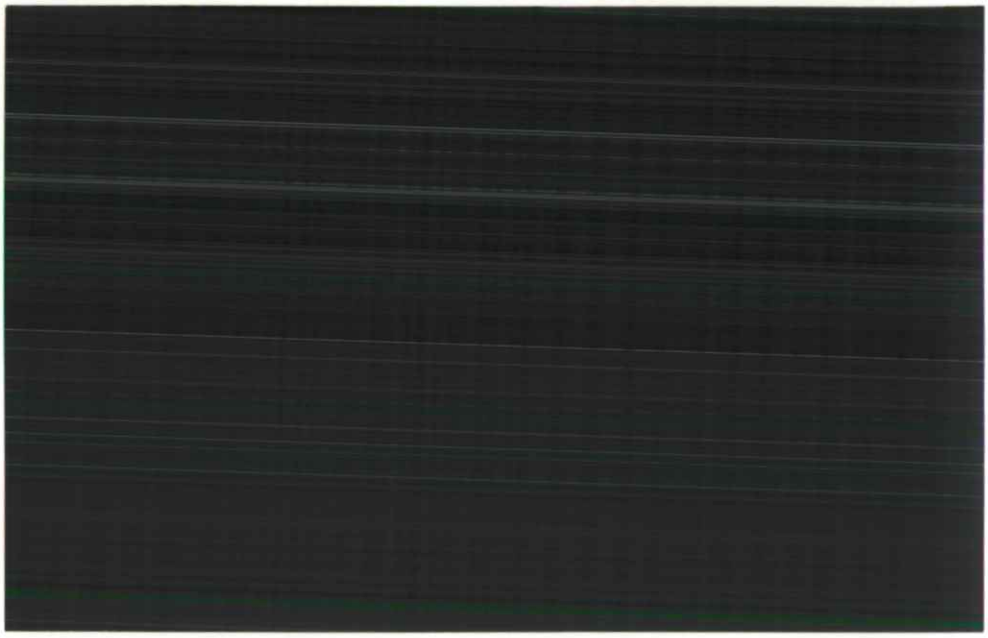
Centre for Ecology & Hydrology



Natural Environment Research Council

UPLAND FOREST CANOPY CLOSURE - THE IMPLICATIONS FOR HYDROLOGY AND ECOLOGY.

CEH INTEGRATING FUND
PROGRESS REPORT FOR 1995/96

Hudson, J.A.[1], Gilman, K.[1], Crane, S.B.[1], Hill, P.J.[1], Hughes, W.A.[1], Calder, I.R.[2], Robinson, M.[2], Reynolds, B.[3], Lowe, J.[3], Beaumont, W.R.C.[4] & Tipping, E.[5]

[1] Institute of Hydrology (Plynlimon), Staylittle, Llanbrynmair, Powys, SY19 7DB

[2] Institute of Hydrology, Maclean Building, Crowmarsh Gifford, Wallingford, Oxon., OX10 8BB

[3] Institute of Terrestrial Ecology, Bangor Research Unit, UCNW, Deiniol Road, Bangor, Gwynned, LL57 2UP.

[4] Institute of Freshwater Ecology, River Lab., East Stoke, Wareham, Dorset, BH20 6BB.

[5] Institute of Freshwater Ecology, Windermere Lab., Far Sawry, Ambleside, Cumbria, LA22 0LP

APRIL 1996

Contents

1. Introduction - aims and objectives

From an environmental point of view, canopy closure is an important phase in the life cycle of plantation coniferous forests in the uplands. There is no single objective definition of canopy closure, but it is assumed for the purposes of this project that it occurs at the time the foliage from adjacent trees becomes interlocked, and little understorey remains visible from above. In plantation forests in upland Britain closure occurs between 15-25 years after planting, depending on region, species provenance, growth rate and the initial spacing of the trees. There is a growing conviction that this is the phase of forestry where rapid changes occur in water and chemical cycling that must lead inevitably to changes in the fluxes of water and chemicals in catchment ecosystems.

This assertion is largely based on circumstantial evidence of the differences between mature forestry and moorland, and from physical and chemical principles derived from process studies of hydrological and hydrochemical behaviour. Changes in the hydrological regime, manifest as increased evaporation and reduced flow, will have implications for sediment movement and for water quality, particularly nutrient levels and acidity status. Such alterations to the freshwater environment will inevitably affect fish populations, either directly through increased toxicity: lower pH, higher metal concentrations, and increased algal growth leading to increased BOD and de-oxygenation, or indirectly as they affect the habitat: gravel shoals for spawning, and the freshwater food chain (macrophytes and invertebrates), at the top of which sit the predatory salmonids.

The results from other studies of mature forests suggest that such biological changes occur, but it has never been demonstrated unequivocally that afforestation, and canopy closure in particular, is the principal cause. Neither has it been shown for what proportion of the observed overall change that canopy closure itself is responsible, nor whether the causes are essentially physical, chemical, biological or a combination of these. The Llanbrynmair Afforestation Study has been running since 1982, covering the initial ground preparation and planting phase of upland forestry. There are now up to 13 years of continuous hydrological, hydrochemical and biological data available, making the Cwm experimental catchment an ideal site to study the imminent onset of canopy closure. Changes in the behaviour of this forested catchment can be compared to its pre-canopy closure state, and also to an adjacent, untreated moorland control catchment, the Delyn.

The relevance of the Llanbrynmair study to assessment of environmental changes occurring in the uplands has led to its adoption as the focus of this CEH Integrating Fund project on canopy closure. This document charts the progress that has been made over the first year of the project, which has largely been devoted to improving the instrumentation networks, rationalising and standardising the data collection protocols and procedures, and in bringing the databases up to date, thus providing a platform from which a comprehensive study of canopy closure can be confidently launched.

2. The Llanbrynmair catchments and instrument networks

The history of the study site, and the layout of the forest planting scheme and the environmental monitoring networks have been covered in some detail in other reports (see for instance Roberts *et al.*, 1986 & 1987) and therefore need little introduction here. An initial review of the instrumentation has largely justified the networks as they stand, but has also suggested some improvements to the data collection protocols and the addition of specific instrumentation for this phase of the project and beyond.

The Llanbrynmair Study started life as purely an investigation of how initial afforestation and associated management practices affect water quality, yet the opportunity was taken to install comprehensive hydrometric instrumentation in order to widen the relevance of the catchment study. The instrumentation currently in operation, and also that considered necessary for the canopy closure phase of the study is shown in Table 2.

2.1 Hydrological instrumentation and data processing

Flow data are collected from three structures in the Cwm and the one in the Delyn. In the case of the two main structures, data are currently held on the ORACLE database at Plynlimon. Data for the two subcatchment gauges remain for the present in ASCII files, but loading of these to the database is planned for the near future. ORACLE- and spreadsheet-based procedures have allowed a thorough quality control of the flow data, using graphical techniques and trend analyses to identify suspect values. Once identified, faulty data have been infilled using, in order of priority: backup loggers, relationships with other gauges in the catchments (preferably nested but otherwise adjacent), and relationships with the next nearest gauge on the Afon Dyfi system, at Dyfi Bridge, Machynlleth. Final recourse to rainfall-runoff models has, fortunately, not yet proved necessary.

Using these procedures the flow records for the main catchments are now virtually complete and largely free from systematic errors associated with logger malfunction or poor stage zeroing (cumulative flows, uncorrected for sediment, are shown in figure 2.1). Serious problems with sedimentation in the Cwm Crump weir, the frequency of which is shown in fig. 2.1 and details of which are discussed further in section 3.2, remain to be solved.

Records from the raingauge networks are generally complete over the time periods individual gauges have been operating, but not all gauges were available at the start of the Llanbrynmair Study in 1982. For complete coverage, some infill will therefore be needed for the early years, and this will be achieved using relationships derived with gauges that have existed throughout the study. Some additions will be made to the network where, for instance, the growth of trees makes it difficult to continue with existing ground level gauges without widespread felling of trees to ensure compliance with siting criteria. The ground level network will be augmented with standard or canopy-level gauges. Advantage will be taken in the first instance of the recently-installed AWS tower to install a canopy gauge. This will also allow assessment of the relative performance of ground level and canopy level gauges at the same location, which may help to resolve a controversial issue that is crucial to the credibility of upland raingauge networks. Direct information is lacking, the adoption of the two types of gauge in mixed networks at Plynlimon having relied on statistical tests of comparative behaviour that gave positive indications for use of the canopy gauge (Newson & Clarke, 1976).

Table 2 ***Existing and proposed (in bold) instrumentation in the Llanbrynmair catchments and its surrounding area***

Instrument	Catchment, type and numbers	Recording frequency	Years of operation
Storage r/gauge	Cwm (3 GL), Delyn (2GL + 1 standard removed in 1992), Pentre Celyn (standard)	Fortnightly	GLs mostly 1982-present; Cwm North End
Recording r/gauge	Cwm (2), Delyn (1), Llanbrynmair NRA (1)	Hourly and event timing	Cwm 1983-present; Delyn 1990-present
Occult input	**Cwm (1)**	Hourly/0.2mm event	
Wet deposition	Cwm (1)	Fortnightly	1982-present
Cloudwater deposition	**Cwm (1)**	Fortnightly composite	
Climate - Campbell AWS	**Cwm (1)**	Hourly	
Soil temperature (10cm)	Cwm (2)	Fortnightly	1982-present
Earth temperature (30cm)	Cwm (2)	Fortnightly	1982-present
Grass minimum temperature	Cwm (2)	Fortnightly	1982-present
Stream temperature	Cwm (4), Delyn (1)	Hourly	1990-present
Streamflow volume	Cwm (1), Delyn (1), Ceunant Ddu (2)	15 mins	Cwm, Delyn1982-present; Ceunant Ddu 1990-present
Streamflow chemistry - composite	Cwm (3), Delyn (1)	Fortnightly (0.5 hr shots)	Main catchments 1982-present; Ceunant Ddu 1992-present
- gulp		Fortnightly	Main catchments and Ceunant Ddu1984-present; Ceunant Ddu mire 1990-1992; North Cwm 1987-present.
Continuous chemical monitoring (pH, cond, O2, redox, temp)	Cwm (1), **Delyn (1)**	15 mins	Cwm 1995-present
Bedload	Cwm, Delyn	Periodically (trap full)	1982-present
Suspended load	Cwm (3), Delyn	Event threshold	1982-1987
Turbidity	**Cwm, Delyn**	15 mins	
IFE fish counter	Cwm (1)	Event	1994-present

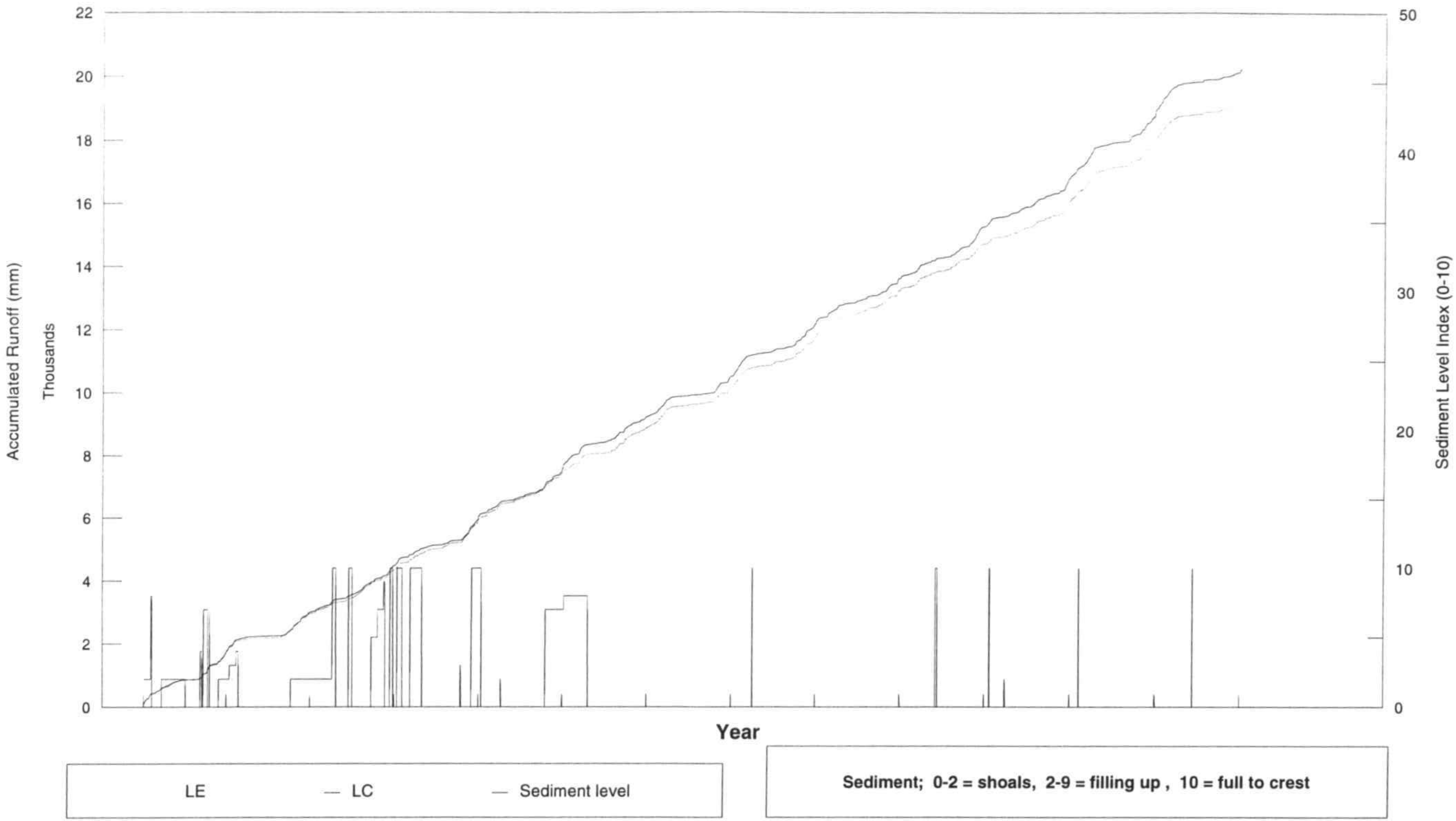


Figure 2.1 Cumulative runoff (mm) from the experimental and control catchments and an index of sediment level from the experimental weir.

At the same time a cloud water collector will also be installed on the tower from which it is hoped the volume (as well as quality - see also section 2.2) of direct condensation can be estimated. In association with net precipitation gauges and soil moisture recording under the new trees, this set-up will be used in the estimation of interception and transpiration rates from the new crop.

It has not been easy to interpret the hydrological record from Llanbrynmair in the context of long term climatic changes, or variations in atmospheric demand for moisture, because of the lack of suitable climatic data. The nearest thing to an index of climatic variability is the usefully damped temperature record from the soil and earth thermometers (Emmett *et al.*, 1994). To rectify this deficiency, a Campbell AWS is to be tower-mounted above the canopy in the Cwm in Spring 1996. In addition to the standard range of sensors, this will include soil temperatures as these are considered important as indices of climatic change, and as inputs to soil chemical models.

2.2 Chemical Instrumentation

One objective of the study is to obtain good quantitative estimates of atmospheric inputs in order to run the ITE Bush atmospheric deposition model and to predict how inputs might change as the forest grows. These data would then be used as input to the MAGIC and other long-term acidification models. An initial step has been the provision of a new wet deposition collector (Warren Spring pattern), which will be supplemented by passive cloud water gauges and an automatic weather station. It is intended that NO_x tubes will be deployed at the site and an SO_2 bubbler at the Plynlimon labs. Although several kilometres away from the Llanbrynmair catchments, this will provide a regional estimate of air SO_2 concentrations suitable for modelling purposes. Plynlimon has also been suggested as a suitable site for ammonia monitoring as part of a new national network of sites administered by ITE Bush and funded by the DOE.

Many of the effects associated with initial afforestation and canopy closure will be seen as changes in the response of the catchments to storm rainfall. Existing chemical samplers can only give an integrated idea of the chemical variation with flow. To interpolate the responses requires either a programme of high frequency sampling over the storm hydrograph or continuous monitoring of chemical determinands that are capable of being measured by in-stream sensors e.g. pH, temperature, dissolved oxygen, redox, conductivity, and certain ion selective electrodes e.g. nitrate and ammonia. In the first instance a HYDROLAB[R] monitoring system has been installed at the Cwm weir. A second is in the process of being set-up to be used initially on the Delyn, and afterwards in opportunistic mode at various sites of interest within the catchments, for instance near suspected groundwater inputs.

2.3 Spatial data

An important component of this multi-disciplinary study is to integrate data from the different institutes. A geographical information system (GIS) for the catchments is seen as providing an important platform for this integration process. As an initial step towards developing the GIS, the following have been digitised on to ARCHINFO at Bangor: catchment boundaries, soils data, drainage pattern and afforestation programme.

Geological data and a vegetation map of the catchments prior to afforestation will be added to the GIS soon. Digital terrain data are also available at Bangor in the form of a 1:50,000 digital terrain model which will be supplemented by 1:10,000 contour data. An example of the use of these data will be the parameterisation of a model for atmospheric deposition to the catchments as a basis for predictive hydrochemical modelling. The latter will also require spatial information regarding soils and vegetation within the catchment.

3. Hydrological Issues

3.1 Rainfall

Rainfall data is required for water balances, for rainfall-runoff modelling and for establishing chemical input fluxes. The data from Llanbrynmair are intensive enough, both spatially and temporally, to be also used for long term assessment of changes in rainfall patterns and volumes resulting from climatic fluctuations. Although not as comprehensive as the Plynlimon networks for instance, this is no great disadvantage as the spatial variation in rainfall at Llanbrynmair is less. They may also, as yet, be criticised as being of insufficient longevity to be used in their own right for this purpose, but this does not prevent them being linked with other networks to give a usefully broader base to climate studies in the uplands of Wales.

A routine has been derived to enable the storage gauges in the network, which are generally read fortnightly, to be distributed to daily rainfall using the daily read NRA/Met. Office gauge at Pentre Celyn. The relationships between individual gauges and Pentre Celyn (and the rest of the network when available) will also be used to extrapolate daily rainfall values for more recently installed gauges back to the beginning of the study in 1982. This will aid all the hydrological and hydrochemical studies involved in the project.

Ultimately, the development of sophisticated hydrological models, such as distributed catchment models or canopy evaporation models, will require hourly rainfall values or shorter. Distribution of period rainfall totals to hourly time intervals should be possible (snow periods excepted) using the two tipping bucket gauges linked to Campbell loggers that are in operation. For shorter time interval rainfall, it may also be possible to distribute to 'time of tip' using the Delyn rainfall recorder, which is currently logged in appropriate format onto a Rainlog[R] event recorder.

3.2 Flow

Of the four streamflow structures in operation, three, the Delyn compound sharp-crested weir, and the two steep stream flumes in the Ceunant Ddu tributary of the Cwm, have proved to be relatively trouble free over their lifetimes. The Cwm Crump weir on the other hand has suffered from sedimentation problems; predictably this is largely a result of the nature of the land use change being studied. The major effect has been an increased discharge of sediment from drainage ditches and newly-constructed roadside embankments. Sediment deposited by the stilled water in the approach section (apron) of the Crump weir, periodically causes the effective weir height (P) to fall below the 0.372m used in the

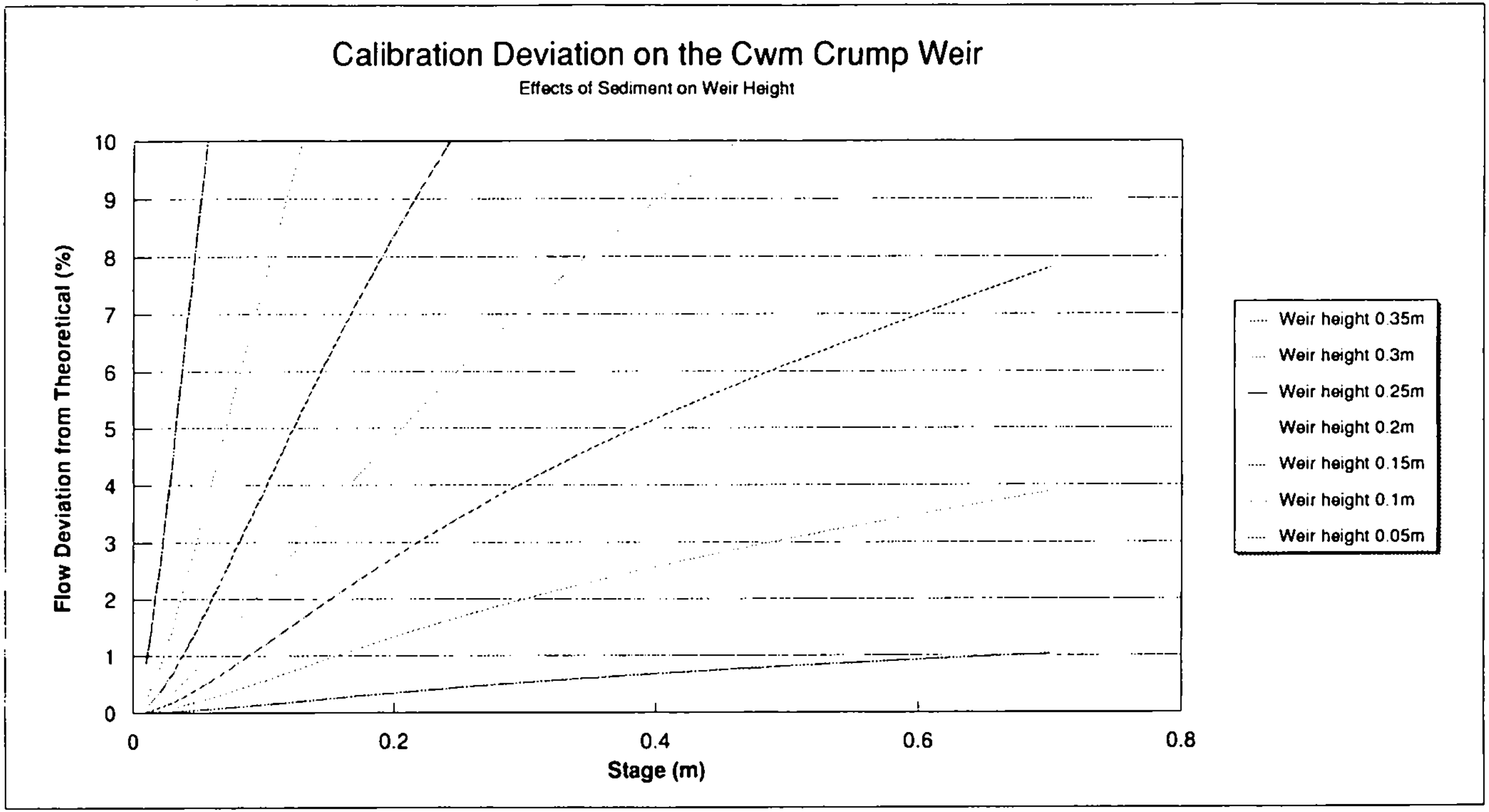


Fig. 3.2.1 *The effects of sediment deposition in the Cwm Crump weir on the percentage deviation from theoretical flow.*

design rating for the structure.

To some extent, account can be taken of sedimentation by reducing the weir height in the calibration equation. However, as the effective weir height approaches zero, not only does the rating change, but the maximum stage (and hence flow) that can be measured with the laboratory-derived discharge coefficient is also reduced. In such circumstances the maximum gaugeable stage is likely to be exceeded for an appreciable proportion of the time. Whatever happens, it is important to know the depth of sediment at all times so that the correct rating can be selected for each stage measured. The sensitivity of the rating to bed level changes is shown in figure 3.2.1, as the percentage difference from the theoretical rating that is introduced if the sediment is ignored. This shows how the errors become uncontrollable, and the weir becomes incapable of being rated, once the weir height declines below c. 0.2m. At such times the flows may have to be modelled using relationships with other catchments.

Unfortunately, although sediment loads have been recorded by volume and weight each time the weir is emptied of sediment, the procedure has not always included a depth survey of the stilling pool from which sediment depth at the tapping point can be extracted. This leaves the problem of interpolating an intermittent sediment record between the times when it is known the weir is empty and when it is 'full'. A saw-tooth interpolation is the easiest way to do this, and can be used as a starting point for interpretaion of potential errors. However, in reality, it is a method that takes little account of the fact that the distribution of flows within the accumulation period gives rise to intermittent and unpredictable jumps in sediment depth. Furthermore, it is not unknown for particularly erosive flows to scour sediment rather than deposit it, making it quite possible for sediment levels to fall as well as rise during the passage of a flood. Flow-weighted accumulation models give a more realistic chance of determining the correct rating for each set of conditions, yet, depending on the distribution, frequency and magnitude of floods within any sediment accumulation period, there are still many sequences of build-up that could be envisaged. Early indications are that the type of model chosen is far less crucial than the fact that the sediment effect is being incorporated in the flow correction procedure at all.

3.3 Water balances

Initial indications of P-Q from the main catchments' water balances were given in Hudson *et al.* (1993). These showed a relative increase in P-Q from the Cwm compared to the Delyn, against a background of an overall decline in P-Q for both catchments. This analysis, however, was carried out before the full extent of the sediment problem became clear. If all other aspects of the hydrology had remained equal, ignoring the effect of the sediment on the Cwm rating should not have made any difference to the Cwm/Delyn comparison. However, the Delyn data indicate that flow distributions have changed over the study period. It is also clear from figure 2.1 that the build-up of sediment was not consistent due to the higher stream sediment loads evident at the time of afforestation and road construction (Leeks & Roberts, 1987) which filled the weir pool more frequently.

Clearly the sediment effect cannot be ignored, but neither should the effects of the sediment build-up be over-emphasisied, as they are relatively small in terms of percentage error for most of the time, and the errors can in any case be corrected using the alternative ratings. The main problem will be in the early years when the weir pool occasionally filled to the brim. For this reason data trends will have to be examined very carefully.

3.4 Flow durations - low flows

This will be one of the key areas of hydrological research to emerge from the Llanbrynmair Study. There has been considerable encouragement for research on the topic, particularly from the Forestry Industry, who are being affected by current limitations on forest planting resulting from the perception of the Water Industry, not unanimously backed up by hard scientific evidence, that new forestry reduces low flows.

In spite of the problems with sediment in the Cwm, the absolute values of low flows are not in dispute as their measurement is not much affected by reduced weir height. The data are probably adequate in their present form to be used in regional studies and also to investigate long term trends at individual sites. Catchment comparisons that depend on identification of changes in flow duration are usually based on the quantification of Q_{95}, which again is not affected by errors at high flows. Ultimately, however, rigorous analysis will require that Q_{95} values are expressed as a ratio with average flows from the catchment, and these will clearly be affected by errors in the rating. A preliminary analysis of low flows is currently in progress, which is also contributing to the EU project (FOREX) on 'Forestry and Extreme Flows'. Further advances must await a solution to the Cwm sediment problem.

3.5 Flood response

This is also an important issue with respect to the changes in hydrological response expected at canopy closure, and will form an important component of the present study. The analysis will be seriously flawed if data is used that has not been corrected for the sediment problem in the Cwm.

4. Water quality

4.1 Sampling strategies

The chemical sampling programme at Llanbrynmair has evolved gradually, the original two streamflow sites at the outfall of the main catchments being augmented by two sites in the Ceunant Ddu basin in 1984, with a further site on the main limb of the Cwm above the confluence with the Ceunant Ddu added in 1990 (North Cwm). Originally, composite samples were taken as half-hourly subsamples bulked over a fortnight, using vacuum samplers made by North Hants Ltd (later Automatic Liquid Samplers Ltd.).

Composite samples are useful for calculating fluxes as they give an average value of concentration over a period for which flow is known. Spot samples on the other hand have the advantage of representing a specific instantaneous set of environmental conditions, and can therefore be used to establish causal relationships that can form the

Fig. 4.1 *Comparison of spot and composite samples from the Cwm catchment, Llanbrynmair*

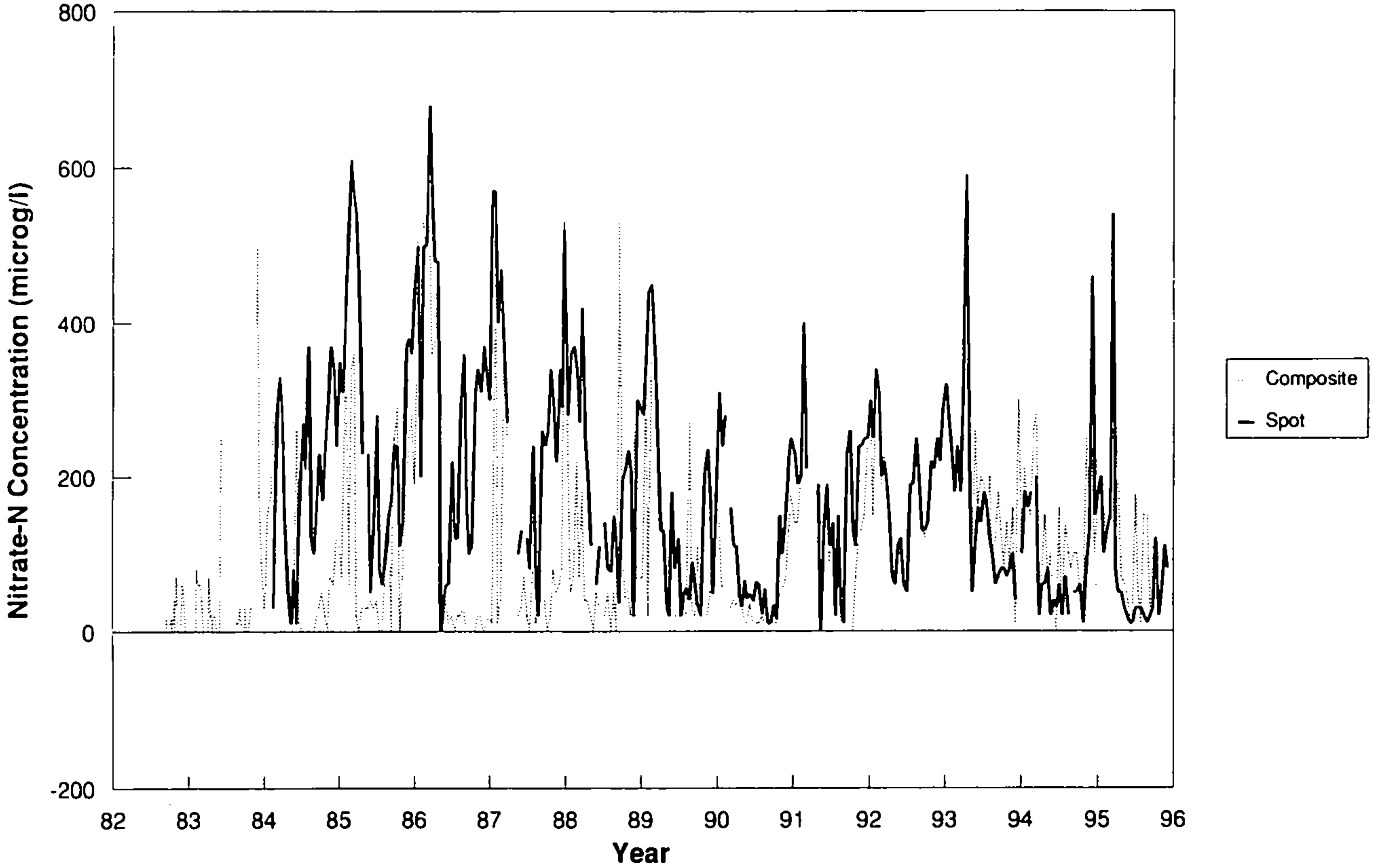
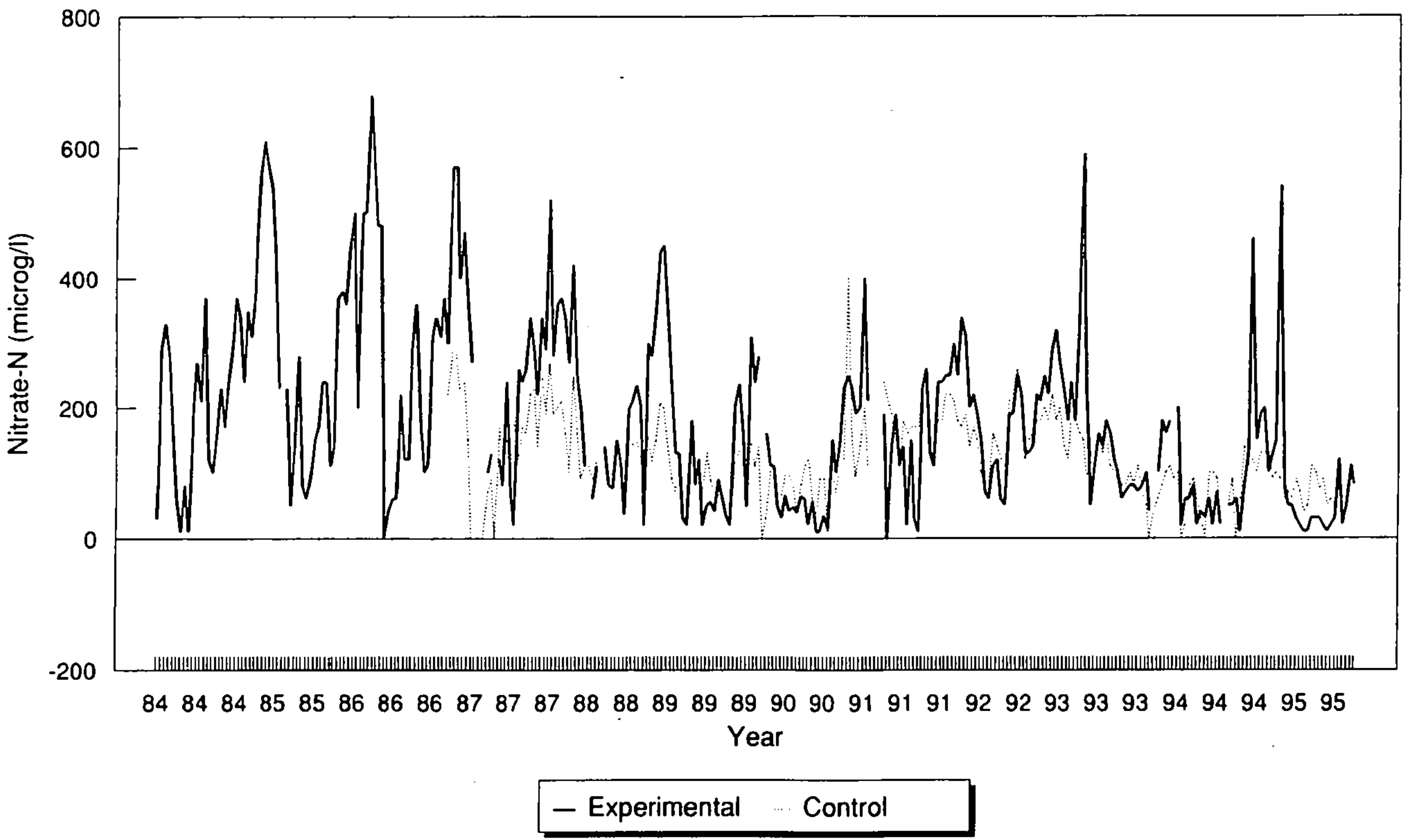


Fig. 4.2 *Comparison of nitrate concentrations in spot samples from the forested and moorland catchments at Llanbrynmair.*



basis of predictive models of ecosystem behaviour. Ideally, both types of sample should be taken at each site. This early realisation spawned the instigation of a parallel spot sampling programme at most of the sites at Llanbrynmair. Spot sampling was introduced at the Cwm outfall in 1984, and at the Delyn in 1987, while composites were added to the original spots at the Upper and Lower Ceunant Ddu in 1992.

By chance, this policy solved a further unforeseen problem, that of degradation of composite samples during field storage. Samples from the ALS Ltd. equipment are not only extracted from the stream by vacuum suction, but are also held under vacuum throughout the sampling period. This resulted in rapid decline in nitrogen concentrations in the samples relative to the spots taken at the beginning and end of each sampling period, suggesting possible anaerobic processes such as denitrification were at work on the samples. Replacement of the ALS samplers with EPIC^R samplers solved this problem, as can be seen from the spot/composite comparison in figure 4.1. Although EPIC samplers use a vacuum pump for extraction, the samples are kept at atmospheric pressure during storage. It is unclear at present whether this effect is also evident for other chemical species, and this is an area that will receive further investigation. Of particular concern are those chemicals involved in biological activity such as P and K, and also soluble organic carbon which could be involved in methanogenesis reactions in the anoxic conditions of the ALS samples, or in anaerobic respiration or fermentation to form CO_2.

There remain detail differences between the data from the two types of sample which suggest that the initial argument used to justify a combined spot plus composite approach is valid. Changes have been made to the sampling protocols, however, to bring them into line with techniques used by the NRA and the recently-completed 'Acid Waters re-survey of Wales' (sponsored by NRA, CCW and Welsh Office), and to simplify field and laboratory procedures. This involves the use of disposable 0.45μm filters in the field on samples destined for major ion analysis, and the collection of two further unfiltered samples, one for pH and conductivity, the other an air-excluded sample for alkalinity determination.

4.2 Long term chemical changes

The advantage of using an existing study like Llanbrynmair is that the effects of canopy closure will be evident as a change in the relationship between the forested experimental catchment and the moorland control. Stream chemistry data collected from the main outfalls since 1984 (see for example the nitrate data in figure 4.2) indicate that the initial effects of the afforestation practices have died down. At present, the losses of NO_3 in streamflow are higher from the moorland than the forest, presumably because the growing trees are taking up soil NO_3 in large quantities. This effect is most clear in the growing season. There is an underlying variability from year to year, and over the longer term, that emphasises the importance of controlled experiments. These minimise the chances that climatic and other factors affecting both catchments are misleadingly ascribed to the land use change. So far there is little in the NO_3 data indicating a canopy closure effect.

4.3 Spatial variability in chemistry

Despite the apparent uniformity of geology, soils and landuse within Welsh upland catchments, work at Plynlimon and elsewhere has highlighted the hydrochemical heterogeneity of these systems even at relatively local scales (less than 5 km^2). Earlier work at Llanbrynmair had also indicated that there might be relatively alkaline water sources within this catchment, even though it is dominated by base poor rocks and acid upland soils. Furthermore, biological monitoring within the catchment has highlighted some unexplained spatial variability in fish populations and recruitment within the Cwm catchment. Local variations in water quality may be an important controlling factor.

In July 1995, a detailed hydrochemical survey was undertaken within the Cwm catchment in order to characterise the spatial variations in stream chemistry under low flow conditions. A total of 37 samples was collected and these were analysed for pH, alkalinity, conductivity, base cations, acid anions, nutrients, dissolved organic carbon (DOC), aluminium, silicon and absorbance at 340 nm (a surrogate measurement of water colour). Stream temperature was recorded at each sample point.

Table 4.3 Summary of the chemical characteristics of low flow samples collected from the Cwm catchment in July 1995 (catchment outlet flow was 0.0157 m^3 sec^{-1}).

Determinand	Mean	Min	Max
Temperature (°C)	13.9	11.2	16.8
Conductivity (µS cm^{-1}) @ 25 °C	59.8	40.8	103.7
pH	6.54	4.63	7.58
Alkalinity (µeq l^{-1})	189.3	-31.4	644.5
Na (mg l^{-1})	4.54	3.50	5.35
K (mg l^{-1})	0.13	<0.01	0.38
Ca (mg l^{-1})	3.24	0.84	8.40
Mg (mg l^{-1})	1.86	0.74	4.08
NH_4 (mg l^{-1})	0.04	<0.01	0.29
NO_3-N (mg l^{-1})	0.04	<0.01	0.18
SO_4 (mg l^{-1})	5.38	1.73	10.99
PO_4-P (mg l^{-1})	0.003	<0.001	0.05
Cl (mg l^{-1})	7.65	3.72	11.92
Si (mg l^{-1})	1.67	0.67	2.78
DOC (mg l^{-1})	11.49	3.70	36.00
Al (mg l^{-1})	0.03	<0.01	0.29
Absorbance @ 340nm	0.266	0.006	1.39

Table 4.3 shows a summary of the data from the 37 sites sampled within the Cwm catchment, during rain but before flows had a chance to rise. The degree of variability is immediately apparent with, for example, pH ranging between 4.63 and 7.58, alkalinity between -31.4 and +644.5 µeq l^{-1} and DOC between 3.7 and 36 mg l^{-1}. There are highly significant ($p<0.01$) positive correlations between pH, divalent base cations and alkalinity. Unexpectedly there are also significant positive correlations ($p<0.01$) between sulphate, pH and the divalent base cations. The latter are also positively correlated with silicon which is positively correlated with alkalinity and sodium but shows no relationship with pH. Aluminium and DOC are highly positively correlated, but both are negatively correlated with pH. For DOC there is a significant negative correlation with sulphate but a highly significant positive correlation ($p<0.01$) with absorbance at 340 nm.

Closer examination of the data indicates that the most acid, aluminium and DOC rich samples are those collected on the flatter interfluves dominated by deep peat and peaty podzol soils. These waters are relatively enriched in sodium and potassium but depleted in divalent base cations. Sulphate concentrations in these samples average 4 mg l^{-1}. Another chemically distinct set of waters, which are clustered in a group of small tributaries towards the centre of the catchment, are enriched in divalent but depleted in monovalent base cations. These samples have the highest observed pH and alkalinity values and average sulphate concentrations (c. 8.5 mg l^{-1}) are double those recorded in the acid, DOC rich samples, although larger sulphate values are observed elsewhere in the catchment. These highly alkaline waters also had the lowest recorded temperatures which, coupled with the chemistry, is indicative of a groundwater source.

These data provide further evidence of the spatial heterogeneity of upland catchments in relation to streamwater chemistry. As observed at Plynlimon, it appears that groundwater may have a significant effect on the hydrochemistry of this catchment. This needs to be followed up by additional surveys to confirm observed patterns in stream water chemistry and by installation of boreholes. The presence of alkaline water within the catchment will need to be considered in any predictions of changes in stream acidity as a result of either tree growth or following controls on the emissions and hence deposition of acidifying pollutants. In addition, the most alkaline waters in the catchment, presumed to be of groundwater origin, had some of the largest concentrations of sulphate. If groundwater is providing a significant amount of sulphate to the streams, then depending on the size of this input, it could buffer the effects that any changes in atmospheric sulphur deposition might have on stream water sulphate concentrations and fluxes.

4.4 Hydrochemical modelling

The application of CHUM (CHemistry of the Uplands Model) to the Cwm catchment provides the framework for the hydrochemical modelling component of the study, with the aim of calibrating the model to allow prediction of the effects of afforestation across the uplands.

Considerable thought has been given as to how to conceptualise the different parts of the catchment so that the model could take some account of heterogeneity. After consideration of the drainage network, the soils and the topography, it seemed that a straightforward initial method could rely on the assumption that water falling on a given soil type would be routed to a stream without passing through another soil type. A more complex system is unlikely to be justified given the short time scale of the project and the lack of specialised data.

The model framework is based on domains or sub-catchments each of which has uniform properties with respect to:

soil type (peat, stagnopodzol, crown podzol, gley)
nature of forest (age)
average slope
groundwater influences

In principle there can be any number of these. Each domain will be treated on a daily time step, taking into account inputs (if any) of rain and dry deposition, 'tree activity', weathering, changes in soil chemistry etc. The individual domain outputs will then be mixed to generate different streamflows and compositions at different points in the stream network.

Initially, the system has been set up using soil characteristics established for a catchment in the Lake District, but with the physical properties of the Cwm (slopes, rainfall volumes). The simulated streamwater flow at the catchment outlet for 1983 has been computed (see figure 4.4), without altering any of the parameters determined for the Lake District site. Clearly, the model does not produce the flashiness of the Cwm flow record, although it distributes the rainfall in time reasonably well. If the measurements for rainfall and flow are compared, they are found to be very similar in volume, implying a very rapid transfer of rainwater to the stream. The model, as it stands, will find it difficult to simulate this, so modification of the hydrological sub-model will be required.

The main question raised by the initial model trials is the problem of dividing the Cwm catchment into sub-catchments. This decision will have to be informed by consideration of the soils/forest distribution, which will be dependent on the outcome of a detailed soils survey to be implemented in Spring 1996. Also of importance is the spatial distribution of groundwater resources. This has to some extent been identified through the chemical survey (see section 4.3) and will be hopefully confirmed by a spatial flow survey to be carried out in Summer 1996.

5. Biological effects

5.1 Habitat and food chain

A survey of the invertebrate fauna was carried out in August (table 5.1). Three minute kick samples were taken from each of the IFE sites and identified to family level. The number of taxa and the BMWP (Biological Monitoring Working Party) score showed clear reductions in sites near the source (fig. 5.1.1). Reasons for this include reduced faunal diversity and water quality near the source. A regression of BMWP score against altitude showed a clear decrease (fig 5.1.2). However, data from the eastern tributary (Ceunant

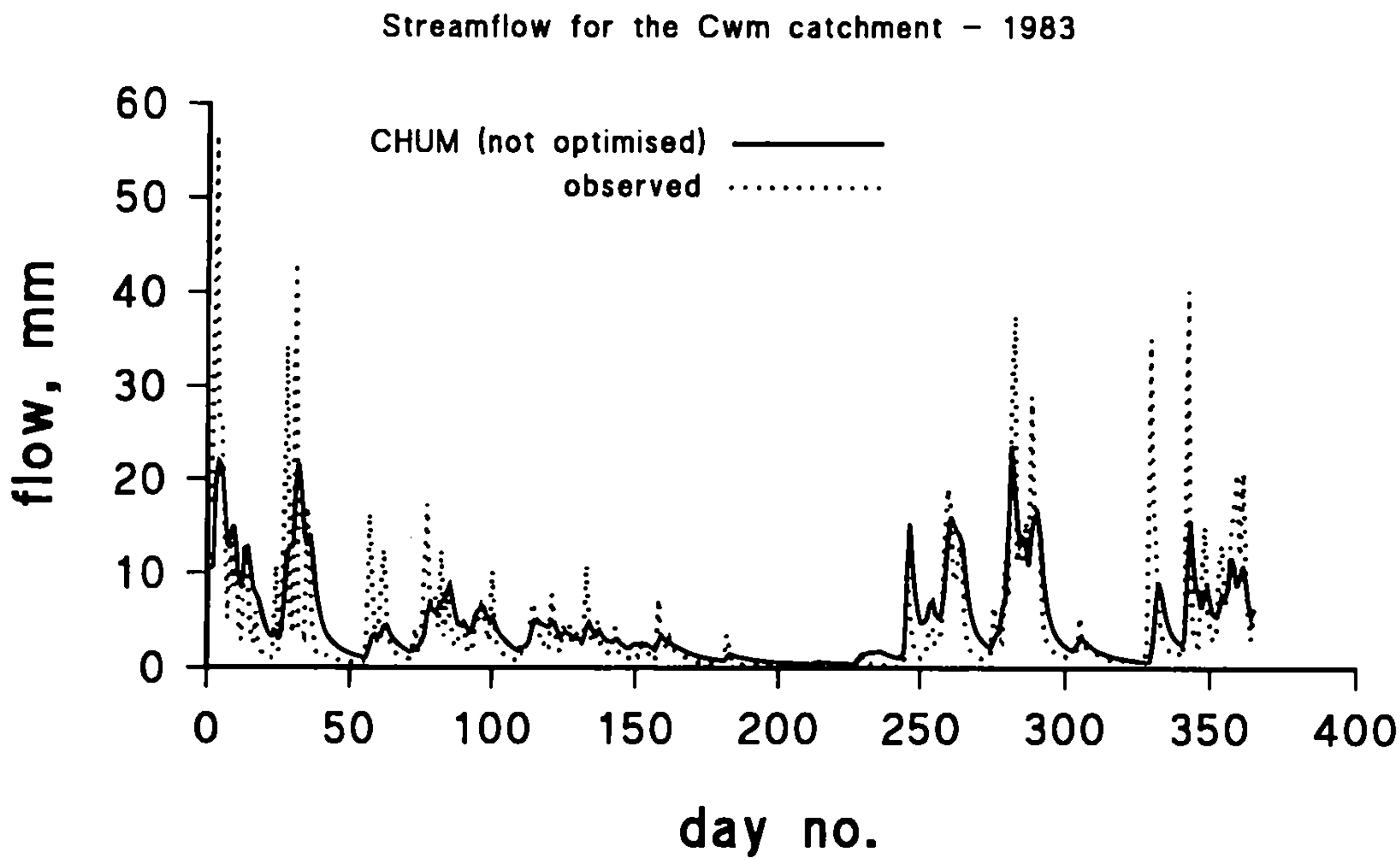


Fig. 4.4 *Predicted flow from the hydrological component of the CHUM model compared with observed flow for the Cwm catchment.*

Table 5.1 Results of the 1995 spatial invertebrate survey in the Cwm and Delyn.

Invetebrate Data: Control Site + Afon Cwm: 1995

Family	BMWP score	Control 1	Control 2	Stn 2	Stn 3	Stn 4	Stn 5	Stn 6	Stn 7	Stn 8	Stn 9	Stn 10
Heptageniidae	10	1	1	1	1	1						
Ephemerellidae	10	1	1	1	1				1	1		
Leuctridae	10	1	1	1	1	1	1	1	1	1	1	1
Perlidae	10	1	1									
Perlodidae	10								1			
Chloroperlidae	10	1										
Beraeidae	10	1										
Odontoceridae	10	1										
Seracostomatidae	10				1							
Nemouridae	7									1		
Rhyacophilidae	7	1					1			1		
Polycentropodidae	7	1		1	1			1	1	1	1	
Limnephilidae	7			1								
Ancylidae	6	1	1						1			
Hydroptilidae	6			1					1			
Tipulidae	5	1	1	1								
Simulidae	5	1	1	1				1		1		1
Dytiscidae	5		1	1	1	1	1		1	1	1	1
Elminthidae	5			1	1	1	1		1	1	1	1
Hydrophilidae						1				1		
Helodidae							1					
Baetidae	4	1	1	1	1	1	1		1	1	1	
Sialidae											1	
Chironomidae	2	1	1	1	1	1	1	1	1	1	1	1
Oligochaeta	1	1							1	1		1
No Taxa		15	10	12	9	9	7	4	10	13	7	7
BMWP		107	67	76	63	51	38	24	65	74	37	36
ASPT		7.13	6.7	6.3	7	5.7	5.4	6	6.5	5.7	5.3	4.6
Altitude				282	290	335	375	415	343	369	343	389

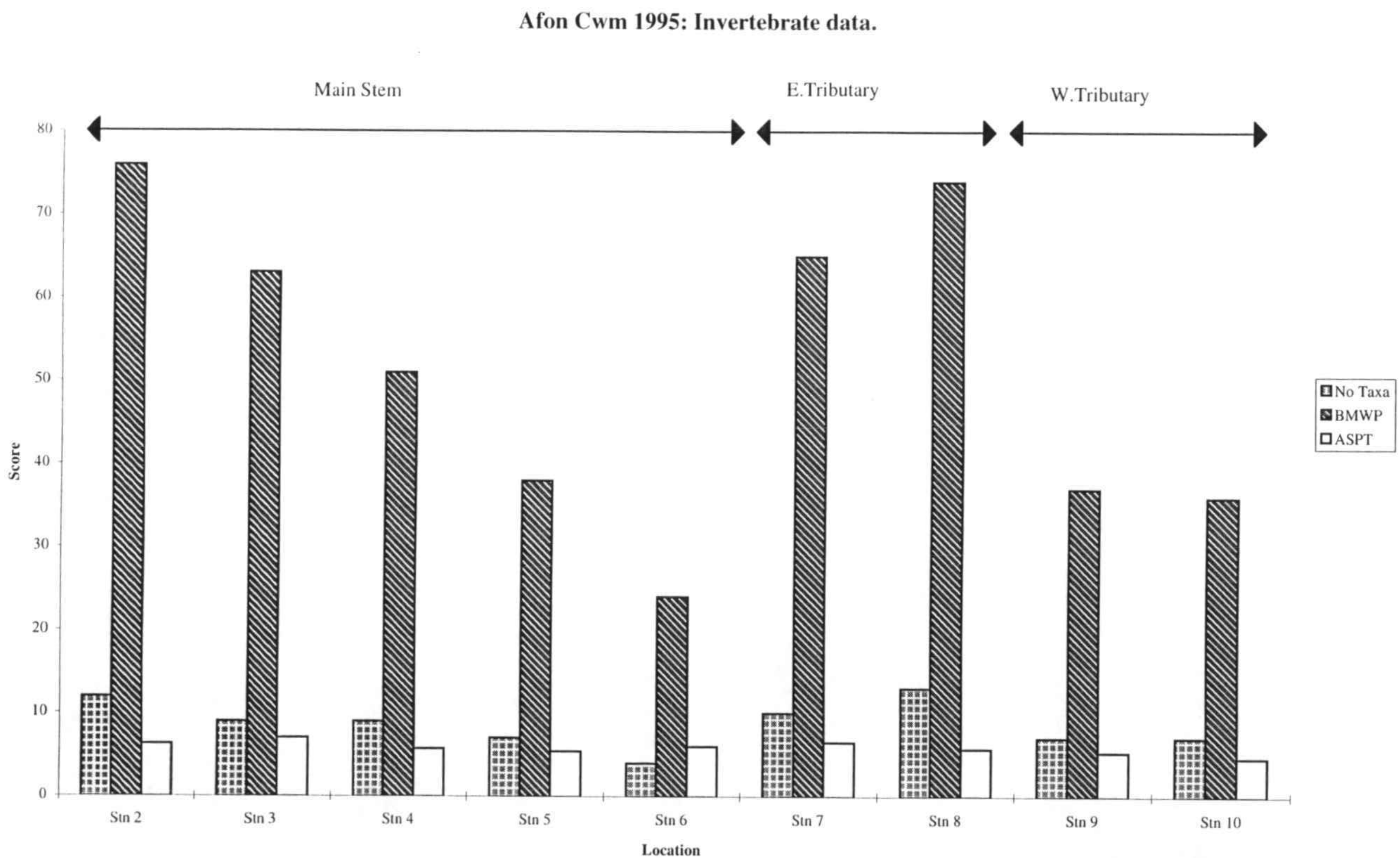


Fig. 5.1.1 Invertebrate densities (BMWP) and species diversity (number of taxa) at each of the sites in the Cwm catchment.

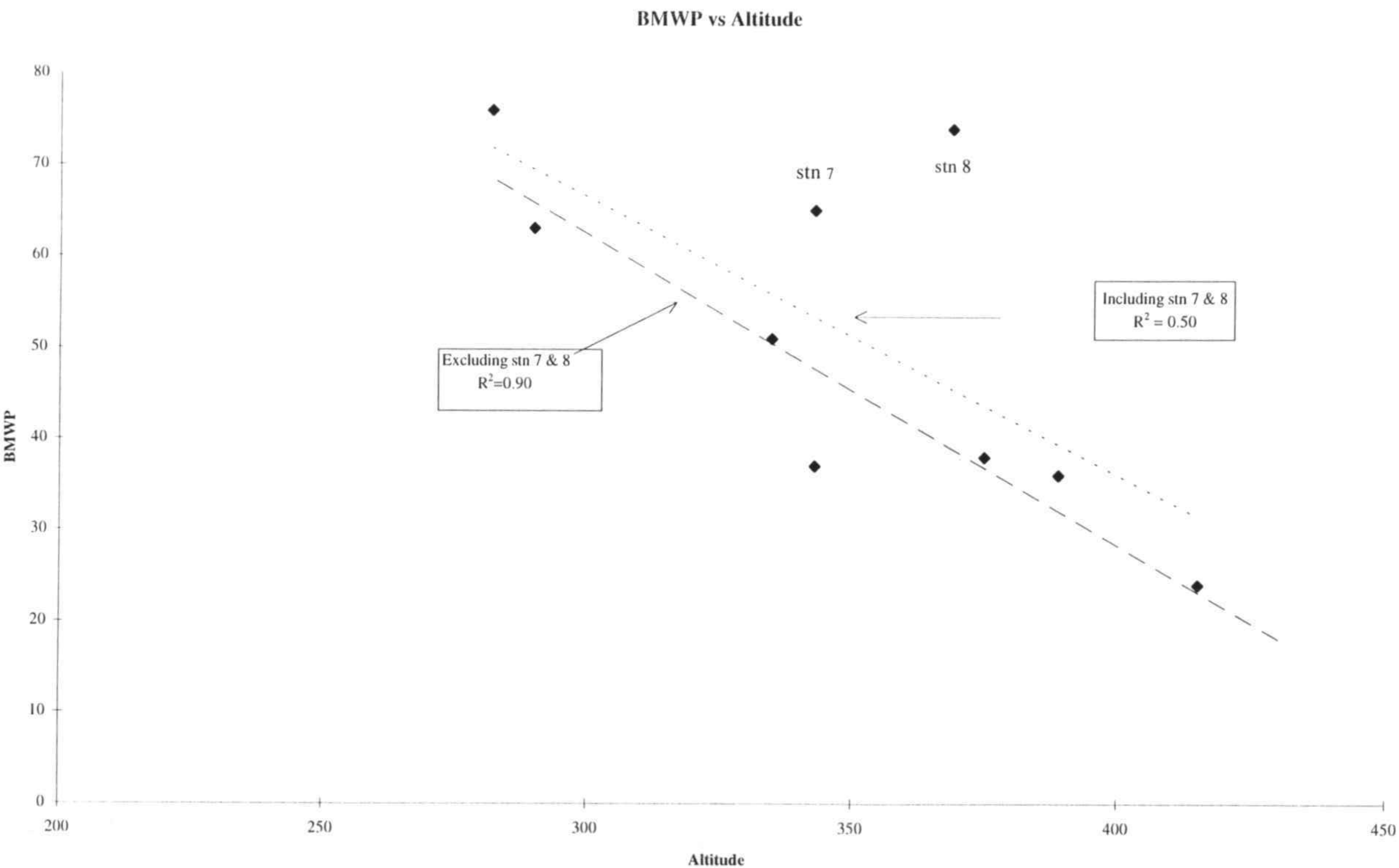


Fig. 5.1.2 Relationship between invertebrate score and altitude in the Cwm catchment.

Ddu) do not fit the relationship, and removing the data increases r^2 from 0.5 to 0.9. Preliminary chemical data indicate that the eastern Cwm catchment may have significant groundwater input. This supposition will be investigated further in the light of the chemistry data.

An intensive temperature survey of one of the eastern tributaries was carried out in November 1995 (fig 5.1.3). The tributary was, significantly, 1°C higher than the main stem, indicating the presence of a groundwater input that could have important implications for both invertebrate and fish populations.

5.2 Fish populations

Trout populations have been monitored in the Afon Cwm for 11 years, making this one of the longest studies of upland trout populations in the UK. Populations are assessed three times per year, in April, July and September (fig 5.2), using the methodology described in Crisp & Beaumont (1995). The April and September surveys are part of a long term MAFF funded project, with the July survey done specifically for this study. Data from both surveys are used for both projects. In 1995, bad weather delayed the July sampling until August, however, between-year comparisons with the previous July data will still be valid.

Population numbers of 0-group trout in August were high. Estimated numbers at the two multiple fished sites (2 & 4) were the second highest recorded, and estimated 0-group numbers above the weir were the fourth highest recorded. HABSCORE data from sites 2 & 4 however indicated that densities found were still within the expected range for the habitat. This probably means that, far from the densities found this year being 'high', 'normal' densities found are sub-optimal.

Populations of >0-group trout were low. Numbers at sites 2 & 4 were the second lowest recorded and total numbers from all sites above the weir were the third lowest recorded, continuing the trend of declining numbers observed since 1989. HABSCORE data from sites 2 & 4 indicate that habitat utilisation is significantly below that expected.

An assessment of the number of adult sea trout ascending the Cwm is given by an automatic fish counter mounted on the IH weir. Power supply to the equipment has caused problems that the installation of a wind generator has only partially alleviated. Tests will be carried out over the Summer 1996 in an attempt to reduce the power consumed by the equipment.

An assessment of the long term flow patterns within the Cwm shows some promise as part of the explanation for observed trout populations. Fish counter data will be correlated with flow in order to assess the optimum flow conditions for adult sea trout migration into the system. Historic recruitment data from the tri-annual surveys will be compared with autumn/winter flow patterns in order to assess the likelihood of past adult immigration in each year of the record.

Trout and invertebrate studies were also carried out in the Delyn control catchment. Populations were atypical, with no 0-group trout, and highly significantly fewer >0-group

Temperature Survey: Afon Cwm 16-11-95

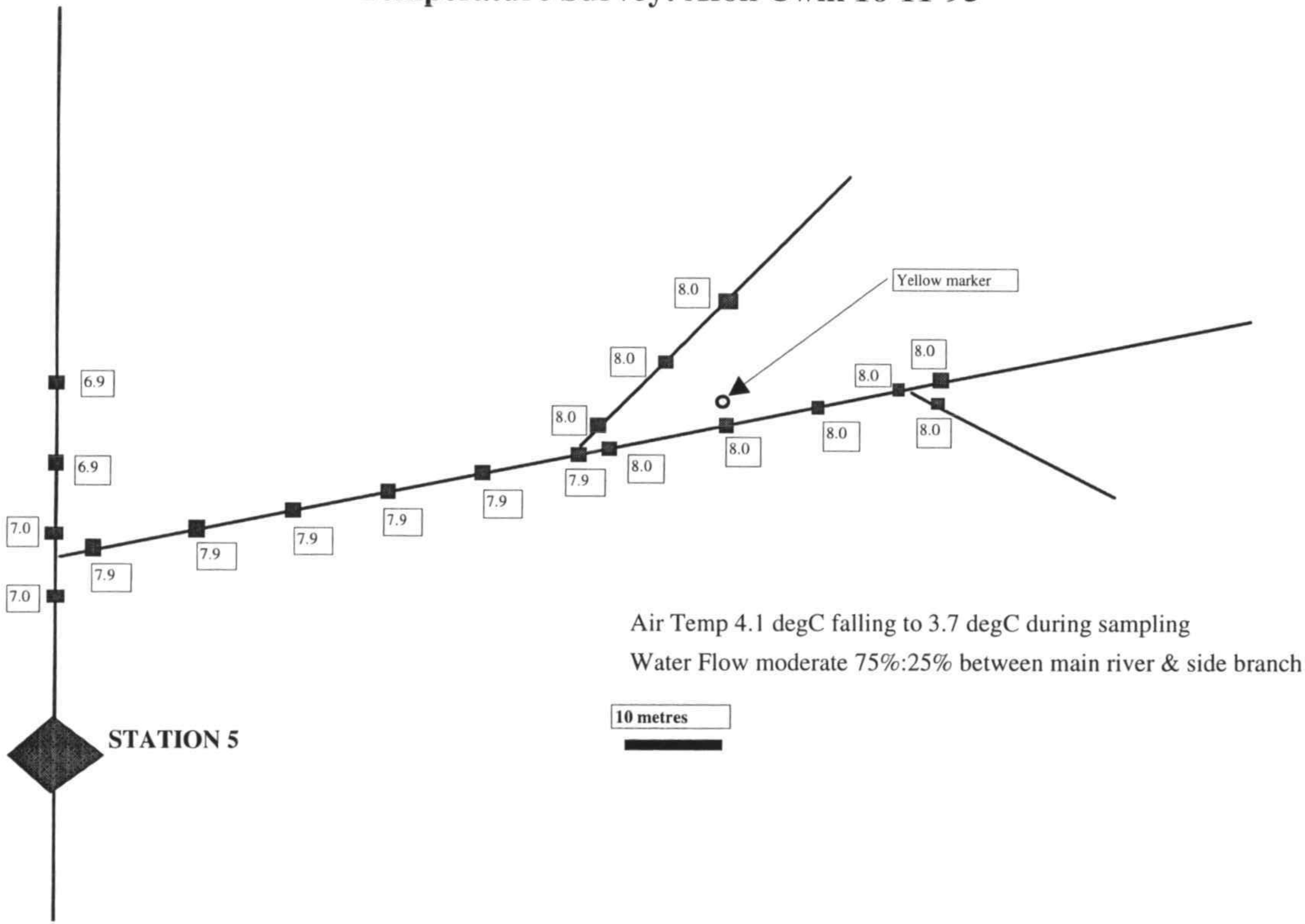


Fig. 5.1.3 ***Results of the 16/11/95 temperature survey on the eastern tributary and main stem of the Cwm.***

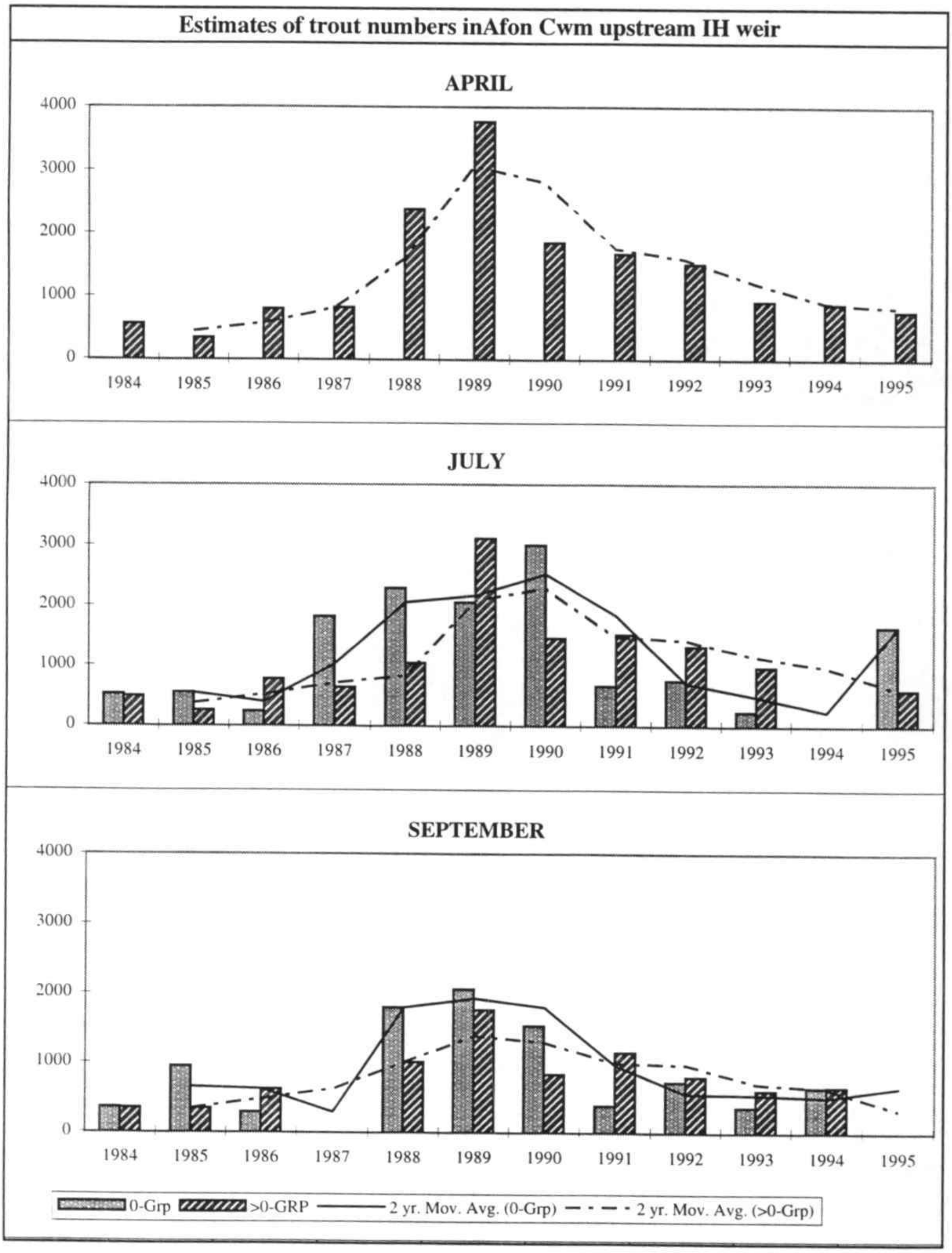


Fig. 5.2 ***Long term variability in the trout population of the Cwm from April, July and September surveys.***

fish present at the site. The stream gradient at the site appears to be much steeper than that found in the Cwm, to the clear detriment of recruitment.

6. Future programme

Over the next year, the following priorities will be tackled*:

* **NB** time, staff, funding and/or equipment availability permitting,

6.1 Instrumentation and data processing

1. Installation of an AWS and canopy raingauge on a tower in the Cwm.
2. Installation of cloud water collectors for quantity and quality.
3. Replacement of the ITE wet deposition sampler with a Warren Spring pattern collector.
4. Continuous monitoring of water quality using HYDROLAB equipment for short campaigns at selected stream sites in the Cwm and Delyn.
5. Current metering calibration of the Cwm Crump weir at different sediment levels*.
6. Production of sediment corrected flow data from the Cwm Crump weir. Infill of irrecoverable, sediment-affected data.

6.2 Process studies

1. Installation of an interception site near the AWS, including net rainfall gauges*.
2. Possible use of heat pulse, deuterium tracing and tree cutting techniques to measure transpiration.
3. Installation of soil moisture instrumentation at the interception site for transpiration studies and for input to soil water chemistry models*.
4. Installation of soil temperature probes at the interception site for heat budget and soil chemical reaction work*.
5. Second spatial chemistry survey at higher flows than before.
6. Low flow spatial gauging survey for contributing areas.
7. Installation of borehole in high alkalinity source area for groundwater level and chemistry monitoring*.
8. Initial runs of the full CHUM chemical model, optimising the hydrology and chemistry on Llanbrynmair data.

6.3 Catchment characteristics

1. Use of NERC GPS system for locating instrumentation sites.
2. Aerial survey of catchments by NERC aircraft (if operational)*.
3. Further digitisation of information from maps, photographs and multi-spectral images, for eventual loading to ARCHINFO*.
4. Use of GIS data for development of TOPMODEL as a base for catchment hydrochemical modelling.

7. References

Crisp, D.T. & Beaumont, W.R.C. (1995) The trout (*Salmo trutta* L.) population of the Afon Cwm, a small tributary of the Afon Dyfi, mid-Wales. *J.Fish Biol.*, 46, 703-716.

Emmett, B.A., Hudson, J.A., Coward, P.A. & Reynolds, B. (1994) The impact of a riparian wetland on streamwater quality in a recently afforested upland catchment. *J. Hydrol.*, 162, 337-353.

Hudson, J.A., Crane, S.B. & Robinson, M. (1993) The impact of new plantation forestry on the quantity and time-distribution of streamflow in the Llanbrynmair catchments, mid-Wales. *Annales Geophysicae*, Vol12, Suppl.II, Part II, C429.

Roberts, G., Hudson, J.A. & Blackie, J.R. (1986) The Llanbrynmair Moor Afforestation Study. Report to the Upland Water Quality Consortium. *Institute of Hydrology*, Wallingford, Oxon.

Leeks, G.J.L. & Roberts, G. (1987) The effects of forestry on upland streams - with special reference to water quality and sediment transport. in *Environmental aspects of plantation forestry in Wales* (ed. J.E. Good), ITE Symposium No. 22, 9-24.

Newson, A.J. & Clarke, R.T. (1976) Comparison of the catch of ground-level and canopy-level raingauges in the upper Severn experimental catchment. *Met. Mag.*, 105, 2-7.

Roberts, G., Reynolds, B. & Talling, J. (1987) Upland management and water resources. Report to the Department of the Environment and Welsh Office, *Institute of Hydrology*, Wallingford, Oxon.