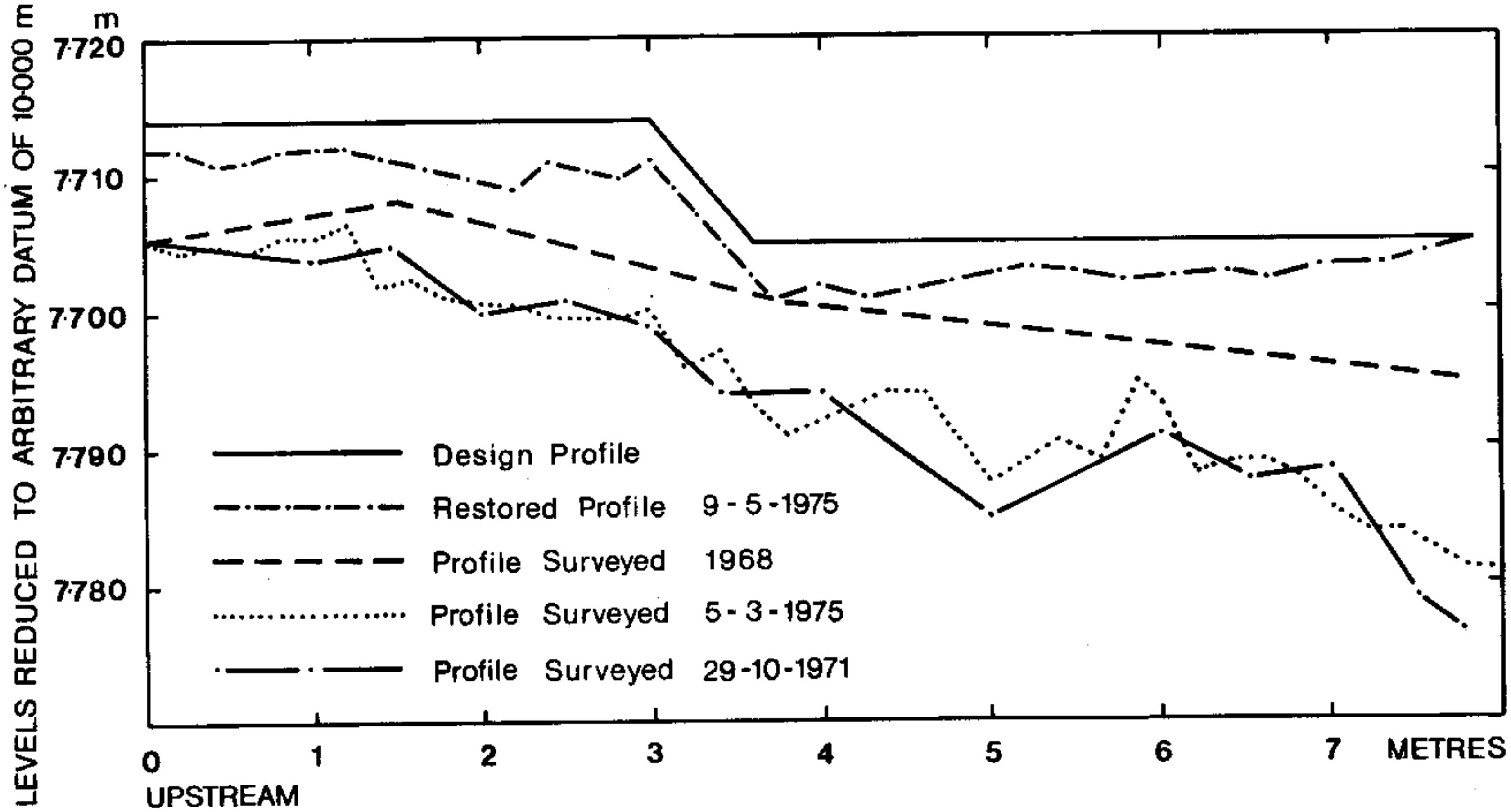

Figure 1 SEVERN TRAPEZOIDAL FLUME
Longitudinal profiles surveyed along centre line of invert

When the shoal was removed progressively, it was found that if the area between the wing walls was cleared to approximately the invert level, then the stage recorded in the stilling well remained unaffected by the shoal upstream. This area was concreted in October 1972 to provide a reference level for the periodic removal of sediment that is needed.

Sediment traps

Although the return-to-datum conditions could readily be achieved, the presence of sediment in the flume approach affected records on the recession limb of a flood hydrograph. It was thought that the constuction of a sediment trap might alleviate the difficulty. However, nothing was known about the amounts of sediment in movement. An estimate of 312 tonnes/year was made by HRS (equivalent to approximately 155 m^3). In three separate operations three traps were excavated; (i) the shoal and pool immediately upstream of the flume, (ii) the stilling pool behind the old sharp-crested weir 0.4 km upstream (70 m^3 capacity) and finally, in December 1974 (iii) 160 m^3 trap 0.5 km upstream cut in glacial clay on the stream bed (Plate 2). The cumulative capacity has been adequate to trap the bed load in all floods experienced since their construction and no further problems of deposition in the approach to the flume have occurred since December 1974.

Abrasion of invert by bed load

The movement of large quantities of angular fragments through the flume eroded the concrete invert and the base of the side slopes, the first signs of which were evident in May 1969. This developed into pot-holing and repairs were attempted by plugging the sides with a mastic compound that hardened under water. However, the concrete continued to erode around the mastic.

In October 1971 a longitudinal profile was surveyed along the invert and the extent of the erosion could be seen by comparing it with the profile drawn using six spot heights surveyed after construction in 1968. In March 1975 the bypass channel was constructed, the flume drained and a second profile was surveyed prior to the restoration of the invert using metal tiles. On completion of the restoration work the profile was resurveyed and the combined results of the surveys are shown in Figure 1.

1.2 Compound Crump Weir on the Wye at Cefn Brwyn

The existing weir on the Wye at Cefn Brwyn was redesigned by the Hydraulics Research Station into a modified Crump Weir (Plate 3) to gauge discharges from a catchment at the head of the Wye. The modifications were completed by the Wye River Authority in 1968. The design criteria were as follows:

Catchment area	10.55 km^2
Stream slope	0.011
Minimum discharge to be measured	0.020 cumecs
Maximum discharge to be measured	52.4
Natural channel Froude number at bank-full discharge	0.53

The weir is built at the downstream end of a 50 m long natural stilling pool. This acts as an effective sediment trap which requires cleaning approximately once every two to three years.

The weir was constructed in concrete with twin piers separating the centre crest which is at a lower level than the two flanking crests. The crests are made of gunmetal. Stage levels are measured in a stilling-well connected by a pipe to the left side of the structure with the inlet set in the apron floor at approximately the same level as the centre crest. As in the Severn trapezoidal flume, both Leupold and Stevens and Fischer and Porter recorders were installed initially. The layout, dimensions and section through the crests are shown in Appendix I.

Performance

The weir has operated successfully since modification. The chart trace exhibits 'waves' of approximately 10 mm amplitude at times of low flow. These appear to be due to the wind effect on the long stilling pool with wave reflection from the exposed crest. They tend to blurr the trace without seriously affecting its interpretation. Once the crest is covered (a stage of 378 mm) the waves on the trace disappear.

Sediment has not been a problem. The aprons require cleaning after some floods and occasionally the stilling pool needs dredging. The gunmetal crests have withstood abrasion but the base of the piers in the centre section have needed minor repair. The downstream side of the crest below the gunmetal has been roughened. However, erosion of the structure has been much less than that encountered at the Severn flume, due possibly to the smaller amounts of material in movement and the lower average size of fragments. (J.C. Mosedale, personal communication).

Sediment size

The stilling pools immediately upstream of both the Severn trapezoidal flume and the Cefn Brwyn weir intercept the bed load in movement down the rivers. The parent rocks from which this material is derived are mudstones and shales which break down into fairly regular rectangular shapes. A measurement of the three axes of the individual pebbles therefore is a reasonable indication of their size.

One hundred pebbles were picked at random from each stilling pool and their axes measured. This sampling was carried out on the same day in both pools. The results are given as histograms in Figure 2. Although these results substantiate what is obvious on site, ie that the particles moving through the Severn flume are bigger than those moving through Cefn Brwyn, the actual sizes given should be treated with caution. More work would be essential to verify that the sizes of the pebbles sampled did not merely reflect a transport characteristic of the last flood.

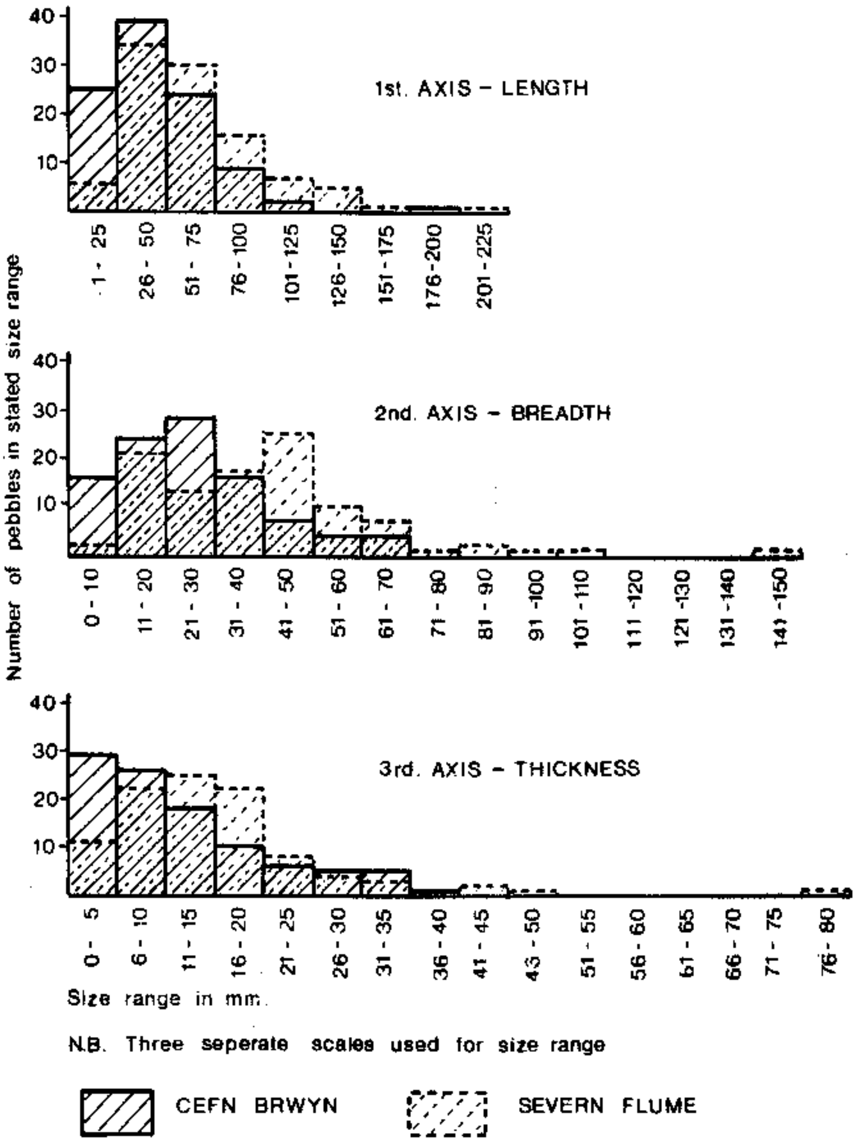

FIGURE 2 Comparison of pebbles found in settling pools of Severn flume and Cefn Brwyn weir by measurement of three axes.

PLATE 3 The compound Crump weir on the River Wye at Cefn Brwyn

1.3 The steep stream structures on the Hore, Hafren, Tanllwyth, Cyff, Gwy and Iago

The six tributary streams are characterised by their steep gradients, heavy sediment loads and high flood/drought ratios. The Hydraulics Research Station designed a new type of structure to permit the accurate measurement of flow in these streams. The theoretical design was then matched to the relevant catchment characteristics given below:

Stream	Catchment area km^2	Stream slope	Minimum flow cumecs	Maximum flow cumecs	Natural channel Froude no.
Hore	3.08	0.027	0.011	14.15	1.07
Hafren	3.67	0.022	0.009	10.19	0.75
Tanllwyth	0.89	0.056	0.003	2.26	1.21
Cyff	3.13	0.021	0.009	9.91	1.03
Gwy	3.98	0.026	0.014	17.83	0.98
Iago	1 02	0.022	0.003	3.96	0.82

It was obvious that to build precision structures in the Plynlimon environment would be difficult. It was therefore decided to prefabricate the channel sections in glass fibre which could be bolted together on a prepared base on site. Suitably-braced, these then acted as shuttering for concrete to be poured around them to give a resultant solid structure with a channel section in glass fibre. The advantages were that the prefabricated sections were built under factory conditions permitting greater accuracies. The finished surface was very smooth, resistant to both abrasion by sediment and algal growth. The technique also eliminated the need for expensive shuttering on site and speeded up the construction. To reduce costs the glass fibre sections were standardised and the Froude number of 0.5 in the approach, recommended by the design report, was changed to 0.55. The anticipated error thus introduced was thought not to exceed 4% of total discharge.

Three flumes were built by this method, those on the Hafren, Tanllwyth and Iago. They fulfilled the basic hydraulic requirement of passing the sediment load without deposition or damage but there were doubts about the stability of the hydraulic conditions in the approach. In addition, construction problems had arisen with the glass fibre panels, which was manifest by bulges in the sides of the flumes.

A likely explanation for the bulges was deduced whilst modifying the Hafren flume in 1974. The glass fibre modules had very few lugs or keying points by which they would be held by the concrete. Thus, after the internal bracing was lifted ready for the second pouring, slurry and fine material found its way down between the lower pouring and the glass fibre, causing bulges. This happened on successive 'lifts' and the precise geometric shape was lost in a series of bulges. An attempt was made to glue the panels back but it failed. Later they were bolted back to the concrete so that at least the flumes have a stable shape even though distorted. This method of construction was therefore abandoned in favour of reinforced concrete which gave greater flexibility of hydraulic design; the Hore, Gwy and Cyff flumes were all built in concrete.

The floor of the structures is triangular in section to focus sediment flow. Stage levels are measured in a stilling well which is connected by a pipe to the base of the vertical flume wall to avoid risks of deposition in the pipe as far as possible. The plan dimensions and layout of the structures are shown in Appendix I.

Leupold and Stevens chart recorders were fitted at each flume. The anticipated use of the data did not appear initially to warrant the duplication of recorders as at the Severn and Cefn Brwyn structures. This philosophy was changed when the Institute's own design of recorder using a magnetic tape logger became available, making it possible to process the data without the digitisation of charts.

Performance

It was anticipated that there might be problems in the use of an entirely new type of structure and this indeed proved to be the case.

However, it is fair to say that the difficulties experienced have been due to the adaption of the design to specific locations rather than to shortcomings in the theory.

Sediment transport

With the exception of the Hore flume, none of the structures have had problems with the deposition of sediment. The design report required that the entry to the flume should be down a 1:3 ramp so that sediment is kept in motion. Entry to the Hore is down a waterfall some 3.5 m upstream of the flume. Sediment collects in the flume and must be removed by hand after relatively modest floods.

In all cases, the velocity of the water leaving the structure on its way downstream is dramatically reduced leading to the formation of shoals. Under extreme conditions these can build up in a single flood and drown the structure (see Plate 4). Normal vigilance prevents accumulations.

PLATE 4 Downstream drowning of the Hafren flume by shoal of cobbles and gravel.

Extreme flows

The structures were designed to gauge all flows up to and including those with a return period of 1:10 years, based on the scant hydrometric data available at the time.

Low flows The expected low flow levels incorporated in the design proved to be too high and water levels dropped below the tapping points increasingly frequently as the summers became drier in the 1970s (Plate 5). Steps or false floors were built into the throats of the Hafren - 25.4 mm (1"), Iago - 25.4 mm (1") and the Tanllwyth - 50.8 mm (2") flumes so that water would be ponded in the approach section and flows would be superimposed and capable of measurement. Fears that the steps might cause deposition were unfounded. The extra dry summers of 1975 and 1976 made this remedy useless and direct spot measurements of stages were made in the approach section of each structure during droughts.

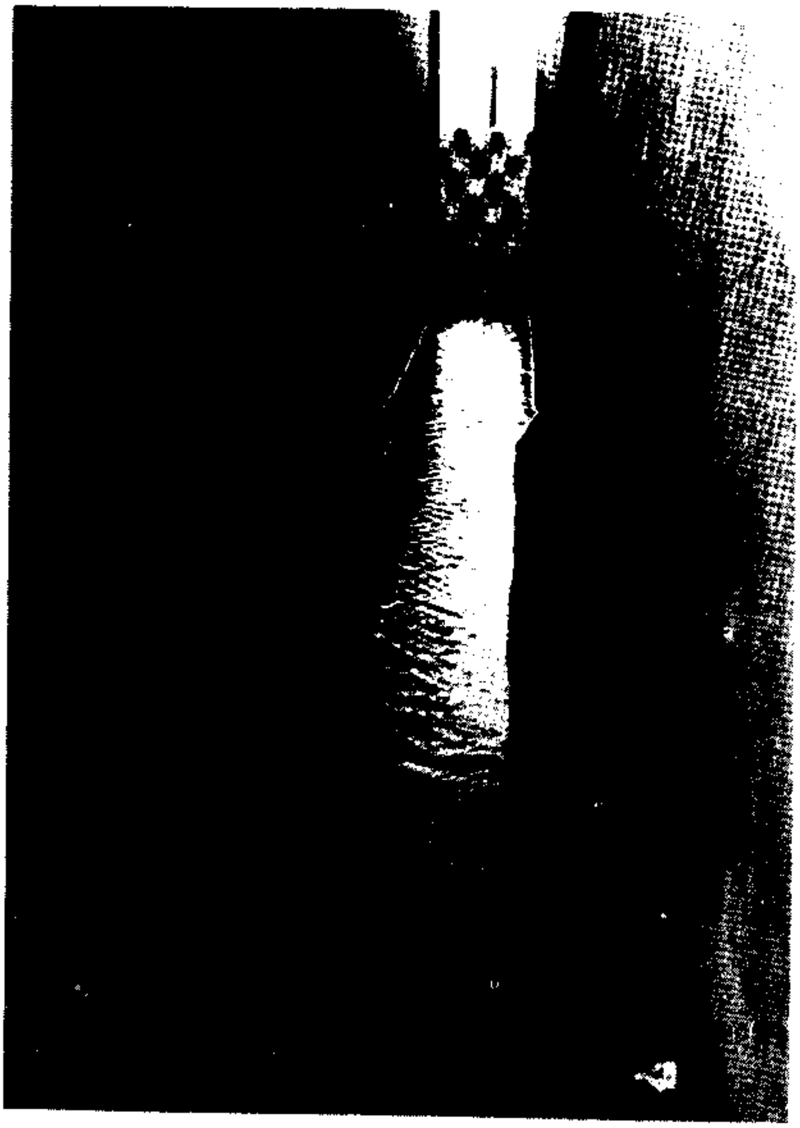

PLATE 5

Typical minimal flow in flume during drought periods

High flows Extreme high flows exceed the capacity of the flumes. All structures have been overtopped, notably on 5/8/73 when a flood with a return period of approximately 1:100 years occurred*. Overtopping is known to have occurred on a number of other occasions at the flumes (Plate 6)**.

It is unrealistic to expect any structure to accommodate events with very long return periods with the same precision as the gauging of normal flows but some contingency is required in the design so that rare events are not completely missed. In the case of the flumes on the Cyff and Gwy this is present in the form of a wing wall.

PLATE 6 Flume over-topping during storm

Stability of hydraulic conditions

The need to pass sediment through the structure means that the velocity and depth in the approach section would have to be the same as in the natural stream. In this situation the Froude number would be about unity and the standing waves present would prevent accurate measurement of stage. If the cross section of the stream is made narrow and deep the cross-sectional area remains the same as the natural stream but the Froude number is reduced. This eliminates the unstable water surface and stage can be measured accurately.

* *IH Report No. 26 The Plynlimon floods of August 5/6 1973*

** *A second rare event on 15.8.77 was confined to the Severn catchment only and caused overtopping at all the flumes in that catchment.*

The changes in dimension of the approach are therefore dictated by the required value of the Froude number. This was set at 0.5 in the design but later relaxed to 0.55 as explained earlier. In the case of the Hafren flume the resultant Froude number was 0.57 and at stages in excess of 376 mm the hydraulic jump was swept out of the flume, see Figure 3. The throat was therefore contracted by 75 mm giving a Froude number of .481 in the approach section and conditions in the throat were stabilised satisfactorily.

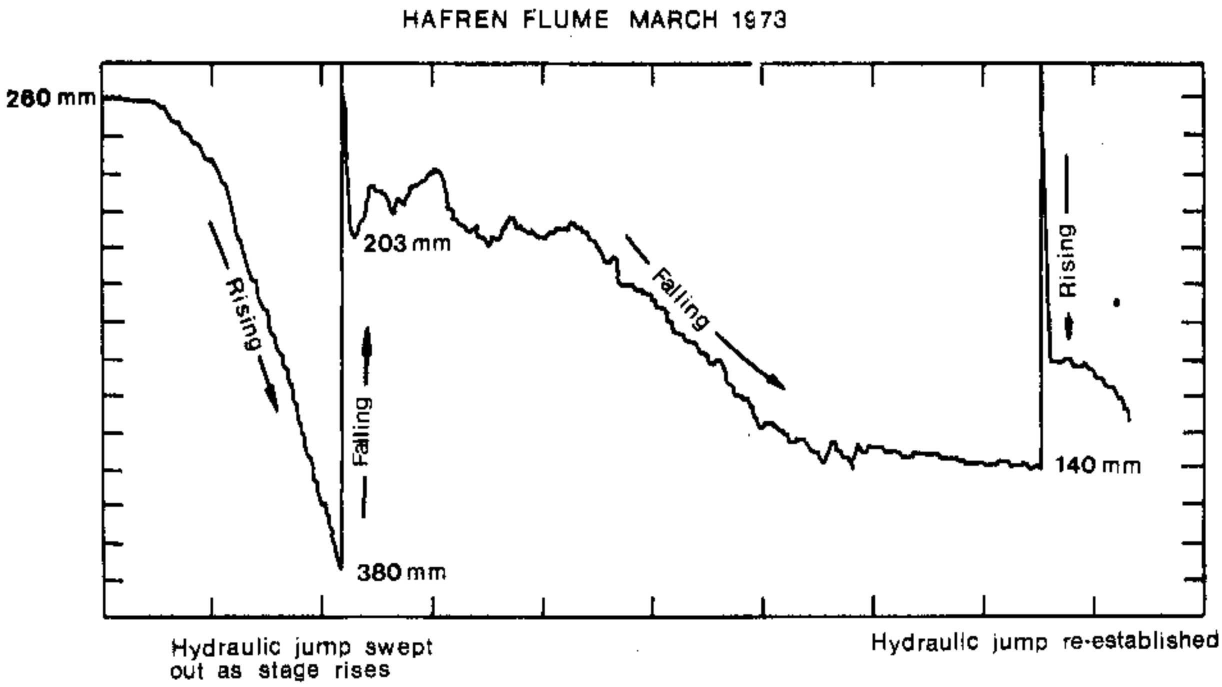

FIGURE 3 Diagram of Leupold & Stevens recorder chart showing disruption in hydraulic jump. /Note: this recorder has a device by which the recording pen reverses in direction when it reaches the margin of the chart./

Erosion by sediment movement

The glass fibre units have shown no sign of abrasion. This contrasts with the concrete structures in which the cement matrix has been eroded leaving the aggregate standing proud. This type of erosion is confined to the invert except for the lowest few centimetres of the vertical walls. Some idea of the scale of the problem can be gained from the fact that a boulder 760 mm x 380 mm x 355 mm was left in the Gwy flume after the flood of August 1973. An even larger boulder was stranded just downstream.

The steps fitted in the throats of the Hafren, Iago, and Tanllwyth flumes have a top face of aluminium alloy. A close examination shows multiple bruising which cannot be felt with the finger tips but is revealed by algal growth anchored in the minute roughness where boulders have bounced. In the Severn trapezoidal flume the metal tiles were made from two distinct batches of alloy. One batch supported either an algal growth or a chemical deposit and the other batch remained clear. The growth at the Severn resembles a close colony of tiny barnacles. This phenomenom has not been investigated by laboratory tests. As an initial field test the duralumin sheets in the Severn were scoured clean causing well levels to drop by 4 mm but the 'growth' returned. Any deformation of the surface must alter roughness coefficients but the significance is unknown. If the bruising is cumulative this presumably could lead to a roughening of the surface. Similarly, if the growth is a chemical reaction, the surface will deteriorate and roughen. In both cases the roughness factors used in calibrations will be affected.

2. OPERATING THE STRUCTURES

The gauging structures provide continuous and automatic records of discharge from both the two main and six sub-catchments with sufficient accuracy to permit inter-catchment comparisons. The principles of the Severn trapezoidal and Cefn Brwyn structures are well established and the theory of the six steep stream structures has been demonstrated by model investigation. In every case the recording of stage is done by a Leupold and Stevens A35 chart recorder housed in a recorder hut over the stilling well, the well being connected to the flume by a pipe. On the two main structures there was also a Fischer and Porter punched tape recorder as a back-up device but in June 1975 these instruments were withdrawn and all the flumes were equipped with the Institute's own water level recorder*.

In the severe Plynlimon climate, the performance of all instrumentation and structures must be constantly checked by an observant and vigilant field staff.

2.1 Maintenance of the structures - by-pass facilities

Although the theory of gauging structures is well established, the necessity for high standards of construction and maintenance was not fully appreciated at the outset. This point is even more pertinent in the Plynlimon experiment as streamflow is the only element in the water balance that is measured rather than sampled.

The difficulty of constructing a precision instrument in a severe environment should not be underestimated and the budget should recognise this fact. The design should make provision for adequate maintenance and inspection facilities and supervision of construction should be based on an understanding of how the structure will eventually work.

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* *Logging river level on magnetic tape* *I C Strangeways and R F Templeman* *Water Services*, *Feb 1974, 57-60.*

None of the structures was equipped initially with a permanent by-pass channel. Flow was diverted around all structures during their construction but after completion each diversion was filled in and the subsequent construction of by-pass facilities was therefore a costly duplication of expenditure. There was also no provision for examination of the wells; although an inspection chamber round the well at the Severn trapezoidal flume appeared on the HRS design drawing this was not built.

These inadequacies meant that the inspection and maintenance of each structure had to be done initially with the stream flowing through it This made the detection of leaks and erosion more difficult and the operation of the manometer originally used for zeroing far less precise than it need have been. There was a risk in the oversight regarding by-pass facilities that flume work would be a summer task only,due to the discomfort of working in very low water temperatures; considerable dedication was necessary to remove under water the retaining screws from a baffle plate over the entrance to a tapping pipe. Without this the manometer zeroing device could not be used.

2.2 Stilling well inspection facilities

The stilling wells are constructed from concrete pipe sections set vertically. These were not cut off at the concrete floor level within the huts so that when the tables supporting the recorders over the wells were built, access to the wells in the case of the Cyff, Tanllwyth and Iago flumes is impossible without removing the table. To remove the table top is feasible but does disturb the zeroing datum. Where records span many years the continuous alteration of a datum represents a potential source of error.

The concrete sections used in the wells were damaged before or during installation and some were not sealed between joints. This damage resulted in leaks both into and out of the wells. On the Severn trapezoidal and Cefn Brwyn structures the leaks were small and except for the difficulty this posed in zeroing the recorders with the manometer the records were unaffected. In the case of the Hore flume, the leaks were so large that flows over 1037 mm stage are valueless before 5.4.76 when the leak was discovered and plugged. This type of problem may possibly have been avoided by better supervision during construction and the application of leak tests before accepting the structures. The idea of building an inspection chamber round the well specified by the HRS drawing for the Severn trapezoidal flume was excellent and should have been implemented at all structures.

Had the inspection chambers around the well been built, the chambers could have been extended to the wall around the tapping pipe without much problem except at the Severn and Cefn Brwyn structures. Thus a complete surveillance of the structures would have been feasible at any time.

2.3 The recording of stage levels

Reference has been made earlier to the use of glass fibre modules and their excellent resistance to abrasion. The use of aluminium alloy appears to be only slightly inferior in this context, with concrete least able to withstand the passage of heavy bed loads. Unfortunately, the ease of construction is in the reverse order, with concrete being the most flexible medium. Because all engineers and construction gangs are familiar with concrete, it is likely to continue to be the material used.

The strength properties of the concrete used in the Plynlimon structures may have varied. Thus erosion was evident in the invert of the Severn flume as early as May 1969 and this situation deteriorated until May 1975 when the entire invert was rebuilt in aluminium alloy tiles. No record exists of the invert surface as built but the extent of the erosion in comparison with the design and the rebuilt invert can be seen in Figure 1. The concrete appeared to break up as large holes as if a skin were punctured and erosion took place all round the periphery of the puncture. In the other concrete structures on the Cyff, Gwy and Hore the erosion was of a different type. In this case the softer cement matrix around the aggregate was eroded leaving the coarse fragments protruding, in some instances up to 3 to 4 mm.

Progressive erosion alters the roughness coefficients which in turn affect the calibrations, especially at low flows. It can be allowed for provided it is recognised and measured periodically. Although the effect on stage levels will be fairly small, in the long term it will be important since it is a progressive error.

Sediment deposition

A more dramatic effect related to individual events is caused by the deposition of sediment. Any deposition within the proximity of the structure can affect the stage measurement. Deposition upstream of the throat in the Severn causes the flow to accelerate past the tapping point. As the velocity increases the water cross section decreases in depth and the stage measurement in the well goes down. When the shoal is removed stage levels in the well rise.

This broad analysis of what happens to the stage when a shoal forms in the approach to the flume was substantiated on two separate occasions, in October and November 1971, and is shown graphically in Figures 4 and 5. In October 1972 the area between the approach walls was concreted at approximately invert level. In June 1974 the shoal re-established itself in the approach and the opportunity was taken to clear the shoal front back progressively and note the effect on the stage. The results shown in Figures 4, 5 and 6 suggest that although the stage was sensitive to the shoal geometry, the magnitude of the effect was not very significant.

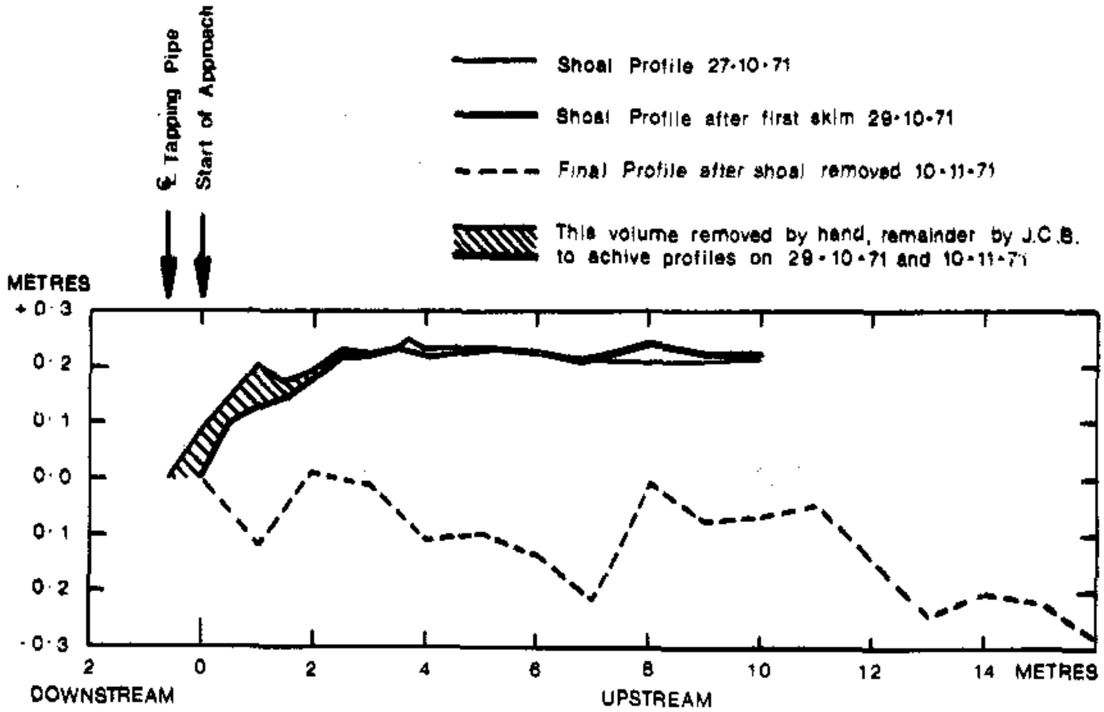


FIGURE 4 SEVERN TRAPEZOIDAL FLUME - EFFECT OF SHOAL ON STAGE

First skim caused rise in stage of 32 mm) Total rise in
Final profile caused further rise of 58 mm) stage when shoal removed, 90 mm

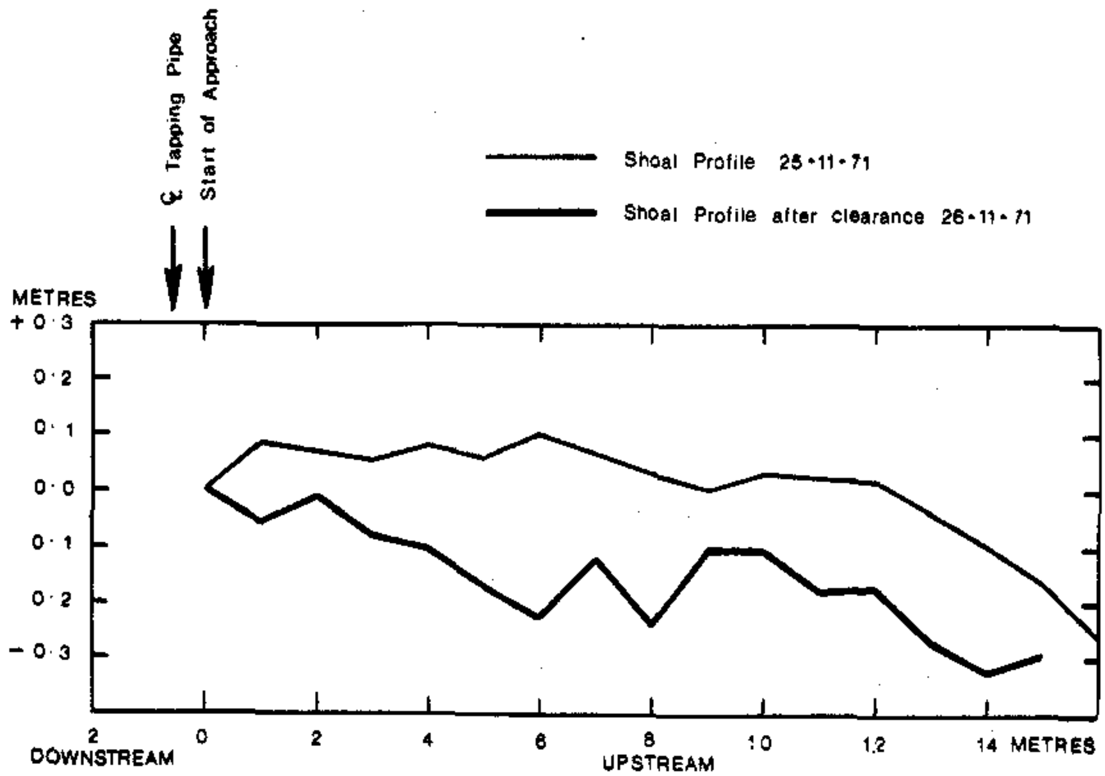


FIGURE 5 SEVERN TRAPEZOIDAL FLUME - EFFECT OF SHOAL ON STAGE

Removal of shoal caused rise in stage of 9 mm

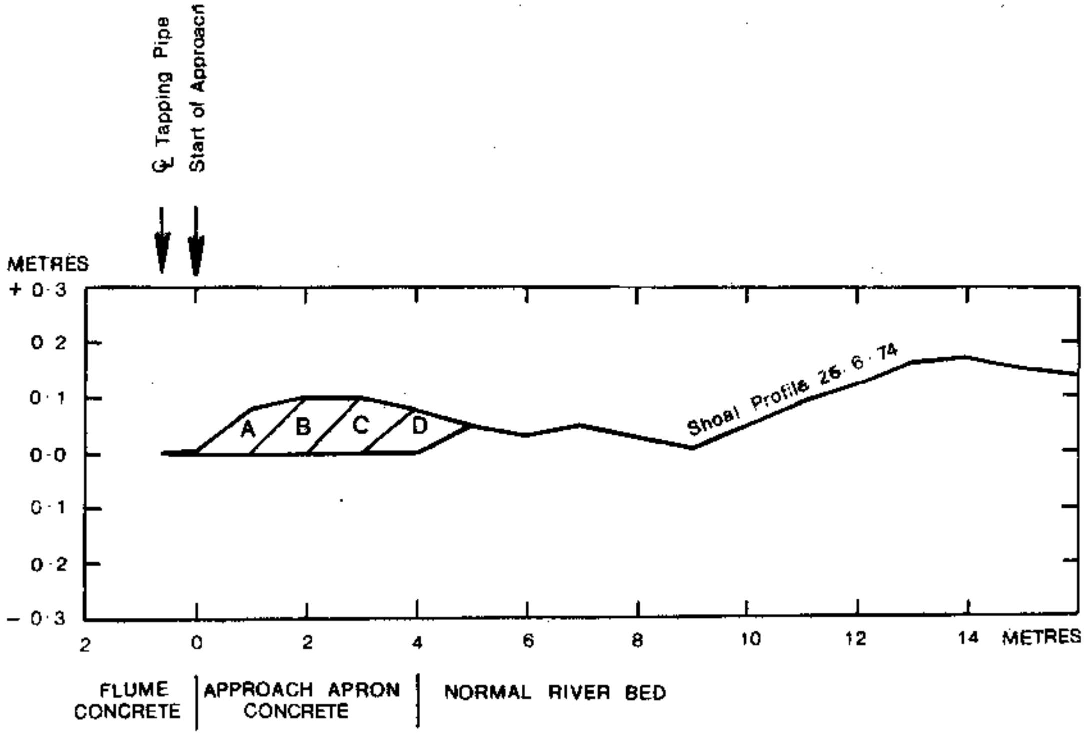


FIGURE 6 SEVERN TRAPEZOIDAL FLUME - EFFECT OF SHOAL ON STAGE

When A was removed, stage dropped 8 mm
B was removed and pipe cleaned, stage rose 5 mm
C was removed, stage rose 5 mm
D was removed, stage dropped 2 mm
remainder of shoal removed 1.7.74, stage dropped 6 mm.

Deposition of fine material in the tapping pipe at worst could block the pipe entirely. This has not happened at Plynlimon but a partial blockage on the Severn was removed (25/11/71) by flushing out the pipe from the well end. This resulted in a rise in stage of 6 mm in the well. Deposition downstream on a recession can cause the formation of shoals which pond the water back and drown the structure.

The Plynlimon experience is that rather than deal with the problems caused by sediment moving through the structures it is better to prevent them by the provision of sediment traps. However, the siting and operation of a sediment trap demands access and working platforms on the bank suitable for mechanical diggers; decisions regarding such facilities cannot be safely made until information is available about frequency of floods and quantities of sediment in movement.

TABLE 1 SEVERN TRAPEZOIDAL FLUME - EFFECT OF SHOAL ON STAGE

Longitudinal profiles upstream of flume along projected centre line of flume - measurements in metres

Distance upstream from flume	Top of shoal before removal 27/10/71	First skim removed 29/10/71	Final profile 10/11/71
T.P. - 0.6	0		
0.0	+ 0.084	0.001	
0.5	0.145	0.095	
1.0	0.202	0.125	- 0.118
1.5	0.174	0.146	
2.0	0.194	0.181	+ 0.014
2.5	0.230	0.221	
3.0	0.235	0.227	- 0.006
3.5	0.245	0.239	
3.7	0.250		
4.0	0.235	0.227	- 0.109
5.0	0.237	0.232	- 0.092
6.0	0.228	0.224	- 0.131
7.0	0.215	0.220	- 0.215
8.0	0.210	0.242	- 0.004
9.0	0.212	0.220	- 0.075
10.0	0.218	0.227	- 0.067
11.0			- 0.044
12.0			- 0.142
13.0			- 0.242
14.0			- 0.202
15.0	0.077		- 0.220
16.0	- 0.205		- 0.282

Notes: The invert at the tapping plate was used as the datum for levels-
First skim cuased rise in stage of 32 mm, removed by hand.
Final profile achieved by removing shoal with J.C.B., caused further rise in stage of 58 mm.
Total rise caused by removing shoal - 32 + 58 = 90 mm.

TABLE 2 SEVERN TRAPEZOIDAL FLUME - EFFECT OF REMOVING SHOAL

Longitudinal profiles upstream of flume along projected centre line of flume - measurements in metres

Distance upstream from flume	Top of shoal before removal - 25.11.71	Top of shoal after removal - 26.11.71
Centre line of T.P. - 0.6	0.000	0.000
0.0		+ 0.001
1.0	+ 0.090	- 0.054
2.0	0.076	- 0.006
3.0	0.058	- 0.079
4.0	0.083	- 0.099
5.0	0.062	- 0.162
6.0	0.103	- 0.222
7.0	0.070	- 0.119
8.0	0.033	- 0.236
9.0	0.002	- 0.103
10.0	0.033	- 0.105
11.0	0.029	- 0.179
12.0	0.023	- 0.171
13.0	- 0.034	- 0.272
14.0	- 0.092	- 0.327
15.0	- 0.160	- 0.297
16.0	- 0.259	
17.0	- 0.227	

Notes: The invert at the tapping plate was used as the datum for levels.
Removal of shoal caused rise in stage of 9 mm.
On 25.11.71 the tapping pipe was partially blocked with gravel/sand. This was flushed by filling well and releasing. This caused a rise in stage of 6 mm.
Effect of cleaning pipe and shoal - 6 + 9 = 15 mm rise in stage.

2.4 The response lag of the stilling well

Although deposition in the tapping pipe is unlikely to block the pipe entirely the effect of a partial blockage is to increase the time it takes for the well to reflect the changing stage in the flume. The original design assumed a maximum change in stage in the natural stream of 305 mm/hr (1 ft). This would be doubled in the approach section. On this basis the tapping pipe was calculated at 19.05 mm diameter (¾") and the well 1482 mm diameter (3.88 ft). Because of the risk of sedimentation blocking a narrow bore pipe, the tapping pipe was increased to 76.2 mm (3") and the flume end covered with a baffle plate having a variety of apertures. The well was reduced to 760 mm diameter. The cross-sectional area of the apertures in all cases exceeded the original cross-sectional area of the ¾" pipe and the overall effect of these adjustments was to decrease the likelihood that there would be a significant lag in well response. This was fortunate since flood recordings have shown that maximum rates of change can exceed 3000 mm/hr, five times greater than the original assumption.

Well response tests were made on the Tanllwyth, Iago, Gwy and Cyff flumes. In these tests the downstream end of the flume was blocked and the rising levels were measured and timed simultaneously in both flume and well. The results are shown in both table and graph form, together with a table giving details of tapping pipes, etc. The tests confirmed the adequacy of the tapping pipe and wells as built (Figures 7, 8, 9 and 10).

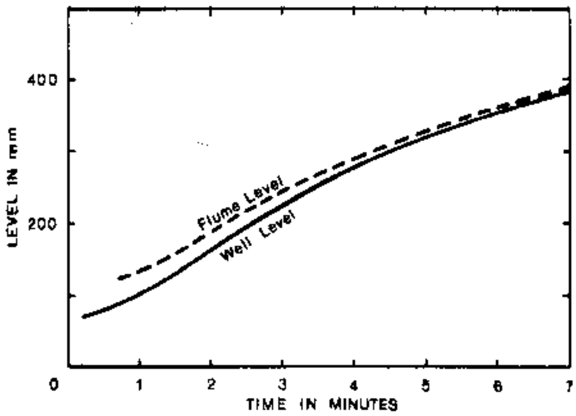
An early inspection of the Severn trapezoidal flume by HRS in 1969 drew the comment that the baffle plates should be set flush in the flume walls, not the case in this structure, possibly because of erosion around the plate. The hydrostatic pressures set up in the pipe by discontinuities could lead to inaccuracies in stage measurement in the well. The plate was reset but no effect was identifiable.

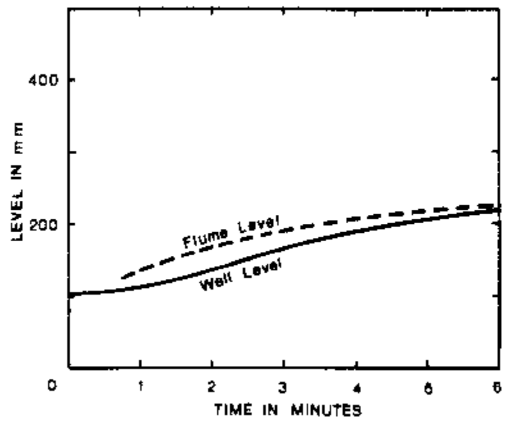
TABLE 3 DETAILS OF TAPPING PIPES AND WELLS

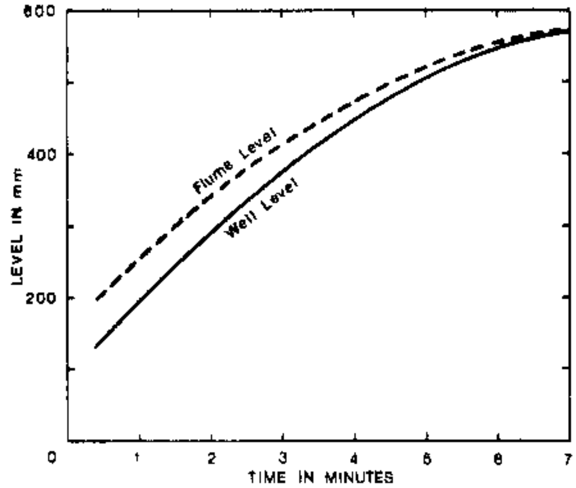
	Apertures through baffle plate area mm^2 (i)	Pipe cross-sectional area mm^2 (ii)	Well cross-sectional area mm^2 (iii)	Ratio of apertures to Pipe (i:ii)	Ratio of apertures to Well (i:iii)
Severn	1014	18872	650473	18.6	641
Hafren	380	4186	453704	11.0	1194
Tanllwyth	901.4	4186	453704	4.6	504
Hore	601.6	4186	453704	7.0	754
Iago	380	4186	453704	11.0	1194
Gwy	901	962*[2]	453704	1.1	504
Cyff	601.6*[1]	4186	453704	7.0	754
Cefn Brwyn	4561	18388	453704	4.0	99

*[1] Not in use since September 1975

*[2] Liner inserted because of leaks 22.5.1972







FIGURES 7-10

Well response tests on the Tanllwyth, Iago, Cyff and Gwy flumes.

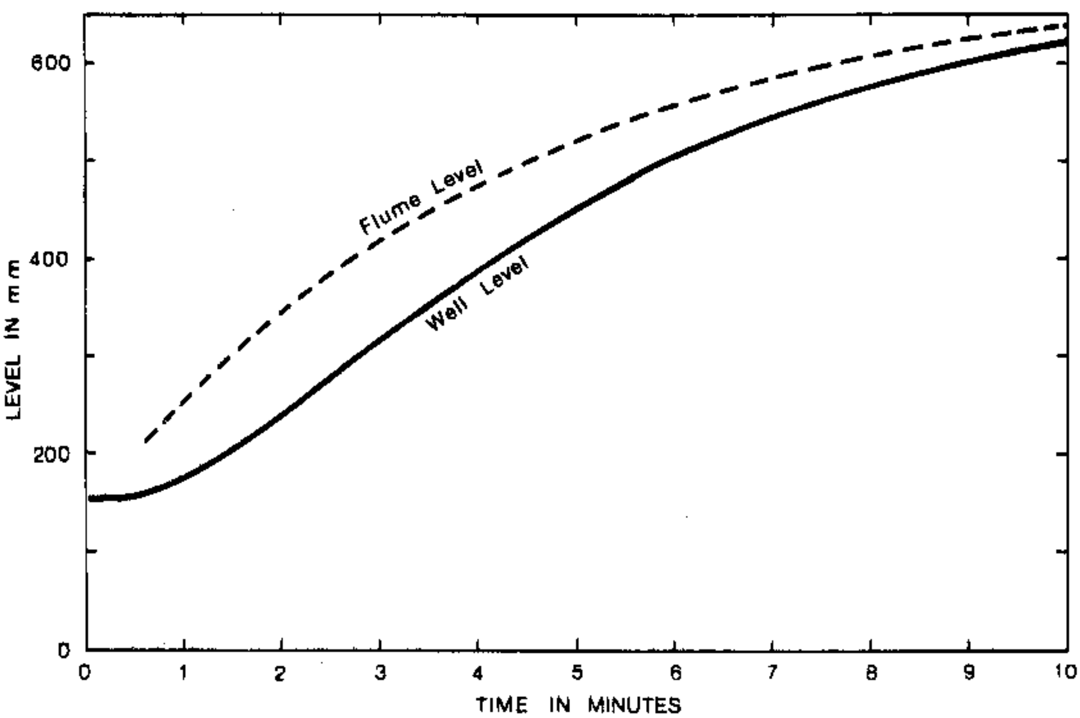


TABLE 4 WELL RESPONSE TESTS

GWY 4.9.1975

Min	Rate of rise in flume	Rate of rise in well
1	-	23 mm/min
2	91 mm/min	66
3	73	78
4	57	68
5	45	62
6	36	51
7	28	43
8	23	34
9	19	26
10	11	14
11	13	14
12	7	9
13	5	6
14	4	4
15	4	3

TANLLWYTH 4.9.1975

1	60 mm/min	48 mm/min
2	75	66
3	55	61
4	45	52
5	38	43
6	27	32
7	20	20
8	12	13
9	10	11
10	13	12
11	10	11
12	10	11

IAGO 4.9.1975

1	-	10
2	28	23
3	23	30
4	15	24
5	11	18
6	8	13
7	5	8
8	3	4
9	3	3
10	2	2

CYFF 4.9.1975

Min	Rate of rise in flume	Rate of rise in well
1	-	60
2	92	93
3	73	88
4	55	73
5	43	59
6	21	35
7	26	28
8	18	20
9	15	14

In the steep stream structures the tapping pipes terminate in brass surrounds into which retaining bolts are fixed to the baffle plates. In the concrete flumes the surface round the brass plate has become pitted. The turbulence these pits create is undesirable but their effect is unknown. Access to the tapping pipe can only be achieved by removing the baffle plate; the difficulties of doing so under water have been mentioned earlier.

The concrete/tapping pipe junction and the method of securing the baffle plate are design weaknesses. If the end fitting had been larger any turbulence arising from erosion or pitting of the concrete would have been further removed from the pipe. The need for the baffle plate as a precaution against sediment deposition has been disproved by operating the Cyff flume without a baffle plate since 1.9.75 which has not affected the trace on the recorders.

2.5 The question of the validity of the well to reflect flume levels

The design of the tapping pipe, its position and well sizes followed the HRS advice except that the position was modified to achieve standardisation in the glass fibre flumes.

A routine check during a severe flood on the Hore revealed an alarming difference between a well level of 1038 mm and a flume level of 2479 mm. A flood on 31.12.75 was monitored for four hours by taking simultaneous readings in the well and the flume. The characteristic trace of the recorder in this period was later identified on the charts covering other earlier floods.

An investigation of the well, initially by a leak test and then by a physical examination inside the well, showed a huge leak through a broken joint between the well rings. This was sealed. The only opportunity to test the efficacy of the repair occurred on 15.10.76. The stages in both well and flume were monitored for an eight-hour period, see Figure 11, throughout which well levels exceeded the level of the repair. Differences between flume and well were of the order of 30-60 mm for reasons unknown. The well was rechecked for leaks after these observations but no faults could be found. The datum marks on the flume itself and on the stilling well were similarly checked satisfactorily. The only odd fact concerning the tapping pipe in the Hore is that it enters the flume wall at right angles and continues for 430 mm. It then bends at an angle of 138°, and continues for 1650 mm before entering the well. (Further evidence for the need for adequate supervision during construction).

The possibility that the well does not always reproduce flume levels was investigated by taking weekly measurements of the water surface in both flume and well. These were combined with more intensive observations through specific storms. This dual technique ensured that results did not reflect a freak condition occasioned by sediment deposition, for example.

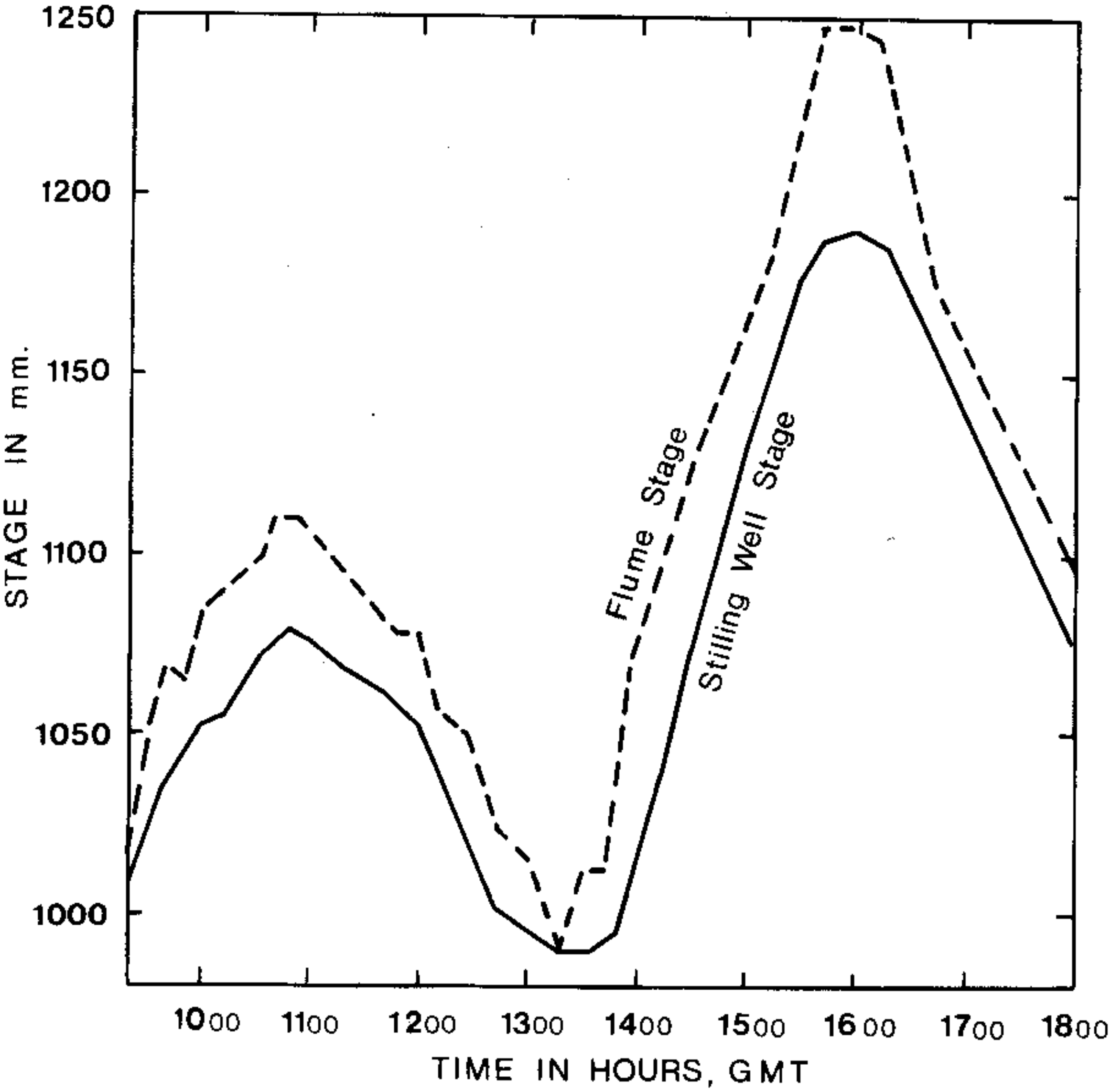


FIGURE 11

HORE FLUME - monitoring of well and stage levels, 15.10.76.

The discrepancy between the two levels was plotted against the observed well level. Comprehensive results are not available for all flumes (by April 1977) but those obtained for the Hafren are reproduced in Figure 12.

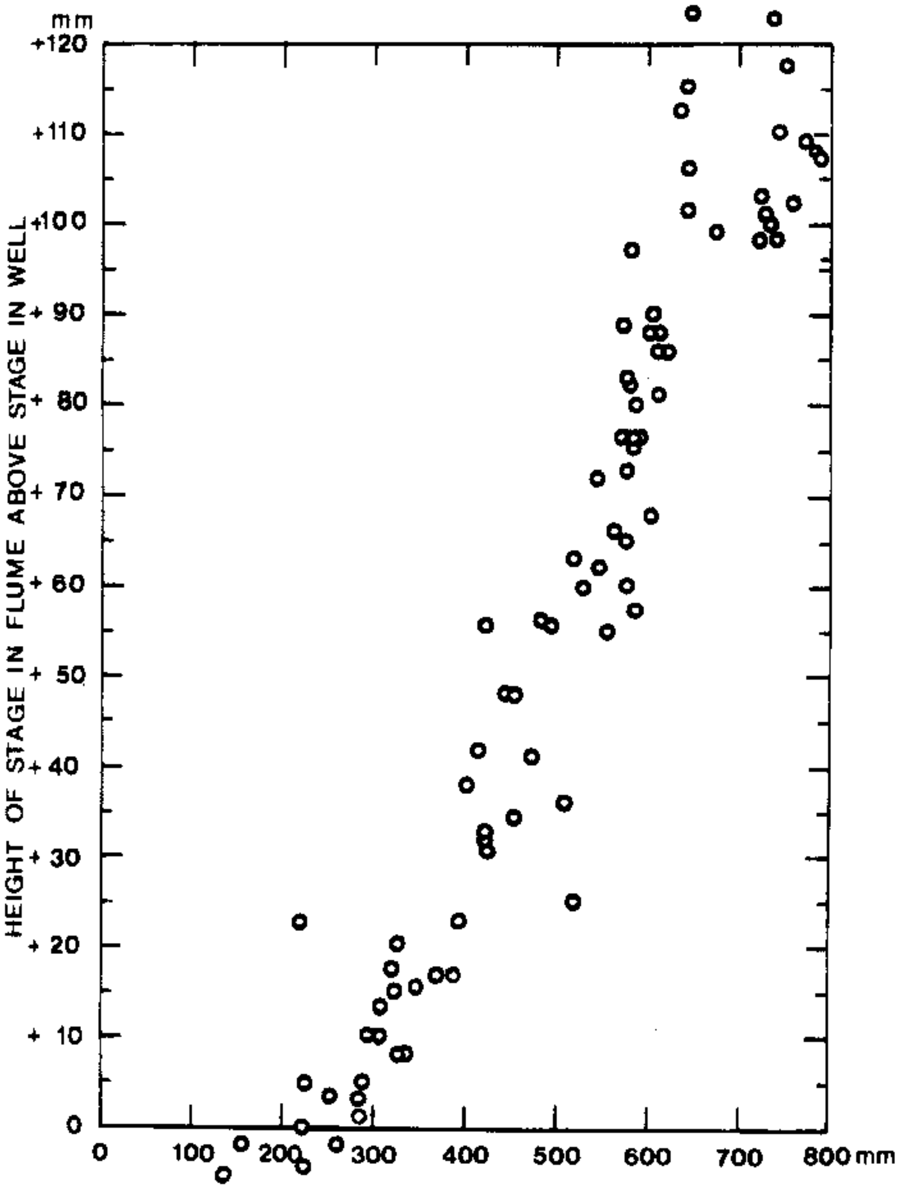


FIGURE 12

Discrepancy between well and stage levels, Hafren flume

It should be emphasised that the sonic plumb bob used in the flume detects the water surface. Aeration appears to be a progressive hazard that increases with stage (Plates 7a, b and c) and this phenomenon doubtless affects the flume results since the sonic plumb bob detects the water surface but the extent of the aeration is unknown.

The problem thus remains and awaits the production of a suitable instrument to record the levels in both well and flume simultaneously.

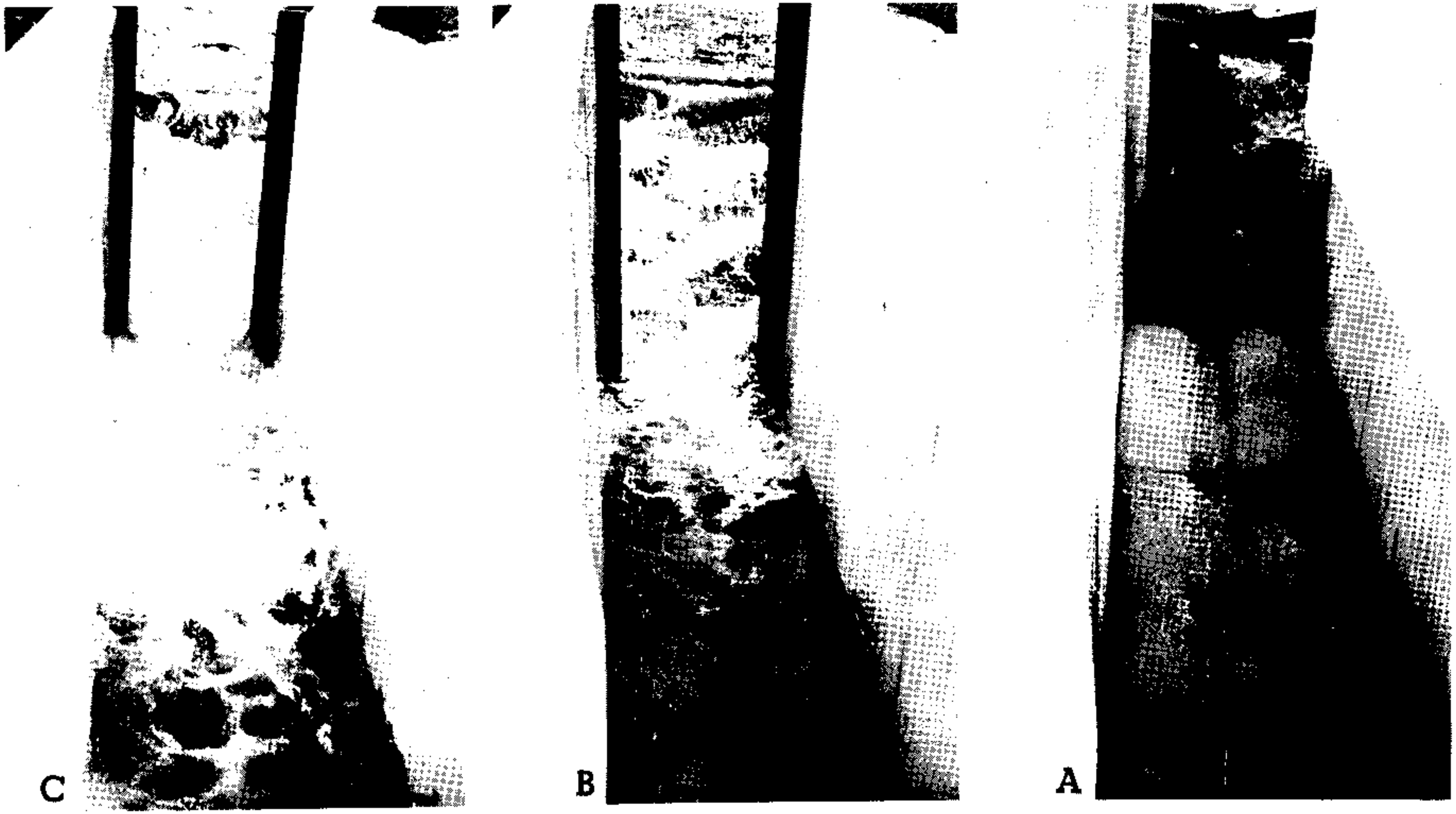


PLATE 7 Nant Iago flume. Water level = 106 mm in A, 248 mm in B and 350 mm in C.

During a recent current metering exercise on the Severn flume measurements were taken in both well and flume. Up to a stage of 331 mm the flume levels exceeded well levels by just under 2 mm. Between 331-538 mm the flume levels were 1 mm below well levels. Above 538 mm the differences in level were random and reflect the difficulties of making accurate measurements of the open water surface. The results from the Severn suggest no serious discrepancy.

2.6 Water level recording devices

All flumes were equipped originally with Leupold and Stevens A35 chart recorders. Apart from minor problems*, they have functioned satisfactorily in the unheated recorder huts. The weight-driven clocks have been found to be more reliable than the spring driven clocks.

Some loss of data has resulted from clock stoppages and minor malfunctions and a back-up recorder has been a useful investment to ensure continuity of measurement. The second instrument was originally a Fischer and Porter punched tape recorder installed on the Severn and Cefn Brwyn structures.

The development of the Microdata logger led to the design of the Institute's own water level sensor in which three potentionmeters are used to monitor water levels at five minute intervals. The logger stores the water level information on standard C60 tape cassettes.

The interpretation of the stage level recordings is a two-tiered operation. An initial inspection of the chart is made in the site office followed by measurements made at Wallingford of the area under the hydrograph curve. Coupled with a time base and a calibration equation, the discharges can then be computed.

The chart record has the advantage of being available for field inspection and adjustment as well as site editing. The magnetic tape record has the advantage of being immediately computer compatible. Editing of the magnetic tape cannot be done at source or malfunctions identified in the field. A chart recorder therefore has immensely practical advantages in allowing early detection of problems such as the effects of shoals or well leaks, etc.

2.7 Zeroing arrangements

Except for the Cefn Brwyn flume, the structures are all critical depth flumes. The height of the invert where the flow goes critical is therefore the datum. The position in the throat where this occurs migrates with stage but remains within the throat. If follows therefore that the invert should be horizontal. In any structure this is diffi-

**The correct alignment of the jockey wheel is often overlooked in maintenance but is fundamental to recorder performance.*

cult to make absolutely true though the departures can be kept small[1].

The stage recorders must therefore be related to the datum and a manometer[2] was designed which sat in the throat of each structure. This was linked to a pipe bung which was fixed into the flume end of the tapping pipe. The manometer and well were thus connected as a 'U' tube. The reading by point gauge of the water surface in the manometer standing over the datum point in the invert could therefore be transferred via the well water surface to the trace on the recorder, and any setting or adjustment made to the recorder (Plate 8).

PLATE 8

Manometer in use in flume

[1] *Normal construction difficulties in a difficult environment mitigate against perfection and the idea of using prefabricated glass fibre modules cast around the same mould and bolted together on site, has much to commend it. The decision to reallocate finances in the cost of building and running a structure so that future running costs are reduced by applying this money in the design and construction phases is to some extent an act of faith, but in the light of the Plynlimon experience it is a management approach that should be made.*

[2] *IH Record of Research 1969, p12.*

The system was portable and very precise. However, it had the following disadvantages. Firstly, it depended on either the invert being horizontal or the same position in the throat being selected each time; a variation in either would result in a new datum. Alternatively, the manometer could have been levelled to a datum on each occasion. This was not done - erosion in the concrete inverts created inaccuracies.

Secondly, the manometer could only be used during low flows or else it would be swept out. In winter the difficulty of getting the tapping plate off and the bung secured precluded all but the most determined efforts to achieve a monitoring and were not conducive to the attention to detail necessary for such a fundamental operation.

The method was superceded in 1973 by the establishment of an arbitrary flume datum at each structure. A second and related datum was set up on the recorder table above the well and an electrical plumb bob was used from this datum. The invert was levelled along its length to the flume datum and thus without recourse to any measurements in the flume itself, except for periodic relevelling of the invert, the performance of the water level recorders could be checked at any time or stage level.

Additionally, the low flows of 1975 and 1976 necessitated the direct measurement of stage in the flume approach when the water level in the flume fell below the tapping point. This was achieved simply by a plate overhanging the flume wall whose level was related to the datum. A sonic plumb bob completed the apparatus required to maintain stage measurements in drought conditions when the tapping pipe and well were isolated from the flumes. These measurements were spot readings but the steady levels of base flow were such that these intermittent readings were adequate for the continuity of records.

3. CALIBRATING THE STRUCTURES

3.1 Dilution gauging

There was much to commend dilution gauging as a suitable method of calibration but a basic disadvantage at Plynlimon was the 'flashy' nature of the streams. To obtain calibrations over the full range of discharges would take much time because of the need to wait for extreme flows. Attention was therefore focussed on the possibility of designing an automatic method.

In 1969 a feasibility study suggested that a stage-triggered gauging using sodium dichromate as a tracer offered the best chance of success and a research contract was placed with Lancaster University in 1970 to design and produce automatic gauging equipment. This contract was completed and after suitable modifications to suit the location, the first trial set of equipment was installed on the Severn trapezoidal flume in December 1972.

Unfortunately, the severity of the environment and its affect on the equipment was underestimated. The fact that the equipment had to stand idle for long periods and then operate efficiently when triggered by a rising stage required either excellent insulation from the damp and cold or equipment so designed and powered to overcome the corrosion and resultant friction inevitable under the circumstances. The need for such safeguards had not been appreciated and the equipment installed on the Severn failed to operate.

In the meantime, manual dilution gauging had been carried out. With the expectation of 'as built' variations in flume design, differences between dilution gauging results and design calibrations caused some initial concern but not alarm. This concern was expressed in a general tightening of experimental discipline but the continued differences required a more critical examination of the technique. From this work it became clear that the time required for a continuous injection of tracer to reach plateau levels had been underestimated. Fortuitously, these conclusions were reached during the drought of 1976 and using the new plateau times, advantage was taken of the low flows to make dilution gaugings simultaneously with volumetric gaugings.

The tightening of experimental design and the more critical examination of the technique improved confidence in the field and laboratory work. At the same time it acted as a stimulus into research for alternative tracers. Sodium dichromate had originally been selected in favour of sodium chloride, tritium, or the xanthene dyes. There were doubts concerning the toxicity of sodium dichromate which were ultimately accepted because of the high dilution factors involved. The unpleasantness of the chemical for the operator required strict attention to hygiene and a special mixing bay and disposal tank for waste was constructed at the field station office at Plynlimon. Fortunately the need for these provisions was circumscribed by the evolution of a technique using sodium iodide. This compound, being non-toxic, is environmentally and operationally acceptable but the necessity for experimental discipline and hygiene remains the same. Much of the original feasibility report is still valid as is the need for a portable and automatic field gauging method.

3.2 Volumetric gaugings

During the prolonged low flows in the summer of 1976 the structures were partially calibrated by measuring the discharge volumetrically (Plate 9). Thin sheets of aluminium were sealed against the downstream end of the flume and the flow was directed into containers of known volume. The containers were filled ten times to allow the calculation of confidence limits for mean discharge; the volume of the receiving tanks was also weighed ten times for the same reason.

During this period the water surface in the flumes was below the tapping pipes and the stage was measured in the flume alone using the sonic plumb bob.

The volumetric calibrations are particularly valuable for a number of reasons:

(i) at low levels, constructional deformations or those resulting from erosion have greater proportional effect on discharge than at higher stages, so that extrapolation of theoretical rating curves is increasingly unreliable

(ii) dilution gauging and current metering techniques are less practicable at low flows

(iii) B.S. 3680 Part 4c 1974 Sec 551 sets the minimum lower limit of head in the flume as .05 m or .05L (L = length of throat), whichever is the greater. Below this value the theoretical calibration should not be used. Values for the lower limit of h are given below, together with the percentage of time in 1975 in which the stage was between stated levels.

PLATE 9

Manual volumetric measurements of discharge, 1976

TABLE 5 STAGE LEVELS FOR 1975

FLUME	.05L	% of time stage in stated band		
		0-100 mm	100-200	200-300
	mm			
Severn trapezoidal	212	6.4	31.7	30.5
Tanllwyth	183	45.2	43.1	7.1
Hore	343	0.0	50.6	26.1
Iago	183	38.6	41.2	8.0
Gwy	275	0.0	36.0	36.4
Cyff	237	0.0	38.5	22.1

Note: Hafren flume not operational during 1975

3.3 Current meter gaugings

Flow velocity was measured in the Severn trapezoidal flume and in each of the six steep stream flumes using Braystoke current meters fitted with 63.5 mm diameter propellers. Five meters were mounted on a 25 mm diameter metal rod at distances of 0.1, 0.2, 0.3, 0.4 and 0.5 m above the bed, while another five meters were mounted on an identical rod at greater intervals for flood flows, namely 0.1, 0.2, 0.4, 0.8 and 1.2 m above the bed. The meters were connected to five counters controlled as a group by an adjustable electronic timer. The output of both timer and counter are pulsed and assumed to be accurate to one count at all readings. Operational guide lines set a minimum time interval of 100 seconds and a minimum meter count of 100. The meter rod was clamped vertically with the meters pointing directly upstream. In the case of the Severn trapezoidal flume the meter rod was clamped to a portable bridge (see Plate 10) across the flume positioned such that the metering positions were opposite the tapping pipe. To locate the metering positions accurately across the stream the bridge was marked out in .125 m intervals. At high stages metering was done at .250 m intervals, the criterion for interval choice being the requirement of at least 15 verticals in the cross section,whilst gauging traverse time does not exceed approximately 45 minutes if the stage is changing rapidly. The average number of verticals used was 14 with an average traverse time of 35 minutes.

All the equipment described above was loaned for the calibration period by the Hydraulics Research Station. For the steep stream structures the Institute designed and made a system of sectionalised rods and clamps which was easily portable and could be adapted to fit across each gauging structure. It consisted of a metal bar across the flume with 75 mm graduations engraved along it; it was levelled and secured

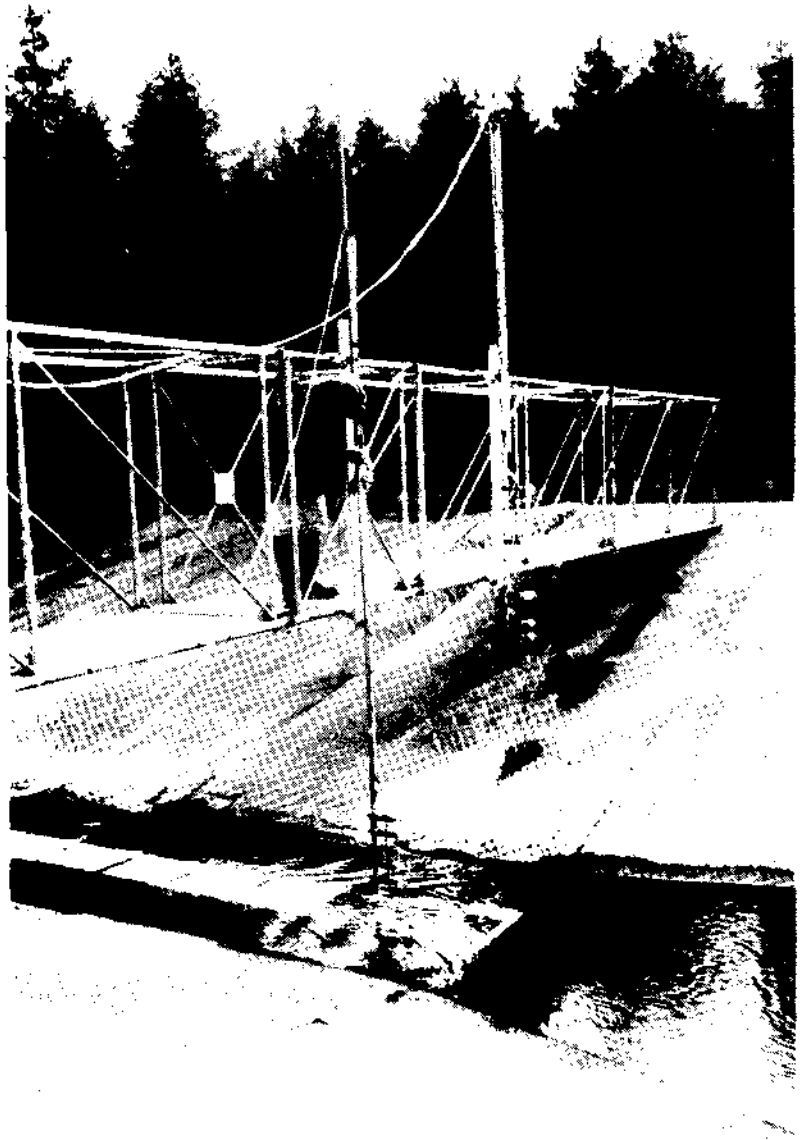


PLATE 10

Portable bridge
for current metering
River Severn

to two metal base plates, one on each wall of the flume and the graduations centred. The meter rod was attached to a sliding clamp on the metal bar; near the base of the flume the rod was supported and the metering positions located by means of a horizontal line of plastic "cotton reels" centred and corresponding to the graduations on the metal bar at the top of the flume. The line of "cotton reels" was held in position by a hydraulic jack. As with the Severn trapezoidal flume the meters pointed directly upstream and were opposite the tapping pipe (see Plate 11). The operator stood on a metal support platform behind the meter rod. There were 11 meter positions across the steep stream structures except for that in the Gwy in which there were 15. Average time for a complete metering traverse was 25 minutes for the flumes with 11 positions and 35 minutes for the Gwy flume.

PLATE 11

Current metering in flume

Water depths in all the flumes were measured by setting the wedge tip of the meter rod to the water surface as if it were a point gauge and measuring the movement of the rod down to the flume invert using a steel tape, to the nearest millimetre. This was done at the beginning, middle and end of every gauging, and additionally in the Severn trapezoidal flume whenever the position at each side of the invert was occupied. At the same time measurements of well water level were made using the sonic plumb bob from the fixed datum on the side wall above the tapping pipe.

At the Severn flume 36 current meterings were made over stages ranging from 185 mm to 1346 mm. Field work extended over the months December 1975 - March 1976. Work commenced on gauging the steep stream flumes in May 1976 and was completed in July 1977. The table below shows the number of steep stream meterings and the stage range covered.

TABLE 6 CURRENT METER GAUGINGS FOR FLUME CALIBRATIONS

Flume	No. of gaugings	Range of stage covered mm
Severn Trap	32	180 - 1437
Tanllwyth	32	91 - 478
Hafren	32	130 - 800
Hore	31	141 - 658
Iago	30	162 - 770
Gwy	31	130 - 992
Cyff	30	164 - 702
Cefn Brwyn	Not gauged	

From this table it can be seen that the flumes operate for considerable periods at levels below which the theoretical calibration should not be applied. The existence of reliable volumetric gaugings in the most problematic flow regimes is obviously a great asset.

With hindsight, some provision for facilitating volumetric gaugings in any structure would be of great value. The simplest modification which would yield the maximum benefit would be some means of extending the invert at the exit permitting the additions of pipes or conduit to route the water conveniently to a tank.

3.4 Summary

The results of the three calibration methods (dilution gauging using extended plateau times, current metering and volumetric gauging) can all be presented as a single calibration graph for individual structures. This however makes the assumption that the method of recording stage is without ambiguity.

As discussed earlier there is reason to believe that well and flume levels differ, most obviously at high flows. Furthermore, at low flows the water levels may fall below the tapping point. For these two reasons the tapping pipe/stilling well arrangement which is traditionally specified, and is normally accepted because of its analogy with a 'U' tube, may not be suitable. The performance of a 'U' tube is beyond doubt when the liquid involved is motionless, but when one limb is exposed to fast moving water the performance is less certain.

The presence of varying amounts of air in the flume water makes the detection of the water surface of questionable value unless the degree of aeration can be measured. This criticism applies both to the use of the sonic plumb bob and to the use of the current meter rod. The criticism in the current metering situation is compounded because the depth measurement thus obtained is used to calculate the cross sectional area and combined with recorded velocities to give discharges.

The extent of the errors caused by those problems remains unknown. The production of a device that can accurately measure head in the flume will eliminate the need for stilling wells, but may prove a difficult research project.

4. CONCLUSIONS

Gauging streamflow from small upland catchments is essential to the applied hydrologist but is never easy. The high standards of data required by the Plynlimon experiment have made the exercise even more difficult. This report has sought to identify and improve or remedy the sources of difficulty in gauging. Specific problem areas are as follows:

The need for a new design of structure for steep channels with extensive bed-load ;

the protection of conventional structures against gravel shoals and abrasion by bed-load;

the collection of analogue and digital records of water level in all structures to a satisfactory standard of precision and of accuracy to meet the terms of reference of the investigation, carried out under difficult environmental conditions;

the minute survey of structures to compare built dimensions with their design counterparts;

the field calibration of structures with a wide flow range and flashy regime. The presence of aeration complicates the calibration by current metering;

the need for care in assuming that stage levels in the wells accurately reflect the stage levels in the flumes.

Acknowledgement

The field work described in this report was carried out by the staff based at Plynlimon. In particular, the current meter gaugings were organized and executed by Anna Newson.

APPENDIX I

Detailed layout and dimensions of the Plynlimon flow measurement structures.

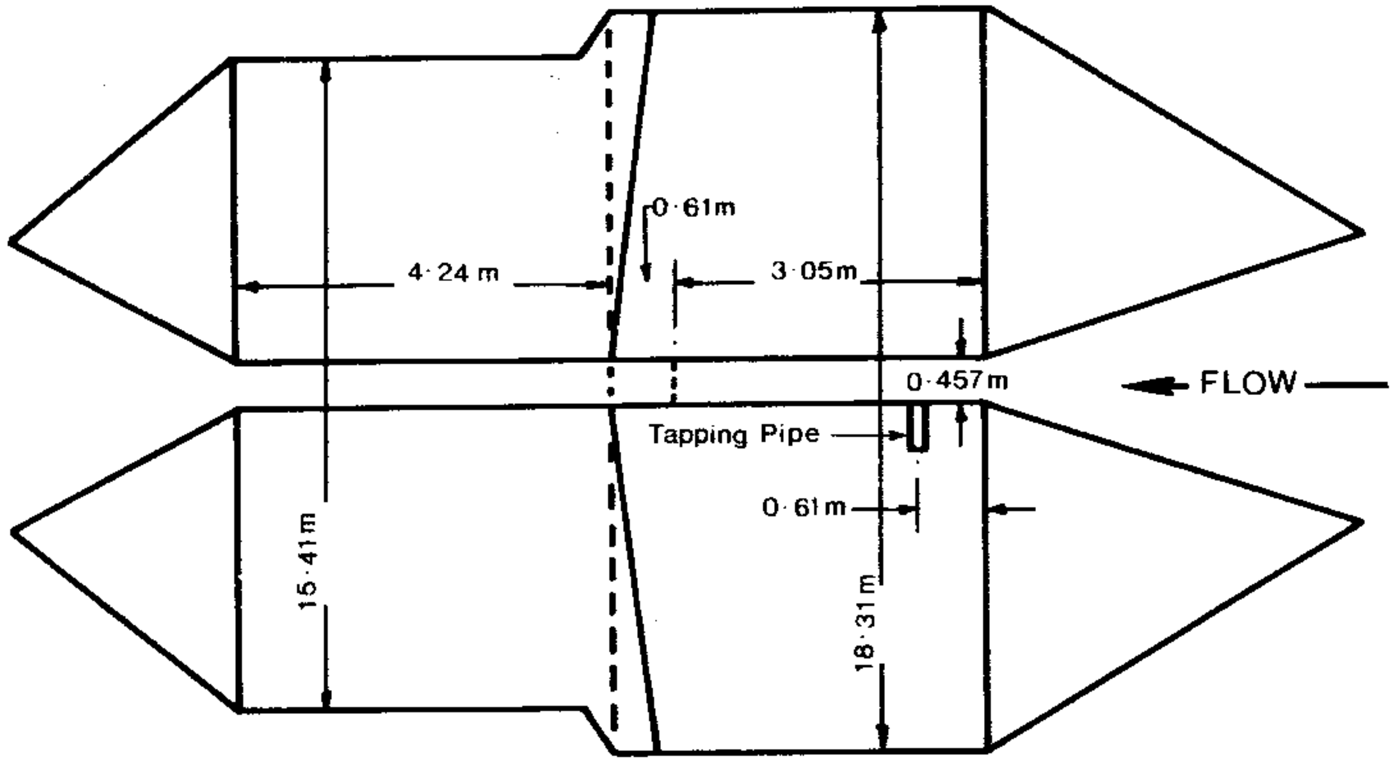
SEVERN TRAPEZOIDAL FLUME

Catchment area	8.70 km^2
Design flood Q	41.03 cumecs
Design drought Q	0.023 cumecs

As built dimensions

Lengths:	Approach section	3050 mm
	Throat section	4240 mm
Invert width:	Approach	457 mm
	Throat	457 mm
	Step height	-10 mm in 610 mm*
Side slopes:	Approach - left	1 : 3.85
	right	1 : 3.90
	Throat - left	1 : 3.27
	right	1 : 3.20
Materials	Invert and first 150 mm of side slope alluminium alloy; remainder in concrete	

**Step of 10 mm down from approach to throat achieved between 3.050 and 3.660 mm, measured from start of approach section.*



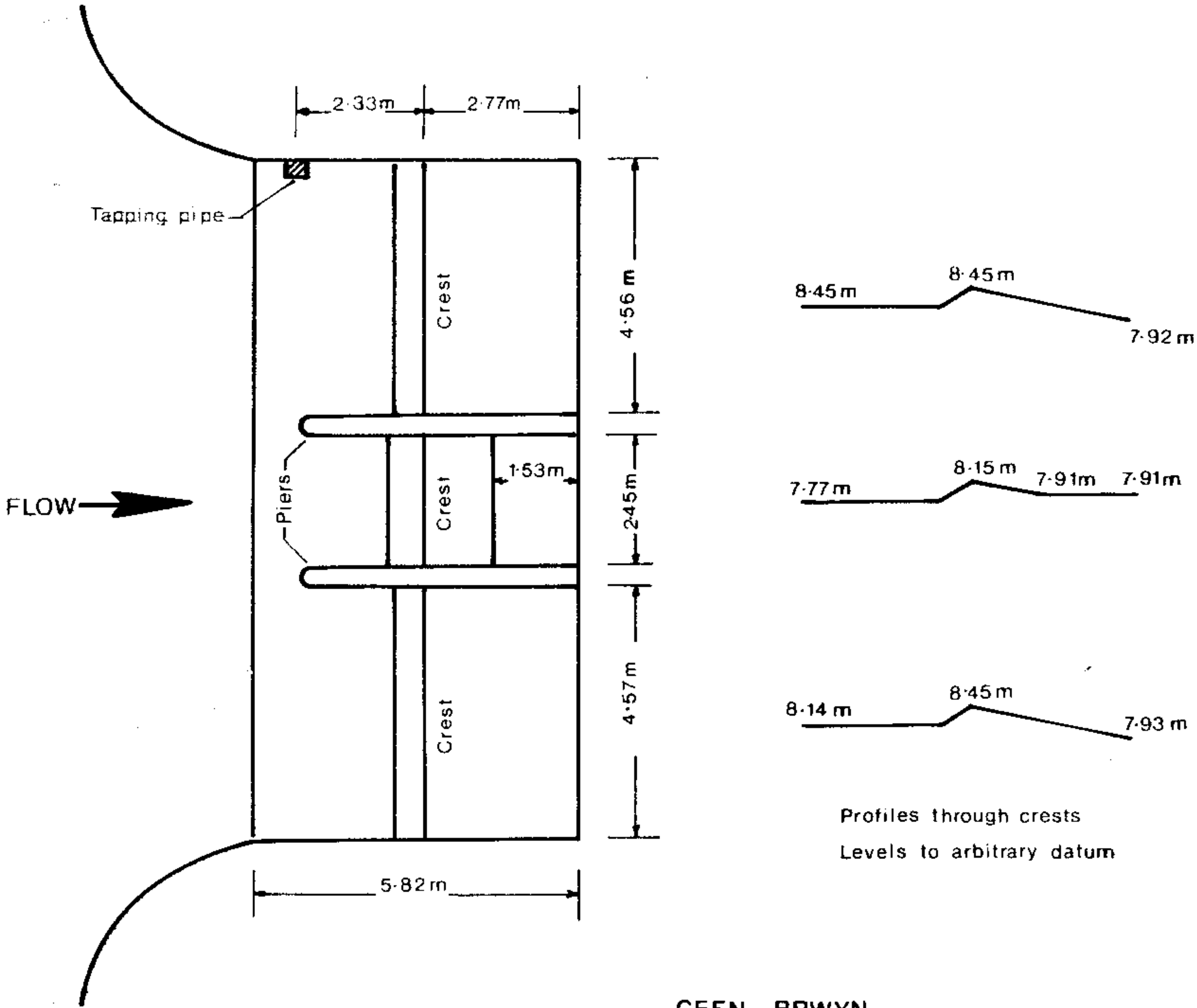
PLAN OF SEVERN TRAPEZOIDAL FLUME

CEFN BRWYN WEIR

Catchment area	10.55 km^2
Design flood Q	52.350 cumecs
Design drought Q	0.020 cumecs

As built dimensions

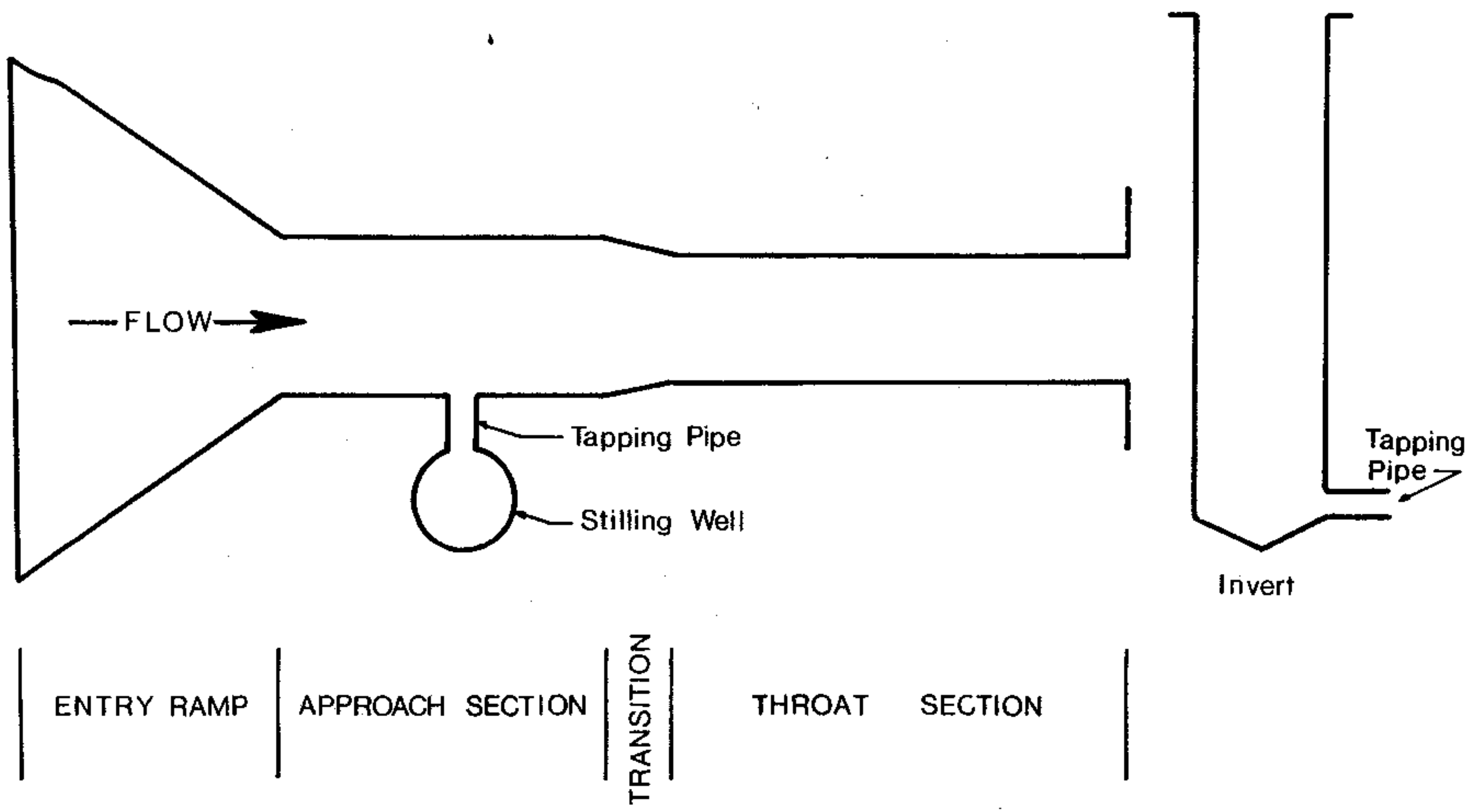
Crest widths	Left bay	4560 mm
	Centre bay	2450 mm
	Right bay	4575 mm
Crest levels	Left bay	+ 377 mm
	Centre bay	0
	Right bay	+ 378 mm
Crest slopes	Left - upstream	1 : 1.839
	downstream	1 : 5.226
	Centre - upstream	1 : 1.737
	downstream	1 : 5.167
	Right - upstream	1 : 1.645
	downstream	1 : 5.327
Materials	Cencrete; gun-metal crests	


2·33m
2·77m
Tapping pipe
Crest
Crest
Crest
4·56 m
2·45m
4·57m
1·53m
Piers
FLOW
5·82m
8·45m
8·45m
7·92m
7·77m
8·15m
7·91m
7·91m
8·14 m
8·45m
7·93 m
Profiles through crests
Levels to arbitrary datum

CEFN BRWYN

STEEP STREAM FLUMES

				Lengths, mm			Distance between vertical walls, mm			Construction material		
	Catch-ment area km^2	Design flood Q cumecs	Design drought Q cumecs	Approach	Transition	Throat	Approach sect. at tapping point	Throat	Step height up in throat mm	Approach walls & invert	Throat invert	Throat walls
HAFREN	3.67	10.19	0.009	5480		5890	913	682	25.4	glass fibre	alumi-nium alloy	wood
TANLLWYTH	0.89	2.26	0.003	3660	610	3660	916	701	50.8	glass fibre	Al. alloy	glass fibre
HORE	3.08	14.15	0.011	8160	1040	6860	916	701		concrete	concrete	concrete
IAGO	1.02	3.96	0.003	3660	610	3660	912	759	25.4	glass fibre	Al. alloy	glass fibre
GWY	3.98	17.83	0.014	6640	1000	5500	1214	938		concrete	concrete	concrete
CYFF	3.13	9.91	0.009	5600	920	4730	982	759		concrete	concrete	concrete



PLAN OF STEEP STREAM FLUMES