INSTITUTE of HYDROLOGY

Nant-y-Moch Grassland Improvement Study

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Abstract

The initial stages of a catchment-scale study of the effects of upland pasture improvement on streamflow and on nutrient and sediment losses are described.

Major changes in upland use will affect not only the quantity but also the quality of receiving waters, and hence the biota they contain. In particular, deterioration in stream water quality resulting from intensification of upland management could reduce the beneficial diluting effect of upland runoff. Increasing nitrate concentration is of concern because of possible health implications. The eutrophication which can follow the release of phosphorus and potassium may lead to algal blooms and hence discolouration and odour in water supplies. Sediment loss may reduce reservoirs' capacity and harm fish spawning grounds.

Although much less widespread than afforestation, pasture improvement is a significant land use change in the Welsh uplands. This study compares two catchments draining into Nant-y-Moch reservoir: one acted as a control, while the other was subjected to pasture improvement, involving direct drilling of grass seed and surface application of fertilisers. Nutrient concentrations, rainfall and runoff were measured; sediment losses were estimated.

Elevated concentrations of ammoniacal nitrogen and total phosphorus followed the grassland improvement schemes, but they were insignificant on a catchment scale. No changes in suspended or bedload sediment were detected.

1. Introduction

This report describes the initial stages of a catchment-scale study conducted by the Institute of Hydrology (IH) into the effects of upland pasture improvement on streamflow and on nutrient and sediment losses. It is one of a range of related studies carried out by the Institute of Terrestrial Ecology (ITE), the Institute of Freshwater Ecology (IFE) and IH, under contract to the Department of the Environment (DoE) and the Welsh Office (WO). The locations of the various studies are shown in Figure 1.

The programme of research attempts to cover important aspects of upland use change with a view to predicting the effects on the quality and hence on the biota of receiving waters. From this an indication may be obtained of the implications of future land management for upland waters, valuable resources which have been taken for granted in the past because of their abundance and high quality.

Upland use change has implications for both the quantity and quality of streamflows. Most research in the past has concerned quantity and disregarded changes in quality. However, growing concern about the quality of British rivers has raised fears that more intensive management of the uplands may result in deterioration in water quality: this could reduce the beneficial role of upland runoff which dilutes waters downstream polluted by agricultural, industrial and sewerage effluents.

Of immediate concern to the water industry is the increasing concentration of nitrate in water supply sources (Royal Society, 1983). High concentrations of nitrate have been implicated in the deaths of young babies from a disease known as methaemoglobinaemia, although such occurrences have been rare in Britain. More recently the ingestion of large amounts of nitrate has been blamed for cases of gastric cancer, but the evidence for this is not conclusive. However, whilst doubts exist, a limit has been set on nitrate concentrations in potable water. In the past the recommended limit was 11.3 mg N/ℓ, with an acceptable limit of 22.6 mg N/ℓ (WHO, 1970). More recently, the European Economic Community issued a directive (EEC, 1980) which effectively halves the recommendation of the World Health Organisation. Although nitrate concentrations in upland watercourses are unlikely to reach these levels, the fear is that deteriorating quality, coupled with the reduced water yields resulting from more intensive upland use, will diminish the role of upland water as a downstream dilution agent.

Another cause for concern is the eutrophication of rivers, lakes and reservoirs as a result of the release of phosphorus, and to a lesser extent potassium, following upland use changes. This may lead to the growth of algal blooms: when they decay, these may cause discolouration and unpleasant odours in water supplies. Soil disturbance can also increase sediment losses, which, if significant, can reduce the storage capacities of reservoirs and can be detrimental to fish spawning grounds.

Pasture improvement is much less widespread in areal extent than afforestation, currently the biggest land use change occurring in the British uplands. Nevertheless in some areas, particularly in Wales, such improvement schemes

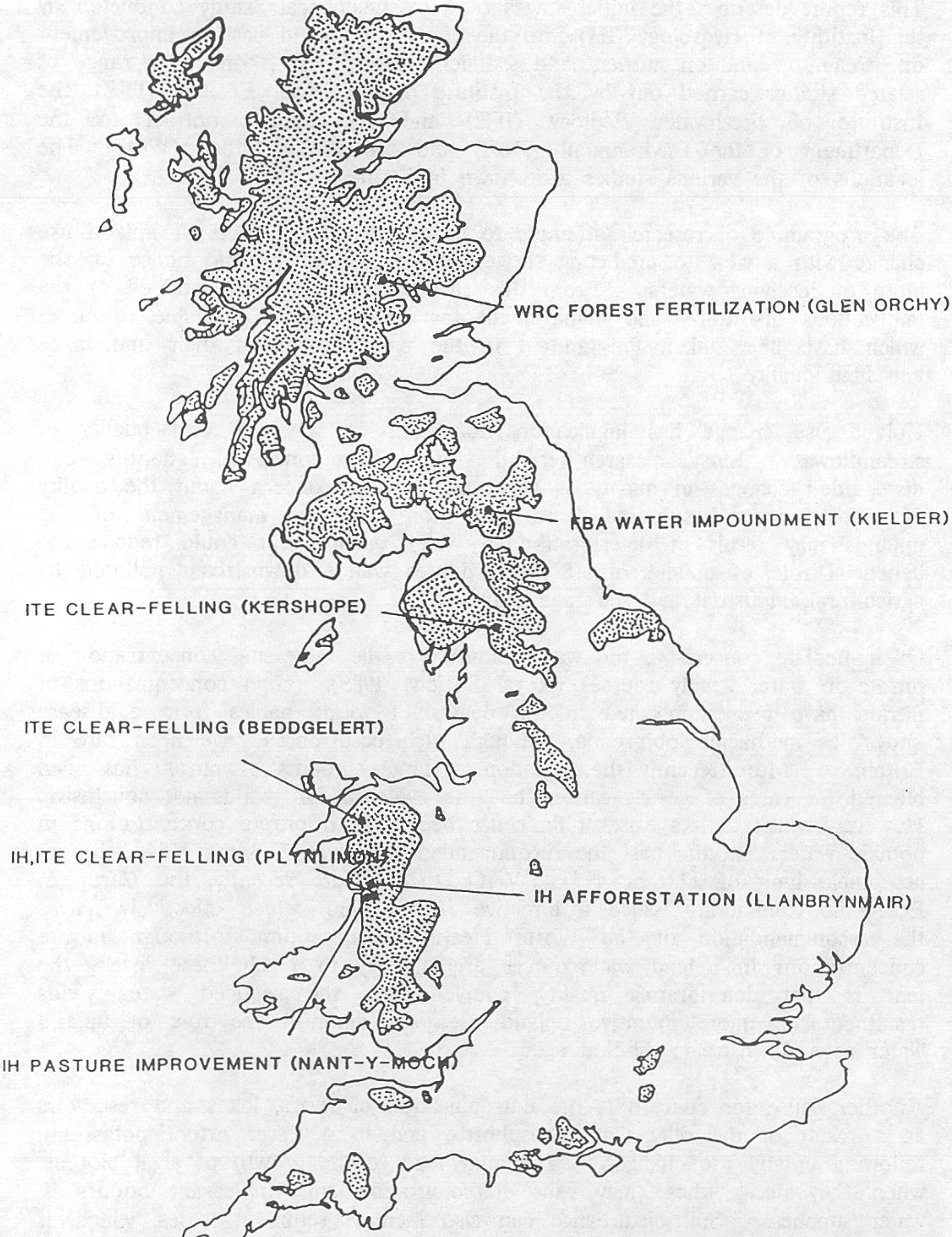

Fig. 1 The uplands of Britain showing the locations of the studies

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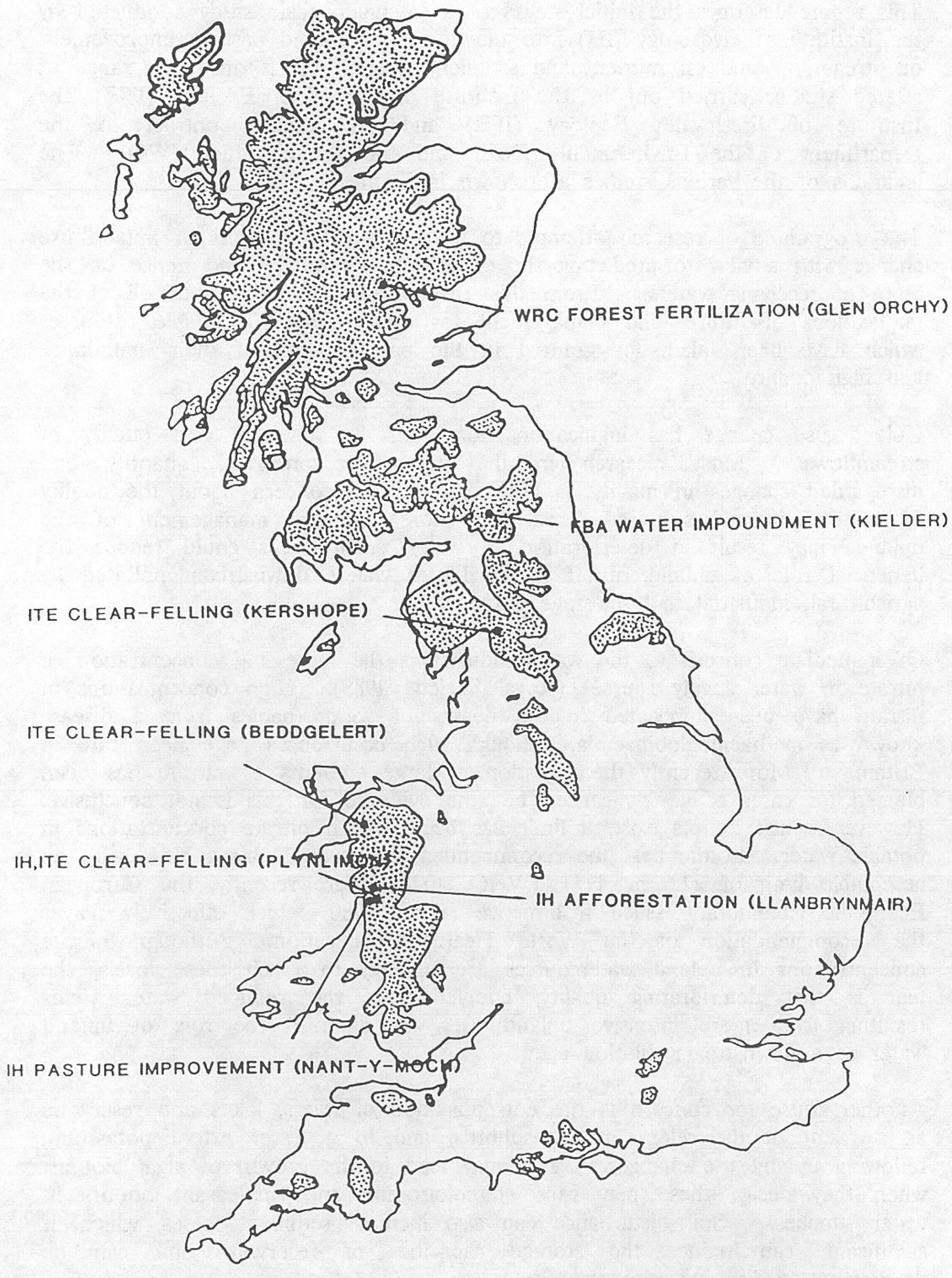


Fig. 1 The uplands of Britain showing the locations of the studies

are a common feature. The intensity of these schemes can vary, depending on the amount of soil disturbance involved, ranging from field drainage and deep ploughing to the more recent minimum cultivation techniques involving the direct drilling of grass seeds and surface application of fertilizers. This particular study involves the latter type of improvement scheme.

Two catchments, both draining into the Nant-y-Moch reservoir in mid-Wales (Fig. 1), were involved in the experiments reported here. One catchment acted as a control, whilst a percentage of the other was subjected to a pasture improvement scheme over a two year period. Although the main object was to study nutrient concentrations, the opportunity was taken to instrument both catchments to measure rainfall and runoff, and to estimate sediment concentrations and losses. Thus the Institute's upland research programme was strengthened at a location immediately to the west of its primary Plynlimon fieldwork but with a different seaward-facing aspect.

2. The uplands of Britain and pasture improvement

The uplands of Britain, generally accepted to be those areas above an altitude of 200 m (Stapledon, 1937), occupy some 7.3 million ha, about one third of the total UK land area. Most of these areas are concentrated in Scotland, with smaller areas in northern England and Wales (Figure 1). All of the areas have been specified as 'less favoured' in an EEC directive (EEC, 1975).

Low temperatures, severe wind exposure, excessive precipitation, persistent winter frost and snow cover are the notable upland climatic features (Taylor, 1976). The geology is varied but is dominated by the harder rocks of low base content. This, coupled with strong leaching by rainfall, results in acidic soils dominated by peats and peaty podzols, often with severely impeded drainage. Freely-drained, acid, brown earths predominate on the steeper slopes. In some areas limestone outcrops, or moraines and meltwater deposits dominated by crystalline limestone, result in less acidic soils. Upland soils are generally rich in organic matter and contain large quantities of soil nutrients, particularly nitrogen (up to 10,000 kg/ha), but only a small part of this, approximately 30 kg N/ha, is available for absorbtion by plants (Floate, 1971).

The combination of soils and climatic conditions ensures that agricultural production in the uplands of Britain is limited (Francis, 1978). Vegetation is generally restricted to those species which are tolerant of acidic, anaerobic and often waterlogged conditions. Grass heaths and heather moorland dominate the vegetation. The most useful natural hill grasses for animal grazing are sheep's fescue (*Festuca ovina*) and wavy hair grass (*Deschampsia flexuosa*); *Molinia* and *Nardus* species are largely ignored. The growing season is limited by soil temperature, 6°C being generally accepted as the critical minimum for plant growth. In upland areas, this threshold is not normally reached until late April or early May and is then sustained for between 5 and 6 months.

After this, the quantity and quality of the vegetation, at best only moderate, decline and the uneaten herbage accumulates and senesces in situ. The breakdown of this organic matter is slow: as a result, a surface layer of peat gradually accumulates (the A_0 horizon).

Most of Britain's upland areas has fall into Grade 4 or 5 on the Ministry of Agriculture land classification scale. Grade 4 land has 'severe limitations due to adverse soil, relief or climate, or a combination of these. A high proportion of this land will be under grass, with occasional fields of oats, barley or forage crops'. Grade 5 land has 'very severe limitations due to adverse soil, relief or climate, or a combination of these. This land is generally under grass or rough grazing, except for occasional pioneer forage crops'.

Traditionally these upland areas have been used mainly for marginal sheep farming and game shooting. There are some 21,000 upland farms in Britain. Although these farms extend over large areas, they are, more often than not, small family businesses. They contribute nearly one half of the sheep and wool production of Britain. Stocking densities range from 0.25 to 1.5 ewes per hectare. The gross output of upland farming amounts to some £830 million, 7.5% of gross agricultural output of Great Britain (Eadie, 1984).

These areas are also vital to the water supply industry as gathering grounds. The low agricultural activity ensures that streamflow is of highest quality and requires only minimal treatment to make it suitable for potable supply. This fact and the high rainfall, low evaporation and hence high runoff rates have resulted in the construction of a number of water supply reservoirs in the uplands. These reservoirs, particularly in Wales and northern England, provide the greatest part of the water supplies to the industrial conurbations in the lowlands. Of particular importance is the role of upland runoff in diluting flows affected by industrial, urban and agricultural pollutants downstream.

The British uplands have long been the object of conflicting interests, including conservation, recreation, water supply, agriculture and forestry. Government demands to increase upland productivity have intensified pressure on the uplands. In particular, proposals have been made to increase the forested areas in the uplands in order to reduce the quantity of timber imported into the UK, currently 90% of requirements, costing £4 billion per year. 1.4 million ha of the uplands have now been afforested; if the plans are implemented a further 1.8 million ha will be planted by the year 2025, mostly in Scotland, increasing the proportion of forested land in the uplands to 47% (Forestry Commission, 1977). On the other hand, a government white paper (Anon, 1975) has called for an increase of 19% in the production of lamb in Great Britain. Much of this increase would be expected from upland areas, based on intensifying agricultural output using the results of work on plant breeding and potential pasture production (Munro *et al.*, 1973). It is difficult to assess the amount of upland pasture improvement that has taken place, because a large number of small areas is involved and diverse types of improvement scheme have been implemented, often over short periods. However, an estimate has been made that a total of 150,600 ha of moorland has been ploughed in the last 30 years in England and Wales alone and that the rate is increasing (Parry *et al.*, 1981). The annual rate of conversion from semi-natural vegetation to re-seeded swards for farming purposes (approximately 5,000 ha) is small compared to the officially intended annual rate of afforestation (around 30,000 ha). Nevertheless the fear is that these improvement schemes have the potential to cause deterioration in upland water quality, with subsequent problems for the water supply industry.

Estimating the extent of the areas affected by pasture improvement is difficult: there are various degrees of improvement scheme and improved swards revert through neglect. There are also large regional differences: the generally small size of hill farm in Wales, with its economic pressures, has made pasture improvement a necessity for financial survival, whereas this has not been the case in most parts of the north of England or Scotland (Eadie, 1984). Methods of improvement range from the erection of a fence to restrict grazing of the indigenous vegetation, through drainage, liming and the application of inorganic fertilisers, to complete reseeding following the destruction of the indigenous vegetation. The type of improvement implemented depends not only upon the physical and chemical characteristics of the area of land, but also upon economic factors such as capital, stock and labour.

The three main limiting factors to pasture improvement in upland situations are the shortness of the growing season, phosphate deficiency and the acidic nature of the soil. In the past, basic slag was a reasonably cheap source of phosphorus and lime, but changes in the steel-making process have made this by-product progressively harder to obtain. Moreover, the withdrawal of the lime subsidy in 1976 meant that farmers became reluctant to maintain reseeded swards.

Although incentives to improve upland pastures do exist in the form of grants under the Farm and Horticulture Development Scheme and a more guaranteed return of investment under the EEC Sheepmeat Regime, a recent reduction in grant aid for land improvement projects from 50 per cent to 30 per cent has made the future of such projects even more uncertain. This uncertainty has led to the concept of an integrated upland management policy whereby, for example, a farmer may sell the less productive part of his land for forestry purposes and use the revenue to improve the more productive land. Alternatively, he may utilise one of the various aid schemes for woodland investment on farms, the planted areas acting as shelter belts which benefit both grass growth and wildlife.

Most upland improvement schemes are carried out under a two-pasture system so as to maintain a balance between summer and winter nutrition (see, for example, HFRO, 1973). Sheep are supplied with the best possible diet from improved pastures during the key stages in their annual cycle: prior to parturition, during lactation and lamb growth, and prior to mating. At other times of the year, the sheep graze unimproved areas, thus giving the improved sward a chance to recover. Under this system, upland pastures are composed of a patchwork of different areas: unimproved, indigenous vegetation is interspersed with smaller, fenced, improved areas and sometimes small plantations of forestry.

Although a small increase in pasture production may be obtained simply by controlling the grazing of the indigenous vegetation, it has long been recognised that the key to improved upland production is the replacement of this vegetation by a mixture of various grasses, preferably including clover. The preparation of the seed bed will depend on local conditions but will normally involve some combination of drainage, liming, removal of the existing vegetation, disc harrowing and a fertiliser application. In the past, the existing vegetation would normally have been removed by deep ploughing, but fears of soil erosion and the loss of mineralised nutrients by leaching have led to the adoption of minimum cultivation techniques (ADAS, 1984): the vegetation is removed either by burning or by herbicide applications and the grass seed direct-drilled into the soil.

Table 1 shows the general advice on pasture improvement given by the Agricultural Development and Advisory Service of the Ministry of Agriculture to Welsh upland farmers.

The prime aim of an intensive pasture improvement scheme is the development of a grass/clover sward and farmers are advised to maintain the clover level at 20-25%. This will contribute about 100 kg of nitrogen per hectare to the sward (Munro & Davies, 1973). In the absence of the clover, because the efficiency of applied fertiliser is only 50%, an annual average application of about 200 kg N/ha would be necessary to maintain a grass-only sward. In most upland situations, this would be too expensive. In addition, clover has a high crude protein content compared to that of grass, a higher level of digestible energy, a higher content of magnesium, calcium and iron, and is high in carotene. On the other hand, its growing season is shorter than most grass species. This has led to the "pepper pot" principle of mixed seed applications, which is done in an effort to ensure that at least some of the grasses survive the initial growth stages and to extend the growth season over as long a period as possible. One drawback to successful clover establishment in the uplands is the acidity of the soil and it is generally agreed that it is necessary to raise the pH of the soil to at least 5.5 before reseeding. This requires an application of lime of between 5 and 8 t/ha, depending on the soil. It is also necessary to correct the phosphate deficiency: this may require the equivalent of 30-40 kg P/ha. During the preparation of the seed bed, a general N, P, K fertiliser is added to give, typically, 40 kg N/ha, 40 kg P/ha and 80 kg K/ha. The seed mix will depend on local conditions and availability, but will generally consist of perennial ryegrass, red fescue, timothy and white clover.

Subsequent fertiliser applications to the reseeded sward would normally be confined to phosphorus, every three years or so, and lime, every eight to ten years. Nitrogenous fertiliser would normally be avoided, relying on the nitrogen fixing capabilties of the clover. In any case, nitrogenous fertiliser application would tend to favour the growth of the tall grasses to the detriment of clover which would be counterproductive.

3. Literature review

A number of catchment-scale monitoring studies (for example, Reid *et al.*, 1981; Roberts *et al.*, 1983) have recently been carried out on the chemistry of streamflow from undisturbed upland catchments. The results obtained testify to the purity of the water. For most chemical determinands, in particular the

Reclamation of rough pasture has long been a feature of hill farming in Ceredigion but their enthusiasm for the plough has misled many farmers on peaty soils. A method has been developed over the last twenty-five years, whose basis is the grafting of a nucleus of sown species on to the old sward and then fostering its development by good husbandry. The aim is to preserve the surface crust overlying the peat. The old vegetation must not be destroyed outright, either by cultivations or chemicals, for the resulting vacuum could well be invaded by moss and rush, besides removing shelter at high altitudes for what are mostly lowland species. It is a gradual process in tune with the environment, which results in a close-knit productive sward, combining the best of the old and the new species, the former being able to utilise more readily the large reserves of nutrients present in hill soils.

The first stage is to apply a modest dressing of ground limestone (5t/ha or 2 ton/ac lime) and a heavy application of basic slag (1.5-2t/ha or 12-15 cwt/ac) to the moorland during the previous summer, when the ground is dry, taking care to do no damage to the surface crust.

The second stage, in March and April, is as follows:-

1. The native vegetation, where profuse, is burnt slowly against the wind or, where too sparse for the fire to run, is cut at ground level with a flail mower: cutting needs time, patience and power: burn before 15 April in the hills or apply for a licence to burn later.

2. The cut material is then windrowed and burnt (or buck-raked into hollows in wet weather): burn before mid-April.

   The bare surface, essential for seeding and subsequent grassland management, is then disc harrowed, preferably with scalloped discs. These are set at an angle, consistent with effective shallow penetration but not the exposure of clods, the number of passes varying from 1-2 in the hollows to 3-4 on the drier ridges. Harrows or spike rotovators, with alternate spikes removed, are alternatives. A strip seeder may be used which cuts a groove, into which seeds fall but this is done more to renovate previously improved pastures which have degenerated.

3. Seeding follows disc harrowing on the first dry day, with no intervening operation, using a fertiliser spreader to which a grass harrow is attached. Inoculate clover with rhizobia for high moorland far from rotational grassland.

   Rolling is only practicable in a minority of cases, but yearling sheep, just back from wintering in early April, are often used to tread in the seeds. In many cases reliance is put only on the consolidating effect of the twin-wheels of the tractor when completing the operation by sowing 400 kg/ha (3 cwt/ac) of say 25:0:16 fertiliser.

5. Seeds mixture

   6.7 kg/ha (6lb/ac) of perennial ryegrass (Barlenna or Talbot)
   9 kg/ha (8lb/ac) of perennial ryegrass (Parcour or Lamora)
   4.5 kg/ha (4lb/ac) of red fescue (S59)
   3.4 kg/ha (3lb/ac) of timothy (S48)
   2.2 kg/ha (2lb/ac) of alsike clover
   2.2 kg/ha (2lb/ac) of wild white clover (S184 or Kent)
   28 kg/ha (25lb/ac) Total

MANAGEMENT

Heavy grazing, preferably with cattle, on a rotational basis should start early in summer to prevent smothering of the young seeds by the native vegetation. Excess growth should be topped at least once in the season. In the following spring, a dressing of about 250 kg/ha (2 cwt/ac) of 20:14:14 or 20:10:10 fertiliser is applied. In the past, basic slag would have been applied every third year and lime every eighth year.

Farmers who are surface-seeding for the first time often delay grazing as they would with conventional reseeding, by which time the native grasses are growing strongly. They have to learn to turn stock in early when the latter are young and succulent, for the treading will more than compensate for a few uprooted seedlings. Again those relying on sheep only, will have to put on a heavy stocking for a short period, otherwise the pasture will grow away, become stale and the ewes restless. It is no good then turning in more sheep but, to cut your losses, turn them all onto fresh ground and top the pasture in readiness for the next time round.

Gwynn Jones
Hill Farming Adviser (Wales)
July 1984

Table 1 WOAD/ADAS Leaflet. Renovation of mountain pastures in Ceredigion.

plant nutrients nitrogen, phosphorus and potassium, outputs in streamflow are considerably less than inputs in rainfall. Similarly, sediment losses from undisturbed catchments are small (Newson, 1980). This situation, coupled with high rainfall regimes, makes these uplands ideal gathering grounds for water supply reservoirs. At the same time landowners have been encouraged to make maximum use of the land. A committee set up by the Ministry of Health stated this as one of its conclusions: "Subject as before to the protection of the reservoir itself and its immediate feeders, we consider that the greatest freedom should be allowed to all farming activities, and indeed that it should be regarded as the responsibility of those undertakers who are large landowners not merely to permit but to insist upon the most productive use of their land." (Ministry of Health, 1948). It would seem, therefore, that the next logical step should have been a series of studies to determine the effects of various land management strategies on the quality of upland waters so that "the protection of the reservoir itself and its immediate feeders" should be assured. Such studies have only slowly been forthcoming, and only recently, following the expansion of forestry and pasture improvement schemes, have results become available.

Substantial nutrient losses, particularly of nitrogen, have been reported as a result of the disturbance of organic soils (Duxberry & Peverly, 1978; Benoit, 1973). The drainage of upland areas, both for afforestation and for pasture improvement, has also been implicated in the release of massive quantities of sediment into upland reservoirs (Newson, 1980). In spite of this, very few studies of the effects of different pasture improvement schemes on the quality of upland streamflows have been attempted. There are several possible reasons for this. In the first place such schemes, being of a gradual nature, are generally regarded as less of a potential problem than afforestation, which is currently a much more widespread and more rapid upland use change. This is particularly so since similar practices are employed in each (drainage, liming, vegetation elimination, fertiliser applications). Once established, grass swards are efficient users of applied fertilisers and so leaching losses are likely to be small (Barraclough *et al.*, 1983), especially at the low rates likely to be applied in upland situations. The research which has been conducted has been aimed at the agricultural sector to find, for example, the response of new grass species to fertiliser inputs. Much work of this type is being conducted at the Hill Farming Research Organisation in Scotland and at the Welsh Plant Breeding Station.

Two aspects of the effects of pasture improvement need to be considered. The first is the short-term effect of the scheme itself; the second the long-term effect of increased nutrient cycling as a result of the improvement. The first effect will obviously depend on the techniques adopted, which in turn depend to a large extent on local conditions. The second effect will depend on the management of the improved areas in terms of grazing density and fertiliser applications. In considering the quality of streams and reservoirs, another important factor is the areal extent of the scheme and how much of its effect will be diluted by the undisturbed areas of the stream or reservoir catchment.

Perhaps the most significant study of the short-term effect on nutrient release was reported by Roberts *et al.* (1986a). Here an intensive pasture improvement scheme, involving drainage, liming, deep ploughing, reseeding and fertiliser applications, was studied in a "natural" lysimeter and on a small, 1.5 ha, drained plot. Enhanced nitrogen (specifically nitrate) concentrations with peak values of 18mg N/l, were observed in flows from both the lysimeter and the main drain from the plot for several months following the implementation of the scheme. Total nitrogen losses attributable to the improvement were found to be 62.4 kg/ha in the first year following improvements and 18.0 kg/ha in the second. Nitrogen inputs in fertilisers were 125 kg/ha in the first year and 50 kg/ha in the second and third years. The effect of the scheme on other nitrogen species and on potassium and phosphorus losses was negligible.

Obviously what was observed in this small-plot study cannot be taken to be representative of what actually occurs on a catchment scale. Therefore a model simulation of a "typical" catchment improvement scheme, over a seven year cycle, was attempted using the data obtained from the lysimeter and from unimproved upland pastures (Roberts *et al.*, 1983). This simulation predicted that average total nitrogen concentrations at the catchment outfall would rise following the improvement from a background level of 0.5 mg/l to 2.0 mg/l. Annual losses would increase from about 10 kg/ha to 40 kg/ha. Thus an interesting comparison may be drawn between nutrient concentrations in the field drain (Roberts *et al.*, 1986a) and those in the cut-off drain, reported in this study.

Nutrient losses from cultivated land under "similar" conditions as reported in the literature vary a great deal reflecting the numerous controls affecting these losses. In the study of a clay and silt cultivated area in Finland (Seuna & Kauppi, 1980) large increases in nitrate concentrations were observed following sub-draining of a whole catchment. The range of annual means of total nitrogen concentration was increased from 1.4 - 3.6 mg/l to 4.9 - 20 mg/l, while increases for nitrate-N were from 0.68 - 7.1 mg/l to 2.0.0 - 17.0 mg/l. Increases in annual loads varied from 15 to 23 kg/ha for nitrate-N. The biggest changes were found in the first two years following the drainage but were still evident after seven years. No clear effect of sub-drainage was observed for phosphorus.

Drainage combined with a fertiliser application at the rate of 45 kg/ha of phosphorus and 85 kg/ha of potassium caused phosphorus concentrations in the runoff from a 16.9 ha peat basin in Finland to increase from 0.018 mg/l to 0.128 mg/l. Potassium concentrations increased from 0.33 mg/l to 1.20 mg/l. The effect of the phosphorus fertiliser on runoff water quality could be detected for at least 5-10 years after application whereas the effect of potassium fertilisation disappeared in 1-2 years (Kenttamies, 1980). Similar results have been found in other parts of Finland.

Studies carried out on several plots in Israel showed massive losses in the organic nitrogen content of the soil following the cultivation of previously undisturbed pasture (Reinhorn & Avnimelech, 1974). The amount of nitrogen released was found to be directly proportional to the original content and was generally of the order of several thousand kilograms of nitrogen per hectare. No indication was given of the fate of this released nitrogen. Olsen *et al.* (1970) on the other hand, in their study of 25 Wisconsin soil profiles, found nitrate-N concentrations to be higher in cultivated soils than in undisturbed soils.

Duxbury and Peverly (1978) found annual nutrient outputs which ranged from 0.6 to 30.7 kg/ha for phosphate-P, 39.2 to 87.5 kg/ha for nitrate-N and 1.0 to

1.9 kg/ha for ammonium-N from cultivated organic soils located in New York. Maximum observed concentrations were 35 mg/ℓ for nitrate-N and 10 mg/ℓ for phosphate-P. Hortenstine and Forbes (1972) found high concentrations of nitrate-N (up to 150 mg N/ℓ) and phosphate-P (up to 30 mg P/ℓ) in soil solutions from unfertilised muckland adjacent to Lake Apopka in Florida. Erickson and Ellis (1971) reported that 18.7 kg N/ha and 1.45 kg P/ha were leached from the Michigan State University experimental muck farm in 1969, while only 4.1 kg N/ha and 1.6 kg P/ha were contained in drainage water from the Holland Marsh, Ontario in the spring of 1971 (Nicholls & MacCrimmon, 1974).

Studies carried out in the upland areas of the UK also show enhanced nutrient losses from improved grassland. Newbould and Floate (1977) reported annual losses of 30 kg N/ha from intensive sheep farming on grass receiving 120 kg N/ha at the Hill Farming Research Organisation. Total mineral nitrogen losses averaged 40 kg N/ha/year from a small (41 ha) catchment under permanent grassland receiving 284 kg N/ha annually (190 kg N/ha as fertiliser, 5,000 tonnes of farmyard manure and 182 m^3 of slurry) at the Great House Experimental Husbandry Farm (Webber & Wadsworth, 1975). On a number of occasions, nitrate-N concentrations of over 10 mg/ℓ were found, with a peak value of 26 mg/ℓ. These high concentrations were associated with heavy rainfall immediately following applications of organic manures or fertilisers. Losses of phosphorus, on the other hand, were very low, usually less than 1 kg P/ha/year.

Leeks (1980) found higher concentrations of both ammonium-N and nitrate-N (0.11 mg/ℓ and 1.6 mg/ℓ respectively) in streamflow from previously improved pasture receiving no fertilisers than she found from unimproved pastures (0.04 and 1.0 mg/ℓ). Ortho-phosphate concentrations were slightly higher in the improved pasture; higher concentrations of chlorophyll 'a' and larger numbers of organisms and higher species diversity were also found in streams draining the improved pastures.

The figures quoted above generally represent the worst possible results. Other studies, many of them unpublished, suggest no detrimental effects. Predicting the effects of a particular land management scheme is therefore a difficult and hazardous exercise. It is hoped that the results obtained from this study add to the information available, thus making such predictions easier.

4. The study area

"From high Plynlimon's shaggy side
Three streams in three directions glide,
To thousands at their mouth who tarry
Honey, mead and gold they carry ...."

George Borrow

4.1 NANT-Y-MOCH

The "three streams" referred to in George Borrow's poem are the Severn, the Wye and the Rheidol. The Nant-y-Moch study area is in the upper catchment of the Afon Rheidol and is covered by the grid square SN2700 to SN2850 and SN2800 to SN2950. The Nant-y-Moch reservoir is situated 26 km south of Machynlleth and 34 km north east of Aberystwyth.

The catchment area for the Rheidol valley (Figure 2) covers an area of approximately 161 km^2 and the region has an annual range of rainfall of about 2,000-2,300 mm. The Rheidol rises on the Plynlimon range of hills on Pumlumon Fawr (720 m). The solid rocks of this district are of Lower Palaeozic age of the Ordovician and Siluvian systems. The whole area was covered by a large ice sheet in Pleistocene times, which streamed outwards from its centre on Cader Idris. The Rheidol valley represents a typical U-shaped glaciated valley; the two stony ridges of terminal moraine which have diverted the river into rock gorges are also typical of a glaciated valley. These moraines probably formed the limit of the glacier at some stage. The upper moraine now contains Dinas Dam, the lower turns the Afon Rheidol into a narrow gorge just below the village of Devils Bridge.

The northern part of the study area has a series of underground aqueducts which channel water into the Afon Llechwedd-Mawr, Afon Hyddgen and Afon Hengwn: these rivers subsequently feed the Nant-y-Moch reservoir. The reservoir is part of the Rheidol Hydro-Electric scheme, constructed between 1957 and 1962. This Central Electricity Generating Board scheme generates 56MW of electricity in three stages.

Much of the area is owned by the Crown Estate Commissioners who proposed a hill improvement scheme in December 1981 to commemorate the marriage of the Prince and Princess of Wales. The project area is part of the land of the manor of Perfedd, where in past years arable crops were grown on the better land while the rest was left to common grazing. The scheme involved improving 120 ha of grassland on the lower slopes and planting approximately 80 ha of shelter belts, fencing some of the common land and constructing a car park and a footpath for visitors. An added complication was the fact that part of the area is specified by the Nature Conservancy Council as a Site of Special Scientific Interest (SSSI). To reconcile the differences between the Crown Estates' proposal and the farming, conservation and tourist interests, the scheme was put before a public inquiry. In December 1983 permission was granted for part of the scheme (Figure 3) and its implementation began almost immediately.

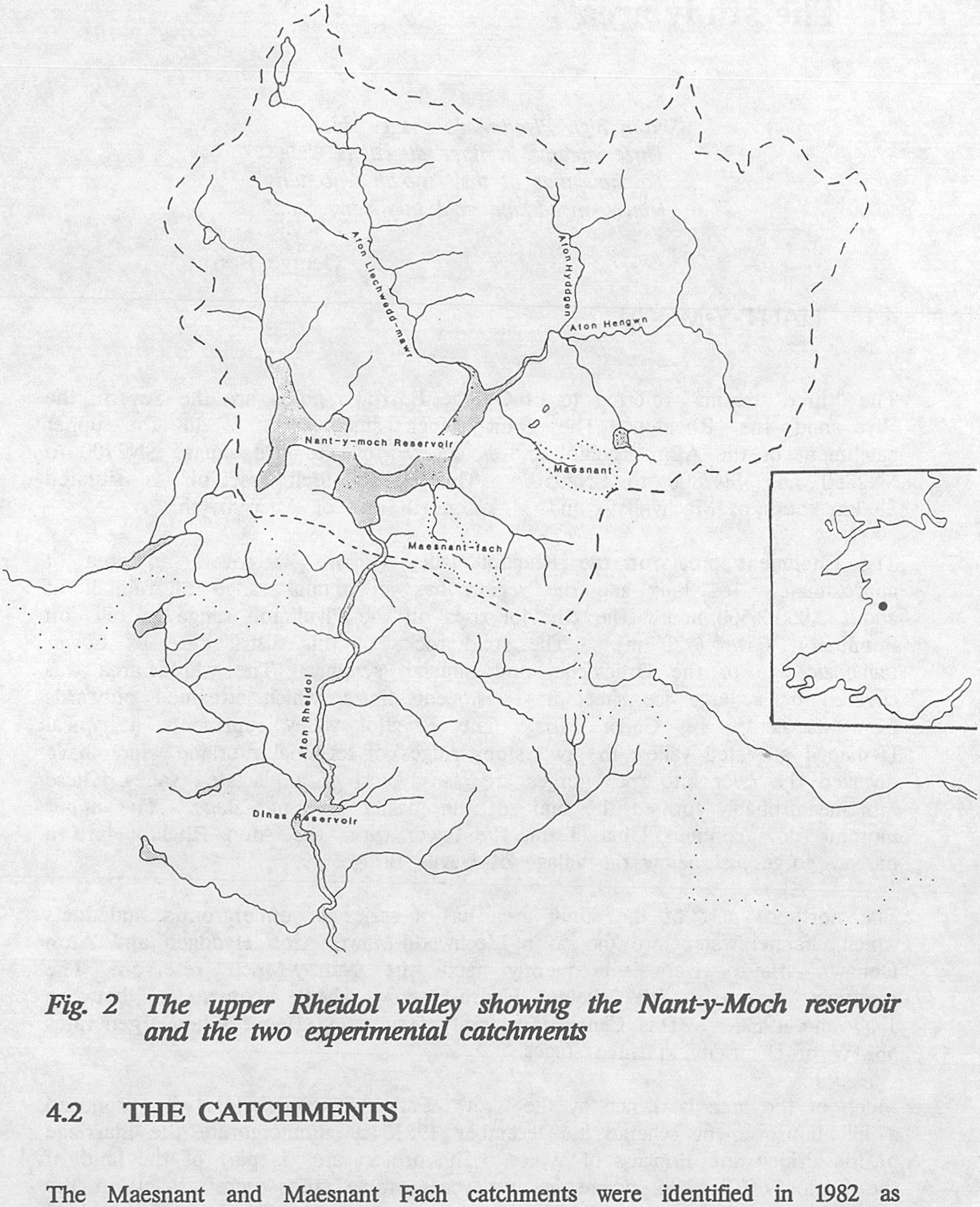


Fig. 2 The upper Rheidol valley showing the Nant-y-Moch reservoir and the two experimental catchments

4.2 THE CATCHMENTS

The Maesnant and Maesnant Fach catchments were identified in 1982 as suitable for monitoring the effects of the grassland improvement scheme. The "experimental" catchment is the Maesnant Fach and the "control" catchment is the Maesnant.

Each catchment is typical of the upper end of a glacial valley. The top ends of glaciers were usually too small to erode their valley sides to any extent and therefore these valleys became deep and steep-sided. The Maesnant and Maesnant Fach flow north-west from these steep sided valleys into the more typical U-shaped glaciated valley of the Afon Rheidol, part of which is now the Nant-y-Moch reservoir.

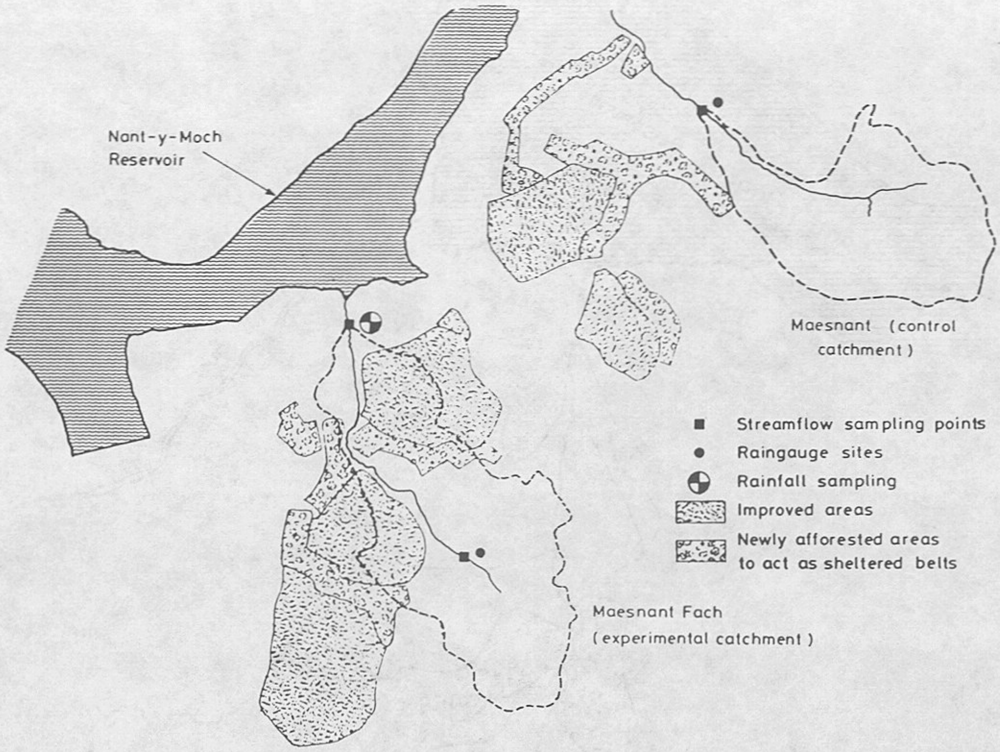


Fig. 3 The Nant-y-Moch grassland improvement study showing the two experimental catchments.

The Maesnant Fach is 80 ha in area and rises from 351 m to the top of Drum Peithnant at 645 m. The Maesnant, the more steep sided of the two valleys, is 56 ha in area, and rises from 472 m to the top of Pumlumon Fawr at 752 m.

Originally the drainage area of the Maesnant Fach was unclear because of an area of boggy ground immediately upstream of the proposed shelter belts to the east of the catchment (Figure 4). To resolve this problem a cut-off drain was dug from this boggy area to the outfall of the catchment and this drain now forms an effective catchment boundary.

Both catchment areas were initially defined using 1:10,000 topographic maps of the area: subsequently colour aerial photographs commissioned by Montgomeryshire County Council enabled the redefinition of the catchment areas using stereoscopic techniques. The catchment boundaries were confirmed in the summer of 1987 by an extensive ground survey.

4.3 GEOLOGY, GEOMORPHOLOGY AND DEPOSITS

The area between Aberystwyth and Machynlleth provided inspiration for two of Wales's early geologists, O.T. Jones and his student, W.J. Pugh. Jones published his first paper in the early part of this century (Jones, 1909); he

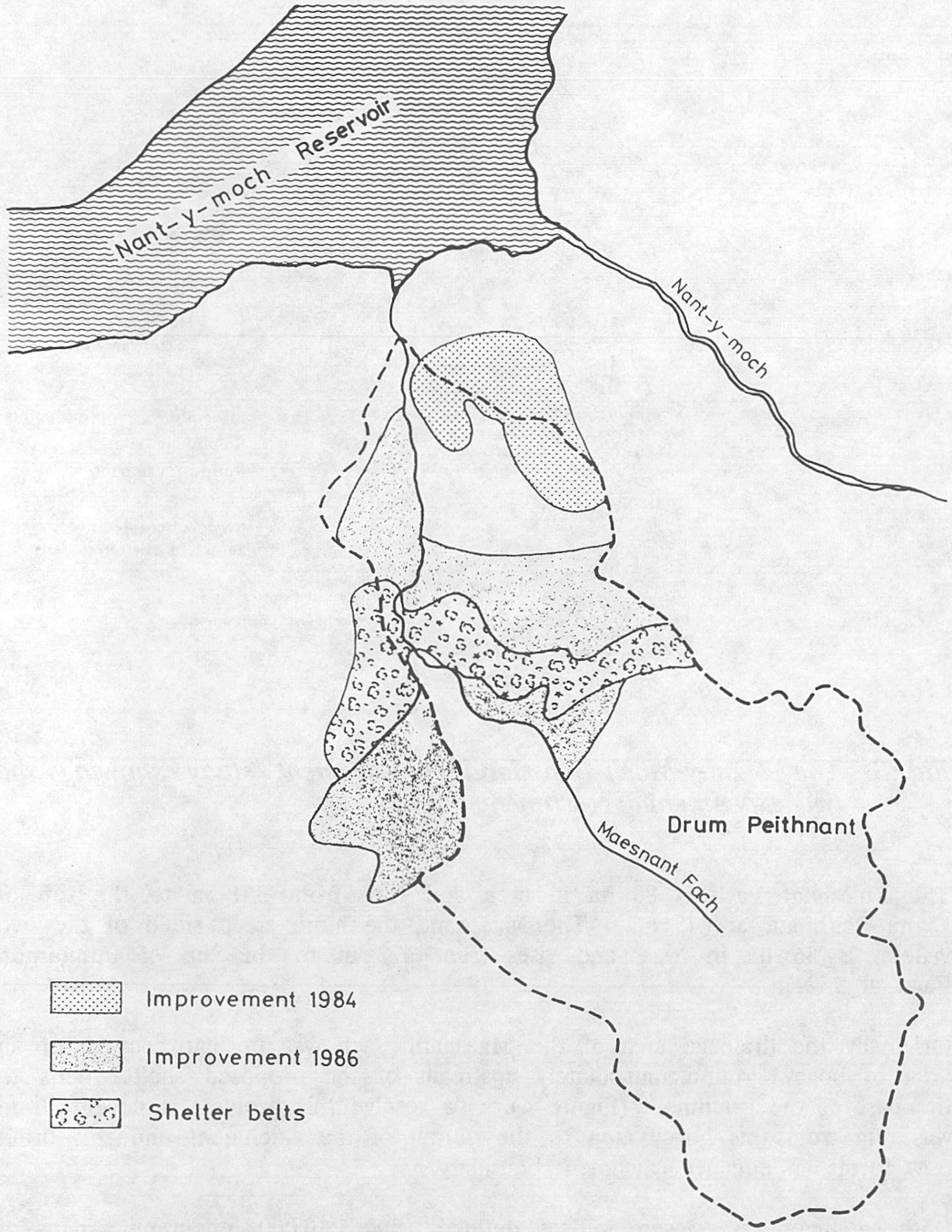


Fig 4 Maesnant Fach showing shelter belts and improved areas

and Pugh subsequently published a series of papers about the mid-Wales area (Jones and Pugh, 1916; 1935a; 1935b). In 1971 D.M.D. James published two papers on the geology and petrography of the Plynlimon area (James, 1971a; 1971b). More recently R. Cave and B.A. Haines published a memoir for the British Geological Survey Sheet 163, England and Wales (Cave and Haines, 1986).

The study area is geologically part of the Plynlimon Inlier, which has been created from Ordovician and Silurian sedimentary rocks. The sediments which formed those rocks were deposited in an ancient sea. The strata were then folded, cleaved and faulted, during and at the end of this era. Much of the sediment originally deposited on the sea bed was derived from rapidly-flowing, turbulent water that moved downslope and spread out along the sea bed. Pulses of this turbulent water led to the laying down of turbidite units each with coarser sediments at the base and finer material above. During periods of less turbulent flow, dark grey mudstones were laid down in oxygen-deficient (anoxic) conditions. The specific area around the two study catchments is of the Ashgill Series of the Ordovician system. This can be classified as in Table 2 (after Cave & Haines, 1986).

Table 2 Stratigraphy of the study area (after Cave & Haines, 1986)

Ordovician	Ashgill	Bryn-glas Formation	Mudstone, medium to dark grey; balled inclusion of sandstone and some thin-bedded siltstone in places	30-195 m
		Drosgol Formation	Mudstone, medium to dark grey, massive; commonly feldspathic and in places pebbly; divided by several sandstones up to 10m thick Pencerrigtewion Member (0-180 m) at top of mudstone, medium grey; siltstone and sandstone in various proportions and states of disturbance	290-405 m
		Nant-y-Moch Formation	Mudstone, medium grey, with thinly interbedded dark grey, pyritous mudstone	280 m

Geologically the Maesnant Fach catchment can be divided almost exactly in half (Figure 5). The lower half is of the Nant-y-Moch Formation. This area, together with a small outcrop around a quarry in the Eirian Valley (SN 69949434), has the most complete exposure of this type of rock. The sediments consist of thin interbeds of arenite and mudstone; the proportion and nature of the mudstone varies throughout the Nant-y-Moch Formation. These differences have allowed the division of the formation into two sub-facies, Dullfan and Maesnant. The Maesnant Sub-facies consists of alternating medium-grey mudstones, which are mainly laminated; they form a separable layer in the surrounding stratified rocks. These rocks comprise pelagic deposits which have fallen from upper waters and settled to the floor of an ancient sea bed.

The upper half of the Maesnant Fach and all of the Maesnant catchment are of the Drosgol Formation. Most of this formation consists of medium to dark-grey, silty mudstone which is divided by beds of greywacke sandstone. The mudstone contains coarse sand-size grains of a silicate of aluminium and potassium. The sandstone outcrops are spread widely over the Drosgol Formation, implying that they were formed by a high energy, unconfined transportation of sand over a flat sea bed (Cave & Haines, 1986).

The Maesnant and the Maesnant Fach trough-like valleys bear all the hallmarks of glaciation. Their existing concave slopes have thick screes on the lower parts. These slopes are evidence of the recent glaciation, but also of scree accumulation under permafrost conditions as shown by the presence of frost wedge structures in them (Watson, 1965). These solifluction terraces are less than 5 metres thick and form the river beds (see Figure 6).

4.4 SOILS OF THE NANT-Y-MOCH CATCHMENTS

Evan Roberts (1939a; 1939b; 1949; 1955) applied to the soils of west central Wales classifications which had initially been applied to North Wales (Hughes & Roberts, 1939). He classified major differences between soil series on Silurian and Ordovician shales and grits, based on "hard shale" and "soft shale" parent materials. Harrop (1955) and Ball (1959) enlarged on Roberts' twofold classification. Taylor (1957; 1960; 1961) indicated that the major cause of variation in soil profile in west central Wales was the differential transportation and sorting of weathered mineral residues on a large scale under glacial and periglacial conditions, particularly on slopes.

The parent materials of the soils in this area are relatively uniform, derived from the Ordovician and Silurian non-calcareous grits and shales. The variety of altitude, slope and aspect (which is mainly due to the alternation of hard grit and softer shale outcrops) has been instrumental in the re-sorting of weathered mineral deposits under the glacial and periglacial conditions. Prolonged periglacial climates are indicated by the massive sludging of soils on slopes.

During the early part of the Late Glacial Period (12,000 - 10,000 BC) the area was a vast perma-frosted wilderness. Frost cracks filled with fine silty materials, and frost action caused the heaving and disturbance of these pre-soils which became mobile in the warmer climate succeeding the Late Glacial Period. Coniferous trees began to grow instead of tundra, and the Atlantic Period (5,000 - 3,000 BC) saw the colonisation of mixed deciduous woodland up to 600 m altitude. The successions of vegetation left their mark on the soil and an active worm population at this period would have promoted the assimilation of organic matter into the soil.

The high rainfall and acid vegetation of the present era have produced the leaching conditions needed to produce a podzol. At altitudes above about 365 m the grey alluvial horizons typical of podzols are widespread, except on the steepest of slopes, in the shallow material over rock and where erosion has disturbed the development of the soil profile. Figure 7 shows the general relationship between soil groups, topography and soil associations (after Rudeforth, 1970).

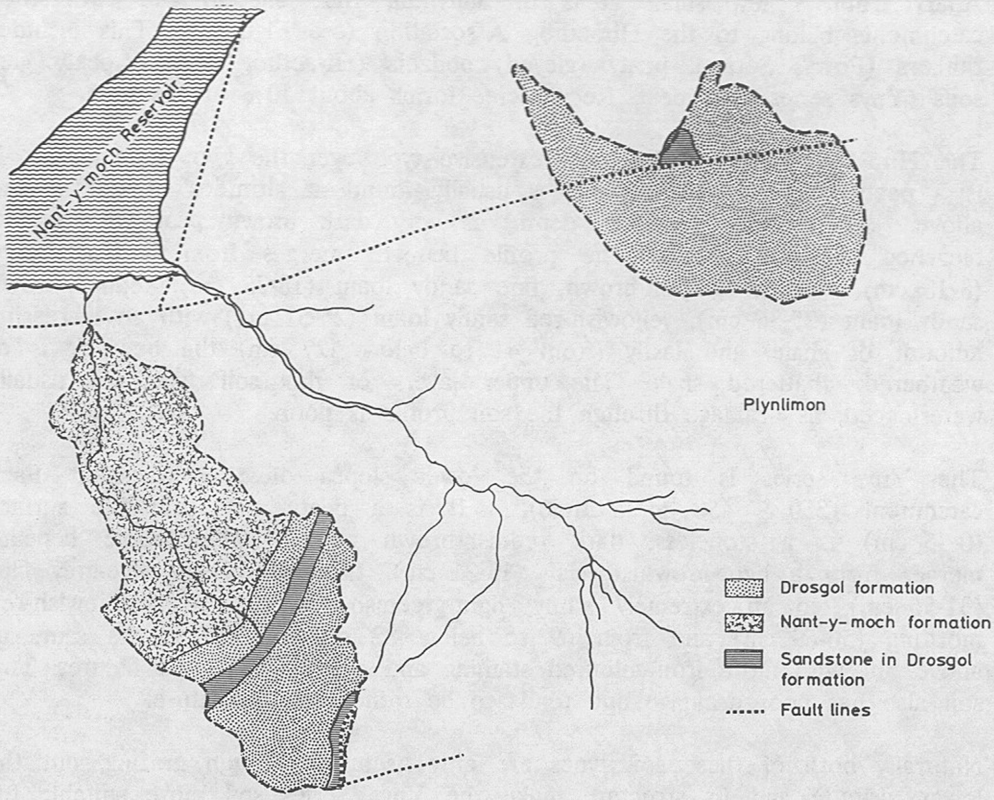


Fig. 5 Nant-y-Moch geological map

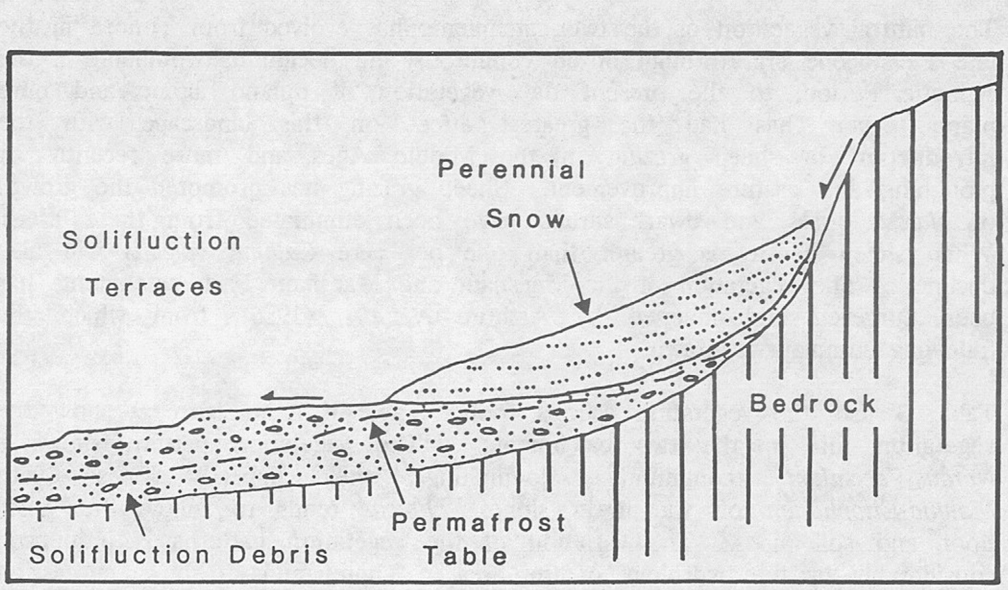


Fig. 6 Development of solifluction terraces

Apart from a few small areas of alluvium, the soils in the two study catchments belong to the Hiraethog Association (see Figure 8). This includes rankers (Powys Series), peaty (gleyed) podzols (Hiraethog Series), peaty gley soils (Ynys series) and peat. Rocky scree forms about 10% of the area.

The Hiraethog series is the most extensive type over the two catchments. It is a peaty (gleyed) podzol which is usually found at altitudes of 400 m and above. The surface (0-8 cm depth) is very dark brown peat with a few bleached sandstone rocks. The profile beneath merges from a black peat (8-18 cm), through greyish-brown, fine sandy loam (18-25 cm); reddish-brown sandy loam (25-36 cm); yellowish-red sandy loam (25-51 cm) with an increasing amount of shale, and lastly (from 41 to below 127 cm) the bedrock is of weathered, shattered shale. The upper layers of this soil type are usually waterlogged, as drainage through the soil profile is poor.

The Ynys series is found on the lower slopes of the Maesnant Fach catchment (350 - 450 m altitude). It is a peaty gley soil; the surface (0-15 cm) is a stoneless, dark reddish-brown peat. The profile beneath merges from a light-brownish clay (15-31 cm), through a light-olive-grey clay (31-56 cm), to an extremely stony, light-greenish-grey clay with yellowish-red mottling (56-69 cm) and from 69 to below 82 cm the soil is the same as above but with more iron-coloured staining and clearer horizontal fissures. This soil also has poor drainage and tends to be rather acid in nature.

Naturally both of these soil types are only useful for rough grazing, but the lower altitude and its structure make the Ynys Series soil more suitable for drainage and subsequent land improvement.

4.5 VEGETATION

The natural vegetation of the two catchments has evolved from Tundra in the late Pleistocene era, through mixed coniferous and deciduous woodland in the Atlantic Period, to the present day vegetation of upland alpine and mire plants. Man has had the greatest effect on this landscape with the introduction of sheep grazing in the Middle Ages and more recently by ploughing and pasture improvement. Sheep grazing has promoted the growth of *Nardus* grass and dwarf shrubs have been eliminated from these areas. When sheep density is greater than one per acre *Calluna vulgaris* will also decline. The vegetation of the Maesnant and Maesnant Fach catchments has been surveyed and mapped by Arthure *et al.* (1985), from which the following summary is drawn.

Table 3 lists the vegetation species found. Table 4 and Figure 9 show the vegetation mix in the two catchments. The vegetation pattern shows a *Nardus-Vaccinium* community dominating the upper slopes with *Molinia-Eriophorum* on the lower slopes. *Juncus* tends to follow the valley floor and soil pipes. The variation of the vegetation patterns is influenced considerably by the hydrology of the area. There tends to be a succession from *Nardus* to *Molinia* to *Eriophorum* with increasing wetness and stagnation. *Nardus* depends on an abundant supply of relatively fresh water and will tend to degenerate in stagnant conditions. It therefore prefers a fairly steep slope

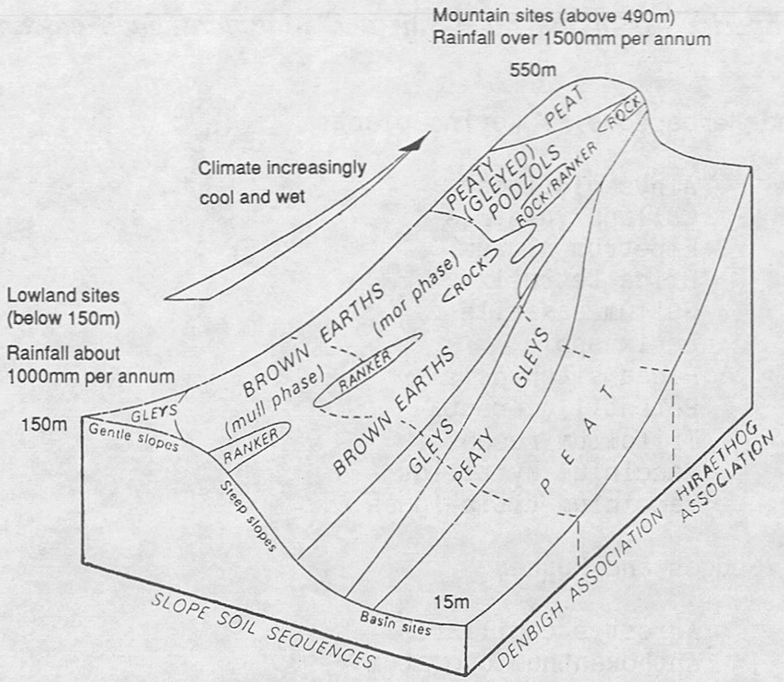


Fig. 7 General relationship between soil groups, topography and soil associations.

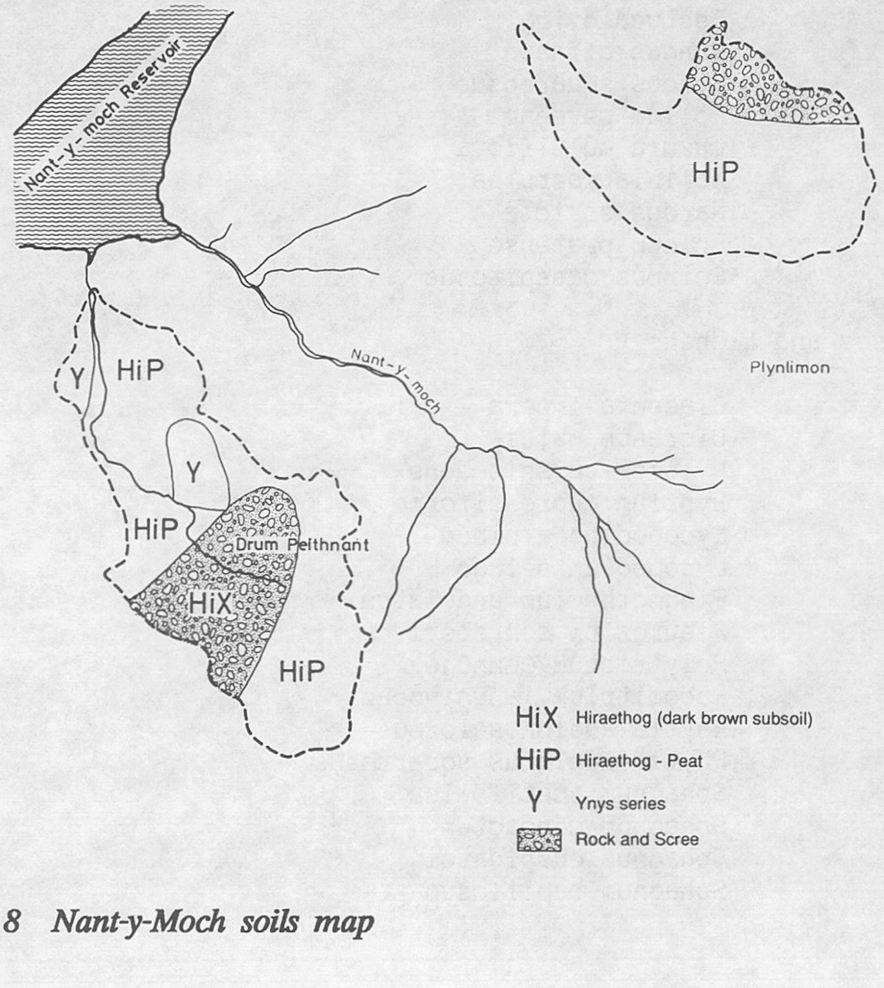


Fig. 8 Nant-y-Moch soils map

Table 3 Species list of the Maesnant and Maesnant Fach catchments

Trees and Herbaceous Flowering plants

Alnus glutinosa
Calluna vulgaris
Empetrum nigrum
Erica tetralix
Galium saxatile
Larix spp.
Picea sitchensis
Potentilla erecta
Trifolium repens
Vaccinium myrtillus
Vaccinium vitis-idaea

Grasses, Sedges and Rushes

Agrostis capillaris
Anthoxanthum odoratum
Carex binervis
Deschampsia caespitosa
Eriophorum angustifolium
Eriophorum vaginatum
Festuca ovina
Juncus effusus
Juncus squarrosus
Lolium perenne
Luzula multiflora
Molinia caerulea
Nardus stricta
Phleum pratense
Scirpus caespitosus

Mosses and Lichens

Cladonia impexa
Dicranum majus
Hylocomium splendens
Hyprium cupressiforme
Lycopodium alpinum
Lycopodium selago
Plageothecium undulatum
Pleurozium schreberi
Polytrichum commune
Racomitrium lanuginosum
Rhytidiadelphus loreus
Rhytidiadelphus squarrosus
Sphagnum acutifolium
Sphagnum compactum
Sphagnum cuspidatum
Sphagnum papillosum

where excessive water drains quickly. Both *Molinia* and *Eriophorum* will grow in wet conditions, but they require different levels of flushing. Where drainage is poor *Molinia*, which tolerates more boggy conditions, will dominate. This is demonstrated in Areas 1 and 2 in Figure 9: they are the less-well-drained slopes of the Maesnant Fach and here *Molinia* dominates. Areas 5 and 8 are the well-drained slopes of the Maesnant, and here *Nardus* predominates, although there is some intermingling of the species in all these areas.

As the flushing of the *Molinia* area decreases, *Eriophorum* increases, becoming the dominant species in the community. The bog mosses, such as *Sphagnum*, are closely associated, as are other mosses such as *Polytrichum commune* and *Pleurozium schreberi*. Larger plants in this *Eriophorum-Sphagnum* bog are rushes (*Juncus effusus*, *J. squarrosus*), grasses (*Molinia*, *Deschampsia caespitosa*) and herbs (*Calluna vulgaris, Erica tetralix, Vaccinium myrtillus*).

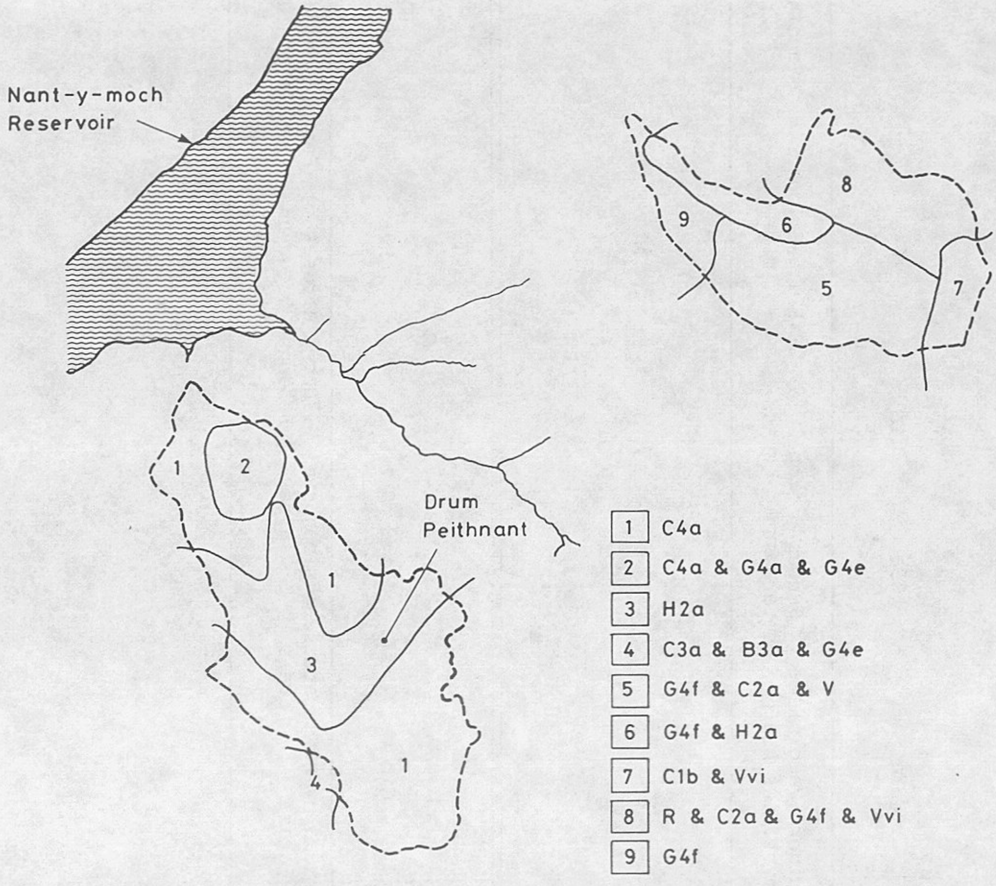


Fig. 9 Nant-y-Moch vegetation map.

Juncus effusus closely follows the streams, as in Area 3 in the Maesnant Fach and Area 6 in the Maesnant. It is also often indicative of sub-surface flows. *Juncus* will tolerate periods of total waterlogging and its boundary with *Nardus* or *Molinia* is hydrologically controlled. The boundary at which *Juncus* bog and *Nardus-Molinia* grass meet is at the level at which the ground is

Table 4 Vegetation mix of the Maesnant Fach and Maesnant catchments

Maesnant Fach

Vegetation Classification	B3a	C3a	C4a	G4a	G4e	H2a
	Southern Vaccinium myrtillus heath	Juncus squarrosus	Molinia grass	Calluna-Eriophorum mire	Vaccinium rich Calluna -Eriophorum mire	Juncus effusus-Sphagnum recurvum mire
AREA 1			*			
AREA 2						
AREA 3						
AREA 4	*	*				

Maesnant

Vegetation Classification	C1b	C2a	G4f	H2a	R	Vvl or V
	Festuca ovina grass	Nardus grass	Eriophorum mire	Juncus effuses Sphagnum recurvum mire	Festuca ovina-Diphasiastrum alpinium grass	Vaccinium vitis-idea or Vaccinium myrtillus also present
AREA 5		*	*			*
AREA 6						
AREA 7						
AREA 8						
AREA 9			*			

permanently submerged during the winter: winter submersion is injurious to *Nardus*. The *Juncus effusus* community contains a mixture of several mosses such as *Sphagnum papillosum*, *Sphagnum cuspidatum*, *Pleurozium schreberi* and *Polytrichum commune*.

The *Nardus-Vaccinium* community covers Areas 5, 7 and 8. *Nardus stricta* is slow growing and coexists on poor substrates such as the leached upper slopes of both catchments. Area 7 covers the eroding peat bogs at the head of the Maesnant and in this area numerous mosses and some alpine lichens, notably *Cladonia impexa*, cohabit with various rushes and grass such as *Agrostis capillaris*; *Galium saxatile* and *Vaccinium vitis-idaea* are also common. The lichen *Racomitrium lanuginosum* is more common at higher latitudes on the less stable eroding and bare mountain areas. Further downslope, Areas 1, 4, 5 and 8 are species-poor. This lack of mixed species within the main vegetation type is due to sheep grazing which selectively destroys many species and promotes the *Nardus* and *Molinia* grasses to the exclusion of everything else.

The planting of shelter belts has only recently taken place and the natural vegetation is still dominant in the ploughed and planted areas. The improved grassland is largely *Lolium perenne*, which is a lowland species. The *Trifolium repens* found within the sward indicates that some lime must be present. The sward contains many mosses and *Juncus squarrosus*. Figure 4 shows the areas of afforestation and improved grassland.

4.6 THE PASTURE IMPROVEMENT SCHEME

As indicated in Figure 3, the land reclamation scheme implemented by the local tenant farmers on behalf of the Crown Commissioners included areas both within and outside the Maesnant Fach (experimental) catchment. The following applies only to those areas within the Maesnant Fach, which are shown in Figure 4.

Three schemes were employed. Ditching for the shelter belts took place in February 1984 and the planting was done in March 1984. The trees planted were predominantly softwood species comprising Sitka spruce, Lodgepole pine and Japanese larch, but there were also areas of Willow, Alder, Beech, Oak and Rowan. The general tendency was to plant an inner core of softwood species, depending upon the nature of the ground within each belt, with groups of hardwoods on the fringe. No fertilisers were applied at the time of planting and it is unlikely that any will be applied in the future, although periodic inspection of the trees will be carried out over the course of the establishment phase. A visual estimation using a 1:10,000 scale plan suggested that approximately 6% of the catchment was affected.

Both improved areas consist of gently sloping ground mostly overlain by peaty soil of the Hiraethog series (Figure 8). The indigenous vegetation was dominated by species-poor *Molinia* grassland with small *Calluna-Eriophorum* mire areas (Figure 9). The techniques adopted during the course of both improvements were similar: cutting and burning the vegetation, an application of lime and a phosphate fertiliser, spike seeding followed by an application of a general fertiliser. In the 1986 improvement, the grass was too wet to burn and had to be removed from the area.

The first improvement scheme, on the northern side of the catchment, east of the stream, was carried out during April 1984. Approximately 19.5 ha was involved of which some 8 ha lay within the Maesnant Fach catchment. Details of the lime and fertiliser applications are shown in Table 5.

In May 1986, a top dressing of Nitram fertiliser was applied to this area equivalent to 17.5 kg N/ha.

Table 5 Fertiliser applications in the first phase of pasture improvement at Nant-y-Moch. Total area ~ 26 ha.

(i) Year 1 (Improvement Year)

80 tonnes of lime

4.5 tonnes of triple superphosphate

4.5 tonnes of 22:11:11 compound fertiliser

Amount per hectare

N	51.5 kg/ha
P_2O_5	108 kg/ha (47 kg P/ha) applied as Superphosphate 26 kg/ha (11 kg P/ha) applied as Compound Fertiliser
K_2O	26 kg/ha (21 kg K/ha)
Lime	4.1 tonnes/ha

(ii) Year 2

1000 kg of Nitram (34.5% N) or 17.5 kg N/ha

The second improvement scheme, on the west bank and further upstream, was carried out during May 1986. Approximately 26 ha was improved, of which some 13.5 ha was within the Maesnant Fach catchment. Details of the lime and fertiliser applications are shown in Table 6. The rates per unit area for N, P and K were identical to those applied in 1984, but the lime application was higher at 5.8 tonnes/ha.

How typical are these two improvement schemes in terms of the practice employed generally in upland Britain? Certainly they conform to the advice given by the Agricultural Development and Advisory Service for Wales (Table

1) and the Hill Farming Research Organisations in Scotland (see, for example, HFRO, 1973). In terms of typical rates of fertiliser applications, those used at Nant-y-Moch are of the same order as those used elsewhere (for example Yates, 1984; Davies, 1984). It is more difficult to judge how the areal extent of improvement at Nant-y-Moch compares with other schemes.

Whereas upland improvement schemes are widespread, they are generally implemented at a very gradual rate. For example, in Wales some 100,000 ha were improved in the 25 years prior to 1978, an area equivalent to 20% of the hills and uplands of the Principality (Jones, 1978). This represents an

Table 6 Fertiliser applications in the second phase of pasture improvement at Nant-y-Moch. Total area - 26 ha

150 tonnes of Lime

6 tonnes of Triple superphosphate

6 tonnes of 22:11:11 compound fertiliser

<u>Amount per hectare</u>

N	51.6 kg/ha	
P_2O_5	108 kg/ha	(47 kg P/ha) applied as Superphosphate
	26 kg/ha	(11 kg P/ha) applied as Compound Fertiliser
K_2O	26 kg/ha	(21 kg K/ha)
Lime	5.8 tonnes/ha	

annual rate of improvement of less than 1% of the area. On a local scale, land use changes have proceeded in the Clywedog Reservoir catchment in mid-Wales where 24% of the catchment has been improved and a further 32% afforested in 20 years (Newson & Hudson, 1976). At the HFRO farm at Sourhope in Scotland, some 107 ha (38% of the total farm area) was improved during the period 1969-1982 (Armstrong *et al.*, 1977). These and other schemes (for example FW, 1983) suggest that upland pasture improvement proceeds at rates of a few per cent of total land per year. Thus the improvement of the Maesnant Fach at Nant-y-Moch proceeded at a comparatively rapid rate (24% of area in two years).

Finally, as the cut-off drain at the bottom of the catchment traverses the 1984 improved area and was proving interesting, the third scheme was implemented to monitor this drain. The results obtained have been compared with observations from a field drain in an area improved by deep ploughing (Roberts *et al.*, 1986a).

5. Method

5.1 FLOW MEASUREMENT

The Nant-y-Moch study has been concerned primarily with quantifying the losses of solutes and sediments in streams, and the variation of these losses with flow conditions. Flow volumes are required to calculate the loading of these materials, in order to construct solute and sediment budgets for the two catchments. Unlike contemporary studies at Plynlimon (Mid-Wales) and Balquhidder (Perthshire) where the main function is to balance inputs and outputs of water, at Nanty-Moch high-accuracy flow-gauging is an advantage rather than a necessity. In general, the degree of uncertainty surrounding measured concentrations of material in streams is far greater than that associated with flow measurement.

Flow measuring structures were required which could be relied upon to gauge flow continuously, which could cope with a wide range of flow without overtopping, and which could withstand the buffeting from occasional extreme flows that would overtop them (Reynolds *et al.*, 1988). A reliable and durable structure of concrete and metal was required; it was then only a small step to achieve high accuracy as well. There is increasing awareness of the importance of small changes in water use in catchments experiencing only minor changes to their vegetation patterns, particularly where the water supply is marginal. Adequate investment in the structures is likely to lead to a large benefit in terms of the information gained. This policy has recently been justified by increasing awareness of the effect of afforestation on water yield to the Nant-y-Moch reservoir and its implications for power generation from the CEGB's Rheidol Scheme.

When choosing flow gauging structures the aim is to use existing designs, with British Standard calibrations wherever possible, and to modify them to fit the channels of the streams under study. This inevitably involves compromise in upland streams, for the following reasons:

(1) Upland streams are sinuous, irregular and steep, causing approach conditions that are asymmetrical and dominated by kinetic forces. It is therefore difficult to measure stage precisely because of unstable water surfaces. Asymmetry introduces the possibility that the water level in the stilling well is not the same as the mean water level across the forecourt. As a result, stage/discharge characteristics of any structure can deviate from the standard calibration, making it necessary to perform checks by independent means such as dilution gauging or current metering.

(2) The high stream-energy encourages the movement of considerable amounts of bedload, which can cause further calibration problems arising from shoaling in the approach channel and blocked tapping pipes. Regular clearing is an expensive and time-consuming consequence.

(3) High flood/drought flow ratios mean that structures are often compounded to give reasonable sensitivity throughout the flow range. This is achieved by running structures in series, which is more accurate but

also more demanding of effort in construction and maintenance. It is also more costly in instrumentation than the most commonly adopted method, which is to run structures in parallel. The latter method requires only one set of instruments for head measurement, but the weirs inevitably interact, causing calibration problems.

The advantage of gauging flow in upland channels is that overbank flow conditions are less common here than in the lowlands. Some artificial constriction of channel capacity is permissible, allowing the use of structures such as Crump weirs and thin plate weirs in addition to the larger-capacity trapezoidal flumes. Depending on the amount of constriction allowed, sharp crested weirs can be used with confidence as long as the accretion of bedload in their approach channel is manageable: that is, the effective weir height is reduced only over a long period. It must also be possible to clear the sediment before it starts to cause a problem. In small structures this can be done by hand, but those used typically in upland research catchments are of a size requiring vehicular access to the forecourt area.

In streams where the bedload yield is high, more specialised structures are available which are designed to pass sediment freely. These tend to be expensive and difficult to build, for example the Plynlimon steep stream flume, and require particular stream profile characteristics for installation, preferably waterfall and pool sequences in a rock channel. It would have been feasible to utilise this design at both Nant-y-Moch sites, but it was thought that sediment problems could be surmounted in these catchments.

The Maesnant Fach and Maesnant streams are both far too steep for Crump weir designs and so sharp crested weirs were chosen instead. Experience of one example of this type of weir at Llanbrynmair Moor has been encouraging (Roberts *et al.*, 1988b), notwithstanding the sedimentation problems which followed a flash flood immediately after its installation. In the light of experience this can be viewed as the result of an extreme event. The geology of the Delyn site on Llanbrynmair was best suited to a contracted form of the sharp crested weir, whereas a full width version was thought to be feasible at Nant-y-Moch, given the better foundation material available for the concrete approach walls. The full-width weir was preferred because of doubts surrounding the effects of the degree of contraction on the calibration of the contracted type.

Ultimately the choice of the exact site for the structures was dictated by factors other than ideal catchment size or channel shape. A cut-off drain was excavated in the Maesnant Fach catchment to define the lower catchment boundary on the eastern side. This discharges into the stream about 40 m upstream from the road culverts (see Figure 10). The structure had to be placed in this 40 m reach in order to include flow from the drain and to avoid both flow off the road surface and from the steep channel downstream of the road culvert.

Similarly, the Maesnant site had its upstream limit set by the boundary of the Plynlimon SSSI, above which it would not have been expedient to build. Its downstream limit was set by a Welsh Water Authority supply off-take (see Figure 11) below which complications would have arisen through loss of water. The compensation V-notch weir at the abstraction site was not constructed to a sufficiently high standard to be used even in a modified form; a reach

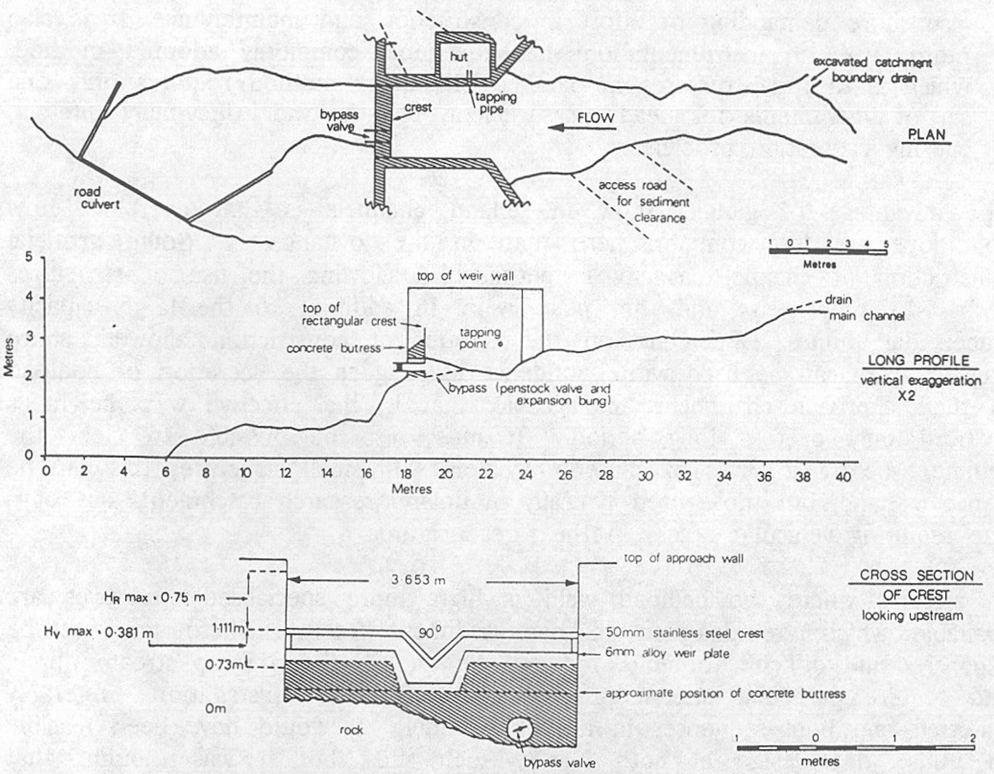


Fig. 10 Details of the weir at Maesnant Fach

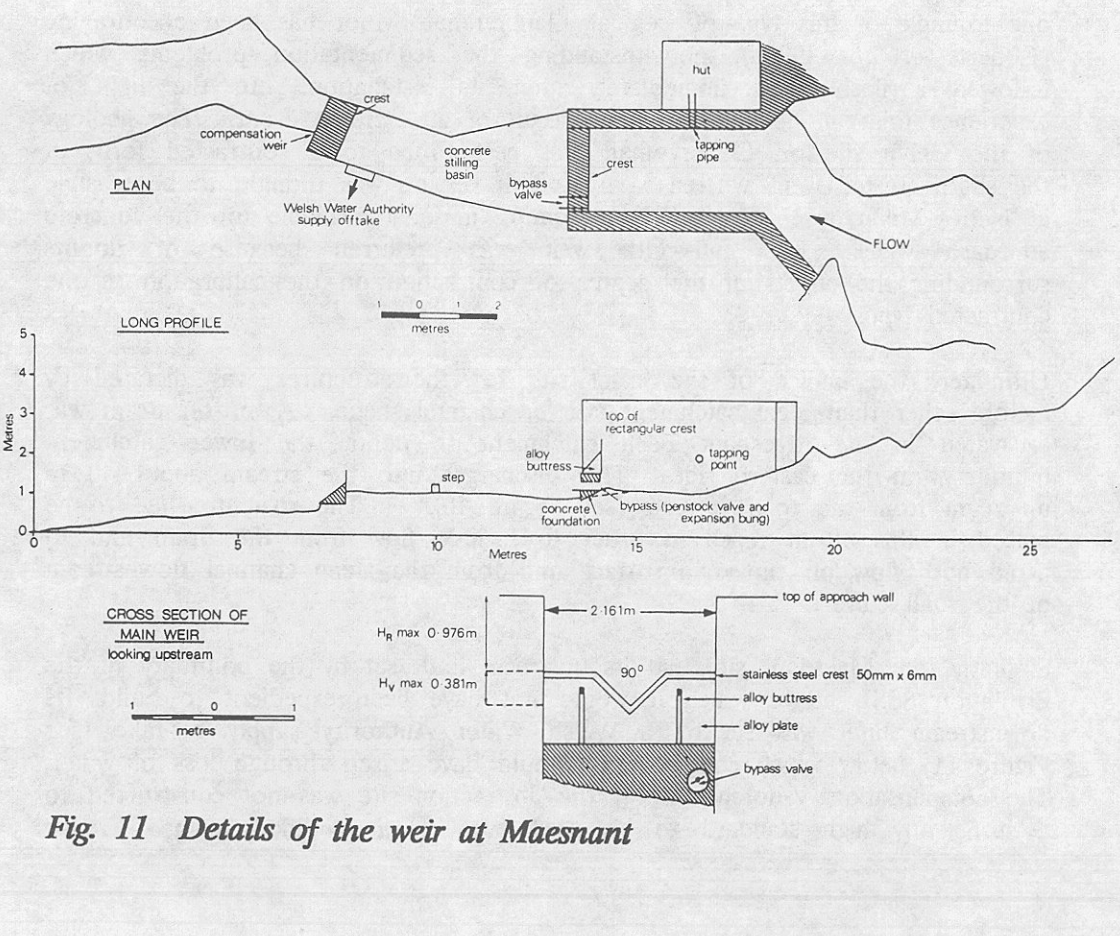


Fig. 11 Details of the weir at Maesnant

downstream of a waterfall between the two limits therefore became the only site available. The compensation weir caused a further problem by making it necessary to raise the height of the new weir crest to avoid drowning out the old weir. It also meant that extreme care was required to avoid contaminating the water supply during construction.

As a result of these constraints the overall dimensions of both structures, particularly the widths, were set within certian limits which approximated to those of the stream channel. Other constraints were derived from the British Standard limits on the calibration (BSI, 1965). The limit on the height of a V-notch weir, h_{max}, is normally 0.381 m, but to utilise the full range the height of the invert above the bed should be 2.5 times this value, i.e. 0.953 metres. Thus the invert of the rectangular weir superimposed on the V-notch would have needed to be 1.334 m from the bed, which would have constricted channel capacity to an unacceptabe degree at both sites. From a study of the Plynlimon and Llanbrynmair flow data the importance of various flow ranges at Nant-y-Moch was predicted (Table 7). To cope with this range of flows, and to avoid a high proportion of them occurring in the transition range from V-notch to rectangular, it was considered that the maximum head over the V-notch (0.381 m) should not be compromised to achieve the required British Standard. It was decided to consider the V-notch as a partially contracted type, whose calibration would be influenced to some degree by the proximity of the bed (but not the banks), and to use the alternative Kindsvarter and Carter equation for flow estimation (Table 8). This equation applies to an angle (θ) of 90°. The coefficient C_e is now a function of h/P, P/b and θ (where P = the weir height in metres and b = the channel width in metres). The effective head (h_e) is equal to the measured stage (h) plus a small constant K_h (0.85 mm) which allows for the effect of fluid properties. Using the tables given in BS3680 (BSI, 1965) it is possible to estimate discharge to a head of 0.60 m if necessary, or more probably up to an h/P ratio of 1.2 (compared to 0.4 in the fully-contracted version).

Table 7 Flow ranges for the sharp-crested weirs at Nant-y-Moch (m^3/sec)

	Experimental		Control	
	Stage (m)	Flow	Stage (m)	Flow
Minimum	0.05	0.000801	0.05	0.000800
Max. V-notch	0.381	0.123340	0.381	0.123062
Min. rect + V-notch	0.451	0.280332	0.451	0.231010
Max. rect + V-notch	1.131	4.403160	1.35	3.904280

Minimum and maximum flows expected at Nant-y-Moch Control: estimated from equivalent flows at Llanbrynmair and Plynlimon - in m^3/s (from Roberts *et al.*, 1986b).

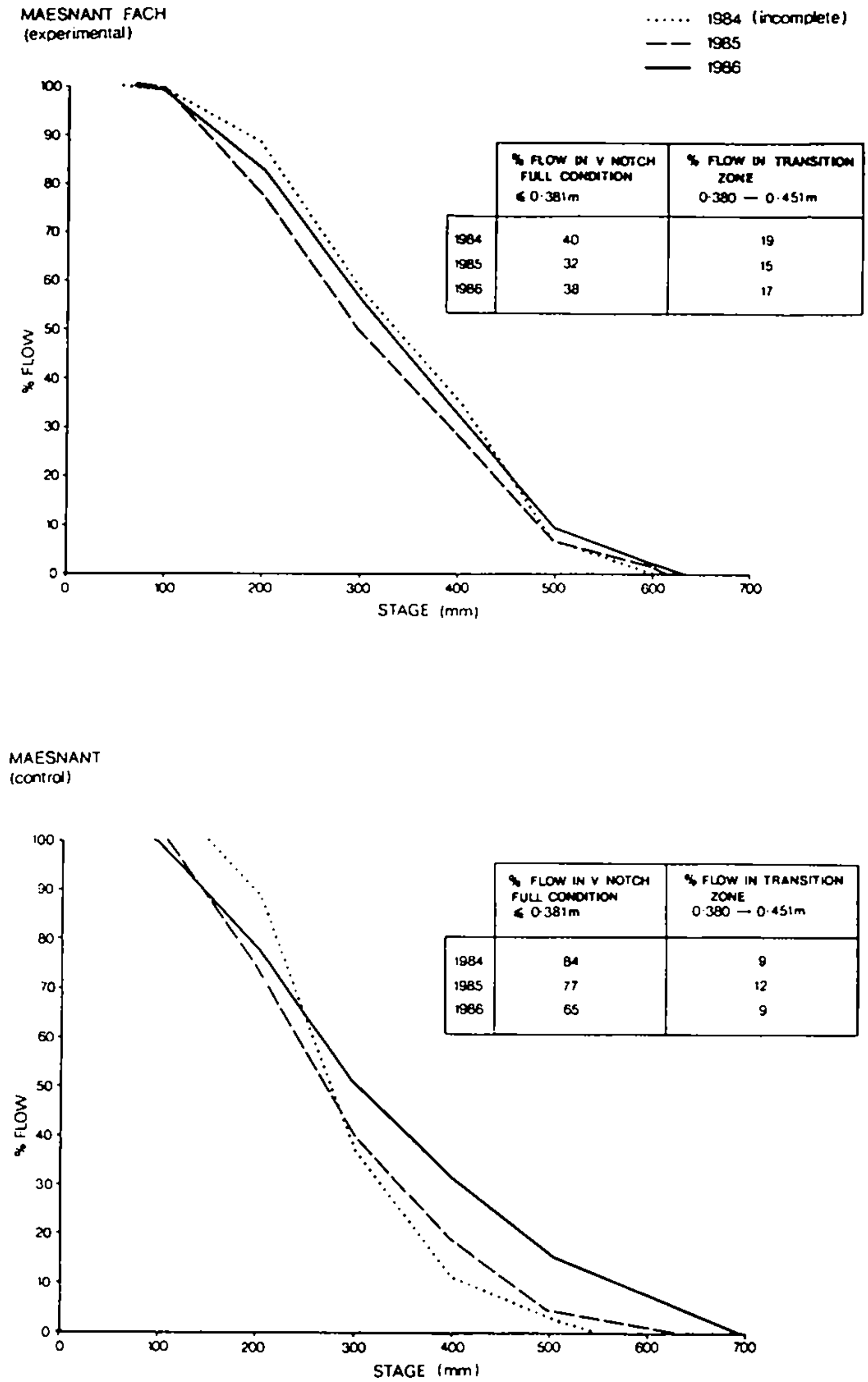
	Plynlimon 1973-1979				Llanbrynmair 1982-1986	
	Cyff	Iago	Gwy	Wye	Cwm	Delyn
Minimum				0.00153	0.000405	0.000800
Maximum	0.590135	0.48179	0.544403	3.392	1.451001	1.503008

Considering both installations as simple, full-width, rectangular weirs for a moment, their capacities are constrained by a maximum head of 0.75 m. In addition, the ratio h/P should not exceed 1.0, which means that the height of the weirs above the bed should equal or exceed 0.75 m. This condition is satisfied in each case, and far exceeded at Maesnant where the whole weir had to be raised to prevent its drowning by the compensation weir downstream and to reduce the effective bed slope caused by the waterfall upstream.

The main problem with this type of compound weir arises from the interaction between the V-notch and rectangular weirs, which requires a special calibration, although they have to be treated separately when defining their dimensions. The Barnes (1916) formula is the most commonly used for this type of compound weir because it allows for an increasing head on the V-notch as the rectangular weir fills (Table 8). Barnes did not have the benefit of later research by Kindsvarter and Carter on the partially -contracted V-notch. Nevertheless discharge values in the V-notch-only flow situation (h < 0.381 m) give agreement to within 1%, well within the target accuracy for this type of study (Table 8). Unfortunately, for h > 0.381 m there is no theoretical check on the accuracy of the estimate. In the absence of an independent check by current metering or dilution gauging, it is sufficient to conclude that errors in the rating will be caused by increasing head over the V-notch when the flow moves into the rectangular section, but that these errors will be small relative to total discharge.

The design of any weir can only be justified fully by its subsequent operation. Neither of the two weirs at Nant-y-Moch has approached the full condition, which could suggest that they have been overdesigned for their original purpose. However there has never been any problem of a lack of sensitivity at the top of the range because of too wide a crest. Similarly, the flow over the V-notch has never gone below the British Standard minimum stage, which suggests that the 90° V-notch was a good choice. On average, the V-notch at Maesnant Fach copes with 63% of the total flow, with only 17% of flow occurring in the troublesome transition stage between the V-notch being full and minimum stage over the rectangular weir (Figure 12). Maximum stage has not exceeded 0.627 m (0.246 m over the rectangular weir) in any of the years 1984 to 1986; the minimum has been 0.055 m.

A similar characteristic is exhibited by the Maesnant structure. In spite of its narrower crest width, the maximum recorded stage is only marginally greater than Maesnant Fach at 0.695 m (0.314 m above horizontal crest level). This similarity exists because of the balance between a narrower weir and a smaller catchment. However, in spite of its smaller catchment area, minimum stage in the Maesnant, 0.091 m, is considerably higher than that in the Maesnant Fach (in the V-notch this transfers directly to a higher flow). This suggests either that the storage capacity in the Maesnant is greater or that the catchment areas have been measured wrongly. Some doubt still surrounds the exact position of the watershed in the Maesnant Fach, as indicated by the unusual water-use figures quoted in Section 6.1, but that of the Maesnant is more certain. It is also possible that the topographical boundary in the Maesnant Fach is correct but that groundwater leakage is occurring. The cut-off drain across the mire is particularly suspect in this context.



	% FLOW IN V NOTCH FULL CONDITION ≤ 0·381m	% FLOW IN TRANSITION ZONE 0·380 — 0·451m
1984	40	19
1985	32	15
1986	38	17

	% FLOW IN V NOTCH FULL CONDITION ≤ 0·381m	% FLOW IN TRANSITION ZONE 0·380 — 0·451m
1984	84	9
1985	77	12
1986	65	9

Fig. 12 Percentage flow exceeding stage curves for Nant-y-Moch catchments

Table 8 Calibration equations for the compound sharp-crested weirs at Nant-y-Moch

The Barnes (1916) formula uses an iteration procedure to calculate Q and this implies the introduction of a velocity head component.

Experimental Maesnant Fach

$$Q=1.35024\ (H_1^{2.48} - H_2^{2.48}) + 4.98549\ H_2^{1.49}\ (17.334/(17.334 + H_2))^{0.11}$$

Control - Maesnant

$$Q=1.34719\ (H_1^{2.48}\quad H_2^{2.48}) + 2.41425\ H_2^{1.49}\ (8.394/(8.394 + H_2))^{0.11}$$

where H_1 is total head on V-notch invert = $h_1 + V_a^2/2g$
and H_2 is total head on the rectangular crest = $h_2 + V_a^2/2g$

An alternative equation for the V-notch only range is given by Kindsvarter and Carter in B.S.3680 (1965):-

$$Q = (8/15) \cdot \sqrt{2g} \cdot C_c \quad \tan\theta/2 \cdot h_e^{5/2}$$

where C_c is the coefficient of discharge
θ is the notch angle (only 90° allowed here)
h_e is the effective stage $(h+k_h)$ = h+0.00085m

A comparison of the two methods for stages 0.05 m < h <0.381 is shown below for the Control V-notch

Stage (m)	Discharge (m^3/ s) Barnes	Kins.-Carter	Ratio
0.05	0.000800	0.000796	0.9953
0.20	0.024889	0.024689	0.9920
0.381	0.123062	0.123029	0.9997

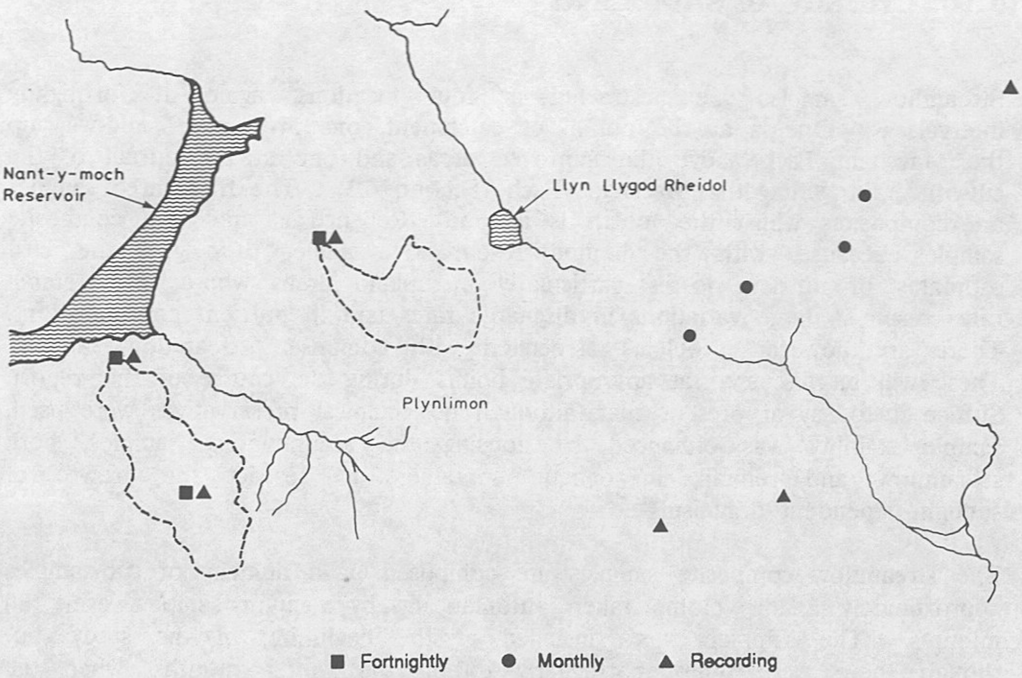


Fig. 13 Raingauges used in the Nant-y-Moch study

5.2 RAINFALL MEASUREMENT

The raingauge network employed at Nant-y-Moch is shown in Figure 13. It consists of three storage and three recording gauges. A rainfall sampler was also installed at the outfall of the Maesnant Fach in July 1984. Sampling takes place at two-weekly intervals.

The period gauge at the outfall of the Maesnant Fach is an octopent standard, as opposed to the ground level gauges employed elsewhere belonging to the CEGB. This gauge is read weekly not normally on the same day as the rainfall sampling. Data from this gauge are available since before the start of the study. The associated recording gauge was installed in August 1984 and produces five-minute rainfall values. The other two period gauges are both at ground level and are read at the same time as the rainfall sample is collected. The gauge in the upper Maesnant Fach was installed in February 1984 and the one in the Maesnant in September 1984. The associated recording gauges were installed in May 1986 and give daily totals. Because of problems of access, raingauges were not originally installed at the head of the catchments. Therefore in order to estimate rainfall, and hence chemical inputs to these areas, it was decided to use part of the raingauge network in the Wye catchment at Plynlimon. The location of these gauges is shown in Figure 13. They consist of four monthly-read period gauges and three recording gauges. Data from these gauges are available since before the start of the study.

A detailed description is given in Section 6.1 of how the data from all the gauges were used to calculate rainfall inputs to the two catchments.

5.3 CHEMICAL SAMPLING

Streamflow samples are abstracted at four locations, again at fortnightly intervals. One is at the outfall of catchment, one at a point mid-way up the Maesnant Fach above the improved areas and one at the outfall of the cut-off drain within the Maesnant Fach (Section 6.2). The first three samples are composites whilst the fourth is a spot. Reliance is made on composite samples because, with the limited resources available, they give the best estimates of nutrient losses particularly in upland areas where high rainfall rates result in large variations in discharge rates and in nutrient concentrations. There are however, problems associated with composite streamflow samples. These will be discussed at appropriate points during the course of this report. Suffice it to say at present that, although no chemical preservatives were used, sample stability was enhanced by housing the accumulating samples, both streamflow and rainfall, in opaque containers to restrict the growth of sunlight-dependent organisms

The streamflow composite samples are composed of a number of sub-samples approximately 2 ml volume taken automatically by vacuum sampler every 30 minutes. The samplers were installed at the beginning of the study, but though there were times, particularly during the winter months, when the samplers failed to work. During these times, spot samples were collected and it became necessary to infill the composite sample data set, as described in Section 6.2.

After collection all the samples were filtered, normally within a few hours, through a 45 μm filter. They were analysed at the Institute of Hydrology's laboratory at Wallingford. Unfortunately, because of pressure of work, several months elapsed before the analyses were performed. During this time the samples were stored in a refrigerator at a temperature of 4°C. The determinands and methods of analyses are shown below.

Ammoniacal nitrogen	Determined colorimetrically by the indophenol blue method
Nitrate nitrogen	Determined colorimetrically by the sulphanilamide method.
Organic nitrogen	Converted to ammoniacal nitrogen by the Kjeldahl method which is then determined as above.
Total phosphorus	Determined as orthophosphate using the molybdenum blue colorimetric method of following a modified Kjeldahl conversion.
Potassium	Determined by flame photometry.
pH	PHM82 Radiometer pH meter.

5.4 SEDIMENT SAMPLING

The sediment transport studies in the Nant-y-Moch catchments concentrated upon yields of bed and suspended load, with some additional sampling of channel bed deposits. Suspended sediment is mainly clay or fine sand.

At Nant-y-Moch instantaneous bulk samples were taken during high flows. It was not necessary to use depth-integrating samplers as the suspended load was found to be well-mixed throughout the cross-section of the channel. This is often the case in turbulent upland channels. The bulk samples taken by the composite samplers were not used for suspended load studies because the residence time in the intake tube would lead to unrepresentative concentrations being analysed. The subsequent laboratory analysis of the instantaneous samples included vacuum filtration using 15 cm glass fibre (Whatman GF/C grade) filter papers.

Suspended load has often been related to flow. For this reason a rating technique is frequently used to express the relationship. This rating curve can then be combined with flow duration data to estimate the catchment's suspended sediment yield. A critique of this method was produced by Walling (1977), but it remains the only practical means of estimating suspended sediment yields for most catchments. Bed-load transport involves the coarser particulate load which remains in contact with the bed as it moves downstream. Size ranges are predominantly from sand up to cobbles and sometimes boulders. Movement tends to be dependent on supply and on the exceedance of flow thresholds: as a result the relationship with flow tends to be more erratic than in the case of suspended load.

As mentioned earlier, measurement of flow in both of the Nant-y-Moch catchments is made by weir structures, which of necessity cause stilling of the water upstream of the crest; as a result, bed-load drops out of the flow. If sediment is permitted to accumulate beyond a certain level it can cause problems in the stage/discharge calibration of the weir (see Section 5.1 of this report). Therefore, the stilling pools are monitored regularly and accumulations of sediment removed when necessary. Each time the deposits were removed, accurate topographic surveys were carried out before and after emptying. Each "after emptying" survey was compared with the following "before emptying" survey to calculate the volume of additional material. These data can then be used to estimate overall catchment yields between emptyings and to give yearly and longer combined-term estimates. Samples of the "trapped" sediments were also subjected to size analysis using sieves at half-phi size intervals to indicate the nature of the material in transport.

It is generally the case that the surface of the British uplands is very stable. Outputs of sediment from slopes to streams is therefore restricted, so that streams carry far less sediment than they are capable of transporting. However, it has already been observed that penetration of surface layers to form open drains, which frequently accompanies afforestation, as well as some upland grassland improvement, may increase supply to streams and enhance sediment yields (Newson, 1980; Leeks & Roberts, 1987). The monitoring scheme outlined above was therefore designed to detect changes in the stream sediment system which may result from ground disturbance associated with the Nant-y-Moch improvement scheme.

6. Results

Routine data collection began in February 1984, although this report covers the period from July 1984, when streamflow data became available, up to the end of 1986.

6.1 HYDROLOGICAL DATA

Rainfall

The main purpose of the raingauge network is to supply areal estimates of rainfall into the two catchments at intervals corresponding to the rainfall sampling frequency. This is to facilitate the calculation of chemical inputs into the two catchments given as the product of rainfall totals and concentration. These are then compared with chemical losses in the streamflows. A secondary consideration as far as this study is concerned is the provision of time-distributed rainfall inputs for water balance and modelling purposes.

Much of the early analysis was directed towards filling in gaps in the data sets from the three storage gauges employed at Nant-y-Moch. These gaps existed mainly at the start of the study before gauges were installed and, less frequently, during winter months when gauges were buried under snow or became flooded.

The storage gauge at the outfall of the Maesnant Fach was read on days which did not necessarily correspond with the sample collection dates. For the purpose of calculating chemical inputs, these rainfall data are not particularly useful. Also, being a standard 1 ft gauge, its catch may possibly differ significantly from a ground-level gauge at the same location. Figure 14 shows rainfall totals for the octopent standard plotted against accumulated rainfall from the recording gauge for the same periods. Although differences do occur, the graph shows approximately the same number of points above and below the 45° line. Many of the differences may have been due to timing errors since it was assumed that the CEGB gauge was always read at 0900 hours GMT, whereas there is no indication of when the gauge was actually read. Since the agreement between the two gauges so good, it has been assumed that accumulated totals from the recording gauge give a good measurement of rainfall at the outfall of the Maesnant Fach.

For the other two raingauge sites, Figures 15 and 16 show comparisons between the period gauge totals and the accumulated daily rainfall totals for the upper Maesnant Fach and the Maesnant. Again, the agreements are good and the regressions calculated by the least squares method have been used to fill in the period gauge data sets for those periods when only daily data were available.

Gaps in the period gauge data sets prior to the installation of the daily

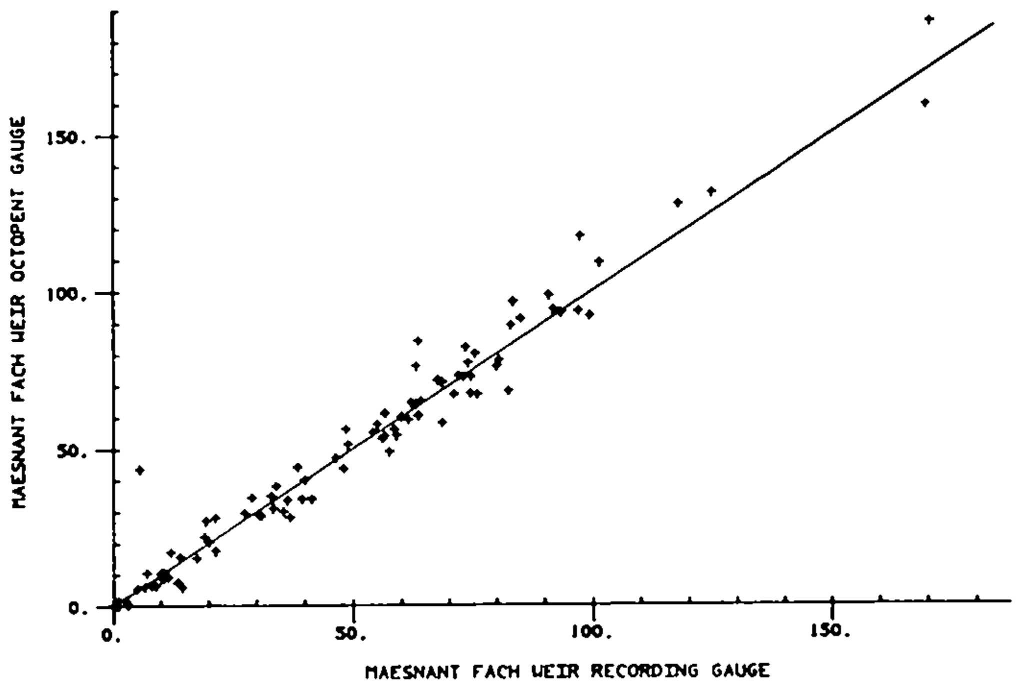


Fig. 14 ***Comparison of rainfall total collected in the CEGB octopent rain gauge and the recording gauge at Maesnant Fach weir***

gauges were filled using regressions between the rainfall catchments in the three period gauges. These are shown in Figures 17 to 19. The most frequently used gauge for this purpose was the one in the upper Maesnant since this has the longest record.

In these ways, a complete record of period gauge data was obtained for all three rainfall sites.

The two catchments are steep, each rising about 300 m in approximately 1.5 km. The Maesnant catchment is approximately 100 m higher in altitude than the Maesnant Fach, and would therefore be expected to receive greater rainfall input. Whilst the raingauges used at Nant-y-Moch would be expected to be adequate for estimating inputs to the lower reaches of the two catchments, the lack of a high altitude gauge meant that inputs to the head of the catchments were not measured. This is particularly serious for the Maesnant because of its higher altitude. The problem was partially alleviated for the Maesnant Fach by the gauge mid-way up the catchment.

Estimates of rainfall in these high altitude areas were obtained from four monthly-read gauges in the Wye catchment on the other side of the Plynlimon watershed. Although these gauges have a different aspect than those at Nant-y-Moch, their altitude range, 612 m to 712 m, is similar to the altitude at the top of the Maesnant Fach, 640 m, and the top of Maesnant, 750 m. The effect of altitude on the total rainfall from 1984 to 1986 for all the period gauges used in this study is shown in Figure 20. Although a general pattern of increasing rainfall with increased altitude is evident, there

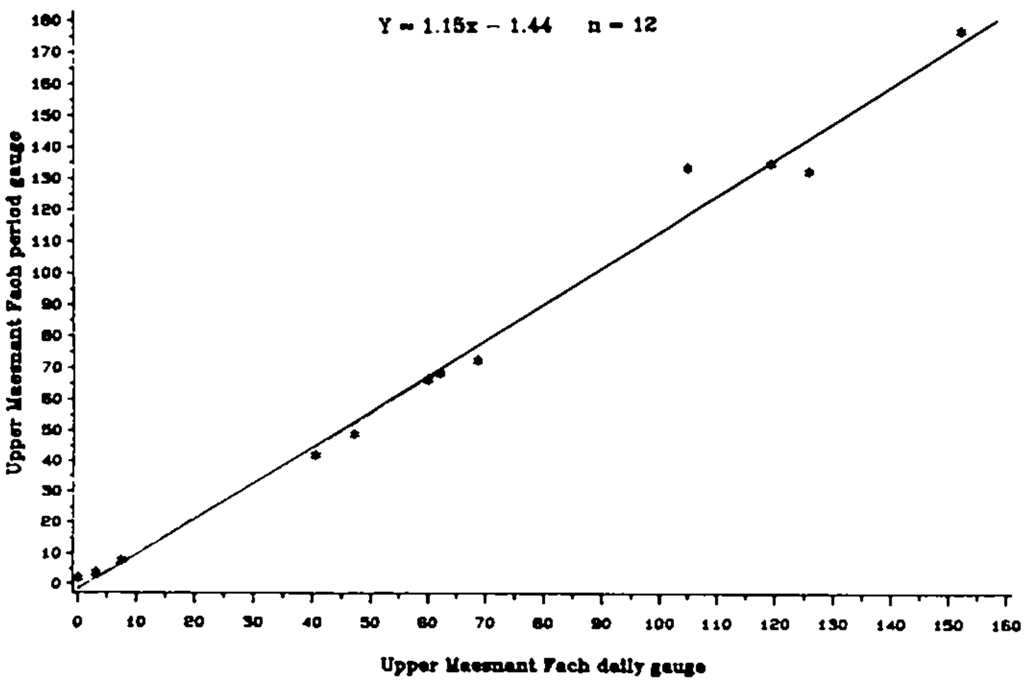


Fig. 15 Nant-y-Moch Regressions Period gauge totals (mm) Upper Maesnant Fach daily gauge v Upper Maesnant Fach period gauge.

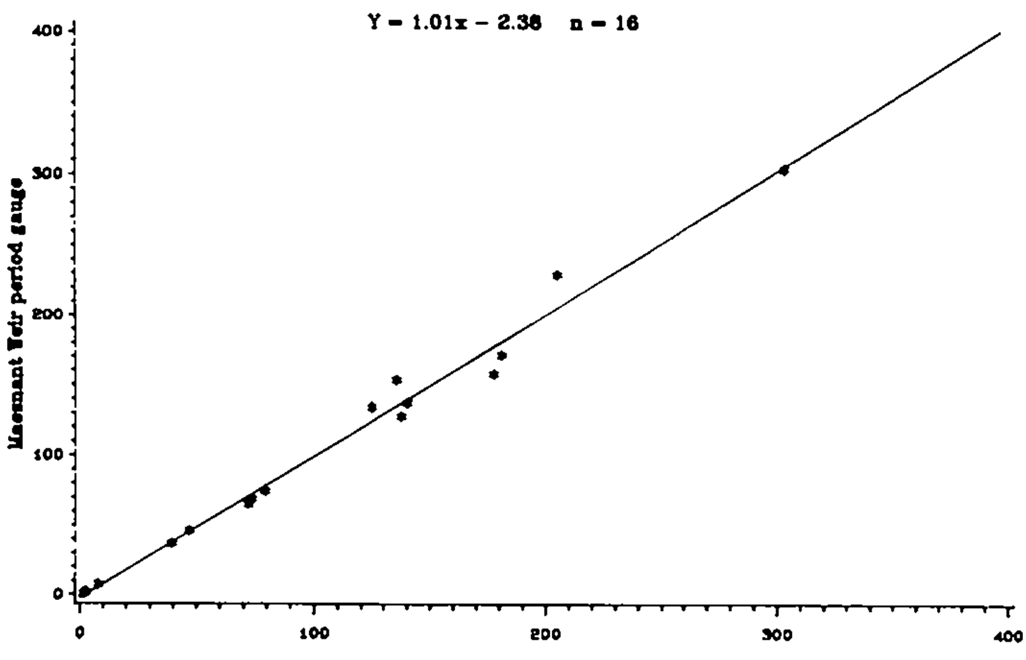


Fig. 16 Nant-y-Moch Regressions Period gauge totals (mm) Maesnant weir daily gauge v Maesnant Weir period gauge.

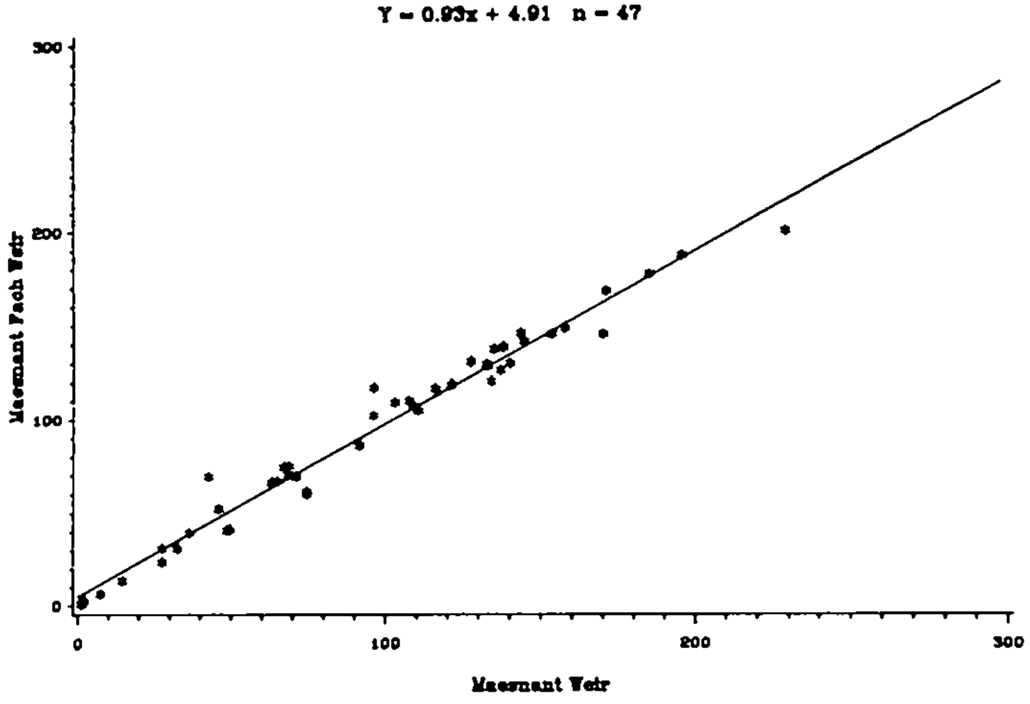


Fig. 17 Nant-y-Moch regressions Period gauge totals(mm) Maesnant Weir v Maesnant Fach Weir.

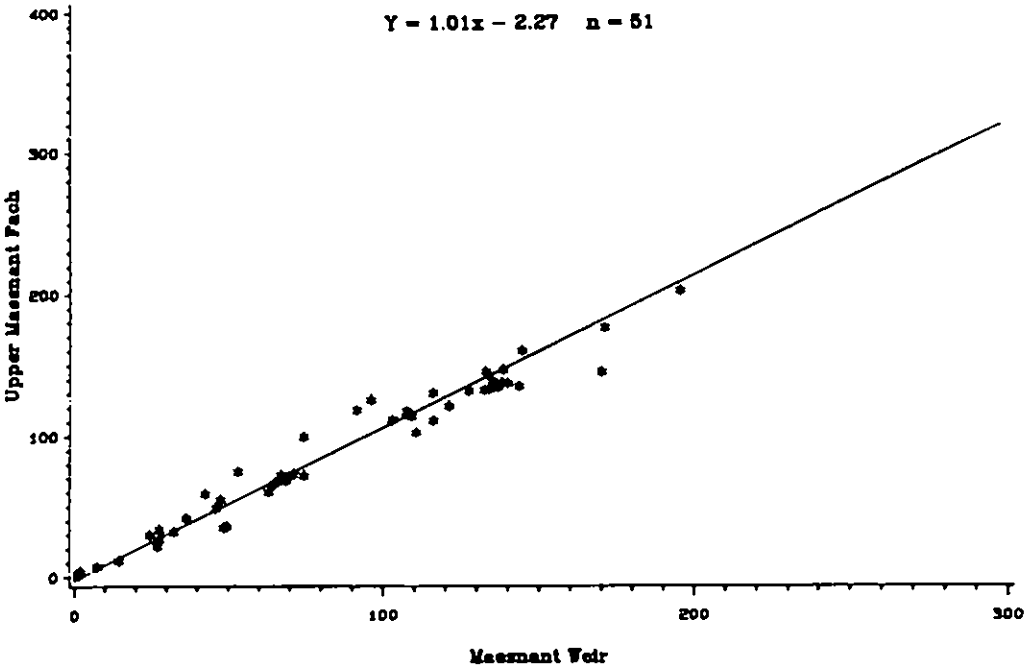


Fig. 18 Nant-y-Moch regressions Period gauge totals(mm) Maesnant Weir v Upper Maesnant Fach

are anomalies. For example the gauge at the Maesnant weir, although at the same altitude as the gauge in the Upper Maesnant Fach, catches approximately 5% less rainfall. More significantly, period gauge D1y in the upper Wye at Plynlimon is significantly undercatching for its altitude. For this reason, it was decided that the rainfall inputs to the upper parts of the Nant-y-Moch catchments would be best represented by the average of the catches of the four Plynlimon gauges rather than trying to "match altitudes". This is likely to lead to an underestimate for the Maesnant and an overestimate for the Maesnant Fach.

To be of any use to this study, the monthly rainfall totals have to be redistributed in time so that they coincide with the rainfall sampling periods. This is done according to the data from three recording raingauges at Plynlimon: at Eisteddfa Gurig, Esgair-y-Maen and Carreg Wen. Period gauge totals appropriate to the sampling periods are obtained by the relationship.

$$PG = \Sigma RG \frac{MG}{MRG}$$

where
- PG = period gauge total
- ΣRG = total in recording gauge for the period
- MG = monthly total in period gauge
- MRG = monthly total in recording gauge.

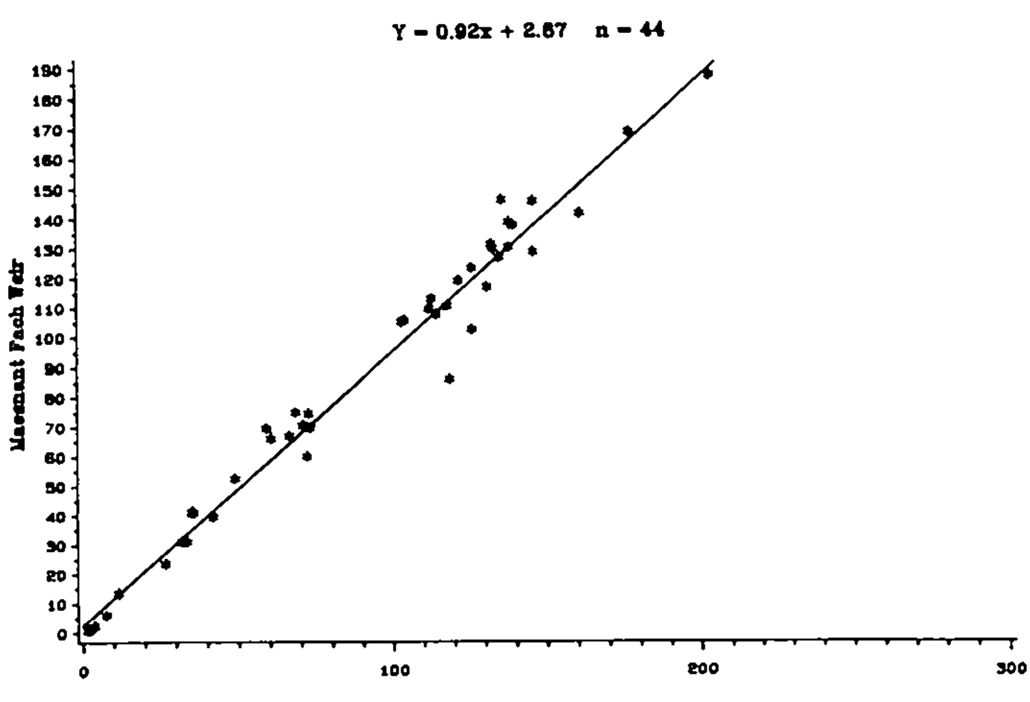


Fig. 19 Nant-y-Moch regressions Period gauge totals(mm) Upper Maesnant Fach v Maesnant Fach Weir

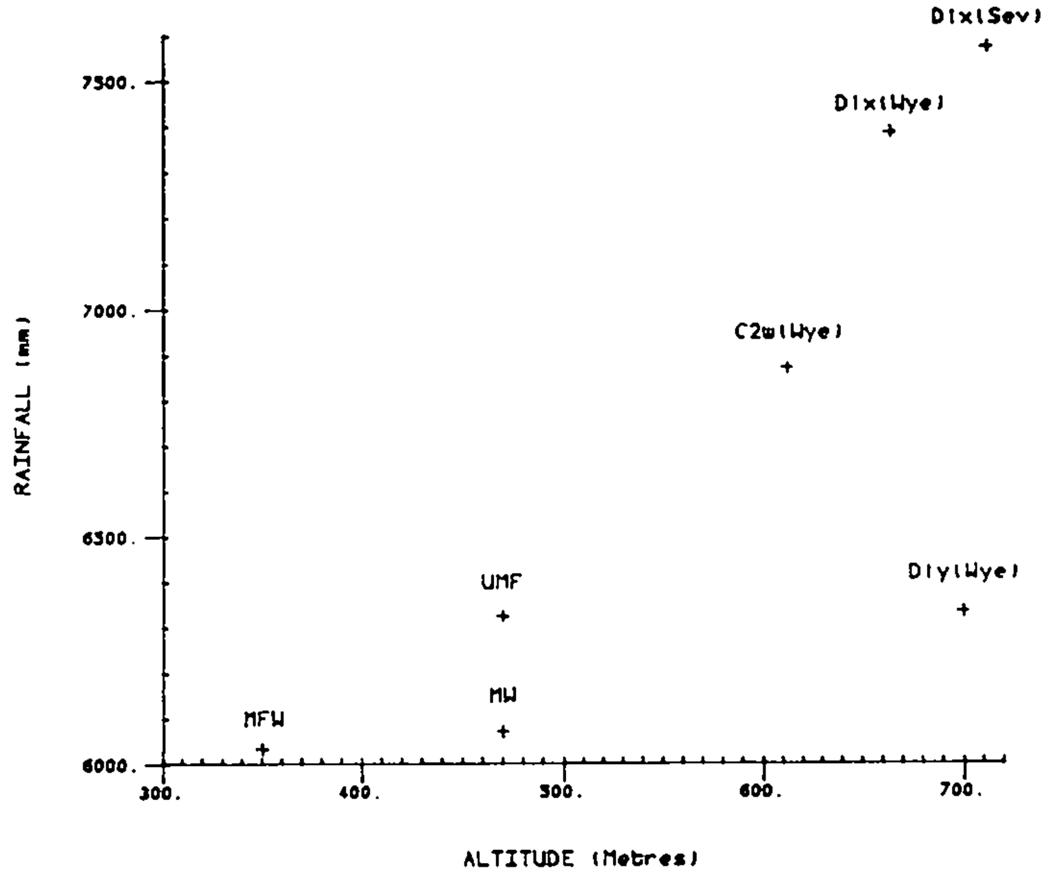


Fig. 20 Rainfall totals (Feb 84 - Dec 86) vs altitude

For those periods straddling two months, two calculations are used, one for the end of the first month and one for the beginning of the next. All available recording gauge data are used, so that if all three recording gauges were working for any particular month, then the data from all three were used to distribute each monthly gauge total. During the first three months of 1986 the monthly gauges were buried beneath snow and the recording gauges were inoperative for long periods. Therefore the period totals were calculated by time-distributing three-monthly totals using the daily rainfall at Moel Cynnedd Meteorological site at Plynlimon. Finally, the two-weekly totals for the four gauges were averaged to give "high altitude" rainfall inputs.

Even with the inclusion of these "high altitude" inputs, an areal estimate for the Maesnant Fach catchment can be made from only three "gauges". In the case of the Maesnant, only two are available. Therefore, it was decided to split the catchments up into rainfall areas according to altitude, each area being represented by one "gauge". This is shown in Figure 21 and the outcome of this is:

Areal rainfall into Maesnant Fach = 0.25 × Maesnant Fach weir + 0.60 x Upper Maesnant Fach + 0.15 × "High Altitude" Rainfall.

Areal rainfall into Maesnant = 0.50 × Maesnant Weir + 0.50×"High altitude" Rainfall.

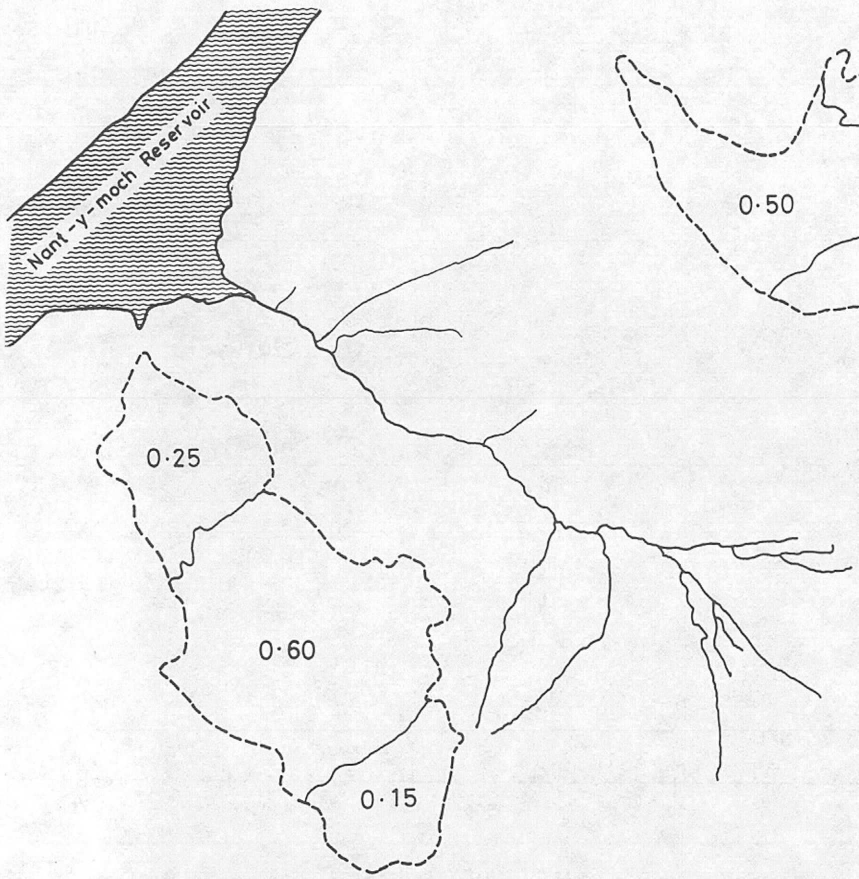


Fig. 21 Catchments split into rainfall areas

Accumulated rainfall totals for the two catchments are shown in Figure 22.

Runoff

Streamflow data from the Maesnant Fach (experimental) catchment became available during May 1984 and from the Maesnant catchment in November of the same year. Therefore it became necessary to fill in the streamflow data for the Maesnant for the period May to November 1984. There were also some periods when streamflow data were not recorded, for a number of reasons, although thankfully there have been no instances to date when both weirs were inoperative at the same time.

The first task, therefore, was to fill in these various gaps in the data sets. This was done by comparing period streamflow totals from the two catchments (Figure 23) and using the regression equation, obtained by the least squares method, to interpolate. Figure 23 shows that the regression was good, although it is noticeable that flows from the Maesnant were significantly greater than those from the Maesnant Fach.

This is confirmed in Figure 24 where rainfall into and streamflow out of the catchments are accumulated and also in the table below where annual rainfall, runoff and water use estimates are shown.

		Rainfall	Runoff	Water Use
1985	Maesnant Fach	2370	1525	846
	Maesnant	2458	1886	572
1986	Maesnant Fach	2612	1661	951
	Maesnant	2732	2086	646

Whilst rainfall to the Maesnant is of the order of 100 mm per year greater than that to the Maesnant Fach, the difference in runoff is between 350-400 mm. Also, the water use of both catchments, but particularly the Maesnant

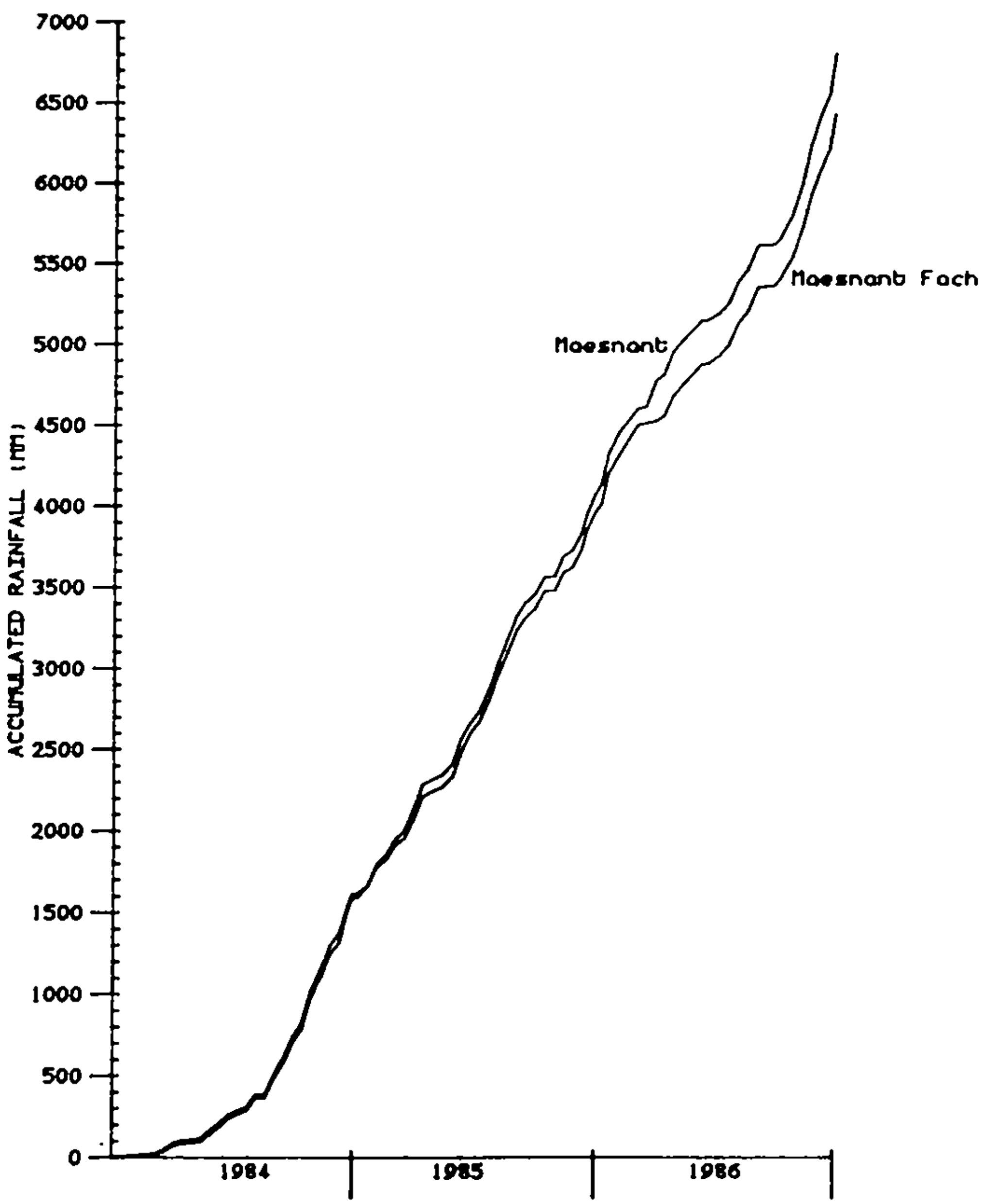


Fig. 22 Accumulating rainfall for the Nant-y-Moch catchments

Fach, is higher than for the grassland catchment at Plynlimon (IH, 1976) and for the Llanbrynmair catchments (Roberts *et al.*, 1986b). These discrepancies are currently being investigated with a view to determining the effectiveness of the sparse rainfall network in estimating inputs to the catchments, particularly during snow periods. The reason for the very low streamflow from the Maesnant Fach, even allowing for increased transpiration from the improved areas and shelter belts, is also being investigated.

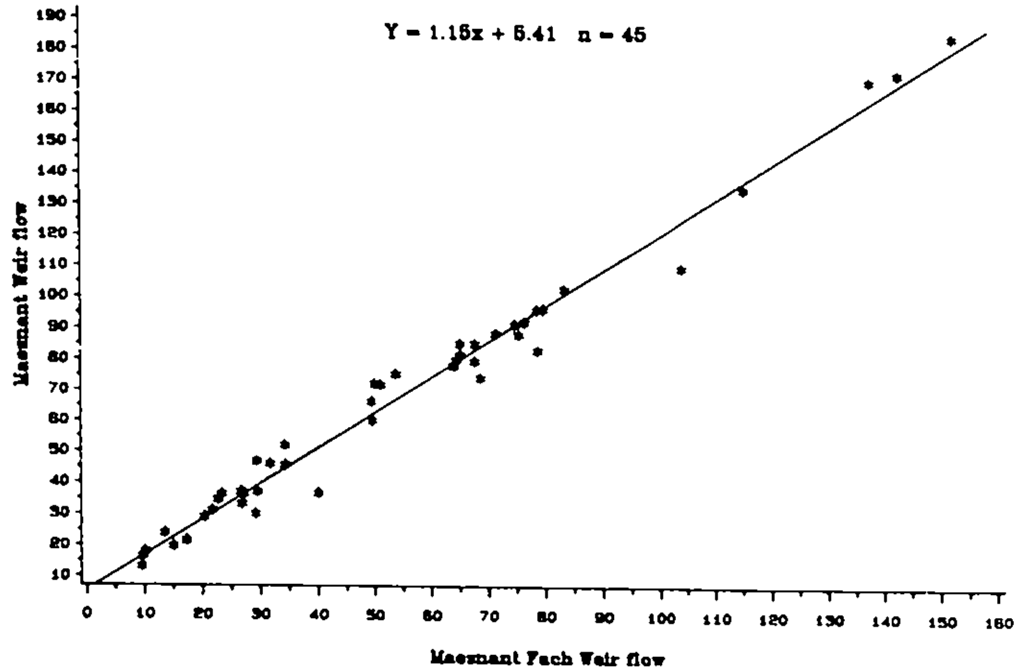


Fig. 23 Nant-y-Moch regressions Flow totals(mm) Maesnant Fach Weir flow v Maesnant Weir flow

6.2 CHEMICAL DATA

Minimum, maximum and mean concentrations of the various determinands in the rainfall and at the various points in the two streams (see Section 5.3) are given in Table 9. The values are only given to indicate relative magnitudes. Direct comparison between the concentrations in the various streamflow samples is not possible, because the values were obtained from a combination of spot and composite samples. For this reason, the mean values are not flow-weighted; this also applies to the mean rainfall concentrations.

Time series plots of the determinands in the rainfall and the various stream sample are shown in Appendix 1. Composite streamflow samples are denoted by two symbols connected by a solid line. Spot samples are denoted by a single symbol whilst combined composite/spot samples are shown as two symbols connected by a dotted line. When the concentration was below the detection limit, it was set to the detection limit. Appropriate values will be given later when describing individual species.

Table 9 Minimum, maximum and mean concentrations in the rainfall and at various points in the two streams at Nant-y-Moch

Ammoniacal-N	Minimum	Maximum	Mean
Rainfall	0.006	1.840	0.405
Maesnant Fach (Expt.)	0.004	1.320	0.041
Maesnant (Control)	0.004	0.082	0.013
Upper Maesnant Fach (Control)	0.004	1.160	0.017
Drain	0.004	0.440	0.048
Nitrate-N			
Rainfall	0.04	1.94	0.257
Maesnant Fach (Expt.)	0.01	0.74	0.067
Maesnant (Control)	0.01	0.94	0.188
Upper Maesnant Fach (Control)	0.01	0.90	0.195
Drain	0.01	2.60	0.143
Kjeldahl-N			
Rainfall	0.01	5.50	0.504
Maesnant Fach (Expt.)	0.01	0.78	0.238
Maesnant (Control)	0.01	1.53	0.191
Upper Maesnant Fach (Control)	0.01	1.33	0.155
Drain	0.01	1.05	0.323
Organic-N			
Rainfall	0.002	4.40	0.272
Maesnant Fach (Expt.)	0.008	0.55	0.218
Maesnant (Control)	0.010	1.51	0.188
Upper Maesnant Fach (Control)	0.010	1.33	0.149
Drain	0.010	0.88	0.275
Total-N			
Rainfall	0.15	5.66	0.822
Maesnant Fach (Expt.)	0.04	1.44	0.302
Maesnant (Control)	0.06	1.53	0.374
Upper Maesnant Fach (Control)	0.01	1.73	0.343
Drain	0.01	3.01	0.462
Total-P			
Rainfall	0.02	0.48	0.034
Maesnant Fach (Expt.)	0.02	0.28	0.047
Maesnant (Control)	0.02	0.75	0.035
Upper Maesnant Fach (Control)	0.02	2.28	0.051
Drain	0.02	2.20	0.163
Potassium			
Rainfall	0.03	4.40	0.542
Maesnant Fach (Expt.)	0.06	1.21	0.221
Maesnant (Control)	0.07	0.54	0.157
Upper Maesnant Fach (Control)	0.03	0.59	0.147
Drain	0.03	7.20	0.355
pH			
Rainfall	3.9	9.0	5.44
Maesnant Fach (Expt.)	3.9	8.2	5.73
Maesnant (Control)	3.9	6.5	5.36
Upper Maesnant Fach (Control)	4.3	8.9	5.25
Drain	3.9	8.7	5.62

In some cases, concentrations in the rainfall samples are higher than in the various streamflow samples, whilst in others the reverse is true, suggesting weathering within the soil profile. For some determinands, strong seasonal fluctuations are apparent; this makes prediction of the factors controlling nutrient release easier. For other determinands, no such patterns are evident; therefore different techniques have been used to fill in gaps in the streamflow composite concentration data sets.

For the Llanbrynmair data, these gaps were filled using a "similar period" approach (Roberts *et al.*, 1986b). In the case of Nant-y-Moch, a more rigorous method has been adopted. An attempt has been made, using such

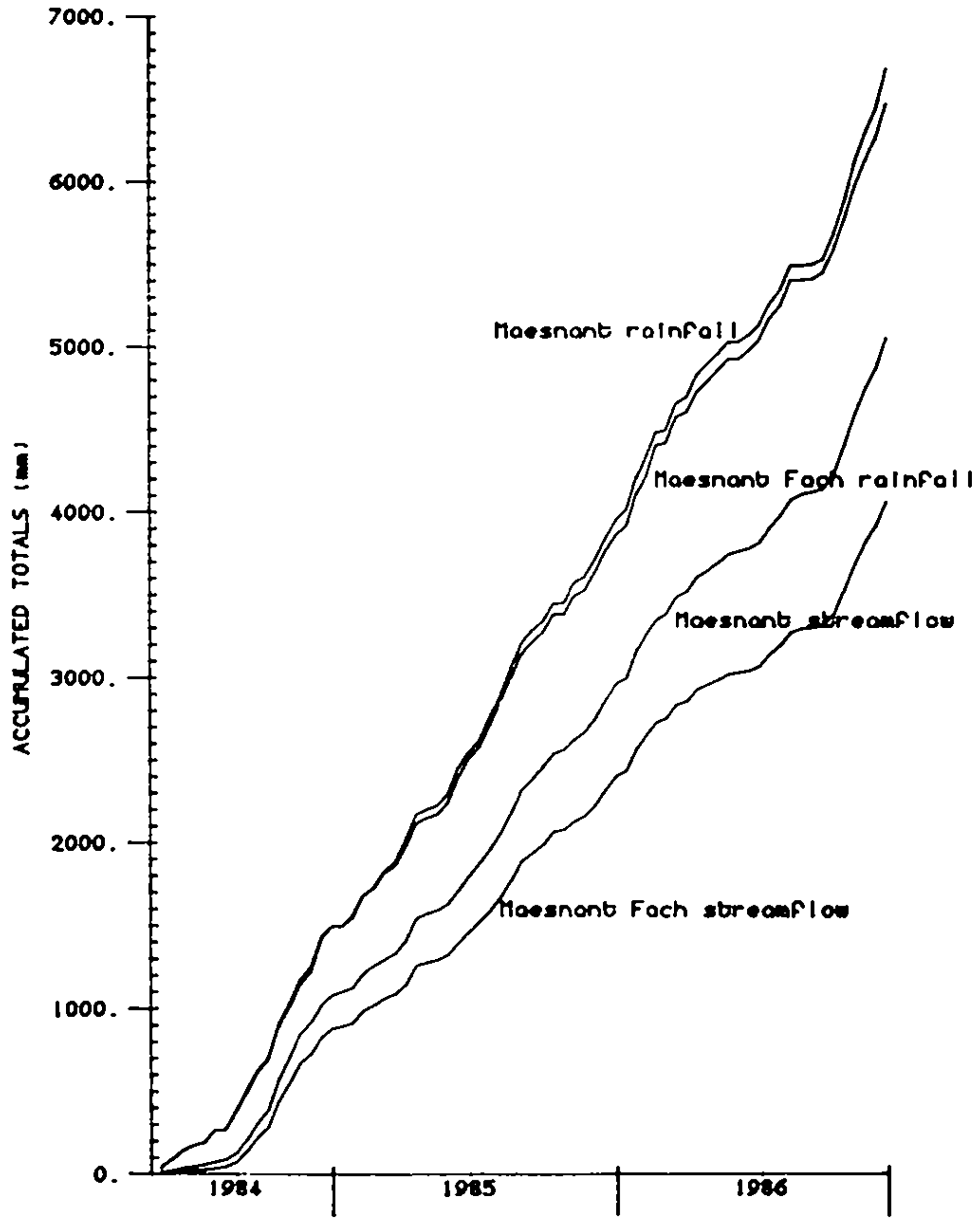


Fig. 24 Accumulated rainfall and flows for the Nant-y-Moch catchments

variables as soil temperature, soil moisture deficit, mean daily flow, percentage baseflow and rainfall concentrations, to fit regressions to the available composite sample data. For those determinands where this has not been possible and where neither the spot nor the composite concentrations fluctuate, it was assumed that the mean period or composite concentration was simply the average of the pre- and post-period concentrations.

$$\text{MEAN PERIOD CONCENTRATION} = \frac{(C_{n-1} + S_n)}{2}$$

where C_{n-1} = composite concentration in previous period <u>OR</u> spot concentrations at end of previous period

S_n spot concentrations at end of current period

For the other determinands simple models have been developed and these have been used to predict composite concentrations. These values have been combined with the results from the spot samples as follows:-

$$\text{MEAN PERIOD CONCENTRATION} = \frac{\left\{\frac{(C_{n-1} + S_n)}{2} + \text{PREDICTION}\right\}}{2}$$

where PREDICTION = predicted composite concentrations

C_{n-1}, S_n are as explained previously.

Using this technique, year to year variations and the conditions during each particular period are taken into account. The single models that have been developed are only regarded as a first step towards predicting nutrient release. It is hoped that they will be developed in the future to give more accurate predictions.

Concentrations in the rainfall samples at Nant-y-Moch have been compared with values from five other sites in mid-Wales (Roberts, 1987). Although variations were observed for some periods, particularly during the dry summer months, annual comparisons were generally good, indicating not only that the Nant-y-Moch site is typical of much of mid-Wales, but also that the chemical analysis techniques employed in this study give results comparable to other laboratories. Gaps in the rainfall concentration data set were filled in using values from the most appropriate of the other five sites.

Composite concentrations, both observed and interpolated, have been combined with rainfall and streamflow totals to give estimates of inputs to and outputs from the catchments. These are shown as accumulating totals in Appendix 2 and as annual totals in Table 10.

Nitrogen

Three species of nitrogen were analysed: ammoniacal-N, nitrate-N and Kjeldahl-N. Their limits of detection were: ammoniacal-N 0.004 mg/ℓ,

Table 10 Annual nutrient inputs in rainfall and outputs in streamflow for the Nant-y-Moch catchments

	Maesnant Fach (Expt.) Rainfall	Maesnant Fach (Expt.) Streamflow	Maesnant (Control) Rainfall	Maesnant (Control) Streamflow
Ammoniacal - N (kg/ha)				
1985	8.71	0.18	8.70	0.11
1986	8.04	0.28	8.02	0.22
Nitrate-N (kg/ha)				
1985	4.82	1.05	4.86	3.77
1986	5.73	1.19	5.47	3.56
Organic-N (kg/ha)				
1985	1.82	3.14	1.96	2.59
1986	2.37	3.92	2.35	2.29
Total-N (kg/ha)				
1985	14.74	4.37	14.89	6.54
1986	15.05	5.37	14.76	6.03
Potassium (kg/ha)				
1985	10.25	2.61	10.60	2.62
1986	9.35	3.30	9.06	2.80

nitrate-N 0.04 mg/ℓ and Kjeldahl-N 0.05 mg/ℓ. Organic nitrogen concentration is given by the difference between Kjeldahl-N and ammoniacal-N. In some instances, particularly in rainfall samples during high nitrogen concentration periods, problems have arisen because the ammoniacal-N concentration has been higher than the Kjeldahl-N. This was also observed during analyses of the Llanbrynmair and Hore/Hafren samples by the Severn-Trent Water Authority and no reason is yet apparent. The discrepancy is generally small, less than 0.1 mg/ℓ and until further evidence becomes available, it has been assumed that the ammoniacal-N determination, being by far the more straightforward, is correct and that the Kjeldahl-N determination is underestimating. When this happened, the organic-N concentration was set at the Kjeldahl-N limit of detection, 0.05 mg/ℓ.

For the purpose of filling in gaps in the composite sample concentration record, the three nitrogen species were considered separately. However, when comparing nitrogen inputs in rainfall and outputs in the streamflows, total nitrogen as also considered because of the various nitrogen transformations between rainfall and the streamflows. Total nitrogen was expressed as Kjeldahl-N plus nitrate-N, or as ammoniacal-N plus nitrate-N when ammoniacal-N was greater than Kjeldahl-N.

(i) Ammoniacal-N

Ammoniacal-N concentrations in the rainfall and various streamflow samples are shown in Figure 41 in Appendix 1. Concentrations in the rainfall samples were generally much higher than in the streamflow from any of the sampling points.

Concentrations in the rainfall samples were generally low, during the winter months, up to 0.5 mg N/ℓ, whereas the drier summer months were characterised by much higher values, with a maximum of 1.84 mg N/ℓ. Such a pattern is normal, the high values being due to the leaching of windborne organic matter within the sampler (Roberts, 1987).

The concentrations in the various streamflow samples, on the other hand, were much lower, often below the limit of detection. Long periods of very low concentrations were interspersed with short periods of higher concentrations, particularly for the drain and the outfall of the Maesnant Fach. This is demonstrated in Figure 25 for the drain in 1984, the increases in the summer/autumn presumably resulting from the leaching of applied inorganic fertilisers following improvement in the spring. Similar increases occurred in the samples from the outfall of the Maesnant Fach during the winter 1984-85, with a peak concentration of 1.32 mg N/ℓ. However, these increases were more short-lived than those in the drain samples.

In terms of mean values (Table 9), those in the drain and at the outfall of the Maesnant Fach were higher than those in the two controls, although the single value of 1.32 mg N/ℓ in the Maesnant Fach had a great influence on the mean.

The pattern of concentrations (predominantly very low) at the outfalls of the two catchments, particularly the Maesnant, makes the filling in of gaps in the composite concentration data sets a relatively easy matter. The lack of any seasonal pattern suggests that no correlation exists with soil moisture deficit and there was no hint of any relationship between concentration and period

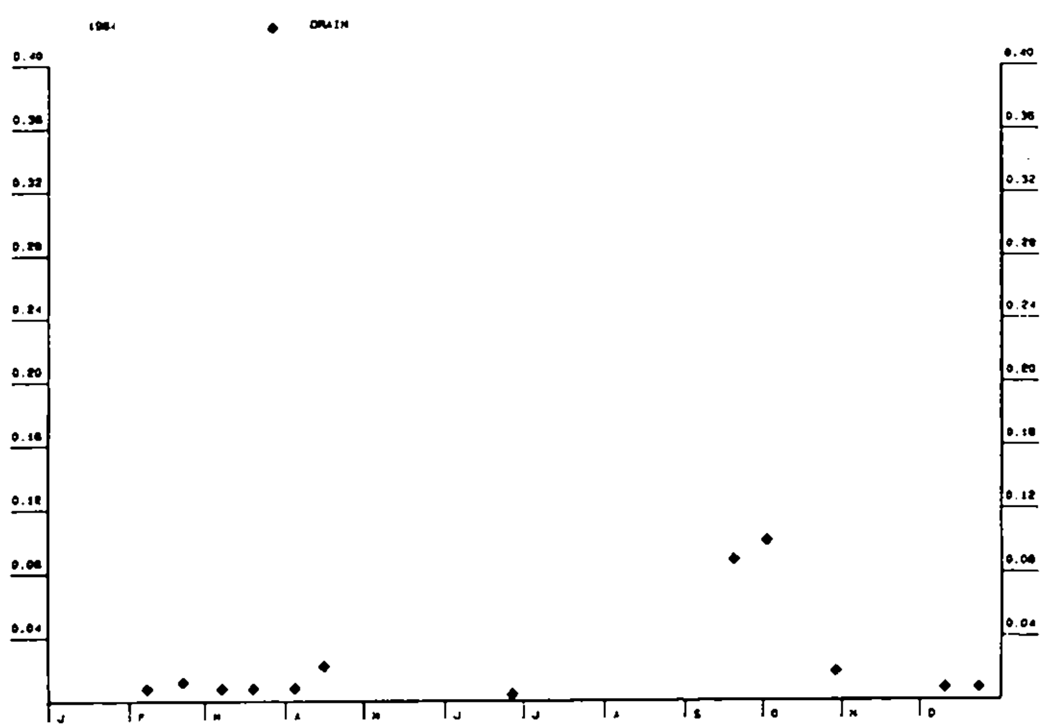


Fig. 25 Ammoniacal-N concentrations (mg/ℓ) at Nant-y-Moch

mean flow. Moreover there did not seem to be any great differences between concentrations of spot and composite samples during apparently similar periods. Therefore it was decided to assume that spot samples were representative of the preceding period. There is one period, January and February 1985, for the outfall of the Maesnant Fach where this may not have been strictly applicable, but the relatively smooth decrease in concentration in the spot samples from the peak in December 1984 suggests that no great error will have been introduced.

Accumulating ammoniacal-N inputs in the rainfall and outputs in the streamflows are given in Figure 46, Appendix 2. Annual totals are given in Table 9 . The results show that inputs in the rainfall are very much higher than outputs in the streamflows. The accumulating totals also show the effects of high concentrations in individual samples and, whilst these are probably "correct" for the rainfall samples, some of the streamflow samples are dubious. Nevertheless, the overall higher concentrations in the Maesnant Fach stream as opposed to the Maesnant stream, especially during the winter 1984, is quite evident.

(ii) Nitrate-N

Nitrate-N concentrations in the rainfall and various streamflow samples are shown in Figure 42 in Appendix 1. Concentrations in the rainfall samples were generally higher than those in the streams with the highest streamflow concentrations being observed at the two control sampling points, the Maesnant and the upper Maesnant Fach.

The data exhibit strong seasonal trends. In the rainfall samples, concentrations were generally higher during dry summer periods with levels up to about 2 mg N/ℓ, probably caused by contamination from windborne debris. On the other hand, concentrations at the sampling points in the streams were generally higher in the winter months (values up to about 1 mg N/ℓ), with concentrations in the summer months being below the detection limit of 0.04 mg N/ℓ presumably as a result of biological uptake from the soil (Reid *et al.*, 1981). There is no indication yet that the planting of the shelter belts or the pasture improvement schemes have had any sustained effect on the concentrations at the outfalls of the Maesnant Fach, although isolated high concentrations were found in the cut-off drain during the springs of 1985 and 1986.

The strong seasonal trends in the nitrate-N concentration at the outfalls of the Maesnant and Maesnant Fach catchments provide an opportunity for a rational approach to the problem of filling in gaps in the composite sample data sets. For this purpose, it was decided that models would be developed to predict concentrations in the composite samples.

As indicated previously, the concentrations in both streamflows during the summer months were below the detection limit, 0.04 mg N/ℓ. A more detailed inspection of the data alongside soil temperatures, collected at the Moel Cynedd Meteorological station at Plynlimon, showed that this isually occurred when the soil temperature at 10 cm depth was greater than 6°C, the most widely accepted temperature for plant growth. Therefore for prediction purposes, separate periods were considered: those when the soil temperature was less than 6°C and those when it was greater than 6°C. For the latter periods, the predicted concentration in both streams was 0.04 mg N/l and this value was used to estimate the 'true' composite concentration.

For periods when the soil temperature was less than 6°C the situation was much more complicated. The approach used was to take the nitrate concentrations in the incoming rainfall and, using the available streamflow composite concentrations, assess the modifying effects of the soil on the rainfall before it became streamwater. By doing this, it immediately became apparent that the two catchments behaved very differently. In the Maesnant Fach, the concentrations in the stream were invariably lower (with the exception of one period) than those in the antecedent rainfall. For the Maesnant, the reverse was true.

Although the two catchments had opposite effects on the nitrate concentrations in rainfall during the winter months a similar approach was adopted for predicting composite streamflow concentrations in each. The first step split each sampling period into "stormflow" and "baseflow". Then it was assumed that each type of flow had a different modifying effect on the rainfall. For example, it would be expected that concentrations in stormflow would be similar to those in rainfall, but those in baseflow would be greatly modified as the water spends a considerable time passing through the soil profile. Using the available composite streamflow concentrations, some simple models depicting the modifying effects of the catchments on the rainfall were tested. If a particular period had no rain at the beginning, the concentrations in the previous periods' rainfall was used. This applied until the first significant increase in flow, at which time the concentration in the present periods' rainfall was used. Baseflow was set arbitrarily at 5 mm/day. For both catchments it was found that the most significant factor was soil temperature, and so those values found at Moel Cynnedd were used as the controlling variable.

In the case of the Maesnant Fach, the best agreement with the available data was found by assuming that a concentration reduction occurred during baseflow periods, whilst a concentration enhancement occurred during stormflow. Least squares regression suggested the following equations:

BASEFLOW PERIODS: $S_c = R_c - 0.11\,T$

STORMFLOW PERIODS: $S_c = R_c + \frac{0.5}{T}$

where S_c = streamflow composite concentration mg/l
R_c = rainfall concentration mg/l
T = soil temperature °C

For the Maesnant, the best fit was found by assuming that concentration enhancement was occurring during both types of flows in the following manner:

BASEFLOW PERIODS $S_c = R_c + \frac{0.44}{\sqrt{T}}$

STORMFLOW PERIODS $S_c = R_c + 0.003 + T$

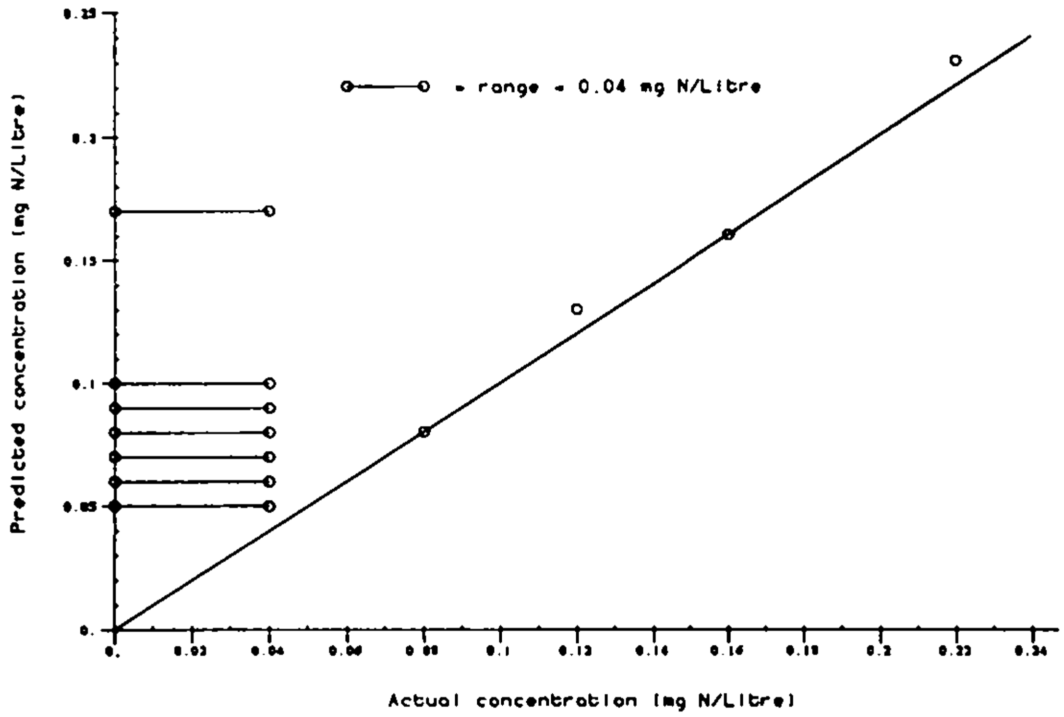


Fig. 26 Predicted and actual composite streamflow nitrate concentration in the Maesnant Fach. Temp < 6 deg C.

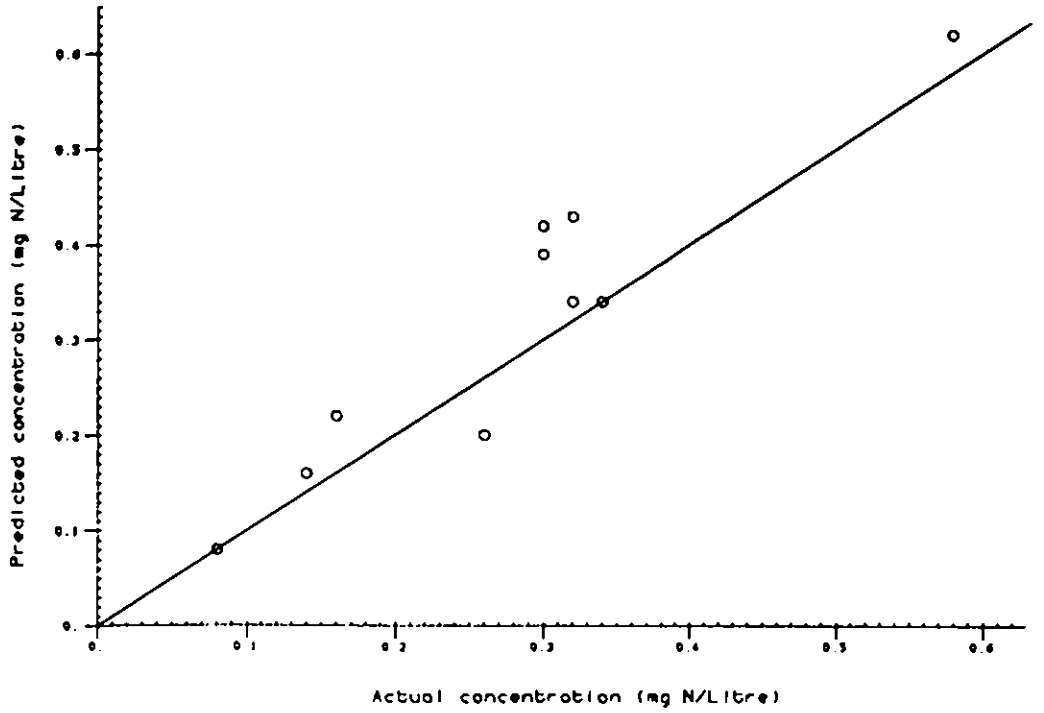


Fig. 27 Predicted and actual composite streamflow nitrate concentration in the Maesnant. Temp < 6 deg C.

Predicted concentrations, given as the sum of the contributions from each type of flow in the period, are plotted against actual concentrations in Figure 26 for the Maesnant Fach catchment and in Figure 27 for the Maesnant. In general, the predicted values are higher than those observed, though considering the assumptions adopted the agreement is good.

These above simple models were used to predict concentrations for the periods when composite samples were not available. In order to judge how realistic the predictions are, these values have been plotted against the average concentrations of the spot samples before and after the period. This is shown in Figure 28 for the Maesnant Fach and in Figure 29 for the Maesnant. Although such a comparison is not strictly valid, it does show predicted values for the Maesnant of the right order of magnitude. For the Maesnant Fach the agreement is not so good, although very high concentrations obtained in two spot samples taken during high flow periods are to a large extent responsible for the worst discrepancies. The predicted values seem to be constant underestimates, a point that will be discussed later.

Accumulating nitrate-N inputs in the rainfall and in the outputs from the two catchments are given in Figure 47, Appendix 2. Annual totals for 1985 and 1986 are given in Table 10. Inputs are higher than outputs for both catchments. This is particularly so for the Maesnant Fach, a reflection of the lower streamflows from this catchment. More significantly, there are lower concentrations in this stream when compared with the Maesnant during the winter months.

(iii) Organic-N

Minimum, maximum and mean organic nitrogen concentrations in the rainfall and various streamflow samples are given in Table 9. Time series plots are given in Figure 43, Appendix 1. Concentrations in the streamflow samples, particularly in the drain, are generally higher than those in the rainfall, suggesting that they result from soil erosion.

Although higher concentrations were generally obtained in the rainfall samples during dry summer periods, no seasonal trends were found in the streamflow concentrations. To fill in gaps in the composite sample concentration data set, it was therefore necessary to use conditions applying in the individual periods. Initial analysis of the available data suggested that higher concentrations were found during wetter periods, particularly during the summer months. This reinforces the hypothesis- that the presence or organic N in the streams is due to soil erosion, because this is likely to be at its greatest during floods following dry periods.

Composite streamflow organic-N concentrations are plotted against the product of mean daily flow and mean daily soil temperature in Figure 30 for the Maesnant Fach and in Figure 31 for the Maesnant. Although there is a great deal of scatter, there does seem to be some correlation. Least squares regression suggests that the dependence on flow and temperature is small, particularly for the Maesnant, confirming the initial observation of a lack of any real seasonal trend.

These regressions were used to predict composite concentrations for those

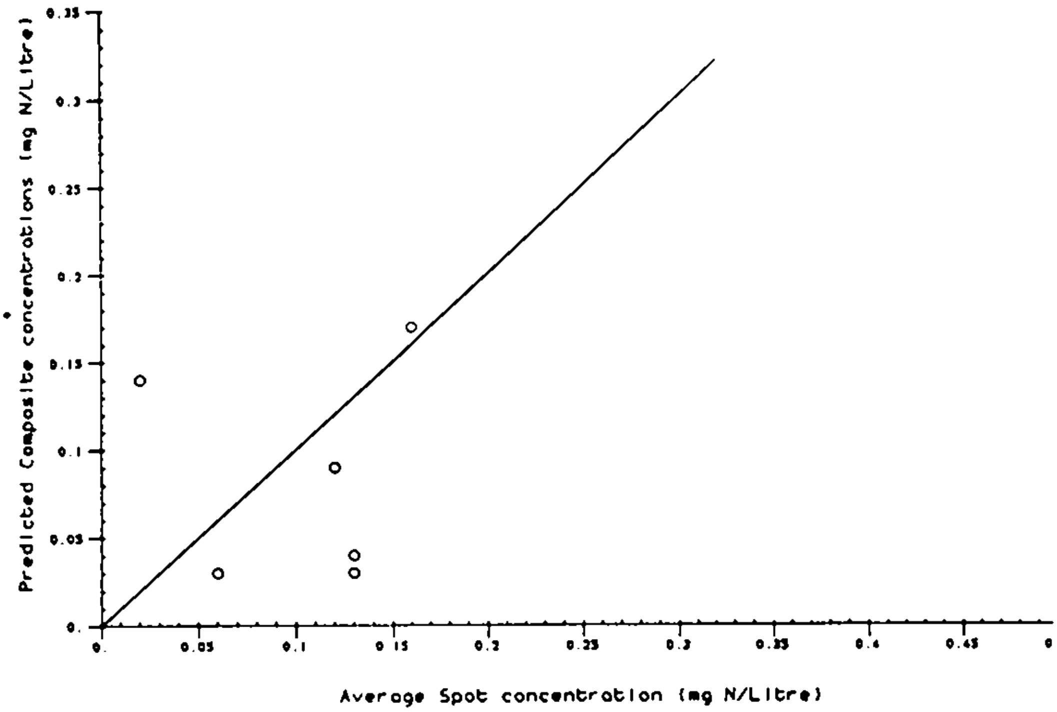


Fig. 28 Predicted composite and average spot nitrate concentrations for the Maesnant Fach. Temp < 6 deg C.

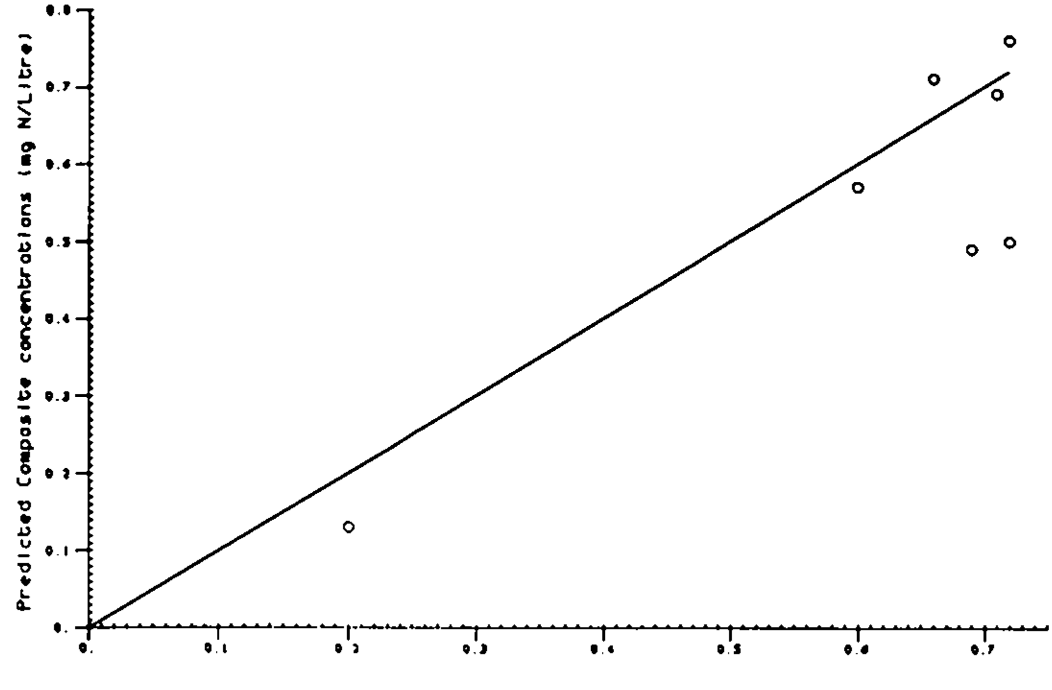


Fig. 29 Predicted composite and average spot nitrate concentration for the Maesnant. Temp < 6 deg C.

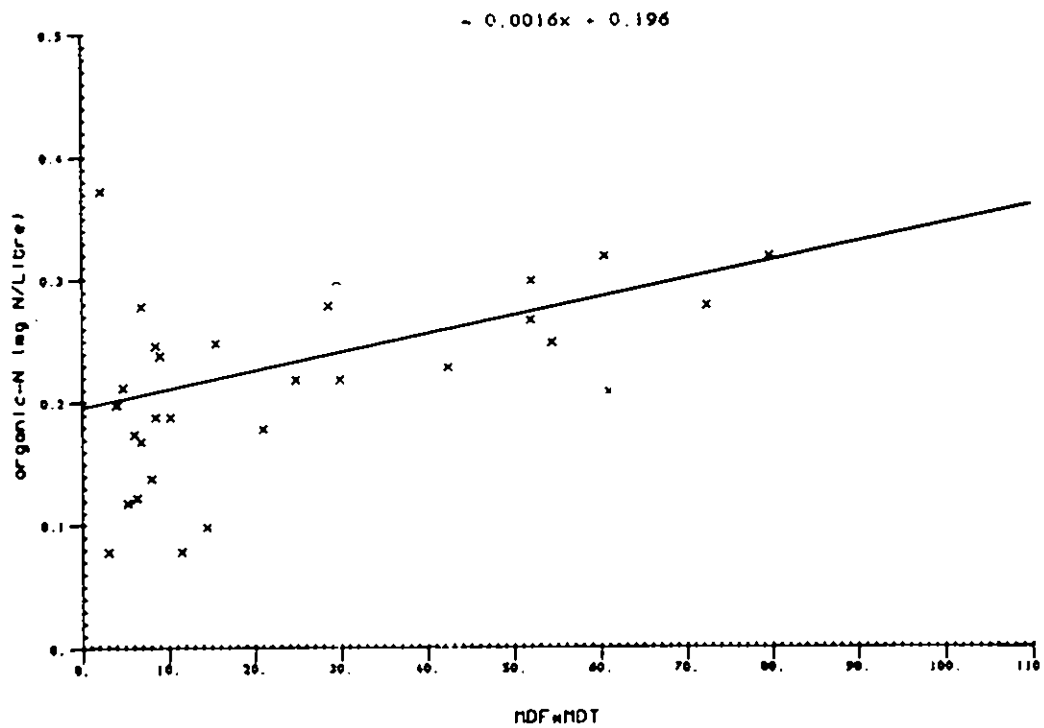


Fig. 30 Regression of composite streamflow organic-N concentration against mean daily flow mean daily temperature for the Maesnant Fach

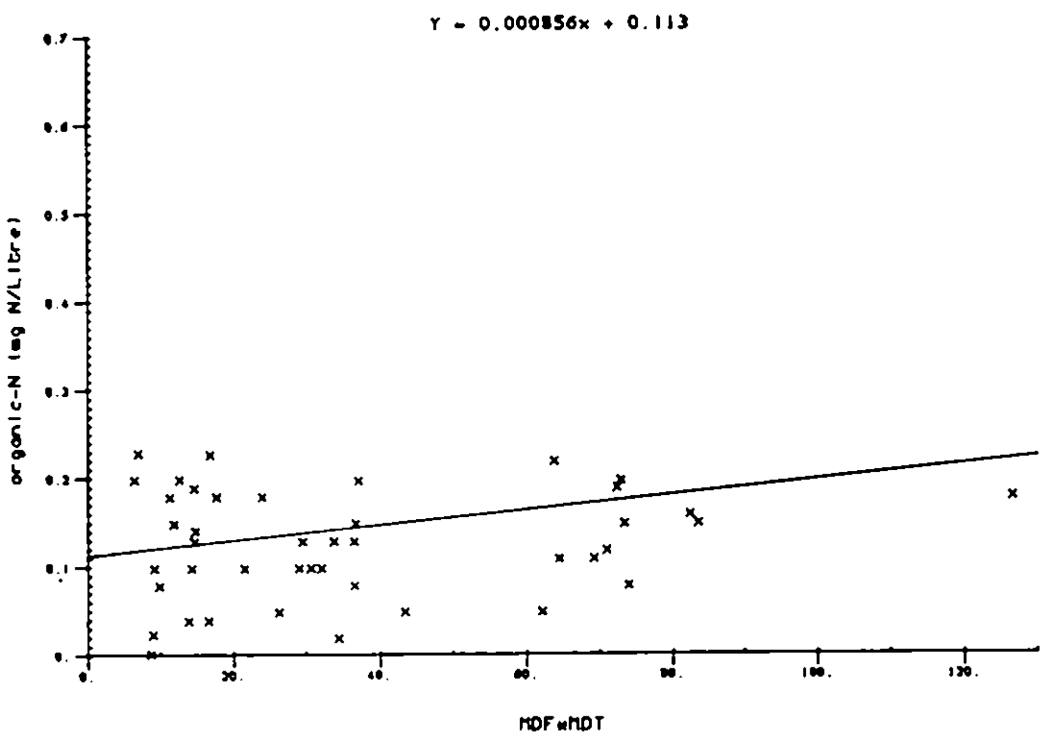


Fig. 31 Regression of composite streamflow organic-N concentration against mean daily flow mean daily temperature for the Maesnant

periods when the samplers were not working. To give an indication of how realistic these predictions might be, they were plotted against the average concentrations before and after the period. The graphs are shown in Figure 32 for the Maesnant Fach and in Figure 33 for the Maesnant. If such comparisons are valid, it appears that the predictions are overestimating for the Maesnant Fach. There are two possible reasons: firstly, most of the gaps in the data set occurred in the winter months, at which times concentrations were at their lowest; secondly it could result from uptake of inorganic N in the composite samples and its conversion to organic nitrogen. This agrees with what was observed for nitrate-N when the predicted value seemed to be underestimating (Figure 29). Clearly this needs further investigation. For the Maesnant the predicted values were more or less constant, reflecting the small dependence on flow and temperature, whereas concentrations in the spot samples were much more variable. Again, further analysis is required to clarify this issue.

The predicted values have been combined with the spot values to fill in the gaps as indicated previously. These interpolated and measured values have been combined with streamflow totals to give organic-N loads. These are shown, together with rainfall loads, as annual totals in Table 10 and as accumulating totals in Figure 48, Appendix 2.

(iv) Total N

Total nitrogen concentrations have been calculated as Kjeldahl-N plus ammoniacal-N. Minimum, maximum and mean values are shown in Table 9. Whilst the mean concentrations in the streams are approximately of the same magnitude, those in the rainfall samples are an order of magnitude higher, which ismainly a result of high summer concentrations.

Gaps in the composite sample concentration sets have been filled by summing the estimated ammoniacal-N , nitrate-N and organic-N values. These and the measured concentrations have been combined with streamflow totals to calculate total nitrogen losses from the Maesnant and Maesnant Fach catchments. These losses are shown, together with inputs in rainfall, as annual totals in Table 10. They show that rainfall inputs are more than an order of magnitude greater than outputs in streamflow. This is the normal pattern for undisturbed upland catchments (Roberts *et al.*, 1983). The inputs and outputs are well within the ranges normally quoted for upland catchments (Roberts, 1985). One interesting aspect concerns the relative contributions of the various nitrogen species to the total nitrogen loads in the rainfall and streamflows. For the rainfall, the average contributions are ammoniacal-N 53%, nitrate-N 33% and organic-N 13%, which are typical figures for upland areas (Roberts, 1987). However, the relative contributions in the two streams are very different. Whilst the ammoniacal-N contributions are similar at about 4%, the nitrate-N is 58% in the Maesnant but only 22% in the Maesnant Fach. On the other hand, the organic-N contribution is 39% in the Maesnant, whilst it is 72% in the Maesnant Fach. This illustrates the impact of different factors controlling nitrogen release from upland catchments.

With regard to the pasture improvement scheme apparently there have to date been no significantly increased nitrogen losses from the Maesnant Fach. Even the enhanced concentrations in the drain outlet are hardly likely to be of concern to the water industry.

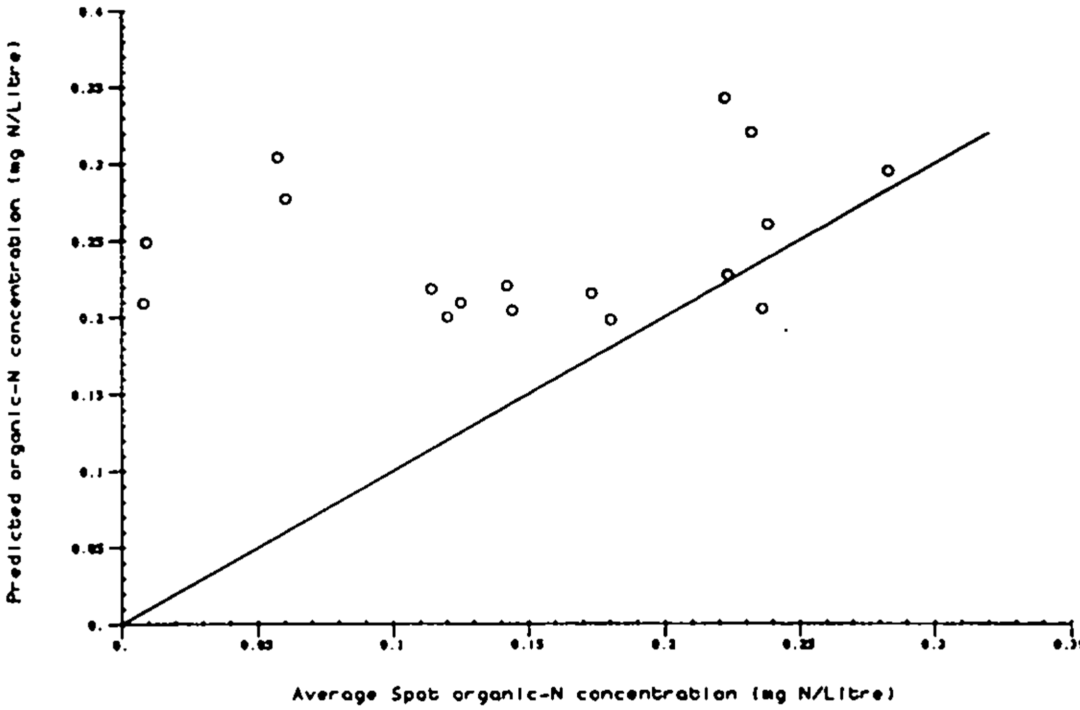


Fig. 32 Predicted composite organic-N concentrations and average spot concentrations for the Maesnant Fach

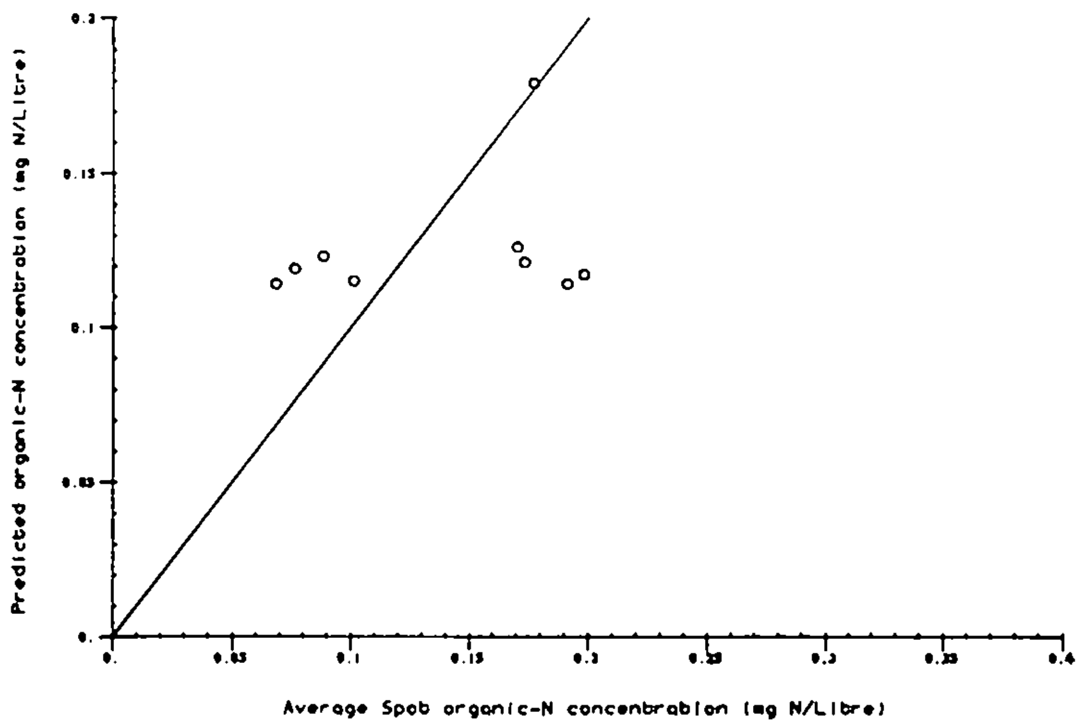


Fig. 33 Predicted composite organic-N concentrations and average spot concentrations for the Maesnant

Phosphorus

Minimum, maximum and mean total phosphorus concentrations in the rainfall and streamflow samples collected at Nant-y-Moch are shown in Table 9. For most of the time the concentration in all five types of sample was below the detection limit, 0.02 mg P/ℓ. For this reason no attempt has been made to predict phosphorus concentrations or to estimate inputs in rainfall or outputs in streamflows.

An exception to this is the set of samples collected from the cut-off drain during 1984 (Figure 34). Here, concentrations rose to a maximum value of 2.2 mg/ℓ, the response being remarkably similar to that of ammoniacal-N (Figure 25). This was presumably a result of loss of fertilizer following the improvement scheme in the spring. As with ammoniacal-N, no response in phosphorus concentration was found following the 1986 improvement.

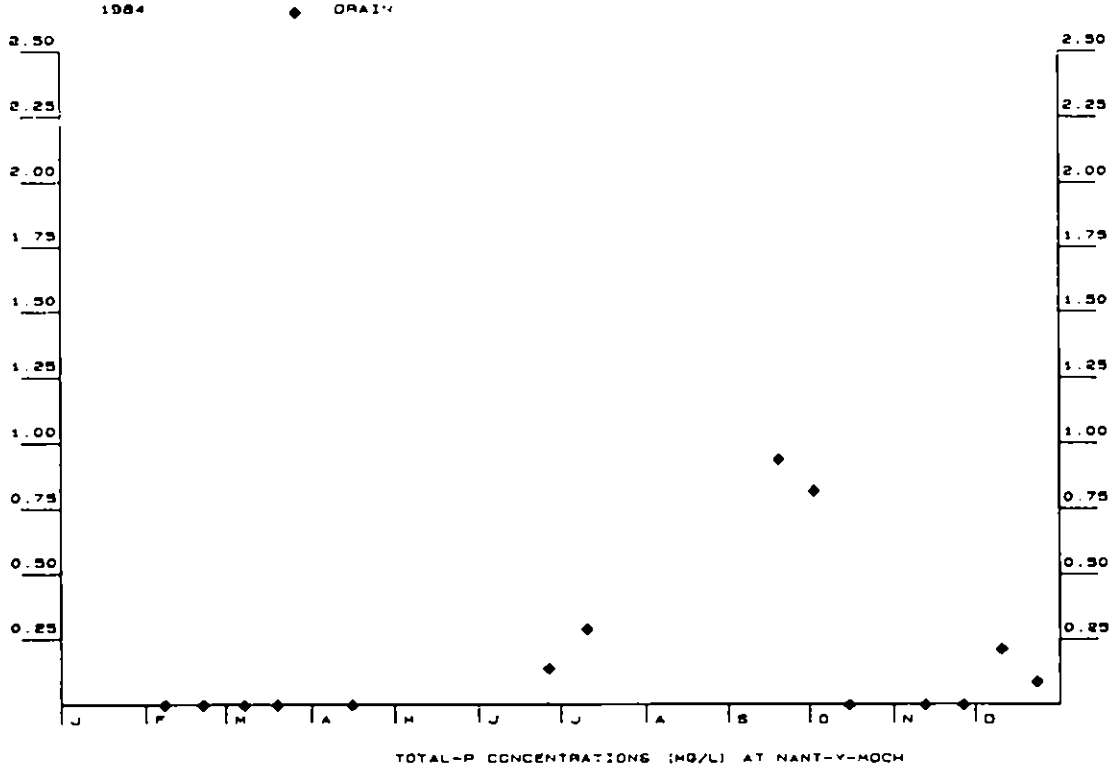


Fig. 34 Total-P concentrations (mg/ℓ) in the drain in the Maesnant Fach

Potassium

Minimum, maximum and mean total potassium concentrations in the rainfall and various streamflow sites are given in Table 9. Time series plots are given in Figure 44, Appendix 1. The mean concentration in the rainfall samples was higher than those in the streamflow samples. This was a result of enhanced rainfall concentrations during the summer months. Concentrations in the streams, on the other hand, are slightly lower during the summer.

With regard to the pasture improvement schemes, enhanced concentrations were observed in the cut-off drain (Figure 35) and at the outfall of the Maesnant Fach (Figure 36), particularly during 1984. These could have resulted from leaching of applied fertiliser or from a release of potassium as a result of burning the indigenous vegetation, a phenomenon observed following slash and burn in a forest in New Zealand (Neary *et al.*, 1978). Interestingly, enhanced concentrations were observed in the rainfall samples during 1986 (Roberts, 1987); whether these occurred as a result of the two pasture improvement schemes is not known.

A comparison of composite streamflow potassium concentrations at the outfalls of the Maesnant and Maesnant Fach with mean period daily flows and temperatures shows only slight dependence. This, together with small seasonal variation, makes prediction of streamflow concentrations difficult. Therefore, gaps in the composite data sets have been filled in using "predicted" values equal to the mean of the available composite concentrations as follows:

Maesnant Fach	Mean = 0.19 (n=46), standard deviation = 0.13
Maesnant	Mean = 0.14 (n=61), standard deviation = 0.08

When estimating the mean and standard deviation for the Maesnant Fach catchment, the enhanced values in the summer of 1984, which are presumably the result of the improvement scheme, are ignored. During this period there were no gaps in the composite data set. Finally, the "predicted" values were combined with the spot values to provide best estimates of the composite concentrations.

Annual potassium inputs in rainfall and outflows from the two catchments are shown in Table 10. Accumulating loadings are shown in Figure 49 in Appendix 2. The inputs are three to four times greater than the outputs. The inputs have been shown to be rather variable in the mid-Wales area (Roberts, 1987), these at Nant-y-Moch being higher than at other sites.

pH

Mean, minimum and maximum pH values in the rainfall and in the various streamflow samples are given in Table 9, and in Figure 45 in Appendix 1. The mean value in the rainfall, 5.44, was surprisingly high, but this was influenced by a number of high values during the summer months, presumably arising from contamination. Rainfall weighted mean values were appreciably lower (Roberts, 1987).

pH values in the streams are of the same order as those in the rainfall, which suggests that the buffering capacity of the soil is low. Whilst the pH in the Maesnant and upper Maesnant Fach catchments have remained more or

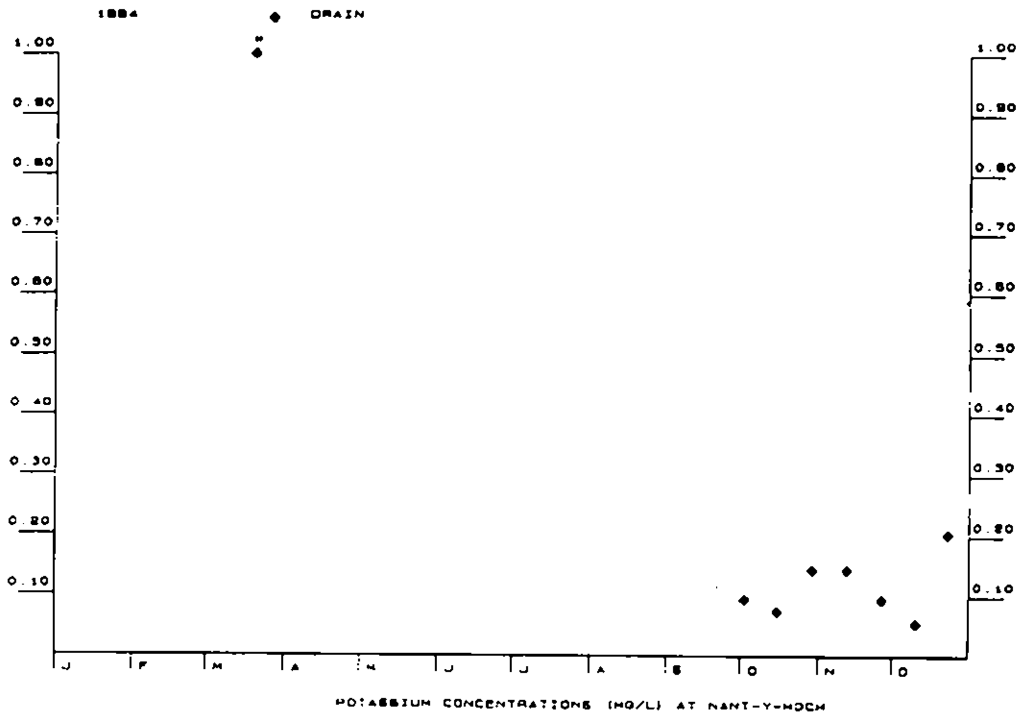


Fig. 35 Potassium concentration (mg/l) in the drain in the Maesnant Fach.

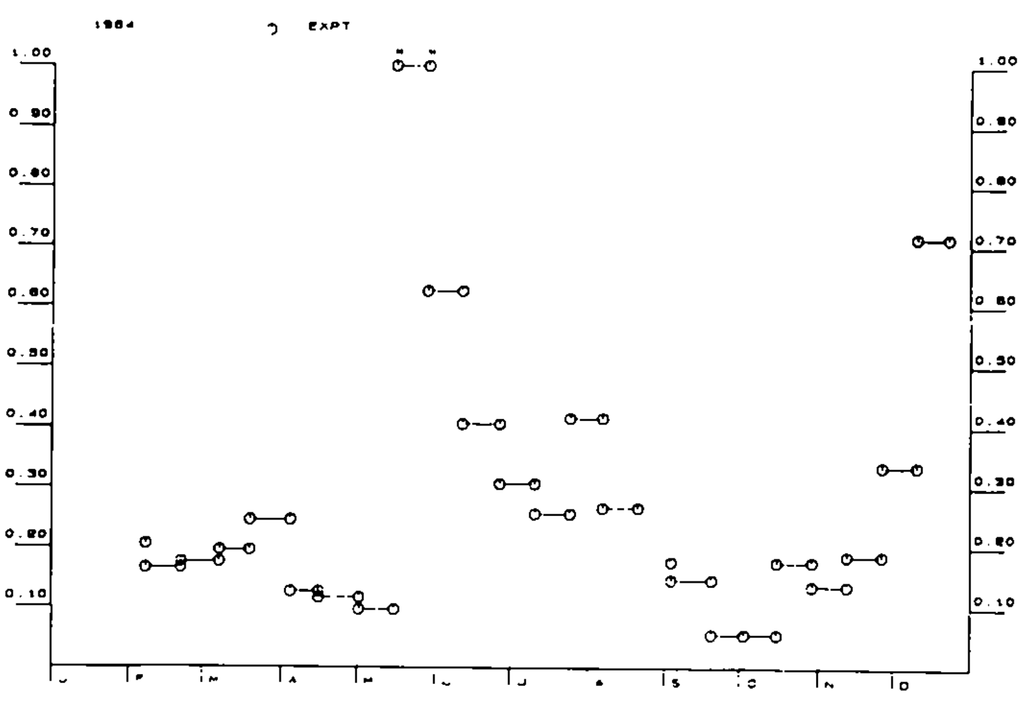


Fig. 36 Potassium concentrations (mg/l) for the outfall of the Maesnant Fach.

less constant throughout the three years of study, those in the drain and at the outfall of the Maesnant Fach have risen by 0.8 and 0.5 of a pH unit respectively, a reflection of the effect of the lime applied to the improved areas during 1984 and 1986.

6.3 SEDIMENT DATA

The sediment transported through the Nant-y-Moch catchments can be divided into suspended load and bed-load as described in Section 5.4. The two types of sediment transport will first be considered separately then in combination and in the context of sediment output, or yield, estimates from other upland streams both in the region and elsewhere.

Suspended load

The output of suspended sediment from the Nant-y-Moch catchments was not studied in great detail. A limited number of samples was taken indicate whether sediment concentrations were enhanced following land improvement. It was expected from past experience of ground disturbance in upland catchments (Leeks & Roberts, 1987) that, if the suspended load did react to the improvement activities, it would be evident within the first year of study. However, suspended load outputs from the Maesnant Fach remained low relative to other mid-Wales streams. The range of suspended sediment concentration following improvement in the Maesnant Fach was from <0.001 g/ℓ up to 0.035 g/ℓ. In the control catchment a range of <0.001 g/ℓ up to 0.016 g/ℓ was measured. Sampling frequency was therefore restricted, permitting resources to be concentrated on other catchment studies.

Although there was considerable spread in the data, typical of upland channels (Reynolds *et al.* 1988), best-fit curves were applied to these limited data (Figure 37). Analysis was then taken a stage further by combining rating curves of suspended sediment versus water discharge with flow duration data in order to provide estimates of annual suspended sediment load. These values were then divided by the catchment area in square kilometres to afford a comparison of yields between catchments of different sizes. This analysis gave estimates of 8.26 $t/km^2/y$ for the Maesnant Fach and 2.9 $t/km^2/y$ for the Maesnant.

Bed-load

The ratio of bed-load output from the Maesnant Fach to that from the Maesnant is very similar to the suspended load ratio. Annual yields of bed-load (Figure 38) are in the range 6.7 to 8.79 $m^3/km^2/y$ in the Maesnant Fach and 1.5 to 2.72 $m^3/km^2/y$ in the Maesnant. An earlier study (Lewin *et al.* 1974) made a similar estimate of 1.1 $m^3/km^2/y$ for the Maesnant catchment.

Over the period of this study, peak values for bed-load yield were attained in 1986. Since this peak occurred in both catchments it is unlikely to be associated with the improvement scheme. A more probable reason for high 1986 yields is the higher water discharges which are evident in the flow duration diagrams shown in Figure 39. Bed-load movement occurs most frequently during higher flows when complex entrainment thresholds are exceeded. These depend upon flow characteristics, the physical properties of individual particles and the channel bed (e.g. Klingeman & Emmett, 1982). Therefore, provided that sediment is available for transport, greater yields are likely in those years with longer durations of higher water discharges.

When substantial amounts of new material are made available to the stream system, changes often become apparent in the size distribution of the particulate load. The size analysis of the bedload, from the series of consecutive trappings, shows little evidence of significant systematic change in

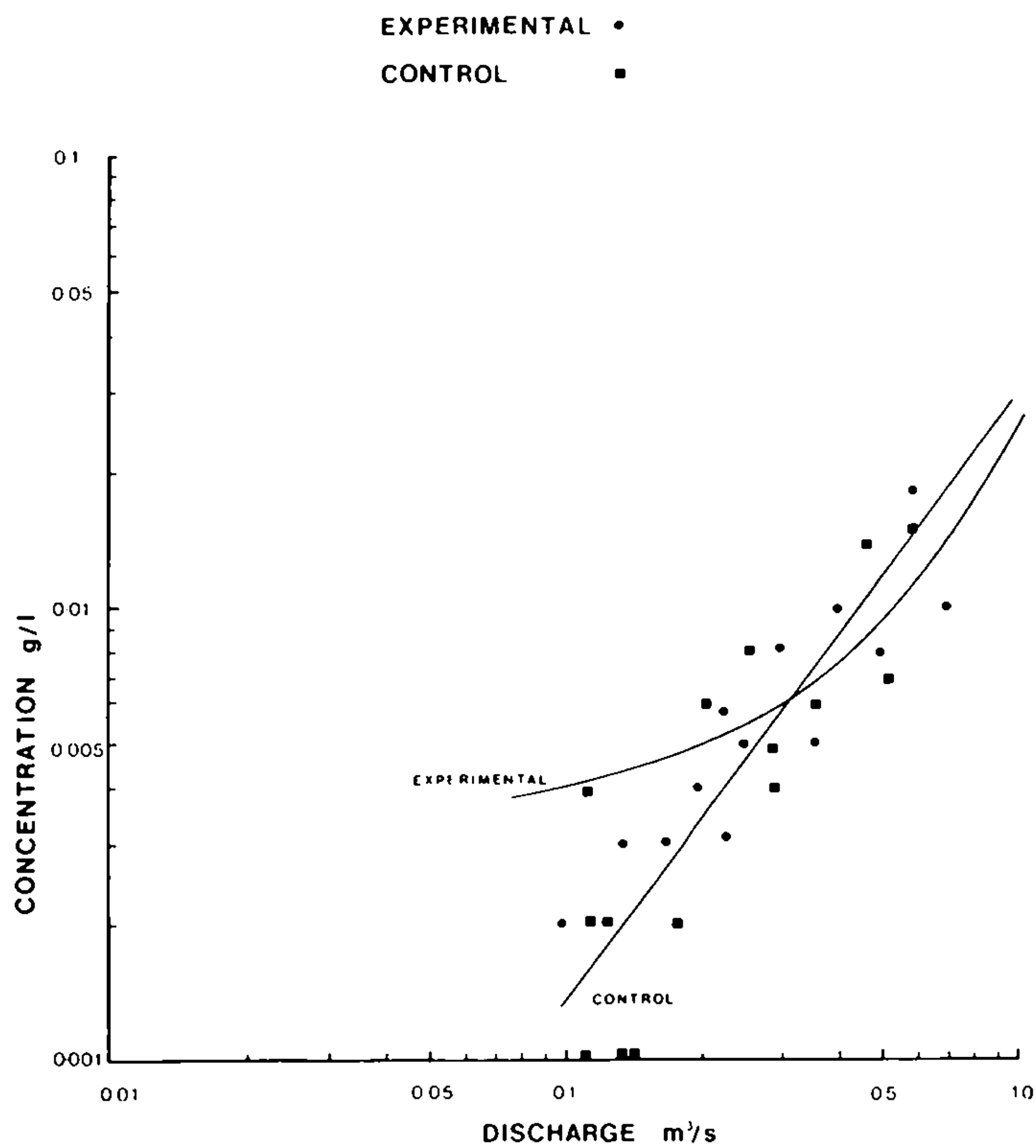


Fig. 37 Nant-y-Moch catchment suspended sediment concentration vs water discharge

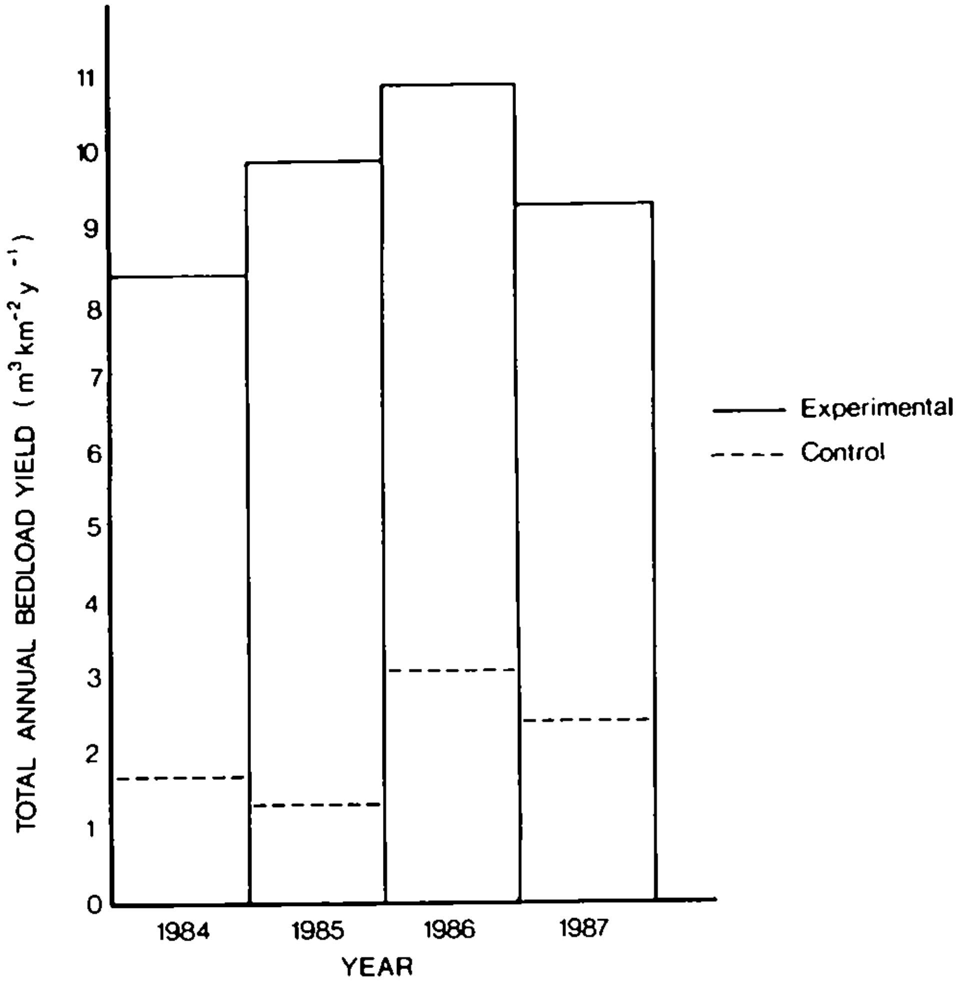


Fig. 38 Nant-y-Moch catchments bed-load yield.

the material which has been transported (Figure 40). This again suggests that the improvement had little impact on the bed-load output.

There is, however, a notable difference in the size distribution of bed-load between the two catchments, as illustrated by the grouping at the coarse ends of the distribution curves in Figure 40. All the bed-load samples from the Maesnant have a relatively higher percentage of material with a sieve size equivalent diameter greater than 22.4 mm. This may indicate a relative paucity of supply of finer material in the Maesnant. It is to be expected that the availability of sediment to the streams will vary between the two catchments and this may be a reason for the observed contrasts between the catchment yields. The calculated bed-load yields are within the range reported for undisturbed grassland catchments in mid-Wales: between 1.1 and 9.9 $m^3/km^2/y$ (Newson, 1981).

Conversion of trapped volume of bed-load to weight permits a comparison between the two forms of particulate load. Approximately 60% of total load in the study catchment is represented by bed-load. The similarity in yields of bed-load to suspended load is typical of many other small British upland streams (Newson, 1986; Newson & Leeks, 1987).

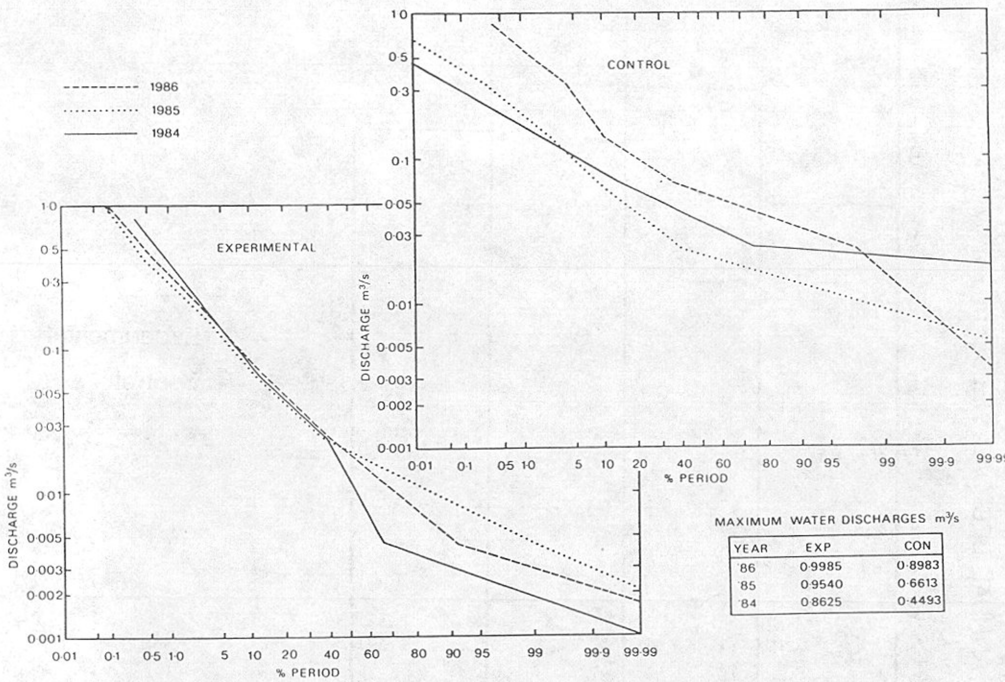


Fig. 39 Water discharge vs % duration, Nant-y-Moch catchments.

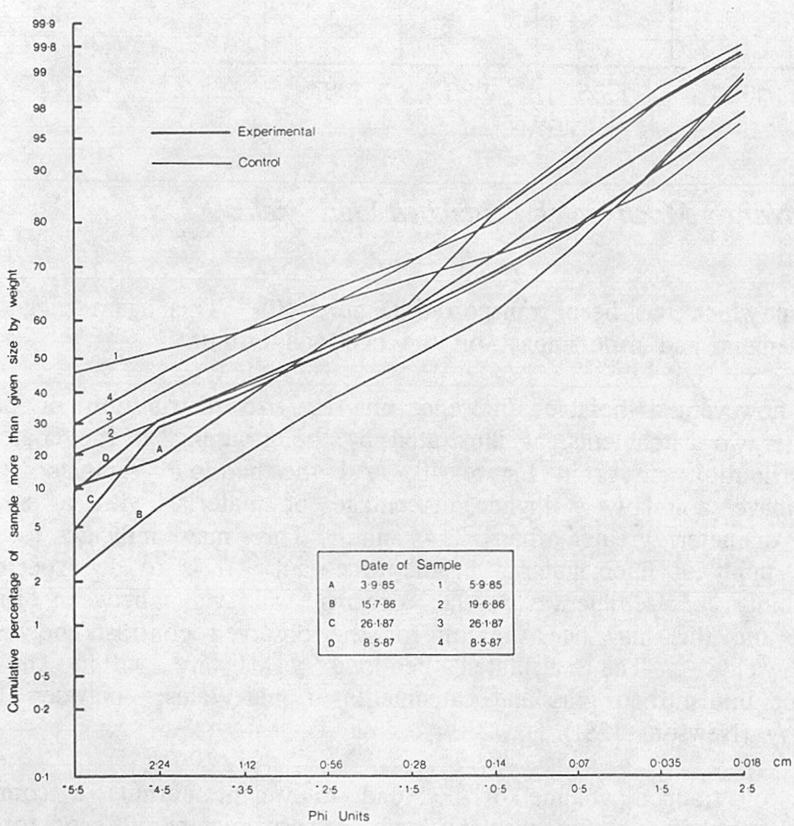


Fig. 40 Nant-y-Moch catchments bed-load size analysis.

7. Conclusions

7.1 Main conclusion

Following the grassland improvement schemes within the Maesnant Fach catchment, the main findings are:-

i) Elevated concentrations of ammoniacal-N and total phosphorus at the outlet of the interceptor drain. The increases in the concentrations of nitrogen were evident following the two schemes in 1984 and 1986, whereas phosphorus concentrations only rose in 1984, following the applications of phosphorus in that year.

ii) On a catchment scale, although increased concentrations of ammoniacal-N were observed in terms of fertiliser losses, these were insignificant and unlikely to be of concern to water users with interests downstream.

iii) No detectable changes in suspended sediment or bed-load were observed.

7.2 Secondary findings

The secondary findings observed were:

(i) Stream flow and water use

While the rainfall in the Maesnant catchment is approximately 100 mm per year greater than in the Maesnant Fach, the annual flow from the Maesnant is 350-400 mm greater than from the Maesnant Fach.

The water use of both catchments, particularly that of the Maesnant Fach, is higher than that found for the grassland catchment at Plynlimon. The main contributory factor to the higher baseflows in the Maesnant is likely to be its greater storage. At Plynlimon, streams with their sources on the grits of the exposed core of the Plynlimon anticline have been shown to have higher base flows that those with sources lower down. The Maesnant, rising on Pumlumon Fawr, has this grit aquifer as its source, while the Maesnant Fach is wholly underlain by Silurian shales and mudstone.

(ii) Chemical data

Nitrate-N

Accumulating rainfall inputs of Nitrate-N were higher than flow outputs for both catchments, especially in the experimental catchment. More significant was that lower concentrations were found in the Maesnant Fach than in the Maesnant during the winter.

Phosphorus

Sample concentrations were below the detection limit and therefore no attempt was made to predict phosphorus concentrations or to estimate inputs or outputs. One exception was found in the cut-off drain in 1984, where high values were found following the pasture improvement during the spring of that year. The fact that there was an increase in phosphorus at Nant-y-Moch and not in the field drain in the Nant Iago Study (Roberts *et al.*, 1986a) is due to the different methods of cultivation and fertiliser application used in the studies.

Potassium

The mean concentrations found in the rainfall samples were greater than those found in the streamflow samples: this was probably due to enhanced rainfall concentrations in summer. The pasture improvement scheme produced larger concentrations in the cut-off drain and at the outfall of the Maesnant Fach, particularly during 1984, which was due mainly to the burning of the indigenous vegetation. Rainfall inputs of potassium tend to be variable in mid-Wales: the Nant-y-Moch sites were found to give higher concentrations that at other sites in mid-Wales.

pH

The effect of liming on the experimental catchment during 1984 and 1986 can be seen in the values found in the drain and at the outfall of the Maesnant Fach.

(iii) Sediment

Analysis of suspended load sediments gave estimates of 8.3 $t/km^2/y$ from the Maesnant Fach in comparison with 2.9 $t/km^2/y$ for the Maesnant. Peak values of bed-load yield were found in 1986 for both catchments.

Acknowledgements

Thanks are given to all of the Institute's Plynlimon Staff: particularly Graham Leeks for his contribution on sediment transportation, Phil Hill and Alun Hughes for constructing the flow measuring structures, Mrs Sue Hill for the data and sample collection, and sandwich course students Deborah Barnes and Ian Thomas for the technical drawing work.

Also our thanks to members of the Institute's Wallingford staff, Peter Andrews, Alan Warwick and John White, during the weir construction phase. The chemical analyses were carried out by Christopher Smith and his colleagues, James Walls and Peter Billingham. The processing of the rainfall and streamflow data was done by Mrs Ann Matthews, and the typing of this report by Mrs Jean Hornsby.

Finally, the authors gratefullly acknowledge the cooperation of the tenant farmer at Nant-y-Moch, Mr Christopher Evans, and of the staff of Welsh Water, the Central Electricity Generating Board and the Department of Geography, Aberystwyth University.

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Appendix 1

Time series plots of chemical determinands in rainfall and stream samples.

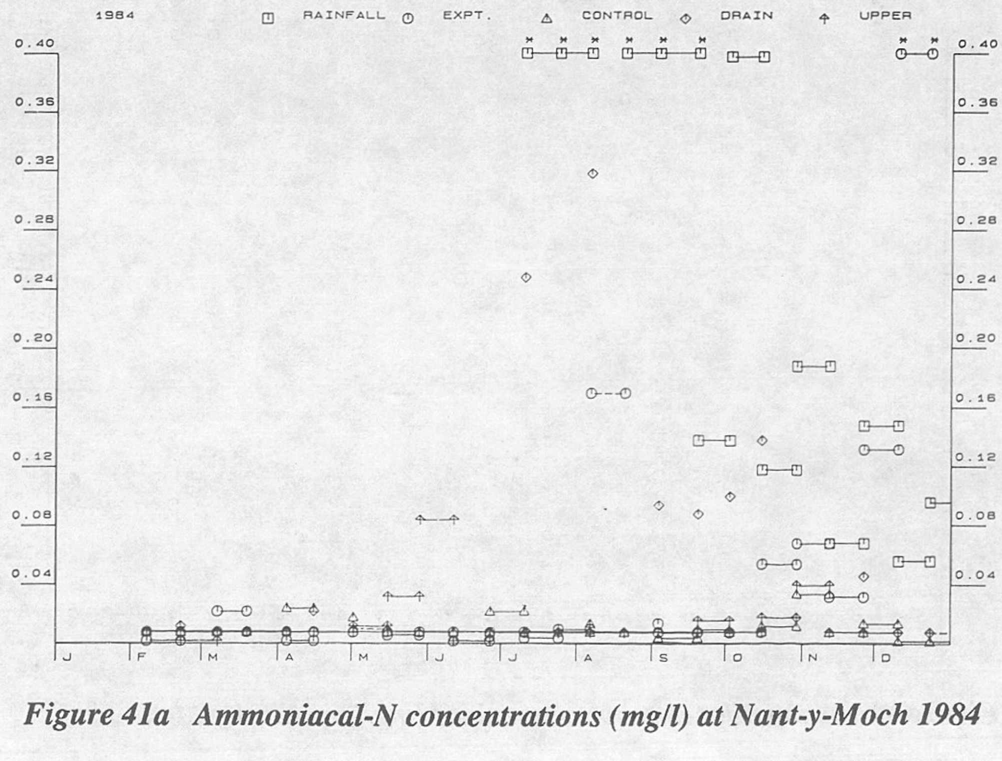

Figure 41a Ammoniacal-N concentrations (mg/l) at Nant-y-Moch 1984

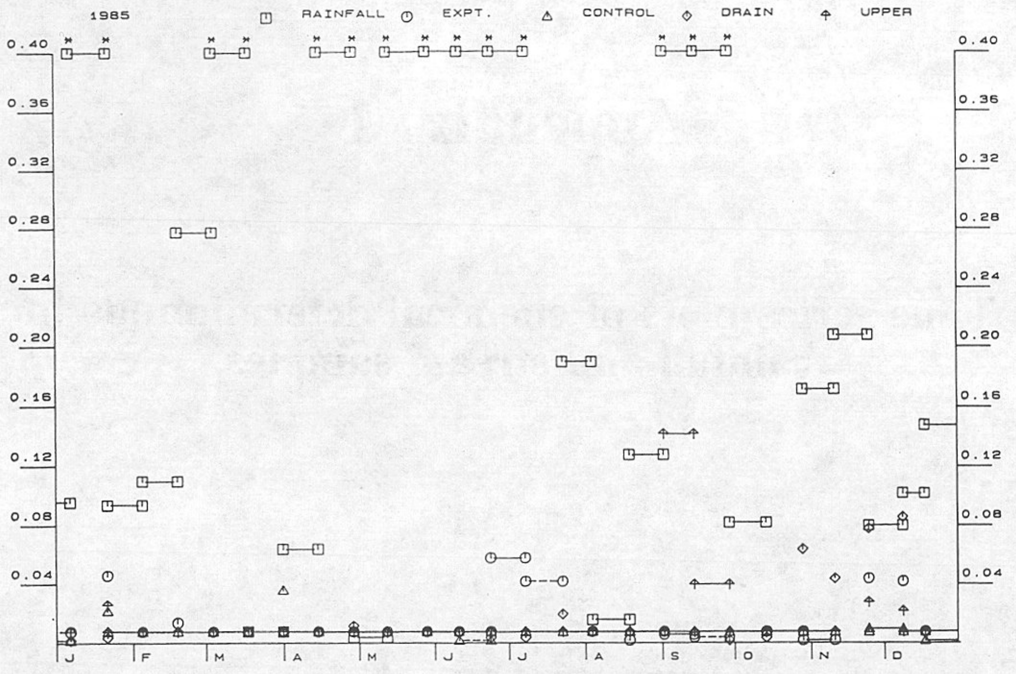

Figure 41b Ammoniacal-N concentrations (mg/l) at Nant-y-Moch 1985

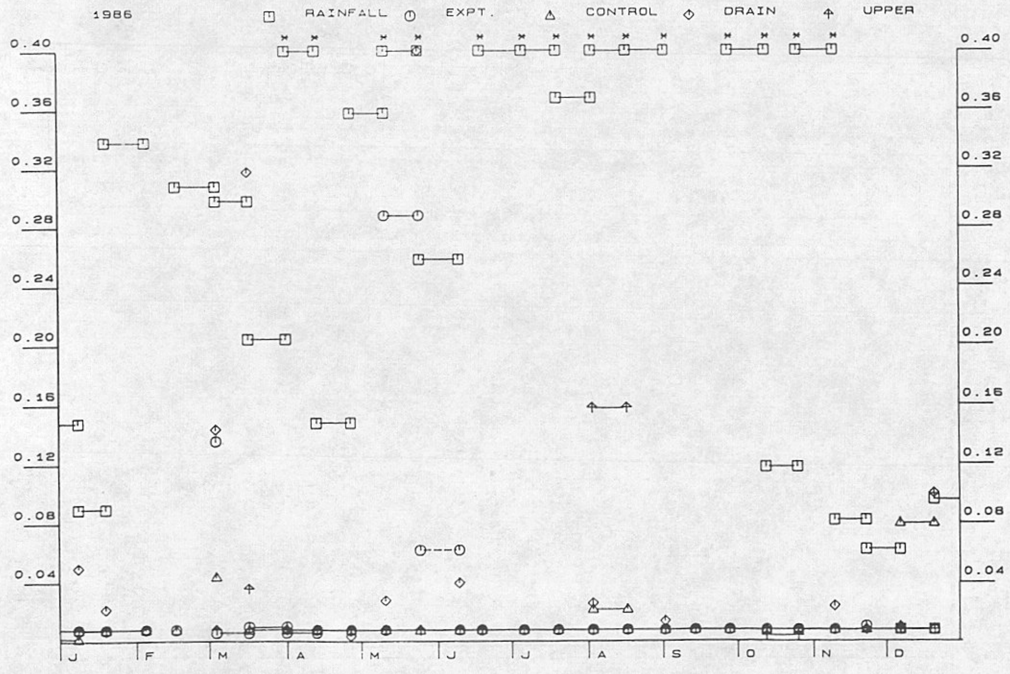

Figure 41c Ammoniacal-N concentrations (mg/l) at Nant-y-Moch 1986

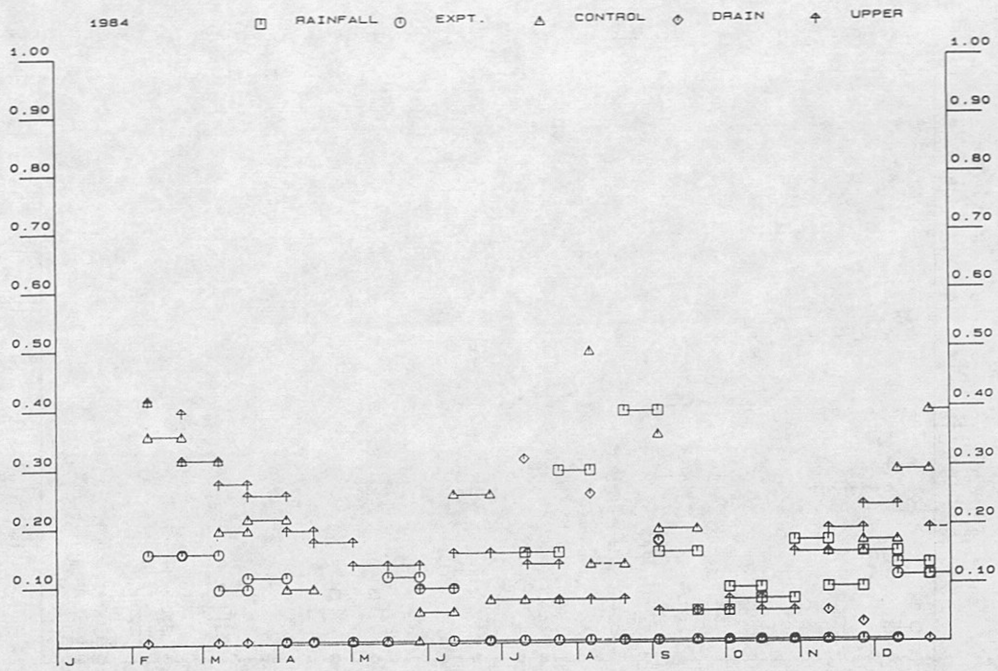

Figure 42a Nitrate-N concentrations (mg/l) at Nant-y-Moch 1984.

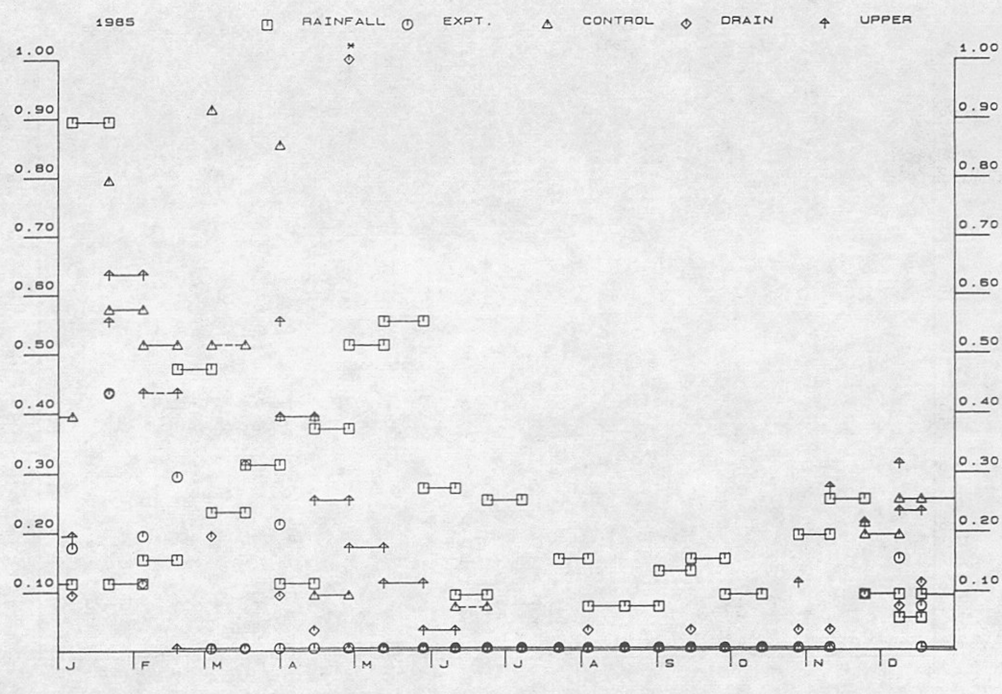

Figure 42b Nitrate-N concentrations (mg/l) at Nant-y-Moch 1985.

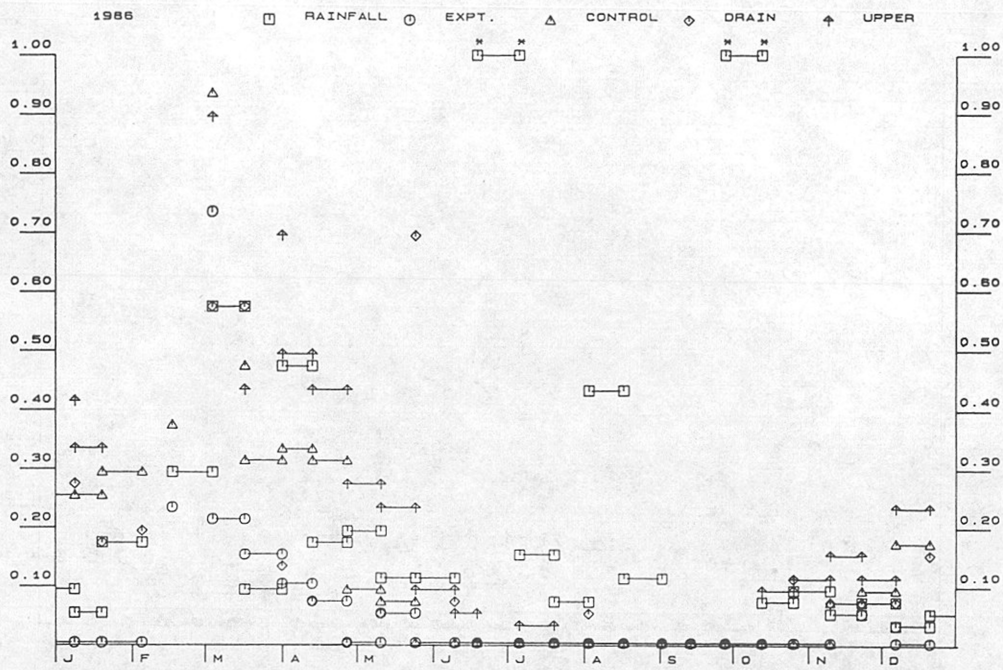

Figure 42c   Nitrate-N concentrations (mg/l) at Nant-y-Moch 1986.

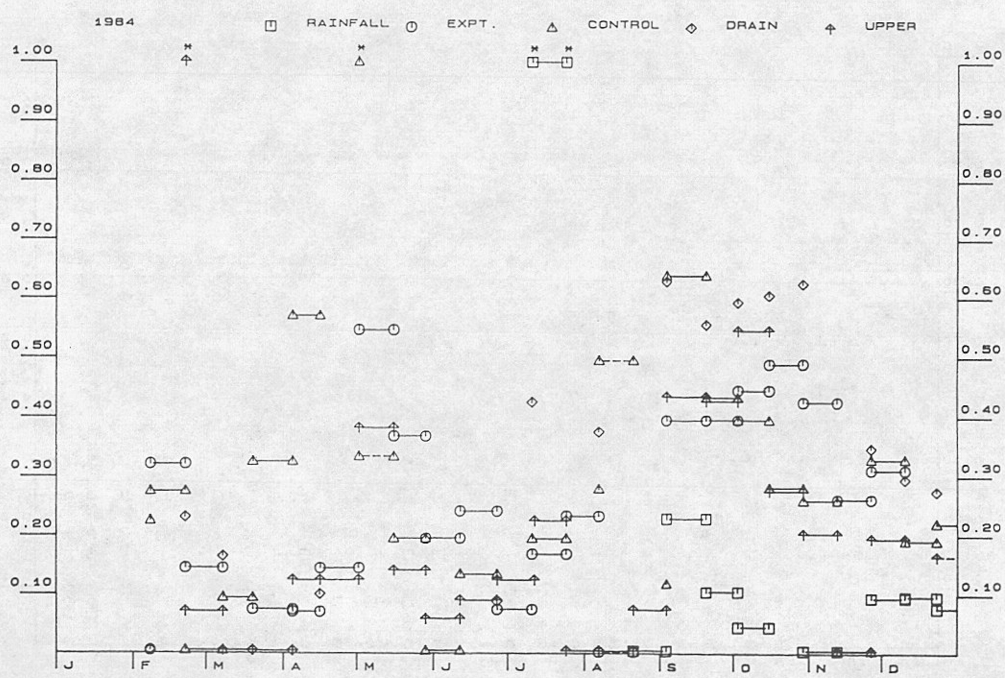

Figure 43a   Organic-N concentrations (mg/l) at Nant-y-Moch 1984.

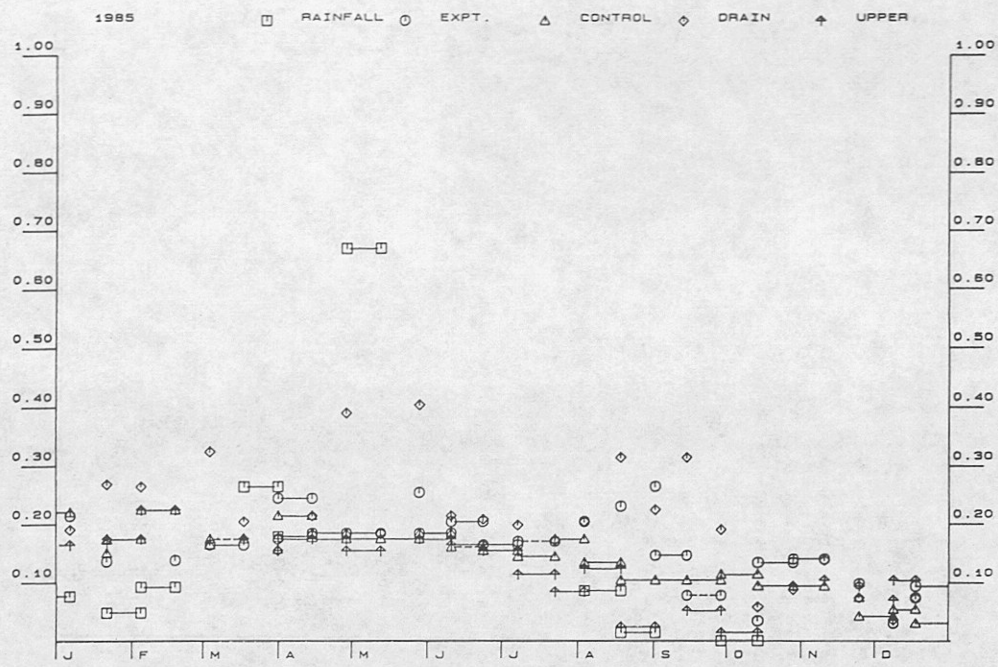

Figure 43b Organic-N concentrations (mg/l) at Nant-y-Moch 1985.

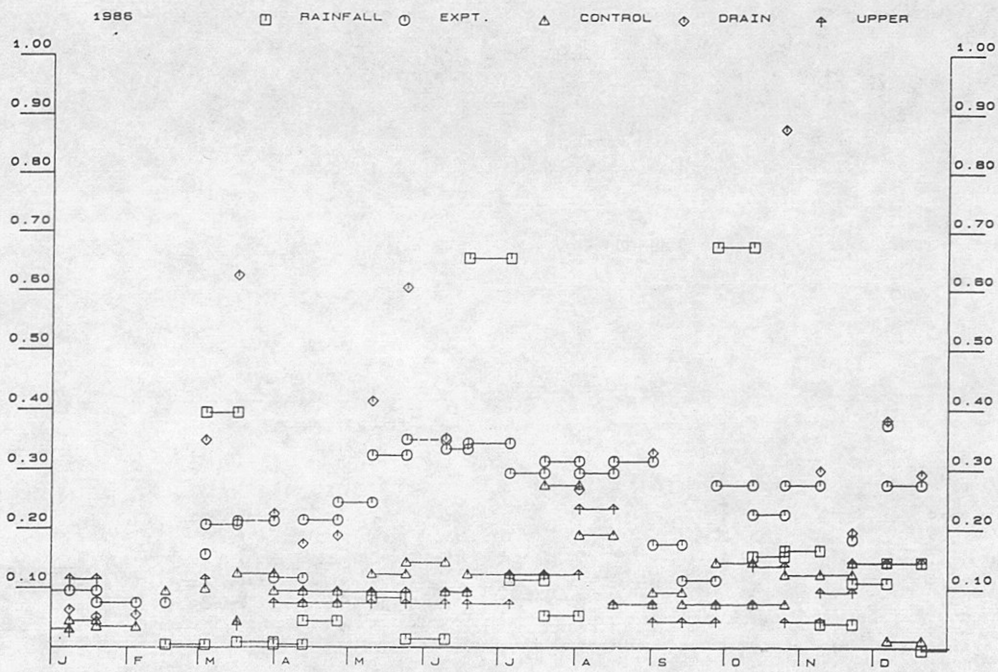

Figure 43c Organic-N concentrations (mg/l) at Nant-y-Moch 1986.

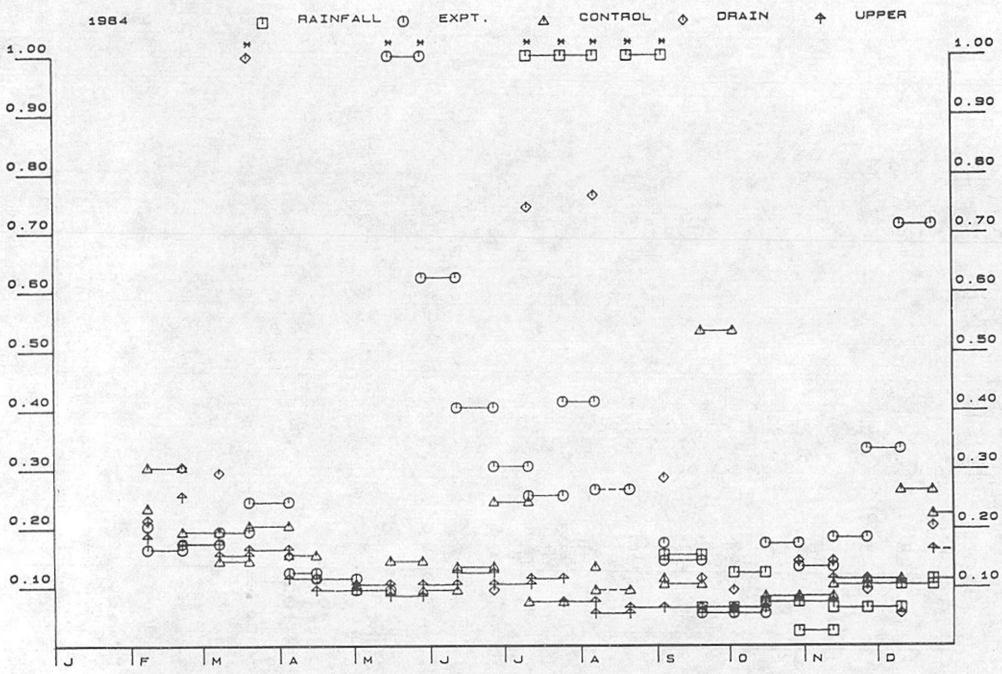

Figure 44a   Potassium concentrations (mg/l) at Nant-y-Moch 1984.

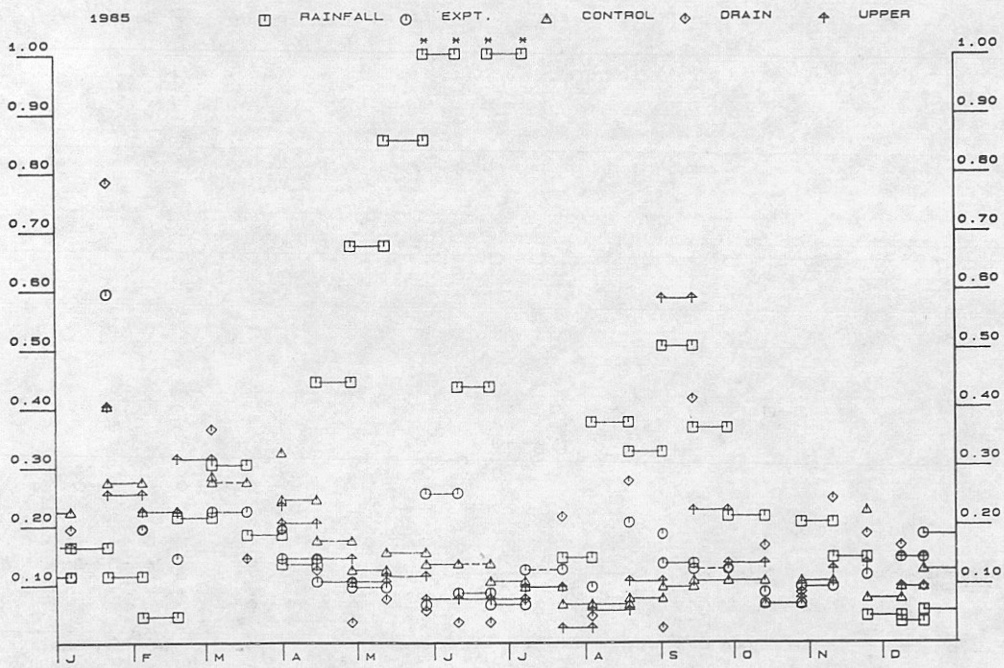

Figure 44b   Potassium concentrations (mg/l) at Nant-y-Moch 1985.

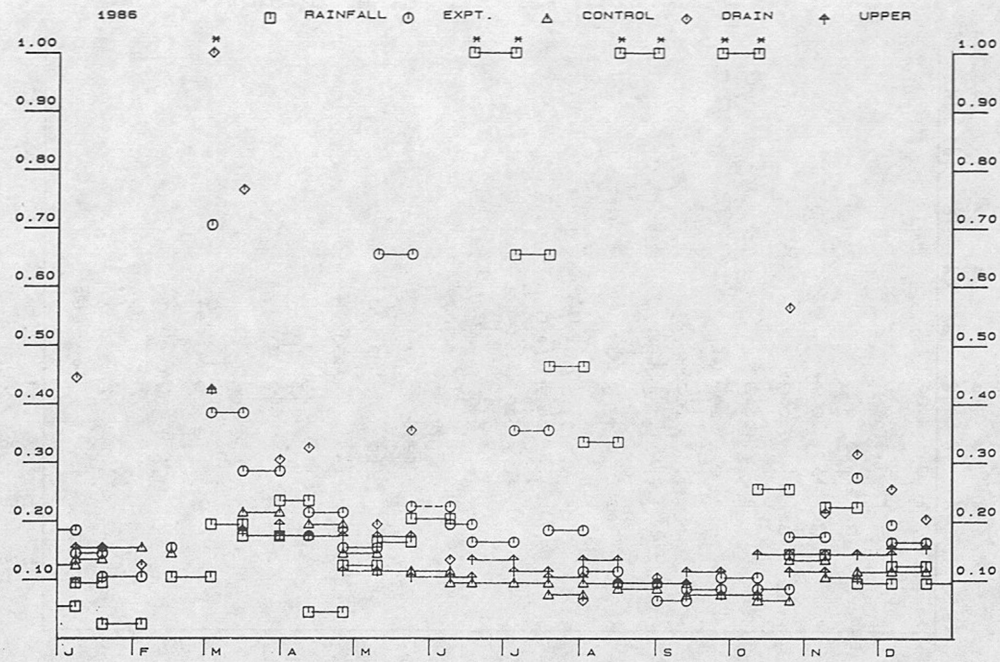

Figure 44c Potassium concentrations (mg/l) at Nant-y-Moch 1986.

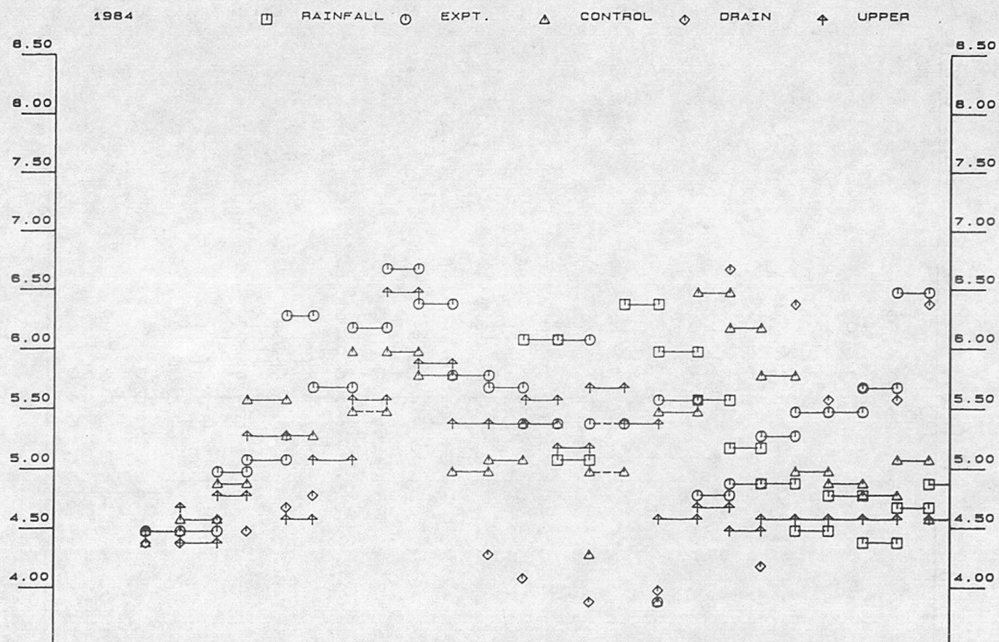

Figure 45a pH values at Nant-y-Moch 1984.

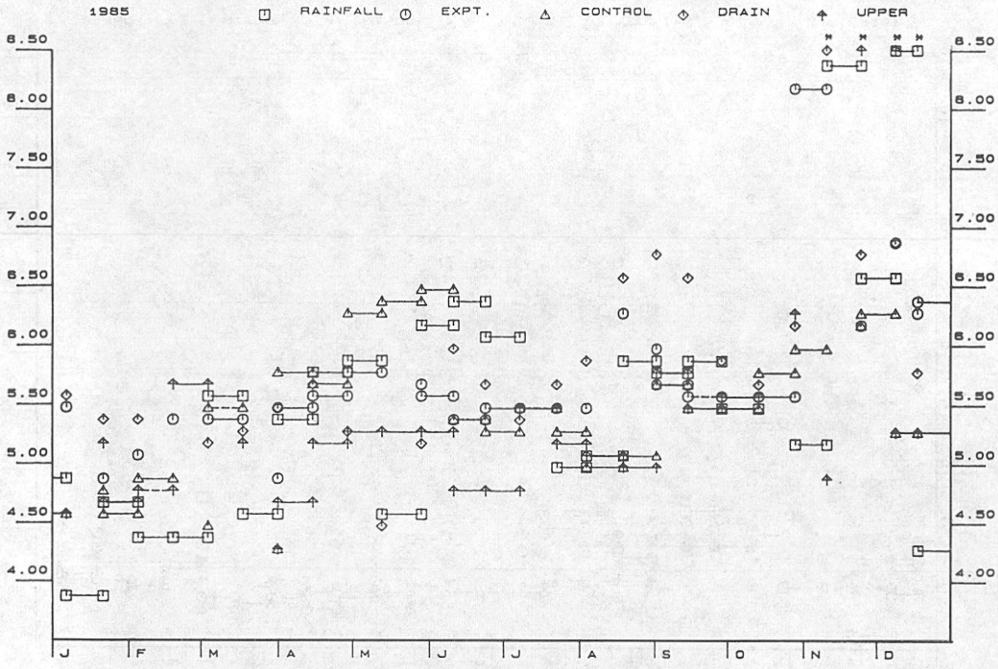

Figure 45b pH values at Nant-y-Moch 1985.

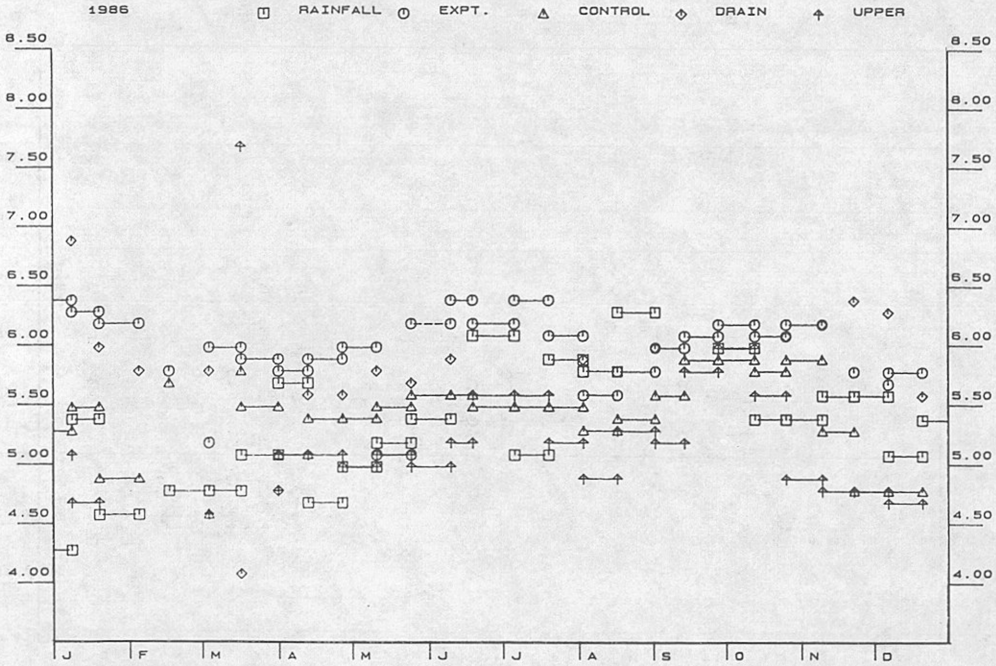

Figure 45c pH values at Nant-y-Moch 1986.

Appendix 2

Accumulating inputs/outputs of chemical determinands

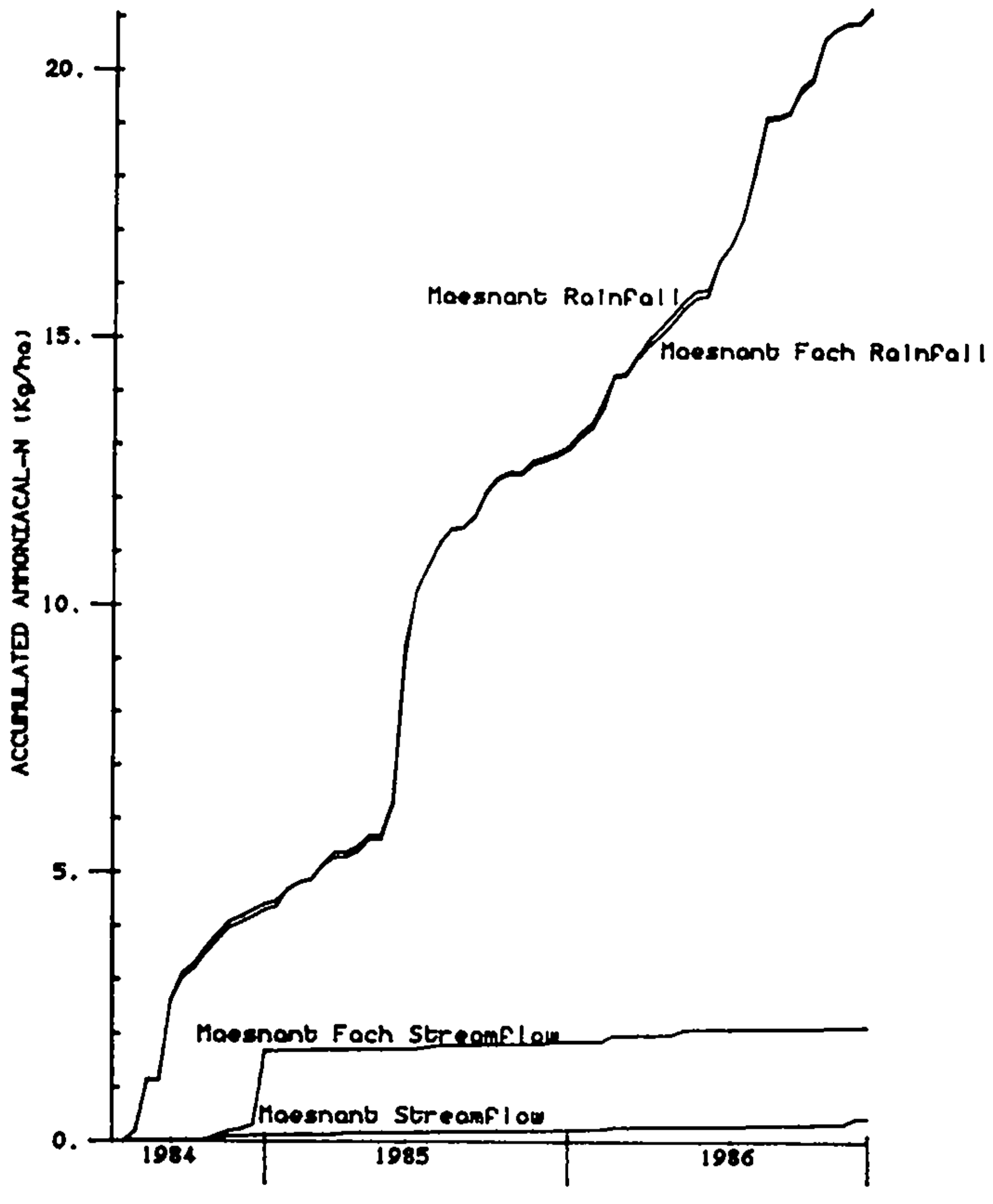

Figure 46 Accumulated ammoniacal-N inputs/outputs for Nant-y-Moch catchments.

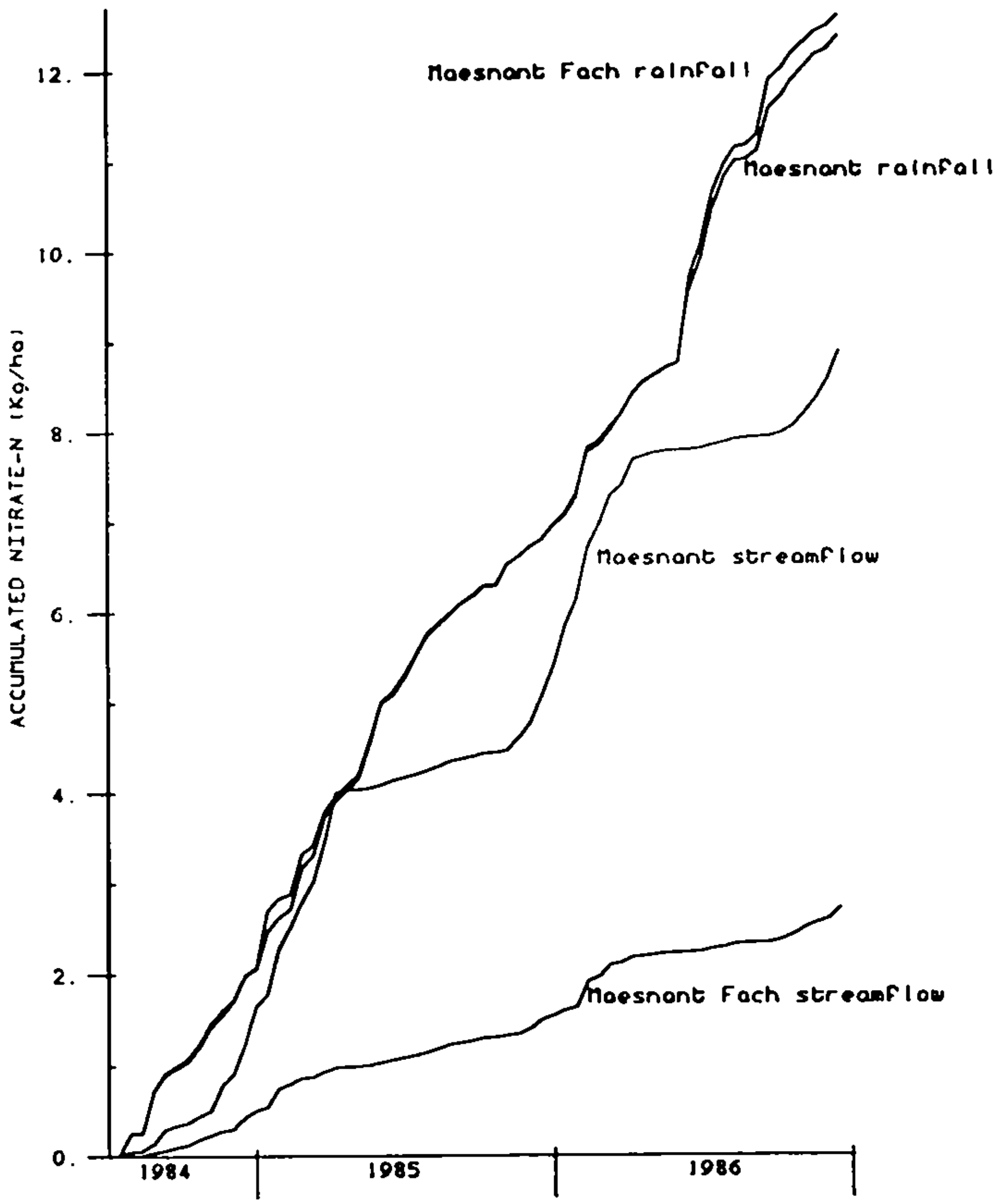

Figure 47 Accumulated nitrate-N inputs/outputs for Nant-y-Moch catchments.

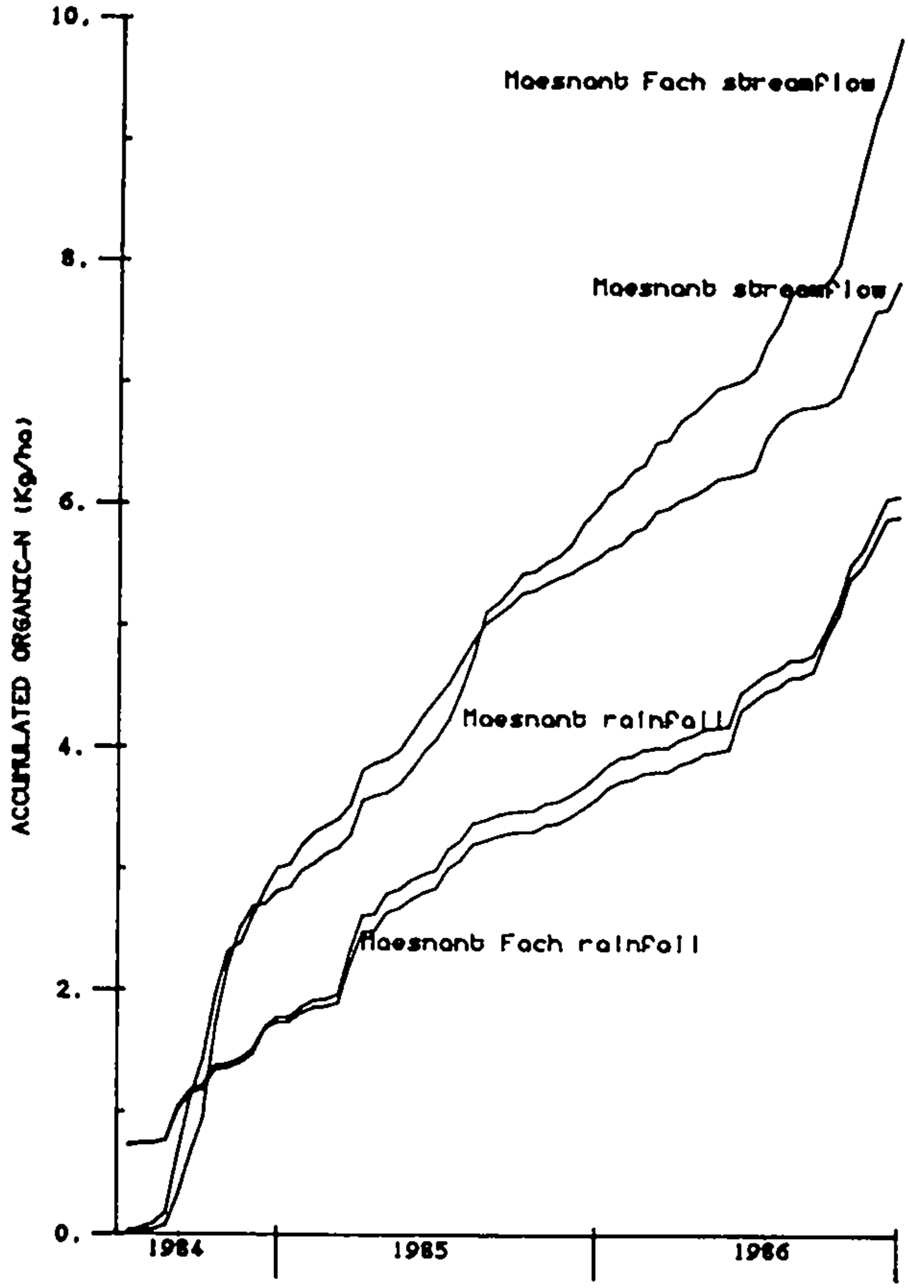

Figure 48 Accumulated organic-N inputs/outputs for Nant-y-Moch catchments.

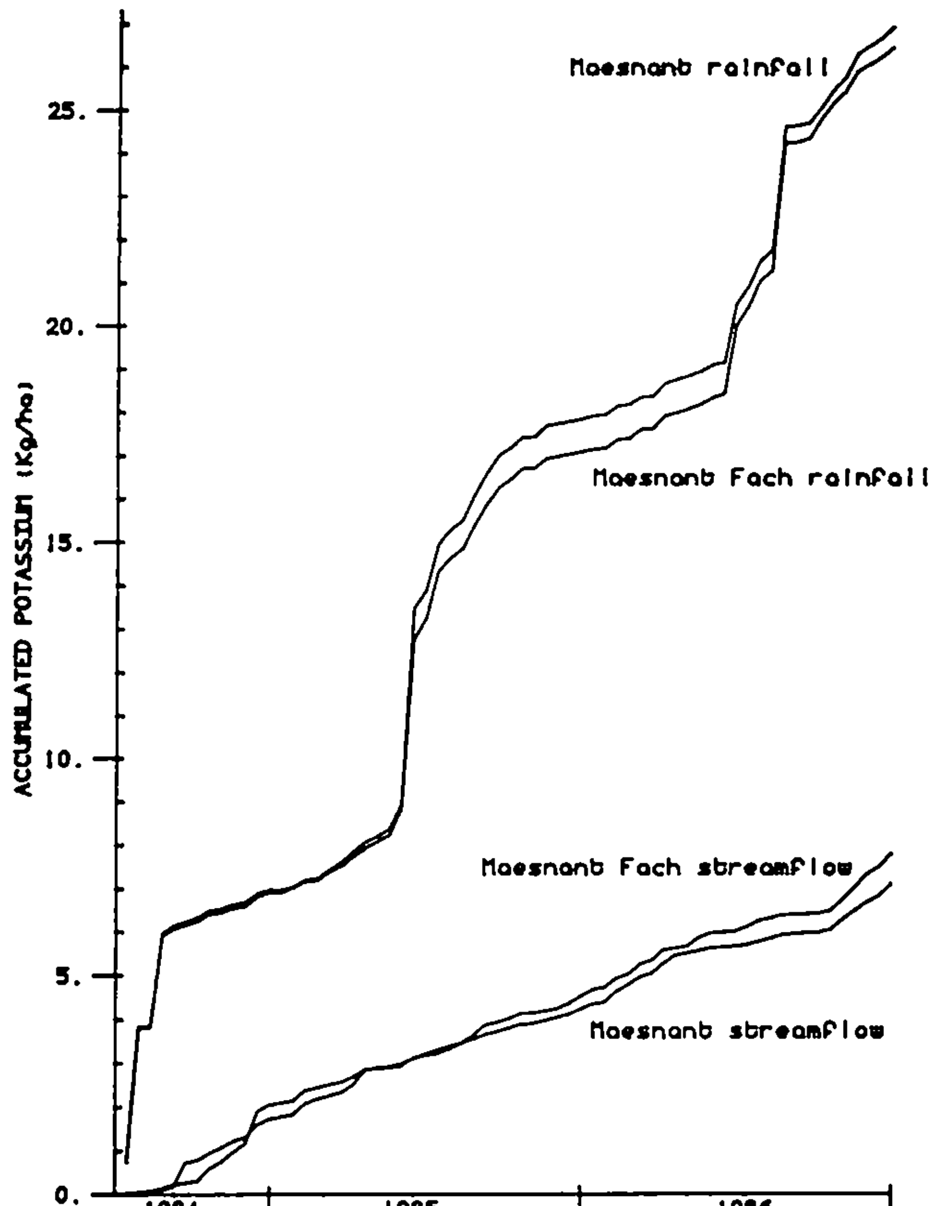

Figure 49 Accumulated potassium inputs/outputs for Nant-y-Moch catchments.