INSTITUTE OF HYDROLOGY

CHANNEL STUDIES IN THE PLYNLIMON EXPERIMENTAL CATCHMENTS

by

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ABSTRACT

The Report contains a collection of field observations on the classification, distribution, suggested origin, capacity and throughput characteristics of channels in the Plynlimon catchments. The fieldwork methods covered include mapwork, the use of a channel cross-section device, dye tracing and dilution gauging. Four types of perennial surface channel are described, as well as ephemeral channels, soil pipes, 'flushes' and artificial drainage ditches. The open channels are investigated for relations between dimensions at the channel-full stage and catchment area. Considerable smoothing of data is required to obtain a good power-relationship and the results contrast with those from areas where bedrock is less influential on channel shape.

The hydraulics of these irregular channels have been studied empirically by selecting reaches of the Severn (50 m long) and performing dilution gauging at a variety of flows. Velocity changes most rapidly with discharge. The results are also interpreted in terms of dynamic storage relationships for each reach. A comparison with two surveys of total storage is made. Times of travel have been established and resemble the findings of Pilgrim; linearity of channel response in flood is suggested. Finally, the techniques applied to open channels and their flow are used to calibrate the flow characteristics of soil pipes, flushes and overland flow.

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INTRODUCTION

It is convenient to divide the runoff phenomenom into slope and channel phases. This serves both as a framework for study and as an organizational subdivision for mathematical runoff models in which surplus water modelled from slopes is routed down the channels to the point of interest. Thus field studies of source-areas and channels are complementary.

The inter-relationship of the lowest orders* of channels (including temporary routes for flood runoff) with runoff source areas is also a key one in the calibration of the response of those areas. The more permanent channels of higher orders may not, themselves, traverse important runoff source areas but their geometry provides information about the build-up of channel-forming flows down the catchment. This relationship has often been used in the design of stable artificial channels and in flood prediction.

Low order channels and contributing areas

The importance of low order channels is implicit in the assumption that channelized runoff is more rapid than sheet runoff or percolation through soils. Hence, the development of permanent channels was seen by Horton (1945) as a stage in the build-up of flow with increasing distance down slope. The change from the Hortonian to a partial contributing area concept of runoff, in which only part of the catchment is responsible for rapid runoff, has indicated that such runoff areas contribute to a large channel (eg. valley-bottom mires) or to a dense network of finger-tip tributaries which expands and contracts according to runoff conditions. Expansion of the low order network occurs in 'ephemeral' channels such as gullies (open) and pipes (closed tunnels). The state of this expanded network at any given time can be used for flow prediction (see Blyth and Rodda, 1973).

Higher order channels and contributing areas

Turning to the relationship between higher order channels and their formative discharges, little work has so far been conducted on small upland catchments where bedrock controls are dominant. Larger, alluvial rivers are widely reported to have an equilibrium between

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* *The order of channels is based on the bifurcation of the network; in most systems first-orders are the smallest tributaries, forming second orders where they join and so on. Numerical ordering is not used here since the scale of treatment, down to the non-dendritic soil pipes, is much more detailed than normally chosen for ordering.*

channel capacity and the bankfull discharge; the latter is widely assigned a return period of 1-2 years although Harvey (1969) demonstrates that this depends on general streamflow regime, flood duration, etc. His results suggest that, with a flood regime, the higher up the catchment, the more frequent are bankfull conditions. Bankfull capacity can therefore only be used, with care, as a rough guide to the build-up of flows of an annual return period or less. Consequently channel capacity can also be used to index contributing areas where departures from a linear relationship between channel capacity and catchment area cannot be explained by channel slope or other variables.

Channel routing

Channel geometry is also a required input to routing models, particularly in very rough channels in upland areas which cannot be assumed to have the more predictable shapes of true alluvial channels. Bedrock, or deposits of coarse glacial sediments, exert a much greater influence on channels and their flow in the Plynlimon catchments than in most lowland streams where flow regime adjusts its channel hydraulically by erosion and deposition. At Plynlimon the presence of sub-surface channels of various types also poses problems in the extrapolation of theoretical models from other environments.

The hydraulics of flow in rough, or roofed-over channels need to be understood by experimentation, especially since there are likely to be non-linearities and threshold effects on flow due to the dominance of the channel boundaries. Surface flows on slopes, too, need investigation where they dominate response.

1. METHODS

If a mathematical catchment model is to be based on known processes and their field calibration, techniques used in the field must essentially be simple and, if possible, rapid. Whilst Plynlimon channels have been the topic of a detailed study, reported here, the authors' aims are always to stress short-cuts and generalizations, capable of extrapolation without further calibration.

1.1 Maps

Channels are depicted on all topographic maps although their density is normally variable with map scale (see Newson, 1976). The Plynlimon catchments were, however, mapped at scales of 1:5,000 and 1:10,000 from aerial photography, thus providing an excellent basic reference point for channel studies. The fault of these Hunting Surveys, if any, is over-representation. Only fieldwork can distinguish the true situation, especially in the forested Severn, where planting had already occluded many elements of the drain pattern apparent from aerial survey. A set of RAF aerial photographs at a scale of 1:10,000, taken in 1951, was used to discover the more natural pattern of drainage in the Severn catchment before the most extensive phase of afforestation.

A summary of findings based on morphometric analysis of Plynlimon channel networks (Newson, 1976) is:

1. The channels have cut into deep accumulations of drift in the valley floors; the influence of drift has caused minor changes in network shape. In most cases bedrock or drift boulders now form the channel bed and lower banks.

2. Whilst the density* of natural channels in the Wye and Severn is similar, the slope of channels in the Severn is steeper. Stream frequency* is higher in the Severn, indicating shorter, more numerous streams than the Wye.

3. The Wye has a more pronounced peak to its "Stream Frequency Diagram" (number of channels contributing at unit distances upstream) compared to the Severn. Forest drainage has contributed to a more even drainage pattern by additions to the network in areas where longer, lower slopes without open channels would normally prevail.

A general conclusion is that the channels and slopes of the Severn would be the more rapid to respond to flood runoff in the absence of afforestation (and especially since drainage, but before canopy-closure).

1.2 Field survey - the channel survey device

The inspection of all channels would be impossibly time-consuming. Consequently the classification arrived at in Section 2 is a great aid. A mixture of field survey and interpretation of aerial photographs was used to extend the classification to both catchments. Pipes were mapped symbolically by two people walking every slope in the Wye in the quarter and three-quarter slope positions. Thereafter typical examples of gullies, flushes and pipes were treated in more detail by conventional field survey techniques (see Section 2) whilst a sampling programme was initiated to quantify the geometry of all permanent open channels (Section 3), and the detailed hydraulic geometry of some reaches (Section 4).

The basic equipment for the channel geometry sampling programme is shown in Plate 1. It consists of portable sections of I-section alloy, which can be bolted together to cross any Plynlimon channel. The alloy is perforated on its upper and lower sides, to allow 2 m

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* *Channel density measurements refer to the length of channel per unit area whilst frequency measurements refer to the number per unit area.*

lengths of 19.1 mm (¾ in) gas pipe to slot through at 25 cm intervals.

The gas pipe has been etched and painted at 10 cm intervals, white on black. The mode of operation is to level the alloy boom across the channel with each end resting on the chosen morphological level of bankfull (for definitive details please see Section 3). Sagging of the boom on wide sections is prevented by its own rigid section and support provided by 'dummy' gas pipe, unmarked but equipped with adjustable collars to support the boom level. The bank ends of the boom are equipped with stabilizing feet and the whole equipment rests secure whilst it is photographed using a wide-angle lens (28 or 35 mm are best) and close-grain black and white film (Pan F) for clarity.

PLATE 1 Rapid channel survey device in use on the Wye just above Cefn Brwyn weir. A library of such photographs was used to derive channel cross-section dimensions

During six weeks of summer 1975, all Severn and Wye perennial open channels were photographed at approximately 100 m intervals. In addition, the work on the main Wye and Severn streams was accompanied by slope, velocity and roughness studies. These formed the basis of student dissertations by Miss Janet Groves, University College of Wales, Aberystwyth and Miss Gillian Pauley, North London Polytechnic, working in the Severn and Wye respectively.

The definition of channel capacity measured was suggested (by Miss Groves) as "channel-full" rather than bank-full since these channels do not possess conventional banks in most places - certainly spillage on to a flood plain does not occur at stages above the defined one, as in the classic definition. However, a variety of vegetational, slope and shape conditions were used to obtain a channel-full definition in the field and on the Wye this definition was checked during the highest flows of 1975-6 winter to our satisfaction. Of the vegetational guides, the colonization of infrequently eroded banks by *Polytrichum commune* was used in a similar way to that proposed by Gregory (1976) for lichens.

1.3 Dye tracing

Water-tracing technology made significant progress with the introduction of the portable fluorometer. The model used in this study was the Turner Model III.

Fluorescence is the instantaneous emission of light from a molecule or atom which has absorbed light. Any fluorescent molecule will have two spectra - the excitation and emission spectra. Fluorometric measurements can detect concentrations of fluorescent materials as low as a few parts per trillion. The fluorometer uses a primary filter between light source and sample to produce the desired wavelength to be measured. The photodetector produces a current proportional to the intensity of the fluorescent light which is shown on a dial or recorded on a chart. The relationship of fluorescence to concentration is linear.

The fluorometer has been developed as a hydrological tool in a variety of situations. Dr. T.C. Atkinson, University of East Anglia, kindly instructed the authors in its use at Plynlimon. Two fluorescent dyes were used as tracers - Pyranine (retailed by Bayer Dyestuffs) and Rhodamine WT (retailed by Dupont UK); of these the latter is preferred, being in liquid form from the manufacturer and less affected by peat, sediment and exposure to sunlight. However, only large quantities are available in Britain at the time of writing (early 1978).

Both chemicals are relatively harmless (Smart and Laidlaw, 1977) and it is only the colouring which reduces potability. However, although the remoteness of the Plynlimon channels from habitation and water-supply intakes does not prohibit the use of dyes at visual concentrations, it was considered wise on economic grounds to use as little as possible on most traces whilst ensuring detection by the fluorometer. Various empirical relationships were used to determine the approximate dosage for full-length traces down the Wye, Severn and major tributaries, eg. Dunne (1968), Kilpatrick (1970).

However, the dispersion characteristics of these upland channels led to some failures in both directions (unintended visual traces and concentrations falling below fluorometric range). The major problems were as follows:

1. Concentrations were markedly reduced at low flows due to pronounced dispersion which reduced the dye wave to a low, long shape. As much dye is required at very low flows as in floods.

2. Middle-order flows can prove difficult in rocky channels since there appears to be a critical mean stage above which travel-times are sharply reduced. Thus the same slug of dye may give an unintentional visual at discharges only slightly above those where perfect results are achieved.

3. The normal relationship of "more discharge, more dye" requires careful attention during flood discharges if excessive dilution is not to occur.

Basically, the approach has been to use approximately 250 ml Rhodamine WT (20% solution) for full-length traces of all main channels at moderate flows and to double this for both very low (as advised by Dunne) and very high flows. Pyranine quantities have been proportionally higher, 200 g of Pyranine dissolved in 500 ml of water to form the basic slug.

Three strategies of dye sampling have been adopted:

1. Manual collection of water samples in 60 ml polythene bottles on very long traces, three sampling runs per day.

2. Use of the samplers (one hour, half-hour) now retailed by Automatic Liquid Samplers Ltd*. These yield up to 500 ml of sample by a vacuum-release effect operated by spring or battery clocks. Care is required in cleaning the sampling tube between traces.

3. Use of the Turner fluorometer in the field powered by a Honda E300 generator in conjunction with a peristaltic pump (worked by 12 v battery) and a Smith's servoscribe (also powered by a Honda generator). Plates 2 and 3 show this configuration in use in the Institute's 'bog-trotter' Land Rover, in which all locations on the catchments could be reached.

Configuration (3) has been used for getting a continuous record of full-length water traces and also for research on the storage, mean velocity and discharge characteristics of individual reaches. In the latter experiments, seven channel cross-sections have been chosen on the Severn and at these 50 m of reach upstream is used for dye tracer or salt dilution tests. The Rhodamine slug this time is 2-10 ml from a dropping bottle, dissolved in 4.6 l of water (1 gallon). A calibration of dilutions is obtained in the laboratory and this, combined with the recorded wave of fluorescence in the field, can be used to give a measure of discharge by the 'gulp' dilution method. The method is more fully illustrated below with reference to common salt.

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* *formerly North Hants Engineering Ltd.*

PLATE 2

The 'bog-trotter' off road to gain access for continuous fluorometry during work on individual reaches

PLATE 3

Fluorometer and servoscribe *in operation, powered by* generators

1.4 Dilution gauging by common salt

Oestrem (1964) has described an ideal method for gauging turbulent streams in remote locations with common salt, the dilution effect being monitored with a conductivity meter. Calkins and Dunne (1970) have demonstrated the use of this technique although with a pH meter and sodium ion probe. They advised the use of a basic 'gulp' slug of 273 g (½ lb) of common salt. This was diluted in 4.6 l (one gallon) of water to give the primary solution and its successive dilution is performed in the laboratory to obtain a calibration with electrical conductivity (see Figure 1). In the field, a crate of 25 230 ml plastic bottles has been used to sample the salt wave, its arrival being demonstrated for the benefit of the person sampling by means of a small amount of fluorescent dye in the primary solution, or by using

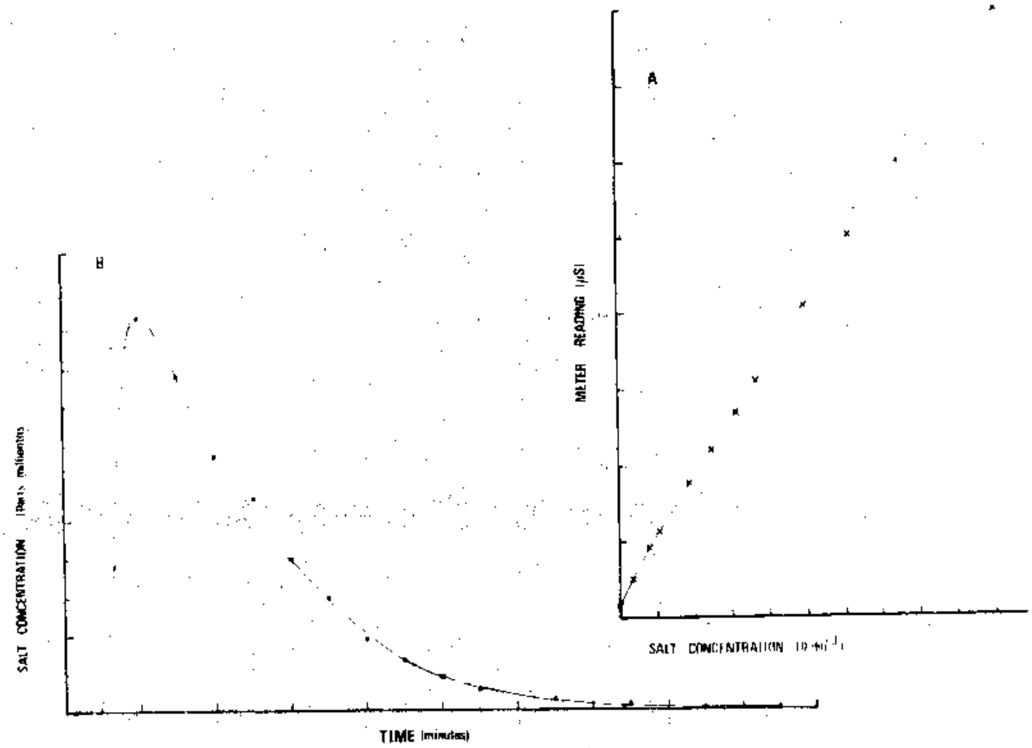


FIGURE 1 Principles of dilution gauging with NaCl. Field readings of conductivity are converted via A to B. Equation C is then computed

$$Q = \frac{V}{A.a.b}$$

where Q = discharge (ls^{-1})

A = area under curve (cm^2) - see (b) in this Figure

a = 1 cm division on time axis (sec)

b = 1 cm division on salt axis (parts millionths) the conductivity meter. The person sampling uses the bottles sequentially (the crate being numbered), and a stop-watch to select the sampling interval; this can be varied with manual sampling. At low flows the crate of bottles can be dispensed with and the LTH Electronics 7B/1 portable conductivity meter (Plate 4) can be used directly to observe the salt wave. The sampled salt wave is then plotted up, after conversion to concentrations, and integrated. The discharge calculations are shown in Figure 1. Both dye and salt methods are ideal to give velocity and dispersion information simultaneously with an estimate of discharge. However, because of doubts regarding the accuracy of discharge measurements with the two methods the seven reaches were chosen close to permanent gauging stations (see Section 4).

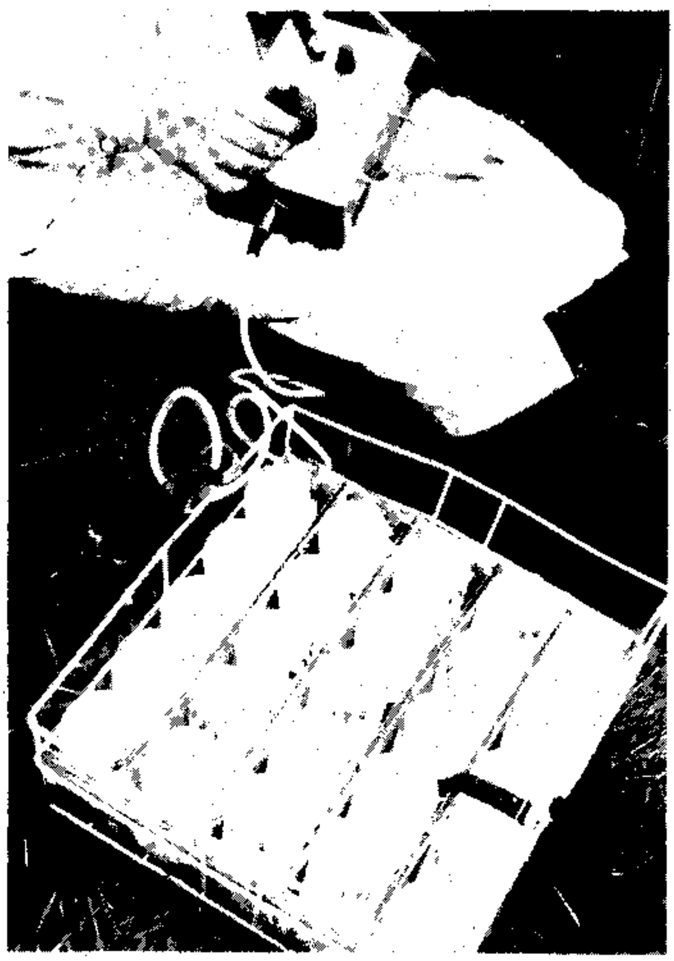


PLATE 4

Using a portable conductivity meter to define a wave of salt dilution sampled in the crate of bottles. At low velocities the meter probe could be used directly in the stream.

2. CLASSIFICATION OF CHANNELS

Channelized flow has been proved to occur far beyond the boundary of the permanent network shown on topographic maps. Whilst the whole system has continuity, there are obvious differences in channel types which may manifest themselves in the hydraulics of runoff. The most obvious subdivision is that between open and closed channels. The latter are thought to be a special feature of peaty catchments and information on their distribution is as yet scarce. Special hydraulic features of closed channels are perhaps their network shape, finite capacity and smooth walls. The open channels of the catchments in places reflect peaty influence too, being wholly in peat in their upper reaches and with peat/alluvium banks lower down. An important subdivision of open channels in both catchments is between channels whose plan and cross-section are determined by bedrock and those whose plan and geometry represent the inter-relationship of fairly frequent channel flows and sediment transport. Only restricted parts of the Middle Wye and Severn exhibit this latter "alluvial" behaviour. Consequently the literature of fluvial morphology, which refers mainly to this type of channel, is of restricted relevance to Plynlimon. Even in non-bedrock reaches the most significant elements of beds and banks are residual boulders from glaciation which are moved only infrequently by contemporary fluvial processes. Figure 2 shows a mapped classification of Plynlimon channels whilst separate mapping of the dense soil pipe network in the Wye is shown in Figure 3. The features itemised in the map key and in Table 1 are described in more detail in the following sections.

TABLE 1 CLASSIFICATION OF PLYNLIMON CHANNELS

CLASS	REGIME	TYPE	DESCRIPTION
CLOSED CHANNELS	ARTIFICIAL	TILE DRAINS	An unrepresentative absence in the Wye catchment.
	INTERMITTENT	SOIL PIPES	Those in the Wye first described by Pond & [illegible]. Flow only during and after moderate or heavy storms. Common midslope in the Hiraethog/Hafren profile.
	PERENNIAL	FLUSHES	The perennial pipes of Gilman - bedrock depressions with peat infilling. [illegible] most useful indicator.

OPEN CHANNELS	INTERMITTENT	EPHEMERAL CHANNELS	Includes the extending network of the eroded peaty plateaus and the grassy "gullies" of Bell & Calder. Both types may initially have been formed during previous cover/climate conditions. Formed in unconsolidated superficial deposits.
	PERENNIAL	PEAT-LINED CHANNELS	The upper channels of both Wye and Severn mainstreams flow between peaty banks. Channel bed is often in peat. Active erosion represents failure of peat to roof over stream completely.
		BEDROCK CHANNELS WITH FALLS-AND-POOLS	Particularly common in upper reaches where channels cross the strike of the local rock. Flow path swings criss-cross to channel direction.
		BOULDER CHANNELS WITH ALLUVIAL BANKS	Glacial dumps of boulders occur prominently at base of steep fall-and-pool reaches.
		ALLUVIAL CHANNELS	Banks are of peat and silt on cobbles. Bed of cobbles and gravel. Meanders, riffles and pools.
	ARTIFICIAL	DRAINAGE DITCHES	Dominant in the middle part of the Severn catchment in deep peat. Some old open drains in Wye, mainly vegetated over.

2.1 Soil Pipes

Pipes are most commonly found on the slopes of the Wye catchment although small-scale systems have been found on the unforested Upper Severn. Pipe systems were possibly a common feature of the Severn catchment before extensive draining and afforestation took place, although it is also possible that with shorter, steeper slopes this was not the case. Pipe flow has been recorded from forested areas, in dessication cracks caused in the peaty planting ridges; these have not so far been discovered in Hafren. Pipes are found on the longer slopes mantled with a variable, but mainly podsolized, peaty soil, most frequently classified as the Hiraethog Series (Rudeforth, 1970) or Hafren Series (Lea, 1974). The pipes are around 10 cm in diameter (average cross sectional area = 67.5 cm^2) and frequently occur at or near the junction of the peaty A horizon with the finer, mineral, B horizon, (average depth 17.7 cm) probably because of the permeability change at that point. However, many are "floating" entirely within the organic horizon for much of their length and it is possible that a process associated with the peat alone explains the localization of the soil pipe (given that the permeability change initiates the lateral flow). Peat dessication cracks are suggested below as their likely origin, a view reinforced by Miss Morgan's dissertation.

In plan, most networks are branching but not truly dendritic, having a greater resemblance to a system of karst caverns than to a surface stream channel network (Newson, 1976). Their average drainage density is 180 km/km^2. In many cases the pipe network descends the whole slope, as has been described by Knapp (1974), to the edge of the mires which fill the valley bottoms in the Wye catchment. In others the network runs towards a "rush flush".

The hydrological significance of rapid pipe drainage may therefore be reduced because pipes rarely discharge directly into the surface channels of the catchment; however, the pipe networks certainly constitute a major source of saturation in the flushes and valley-bottom mires and therefore may control the moisture conditions in the partial contributing area. Another important feature is that at the upper end of most pipe systems there are surface or subsurface outlets from the blanket peat on the flatter interfluves. Thus the pipes 'short-circuit' the long slopes between such productive source areas for runoff and the valley-bottom source areas. Their flow velocities are three orders of magnitude more rapid than matrix throughflow. The hydraulics of pipe flow are returned to in Section 5.

Since the peat of the A horizon is not actively forming under the typical *Nardus/Festuca* grassland mat, we may assume that the key to pipe formation is in the slight desiccation of the soils under present climatic conditions, a process which develops positive feedbacks as the pipes grow and drain the slope. Polygonal systems of cracks are observed if the vegetation and upper A horizon are carefully removed; some of the cracks have become pipes. The cracking is possibly a desiccation phenomenon although mass movement is involved, especially at the edge of the blanket peat and down the sides of flushes. The cracks are approximately 0.5 mm wide (up to 4 cm wide during the 1976 drought), 20 cm apart and some reach to the surface (as do mature pipes where *Polytricum spp.* mosses frequently mark their approximate line). Plate 5 shows the network of cracks either side of a soil pipe excavated during the very dry summer of 1976.

Another possible explanation for pipes is that they result from mammal activity. A study of a mole run network on improved pasture in the Wye catchment led to the following conclusions. Firstly, the very low density of molehills in the piped areas contrasts significantly with the high density of molehills for the major mole runs. Secondly, the major molehill sites are on soils of a brown-earth type, or where the organic horizon of the podzol has been mixed by cultivation to give an almost loamy topsoil: Structurally, the runs are smaller than pipes (less than 5 cm diameter), of variable position in the A horizon or plough layer (often reaching the surface)

PLATE 5 Composite photograph of soil pipe and crack network, at the height of the 1976 drought, Cerrig yr Wyn, Wye catchment. The existing soil pipe is in the bottom half of the photograph, meandering from left to right.

and have less stable walls. The network shows no signs of linking hydrological source areas to the channel although several of its major links are up and down slope and obviously water can flow through these runs. The network also shows more exterior links than that of soil pipes and, to this extent, appears more haphazard. The mole run is essentially a 'pit-fall trap' system and it is possible that moles use pipe systems for this purpose since they have been discovered dead in the measuring weirs used by K. Gilman (personal communication).

2.2 Flushes

Ingram (1967) describes the 'water tracks' of an intact mire and their detection by means of surface vegetation. No exact term has yet been discovered in the literature of peat-lands, however, to describe the *Juncus*-covered peaty channels found in the Wye catchment and elsewhere. The author therefore prefers the term "flush" because of their slightly higher nutrient status. The most significant opportunity for investigating them came as the result of the catastrophic failure of one in a flood (Newson, 1975). The following points emerged:

a. They represent buried first order channels in that they occupy distinct declivities, either between lobes of drift or cut into bedrock.

b. The present-day channel is mostly buried in a tunnel, which may be large enough to crawl through, at the peat/drift or bedrock surface.

c. Mass movement, almost a slow flow, can be observed in the peat mass and ruptures in the roof of the buried channel allow surface flow over parts of the flush's length, especially during floods (see Figure 4).

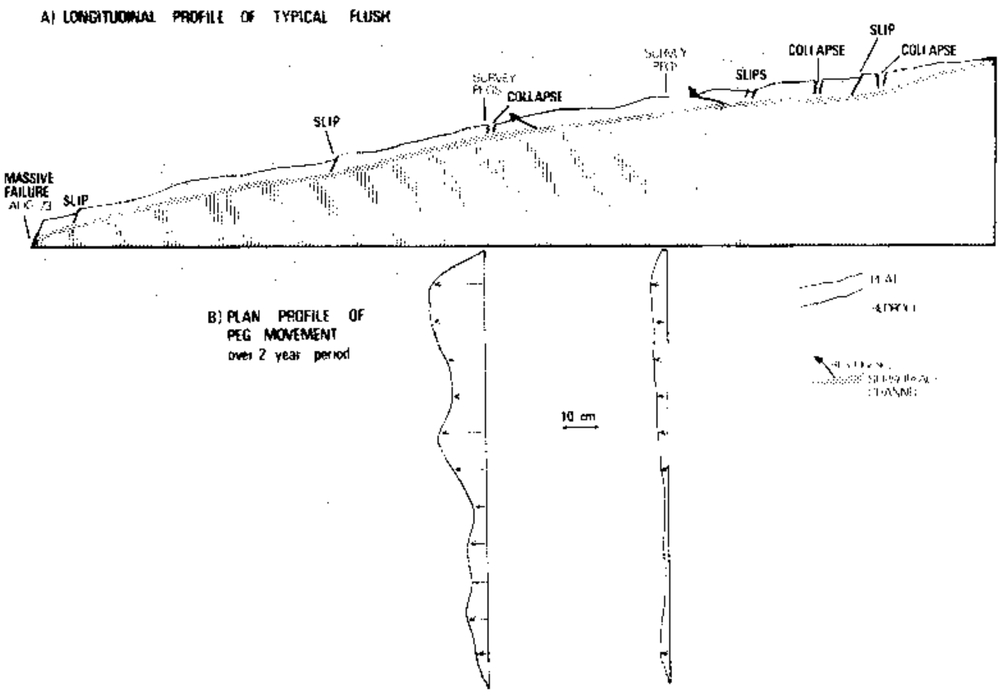


FIGURE 4 Flush profiles

It is difficult to decide whether formation or destruction is the dominant present-day process in flushes; their gradient is in many places critical for peat stability when saturated but in others, where their drainage is interrupted, an active bog flora indicates growth. Much of the peat filling could be re-deposited and both pipe erosion on slopes and peat erosion on plateaus contribute organic and mineral material to the flushes; mineral layers can be observed in the peat. The channel is obviously incapable, or has been during recent climatic phases, of removing this material and keeping itself open.

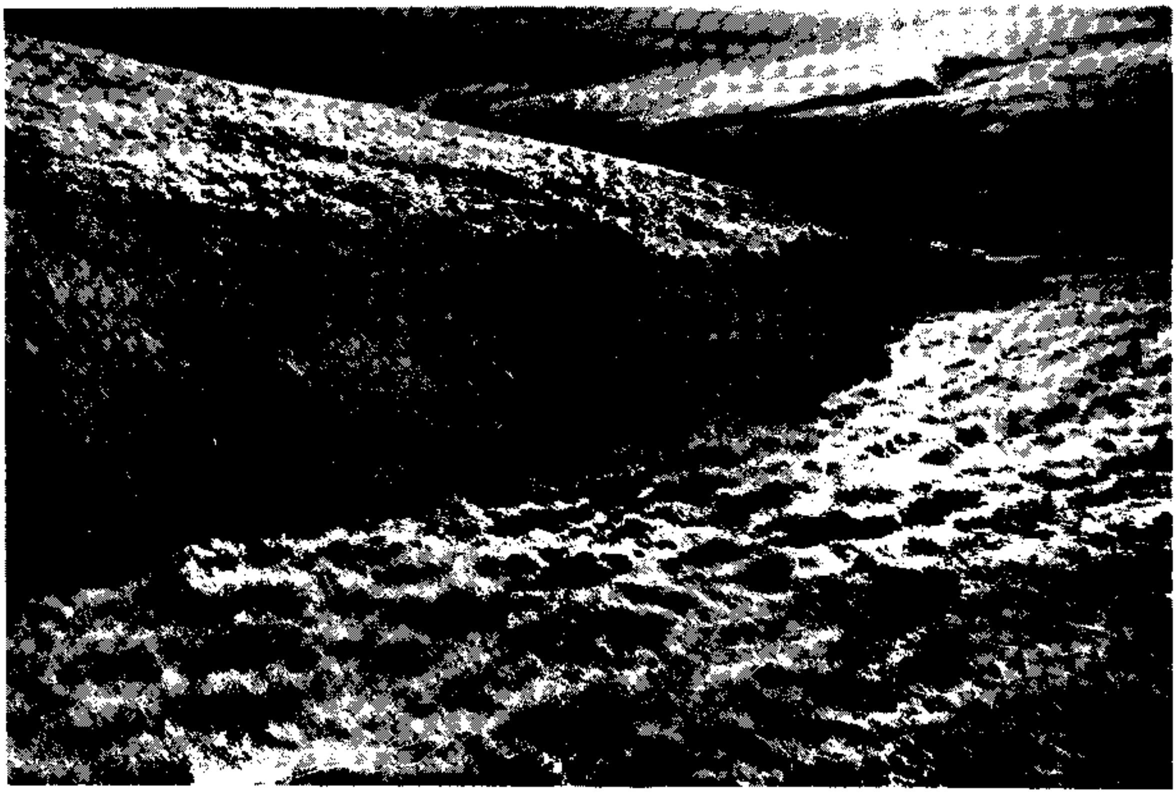


PLATE 6 The Cerrig yr Wyn 'flush', *Juncus* dominated, bordered by *Nardus* with patchy *Molinia*.

The flow of the flush channels is perennial; of the two gauged, one failed after 30 days of drought but another flowed throughout the 1976 drought. Gilman (Inst. Hydrol. internal report) has therefore called these streams 'perennial pipes'. They have a high flood runoff potential too but the inefficiency of the channel and storage imposed by blockage, diversion etc. does not make this a rapidly responding system.

2.3 Ephemeral channels

The small-scale relief of both the Wye and Severn catchments is spectacular. Even the 'straight slopes' drained mainly by pipes have a surface system of shallow declivities. There are three sites which are, however, typified by their infrequently-used surface channels:

a. *Areas within or at the edge of blanket peat*

The upper parts of the Wye and Severn exhibit networks of channels which are similar in nature but differ in that blanket peat is still a feature of the upper Severn but has largely been eroded from the upper Wye. The channels ("groughs") are shallow, cut in a narrow layer of grit regolith or partly into the bedrock. In the upper

Severn they exhibit high discharges during floods since they are still fed by peat runoff and the dense network of minor channels between the peat haggs. In the Wye they flow in floods but less spectacularly - infiltration into the exposed grit regolith may predominate once the blanket peat has gone.

b. *Areas of stratified scree*

Parts of the right-bank slopes of upper Cyff, lower Gwy, Nant Iago and Hore exhibit very dense networks of gullies cut in fine shale (see Plate 7). These owe their depth and density to the rapid erodibility of the scree once the vegetation mat is broken, a process aided by sheep. They carry runoff only during intense rainfall and spectacular washing out of scree can occur (eg. July 4th, 1976). They are also found, in a shallower form, cutting into coarser regolith or even bedrock and it may be that these gullies have been superimposed from a shaley cover, now eroded, or represent type (a) channels radiating from a now-absent blanket peat cover.

PLATE 7 Gully networks photographed across the Upper Cyff, looking south.

c. *Edges of the drift terrace*

The steep edge of the drift terrace which borders most channels in the Plynlimon area, especially north-facing, is subdivided by rotational slips into finger-likc projections between which are wet hollows. After a slip it can be observed that a subsurface channel is exposed in the hollow (Newson, 1975).

2.4 Peat-lined channels

As an example, the source of the Severn is a marshy, open channel which is the focus of runoff from blanket peat. The stream gradient gradually increases away from the source area and the water is focused into a narrow free-flowing channel (Plate 8). At this stage the stream is still within the area of deep blanket peat and the channel is often roofed-over. This type of underground flow seems to have once been even more extensive on the upper Severn but roof collapse has now re-opened much of the channel. Possibly this development sequence is typical of most of the peat channels in the Severn and Wye catchments.

PLATE 8

Peat-lined channel of the Upper Severn (this is reach No. 7 in storage studies).

The peat-lined channel is usually deep and symmetrical with near vertical banks and with the bed usually of stoney clay. On some reaches, where the blanket peat is deeper, the channel bottom will also be peat-lined and, characteristically, there is a more rounded form to the channel.

In both catchments, undercutting of mineral material below the peat banks leads to the collapse of large blocks of peat, especially after floods.

On straighter reaches the cohesiveness and smoothness of the peat channel walls produces an efficient channel shape. However, at bends, the peat-lined channel is often obstructed by the blocks of peat which have broken away from the channel walls or are the remains of roof-fall.

The peat-lined channel of the upper Gwy has formed on steeper gradients than the upper Severn. The stream bed of the Gwy is strewn with cobbles and small boulders eroded from glacial till and is thus much rougher than that of the upper Severn. This channel sediment provides abrasive power during high flows and bank undercutting is even more prevalent. The peat-lined sections of the Gwy channel are characterised by steep, often over-hanging, banks and a flat floor. Long riffles, strewn with small boulders, connect deep, narrow pools.

2.5 Bedrock channels with falls and pools

The steep, incised channels of the Wye and Severn catchments have numerous bedrock reaches and this has had a marked influence on channel forms.

The bedrock reaches, in the upper stages of most of the south-easterly flowing streams, are characterised by steeply inclined beds which cut across the channels at roughly right-angles to flow. Bedrock, in these reaches, has formed a series of pools and falls with water often falling down the inclined bedding plane and pooling in an erosional depression at the bottom of the falls. Blaen-Hafren falls are spectacular examples. A series of steps may be found on the longer bedrock reaches where the stream passes through a number of pools and falls.

Where the channel cuts obliquely across the inclined shale and mudstone beds, a series of angled falls and pools will be found. In this situation, during low flows, the stream is forced to zig-zag through the exposed beds before spilling over the brink into the next pool.

Rapids and large pools are characteristic of the lower reaches where the bedrock inclination is less steep. Occasionally, where the flow follows the cleavage of inclined beds the channel becomes a well-defined mini gorge.

PLATE 9

Bedrock channel above Blaenhafren Falls (part of reach No. 5).

2.6 Boulder channels with peaty alluvial banks

The alluvial banks in this type of channel are not the main source of the medium-to-large boulders found among the channel floor sediments. The banks are usually formed of a thin valley-bottom peat which overlies silt and cobbles. The boulders in the channel are eroded from glacial tills in the higher reaches.

The boulder channel is often found immediately below a steep bedrock reach. The dumping grounds for large boulder sediments are most commonly found immediately beyond the bedrock channel in reaches where the stream gradient has decreased. In other locations the deposition may have been glacial.

PLATE 10

Boulder channel below Blaenhafren Falls (reach No. 4).

Boulders in this type of channel may:

(1) be randomly scattered throughout the stream floor, causing a major obstruction to low flows and creating heavy turbulence during high flows. Or:
(2) piled into a series of banks creating irregular pools and riffles.

Randomly-scattered boulders are usually found on the straighter reaches with a steadily falling gradient and little or no influence from bedrock. Pools and riffles are usually found where channel constrictions, such as bedrock protrusions, cause a natural dam which is then emphasised by boulders. Secondly, pools and riffles, in a boulder-strewn channel can be caused by small gradient changes where the boulders become arranged into a series of banks across the channel.

Erosion and undercutting of the alluvial banks provides a source of smaller sediment for redistribution.

2.7 Alluvial channels

These channels are usually associated with the middle or lower, wider reaches.

The banks are composed of material similar to the channels discussed in the previous section. However, these banks tend to be lower and grassed to the water's edge, especially in the Wye.

Channel migration is a common feature and this has created a narrow flat floodplain and meandering river on the lower Gwy.

The migrating channel leaves a gravel (or even finer) deposit on the inside of its curving path while the opposite side of the stream undercuts its bank, providing a further source of finer sediment.

PLATE 11

Transition to more alluvial features, lower Hafren meander belt (reach No. 3).

Pools and gentle riffles are a common feature of the alluvial channel, the small sediments being easily manoeuvered by flood waters to form banks, shallows or gouged-out pools. Miss Groves' dissertation confirms the irregularity of riffle and pool spacing throughout the Severn channel; average riffle spacing/channel width ratios of 1.6 (compared with 5 to 7 in the literature of longer, purely alluvial channels) were obtained. It was concluded that only in the lower parts of the catchment did the spacing begin to increase, free of the influence of bedrock. Figure 5 shows Miss Groves' surveyed reaches (sections), A-G down the Severn.

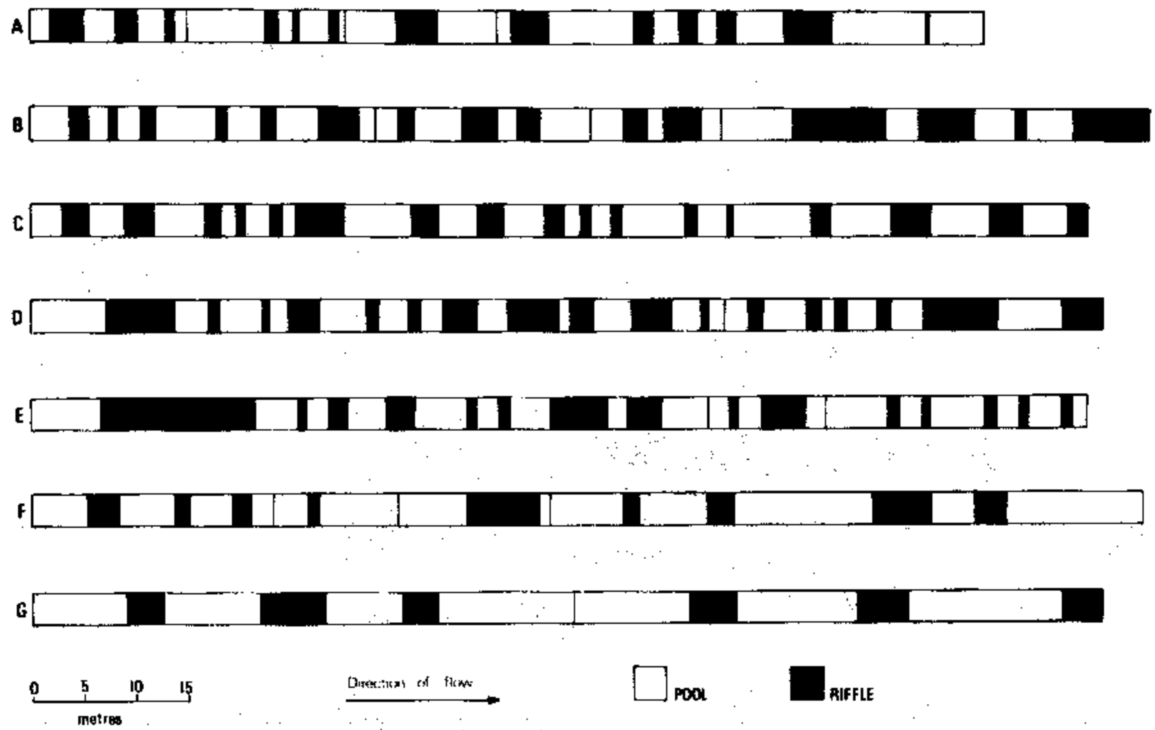


FIGURE 5 Diagrammatic representation of pool anf riffle sequences in the Severn *(after J Groves)*.

2.8 Drainage ditches

Open ditches are mainly associated with the afforestation of the Severn catchment (Plate 12); in the Wye some were dug but were found to be a danger to livestock and abandoned. The depth of drainage ditches is largely determined by the capacity of the ploughing equipment and the position of bedrock relative to the surface. In the deeper peats of the Severn catchment, some of the ditches are as much as 1.5 m deep. Alignment of the herringbone pattern drains is usually made as close to the contour as possible whilst retaining a sufficiently steep gradient to prevent silting-up and vegetation growth. Theoretically a slight scouring action keeps the drain clear without causing erosional damage. In practice, severe erosion has occurred in much of the network, especially in main drains leading directly downslope through podzol soils. In some of the flatter, basin areas, however, insufficient gradient has meant that ditches have become overgrown, causing a rise in water-table and the stunting of trees.

Drain spacing is primarily a function of slope. Design recommendations are:

Ground slope (degrees)	Drain Interval (metres)
0-2	20-25
2-4	25-35
4-6	35-50

(Everard & Fourt, 1971)

Prior to planting, the ground area between main drains is usually ploughed into furrows and mounds. The mounds are used as nursery beds for the young trees and furrows act as collecting lines for the removal of water.

PLATE 12

Forest ditch in good condition, Hafren Forest.

The furrows are usually aligned up and down the slope leading into the network of deeper drains which, in turn, lead the water into natural courses. For example, the flushes of the Severn catchment have been utilised by digging them out.

As trees mature the shallow, closely spaced, planting furrows become less and less effective and it is the deeper, permanent drains which continue to remove excess water.

The hydrological performance of forest drains clearly varies throughout the crop cycle. Large amounts of stored peaty water are released during early draining; natural floods may be exaccerbated. Later a storage capacity is produced by the new lower water table and finally canopy closure leads to lower net rainfall. All these effects are under investigation.

Hafren Forest is widely quoted as an extreme case of forest drainage - the steeper slopes of Snowdonia and South Wales are quoted by foresters as the reason for the lower density of drainage in other upland parts of Wales.

A network of old open drains, originally 1.0 m deep and of similar width, can still be seen on the Cyff valley floor. The drains were dug to improve the pasture in an extensive valley bottom bog. However the low-gradient drains have not been maintained and are now largely overgrown. Inevitably the water table has risen although the original peat-forming vegetation is partially excluded by occasional burning.

3. BANKFULL CAPACITY AND GEOMETRY OF OPEN CHANNELS

The survey work described in Section 1.2, using the boom apparatus to define channel cross-sections, was conducted as follows. At approximately 100 m intervals (Figure 6) the channel-full dimensions were established. Stratification of sampling by normal fluvial features (eg. pools only, riffles only) and strict adherance to 100 m interval proved impossible due to the irregularity of Plynlimon channel form.

From "en-prints" of each camera shot, numbered and mounted in a file, dimensions were copied into digital form. The following indices were evaluated:

1. Bankfull width of channel
2. Average depth of channel
3. Standard deviation of individual depth measurements (as an index of x-section roughness)
4. Wetted perimeter of channel

5. Hydraulic radius
6. Cross-sectional area of channel
7. Distance downstream of station) from Huntings 1:5,000 maps
8. Gradient of channel at station)
9. A combination of (7) and (8) in Hack's SL index ($SL = \frac{\Delta H \times L}{\Delta L}$, Hack 1973)
10. Catchment area to station

An immediate calculation from this basic information which is of interest to quantitative studies of runoff is the total surface area of open natural channels at bankfull. This was obtained by treating the channel width measurements as representative of the inter-station length.

Severn .033 km^2 (0.4% catchment area)
Wye .050 km^2 (0.5% catchment area)

Clearly only very small areas produce runoff from "channel precipitation" although in flood conditions 25 mm of rain in an hour over the channels alone would lead to an average increase in discharge of .229 cumecs in the Severn and .347 cumecs in the Wye. Channel precipitation is obviously capable, therefore, of causing small hydrographs independent of catchment slope runoff.

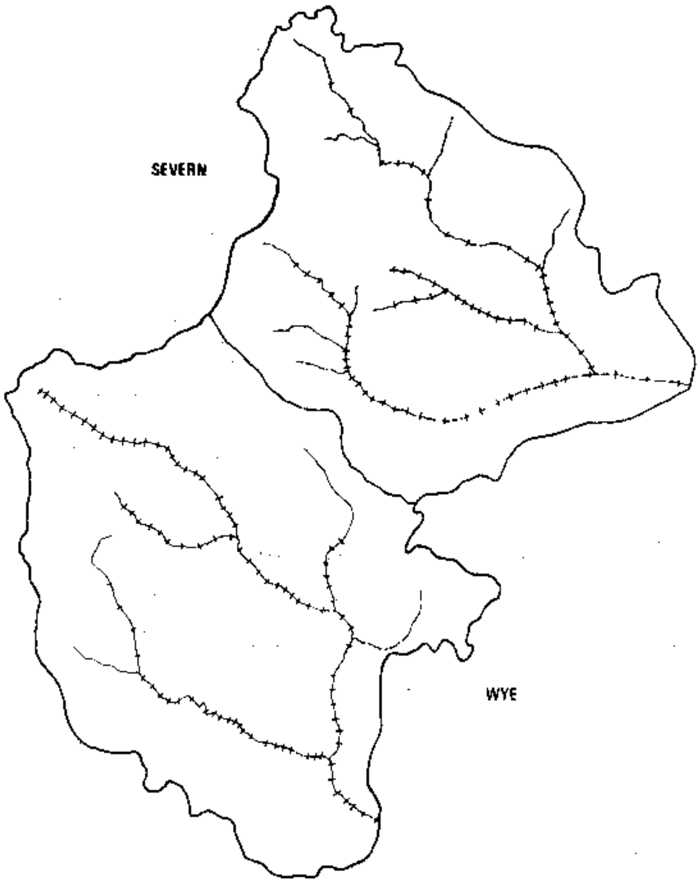


FIGURE 6 Sample cross-section sites used in analyses; 90 stations were measured in the Wye, 57 in the Severn.

3.1 Statistical analysis

Indices 1-10 were set up as a file for analysis by the ASCOP statistical package running on the Univac system at the Institute. Logarithmic transformation of variables gave the correlation and regression relationships shown in Tables 2 and 3. Histograms of the transformed variables confirm the normalizing effect.

Many of the high correlation coefficients present in Table 2 result from the use of the two basic dimensions of depth and width to calculate other indices. For the moment, interest is focused upon the relationships of channel variables with catchment area.

Bankfull channel cross-sectional area is well related to catchment area (distance downstream is almost interchangeable with catchment area). An even stronger relationship results from smoothing the x-sectional data by running averages in steps of five stations. (The influence of the extreme variability of sites is reduced rather than removed with this step-length). However, the components of cross-sectional area vary in their contribution to this relationship. Width is significantly correlated with catchment area at .01 whereas depth is not. In fact depth is not related to any other index in which it does not participate as a dimension. A basic factor involved is bedrock control - increases in depth downstream are impeded by bedrock bars across the channel controlling flow. Another reason for upstream depths appearing equal to downstream is that with steep, active bounding slopes and peaty valley-bottom materials, incised, steep-walled channels are normal upstream (see section 2.3).

No significant relationship exists between the standard deviation of depth measurements across the channel and catchment area, again because of bedrock domination throughout; in other words, a highly irregular bedrock or boulder obstruction is likely at all sites in the sampled channels. (Miss Groves found no downstream pattern to Mannings 'n' calculated at various stations on the Severn). Gradient has a strong negative relationship with catchment area as might be expected.

Table 3 shows regression relationships developed around the major correlations of significance.

TABLE 3 CHANNEL CAPACITY AND SHAPE REGRESSIONS

CHAN AREA*	= 1.66 CATCH. AREA $^{0.52}$		(r^2 = 0.545)
	(t = 10.93)	(t = 12.23)	
WIDTH	= 2.40 CATCH. AREA $^{0.42}$		(r^2 = 0.635)
	(t = 176.66)	(t = 14.73)	
MEAN DEPTH	= 1.87 CATCH. AREA $^{0.07}$		(r^2 = 0.023)
	(t = 98.94)	(t = 1.71)	

(* *Smoothed as described*)

TABLE 2 CHANNEL INDICES - CORRELATION COEFFICIENTS

	CATCH AREA	DISTANCE	SLOPE	SL. INDEX	CH. WIDTH	CH. DEPTH (MEAN)	ST. DEV. DEPTH	WETTED PERIMETER	HYDRAULIC RADIUS	CHAN. AREA
CATCH AREA		.946	-.684	-.199	.797	.151	.033	.816	.410	.738
DISTANCE			-.726	-.215	.711	.171	.037	.749	.437	.714
SLOPE				.827	-.524	-.170	-.042	-.563	-.246	-.468
SL. INDEX					-.159	-.092	-.028	-.182	.007	-.104
CH. WIDTH						.015	.087	.916	.171	.712
CH. DEPTH (MEAN)							-.004	.215	.801	.620
ST. DEV. DEPTH								.138	.108	.148
WETTED PERIMETER									.366	.820
HYDRAULIC RADIUS										.832
CHAN. AREA										

Sample size n - 127
r = 0.230 significant at .01 (**solid** underline)
r = 0.176 significant at .05 (**broken** underline)

3.2 Graphical analysis

The use of a log-linear regression model may reduce the amount of information in the sample. Non-linearities of channel behaviour with increasing catchment area may yield insights to the location of source-areas for flood runoff. Therefore, data for individual subcatchments were treated graphically to investigate the detailed relationship between channel x-sectional area and catchment area. Running averages in steps of five stations were used because of the advantages referred to above.

The results are depicted in Figure 7a, b and c. The immediate impression is of irregularity of the development of bankfull channel capacity in relation to catchment area, even after smoothing. Whilst total data (a) exhibit scatter, when labelled by tributary (b and c) the individual components of scatter can be sketched in (with a series of straight-line links for clarity).

Nowhere is the increase in channel x-section smooth. Some channels appear to show an 'S'-shaped relationship, x-sectional area increasing slowly at the top and bottom of the catchment (see Hore, Cyff and, to some extent, Wye). This is not a gradient effect.

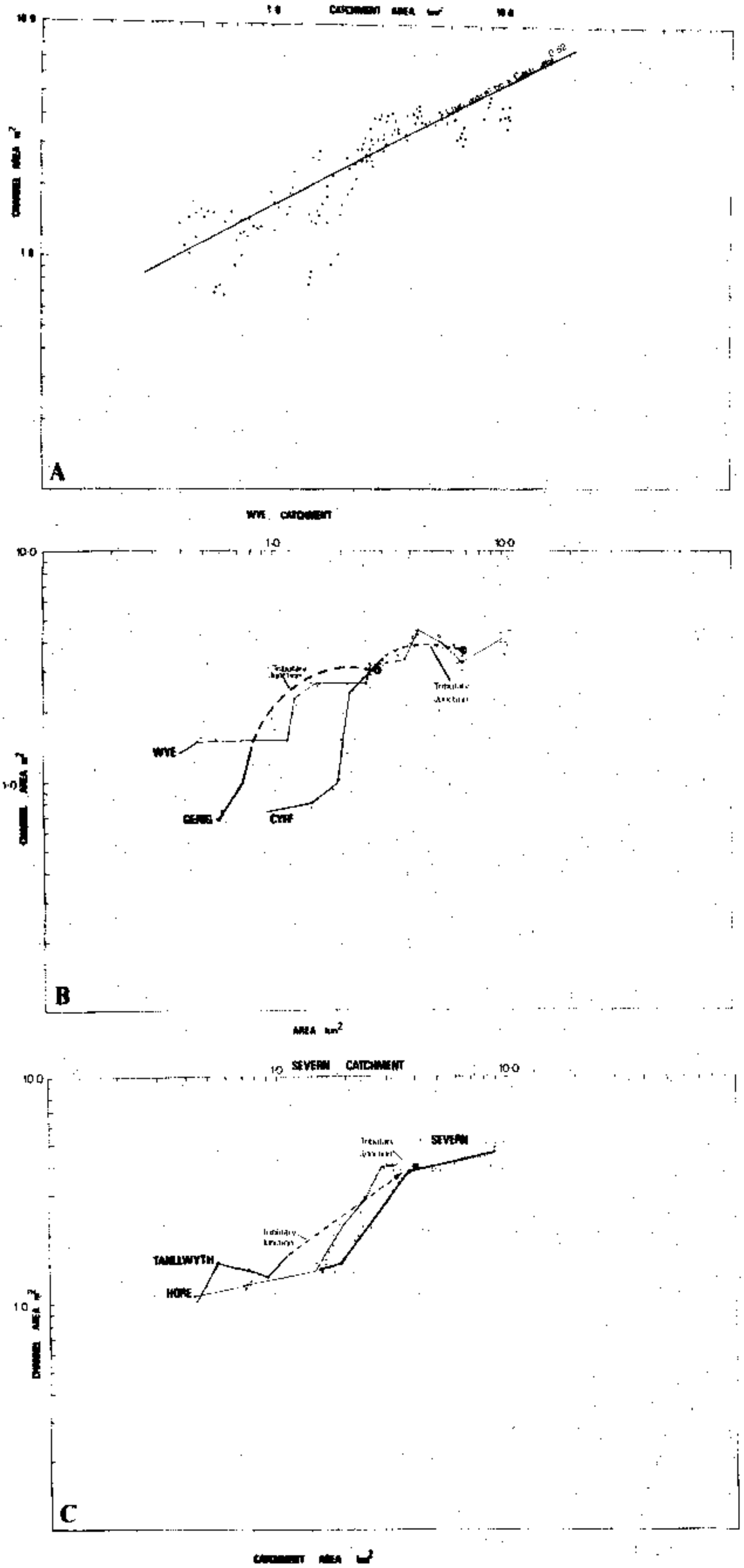


FIGURE 7 The relationship between channel capacity at bankfull (X-sect. area) and catchment area. A. All data, log-linear equation B. Wye catchment, lines by eye C. Severn catchment, lines by eye.

The two Wye tributaries shown, the Gerig and the Cyff, have much smaller channels in their headwaters than the mainstream Wye but quickly reach the same size as the Wye at the equivalent catchment area.

In the Severn the Hore tributary has a larger channel in its middle section than the Severn but the trend changes to give a similar ratio of channel x-section to catchment area just before it enters the Severn. Data for the Tanllwyth are suspect due to forest drainage.

The changing rate of x-sectional response to catchment area may be the result of three factors:

(1) Channel-full discharge may not occur with the same frequency throughout the system,
(2) If it does, the volume of runoff which source areas contribute to the channel-full flood may vary,
(3) Variations in channel gradient, and hence velocity, the other component of discharge, may influence cross-sectional area.

Of the three, (1) has been largely discounted by observation, (2) seems reasonable when the importance of "wet" areas in the catchments is assessed and (3) can be proved of some influence when the negative correlation of channel area and slope ($r = -0.488$) is obtained.

Assuming varying flood frequency to have negligible effect and slope to explain only a small part, one can relate the build-up of channel capacity to the build-up of flows during channel-full floods. In this case the extensive mid-catchment valley-bottom mires, closely approximating the partial contributing area of both Severn and Wye are the ready explanation.

There remains, of course, a fourth possible explanation:

(4) "Noise" introduced by bedrock control of channel size, or by controls of bank erosion by the materials present (Miss Groves however, found that Schumm's (1963) relationship for channel shape based on silt/clay ratios in bank materials did not hold in the Severn although silt/clay ratios are impossible to calculate for peat). (Vegetation, say Zimmerman *et al.*, 1967, may also have an effect). Further smoothing might remove this but has not been considered at this stage. The Wye main channel data are, however, very "noisy".

3.3 Relationship with general hydraulic geometries

The keynote of the above conclusions is irregularity, whilst that of conventional channel geomorphology is predictability. Over two decades of work on more regular rivers (and at much larger scales) have established relationships which have allowed Dury to describe a stereotype humid-zone channel (1976). His paper provides an ideal summary.

Thornes (1974) warns that "we should however..... be intuitively suspicious of the hydraulic geometry framework, at least in the spatial model (downstream)". He gives two main reasons:-

a) Mostly the observations are lumped from many catchments rather than being made truly downstream,

b) steady state may prevail in the channel system as a whole but transient or "explosive" behaviour is possible in any variable.

Thornes' own work centres on the oscillatory behaviour of channel width, discovered by abandoning the conventional approach. Thus Thornes would claim that the regularities of channel adjustment so widely quantified may be due in part to adherance to the conventional power-function model. (It is for this reason that the limited investigation of alternative patterns was conducted in 3.2).

Returning to that conventional power-function approach, how do the Plynlimon regressions compare with others? The only comparable work in upland British catchments is by Park, (1975, 1976), although even that is larger in scale - 50 sites in the 40 km^2 catchment of the Dart in mid-Devon. His results (Park, 1975, Table 3) show much stronger relationships with catchment area than shown by Table 3 in this report, coefficients of determination being 66%, 71% and 38% for channel area, width and mean depth, compared with 55%, 64% and 2% here. The mean depth relationship is much stronger for the Dart (Park describes a mainly gravel bed, not rock or boulders as at Plynlimon).

Park's 1976 contribution is to examine the relationship between catchment area and channel capacity (x-sectional area) once the latter is standardized for channel slope, the dominant secondary factor.

Perhaps the key to Plynlimon channel geometry is provided by Knighton (1975) who looks at deviations from conventional hydraulic geometry both in the downstream and at-a-station senses. He worked in the Bollin catchment, Cheshire (over 250 km^2). He attributed to boundary geology an importance not found in reports dealing solely with discharge (or a surrogate for it such as catchment area). "Discharge determined the magnitude of the channel and hydraulic variables but not to the extent that a fixed set of values characterized cross-sections within a short length of stream". "There is a danger in making generalizations from empirical regularities which, when examined in detail, are non-regular".

Thus, unlike Thornes' doubts about the concept of power functions, Knighton finds them to hold (they are similar for the Bollin and Brandywine Creek, worked on by Wolman, 1955) for a mean state (equilibrium) but does not find the mean state present throughout the Bollin. Plynlimon results can therefore be interpreted as exhibiting even more variation about the mean state as a result of control by bedrock or large detached boulders (see Wilcock's 1967 paper describing their effect on bed-slope). The major systematic departure from the mean state is the low sensitivity of depth and the increased sensitivity of width. The latter is, however, also constrained by the variable materials, mass-movements and time-scales of the bordering slopes at Plynlimon. Finally, the spatial variability of runoff production in the small source area catchments studied may also be a more powerful influence than is obvious in the data collected by workers in larger catchments.

4. HYDRAULICS OF OPEN CHANNELS

Modelling the development and passage of a flood wave requires a method of channel routing, as well as runoff information from source areas. Hydrologic and hydraulic methods are available. Hydrologic methods treat the channel as a computable storage; hydraulic methods use theoretical knowledge of flow processes. Hydrologic calculations based upon successive gauging stations are possible at Plynlimon (Gwy and Hafren have, at some stage, had three gauging stations) but more detail is required about local storages.

The hydraulic methods employ general channel relationships and Section 3 shows that departures from normal are a feature of Plynlimon channels. Consequently some specific research was required.

Since the ethos of the work contained here is simplicity of calibration for a model to predict flows in the ungauged situation, it was decided to maintain the "state-discharge" approach used to model storages and flows from runoff domains in the slope phase.

It is also thought to be particularly appropriate to Plynlimon's rough, steep channels where fall-and-pool sequences are clear evidence of the geological (ie. random) control of depth changes. Hence storage-dominant channel types are more common than in the equilibrium channels of conventional hydraulic models.

4.1 Hydraulic geometry and storage/routing

To assess the storage capacity of a channel reach requires simultaneous channel survey and discharge measurements made in a variety of discharge conditions. Consequently a field study based on reaches of the Severn was initiated, the reaches being around 50 m in length and marked by pegs, with permanent gauge boards at their lower ends. Further subdivision into 10 subreaches of 5 m length has been used for cross-sectional measurement of total storage. The Severn was chosen for ease of access. Within the Severn, the sites were chosen to sample the major types of open channel (see Section 2). The chosen reaches are depicted on Figure 8 with photographs in Plates 8, 9, 10, 11, 13, 14, 15. Table 4 briefly describes their characteristics. A further location consideration was proximity to a permanent gauging-station to check on salt and dye dilution work in view of their error tendencies.

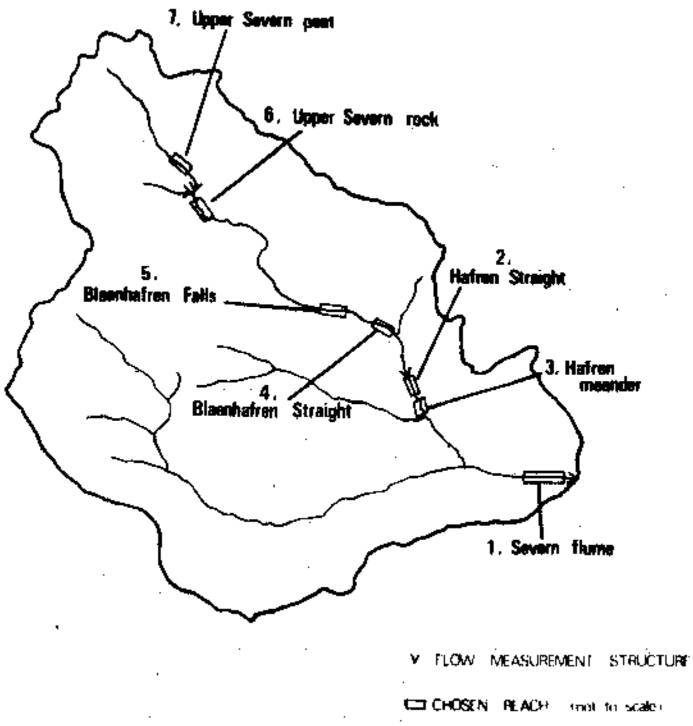


FIGURE 8 The experimental reaches of the Severn

TABLE 4 REACHES OF THE SEVERN SELECTED FOR STORAGE STUDIES

No.	SITE NAME	CHARACTERISTICS	CHECK GAUGE
1.	Severn flume	Straight, bedrock controlled, shallow pool and fall sequence	Severn flume
2.	Hafren straight	Straight reach with peaty banks and cobble bed	Hafren flume
3.	Hafren meander	Reach on river bend with same characteristics as 2.	Hafren flume
4.	Blaenhafren Straight	Large boulders line bed and banks	---- } interpolation
5.	Blaenhafren falls	Spectacular series of waterfalls and plunge pools	---- } interpolation
6.	Upper Severn rock	Bedrock controlled reach - straight	Upper Severn and Nant Arwystli weirs
7.	Upper Severn peat	Deeply incised peat-walled channel, sinuous and partly roofed	Upper Severn weir

PLATE 13

The Upper Severn (rock) reach No. 6.

PLATE 14

The Hafren (straight) reach No. 2.

PLATE 15

The Severn flume reach No. 1.

Using a team of two it is just possible to complete a dilution gauging of all reaches in a day, hopefully at steady flow conditions. Help is gratefully acknowledged to teams from the University of East Anglia, and the Swindon Branch of the British Association of Young Scientists for making intensive spells of this work possible. Since full channel survey (of the 10 x 5 m sub-reaches) is not possible at the same time, a reference cross-section is surveyed at the bottom of the reach. Full survey of the reach was performed twice (at low flows), using level, staff, tape and metre rule. At one high flow the water surface was marked with tent pegs tied to the marker pegs on each bank. However, the post-flood surveys of the marks, and the reaches themselves, were ruined by the flood of 15.8.77. Apart from these three occasions, photographs taken of the reaches on every gauging run have been used to assess changes in flow pattern and storage.

Eight separate runs have so far been made, covering a range of flows at the Severn flume from 0.031 cumecs to 1.479 cumecs.

4.2 Results - hydraulic geometry

Whilst the main aim of the separate reach investigation was to develop channel routing procedures it also yielded further information on the geometry of channels. Since, in this case, flow prevailing at the time of survey defined the channel (rather than the notional formative discharge at bankfull), "at-a-station" changes in width and depth are measurable as well as downstream variations, and mean velocity is added as a variable instead of the surrogate of channel gradient in the bankfull study.

As was the case in connection with the bankfull study (Section 3), upland channels have seldom been investigated before. Keith Beven (1976) states:

"The problem of defining flow relationships for the shallow, rocky, steep, irregular channels that are common to most British upland catchments has been neglected in the past study of open channel flow".

Figures 9a, b and c show the conventional log/log plots of width, depth and velocity against discharge for the seven reaches on the Severn. One does not expect the exponents of the fitted lines to total unity since the velocity is the mean for the reach, not that prevailing in the measured cross-section at the downstream end. However, this does not invalidate comparison of the exponents.

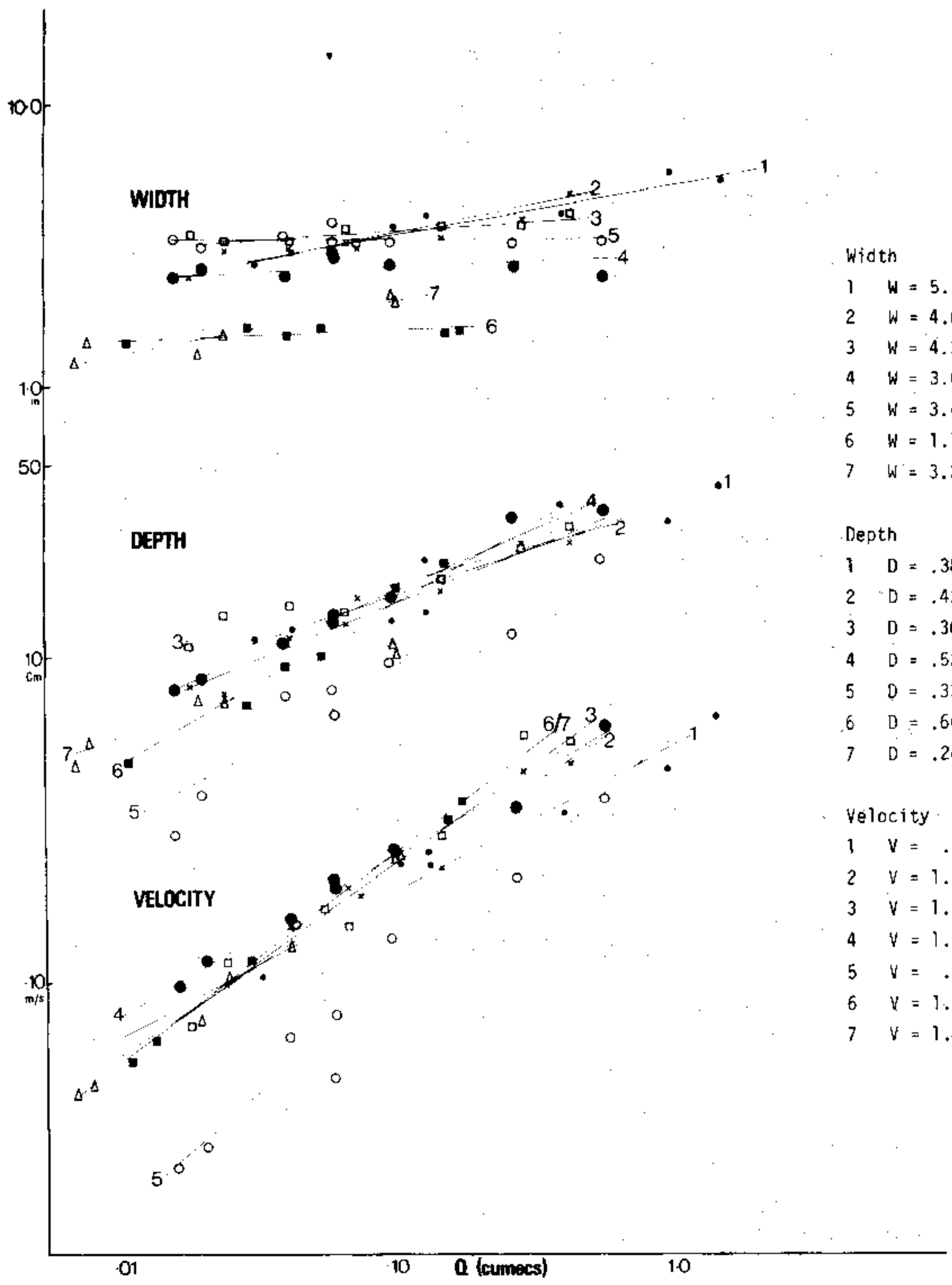
Velocity increases most rapidly during increases in discharge, width least. Average exponents are .699 for velocity, .427 for depth and .099 for width.

Plates 16a, b and c show how channel irregularities become progressively drowned out in a typical bedrock channel. The reasons for increasing depth, rather than width, at higher discharges are obvious from channel shape. The rise of velocity is a corollary of depth increases and the drowning of resistances to flow.

Variability between reaches is not regarded as significant although it is interesting that velocity changes are most significant on the subjectively 'rough' reaches, especially reach 5, Blaenhafren Falls. Thus the average exponent for reaches below the Falls is .576 whereas above them it is .811 - this difference is returned to in Section 4.4.

4.3 Results - storage/routing

The conventional approach to flow routing has been to derive roughness indices for channel reaches to use as constants. The use of Manning's 'n' is now open to doubt on theoretical grounds but Beven (1976) has shown that the more robust Darcy-Weisbach flow formula also produces misleading values in very rough channels. At low flows the resistance parameter calculated is very high indeed since it also includes the effects of distortions to flow caused by the irregularities of fall and pool sequences, bends etc. There are doubts about the values of Darcy-Weisbach 'f' at high flows too, but generally the drowning out of most of the irregularities is thought to improve the derived values.



Width

1	$W = 5.53\ Q^{.188}$	$r = .99$
2	$W = 4.60\ Q^{.140}$	$r = .95$
3	$W = 4.34\ Q^{.073}$	$r = .84$
4	$W = 3.04\ Q^{.059}$	$r = .80$
5	$W = 3.45\ Q^{.007}$	$r = .13$
6	$W = 1.75\ Q^{.041}$	$r = .76$
7	$W = 3.24\ Q^{.199}$	$r = .98$

Depth

1	$D = .38\ Q^{.346}$	$r = .98$
2	$D = .42\ Q^{.419}$	$r = .97$
3	$D = .36\ Q^{.282}$	$r = .97$
4	$D = .52\ Q^{.454}$	$r = .99$
5	$D = .33\ Q^{.571}$	$r = .96$
6	$D = .60\ Q^{.587}$	$r = .96$
7	$D = .24\ Q^{.333}$	$r = .98$

Velocity

1	$V = .71\ Q^{.495}$	$r = .98$
2	$V = 1.13\ Q^{.655}$	$r = .99$
3	$V = 1.49\ Q^{.731}$	$r = .97$
4	$V = 1.10\ Q^{.577}$	$r = .99$
5	$V = .82\ Q^{.870}$	$r = .98$
6	$V = 1.79\ Q^{.780}$	$r = .99$
7	$V = 1.81\ Q^{.782}$	$r = .99$

FIGURE 9 Hydraulic geometry/discharge relationships for selected Severn reaches: A water surface width } B average depth } at the reach outlet; C mean velocity for the reach

PLATE 16 The progressive 'drowning' of bedrock control on the reach above the Severn flume between flows of .122 cumecs (A) and 2.328 cumecs (C).

All methods of channel flow parameterization are dependent on gauging and survey, both of which are beset by practical problems in very rough, upland channels. However, the use of gulp dilution techniques (well suited to turbulent streams) provides a unique opportunity to directly assess storage in the chosen reach. Assuming complete mixing, the output graphs of salt or dye concentrations will represent the output trace of water storage. This we may call dynamic storage ("active storage" - Dovey) since it does not include "dead" water - water not participating in channel flow during the time of the dilution gauging. We can either use the curve's parameters or integrate it to give discharge, mean residence time and their product, dynamic storage volume (assuming a linear reservoir).

The other major line of approach is to sample actual storage volumes in the reach, total storage, by cross-sectional survey at the time a discharge measurement is made. Ideally the survey would be simultaneous with a dilution test but in practice this is not possible for a study of seven reaches! The present study has been restricted to two full surveys by cross-sectioning. A sample cross-section at 5 m intervals in a 50 m reach has been considered adequate on subjective grounds. A longitudinal section of each reach has also been compiled. The results from an example of total storage survey are shown in Figure 10 and Table 5.

TABLE 5 AN EXAMPLE OF TOTAL STORAGE CALCULATION FROM SURVEY

b) Calculation of volume of total storage in reach.
Areas of cross-sections, taken from Figure 10:

Cross-section 1, area =	.04(2.73) = .1092 m^2	
2	.04(3.21) = .1284 m^2	
3	.04(7.81) = .3124 m^2	
4	.04(6.46) = .2584 m^2	
5	.04(3.03) = .1212 m^2	
6	.04(0.53) = .0212 m^2	
7	.04(3.50) = .1400 m^2	
8	.04(3.98) = .1592 m^2	
9	.04(2.93) = .1172 m^2	
10	.04(18.34) = .7336 m^2	
11	.04(1.20) = .0480 m^2	

Taking each as representing 2.5 metres either side of the site:

Volume in reach = 2.5(.1092) + 5(.1284) + 5(.3124) + 5(.2584) + 5(.1212) +5(.0212) + 5(.1400) + 5(.1592) + 5(.1172) + 5(.7336) +2.5(.0480)

= 10.351 = 10.4 m^3

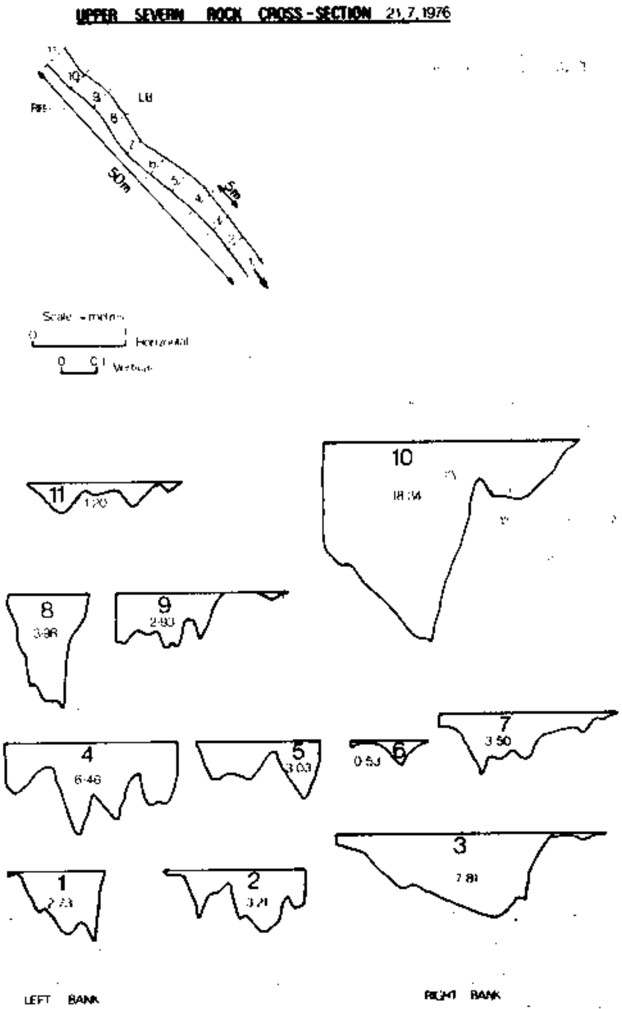


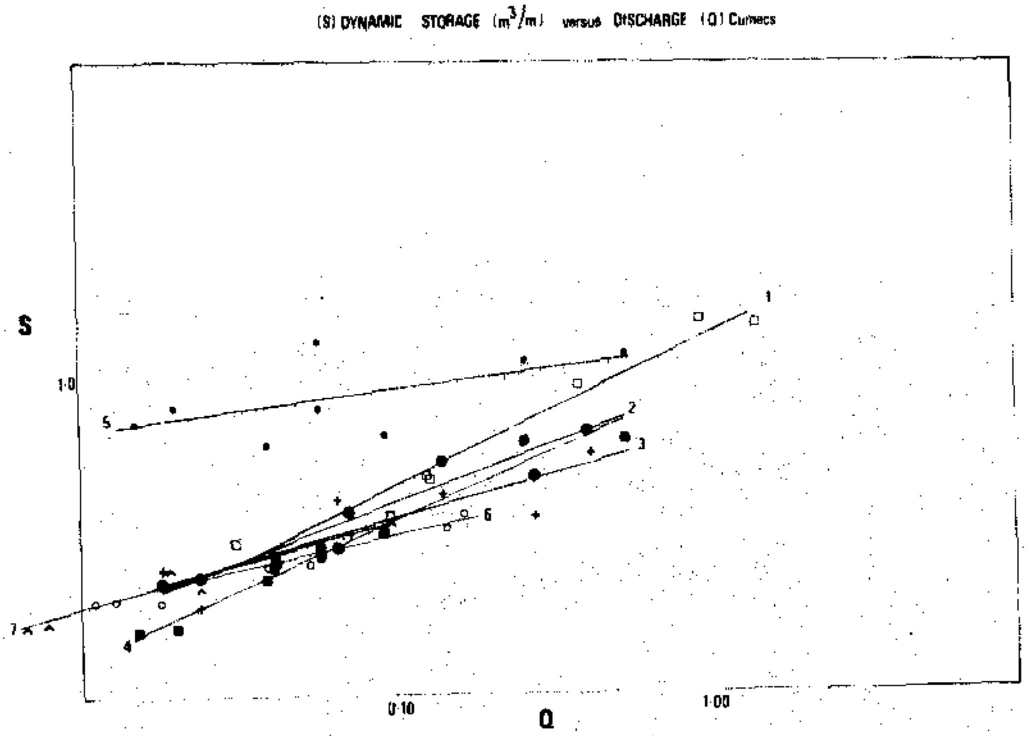
FIGURE 10 An example of reach surveys to determine 'total' storage, Upper Severn (rock), surveyed 21.7.76

Using 'bulk' calculations of storage first, the relationships with discharge for all seven reaches are shown for dynamic storage and for total storage in Table 6. Figure 11 shows the dynamic storage v. discharge plots.

TABLE 6 STORAGE/DISCHARGE REGRESSIONS *(after Dovey)*

	Dynamic storage	Total storage
Reach 1	$S = 1.3275\ Q^{0.5938}$	$S = 3.2874\ Q^{0.4777}$
2	$S = 3.0657\ Q^{0.3993}$	$S = 2.9313\ Q^{0.4585}$
3	$S = 3.9192\ Q^{0.3205}$	$S = 1.0012\ Q^{0.6383}$
4	$S = 1.4140\ Q^{0.5337}$	$S = 1.9512\ Q^{0.4999}$
5	$S = 16.1399\ Q^{0.1755}$	$S = 23.9034\ Q^{0.1200}$
6	$S = 3.1492\ Q^{0.3247}$	$S = 3.7241\ Q^{0.3183}$
7	$S = 2.1333\ Q^{0.5134}$	$S = 2.2439\ Q^{0.2789}$

(Storage here in m^3 for the whole 50 m reach, discharge in litres/sec)



1 $S = 1.353\ Q^{.[illegible]7[illegible]}$ $r = .93$

2 $S = .896\ Q^{.3495}$ $r = .97$

3 $S = .656\ Q^{.2655}$ $r = .85$

4 $S = .920\ Q^{.4188}$ $r = .99$

5 $S = 1.218\ Q^{.1270}$ $r = .56$

6 $S = .512\ Q^{.2132}$ $r = .96$

7 $S = .633\ Q^{.2580}$ $r = .97$

FIGURE 11 Dynamic storage, related to discharge for the 7 chosen reaches

Total storages, (interpolated for several dilution tests when they were not surveyed) were used by Dovey in his dissertation as the basis of a routing technique for the Severn. He proved that percentage errors introduced to downstream hydrograph peaks by routing with the "wrong" reach's storage relationship decline markedly at higher flows (Figure 12). Of course, absolute errors increase because of the higher output discharges. He also pointed out that the shape of hydrographs is an important aim of the total catchment model to which channel storage is to be appended. Hydrograph shape is even more sensitive to the correct storage relationship and investigation of a model efficiency index showed this to be so.

Dovey's pioneering use of the surveyed total storage relationship did not investigate the use of dynamic storage as an alternative but it seems that at high flows the amount of "dead" water in each reach is proportionally lower and hence dynamic storage approximates total storage.

Attempts to extend the comparison of total and dynamic storage to high discharges to study the convergence of their values have been frustrated by the difficulty of making measurements of total storages during floods. Having perfected the method of 'tent-pegs and string', followed by post-flood surveys, the very severe flood of August 15th 1977 altered the configuration of all reaches so drastically that work has been suspended.

We are left with only Dovey's data on which to base a study of the convergence of storages. They were first checked to ensure that, for

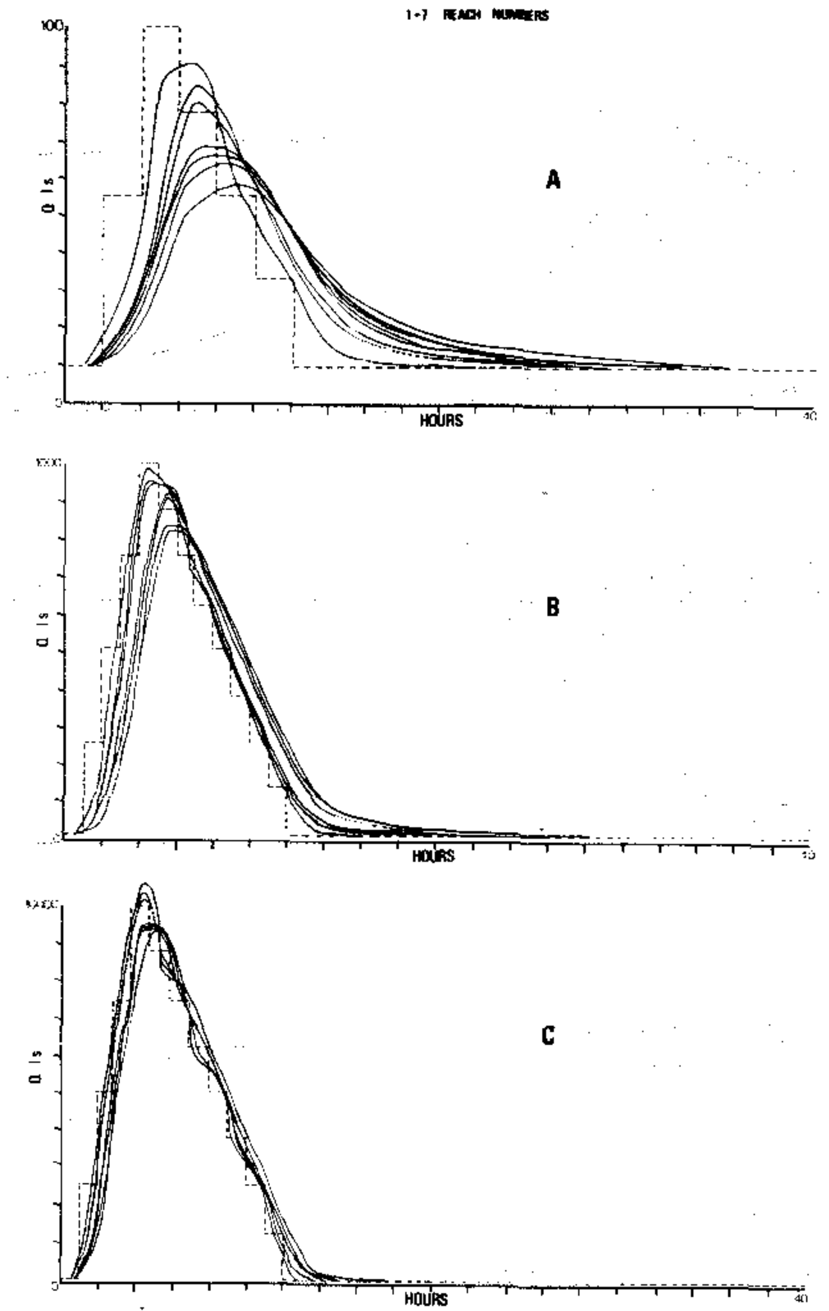


FIGURE 12 Flood routing for the Severn, using the storage coefficients for all 7 reaches, A for a peak input of .1 cumecs, B for one of 1.0 cumecs, and C for one of 10 cumecs

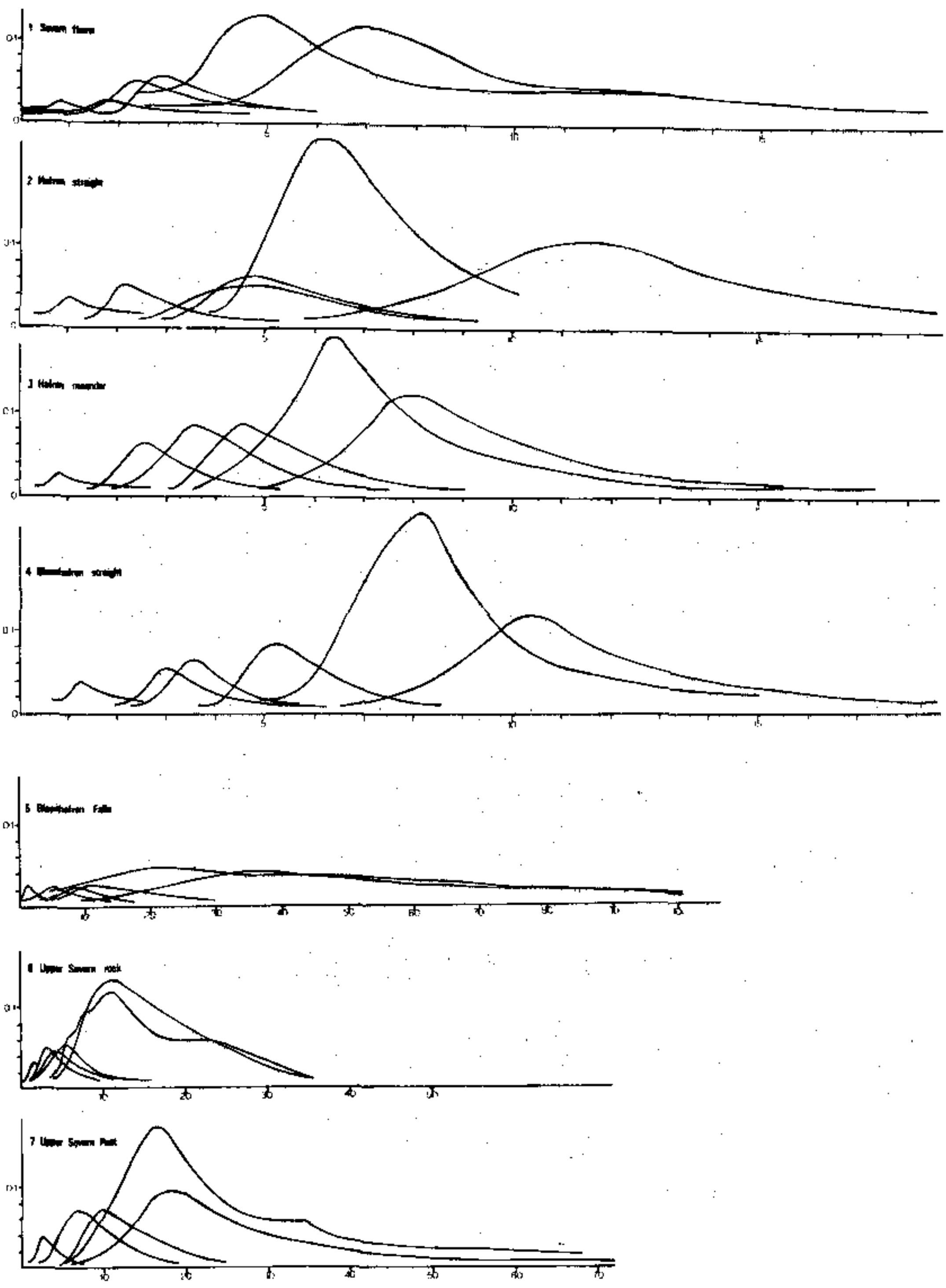
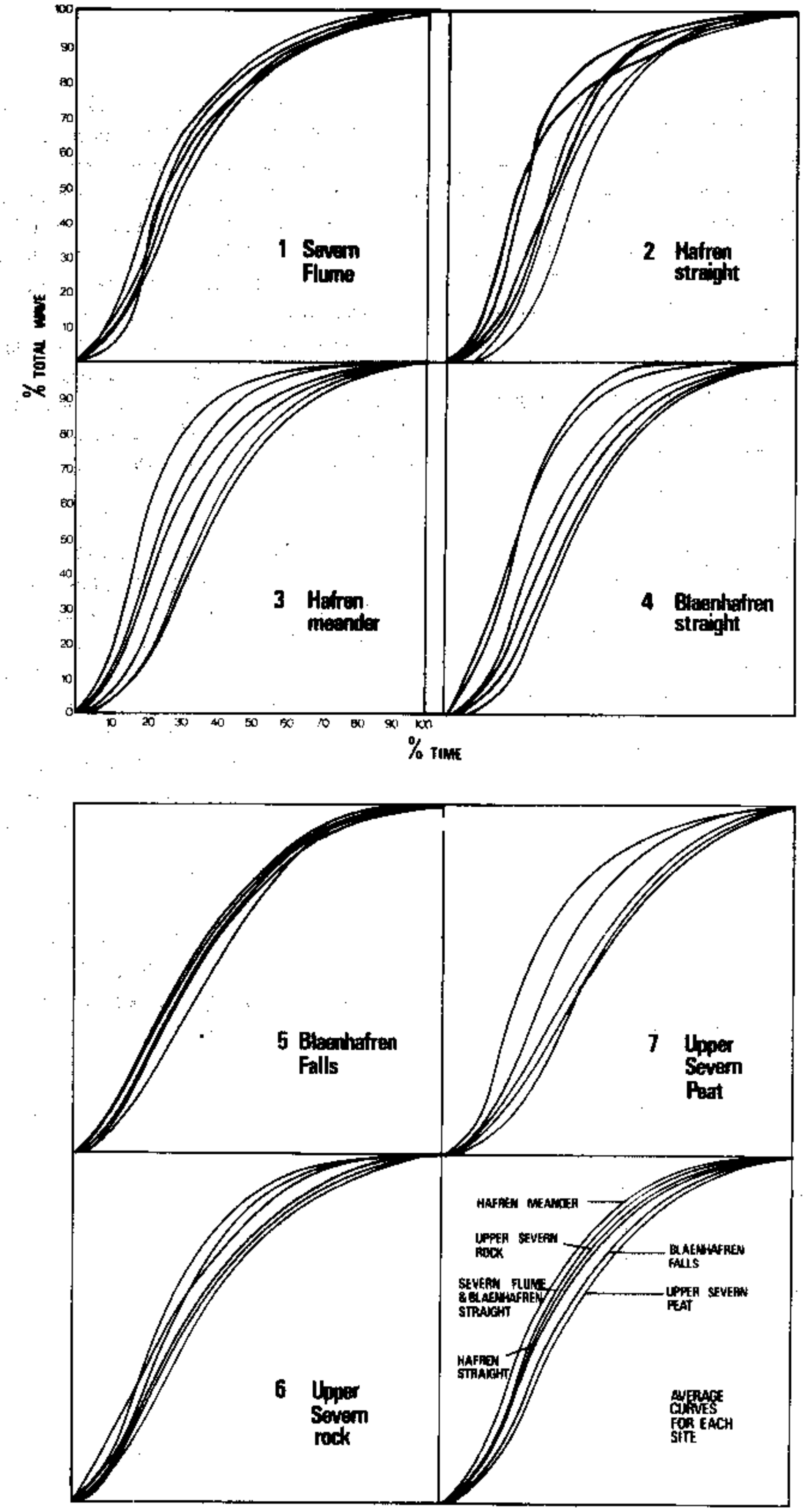


FIGURE 13 Residence time distributions for salt waves
(a) Using field curves with standard salt solution
(b) dimensionless and average curves



(b) Dimensionless and average curves

the two survey runs performed at differing discharges, the volumes of 'dead' storage (total minus dynamic) were approximately the same. Only in Reach One was this condition fulfilled; in three reaches negative amounts of 'dead' storage were calculated, invalidating the comparison. Consequently when plotting Dovey's regressions for total and dynamic storage the range of convergence values was from .015 cumecs to over 1000 cumecs and, irrespective of errors of measurement, it is obvious that the two storages are so similar in trend that the point of convergence will be a very unstable one. Using the best data available (those for Reach One) it does, however, appear valid to consider convergence at quite low discharges (2.3 cumecs for Reach One - mean annual flood 13.5 cumecs). If this is so, the relatively simple assessment of dynamic storage described here will be adequate for flood routing in upland channels.

Turning to Beven's suggestion of using the full 'residence time distribution' (RTD) for routing, Figure 13 shows the output graphs of salt dilution tests on all seven reaches, standardized for a gulp input of 13.6 litres of brine (60 mg/l). Beven suggests that a constant, non-dimensional RTD exists. Figure 13 shows summary ogives of the individual salt traces (representing a good range of flows in each case). Whilst there is variability, much of this may result from errors introduced along the line of calculations - brine recovery, calibration, failure to sample long "tails" etc. Thus, averages for each site were taken (the one anomalous curve for the Severn Flume was omitted); average curves are also shown in Figure 14. Only two distinct features show up - the less "peaky" trace for the very irregular Blaenhafren Falls and Upper Severn Peat and the more "peaky" traces for the other, less irregular reaches. An overall average is also shown in Figure 14. Experimental use of the average RTD for routing has not yet proceded far enough to assess the potential of the method. Attention is also being directed at the variability of the

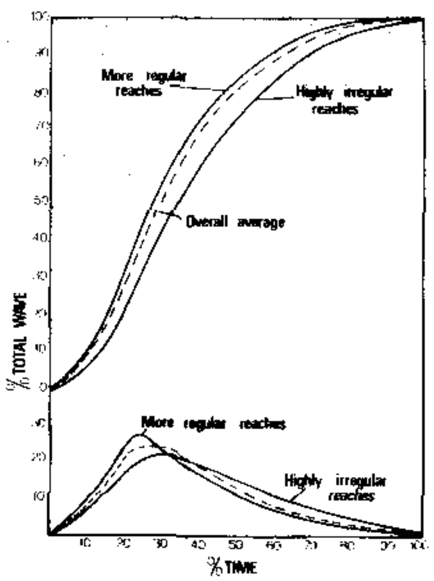


FIGURE 14 Summary of residence time distribution curves

RTD. The peak value of the dimensionless plots in Figure 14, which occurs at around 30% time shows variability of up to ±30% from average. This variability is almost certainly the result of error and of different flow paths being taken at different discharges. Thus the measured 50 m reach can be up to around 75 m in reality when zig-zag flow between obstructions is occurring. The much smaller variability at Blaenhafren Falls, where lateral shifts of flow path are insignificant, backs up this view. Given the above storage/routing information, reach by reach, the question of application is still begged. One could obviously proceed by synthesizing the whole Severn channel using the results for typical reaches and the map in Figure 2. Figure 2 could also be used to apply the work to tributaries or to the Wye. As for application to other catchments, the field-work involved in channel calibrations of this type compares quite favourably in time and expense with conventional methods for an ungauged catchment. Clearly dilution tests are ideal to establish a wide range of flow and channel information. The precise mode of application must await full trials of the channel section of an operational model and these are continuing at the time of writing.

4.4 Time-of-travel studies

Whilst the United States literature on time-of-travel measurements is voluminous there have been few small catchment experiments, most American work referring to long reaches of major rivers as part of pollutant dispersion investigations. By contrast, the work of Pilgrim (1966) on a steep 0.43 km^2 experimental catchment in Australia to examine linearity of catchment response is more appropriate for comparison here. Pilgrim uses radioisotopes of gold and chromium as tracers and argues in favour of the time to peak of output concentration as the time parameter to use in investigating delays between an occurrence of runoff and its maximum contribution to streamflow at the point of interest. However, he advises the use of the centroid of output concentration for the study of storages for routing (see also the views of Calkins and Dunne and Section 4.1 above).

The curves obtained linking time of travel and output discharge for Plynlimon channels (Figure 15) are identical in gross shape to those of Pilgrim, converging to nearly constant values on both axes. The implications are, according to Pilgrim, that the convergent, short, travel times at high discharges represent the catchment's time of concentration, determined by its physiography. He compares the actual minimum time with predictions by well-known formulae; measured times are greater, a fact attributed to channel roughness.

Table 7 compares average unit hydrograph times-to-peak with those predicted by the Flood Study equations and the minimum measured travel times. Whilst times-of-travel are not analogous with hydrograph peaks, the latter being associated with a flood wave, it is unusual to find minimum travel times shorter than hydrograph time-to-peak. Buchanan (1968) quotes flood wave velocities as being 1.3 to 1.7 greater than mean water velocity (although we are here using peaks, not centroids of the dye output to define velocity). In fact,

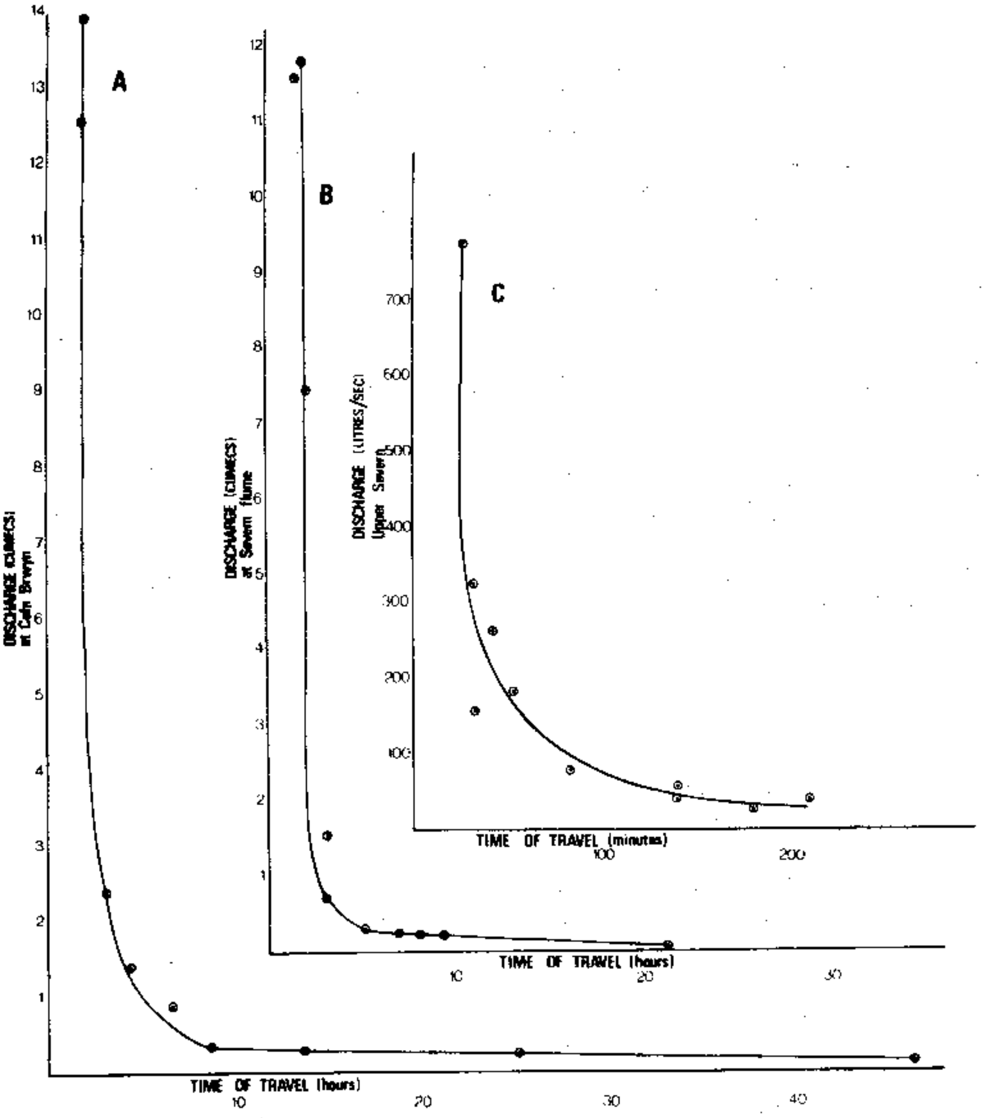


FIGURE 15 Travel time curves for A the Wye and B the Severn experimental catchments, and C the Upper Severn

TABLE 7 TIME-TO-PEAK AND TIME-OF-TRAVEL, PLYNLIMON CATCHMENTS

	SEVERN	WYE
average tp.	2.3 hrs.	2.0 hrs.
predicted tp.	1.9 hrs.	2.6 hrs.
minimum time of travel	1.8 hrs.	1.8 hrs.

recorded times to peak for Wye and Severn can fall significantly below average (minima being 1.0 for the Wye and 1.2 for the Severn).

The anomalies between observed and predicted times to peak - of opposite sign - are possibly the result of land-use differences rather than channel effects. It is noted by Newson (1975, Figure 11) that both Wye and Severn exhibit declining times-to-peak with increasing discharge. Considering the frequent debate concerning the linearity of catchment flood response, it is at least a sign of linearity of the channel phase that a minimum travel time appears to exist for both catchments. The average mean annual flood for the Severn is 13.51 cumecs, for the Wye 16.91 cumecs; it appears that convergence to the minimum time occurs well below these values.

Thus if channel-phase linearity exists, the declining times-to-peak with increasing discharges noted by Newson (1975) must be the result of slope-phase phenomena - this topic is under further investigation. One problem of the unit hydrograph data available is that not enough time-to-peak analyses exist for floods above average mean annual; consequently the existence of a minimum time-to-peak or time of concentration cannot be determined with confidence - there is room here, too, for further study.

To obtain a comparable exponent for travel time versus discharge to those obtained for mean reach velocities in Section 4.1 the travel times were computed as velocities and given a log-log plot in Figure 16. This imparts a false linearity without the prospect of converging minimum travel time (maximum velocity). However, it is instructive to note the higher exponent in the Wye than in the Severn, a result which echoes that for declining times-to-peak already referred to in Newson (1975). The Upper Severn result confirms also that the "rougher" reaches are subject to the most prominent velocity changes.

The latter observation may explain why time-of-travel velocities in the upper and lower parts of both Severn and Wye ("hinges" at Blaenhafren Falls and Gwy Flume, respectively) differ in trend at different flows. Thus Table 8 shows how higher velocities occur in the lower parts of both systems at low to moderate flows, whilst at high flows velocities are higher in the upper parts.

TABLE 8 'SPLIT' TIME-OF-TRAVEL STUDIES, SEVERN AND WYE, SHOWING VELOCITY RATIOS, UPPER/LOWER

WYE					
Discharge Cefn Brwyn (cumecs)	0.287	0.468	0.879	1.324	12.531
Source - Gwy flume (m/s)	0.106	0.153	0.217	0.297	1.186
Gwy flume - Cefn Brwyn (m/s)	0.122	0.244	0.255	0.583	0.611
Velocity ratio	0.869	0.627	0.851	0.509	1.941
SEVERN					
Discharge Severn flume (cumecs)	0.251	1.605	7.460	11.812	
Source - Blaenhafren (m/s)	0.236	0.375	0.658	0.997	
Blaenhafren - flume (m/s)	0.308	0.544	0.619	0.919	
Velocity ratio	0.766	0.689	1.063	1.085	

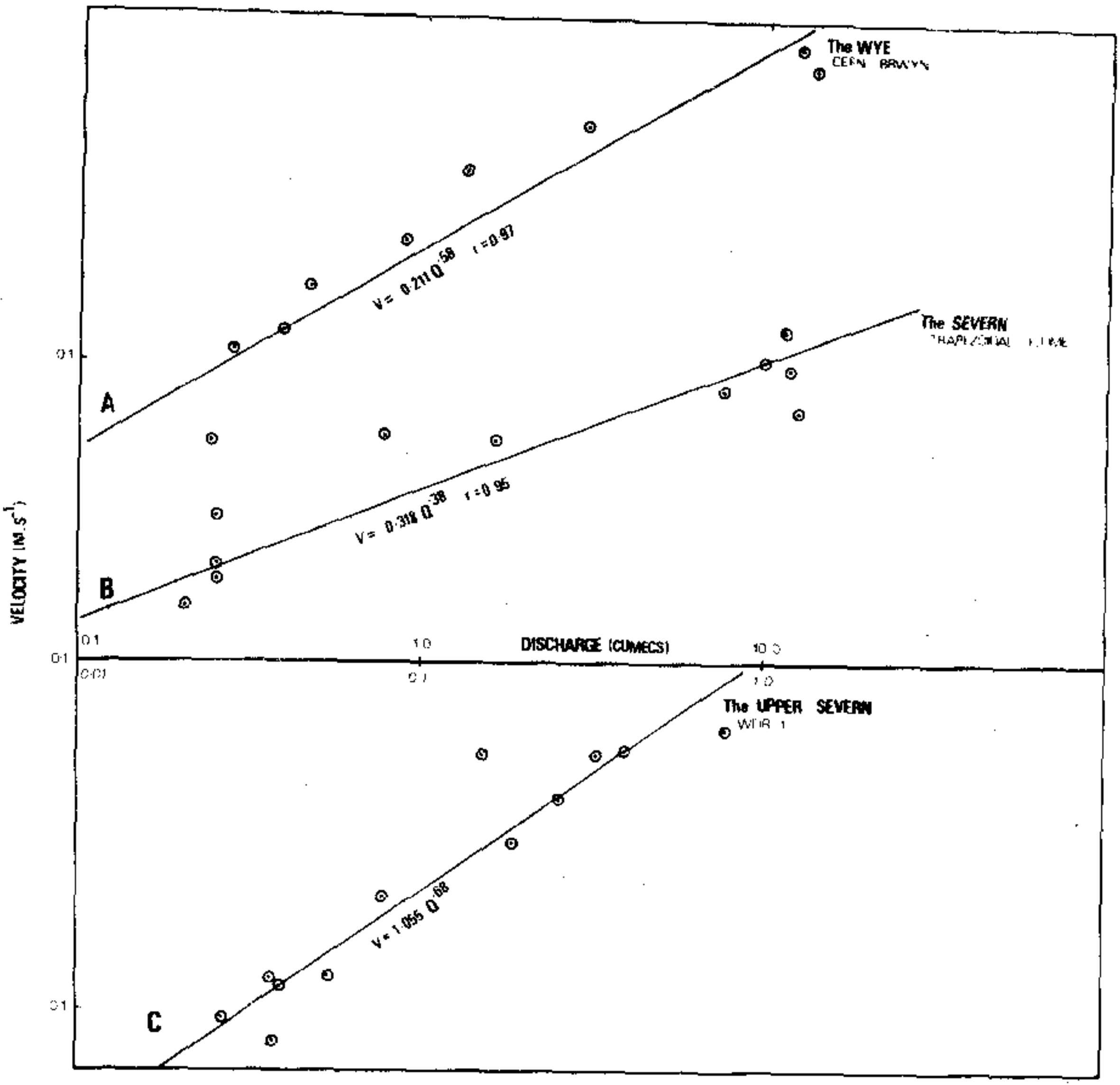


FIGURE 16 Travel times expressed as velocities with log-linear equations

A The Wye } experimental catchments
B The Severn }
C The Upper Severn

5. HYDRAULICS OF PIPE FLOW AND OVERLAND FLOW

It seems an obvious advance that the methods applied above to the main channels of the Plynlimon catchments should be applied to slope runoff where this is at all integrated. Therefore, sub-surface flows in soil pipes, and flushes and across valley-bottom bogs as saturation overland flows, were selected for experiment. Survey techniques required some modification - the soil pipe network required excavation for measurement (flushes proved prohibitively massive for this!) and overland flow required a grid of very accurate survey points across the chosen plot. The techniques of salt or dye dilution described above were used virtually unmodified to investigate flows. In the case of both soil pipes and surface runoff a controlled, variable but artificial supply of water had to be arranged, using gravity feed through plastic ducting or a petrol-driven pump; natural flows in both situations are too unpredictable and unsteady. The authors are grateful for assistance with both aspects to Miss Ann Morgan and Miss Pauline Newman, whose dissertations are referred to in the Bibliography.

5.1 Flow in pipes and flushes

Flow properties of artificial pipes are well documented. However, soil pipes are unlikely to be capable of theoretical hydraulic treatment, such is their irregularity of form. Modelling their flow clearly required sample surveys of their network properties, geometry and flows on a plot scale, and from such sampled properties to gross up to the scale of a complete piped slope. Since the Cerrig Yr Wyn catchment of the upper Wye was found to contain pipes and was being calibrated for modelling, a major network there was selected for detailed study by Miss Morgan. It had already been mapped in detail.

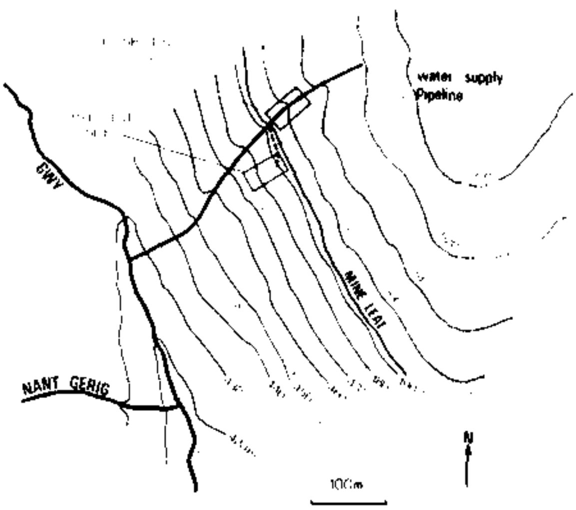


FIGURE 17 Flush and pipeflow test sites, Upper Wye catchment

The pipes were exposed in pits at 10 m intervals giving a total of 84 cross-sections. As well as cross-sectional dimensions and long-profile gradient at each pit, the need to explain the origin of pipes prompted measurements of the depth of the pipe in relation to the peat/clay boundary in the podzol and a sampling programme for materials in the roof and base of pipes. Values relevant to hydraulics are abstracted in Table 9. Using occassional velocity tests with dye and visual detection Miss Morgan concluded that, for most of their length, pipes flow a quarter to half-full at moderate discharges. Velocities of around 0.1 m/sec characterized these tests. Following her work a nearby undisturbed soil pipe 50 m long and without distributary branching (Figure 18) was selected for full velocity tests. Plate 17 shows the outlet of the system under test. The results of computing centroid velocities and discharge are shown in Figure 20. The flush used for testing was that which focuses the Cerrig Yr Wyn slope drainage. Salt or dye solutions were introduced through a breach in the roof and response monitored 50 m below at a point where the flush slipped away during the August 1973 flooding.

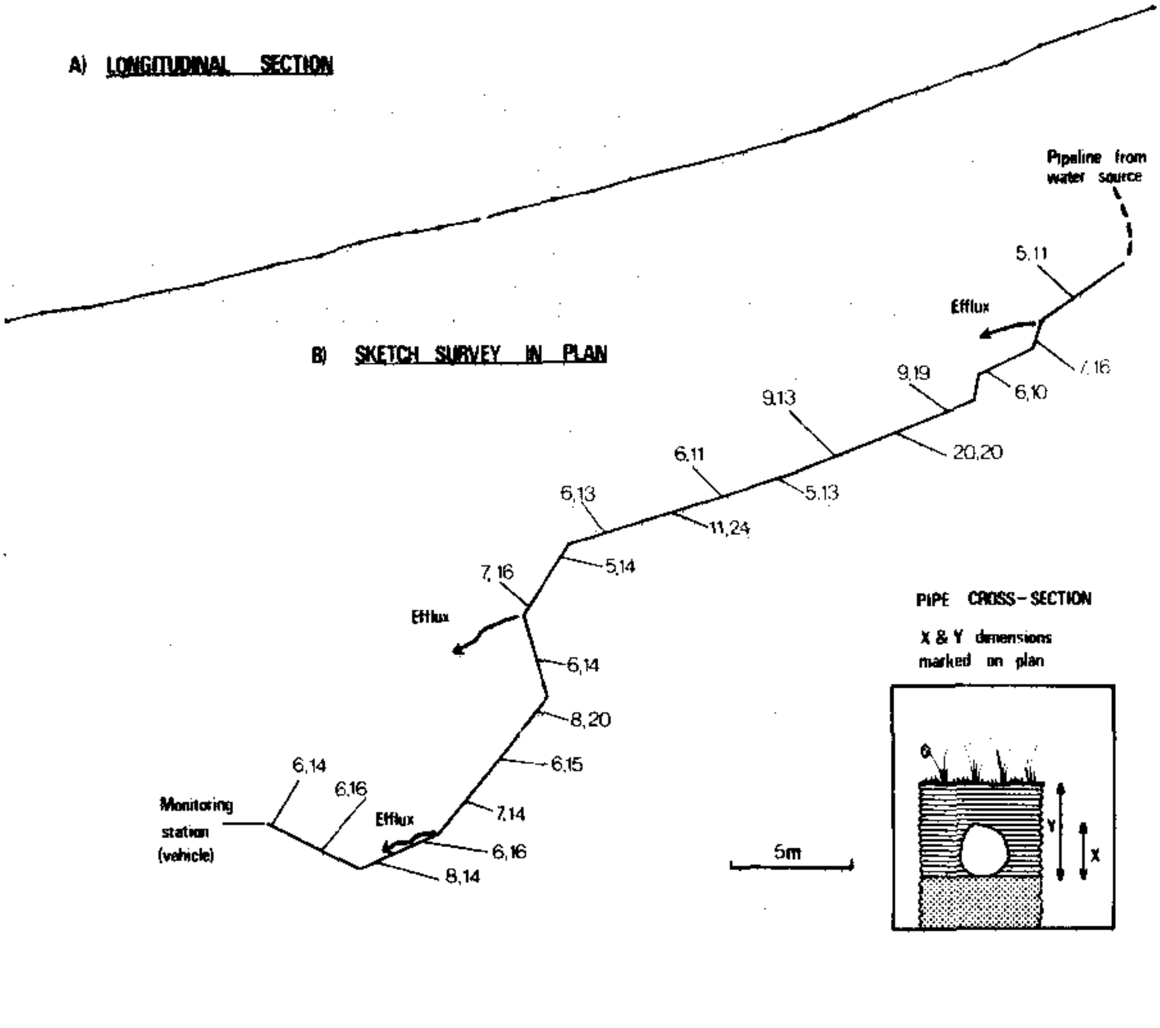


FIGURE 18 Pipeflow test site

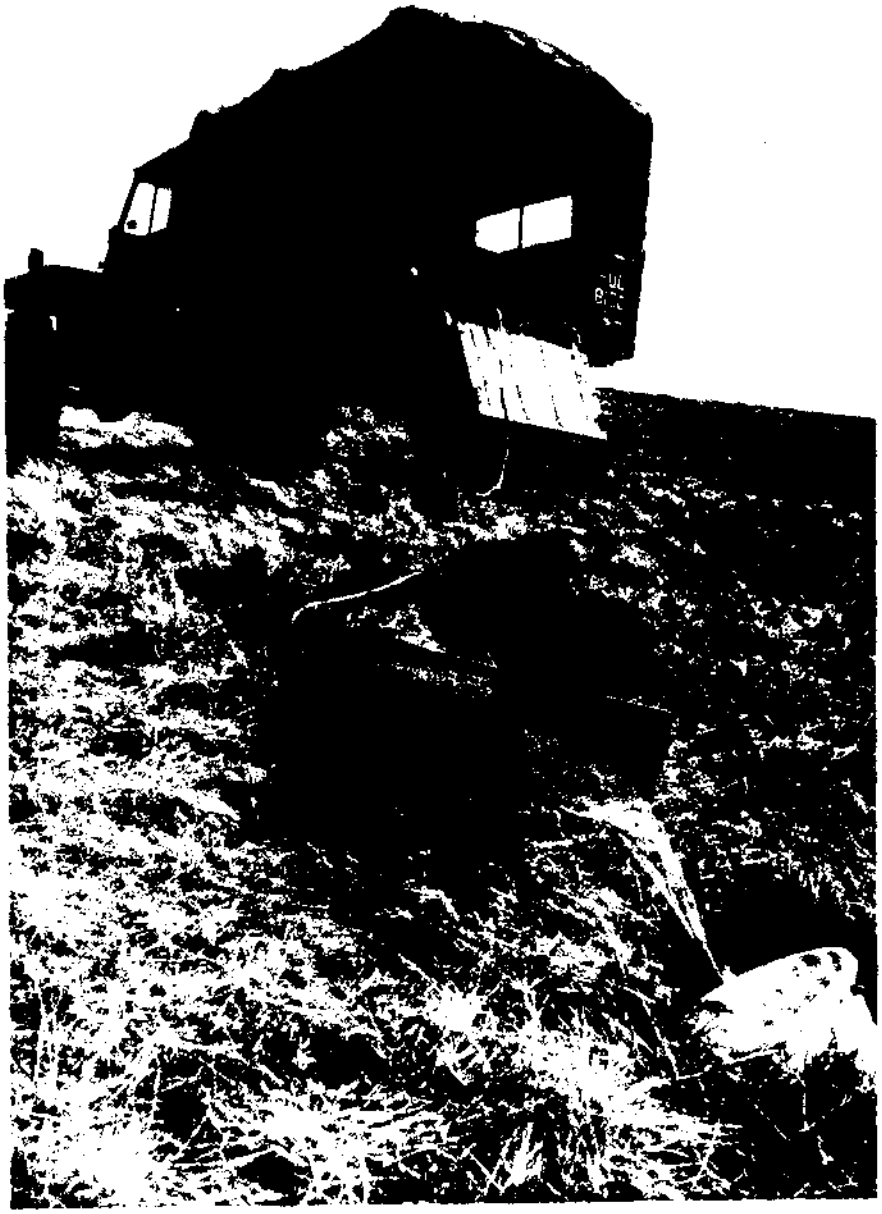


PLATE 17

The outlet flow from a soil pipe network, Cerrig yr Wyn, using artificial input. Flow velocities are being monitored by fluorometer in the 'bog-trotter' vehicle.

TABLE 9 SOIL PIPE STATISTICS FOR HYDRAULIC MODELLING

	Mean	Standard deviation
Depth of base of pipe (mm)	177	5.39
Cross-sectional area of pipe (cm^2)	67.5	5.56
Drainage density of network (m/m^2)	0.18	0.092
Average angle of pipe	9°	0.06°

5.2 Overland flow

As part of an investigation of the spatial characteristics of runoff in the Upper Severn, Miss Newman selected an extensive area of permanently saturated bog for studies of overland flow velocities. The slope angle, vegetation mat and channelization of flow in the area are quite typical of the Plynlimon valley-bottom bogs. Two approaches were used: the selection of sub-sections of the bog of various slopes roughnesses and depths of (natural) flows to scale the sensitivity of overland flow to these variables and the artificial regulation of flow depths over a particular site. This main site is shown in Plate 18 (Figure 19). It is a 10 m long plot varying between almost level, unchannelized and steeply sloping, channelized;

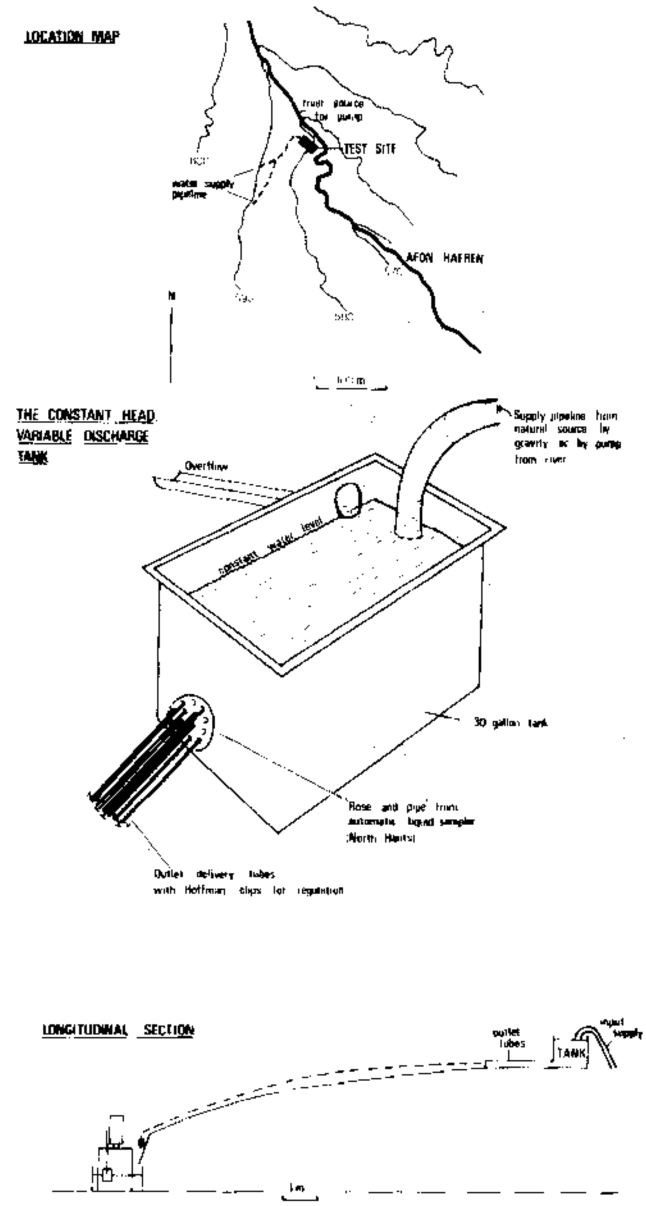


FIGURE 19 Surface runoff test site

PLATE 18 Surface runoff test site, upper Severn

A Looking down the plot (supply tank in foreground

B Looking up the plot (measuring weir in foreground) in other words a convex profile with opportunities to stand a constant head tank at the upper end and to collect all the flow in a weir tank at the lower end. Vegetation on the plot consists of *Sphagnum* and *Eriophorum*.

Eight separate tests were made using a strong brine solution introduced at the outlet tubes. Steady flow conditions were difficult to obtain across the bog surface - 'leakage' of water to storage in the peat below, the slow recession curve and variable proportion of the flow on the actual surface all contributed to making the eight tests occupy a three-week period. Eventually one test was discounted, leaving seven for the regression analyses shown in Figure 20.

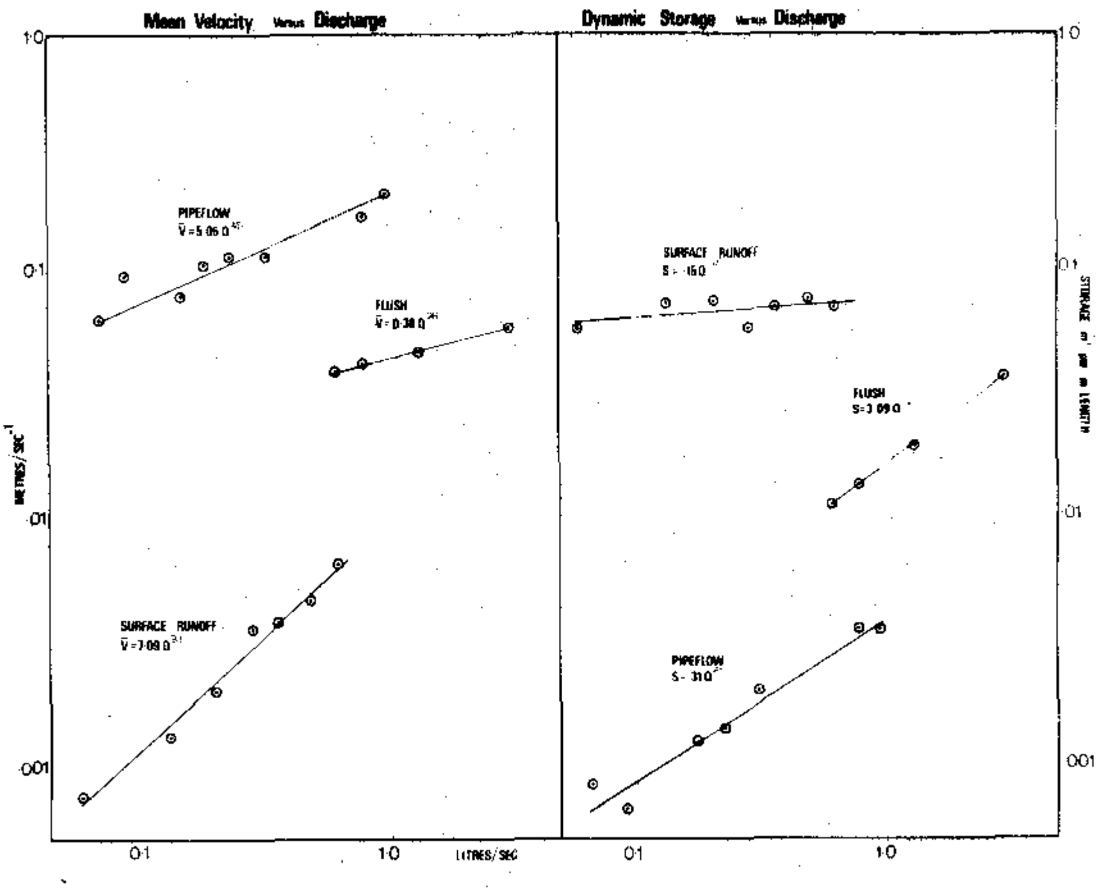


FIGURE 20 Mean velocity and dynamic storage/discharge relationships

5.3 Results

Figure 20 illustrates mean velocity and dynamic storage/discharge relationships for pipeflow, the flush and surface runoff. The discharges calibrated are one to two orders of magnitude lower than those covered by work on open stream channels in Figures 9 and 11.

Comparing the three non-channel sites, pipeflow is clearly the most rapid and surface runoff least. However, surface runoff's large exponent (.93) means that its mean velocity at very high flows becomes comparable with the other two types and, extrapolated ad absurdam, would exceed that of channel flow at comparable discharges! The high but relatively constant storage capacity (exponent .07) of the surface runoff regime is an obvious reason. The storage capacity of the flush is high and increases more rapidly with discharge than would be the case for an open channel. The pipeflow storage/discharge exponent is also high but only comparatively small amounts of storage are available. In fact, by measuring sample cross-sections in the test pipe it is obvious that, at the maximum discharge tested, the pipe has little further storage potential. Efflux of water occurs at the surface, although it sinks elsewhere on the plot. The cross-sections indicate a total pipe space of .00435 m^3 per metre and at the highest test discharge dynamic storage was equivalent to .00420 m^3 per metre, 96.6% of the total storage. Some indication that surface outlets are not the only "leaks" in the pipe comes from the fact that output discharges in the unbranched system were frequently only half of input - suggesting leakage along cracks or the peat/silt-clay interface. Output discharges were used in calculations.

Since the pipeflow and surface runoff discharges were artificially induced, it is necessary to state that the range covered for pipeflow (.08 l/s to 1 l/s) is well within the measured natural range, zero to 2 l/s measured for pipes, whilst a recorder chart left on the surface runoff site during storm rainfall showed a peak of 1.4 l/s, against the .65 l/s maximum tested. Future work will attempt to fit return periods to these and to open channel flows.

Miss Newman's work on subsidiary surface runoff plots seems to indicate the importance of micro-relief in determining velocities to the exclusion of gradient (13^o to 32.5^o slopes tested). Roughness is a variable insofar as it indexes the degree of micro-channel relief of the plot. It has been impracticable to follow up this line of enquiry during the present study but it did lead to the selection of the main test site on the grounds of the full range of diffuse to channelled flows, top to bottom.

Mean depths of surface water measured by Miss Newman varied between 5 mm and 20 mm on the main plot with a positive but irregular relationship with increasing flows. Dynamic storage volumes converted to average depths on the plot show a 68 mm to 90 mm storage for a one metre width (this may be an underestimate of width). Thus much of the flow considered as surface runoff is obviously occurring below the surface through the matted vegetation of Sphagnum moss. This must account for the consistently slower mean velocities recorded for the Plynlimon plot in comparison with others (eg. Emmett, 1970, Lyntik and Yablonsky, 1970). However, the location studied is far more typical of the Plynlimon catchments than those reported in the literature.

CONCLUSIONS

At present the authors' aim has been to draw together the results of an intensive spell of fieldwork. The assumption that irregularity would be a predominant feature of Plynlimon channels has been vindicated, although clear patterns of predictive value are emerging. It is hoped that this rather baldly presented collection of results will form the basis of channel routing procedures for mathematical modelling at Plynlimon and that further thought about the implications of the results will yield material for a further paper shortly. The authors would like to acknowledge thanks to Kevin Gilman and Keith Beven for their very helpful comments on the report and Nick Staley for some excellent draughtsmanship.

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