INSTITUTE OF HYDROLOGY

THE EFFECTS OF GRASSLAND IMPROVEMENT ON THE QUALITY OF UPLAND STREAMFLOW

- a 'natural' lysimeter and small plot experiment on Plynlimon, mid-Wales

by

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ABSTRACT

This report describes the results obtained from a study, funded by the Ministry of Agriculture, Fisheries and Food, of the release of nutrients - nitrogen, phosphorus and potassium - to water courses from drained and improved upland pastures. Natural lysimeters were installed within tile drainage schemes on two areas of mesotrophic grassland in the Nant Iago catchment, Plynlimon, mid-Wales. Nutrient concentrations and flows from both lysimeters and both drainage schemes were monitored before, during and following the improvement of the pasture on one of the areas and on the lysimeter within. The increases in concentrations and loadings in runoff from both the lysimeters and the drains were calculated and related to the separate practices of tile drainage and combined cultivation/fertilizer application. From these results the nutrient runoff from a catchment that is to be improved is predicted for mixed schemes that involve either tile drainage and pasture improvement or pasture improvement alone. The upper Wye catchment is used as an example whereby the effects of the various practices are weighted by their areal extent and the resultant catchment nutrient concentrations and loadings are calculated. The limitations of the simple extrapolation model are discussed and improvements suggested that would include other changes of land use outside the scope of this present report.

REPORT NO 96

April 1986

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1. INTRODUCTION

The drive to increase the yields of British agricultural produce during and following the second world war has led to the development of large areas of rural Britain. The effects are most apparent in the lowland regions where technical advances in machinery, plant breeding and, particularly, a dramatic increase in the use of artificial fertilizers, has meant that crop yields have been improved, but this has resulted in severe ecological problems.

In the uplands of Britain, however, there is still potential for a radical improvement in production and the technology, though late in arrival, is now available. It is in these areas that any future drive towards more intensive agriculture will be most effective. The utilization of these upland areas of Britain has been the subject of a great deal of controversy in recent years. These areas, lying over 250 m above sea level, cover approximately 6.6 M ha or about 30% of the total land area of Britain. They are largely concentrated in Scotland, northern England and central Wales and include 5.8 M ha of EEC - designated 'less favoured areas' (EEC, 1975).

Traditionally, the harsh climate, short growing season and poor soils have restricted upland agriculture to marginal sheep farming that has, in the past, supported a fairly large rural population. Since the economic depression of the 1930s, however, many of the smaller farms have ceased to exist or have been amalgamated to form larger, more viable units. Stocking densities on these farms vary from 0.25 to 1.5 ewes per hectare and little cultivation has been attempted in spite of the availability of subsidies under various development and capital grant schemes in an effort to increase agricultural productivity (HMSO, 1975).

Conversely, the availability of cheap, agriculturally poor land in these upland areas has resulted in a massive increase in the areas afforested by hardy species of conifers. This has been encouraged by successive governments for strategic purposes and has been carried out by the Forestry Commission using public funds and by other forestry groups using private investment. At the present time, 1.4 M ha or 21% of the upland areas have been afforested and if plans are implemented (Forestry Commission, 1977), a further 1.8 M ha will be planted by the year 2025, increasing the proportion of forested land in the uplands to 47%.

The case for upland grassland improvement rather than forestry has been enhanced by the development of grass seed mixes capable of surviving the harsh conditions whilst increasing dry matter production and hence stocking rates of both sheep and cattle (Munro et al., 1973). However, the optimum levels of nitrogen required to maintain such pastures is high on the poorer peat and peaty gley soils common in upland Britain. Although the development of grass species capable of fixing nitrogen is continuing, it is likely that, in the foreseeable future, fertilizer applications will continue to be an integral part of pasture improvement in many parts of the country. As in the lowlands, there will be a price to be paid in economic, energy and environmental terms, for the increased yields.

It is difficult to assess the amount of improvement that has taken place because of the large numbers of small areas involved and the diversity in the type of improvement scheme that has been implemented, often over short periods. However, an estimate has been made that in England and Wales alone, a total of 150,600 ha of moorland has been ploughed in the last 30 years and that the rate is increasing (Parry et al., 1981).

Investigations into the side effects of land use change have concentrated on the implications for recreational facilities, social considerations and for agriculture in general. Although there is recognition of the need for research into the potential environmental effects of sudden changes in land use - for example, reservoir building, estuary barrages, salt marsh reclamation - changes of a more gradual nature are easily neglected because research planning then has to rely on long term economic and strategic forecasts. Upland pasture improvement represents just such a change. The problem is compounded when water resources, often regarded only as a secondary land use, are under consideration.

Natural pastures develop their own controls on losses of nutrients from the soil but those practices inherent in pasture improvement - drainage, cultivation, reseeding and fertilizer additions - upset the delicate balance resulting in the mobilisation of nutrients within the soil system and, possibly, increasing losses from it. Much of the research on relationships between nutrient movements and agricultural practices has been concentrated in lowland situations but clearly the steep slope, high rainfall areas of upland Britain present unique problems which have not been extensively studied because until recently there has been only limited agricultural interest.

The enrichment of aquifers and surface water reservoirs by leaching and surface runoff of soil nutrients has long been recognised as a natural process by ecologists and water engineers alike. However, the post-war increase in NPK fertilizer applications and increased soil disturbances have accelerated the problem. Large sums of money are currently being spent by water authorities to avoid the eutrophication of many reservoirs and to ensure a supply of potable water within the World Health Organization limit of 11.3 mg/litre of nitrate nitrogen. At a time when nitrogen concentrations in some aquifers and rivers of eastern England are rapidly approaching this level, the imminent introduction of more stringent EEC standards (5.5 mg/litre of nitrate nitrogen) will heighten interest in the problem.

In this context, the role of water derived from the uplands is crucial as a source of high quality drinking water, as a habitat for the flora and fauna habitually associated with upland streams and as an efficient dilution agency for lower quality water downstream. Any potential threat to these functions is therefore worthy of study but unfortunately is not covered by any statutory obligations. The Harmonised Monitoring Scheme (Simpson, 1978) provides the guidelines to water authorities for checking point sources of industrial and agricultural pollution. Because there have been no obvious pollution problems associated with upland areas, their effort has been concentrated in the lower reaches of the river systems and changes in water quality in upland streams caused by land use practices have not been monitored extensively.

This study aimed to research, with the cooperation of the Agricultural Development and Advisory Service, the effects of the practices associated with grassland improvement on the quality, quantity and distribution of water resources in the uplands. It forms one part of a series of studies on the effects of various land use practices and supplements existing studies into the differences in the quantity (IH, 1976) and quality (Roberts et al., 1983) of the flows from catchments under rough pasture and established forestry. The study has a broad base and attempts to equate the agricultural benefits with the practical environmental problems. Its main function, however, is to supplement the information required by water engineers, agricultural advisors and those who ultimately arbitrate the conflicting demands on upland resources.

2. LAND IMPROVEMENT IN UPLAND BRITAIN

The rate of improvement of rough pasture has increased in recent years in the uplands of Britain and nowhere are these changes more noticeable than in Wales where 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). In this area the intensive effort and technological investment is manifest most obviously in the rapid change of landscape from the subdued pastel shades of the indigenous vegetation to the stark contrasts of patchwork greens and yellow of the reseeded swards.

Grassland improvement has proceeded virtually unplanned and in recent years has been encouraged by central government with an elaborate system of grant aids and subsidies. Traditionally, arguments for and against rapid land use change have been confined simply to aesthetic and agricultural considerations. However, research of the type reported here has proliferated recently with the result that there is a growing awareness that the secondary problems associated with land use change may have direct consequences on enviromental quality and that funds should be made available to quantify these effects.

A study of the water quantity and quality effects of grassland improvement first has to establish that the type of improvement and subsequent management of the experimental site is typical so that the results are generally applicable. Where the practices vary, both within and between regions as is the case with grassland improvement, some attempt must be made to quantify the effects of different practices separately though this approach is generally dependent on funds being available for experimental replication. In the first place, therefore, it is imperative to decide on a "typical" management scheme for the experiment.

2.1 Grassland Improvement Schemes

The upland areas of Britain are associated with high rainfall, low temperatures and short growing seasons. Grass heaths and heather moorland dominate the vegetation. Soils are mainly acid because of the low base status of many of the rocks from which they have been formed and also because of strong leaching by rainfall. The surface soils are often peaty and the thickness of peat may vary from a few cm in freely drained podzols to 2m or more on flatter land in wet areas. In terms of world soil groups, podzols, gleys and climatic and basin peats predominate. Although the reserves of soil nutrients, particularly nitrogen, are often high, the amount of nitrogen freely available for plant growth is low.

Partly because of these environmental restrictions, upland farmers in Britain have been highly sceptical about the benefits of grassland improvement. Other reasons for this have been the high cost of implementation, the uncertainty and slow response of the benefits to be gained and conflicting advice on how improvement could best be implemented. Not only do opinions vary from area to area but, quite often, identical treatments within particular areas give very different results. Early improvements were restricted to land drainage, applications of lime and slag, and grazing controls to encourage the growth of particular indigenous species.

Research into the effects of various levels of improvements on dry matter yield, its digestibility and nutritional value (ADAS, 1978; HFRO, 1971-73) have shown that by careful choice of areas to be improved and by careful management of the improved areas, stocking densities can be increased fourfold. In particular, much of the recent research has concentrated on developing new strains of grass species that are tolerant of the harsh climatological conditions and provide adequate grazing for as long a period as possible. Foremost in this research has been the breeding of suitable strains of white clover which, when established, supply some if not all of the nitrogen needs of the improved sward by biological nitrogen fixation (Munro, 1970). This development has greatly reduced the cost of replacing grass swards because of the reduced rates of nitrogen fertilizers required and has led to the concept of using mixtures of new grass species, each species fulfilling a particular requirement. A further refinement is the addition of fescue and timothy, among others, to the predominant ryegrass to simulate a naturally diverse vegetation association. This provides certain ecological advantages over a virtual grass monoculture.

Although it is now generally agreed that replacing the existing grass sward with a mixture of new species, including clover, is the most efficient form of improvement, opinions still differ from area to area as to its financial feasibility and implementation. In particular, the use of nitrogenous fertilizer to maintain the new sward following its establishment is carried out in some parts of the country and not in others. The preparation of the seed bed will obviously depend on the ground conditions prior to the improvement but will almost invariably involve drainage, liming and removing existing plant material either by burning, cutting, grazing, use of herbicide or cultivation. The introduction of the new grass seed will normally be accompanied by a moderate application of nitrogen, phosphorus, potassium plus, possibly, some trace elements to stimulate early growth. Once the crop is established, its grazing is strictly controlled, quite often under a two pasture system and, as indicated above, remedial nitrogenous fertilizer applications are made if necessary.

The results derived from a study of the effects of grassland improvement are essentially specific to the environmental conditions of the area in which the study was done. Geological, pedological and climatic differences together with varying regional approaches to husbandry suggests that the quantification of the effects is relevant only on a regional basis. Whilst the extrapolation of purely physical processes, such as evapotranspiration from a coniferous forest has been successfully achieved by various workers (Calder and Newson, 1979; Gash et al., 1980) to other parts of Britain, superimposing the chemical component on to the hydrological basis of the data requires a complex empirical approach to the regional calibration of nutrient

runoff processes. Nevertheless it is hoped that a study of this type although quantitatively relevant only to the uplands of mid Wales, will also provide an experimental framework for future regional extrapolation.

2.2 Potential problems associated with upland pasture improvement

In spite of the future development of alternative forms of water provision e.g. desalination and local groundwater schemes, and the increasing resistance to the further drowning of upland valleys, it is likely that an increasing demand for clean water will be met by the further provision of surface reservoirs in the upland western regions of Britain, or at least by improved management of those that already exist. In contrast to the situation in lowland regions, particularly areas of eastern England where there has been for many years cause for concern over the declining quality of aquifers due to intensive agriculture, the uplands have always provided plenty of pure water, little contaminated by its encounter with traditional, low investment agricultural systems.

By improving methods of precipitation measurements in upland areas, the Plynlimon experiment has shown that the water resource of the uplands is greater than was imagined before its inception (Newson, 1976a). Total flow in major British rivers owes much to orographic rainfall over their upland sources. Although the addition of diffuse and point sources of agricultural runoff and sewage in the lower reaches greatly reduces downstream quality, it is obvious that the problems of water pollution are ameliorated by the dilution effect of upland streamflow. Careful management and monitoring of river quality even allows water authorities to abstract to local impoundments on flood waves of mainly upland origin in order to safeguard potability.

The downstream increase in nutrient concentration was illustrated by Roberts et al. (1983) for the Rivers Severn and Wye. However, it is difficult from such large catchments with a multitude of point and diffuse sources to assess the individual contributions of agricultural and industrial pollutants. Oborne et al. (1980) attempted such an analysis for the Wye catchment but their scale of study was too large to split the effects of rough grazing, improved grassland and forestry in the upper reaches of the Wye.

Traditionally, the agricultural view has been that, unlike cereals and horticultural products, grassland is an effective sink for applied nutrients particularly nitrogen. This is indeed partly true for, during the growing season, even rough or semi-rough pasture takes up nitrogen and in so doing reduces the concentrations in soil water that are available for leaching (Roberts et al., 1983). Also it appears that there is efficient utilization of any applied nitrogen during the growing season when minimal leaching losses occur and hence no pollution is caused at this time. On the other hand, when the growing season is over, the standing crop progressively dies and provides an increasing store of dead organic matter. The nitrogen contained in this is slowly and steadily converted to inorganic nitrogen during the autumn and winter months. As a result, soil water nitrogen concentrations increase reaching a peak in February and March of the following year. This coincides with the winter peak in precipitation and so high flushing rates remove much of the accumulated inorganic nitrogen in runoff. In simple terms, nitrogen applied in spring and summer is stored temporarily in the crop over a single growing cycle but may be lost during the winter months. In practical terms this, together with losses in the form of agricultural produce and gaseous loss, requires yearly inputs either by fixation or by fertilizer applications to maintain fertility.

One of the purposes of this study from the agricultural viewpoint is to ascertain whether the management practices associated with the application of fertilizers are exacerbating the problem of fertilizer wastage, thus causing an economic loss to the farmer. Most of the research directed to the subject of nutrient loss in Britain has been angled towards the agricultural community rather than water quality interests but the results are still of interest. Much of this work comes from sites in lowland Britain which, together with more hydrologically relevant studies from the United States, give some idea of the processes involved even if they are not entirely relevant quantitatively (Hudson, 1975).

The total nutrient loading of a river or water course draining a grassland area represents the accumulation of nutrients from a number of sources, some natural and some as a direct result of the improvement process. There is a continuous natural release of nutrients from established pasture which, over an annual period at least, maintains some equilibrium with the input in rainfall. Improvement may involve drainage, ploughing or harrowing, liming, reseeding and a fertilizer application, each of which can add a fresh pool of mobile nutrients to that occurring naturally. The picture is further complicated by the interaction of the various processes, a clear example being the different transport mechanisms for applied or released nutrients if tile drainage is included in the improvement scheme. If a research project is to be of practical benefit, it must attempt to isolate the various processes involved.

Perhaps the most relevant British study is the long term lysimeter experiment at Rothamsted (Cooke and Williams, 1970) where it was noted that ploughing alone can release enough nitrate to provide maximum yields for many years, particularly from old grassland. Whilst upland soils under grassland are less fertile than their lowland counterparts and high rainfall and leaching rates soon remove nutrients made available by soil disturbance, it can be seen that with careful management there are alternatives to the usual improvement procedures which rely on heavy applications of fertilizer. Present levels of fertilization in Britain are on average about 100 kg/ha/yr of nitrogen for grassland (Church, 1983) but the rates for upland regions are much lower and considerably less than the recommended rates of 100-150 kg/ha/yr of N for Wales (Munro, 1974). Munro has shown that levels of 500 kg/ha/yr of N have induced responses at Pant-y-Dwr Hill Station (Welsh Plant Breeding Station) though such levels would not be recommended because of winter sward damage. On the other hand, however, a movement to more sympathetic farming is encouraged at such places as the Pwllpeiran Experimental Husbandry Farm (ADAS, 1973, 1974) where spike reseeding is used instead of ploughing or harrowing. Drainage is discouraged, reliance being made on the natural drainage of soils using the positive feedback mechanism inherent in increased growth, transpiration and oxidative cracking of soils, particularly peats. This tends to release nutrients without disturbing the grass mat that affords protection from soil erosion and winter poaching by stock.
At the same time, it does not produce the steep piezometric gradients in the water table that are characteristic of tile drainage and which tend to encourage water and nutrient transport to water courses.

From an agricultural point of view, each component part of the improvement process can be subject to some criticism, caused by a reluctance to change traditional farming techniques and conflicting evidence on the benefits to be gained and the problems that can be avoided by the adoption of certain practices. The choices available often result in improvement schemes that are site specific to cope with unique combinations of climate, soils, vegetation and hydrology. In terms of water quality, this makes it difficult to be specific about the likely effects of particular improvement schemes.

3. LOCATION AND DESCRIPTION OF STUDY

The study was carried out in the Plynlimon range of hills in mid-Wales where the Institute of Hydrology have also been conducting a catchment scale study of differences in the quantity (IH, 1976) and quality (Roberts et al., 1983) of streamflows draining rough pasture and established forestry. The two catchments used in these two studies have been fully instrumented to measure rainfall, runoff and the meteorological variables used to calculate evaporation (Fig.1) and data since 1969 are available. Chemical data, specifically nitrogen, phosphorous and potassium concentrations, on a daily time basis are available for the period July 1976 to July 1980.

3.1 The background to the experiment

It was implicit in the choice of Plynlimon in the mid 1960s as a site for research into the hydrological characteristics of the most common land uses in the uplands that the catchments lie in that part considered at the time to be marginal in terms of agricultural production but which in the foreseeable future was likely to experience conflicts of interest in conservation, agricultural improvement, water resources, forestry and amenity. Fifteen years after its inception the same can still be said and it is fortunate that with the increasing involvement of hydrologists in water quality, a well instrumented study area of established hydrological significance is available for use (Fig.1). Indeed, the long running Plynlimon experiment, designed principally to assess the differences in water use of coniferous forest and semi-natural grassland as an aid to water resource planning, has been instrumental in showing that natural environment research is fundamental to constructive upland use planning.

Two contiguous catchments, the Severn and the Wye, rising on the eastern side of Plynlimon, mid-Wales were chosen for their broadly similar geological and morphological characteristics and the fact that in hydrological terms, leakage through the underlying ordovician/silurian hard geology was thought to be minimal. So far, reliable catchment water balance estimates of evapotranspiration for the years 1971-1983 have been obtained for the part-forested Severn and grassland Wye catchments.

A by-product of this necessarily intensive approach to hydrological input, storage and output measurement has been the development of unique process study techniques designed to explain the pertinent characteristics of the water balance results. Some of these techniques, in particular the natural lysimeters (Calder, 1976), have proved ideal for branching into multi-disciplinary agricultural research.

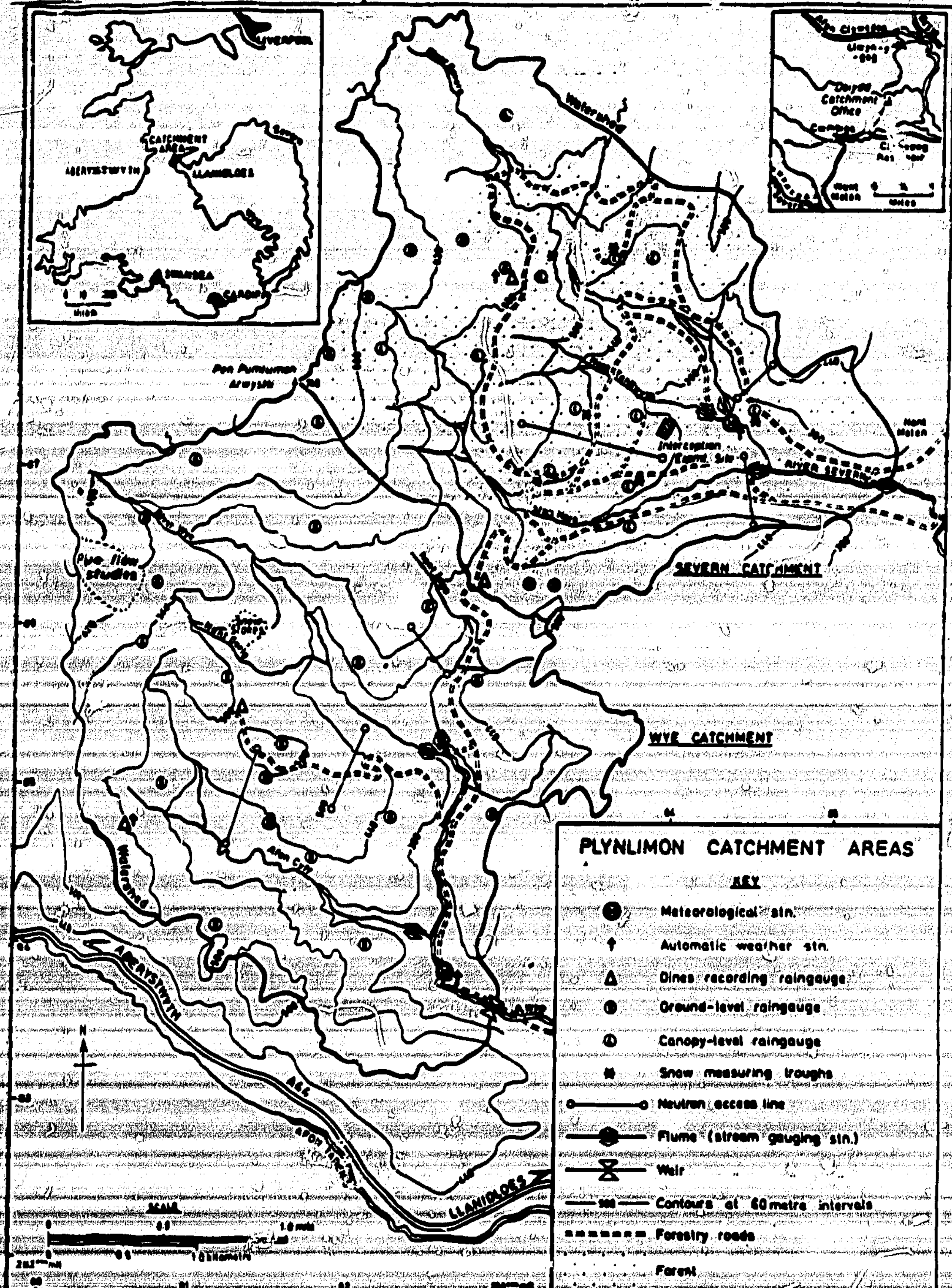


FIGURE 1 The Plynlimon catchments

3.2 The study area

The grassland catchment, the Wye, is 1055 ha in area and has an altitude range of 320-740 m with a mean annual rainfall of 2500 mm. It consists mainly of rough grazing though some 25% of the area has been subjected to various forms of improvement including open drainage, ploughing, liming, slagging and reseeding with ryegrass and clover mainly in the 1920s and 1930s. Fertilizer, in the form of basic slag, is still spread at the rate of 200 kg/ha every two or three years and lime is applied at times of reseeding. The extent of the improved areas is shown in Fig.2. Though the maintenance of the pastures is of low intensity, the residual effects of improvement were manifest in the results obtained from monitoring the flows at various points in the Wye catchment during 1979/80 (Roberts et al., 1983). In particular, pH values were higher in those catchments that had been limed at some time than in the predominantly acid grassland area of the Gwy catchment (Fig.2).

Though a detailed description of the vegetation, physiography and deposits of the Wye catchment is given by Newson (1976b), it is instructive to describe briefly the main characteristics of the Wye catchment to put it into a suitable agricultural context. In terms of soil and vegetation associations, the area is typical of large areas of upland Wales, corresponding to agricultural potentials of U3S and H2 to H4 on the MAFF (ADAS) "Hills and Upland Classification" (Fig.2). The areal variations in geomorphic features, soils, vegetation and associated hydrological characteristics are most easily explained by catena models (Fig.3).

Rudeforth (1970) of the Soil Survey of England and Wales describes the three main domains of the characteristic catena which Newson (1976b) summarizes as follows:-

(i) Valley bottom mires of terrace peat on impermeable drift. The peat is 1-2 metres thick on slopes commonly <10°. Soils of the Ynys peaty gley series (28% of the Wye catchment).

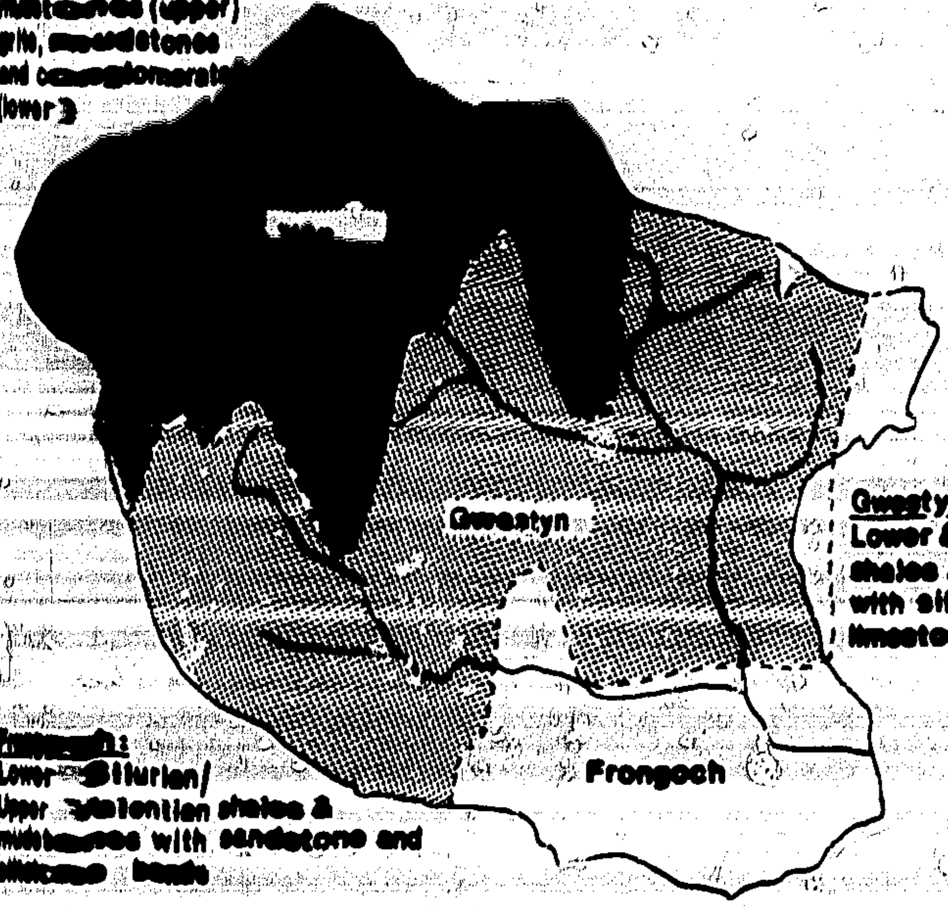
(ii) Slope areas (>10°) where deep peat is unstable and has been eroded. These peaty or peaty gleyed podzolic soils have developed on a regolith of stratified screes composed of gravel sized fragments of shale and thinly bedded mudstones (Hiraethog series - 62% of the Wye catchment).

(iii) Remnant blanket bog consisting of peat 1-2 metres thick, often gleyed and part eroded (hag topography) or thin peat soils over rock (Caron series - 10% of Wye catchment). These soils are usually associated with interfluve, high altitude areas.

Within traditional agricultural guidelines, the Hiraethog series are the only soils which would be considered for improvement. The microtopography of the haggy interfluve areas is usually too severe for economic use of machinery whilst the valley bottom bogs are often too wet for machinery even if tile drainage at practical spacing had much effect. At first glance the soils of the Plynlimon area represent prime examples of the cynical proverb "Tile drainage is only successful on areas where it isn't necessary". However, the lack of improvement on deeper peat areas is probably more a reaction to farm economics and agricultural strategy than to a technological problem. It is evident that schemes for the improvement of such areas would usually involve tile drainage as the initial step.

GEOLOGY
formations

Van:
Upper Ordovician – soft blue shales and bronze weathering mudstones (upper) grits, mudstones and conglomerates (lower)



from B.J.Knapp, Ph.D. thesis

Gwestyn:
Lower & Middle Valentian shales and mudstones with siltstone and impure limestone bands

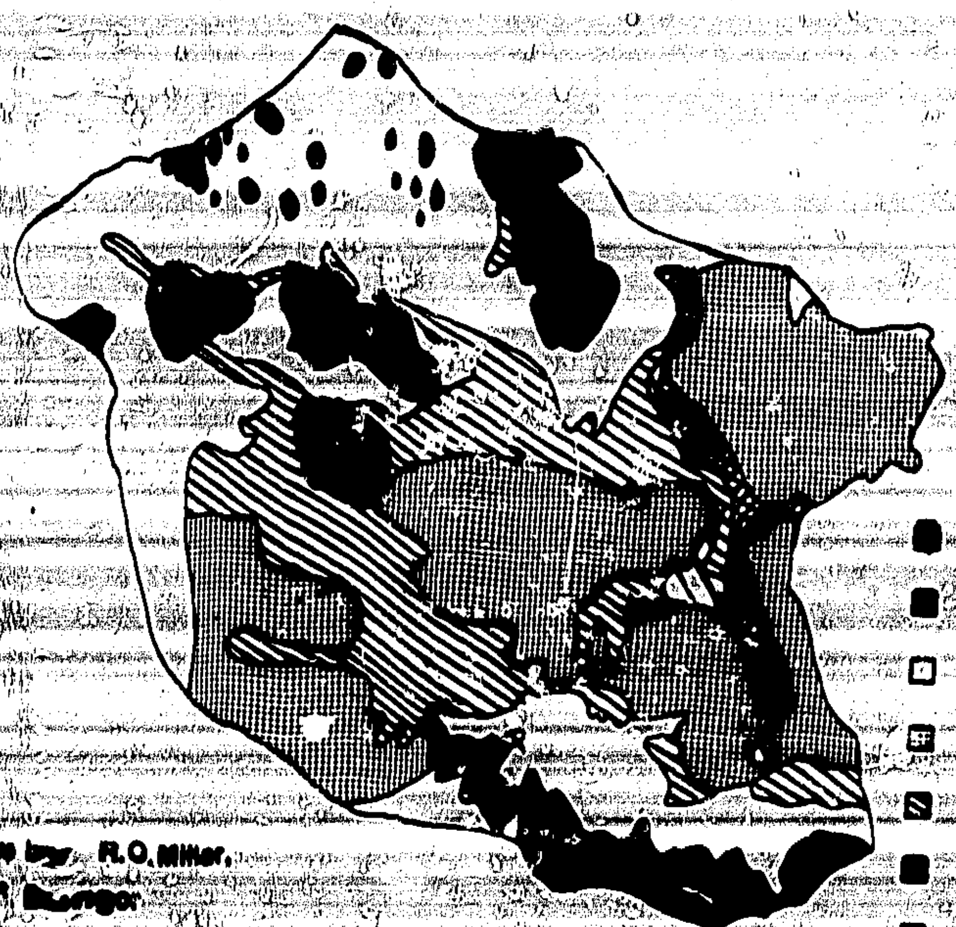
Frongoch:
Lower Silurian/ Upper Valentian shales & mudstones with sandstone and siltstone bands

SOILS

from C.C.Rudeforth, Soil Survey of England and Wales

- Valley complex – gravel & alluvium
- Caron (peat) & Ynys (peaty gley) series
- Thin slope soils – Hiraethog & Dreaged (peaty podzol) & Manod (acid brown earth) series

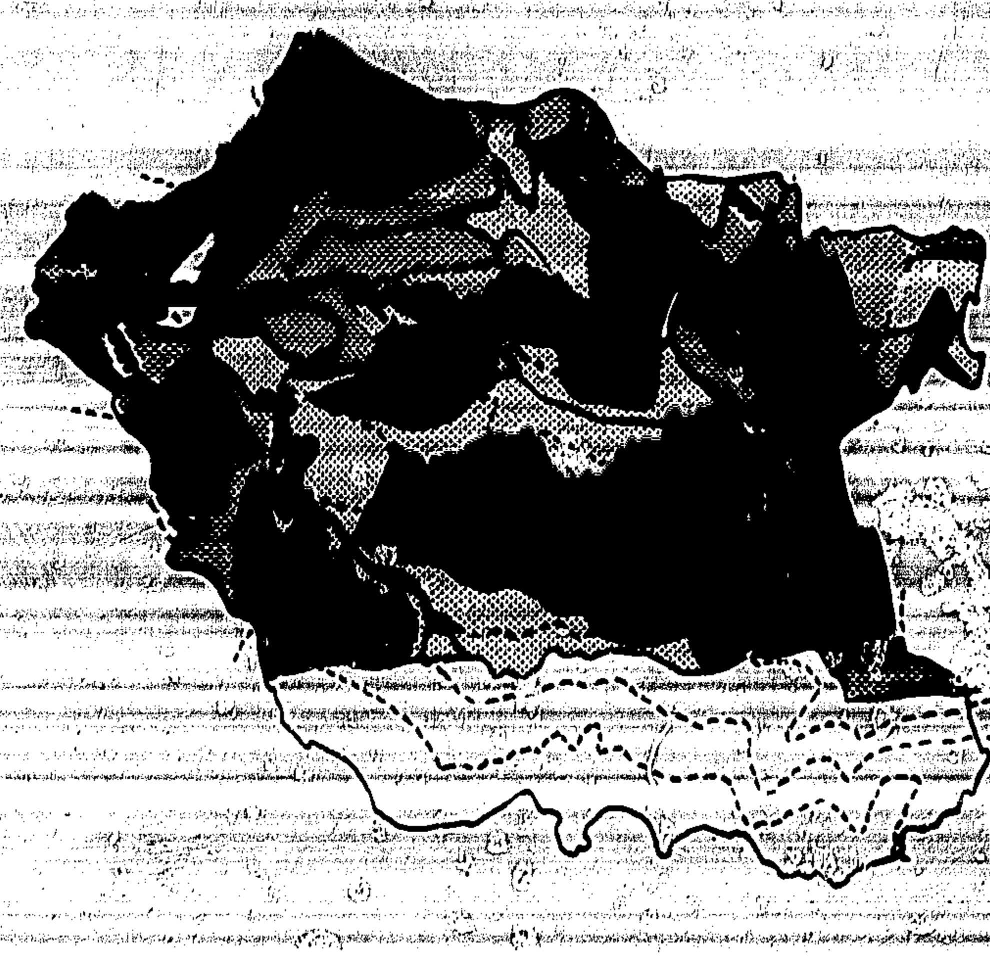
VEGETATION



- Heath
- Montane festuca
- Acid grassland
- Re-seeded grassland
- Mesotrophic mires
- Mesotrophic grassland
- Forestry

map by R.O.Miller, ITE Bangor

LAND-USE POTENTIAL



Upland
- U5 – permanent grazing : but with slope, topographic and shallow soil restrictions

Hill
- H2 – improvable but with slope and topographic restrictions
- H3 – limited improvability but of good grazing value
- H4 – not improvable and of low grazing value

Other
- Forestry
- As yet not classified

FIGURE 2 Plynlimon catchment characteristics

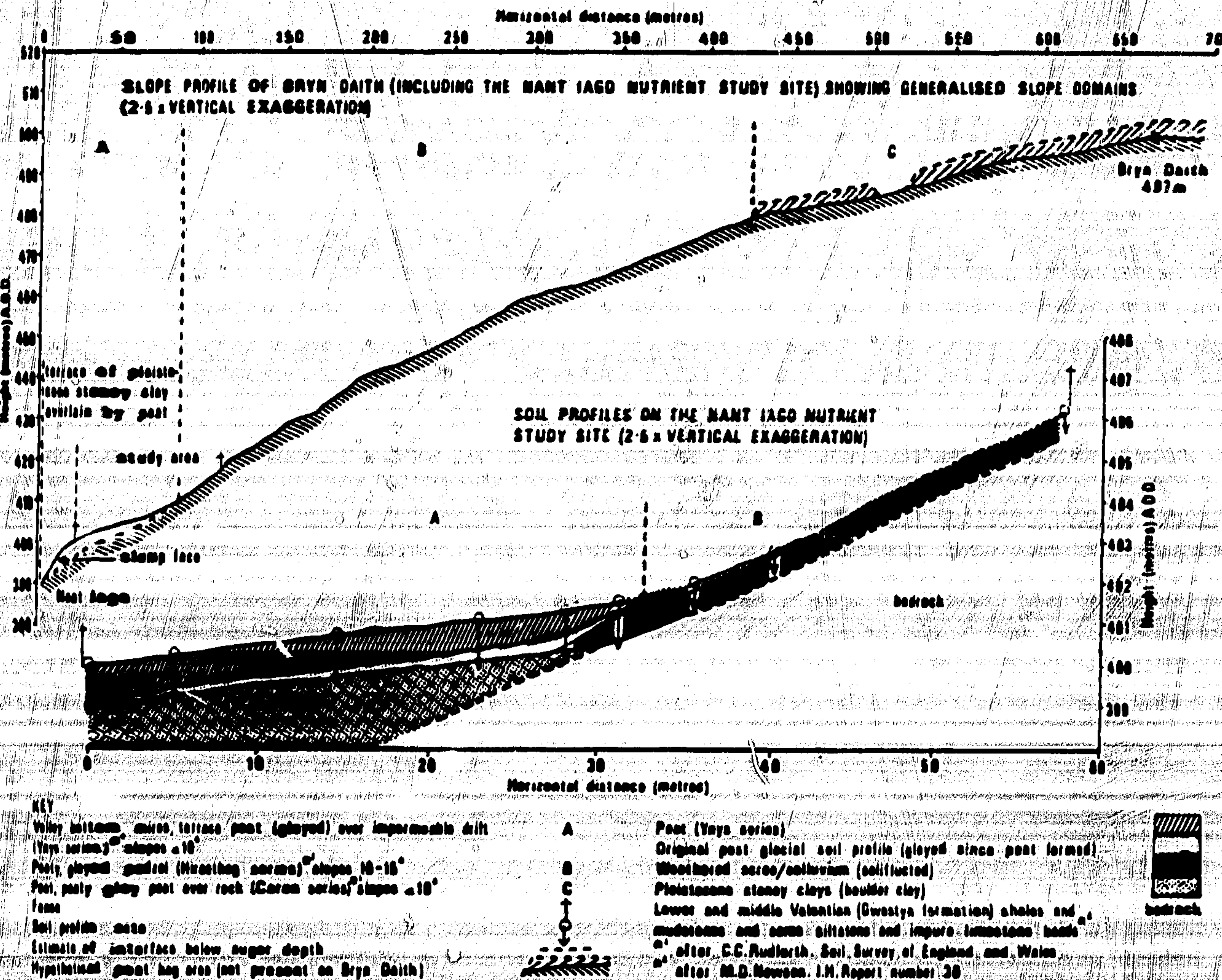


FIGURE 3 Morphology deposits and soil formations of typical slope profiles in the Nant Iago catchment

In agricultural terms, the peat areas can be considered an important resource that has not been tapped to any great extent, except perhaps for timber production. Even after tile drainage, peat can still remain very wet during the winter months and is liable to poaching by stock. Conversely, in the summer months, as witnessed particularly in the drought years 1976 and 1984, the freely drained slopes that are commonly improved dry out quickly, the vegetation becomes parched and the land is of little use for grazing. With recent evidence of increased evapotranspiration losses from improved pasture (Roberts, 1983), it is likely that soil moisture shortages will increase in upland Britain as more dry banks are improved. The improvement of peat areas, particularly valley bottom bogs, can be seen as an alternative source of stress-free summer grazing, and will be particularly useful in flexible farm management schemes during drought periods. The relevance of this study into the effects of peat improvement can now be recognized in terms of the likely direction of future grassland improvement.

3.3 Type of study

The original plans for the nutrient study revolved around the improvement of the smallest gauged sub-catchment of the upper Wye, the Nant Iago (Fig.4) of area 107.6 ha, in conjunction with lysimeter process studies designed to explain any observed changes in nutrient loadings of the Iago stream. Of the remaining instrumented sub-catchments of the upper Wye, either the Gwy (388.3 ha) or the Cyff (307.3 ha) was to be used as a control so that variations in the natural levels of nutrient concentrations could be distinguished from the effects of the improvement.

The most complete environmental studies tend to adopt this "nested" approach, tackling the problem at a variety of scales in the hope of finding corroborative evidence for the catchment results. In the hydrological context, this was the case at Plynlimon, where the large scale catchment study was complemented by lysimeter and small plot hydrometeorological studies. The experiment was approached in this way because of the need to convince the water authorities of the water resource implications of extensive afforestation at the relevant scale of operational purposes i.e. the catchment. This argument can also be applied to water quality studies, especially where water resources are threatened.

Some 40% of the Nant Iago sub-catchment was deemed improvable by local ADAS representatives, so plans were made to implement an improvement scheme and to monitor any quality changes in the streamflow. At the same time, plot studies were to be set up within the catchment on any areally significant combination of soil type, indigenous vegetation and geomorphology, both improved and unimproved, in order to assess their separate contributions to the catchment as a whole. In the event, financial restrictions precluded catchment scale improvement simply for experimental purposes and it was decided that a restricted plot scale study was all that could be attempted in the Wye.

This scheme involved a comparison of two lysimeters, one within and one without an area of grassland improvement. To some extent, the original experimental concept was retained by monitoring the runoff from the field plots surrounding the lysimeters in order to introduce some areal validation of the lysimeter results in qualitative if not quantitative terms.

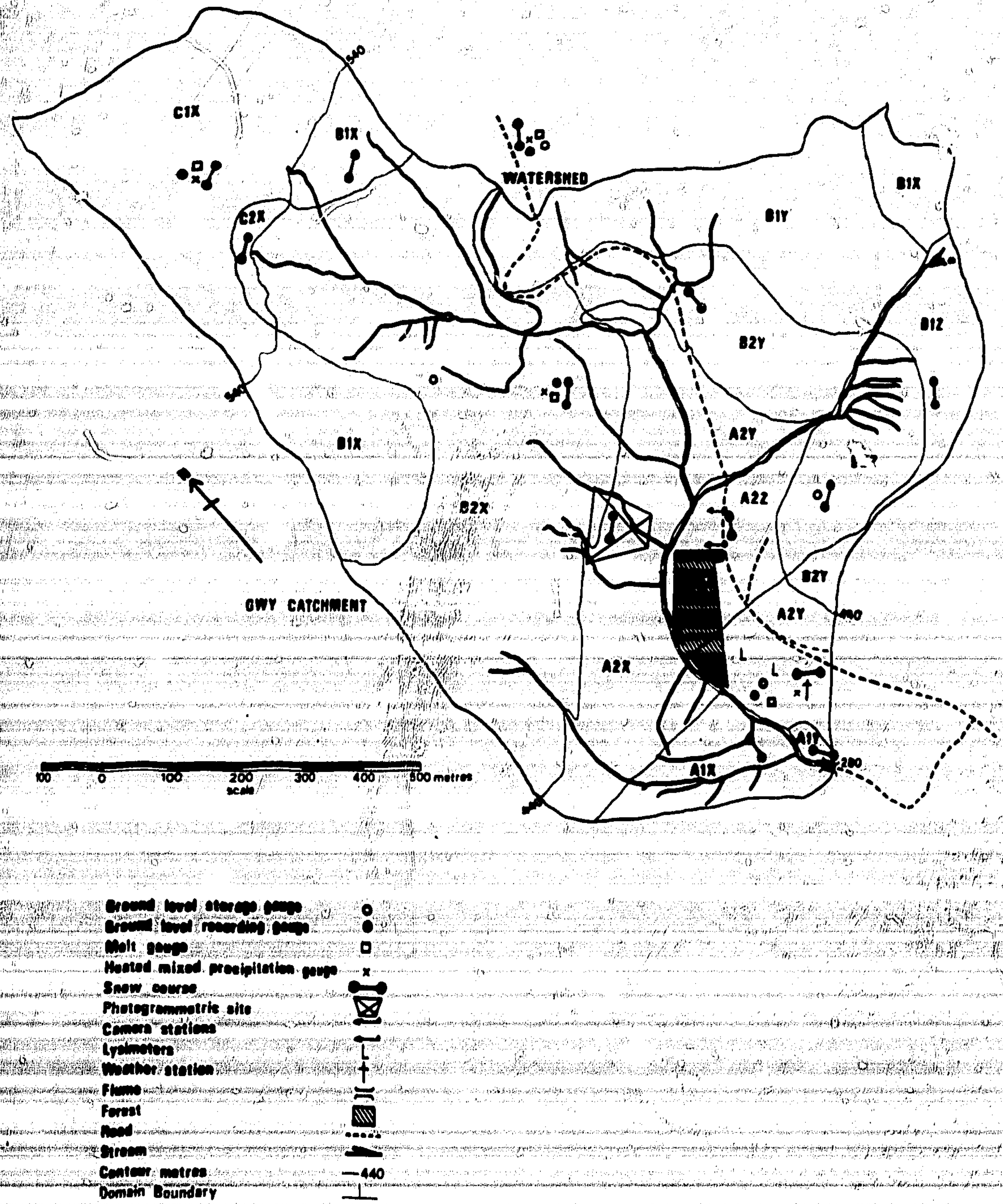


FIGURE 4 Snow measurement network - Nant Iago subcatchment

3.4 The experimental constraints on lysimeter design and site locations

A number of limiting factors had to be taken into consideration when planning the modified study.

(i) That the type of lysimeter used was suitable for the study.

(ii) That the area to be improved was typical of areas that were suitable for improvement.

(iii) That the results would have applicability to nutrient runoff from some, if not all, typically operational catchment areas.

(iv) That the application of the techniques available was possible on the site chosen.

(v) That the site chosen had not been improved at any time in the past to avoid confusion in interpreting the results.

Lysimeters have been used extensively in hydrological and agricultural studies for many years. As used in different parts of the world, the scales of lysimeters have varied from small flower pot size to hundreds of square metres in area and up to 5 metres deep (Kohnke et al., 1940). However, some principal design requirements must be met. These have been described by Slatyer and McIlroy (1961) and summarized by Calder (1976) as:-

(a) Dimensions should be large enough to ensure a fully representative sample of the plant community and to minimize boundary effects.

(b) The container walls should be so designed that the gap between the internal and external crop is as small as possible.

(c) Water-table differences between the lysimeter and the external crop should be minimized.

(d) The soil structure inside the lysimeter must resemble closely that of the surrounding area.

(e) The site should be representative of the area under investigation or the lysimeter should be replicated.

The difficulties involved in the construction of lysimeters have invariably meant that some of the design criteria summarized above have not been fully met. The greatest difficulty lies in ensuring that a watertight seal exists at the base of the lysimeter. Another problem is ensuring that the soil column encased within the lysimeter is as undisturbed as possible. Several variations in construction have been attempted to overcome these difficulties though, even now, the type of study dictates, to a great extent, the type employed. This is certainly true of the study reported here.

The primary aim of this study, as indicated previously, was to ascertain the effect of pasture improvement, involving a considerable amount of ground disturbance, on nutrient release. Bearing this in mind, it is obvious that the most important factors in choosing the type of lysimeter were that the initial construction should involve little ground disturbance and that conditions within the completed lysimeters were as natural as possible. This was to ensure that the effects of the initial construction did not mask those of the grassland improvement and that conditions within the control lysimeter were such that a 'natural' baseline could be obtained.

These criteria obviously ruled out the 'disturbed soil' type of lysimeter whereby a tank, having a drainage outlet at its base, is filled with soil (see, for example, Collison et al., 1933). The effect of the soil disturbance on the hydrological and biological processes occurring within the soil (Cassel et al., 1974) would certainly be as great as the effect of the shallow cultivation associated with grassland improvement. Similarly, the monolith type (Belford, 1979), with its small surface area, was rejected because edge effects due to the insertion of the retaining walls would be unacceptable. This is particularly so in the Plynlimon district where the main soil types are peaty podzols (Newson, 1976b) which undergo irreversible cracking and, ultimately, pipe formation (Newson and Harrison, 1978a) on draining. This will affect the hydrological characteristics of the soil profile and, more importantly in this case, cause an appreciable amount of nitrogen mineralization (Terry, 1980) with subsequent leaching of nitrate-N. Also, the small surface areas would be unlikely to give a true representation in terms of variation in soil type, seed and fertilizer dispersal, and growth of new pasture. The large, fully enclosed type of lysimeter, described by Kitching and Shearer, 1982 was rejected on the grounds of cost and time, bearing in mind that two would be required. Also, the conditions prevailing in the Plynlimon area - restricted access, waterlogged soils and steep slopes - are not conducive to the use of the heavy machinery required.

It was therefore decided that the most suitable type was the 'natural' lysimeter, whereby the base seal is achieved by utilizing a naturally-occurring impermeable layer, even though a complete seal could not be guaranteed. This decision was influenced by the existence of such layers in the Plynlimon district (Newson, 1976b) and the successful utilization of such a technique (Calder, 1976). Another contributory factor in its favour is the practice in mid-Wales of draining waterlogged soils prior to improvement. The recommended distance between the drains in these areas is 10 m so that a 10 m square lysimeter can be regarded as a naturally-occurring unit within such a drainage scheme. Conducting the study in such an area would have the additional advantage that, by monitoring the drain outflows, some indication of the effects of pasture improvement on a 'field' scale could be obtained. The only drawback was the fact that the effects of the drainage, an integral part of the improvement, on nutrient release would be experienced in both lysimeters. However, by allowing sufficient time between lysimeter construction and improvement, it was thought that any such effects would have reduced, if not disappeared. A similar situation would have happened in any case, irrespective of the type of lysimeter chosen.

For extrapolation purposes, it is important to ascertain how representative of typical Welsh upland catchments are the lysimeters and surrounding field plots. Although only 40% of the Nant Iago catchment was deemed improveable by local ADAS representatives, much of the remaining 60% was only disregarded because of the expense and

difficulty of access and not because of any inherent deficiencies in the soils or topography. Some areas, however, were too wet, too steep or covered by mine spoil. The improveable areas included all three types previously described in the catena classification.

Of these three land types, the steeper dry banks with peaty podzol soils and short vegetation are the most difficult to study. It is not sufficient to isolate a portion of slope and then assume that the results are applicable to the rest of the catchment area. This disrupts the most important characteristic of slope behaviour i.e. the accumulation of water and nutrients when runoff moves downslope on the surface or as pipeflow and interflow in the various soil horizons. Attempts have been made to intercept and measure both the quantity and quality of this slope water, with success in some cases (ITE, 1984) but rather less in others (Knapp, 1974) despite results from several observation pits. Patterns of flow on slopes are uncertain and not easy to define from surface evidence. A large number of pits is required to obtain the spatial validity required for extrapolation. Replication on this scale necessitates the need for prohibitive amounts of instrumentation and sample analyses. It is easier to approach the complexities of slope runoff using a catchment composed predominantly of slope soils although, in such cases, explanations for the patterns of nutrient concentration at the catchment outfall are difficult if not impossible to justify.

The two remaining areas, the peaty interfluves and valley bottom bogs, are similar in many respects. Their taxonomical differences arise as a result of the different altitudinal, climatic and vegetational factors responsible for the formation of the Caron and Ynys peats. They do, however, have a distinct hydrological resemblance.

They differ fundamentally however in their relative positions on the catena. The interfluve remnant blanket peats have water and nutrient inputs mainly in the form of rain whereas the valley bottom bogs or "mesotrophic" mires have, as the nomenclature implies, a higher nutrient status due to inputs from downslope runoff. Improvement of either peat area would involve, on present recommendations at least, tile drainage to aid sward development. In their drained state both types of soil behave similarly, as the soil blocks isolated by the tile drain system have little or no contact with downslope runoff water. This is intercepted by the drains during all but the most extreme surface runoff events. Hence a study of the improvement of a valley bottom bog area can be relevant to and representative of some 38% of a typical upland catchment in mid-Wales.

A previous study on the Plynlimon catchments (Roberts et al., 1983) suggested that the mesotrophic mires are an important safety valve for nutrient movement downslope into streams. It was noted that the Cyff catchment which exhibited the lowest nitrogen levels in stream water was also the catchment that had the largest area of grassland draining through a mesotrophic mire. The recycling of mobile nitrogen in the anaerobic bog conditions and the gaseous loss by denitrification were implicated as the controlling factors on nitrogen runoff particularly during the summer months. This suggests that studying details of slope nutrient runoff is less important than the effect of the disruption caused by tile drainage and improvement to this vital "whole slope" controlling role of these mire areas.

By coincidence, the study of the most interesting of the three catena domains is made simpler by the existence of an underlying stratum of glacial drift. This is generally relatively impermeable and can, with careful selection, form the lower limit of a "natural" lysimeter as used successfully by Calder, 1976 under Sitka spruce in the Severn catchment. Unfortunately these pleistocene stoney clays, generally described though misnamed as boulder clay, although they occur extensively in both the Wye and Severn catchments at Plynlimon, have rarely remained in situ since their formation during the last glaciation. Periglacial activity, slumping and solifluction has occurred and the downslope movement to produce the characteristic terraces in the valley bottoms of the mid-Wales uplands has generally involved some redistribution, fissuring and oxidation. This is normally manifest as a yellow mottling in an otherwise smooth blue clay matrix and weathering of the surface layers of stones embedded in the clay. Some deposits do not appear to have been oxidized but even these clays transmit water to some extent but at a slow enough rate not to invalidate the lysimeter technique (Calder, 1976).

Bearing all these points in mind, an extensive survey was carried out in the Wye catchment at Plynlimon to find a suitable site. The obvious candidate was a 1.5 ha area of mire under Juncus effusus and Molinia caerulae cover at an altitude of 400 m in the Nant Iago catchment (see Figs. 3 and 4). A detailed survey on a 100 m by 40 m grid in June 1976 indicated a 1 in 10 surface slope with the peat depth increasing downslope from 0.4 to 1.7 m.

4. METHOD

The area was drained during June 1977 by splitting it into two sections with a main drain dug into the boulder clay in a downslope direction in each section. Lateral drains at 10 m spacing were cut in each section as shown in Fig.5. During the same period, the two lysimeters were constructed to fit within the drainage scheme, with their sides parallel to the general run of the drains.

To ensure that tapping pipes from the base of the lysimeters (up to 1.5 metres below ground level) to the instrumentation hut had sufficient slope, the lysimeters were placed with their topmost corner as near the break of slope as possible. In the case of the lysimeter on the control, or unimproved, plot, this eventually necessitated the removal of the top corner of the lysimeter to obtain a better seal for its base. Finally, that half of the site to be improved was surrounded by a fence to facilitate management of stock.

4.1 Lysimeter construction

Each lysimeter was constructed Fig.6 by digging a trench into the impermeable layer around the 10 metre by 10 metre lysimeter 'block' and sealing it by concreting 8' by 4' rigid plastic sheeting into the trench. Each sheet was cut so that it extended approximately 9 inches above ground level. A waterproof seal between overlapping sheets was ensured by compressing a 2" strip of bitumen impregnated foam between the sheets and bolting the sheets together at 2' intervals along their lengths using two lengths of angle iron to ensure even compression of the foam Fig.7.

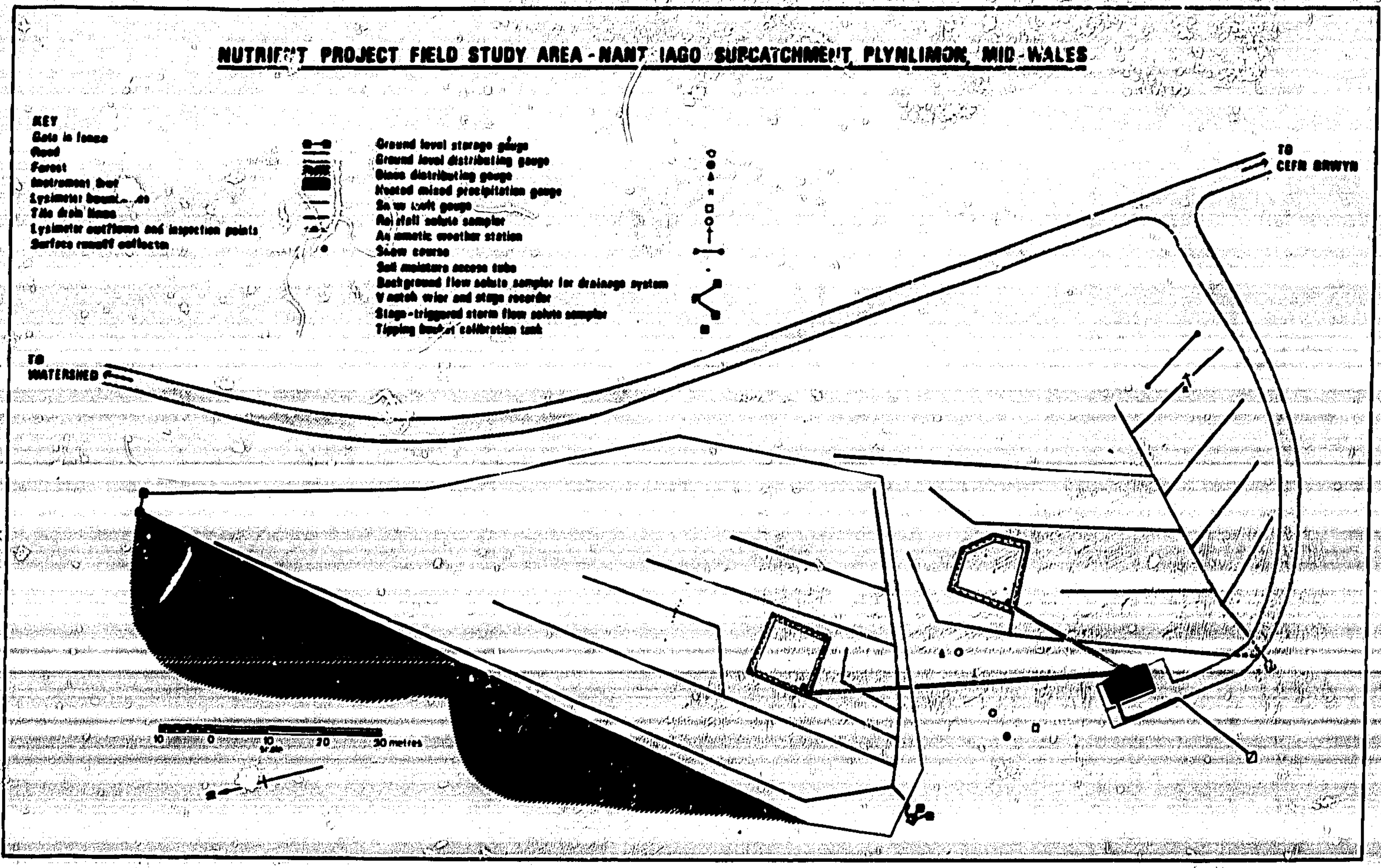


FIGURE 5 Nutrient project field study area - Nant Iago subcatchment

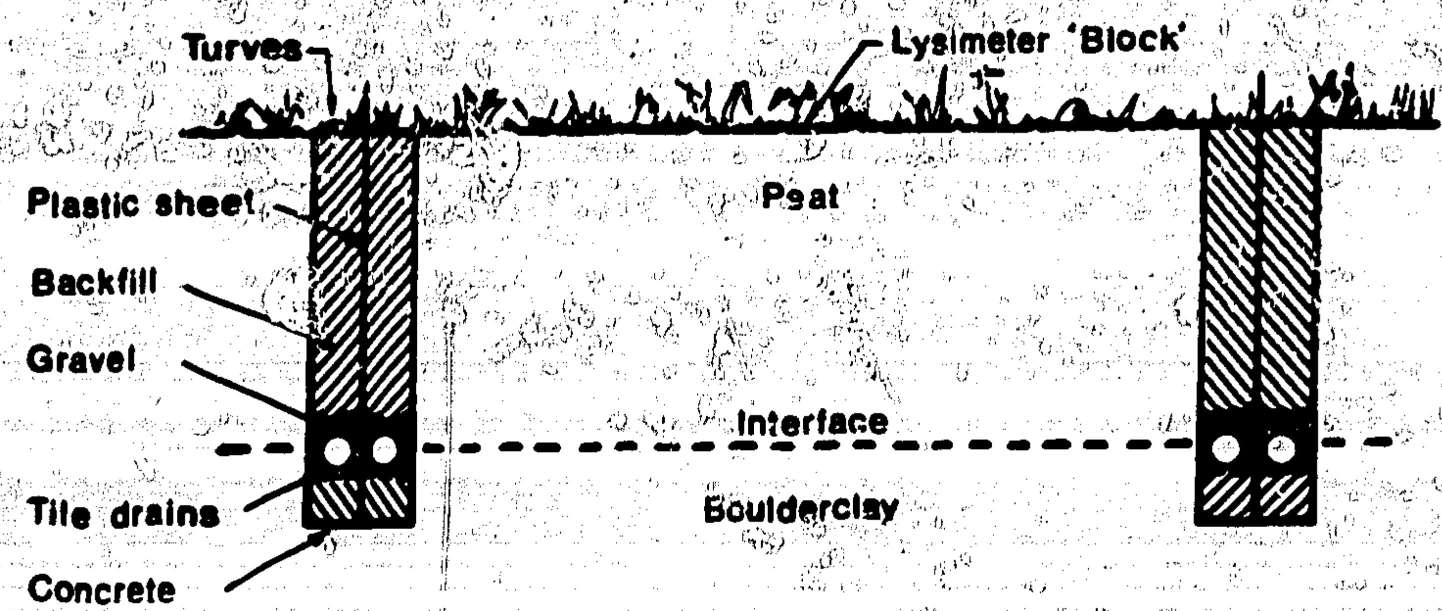


FIGURE 6 Cross-section of lysimeter showing details of construction

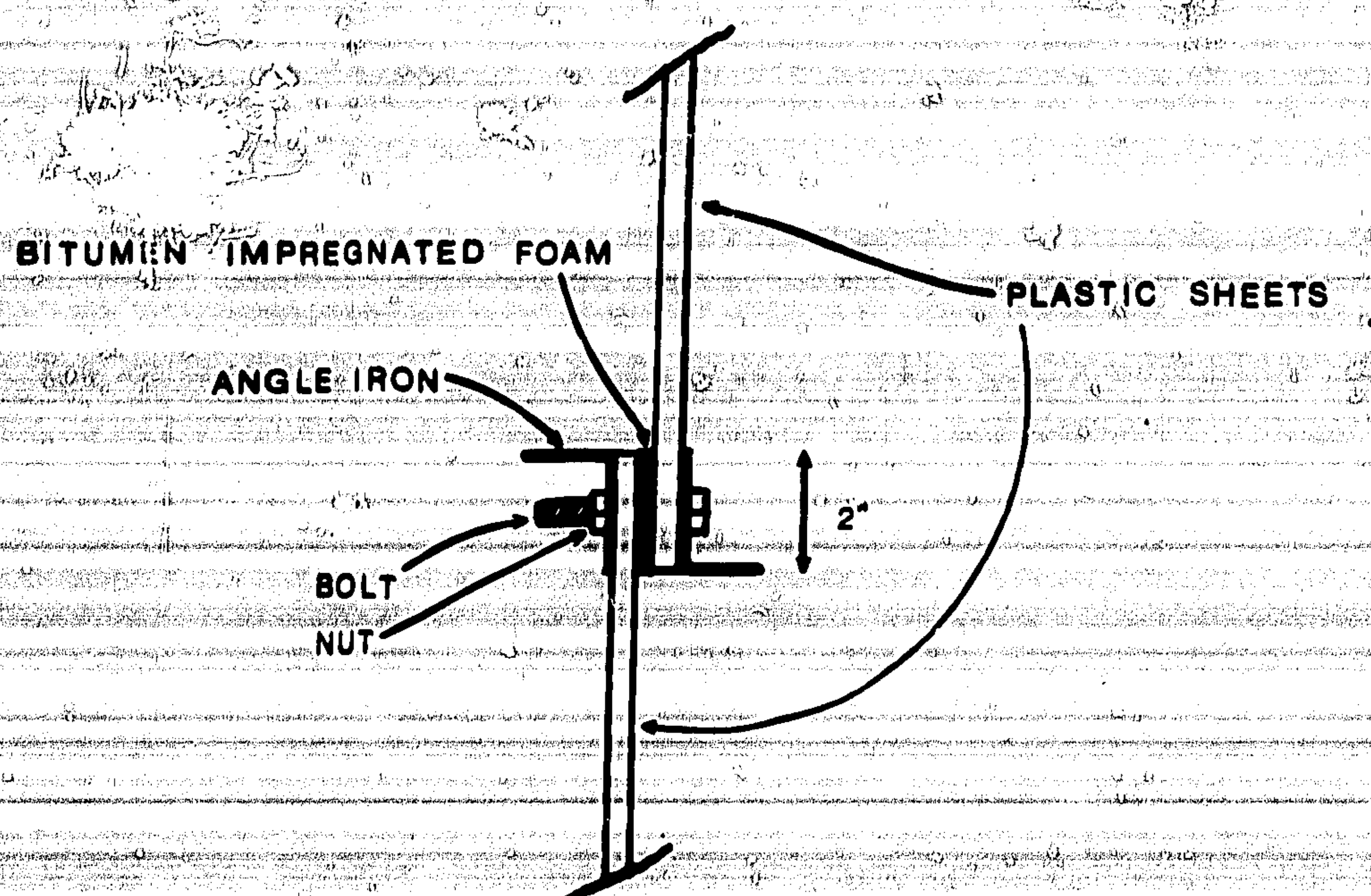


FIGURE 7 Overlap of plastic sheets used to enclose lysimeters

Tile drains were placed in the trench both inside and outside the plastic sheets and covered with gravel. The trench was backfilled with peat and the turves replaced. Those on the inside of the plastic sheeting were angled in such a way that any surface runoff would be led into a collector at the lowest corner of the lysimeter (Fig.8). Sub-surface runoff would be collected, via the tile drains on the inside of the lysimeter, at an exit in the plastic sheeting on the peat/clay interface at the lowest corner of the lysimeter (Fig.8).

The surface area of each lysimeter was measured accurately during September 1978 and found to be 119.2 sq.m and 107.9 sq.m, respectively, for the lysimeter within and without the improvement area.

The surface and sub-surface flows from the two lysimeters were led, via individual 4" plastic pipes, into an instrumentation hut where they were monitored separately.

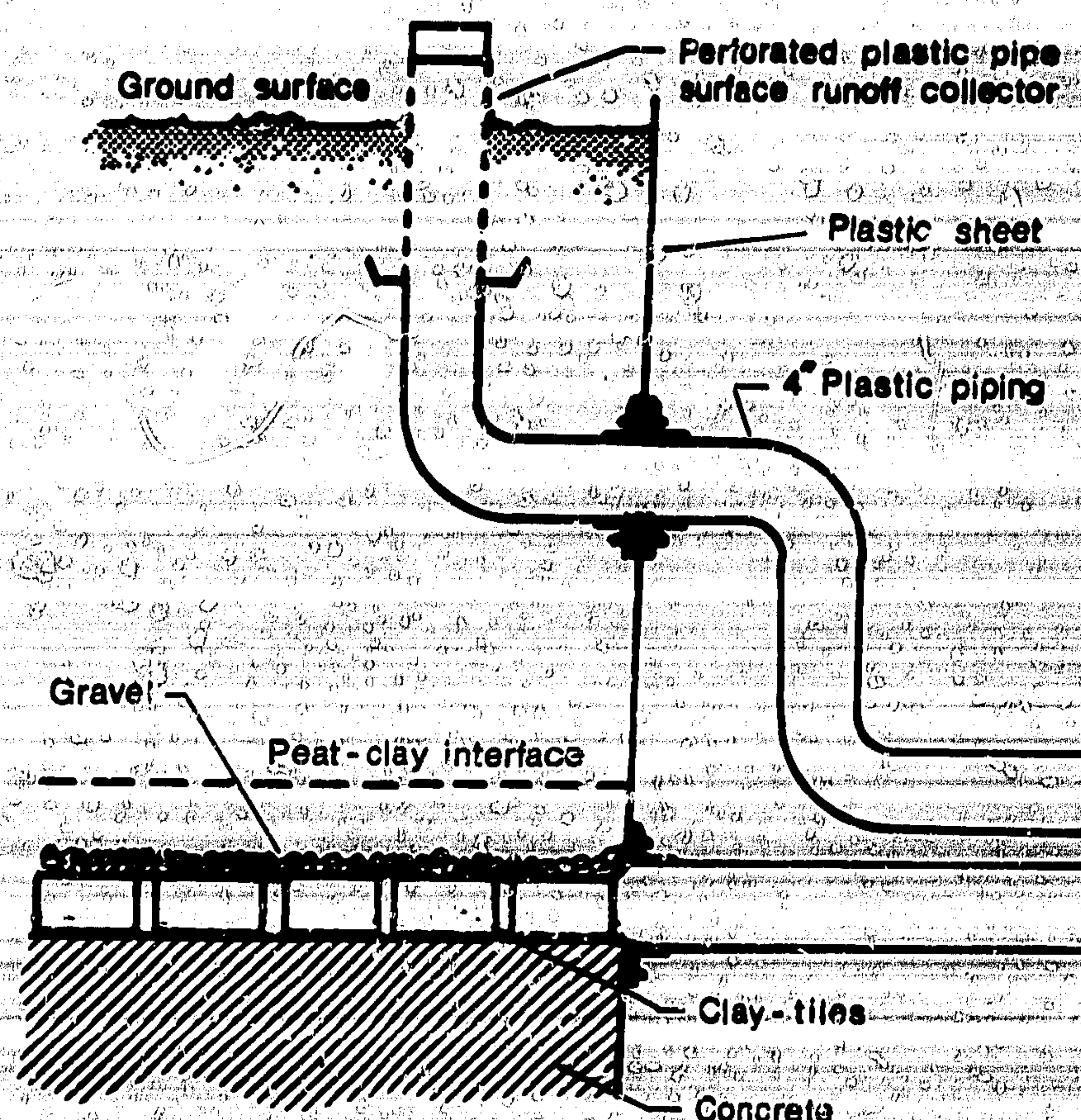


FIGURE 8 Surface and subsurface discharge collectors

4.2 Instrumentation

A minimum requirement for the assessment of the effects of the grassland improvement on the runoff from the lysimeter was the collection of flow samples for chemical analysis and the continuous measurement of runoff. This would ensure that changes in chemical concentrations, the quantity of flow and hence the magnitude of the dissolved nutrient loads could be obtained. Also, similar data were required from the control lysimeter so that seasonal variations in the hydrological and chemical response could be eliminated. In addition, it was felt that additional measurements were desirable, so that further information on the processes occurring could be obtained. The independent monitoring of the surface and sub-surface flows from the lysimeters was an integral part of the study. Additional measurements included monitoring the quantity and quality of incoming rainfall, calculating changes in the quantity and quality of soil moisture and monitoring the flows in the main drains so that the effects in terms of a 'field' situation could be assessed and the representativeness of the lysimeter checked.

Of the data collected, the most important were those obtained by monitoring and measuring the flows from the two lysimeters. Therefore, most of the effort was directed to ensuring that, as far as possible, these data sets were complete and error free. Prior to the start of data collection, much thought was given to deciding what was the most suitable instrumentation to use so as to achieve this aim. Of particular importance was the way in which flow samples were collected. Spot samples taken on a regular time basis may be adequate for monitoring catchment outfalls (Roberts et al., 1983). For this study, however, where the response to incoming rainfall was likely to be much quicker and the nutrient concentrations higher and varying more rapidly as a result of the lysimeter construction and grassland improvement, it was felt that composite flow samples comprising a number of sub-samples, preferably taken on a flow proportional basis, would be more suitable. This type of sample, although not giving any indications of peak concentrations or instantaneous correlations between concentrations and other variables such as flow, are ideal for calculating nutrient losses in flows by automatically imposing a correct flow weighting to each sample. The collection of such samples meant that a system had to be devised to control the timing of an automatic sampler using the flow data. Therefore, the choice of flow measuring instrument was important to ensure that it could measure the range of flows expected from a lysimeter of such size, would give good resolution at low flows and could also be modified to drive the flow sampler.

The primary means of recording each individual flow from the lysimeters was by a tipping bucket discharge recorder (Edwards et al., 1974) connected to a multi-channel logging device (Fig.9). These buckets, with their capacity of approximately 1.5 litres per tip, are capable of measuring flows of up to 1 litre per second, which is much higher than the maximum expected flow rate from an area of 100 sq. metres at the rainfall rates normally expected at Plynlimon. They also give very good resolution at low flow rates. The buckets were fitted with magnets which, when the bucket tipped, activated a reed switch attached to the frame of the instrument. The pulses generated in an electrical circuit by the closures of the reed switch were accumulated and output, via the multi-channel logger, to a cassette tape at five minute intervals. The pulses were also used to activate a flow proportional automatic water sampler as described below. The cassette tape, as well as recording separately the surface and

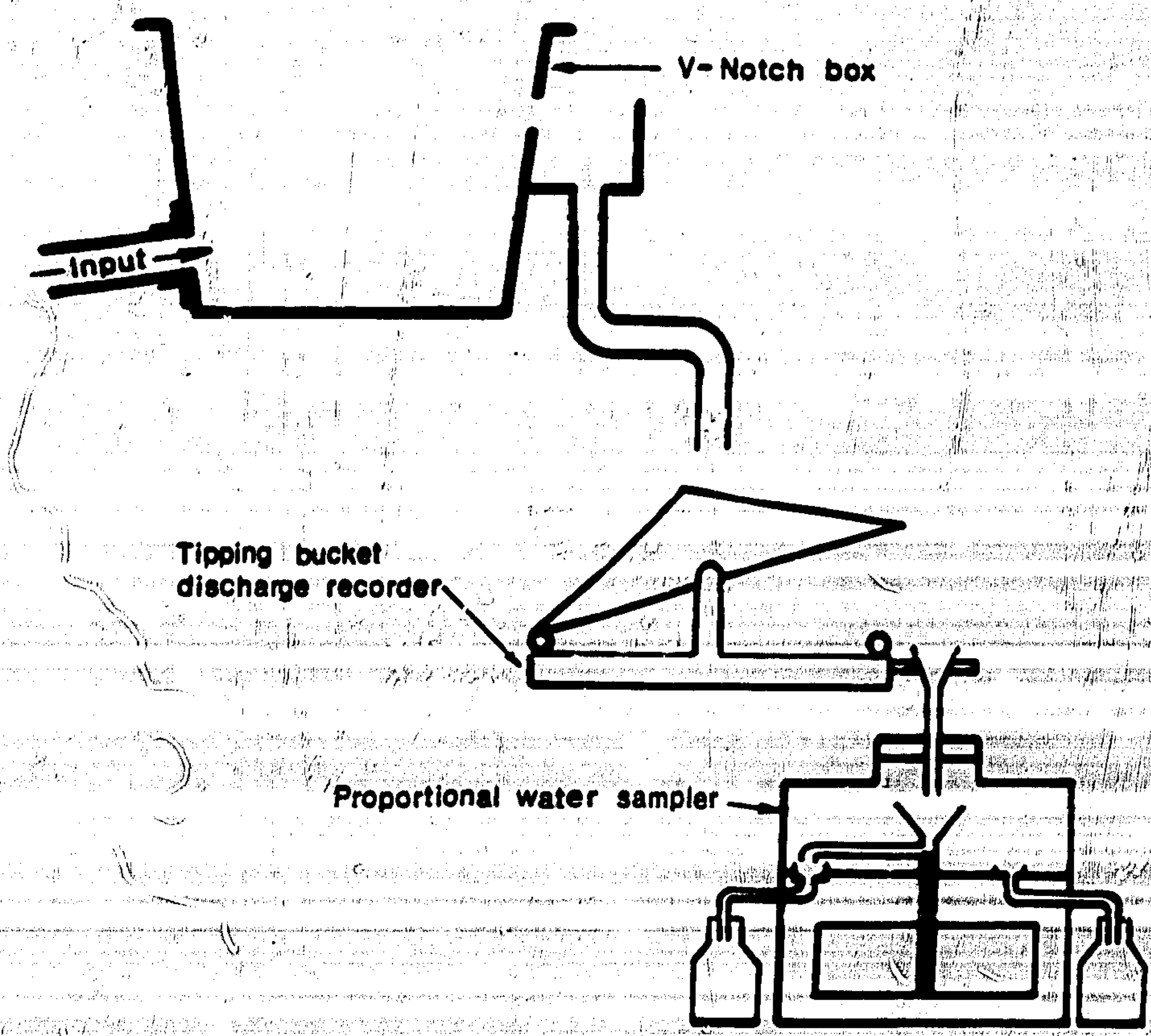


FIGURE 9 Flow measuring devices and proportional water sampler

sub-surface flows from the two lysimeters, was also used to record the rainfall data. It was changed at approximately fortnightly intervals and the data recorded translated at Wallingford (Roberts, 1981). As a precaution against instrument malfunction, each of the flows was also measured using a V-notch weir box (Fig.9). The flow was led into a plastic tank having a ½ 90° V-notch cut into a metal plate as an exit. The level of the water, or head, above the bottom of the V-notch was measured using a float inside a stilling well connected to the V-notch box and recorded at five minute intervals on a paper tape using a Fischer-Porter recorder. Each recorder was serviced at monthly intervals when the used tape was removed and the head as measured by the recorder compared with that measured using a screw gauge depth recorder, and, if necessary, adjustments made. The data recorded on the paper tape were translated at Wallingford (Plinston and Hill, 1974). Each V-notch box also served a secondary purpose, that of a silt trap, thus affording some degree of protection to the tipping bucket and water sampler and natural filtration of the samples.

Water samples from the surface and sub-surface flows from the two lysimeters were collected using automatic flow proportional composite samplers (Fig.9) designed specifically for this study (Holdsworth and Roberts, 1982). Each sampler collects a small proportion of water from every other tip of a tipping bucket using a funnel and leads it, by means of a hollow metal tube clamped to the spindle of a stepping motor, into one of an array of sample bottles. At the same time, the pulses generated by the tipping of the bucket are accumulated in a control box so that after a pre-set number of tips, the stepping motor is activated and the water samples directed into the next bottle in the array. In this way, water samples were collected from each flow, each sample being composed of an accumulation of sub-samples, each representing a set flow. In this particular study, an integrated 1 litre sample was taken from each of the sub-surface flows every 800 litres of flow (equivalent discharge of approximately 8mm/unit area) and from each of the surface flows every 100 litres of flow (equivalent discharge of approximately 1mm/unit area). This was done simply by adjusting the pre-set number of tips that activated the stepping motors and using different sized sample collection funnels.

The flow from each of the main drains was led into a tank having a 90° V-notch cut into a metal plate as an exit. The level of the water, or head, above the bottom of the V-notch was measured using a float inside a stilling well and recorded on paper tape at 15 min intervals using a Fischer-Porter recorder. The paper tapes were collected at monthly intervals and translated at Wallingford (Plinston and Hill, 1974).

Flow samples were collected manually at weekly intervals from each of the drain outlets throughout the course of the study. Following the implementation of the grassland improvement in May 1978, water sampling at the outlet of the drain from the improved area was increased to one sample per day (bulked average of three eight-hourly samples). Also, hourly samples were collected automatically during a number of storm events. Automatic sample collection was discontinued in November 1979 and replaced by spot weekly sampling.

Rainfall at the site was measured by means of one weekly-read period gauge, the totals measured by this gauge being distributed in time using the data obtained from two tipping bucket raingauges each recording at 5 minute intervals, one on the multi-channel logger described previously and the other on the automatic weather station described below. Rainfall samples from the period gauge were retained for chemical analysis. If the sample collected during one week was insufficient for analysis, it was stored in a refrigerator and added to the sample obtained during the following week.

Three neutron access tubes for facilitating the measurement of soil moisture by means of a neutron probe (Bell, 1976) were inserted into each lysimeter. They were read at approximately weekly intervals and the measurements converted into soil moisture totals as described by Roberts, 1981. A series of tubes for collecting soil water samples at different depths in the peat profile were inserted into each lysimeter. Soil water sampling was carried out at infrequent intervals but had to be discontinued after a few months due to increasing difficulties in obtaining sufficient sample volumes for analysis purposes.

The site was equipped with an automatic weather station (Strangeways, 1972). This records solar radiation, net radiation, wet bulb depression, dry bulb temperature, wind run, wind direction and rainfall on a 5 minute time basis. These data were processed at Wallingford to give estimates of daily evaporation losses (Roberts, 1981).

Data collection began in October 1977 and was continued until March 1981 (Fig.10).

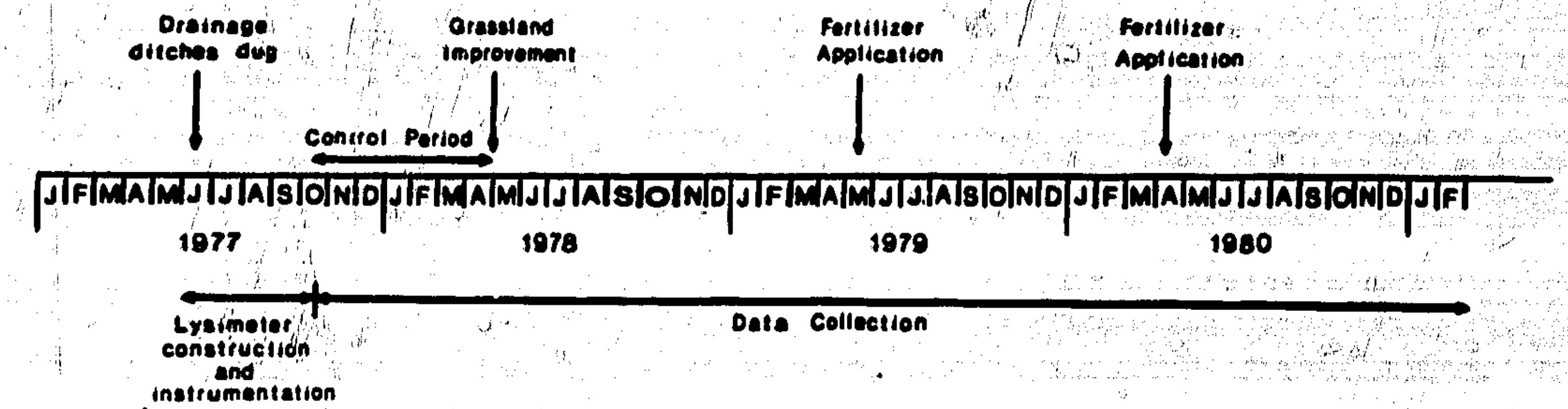


FIGURE 10 Timetable of operations

4.3 Grassland improvement

The grassland improvement scheme was implemented on the 24th April 1978 for the plot and on 19th May on the lysimeter itself (Fig.10). Prior to this, soil samples were collected at several points on the site by local ADAS representatives and analysed at MAFF, Trawscoed. The results obtained are shown in Table 1. These indicate an acid peat of pH 4.6, with a total N content ranging from 2.3% in the upper 30cm layer to 0.4% at 1m. The peat was found to be deficient in phosphorus, potassium and magnesium; analysis of water extracted from the peat showed ammonium-N and nitrate-N in the ranges 2.7-0.8 mg/ℓ and 1.5-0.3 mg/ℓ, respectively, down the profile. These figures are typical of upland soils showing large reserves of organic nitrogen but small quantities of the soluble forms of nitrogen that are readily available to plants (Munro, 1972; HFRO, 1967-1970).

TABLE 1 ANALYSIS OF SOIL SAMPLES TAKEN FROM THE LYSIMETER SITE, 8.3.78

Depth (cm)	NH_4^+N (mg/l) wet soil	NO_3^-N (mg/l) wet soil	Total N (%)	P (mg/l)	K (mg/l)
0-30	2.66	1.54	2.30	12.0(1)	66.0(1)
30-50	1.2	0.28	2.30	4.0(0)	25.0(0)
50-70	1.68	0.56	1.40	3.0(0)	20.0(0)
70-90	1.40	0.14	0.73	3.0(0)	12.0(0)
90-100	0.84	0.28	0.37	6.0(0)	13.0(0)

Depth (cm)	pH	Mg (mg/l)	% dry matter (by weight)	lime requirement (tonnes/ha)	density (Weight/volume)
0-30	4.60	62.0(2)	14.0	15.0	30.0
30-50	4.50	57.0(2)	12.0	16.0	39.0
50-70	4.50	50.0(1)	17.0	16.0	40.0
70-90	4.70	36.0(1)	40.0	17.0	52.0
90-100	4.80	30.0(1)	40.0	12.0	58.0

The improvement consisted of liming, followed by rotavation, reseeding and a fertilizer application. The quantities used are shown in Table 2. They follow broadly the guidelines given in MAFF, 1973. This improvement was carried out on one half of the plot and on the lysimeter within.

TABLE 2 RATES OF FERTILIZER AND SEED APPLICATIONS USED IN THE IMPROVEMENT SCHEME

Lime 3.514 tonnes/acre or 8685 kg/ha

Basic slag 15.1 cwt/acre or 191 kg/ha of P_2O_5

Compound fertilizer (15-15-15) 3.45 cwt/acre or 65 kg/ha of N, 65 kg/ha of P_2O_5, 65 kg/ha of K_2O

Nitrogenous fertilizer (34.5% N) 1.38 cwt/acre or 60 kg/ha of N

in terms of N, P and K, this adds up to:

N 125 kg/ha of N; P 256 kg/ha of P_2O_5 or 119/kg/ha of P
K 65 kg/ha of K_2O or 51 kg/ha of K

Grass seed (kg/ha)

S22	Italian ryegrass	3.50
S23	Perennial ryegrass	13.25
S59	Red fescue	4.50
S48	Timothy	3.50
S134	White wild clover	2.25
	Total	27.0

Subsequent fertilizer applications 50 kg/ha of N

Inspection of the new pasture during September 1978 revealed that the germination rate of the grass seed was high but that clover growth was patchy. The grazing intensity was increased to encourage clover growth.

Subsequent remedial nitrogenous fertilizer applications were made to the improved sward during May 1979 and April 1980 (Fig.10 and Table 2).

4.4 Data processing

The data measured by the tipping bucket discharge recorders were converted into flows using the relationship derived by Calder and Kidd, 1978:-

$$F = \frac{A}{(\frac{t}{n} - B)}$$

where F = flow (litres/sec),
n = number of tips, as recorded,
A = the "dynamic" capacity of the bucket (litres),
t = the recording period (300 secs, in this case),
B = the time taken for the bucket to tip (secs).

The values of A and B for all the tipping bucket discharge recorders used in this study were estimated by calibrating each instrument over a series of flows up to 1 litre/sec using a flow measuring device at the Hydraulics Research Station, Wallingford. By plotting the time for each tip (t/n in the above equation) against the reciprocal of the flow (1/F in the above equation) over a range of flow rates, then the slope of the resulting straight line graph will give a measure of A, the capacity of the bucket, while the intercept will give B, the time taken for the bucket to tip. The flow, F (litres/sec) was converted to discharge, Q (mm/unit area) for each five minute interval using the following equation:-

$$Q = \frac{F.t}{AREA}$$

where t = recording period (300 secs, in this case),
AREA = area of the lysimeter (sq.m).

These were the flow values which were used in subsequent analysis.

The data collected by the Fischer-Porter recorders were converted into flows using the relationship (BSI, 1965) shown below:-

$$F = A.(h+ho)^B$$

where F = flow in litres/sec,
A,B are constants,
h = measured head (mm),
ho = zero head correction (mm) to compensate for the meniscus at the bottom of the V-notch.

The values of A, B and ho for every V-notch box used were estimated by calibration over a series of flow ranges using the flow measuring device at the Hydraulics Research Station. By plotting the natural log of the flow against that of the measured head, then the slope and intercept of the resulting straight line are measures of B and A, respectively. The value of ho is obtained by minimizing the sum of squares of the residuals. Finally, the flows in litres/sec were converted to flows in mm/unit area for each five minute period as shown previously for the tipping bucket data.

Comparisons were made between the flows as calculated from the data measured by the tipping bucket and those calculated from the data measured by the Fischer-Porter for each of the discharges. It was found that at the higher flows, agreement was very good but at lower flows the V-notch boxes overestimated the flows by substantial amounts. This was not entirely unexpected because, as the head above the V-notch falls, so surface tension effects become larger. Accordingly, a series of regressions between the flow data calculated from pairs of tipping bucket recorders and V-notch boxes was derived. These were used to infill any missing tipping bucket recorder data. Comparisons were also made of the flows measured from each of the lysimeters. Using the results of these comparisons, data for one lysimeter could be infilled using the data from the other lysimeter during the rare events when both recorders were inoperative. By these methods, continuous surface and sub-surface flow records were maintained for both lysimeters throughout the study period.

Because of uncertainties in the areas contributing to flow in the main drains, the calculation of flow per unit area was not carried out and subsequent analysis of data for the outfalls of the main drains is restricted to the time variation of nutrient concentrations.

4.5 Chemical analysis

None of the water samples collected during the course of this study was filtered and neither was a preservative added. It was felt that the changes in sample/preservative ratio brought about by introducing a quantity of preservative at the beginning of an accumulation of a composite sample would possibly be more detrimental than not adding a preservative at all. Since more composite samples were collected than any other type, it was decided to be consistent and not preserve the spot samples either.

In order to minimize algal growth, brown glass bottles were used to store all the samples collected. Also, the samples were shaded from sunlight by being stored in the instrumentation hut in the case of the lysimeters and under opaque covers in the case of the main drains. The biggest problem with sample collection was found to be freezing during the winter months and a number were lost due to breakages of the glass bottles.

The samples were collected once a week and transported to MAFF, Trawscoed. Here, they were analysed, normally within a further week, using standard procedures (DOE, 1972) for ammonium-N, nitrate-N, Kjeldahl N, phosphorus and potassium. The inorganic forms of nitrogen were individually converted to ammonia and determined colorimetrically after the addition of Nessler's reagent. Total unoxidized nitrogen was extracted by the Kjeldahl method and determined colorimetrically as above. Total nitrogen and organic nitrogen were calculated as total unoxidized-N + nitrate-N and total unoxidized-N - ammonium-N, respectively. Total inorganic phosphorus was determined colorimetrically as orthophosphate after conversion to molybdenum blue and potassium was determined by flame photometry. The limit of detection of each of the chemical analyses was 0.02 mg/l.

5. RESULTS

For the calculation of losses of applied and indigenous nutrients to have any value, either in the estimation of the effects on streamflow quality or in the economic losses of nutrients from the agricultural system, there must be confidence that all the fluxes of water and nutrients into and out of the lysimeters have been identified and either measured or estimated indirectly. In order to study the balance of these fluxes in a 'real' situation, the watertightness of a natural lysimeter cannot always be the prime concern of the experiment. Early inspection of the rainfall and flow data from the lysimeters made it clear that the balance of rainfall, flow, soil moisture change and evaporation did not match the expected evapotranspiration characteristics of the Wye catchment as a whole. In brief, the flow totals measured were considerably higher than those to be expected for the measured rainfall. Initially, this was thought to be due to a progressive reduction in the water contents of the lysimeters, but in time it became clear that the excessive flows had to be due to one or a combination of the following:-

(i) Precipitation had been measured or estimated incorrectly.
(ii) Flows had been measured incorrectly.
(iii) Inputs to the lysimeters other than rainfall had not been allowed for.

The following section describes the means by which these errors were identified and the data corrected in order to assess the true nutrient fluxes into and out of the lysimeters. Because of the attendant risks in natural lysimeters, the procedures described may be useful for future reference. As a by-product, the information produced by the correction procedures gives considerable insight into the pattern of flows on a typical mid-Wales catena. This is useful, not only for investigating nutrient movements on these slopes, but also for throwing light on the behaviour of water fluxes and stores and their effect on flow routing in upland catchments.

5.1 Rainfall and Flows

Rainfall and total flows (surface and sub-surface) from the two lysimeters are shown as monthly totals in Table 3 and, graphically, as accumulated totals in Fig.11. An inspection of these data shows clearly

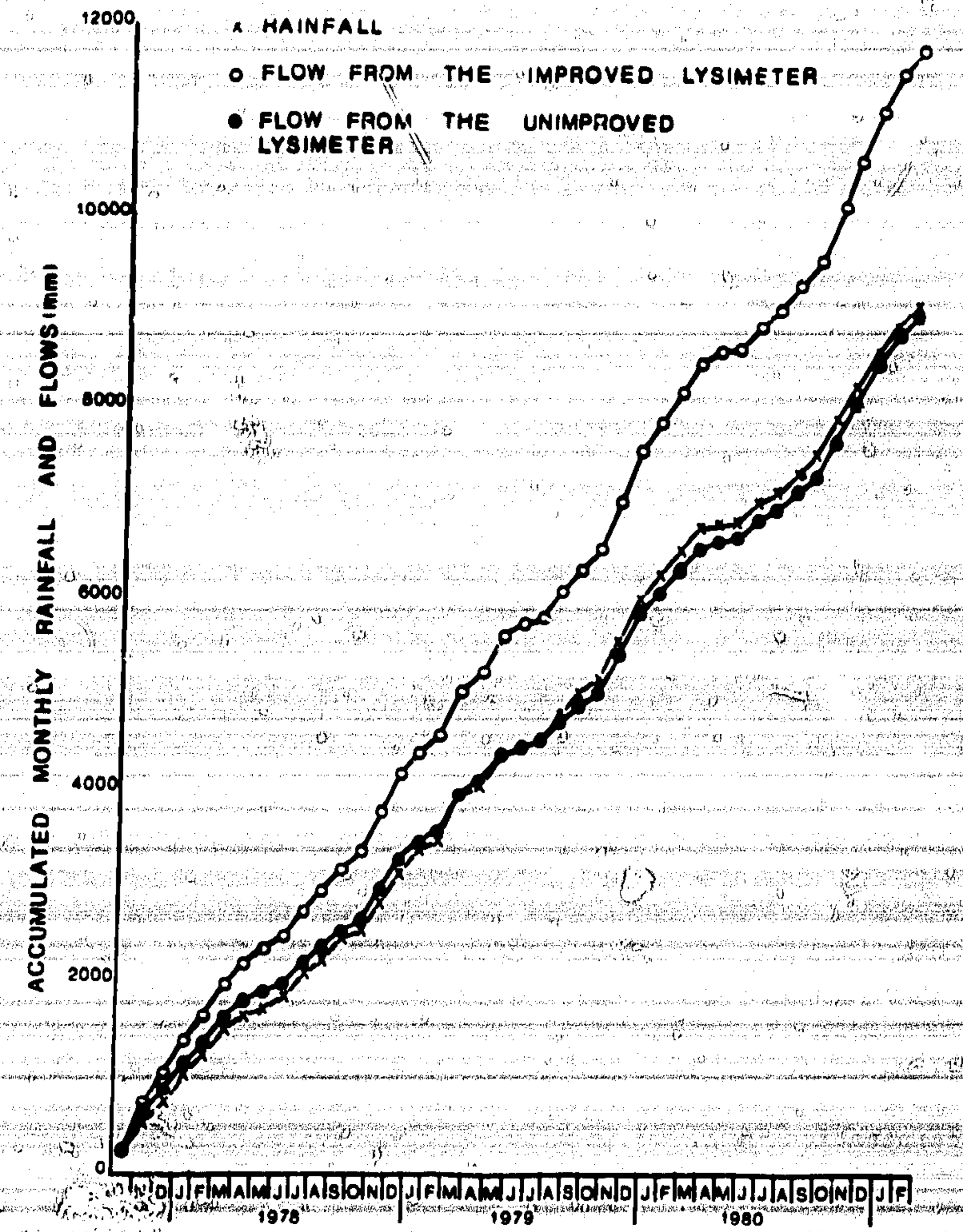


FIGURE 11 Accumulated measured monthly rainfall and total flows from the Nant Iago lysimeters

TABLE 3 MEASURED MONTHLY RAINFALL AND TOTAL FLOWS (mm) FROM THE NANT IAGO LYSIMETERS

		TOTAL FLOW	
MONTH	RAINFALL	IMPROVED LYSIMETER	UNIMPROVED LYSIMETER
1977			
OCT	191.9	263.0	225.0
NOV	333.9	489.0	423.4
DEC	211.6	301.9	242.5
1978			
JAN	297.1	334.4	267.4
FEB	191.0	264.5	207.3
MARCH	265.5	325.5	275.2
APRIL	144.1	221.3	162.7
MAY	53.7	152.0	96.5
JUNE	136.9	123.3	77.2
JULY	250.1	259.2	225.5
AUG	147.2	224.5	167.9
SEPT	235.6	224.0	164.7
OCT	74.5	134.0	116.4
NOV	293.9	403.6	336.5
DEC	295.3	401.3	316.3
1979			
JAN	250.1	224.7	164.3
FEB	97.1	131.3	132.4
MARCH	466.1	475.3	334.6
APRIL	112.9	194.3	130.9
MAY	343.3	367.5	301.9
JUNE	71.5	171.3	77.1
JULY	52.3	65.4	33.3
AUG	265.7	266.3	211.1
SEPT	204.3	274.0	151.7
OCT	152.0	224.3	143.6
NOV	402.1	502.3	403.4
DEC	429.4	524.0	421.4
1980			
JAN	256.4	324.9	203.7
FEB	252.0	300.4	226.5
MARCH	247.4	332.6	239.5
APRIL	13.2	131.9	75.5
MAY	34.7	39.3	26.2
JUNE	209.0	223.3	133.7
JULY	111.5	172.3	109.0
AUG	216.3	253.7	184.4
SEPT	179.0	233.3	173.2
OCT	353.6	597.3	365.8
NOV	335.3	477.2	397.2
DEC	759.5	532.4	406.5
1981			
JAN	296.0	320.1	310.2
FEB	133.6	223.0	173.9

that a classical hydrological balance is not being achieved for either lysimeter. When a simple water balance for the whole study period for each lysimeter is attempted:-

$$P = R + E$$

where P = total precipitation (mm),
R = total runoff (mm),
E = total evaporation (mm) as calculated for the Nant Iago sub-catchment (Roberts, 1981),

then excess outputs, equivalent to 3.0 mm per day and 1.0 mm per day for the improved and unimproved lysimeter, respectively, are evident. Although this

simple water balance makes no allowance for differences in soil moisture storage within the lysimeters at the beginning and end of the study period, such differences will be insignificant compared to the totals calculated and will not change the imbalance to any great extent except perhaps during the first year following drainage when new equilibrium soil moisture levels were being established in the lysimeters. Soil moisture readings taken on the lysimeters are not particularly useful as no readings were taken in the drain backfill, the area of greatest moisture content change.

Immediately on confirming these imbalances, the surface areas of both lysimeters were re-measured and all the flow measuring instruments re-calibrated. Although some very minor differences were detected, they were in no way large enough to explain the imbalances observed.

5.1.1. Rainfall

Rainfall inputs to the lysimeters were estimated by reference to a single weekly-read ground level raingauge (Fig.5), the totals in which were distributed in time by one or other of the two recording gauges on site, one a ground level Rimco gauge and the other a standard configuration Rimco gauge attached to the automatic weather station. Studies of rainfall variation in the Plynlimon catchments (Newson, 1976a; Clarke et al., 1973) have indicated that considerable differences in point rainfall exist over short distances particularly in areas of broken topography. During windy conditions, lee and windward residuals become obvious, often changing in sign and magnitude with different wind conditions.

The microtopography of the lysimeter site terrace is relatively flat but gross wind effects are entirely feasible as a result of the sudden break of slope to the south west of the lysimeter site caused by the progressive collapse of the terrace into the Nant Iago stream. The ground level raingauge used for precipitation input was situated nearer to this slope discontinuity than either of the lysimeters. Also, the improved lysimeter was further from the scar than the unimproved lysimeter. Using the example of a standard raingauge which, when tested in a wind tunnel (Helliwell and Green, 1974), created wind disturbance from the leading edge of the funnel so causing undercatch of rainfall in the gauge itself, it was feasible that the edge of the scar could behave in the same manner, producing low rainfall immediately behind the scar and progressively increasing rainfall to compensate up the slope away from the scar. As a result, both lysimeters could have been receiving more rainfall than the ground level gauge suggested with the improved lysimeter receiving greater amounts than the unimproved.

To test this hypothesis, a standard configuration raingauge was installed next to each lysimeter and read at the same time as the ground level gauge. Standard raingauges were used instead of ground level gauges because it was thought that they best represented the profile afforded to the rain bearing winds by the 9" high walls around the lysimeters. The total catches for the three gauges are shown in Table 4. This shows that, although the rainfall amounts in the two standard raingauges differed considerably in any one period, these differences balanced over the whole recording period. It must be concluded that the two lysimeters were each receiving approximately the same rainfall over the experimental period. This observation produces no explanation for the different flows from the two lysimeters, those from the improved being greater in volume per unit area. If anything, it was expected that flows from the improved lysimeter would be lower because of the increased transpiration from improved grassland noticed by Roberts (1983) in his study of transpiration on the Plynlimon catchments.

TABLE 4 COMPARISON OF THE GROUNDLEVEL AND STANDARD GAUGES INSTALLED AT THE LYSIMETER SITE

DATE	GROUND LEVEL	STANDARD UNIMPROVED	STANDARD IMPROVED	DATE	GROUND LEVEL	STANDARD UNIMPROVED	STANDARD IMPROVED
.03.79	START	START	START	18.01.80	20.5	23.0	22.0
[illegible].04.79	63.0	32.2	37.0	24.01.80	120.5	54.0	54.5
11.04.79	34.0	36.5	35.8	30.01.80	18.5	15.0	14.3
17.04.79	10.2	7.7	7.5	07.02.80	149.4	115.0	120.7
27.04.79	48.9	39.6	38.0	15.02.80	53.0	58.1	58.0
03.05.79	46.7	24.5	28.3	20.02.80	14.0	13.0	12.5
09.05.79	115.9	94.5	95.5	28.02.80	35.5	34.0	34.2
16.05.79	91.3	74.5	73.6	13.03.80	102.0	93.5	86.3
24.05.79	53.7	45.5	47.0	27.03.80	97.0	87.0	82.0
30.05.79	49.5	43.8	44.3	02.04.80	54.5	50.5	50.5
07.06.79	17.0	16.7	16.2	15.04.80	3.0	2.0	2.5
20.06.79	27.0	23.5	23.0	01.05.80	9.0	9.5	9.5
29.06.79	31.0	26.0	26.9	22.05.80	11.1	11.2	10.5
04.07.79	2.3	1.3	1.5	30.05.80	14.5	13.9	14.2
16.07.79	33.0	26.2	28.5	12.06.80	19.0	18.0	18.5
26.07.79	5.5	4.0	4.5	19.06.80	101.5	102.6	98.5
01.08.79	27.0	22.0	24.[illegible]	26.06.80	47.1	46.0	45.0
09.08.79	58.2	52.0	53.6	02.07.80	50.5	42.0	43.0
15.08.79	102.2	36.7	35.2	10.07.80	12.0	10.2	9.5
30.08.79	102.2	90.7	93.5	17.07.80	26.0	23.5	24.5
04.09.79	33.9	32.0	32.5	24.07.80	55.7	47.5	47.9
13.09.79	9.3	8.5	9.5	31.07.80	17.2	15.8	16.2
19.09.79	53.2	42.3	40.0	05.08.80	50.0	41.5	42.8
01.10.79	104.[illegible]	96.0	93.5	15.08.80	105.5	104.7	92.0
04.10.79	17.[illegible]	17.4	17.0	20.08.80	15.0	15.0	16.0
11.10.79	30.5	30.5	30.[illegible]	27.08.80	23.4	20.0	20.0
19.10.79	34.0	32.0	31.0	10.09.80	66.5	61.3	62.7
25.10.79	29.5	27.5	26.9	24.09.80	110.5	101.0	97.0
02.11.79	40.7	39.2	37.3	08.10.80	170.5	123.5	136.0
08.11.79	194.5	149.5	157.5	23.10.80	93.5	83.0	84.0
15.11.79	75.0	70.5	70.0	30.10.80	114.5	95.5	89.0
23.11.79	37.2	31.5	29.2	13.11.80	21.5	22.0	22.0
29.11.79	78.0	64.2	60.5	26.11.80	298.5		
05.12.79	133.6	104.3	[illegible]	09.12.80	54.[illegible]	45.0	47.0
13.12.79	126.5	103.0	104.5				
20.12.79	71.5	63.0	64.7				
03.01.80	133.7	82.5	109.5	TOTAL	3991.5	3329.2	3339.6
09.01.80	47.5	38.1	36.0	%	100	83.4	83.7

As regards the proposition that the ground level raingauge underestimates the true precipitation to the lysimeters, the investigation described here proved inconclusive. Both standard raingauges undercatch the ground level gauge by approximately 16%. However, in exposed conditions, especially when open to the predominantly southwesterly airstream, it is common for standard gauges to undercatch by as much as 30% (Newson and Harrison, 1978b; Rodda, 1967). It is possible therefore that there could be a reduction in catch in the ground level raingauge relative to the true rain at the lysimeter site. However, this hypothesis is not supported by a regression model of rainfall variation with altitude for the Wye catchment or by subcatchment estimates of rainfall using ground level gauges in the Nant Iago (Table 5). For the whole period of the study, the catch of the ground level gauge on the lysimeter site at 400 metres altitude is almost identical to the subcatchment estimate from the ground level raingauges in the Nant Iago (mean altitude of 480 metres, areally weighted), using a Thiessen polygon routine. If anything, the altitudinal regression for the whole of the Wye suggests slightly less rainfall (97.5%) at 400 metres altitude than the lysimeter ground level gauge.

TABLE 5 RAINFALL COMPARISONS FOR THE NANT IAGO LYSIMETER SITE

* snow months

MONTH	LYSIMETER SITE GROUND LEVEL	SUBCATCHMENT ESTIMATES: THIESSEN ESTIMATE	SUBCATCHMENT ESTIMATES: ALTITUDE REGRESSION	SNOW ESTIMATES WINTER MONTHS
1977				
OCT	171.5	231.3	200.1	257.5
NOV	335.9	375.9	345.3	415.6
DEC	211.5	249.7	229.2	231.1
TOTAL 77	742.3	854.4	773.6	904.2
1978				
JAN	297.1	256.2	295.4	242.4
FEB	191.0	173.3	158.7	153.9
MARCH	265.5	250.4	255.5	258.5
APRIL	142.1	133.3	130.5	122.6
MAY	63.7	58.0	55.4	
JUNE	139.5	139.2	130.3	
JULY	250.1	254.2	238.5	
AUG	140.2	151.1	135.4	
SEPT	235.9	213.2	228.1	
OCT	74.5	73.1	68.8	68.8
NOV	293.4	347.7	312.1	307.2
DEC	292.6	313.7	305.9	274.9*
TOTAL 78	2391.3	2358.3	2305.3	
1979				
JAN	250.1	224.3	373.2	642.2*
FEB	97.1	83.5		
MARCH	499.1	400.2		
APRIL	112.4	107.7	100.7	107.5
MAY	342.1	351.9	328.1	
JUNE	71.5	69.4	76.1	
JULY	62.5	64.3	64.3	
AUG	269.7	259.3	256.2	
SEPT	204.3	191.9	135.4	
OCT	152.0	160.4	149.9	160.4
NOV	402.1	417.3	367.5	383.1
DEC	429.4	452.5	361.2	445.5
TOTAL 79	2903.[illegible]	2782.9	2779.6	
1980				
JAN	259.4	202.2	274.1	193.3*
FEB	252.0	247.0	221.5	240.9
MARCH	247.4	250.7	262.4	250.5*
APRIL	13.2	13.2	19.2	15.7
MAY	34.7	52.5	63.0	
JUNE	239.[illegible]	[illegible]	232.3	
JULY	111.5	[illegible]	110.4	
AUG	219.[illegible]	[illegible]	195.1	
SEPT	179.0	[illegible]	159.2	
OCT	352.9	[illegible]	304.3	317.6
NOV	339.3	[illegible]	303.0	337.9
DEC	359.5	[illegible]	353.3	306.8
TOTAL 80	2559.4	2583.9	2533.3	
1981				
JAN	249.0	279.5	266.7	222.9
FEB	135.9	193.4	150.5	163.9*
TOTAL 81	424.9	477.9	447.2	
PERIOD TOTAL	9071.4	9097.9	8845.0	
AS % OF G.L.	100	100	97.5	

For the lysimeters to be receiving more precipitation than the ground level gauge suggests, therefore, that the upper part of the site must be receiving high rainfall for its altitude. This is feasible if the lysimeters are in an area of fallout and the ground level gauge in an area of diminished rainfall due to the wind effects of the scar, the balance between the two giving the correct rainfall for the altitude of the site. However, there is no way of quantifying this. In the absence of any alternative, it must be assumed that the ground level gauge or Nant Iago Thiessen estimate is correct and that the errors in the water balance lie elsewhere.

5.1.2 Flow

Having eliminated rainfall and measured flow as the source of the problem it was concluded that the imbalances were due to leakages into the lysimeters, the leakage being greater into the lysimeter on the improved part of the site.

Few occurrences of surface flow were observed in either lysimeter and the totals involved were very small compared with the sub-surface flows and their effects on the water balances were insignificant.

The possibility of leakages through the plastic sheets forming the boundaries of the lysimeters was investigated by the use of Rodamine dye. This was introduced in the backfill both inside and outside the plastic sheeting surrounding the lysimeters (Fig.6) and at various depths at points upslope of the lysimeters (Fig.5). The purpose of this was to:-

a) Determine the efficiency of the tile drains within the backfill in removing water from the vicinity of the boundary of the lysimeters.

b) Test the seal afforded by the plastic sheeting.

c) Determine whether Rodamine dye introduced upslope of the lysimeters could be detected in the discharges from the lysimeters.

The results obtained from sampling and analysing the discharges from the lysimeters and the main drains showed conclusively that:-

a) The Rodamine dye introduced into the backfill inside the lysimeters was quickly observed in the sub-surface discharge from the lysimeters. Similarly, the dye introduced into the backfill surrounding the lysimeters was quickly observed in the main drains. This shows that the tile drains both inside and outside the lysimeters were very efficient in removing water from the vicinity of the plastic sheeting thus preventing a hydraulic gradient from forming at the boundaries of the lysimeters.

b) No traces of the dye introduced into the backfill inside the lysimeters were found in the main drains. Similarly, no traces of the dye introduced into the backfill surrounding the lysimeters were found in the discharges of the lysimeters. This suggests that no leakage was occurring through the seal afforded by the plastic sheet.

c) No traces of the dye introduced at points upslope of the lysimeters were found in the discharges of the lysimeters. Although this could possibly be due to the absorbtion of the Rodamine by the peat particles or possibly a reflection of the residence time of water in peat, this and the evidence above does suggest that the excess flows from the

lysimeters were as a result of seepage of water upwards through the boulderclay layer as depicted in Fig.12.

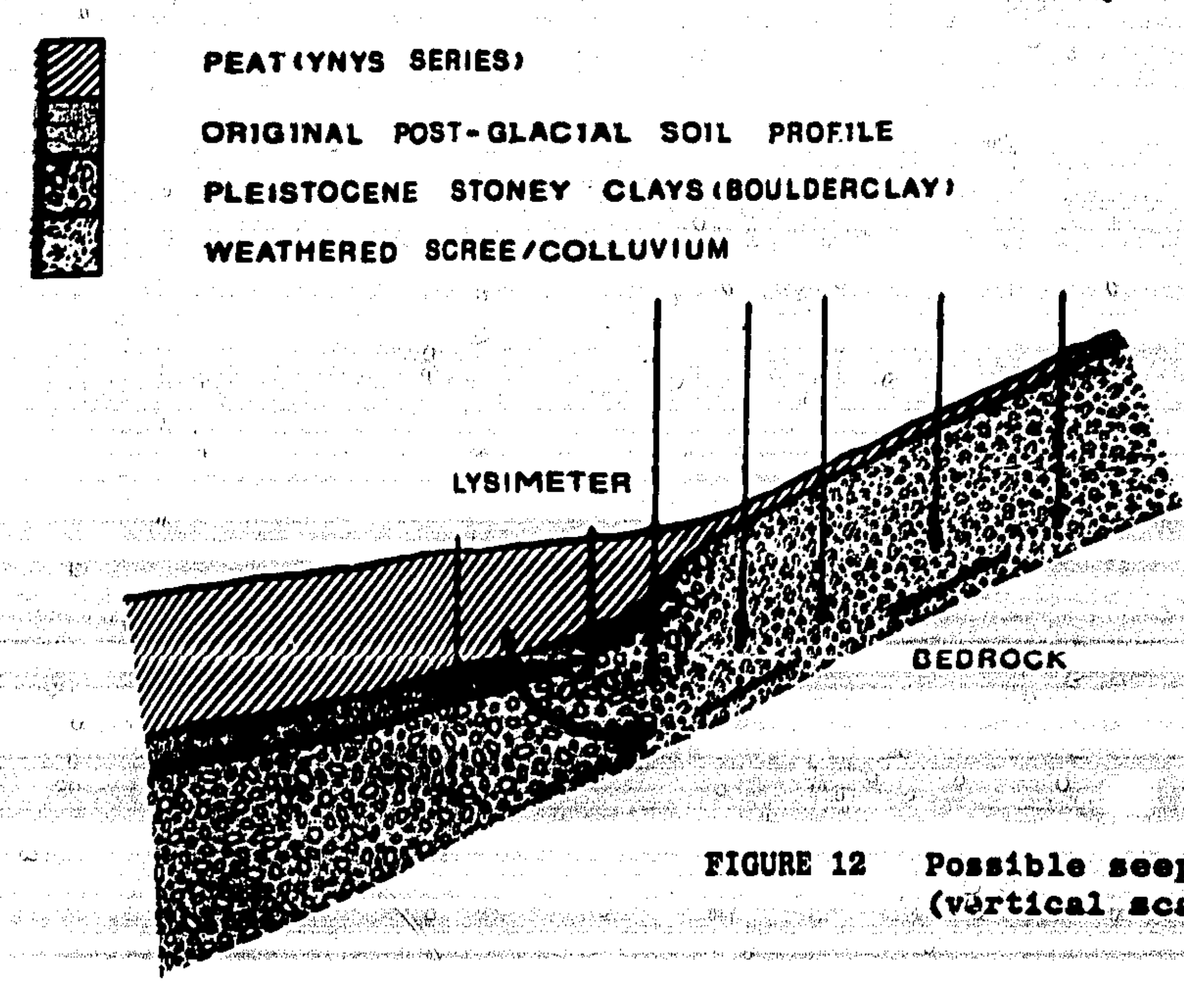


FIGURE 12 Possible seepage route (vertical scale exaggerated)

Having established the probable cause of the excess flows from the lysimeters, the sub-surface flows were analysed to see whether the contributions of the leaks could be identified so that a retrospective correction could be made to the measured flows. In particular, it was hoped that the variations in the rate of leakage over the flow hydrographs could be established and that some relationship between the measured flow rates and leakage rates identified.

Basically, this was done using a hydrograph separation technique utilizing additional information from two further studies. A detailed description is given in Appendix I.

The basis of the corrections applied to the measured flows from the two lysimeters are the curves shown in Fig.13a and 13b. However, during the latter stages of the study, it became necessary to apply additional minor corrections to the sub-surface and surface flows from the improved lysimeter during particularly wet periods. This was as a result of cracks in the above-ground portions of the plastic sheets due to the action of cattle introduced to crop the improved pasture.

When these various corrections are applied to the measured flows and monthly "true" flows calculated, the results shown in Table 6 and, as accumulated totals, in Fig.14 are obtained.

If annual water uses are calculated as the differences between rainfall and runoff totals, then the following values are obtained:

	1978	1979	1980
Improved lysimeter	172	404	74
Unimproved lysimeter	125	451	149

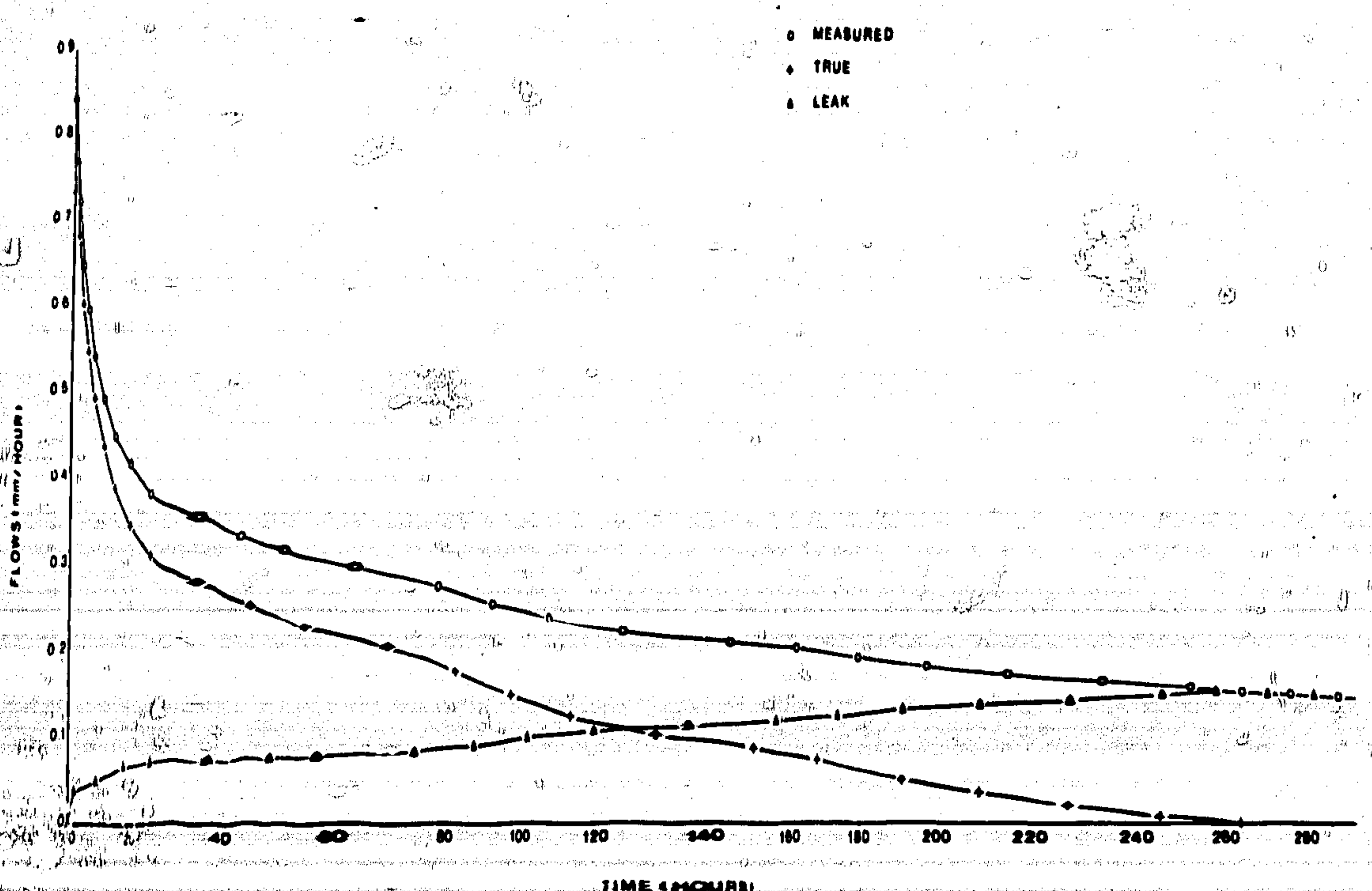


FIGURE 13a Flow hydrographs for the improved lysimeter

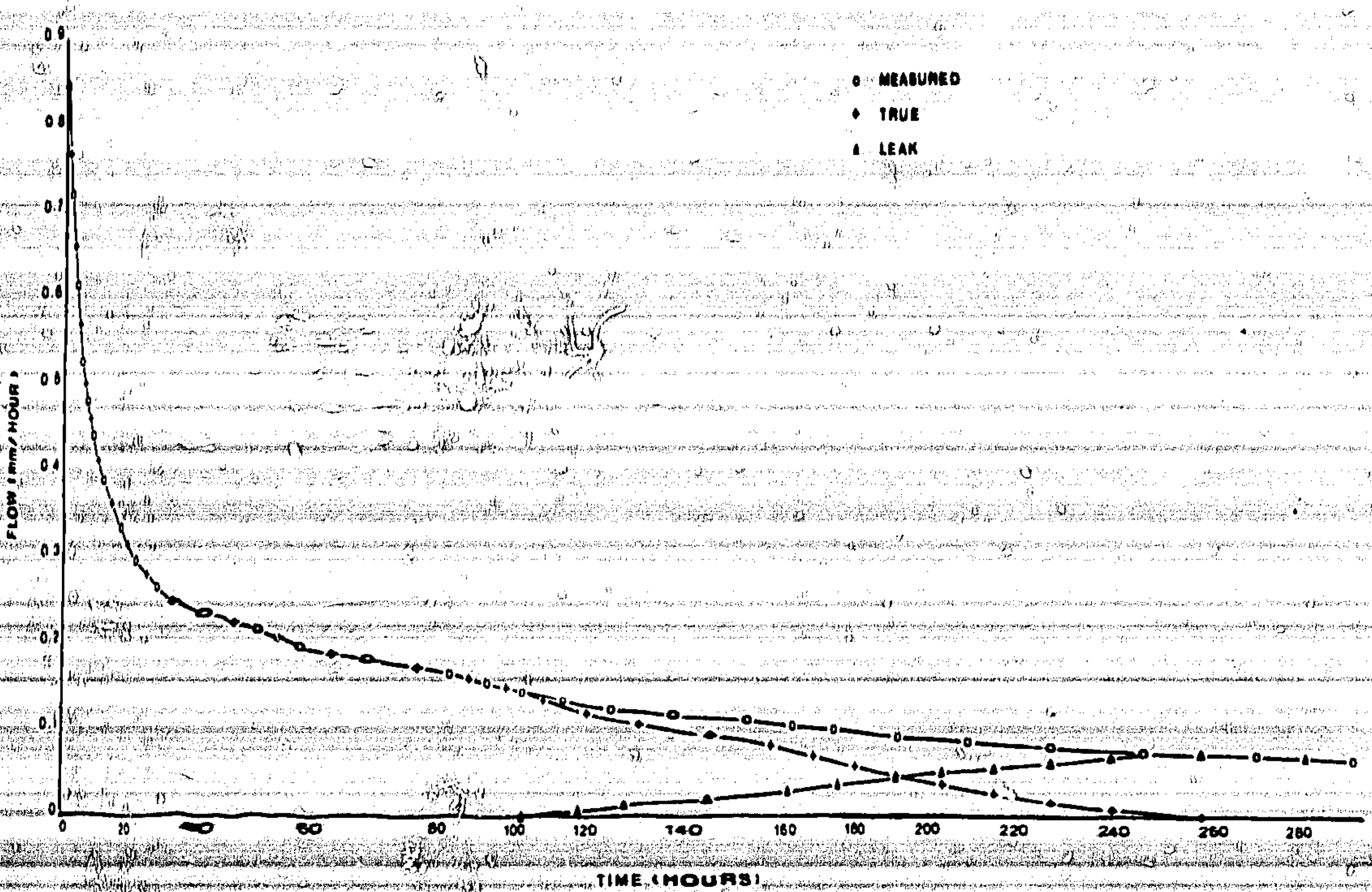


FIGURE 13b Flow hydrographs for the unimproved lysimeter

TABLE 6 MONTHLY RAINFALL (mm) and corrected total flows (mm) FROM THE NANT IAGO LYSIMETERS

MONTH	RAINFALL (MM)	TOTAL FLOWS (MM)	
		IMPROVED LYSIMETER	UNIMPROVED LYSIMETER
1977			
OCT	191.8	194.7	217.9
NOV	338.9	445.7	423.2
DEC	211.6	237.8	234.8
1978			
JAN	297.1	282.3	267.2
FEB	191.0	194.7	195.8
MARCH	265.5	265.3	274.4
APRIL	144.1	145.7	156.7
MAY	63.7	50.3	77.9
JUNE	136.8	39.7	46.7
JULY	250.1	178.9	192.7
AUG	140.2	147.5	162.7
SEPT	235.6	131.8	138.8
OCT	74.5	100.6	108.4
NOV	293.9	346.4	332.2
DEC	298.8	326.3	313.2
TOTAL	2391.3	2219.5	2266.7
1979			
JAN	250.1	131.3	149.1
FEB	97.1	103.2	112.7
MARCH	466.1	405.5	384.4
APRIL	112.9	120.6	127.7
MAY	348.8	304.2	301.1
JUNE	71.5	32.6	49.1
JULY	62.3	0.0	0.0
AUG	266.7	199.2	197.3
SEPT	204.8	139.6	142.6
OCT	152.0	155.9	146.8
NOV	402.1	444.2	408.4
DEC	429.4	423.7	393.4
TOTAL	2863.8	2460.0	2412.6
1980			
JAN	256.4	194.7	160.7
FEB	252.0	246.3	222.3
MARCH	247.4	239.3	236.4
APRIL	18.2	38.9	48.1
MAY	34.7	0.1	3.0
JUNE	209.0	149.3	174.1
JULY	111.5	78.7	85.6
AUG	216.8	169.9	174.4
SEPT	179.0	162.2	165.6
OCT	358.6	397.1	365.8
NOV	336.3	404.0	396.8
DEC	369.5	435.4	406.7
TOTAL	2589.4	2515.9	2440.1
1981			
JAN	296.0	324.6	309.6
FEB	139.6	150.9	166.3
ACCUMULATED TOTALS	9071.4	8550.1	8471.2

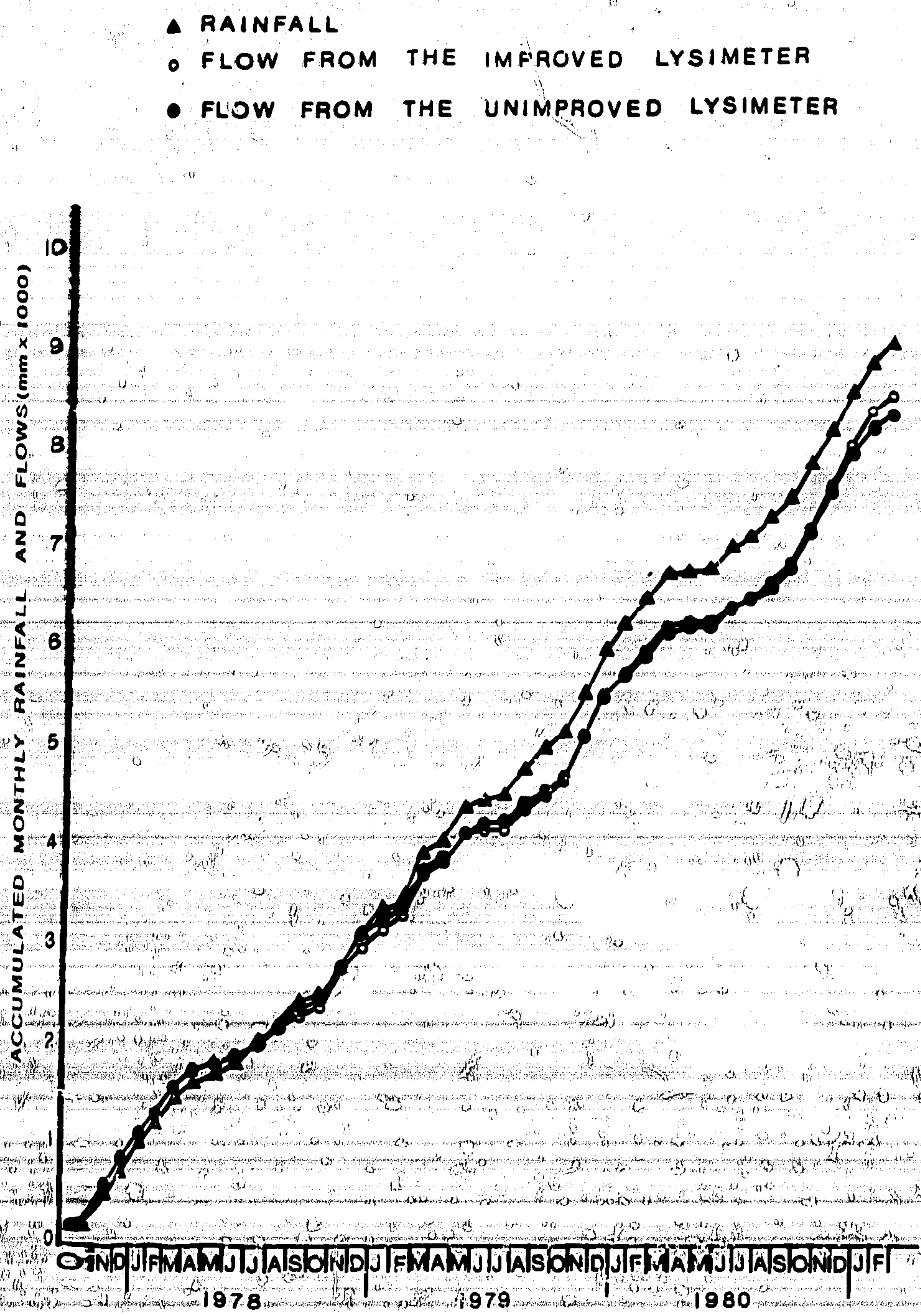


FIGURE 14 Accumulated monthly rainfall and corrected total flows from the Nant Iago lysimeters

The estimated water use of the Wye catchment and the calculated Penman evapotranspiration totals for the same three years are shown below.

	1978	1979	1980
WYE WATER USE	341	367	300
PENMAN ET	422	474	474

Although the differences between the water use of the two lysimeters and that of the Wye catchment appear large especially during 1978 and 1980, as a percentage of total flow the largest discrepency is only of the order of 13%. The above water balances for the lysimeters assume that changes in soil moisture over the balance period are negligible. Although this a reasonable assumption over an annual basis, it may be instructive to examine the effect of short-term changes in soil moisture on these balances. This is done in Appendix II together with a discussion of the implications of upland drainage for flow routing and water resources.

5.2 Nutrient concentrations in the rainfall and in the flows from the lysimeters and main drains

The results of the chemical analyses carried out on the rainfall samples are shown in Fig.15 together with the mean weekly rainfall totals. For most of the periods sampled, phosphorus concentrations were below the limit of detection whilst total nitrogen and potassium were in the range 0-1.0mg/ℓ. Occasionally, high concentrations of potassium and, particularly, nitrogen were found, generally during hot, dry periods. Similar high values in summer rainfall have been found by other workers (Angstrom and Hogberg, 1952; Eriksson, 1952). However, a comparison of the chemical analyses of rainfall samples obtained at the lysimeter site with those collected from a nearby site in the forested catchment during 1980 suggests that some of the extreme high values are probably due to contamination by windborne organic matter (Roberts et al., 1983). It is likely, therefore, that an overestimation of rainfall nutrient input to the lysimeters may have been made during some periods.

A time series presentation of the concentration of some of the nutrients found in the sub-surface discharges of the lysimeters is given in Fig.16. In order that trends and differences can best be illustrated, the data are shown as monthly means. Monthly rainfall totals are shown for comparison. It is evident from the data from that the nutrient concentrations are being affected, to some degree, in two ways. In the first place, the concentrations of some of the nutrients in the sub-surface discharges of both lysimeters are higher than would be expected from the results from th[illegible]all (Fig.15) and from the routine sampling of the Wye streamflow (Ro[illegible] et al. 1983). This effect is evident before the implementation of the grassland improvement in the spring 1978 and seems to decrease progressively throughout the study period. This, presumably, is an after effect of the construction of the lysimeters and is due to the release and subsequent leaching of certain nutrients within the backfill inside the boundaries of the lysimeters. Superimposed on this effect, the concentrations of some of the nutrients in the discharge of the improved lysimeter increased, relative to the unimproved lysimeter, following the grassland improvement.

The most affected nutrient is nitrate-N which exhibits, in particular, very high concentrations (up to 16 mg/ℓ) in samples collected in November 1977, at the beginning of the sampling period. Generally, the concentrations in the improved lysimeter were higher than in the unimproved but both had reduced to similar values of approximately 2.0 mg/ℓ at the end

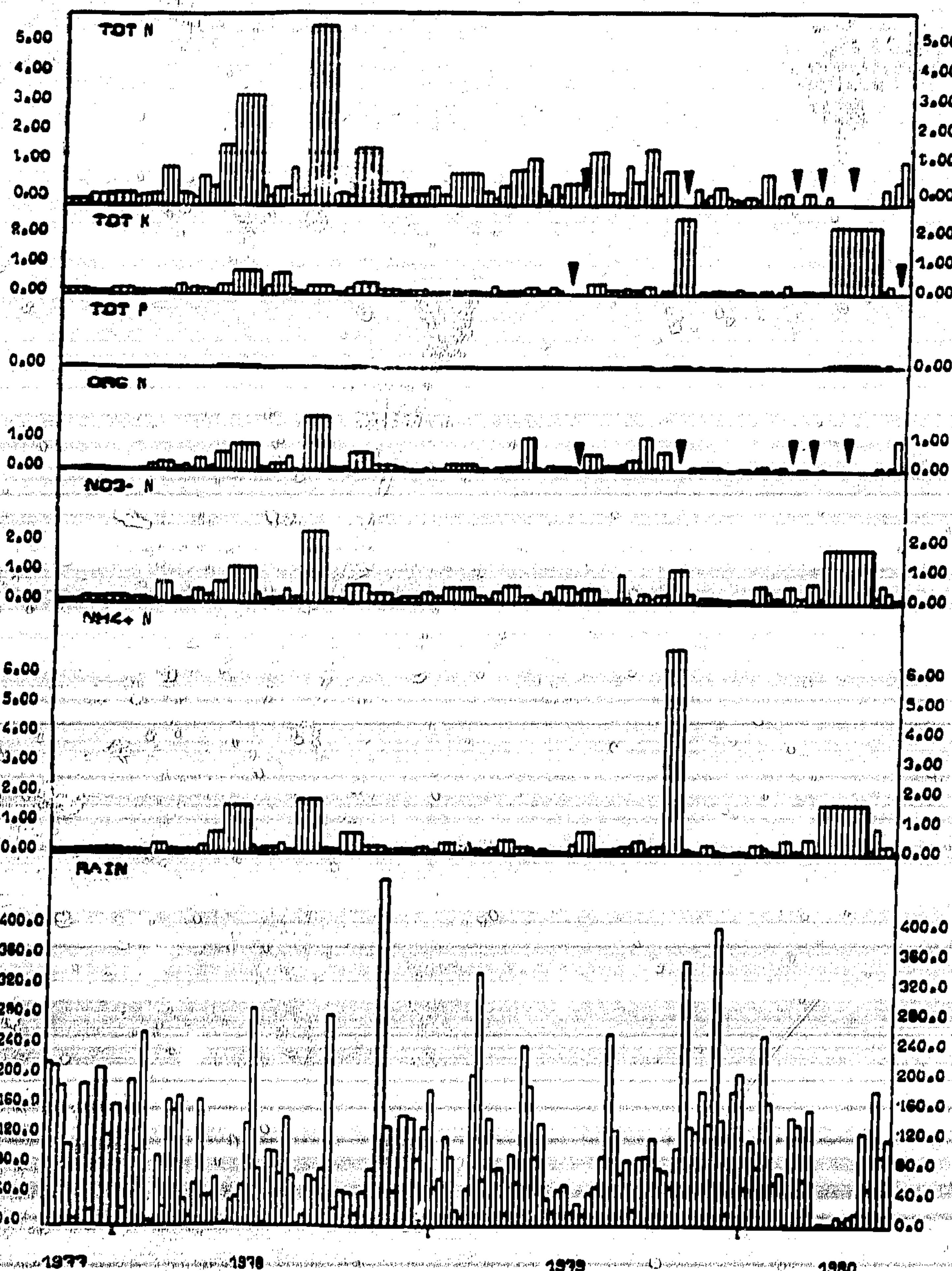


FIGURE 15 Rainfall totals (mm) and nutrient concentrations (mg/l)

▼ no data

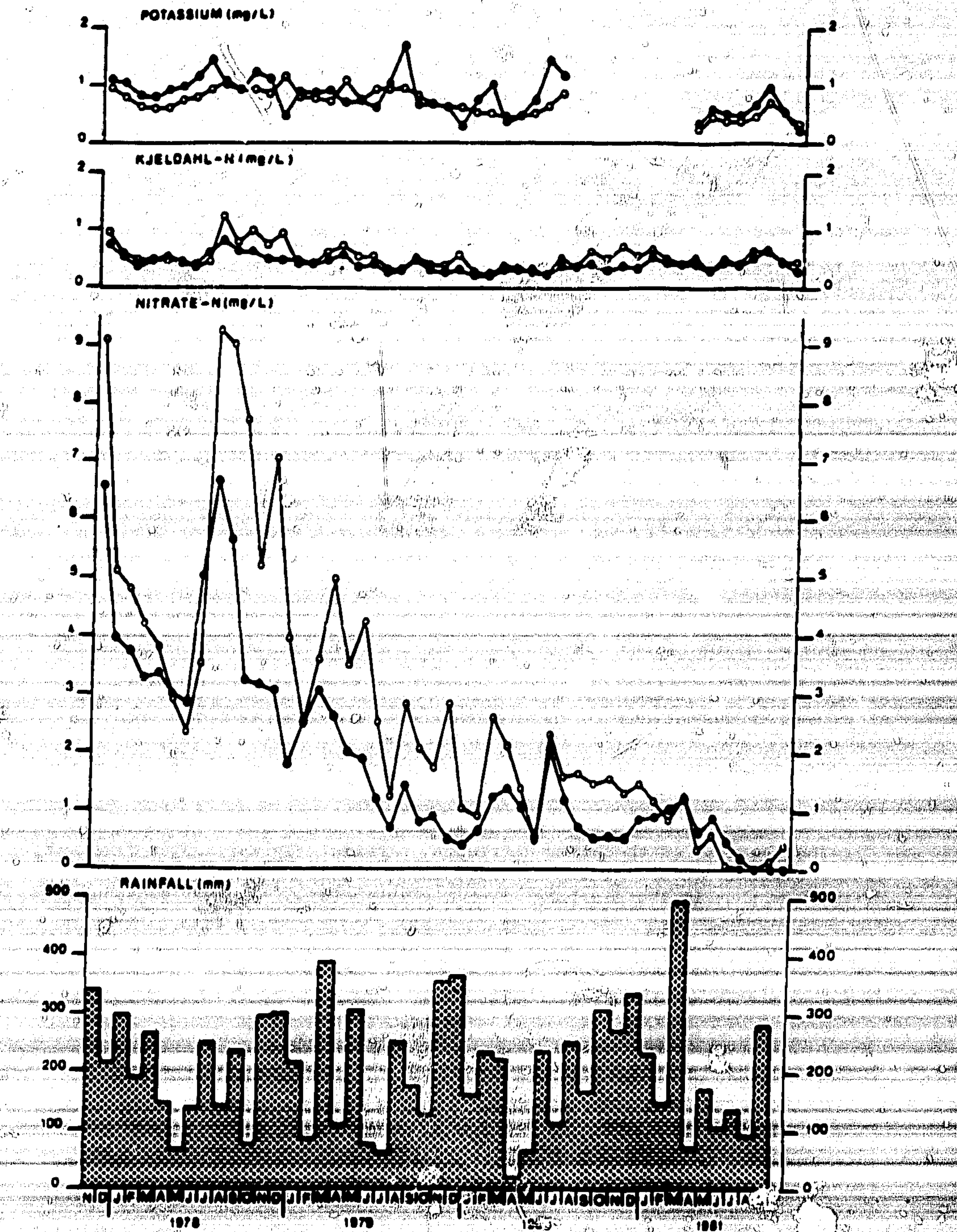


FIGURE 16 Monthly rainfall totals and mean nutrient concentrations in the sub-surface discharges of the Nant Iago lysimeters
o improved lysimeter ● unimproved lysimeter

of April 1978 immediately prior to the grassland improvement. The effects of the improvement became evident in July 1978. Although the concentrations in both lysimeters increased a great deal at this time, the concentrations in the improved lysimeter became substantially higher than those in the unimproved. This remained the case until the end of the study period when the concentrations in both lysimeters decreased to "normal" levels of between 0 and 1.0 mg/ℓ. Superimposed on the decreasing trend in concentrations in both lysimeters from the peak values in July 1978 were smaller peaks, normally during spring and autumn, as more nitrate-N became available for leaching.

In contrast, the concentrations of the other nutrients in the discharges of the two lysimeters were similar with the exception of Kjeldahl N (mainly organic) where enhanced concentrations were found in the improved lysimeter during the autumn months of 1978 and 1980. Potassium concentrations in both lysimeters were slightly higher than expected (Roberts et al., 1983) throughout the study period again, presumably, due to the release and subsequent leaching of potassium ions in the backfill surrounding the lysimeters. No enhancement of potassium concentrations following the grassland improvement was evident. Phosphorus and ammonium-N were generally below the level of detection.

Mean monthly nutrient concentrations in the flows of the two main drains are shown in Fig.17. A direct comparison of the results obtained from the two drains is difficult because not only will flow contributions from upslope of the drainage schemes be included, but also the sampling frequency of the improved drain was much more intense than the unimproved. Both plots, however, show generally similar results to those found in the sub-surface flows of the lysimeters. Nutrient concentration enhancement due to leaching of the backfill in the drains is less evident whilst the effect of the improvement is much more pronounced. In particular, the nitrate-N concentrations in the improved plot are several orders of magnitude higher than those in the unimproved plot during the summer and autumn 1978. There were also smaller increases in nitrate-N concentrations in the improved plot during the springs of 1979 and 1981 and the autumn of 1980.

The reaction of the other nutrients, particularly Kjeldahl N (again mainly organic), to the grassland improvement is also more pronounced in the drain flow than in the discharge from the lysimeter. Although phosphorus and ammonium-N were generally below the detection limit, there is some evidence of enhanced concentrations of the latter in the drain flow from the improved plot during the autumn of 1978 and 1979. Similarly, potassium concentrations were generally higher following the improvement.

Surface runoff from the lysimeters was rare, occurring only during the wet winter months. The nutrient concentrations in the samples obtained were in the range: NH_4^+-N 0-3.5 mg/ℓ, NO_3^-N 0-5.2 mg/ℓ, ORGANIC N 0-2.3 mg/ℓ, P 0-1.4 mg/ℓ, K 0-3.7 mg/ℓ. Nearly all of the higher concentrations were found in samples taken from the improved lysimeter following the improvement. As these higher values were in excess of the concentrations found in the rainfall, it is clear that some of the applied nutrients were lost by being dissolved in surface runoff. However, because of the small amount of surface runoff that occured, the losses in terms of kg/ha were negligible.

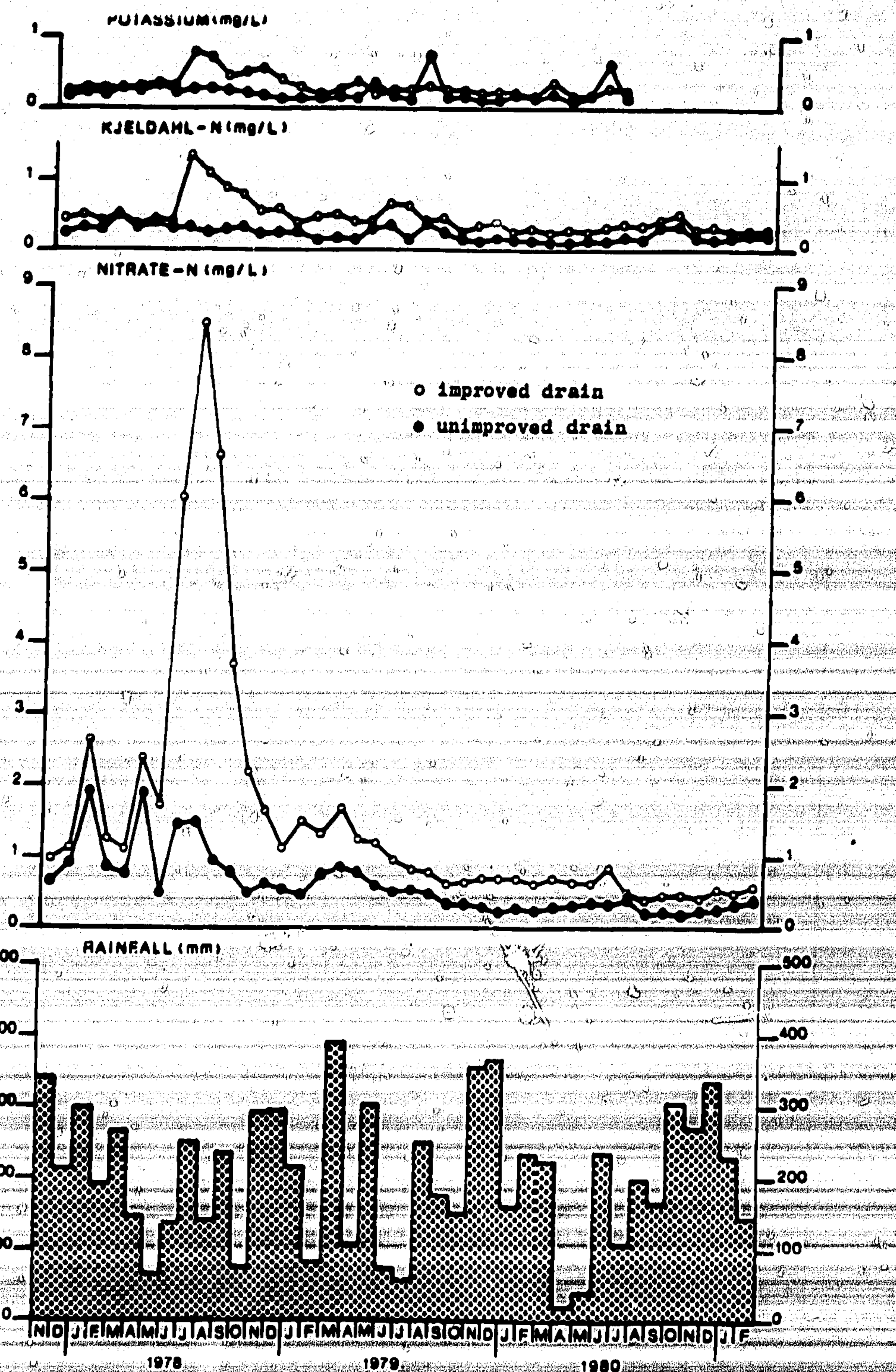


FIGURE 17 Monthly rainfall totals and mean nutrient concentrations in drain discharges at the Nant Iago lysimeter site

5.3 Nutrient loadings in rainfall and drainage

An inspection of Fig.16 shows that the nutrient, in particular nitrate-N, concentrations in the sub-surface discharges of both lysimeters were much higher than those in the incoming rainfall (Fig.15) and those found in the Wye streamflow (Roberts et al., 1983). This indicates that nutrient enhancement was occurring within both lysimeters. Before comparing nutrient losses from the two lysimeters, it is necessary to quantify and correct for the losses occurring as a result of the leakages. To do this, the mechanism of the enhancement must be investigated so that a realistic correction be made.

Some indications of the chemical nature of the leaks may be obtained by comparing nutrient concentrations in rainfall and in the sub-surface discharges during those periods when the calculated leakages into the lysimeters suggest that the measured flow was totally sustained by the leak. Unfortunately these occurrences are rare particularly in the case of the unimproved lysimeter. However, these comparisons are shown in Fig.18 for total nitrogen and potassium. Nitrogen species are not considered separately because of possible transformations between rainfall and flow.

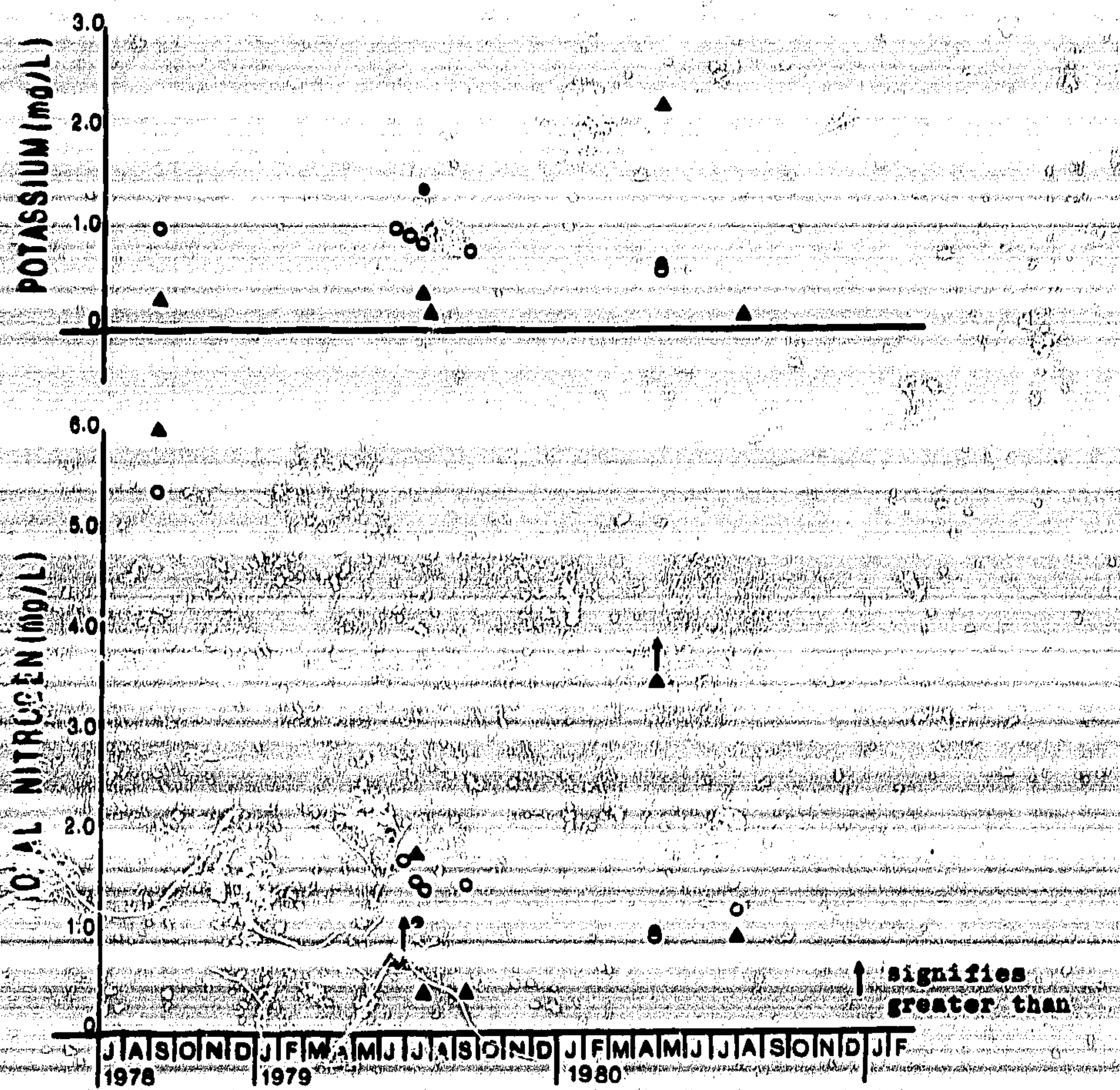


FIGURE 18 Total nitrogen and potassium concentrations in rainfall (▲) and improved (o) and unimproved lysimeters (•) during periods of no true flow

Also phosphorus concentrations in both rainfall and flows were so often below the limit of detection that a valid comparison could not be done. The periods when flow was totally sustained by leakage invariably coincided with periods of low rainfall when nutrient concentrations in rainfall were at their highest and, because of contamination by wind borne organic debris, likely to be overestimated. However, the data shown in Fig.18 does suggest that, in the majority of instances, the concentrations in the measured flows were higher than those in the rainfall.

Some further indications may be obtained by comparing nutrient concentrations in rainfall, average profile soil moisture and sub-surface discharges from the two lysimeters. This is done in Fig.19a and 19b.

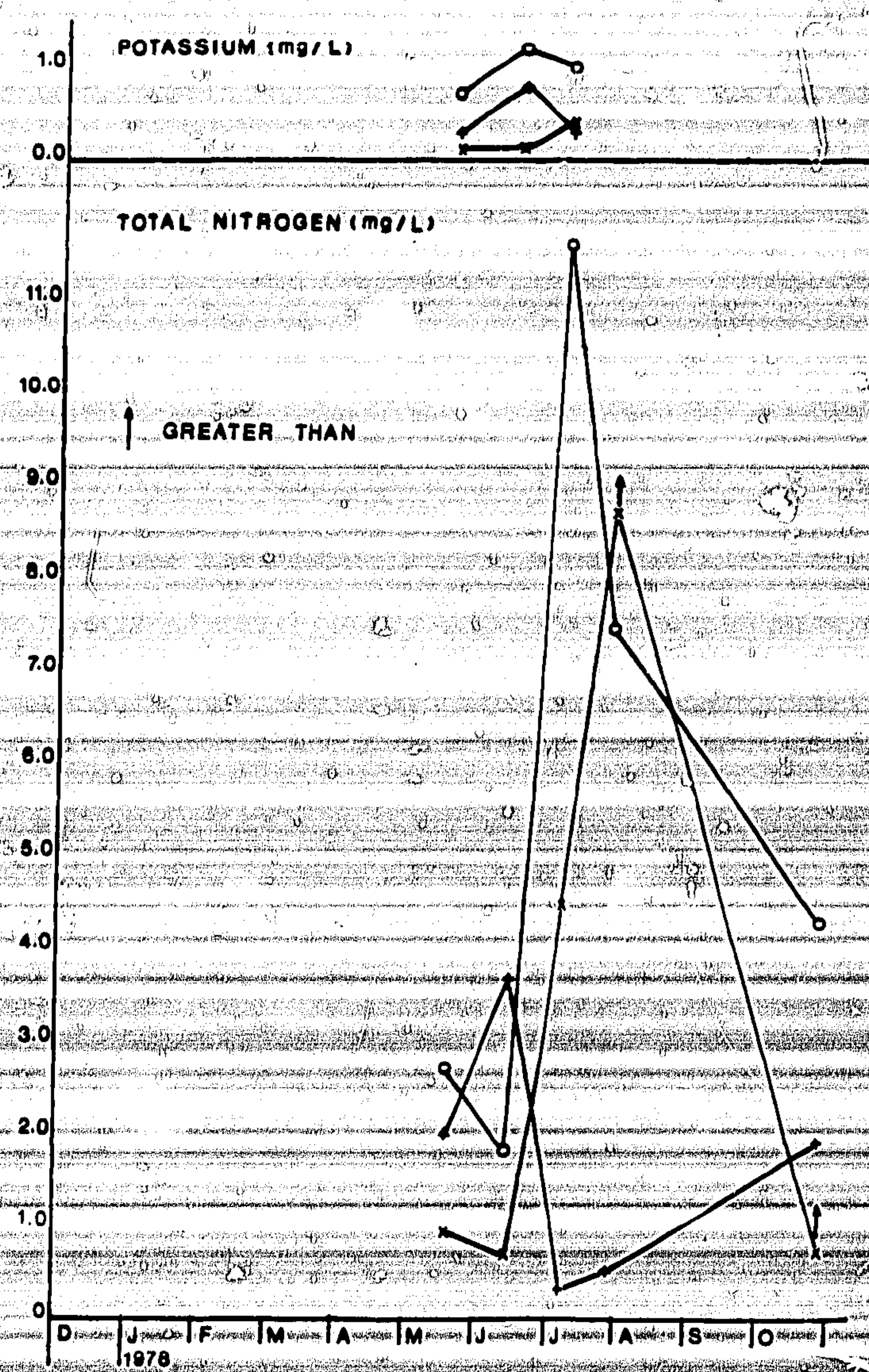


FIGURE 19a Total nitrogen and potassium concentrations in rainfall (+), average profile soil moisture (x) and subsurface discharge (o) from the improved lysimeter

Although the data available are very limited, it is obvious that the concentrations of both nitrogen and potassium are higher in the sub-surface discharges than in either the rainfall or soil moisture samples. Whilst nitrogen concentrations are generally higher in the soil moisture than in the rainfall during the summer months, the data in Fig.19a and 19b do suggest that the main nutrient concentration enhancement occurs not within the lysimeter block but in the downslope backfill immediately prior to sampling.

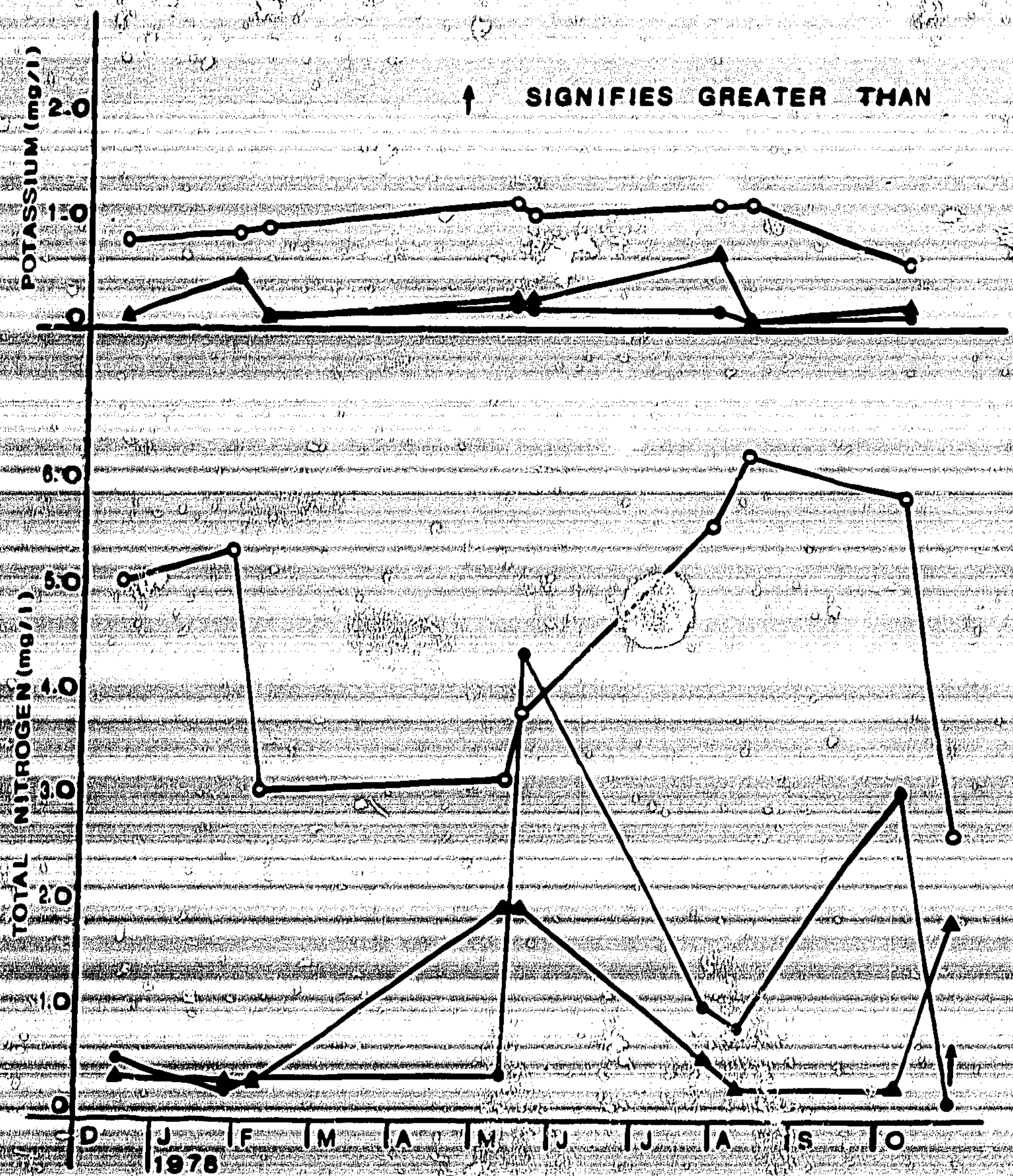


FIGURE 19b Total nitrogen and potassium concentrations in rainfall (▲) soil moisture (●) and subsurface discharge (o) from the unimproved lysimeter

If the trends observed in the limited quantity of available data are consistent and the supposition concerning nutrient concentration enhancement is correct, then the net effect of the leakage is to reduce the amount of available nutrients within the lysimeters by an amount $L(C_{MF}-C_L)$ where:-

L = amount of leakage
C_{MF} = nutrient concentration in the measured sub-surface flow
C_L = nutrient concentration in the leakage

and this must be taken into account when estimating nutrient losses.

The "true" nutrient loss can then be expressed as:-

$$TF.C_{TF} = MF.C_{MF} - L.(C_{MF} - C_L)$$

where TF = "true" flow
MF = measured flow
L = leakage
C_{TF} = nutrient concentration in "true" flow
C_{MF} = nutrient concentration in measured flow
C_L = nutrient concentration in leakage

Since MF and C_{MF} are measured and L estimated as described in Appendix I "true" nutrient loss can be calculated using a suitable value of C_L.

Routine sampling of the water within the clay matrix beneath the lysimeter was not done because of the difficulties involved in obtaining samples. In the absence of such data, the most appropriate substitutes are the concentrations obtained in the routine sampling of the streamflow in the Wye catchment, (Roberts et al., 1983). This is partly justified by the results obtained from the one water sample that was obtained from the clay matrix on the 12th December 1980. This gave NH_4N 0.01 mg/ℓ, NO_3N 0.46 mg/ℓ and ORGANIC N 0.24 mg/ℓ, concentrations not dissimilar to those obtained during winter months in the Wye streamflow. The nutrient concentrations in the leak are therefore assumed to be equal to those in the Wye streamflow and it is these values that are used when calculating the "true" nutrient losses. The correction applied to the nutrient losses as a result of the concentration enhancement of the leak, described above, is very small compared with correcting for the quantity of leakage.

Estimated monthly nutrient gains in rainfall and "true" losses in total flow for the two lysimeters are given in Tables 7a and b and, for nitrogen and potassium, as accumulated totals in Figs.20a and 20b. Nitrogen inputs by fixation and losses by denitrification have been ignored because, for the former, clover establishment was very poor and fixation rates likely to be very low whilst denitrification rates for upland areas are also generally regarded as being very low (Batey, 1982), especially after drainage.

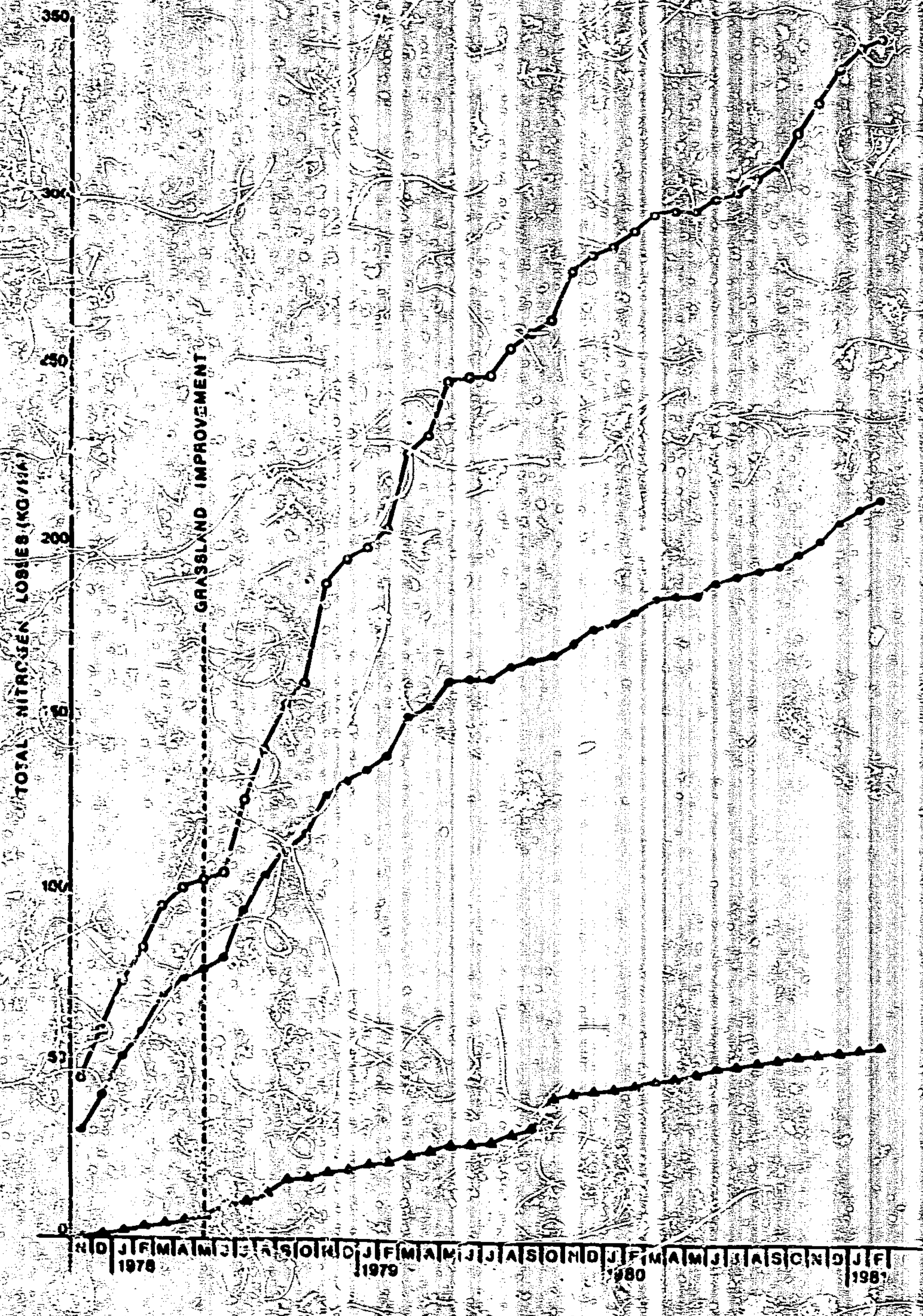


FIGURE 20a Accumulated monthly total nitrogen inputs in rainfall (▲) and outputs in flows from the improved (o) and unimproved (●) lysimeters

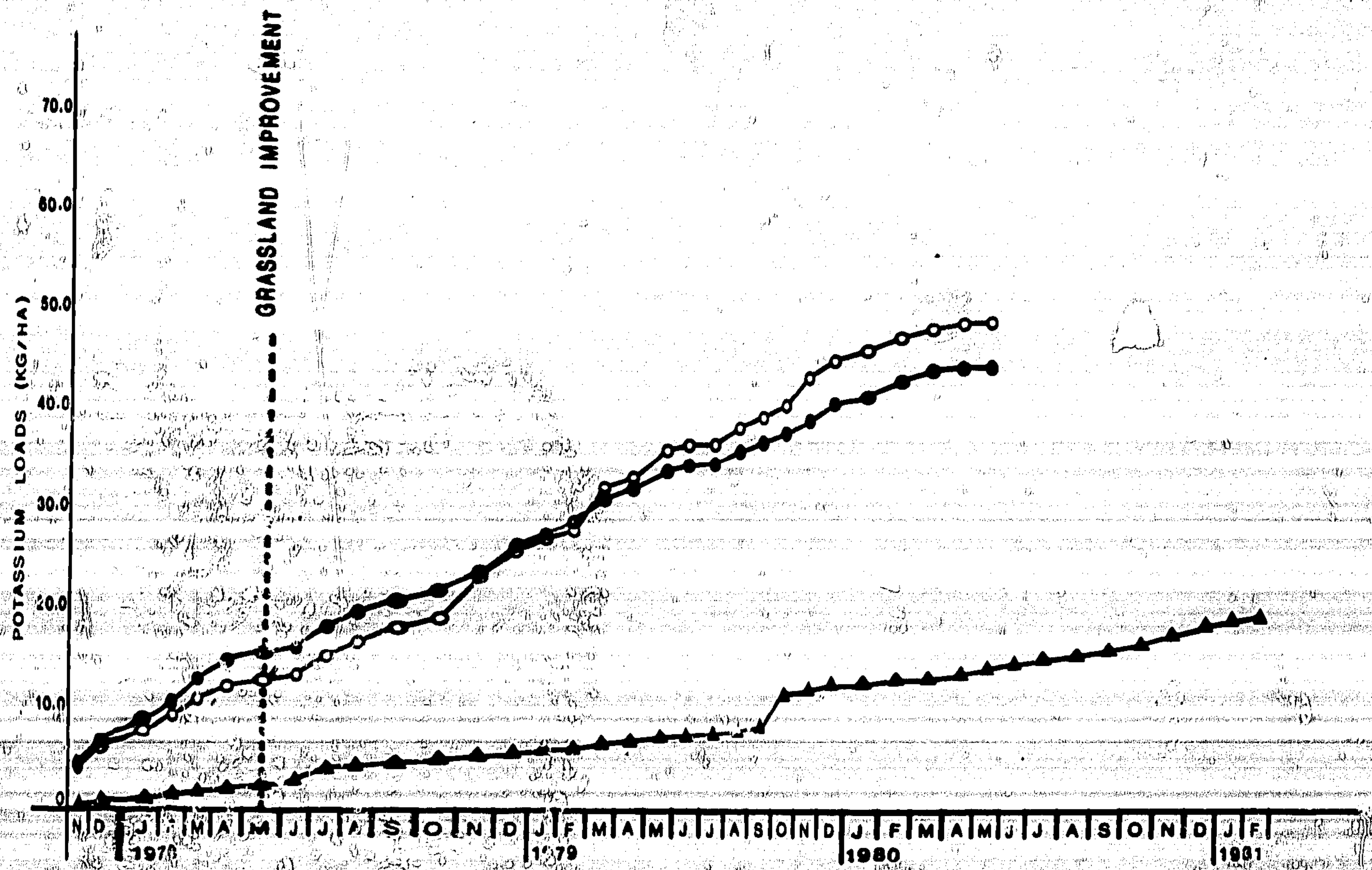


FIGURE 20b Accumulated monthly potassium inputs in rainfall (▲) and outputs in flows from the improved (o) and unimproved (●) lysimeters

TABLE 7a MONTHLY NUTRIENT INPUTS (kg/ha) IN RAINFALL TO THE NANT IAGO LYSIMETERS

MONTH	NH4-N	NO3-N	ORG N	P	K
1977					
NOV	0.31	0.27	0.14	0.10	0.53
DEC	0.32	0.45	0.09	0.02	0.34
1978					
JAN	0.34	0.51	0.21	0.03	0.37
FEB	0.29	0.35	0.41	[illegible]	0.20
MARCH	0.35	0.39	0.32	0.03	0.61
APRIL	0.36	0.47	0.29	0.02	0.23
MAY	0.48	0.45	0.39	0.04	0.21
JUNE	1.22	1.00	0.97	0.05	0.66
JULY	0.40	0.40	0.45	0.05	1.15
AUG	0.62	0.38	1.60	0.01	0.20
SEPT	1.13	1.51	1.10	0.03	0.37
OCT	0.40	0.37	0.36	0.04	0.26
NOV	0.43	0.45	0.36	0.04	0.37
DEC	0.47	0.74	0.31	0.03	0.38
1979					
JAN	0.49	0.77	0.23	0.02	0.20
FEB	0.22	0.33	0.13	0.01	0.09
MARCH	0.64	0.04	0.20	0.04	0.57
APRIL	0.37	0.42	0.65	0.01	0.13
MAY	0.42	0.49	0.44	0.04	0.39
JUNE	0.17	0.35	0.12	0.01	0.11
JULY	0.19	0.13	0.16	0.01	0.12
AUG	0.50	1.22	0.63	0.07	0.46
SEPT	0.51	0.43	1.10	0.06	0.35
OCT	6.76	1.22	0.74	0.09	3.33
NOV	0.52	0.34	0.31	0.14	0.50
DEC	0.34	0.36	0.15	0.04	0.38
1980					
JAN	0.29	0.45	0.13	0.02	0.15
FEB	0.43	0.56	0.22	0.03	0.31
MARCH	0.58	0.30	0.13	0.04	0.20
APRIL	0.25	0.27	0.01	0.02	0.33
MAY	0.54	0.60	0.07	0.03	0.58
JUNE	0.67	0.64	0.66	0.17	0.60
JULY	0.25	0.22	[illegible]	0.09	0.20
AUG	0.54	0.40	0.29	0.16	0.53
SEPT	0.30	0.53	0.37	0.13	0.45
OCT	0.16	0.37	0.47	0.24	0.82
NOV	0.13	0.21	0.31	0.22	0.73
DEC	0.24	0.19	0.39	0.27	0.90
1981					
JAN	0.24	0.13	0.23	0.18	0.62
FEB	0.23	0.33	0.26	0.12	0.39

TABLE 7b MONTHLY NUTRIENT OUTPUTS (kg/ha) IN TOTAL FLOW FROM THE NANT IAGO LYSIMETERS

	IMPROVED LYSIMETER					UNIMPROVED LYSIMETER				
MONTH	NH4-N	NO3-N	ORG N	P	K	NH4-N	NO3-N	ORG N	P	K
1977										
NOV	0.35	41.70	3.98	0.10	4.33	0.57	27.62	2.58	0.09	4.77
DEC	0.06	13.01	1.36	0.06	1.93	0.09	9.34	1.07	0.05	2.29
1978										
JAN	0.05	12.32	[illegible]	[illegible]	1.86	0.07	10.36	0.96	0.03	[illegible]
FEB	0.09	8.95	0.91	[illegible]	1.37	0.06	6.65	0.83	0.04	[illegible]
MARCH	0.10	10.84	1.25	0.04	1.76	0.05	[illegible]	1.34	0.04	2.49
APRIL	0.08	4.69	0.72	0.04	1.27	0.04	4.73	0.59	0.03	1.53
MAY	0.03	1.59	0.31	0.02	0.65	0.01	2.32	0.30	0.01	0.92
JUNE	0.02	1.90	0.30	0.02	0.49	0.01	2.86	0.33	0.01	0.50
JULY	0.29	18.60	2.22	0.06	2.04	0.08	12.69	1.54	0.04	1.95
AUG	0.04	13.23	1.14	0.05	1.40	0.03	8.48	0.87	0.03	1.52
SEPT	0.08	1.56	1.49	0.10	1.23	0.03	5.29	0.96	0.02	1.16
OCT	0.02	[illegible]	[illegible]	0.03	0.95	0.01	3.86	0.56	0.02	1.05
NOV	0.18	[illegible]	[illegible]	0.36	4.21	0.06	9.96	1.46	0.08	1.38
DEC	0.16	[illegible]	[illegible]	0.20	2.47	0.28	3.36	0.96	0.15	2.53
1979										
JAN	0.06	[illegible]	0.39	0.08	1.14	0.10	[illegible]	[illegible]	0.06	1.24
FEB	0.06	5.02	0.83	0.03	1.12	[illegible]	[illegible]	[illegible]	[illegible]	1.02
MARCH	0.16	18.79	2.51	0.26	4.18	[illegible]	[illegible]	[illegible]	[illegible]	2.61
APRIL	0.03	4.56	0.67	0.05	1.02	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
MAY	0.19	13.74	1.77	0.19	2.85	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
JUNE	0.02	1.06	[illegible]	0.02	0.41	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
JULY	[illegible]	[illegible]	0.03	0.01	0.11	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
AUG	0.03	6.16	1.12	0.04	1.56	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
SEPT	0.05	3.34	0.76	0.04	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
OCT	[illegible]	2.86	0.66	0.03	1.24	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
NOV	0.12	12.02	2.24	0.11	2.06	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
DEC	0.32	5.30	[illegible]	0.13	1.33	[illegible]	[illegible]	[illegible]	0.13	1.33
1980										
JAN	0.13	1.80	0.56	0.07	1.00	0.02	[illegible]	0.58	0.05	0.77
FEB	0.03	3.96	0.74	0.05	1.22	0.02	[illegible]	0.68	0.03	1.50
MARCH	0.05	4.78	0.79	0.04	1.21	0.03	[illegible]	0.68	0.02	1.01
APRIL	0.01	0.91	0.17	0.01	0.34	0.01	0.75	0.14	0.01	0.21
MAY	0.01	0.02	0.04	0.00	0.08	0.00	0.07	0.03	0.00	0.10
JUNE	0.03	3.54	0.79			0.04	3.59	0.57		
JULY	0.02	1.60	0.40			0.01	1.15	0.35		
AUG	0.07	3.09	1.27			0.04	1.39	0.58		
SEPT	0.05	2.64	0.94			0.05	1.02	0.60		
OCT	0.08	6.37	2.35			0.05	2.39	1.21		
NOV	0.11	5.52	2.18			0.05	2.73	1.27		
DEC	0.22	6.56	2.68			0.33	3.50	1.80		
1981										
JAN	0.05	3.93	1.60			0.05	2.78	1.28		
FEB	0.05	1.75	0.73			0.03	1.76	0.59		

6. THE IMPLICATIONS OF THE STUDY FOR AGRICULTURE AND THE QUALITY OF WATER RESOURCES

6.1 The effects of the individual improvement practices on water quality

It is evident from the data presented in the preceding chapter that the biggest chemical effect of the agricultural improvement was to cause an increase in nitrogen, particularly nitrate-N, release. Differences between the two lysimeters were evident before the improvement as a result of their construction and clearly, in the absence of the masking effect of the pasture improvement, that difference would also be manifest in subsequent years. It is difficult to assess therefore what proportion of the increased nutrient load from the improved lysimeter compared to the unimproved after the spring 1978 was due to the improvement process. A comparison of mean monthly concentrations and total monthly losses prior to the improvement (Table 8) shows that the values had converged for the two lysimeters by April 1978. With no evidence to the contrary, it seems reasonable to assume that the concentrations in the drainage from the two lysimeters would be similar thereafter and that the increased concentrations from the improved lysimeter following May 1978 can be ascribed solely to a combination of cultivation, reseeding and fertilizing. An inability to split these component parts of the improvement process itself is not a practical limitation as the process would generally be implemented as a whole. Nevertheless, as will be discussed later, it is useful to be able to estimate the effects of the grassland improvement alone in order to calculate the nutrient losses from a slope area that is improved but not tile drained.

TABLE 8 MEAN MONTHLY TOTAL NITROGEN CONCENTRATIONS (mg/l) AND LOSSES (kg/ha) FROM THE TWO LYSIMETERS PRIOR TO THE IMPROVEMENT

		CONCENTRATIONS (MG/L)			LOSSES (KG/HA)		
		IMP.	UNIMP.	RATIO	IMP.	UNIMP.	RATIO
MONTH							
1977	NOV	10.06	7.29	1.38	46.03	30.77	1.50
	DEC	5.66	4.47	1.27	14.43	10.50	1.37
1978	JAN	5.23	4.08	1.28	14.13	11.29	1.25
	FEB	4.66	3.74	1.25	9.95	7.54	1.32
	MARCH	4.29	3.88	1.11	12.19	10.54	1.16
	APRIL	3.28	3.39	0.97	5.49	5.36	1.02

Some estimate of the effect of the grassland improvement on nutrient losses from the lysimeter can therefore be made assuming that mineralisation losses from the backfill were similar for the two lysimeters after May 1978. The improvement losses are then given as the differences in losses from the two lysimeters. This is done on a monthly basis for total nitrogen and potassium in Table 9 and, graphically, in Fig.21. It is not done for phosphorous because, as indicated previously, its concentration in the water samples were more often than not below the detectable limit. Table 9 and Fig.21 show that the effect of the grassland improvement on losses of potassium is much less than on those of nitrogen. In some months, the enhanced losses are negative though it is true to say that for most of the months for which data are available, the differences in potassium losses are within those experienced prior to the improvement (Table 7b). However, it can be concluded that some enhancement is due to the improvement since the losses from the unimproved lysimeter were higher than those from the improved lysimeter prior to May 1978, whilst the reverse was generally true following the improvement.

TABLE 9 ESTIMATED NITROGEN AND POTASSIUM LOSSES (kg/ha) ATTRIBUTABLE TO THE GRASSLAND IMPROVEMENT

	NITROGEN			POTASSIUM		
MONTH	IMPROVED	UNIMPROVED	DIFF.	IMPROVED	UNIMPROVED	DIFF.
1978						
MAY	2.02	2.03	-0.01	0.65	0.92	-0.27
JUNE	2.28	3.20	-0.92	0.49	0.60	-0.27
JULY	21.11	14.29	6.82	2.04	1.98	0.06
AUG	14.41	9.38	5.03	1.40	1.52	-0.12
SEPT	13.13	7.28	5.85	1.28	1.16	0.12
OCT	6.08	4.43	1.65	0.95	1.08	-0.13
NOV	25.03	11.43	13.60	4.21	1.88	2.33
DEC	7.52	4.60	2.92	2.47	2.53	-0.06
1979						
JAN	3.36	3.12	0.24	1.14	1.24	-0.10
FEB	5.91	3.77	2.14	1.12	1.02	0.10
MARCH	21.46	11.93	9.53	4.18	2.61	1.57
APRIL	5.26	2.96	2.30	1.02	0.92	0.10
MAY	15.70	7.15	8.55	2.35	1.31	1.04
JUNE	1.30	0.81	0.49	0.41	0.50	-0.09
JULY	0.14	0.07	0.07	0.11	0.06	0.05
AUG	7.31	3.35	3.96	1.56	1.35	0.21
SEPT	4.15	1.70	2.45	1.03	0.82	0.21
OCT	3.56	1.67	1.89	1.24	0.88	0.36
NOV	14.38	3.22	11.16	2.68	1.20	1.48
DEC	5.25	4.90	0.35	1.83	1.83	0.00
1980						
JAN	2.56	1.85	0.71	1.00	0.77	0.23
FEB	4.73	3.00	1.73	1.22	1.50	-0.28
MARCH	5.62	3.90	1.72	1.21	1.01	0.20
APRIL	1.09	0.90	0.19	0.34	0.21	0.13
MAY	0.07	0.10	-0.03	0.08	0.10	-0.02
JUNE	4.36	4.20	0.16			
JULY	2.02	1.51	0.51			
AUG	4.43	2.01	2.42			
SEPT	3.63	1.67	1.96			
OCT	9.30	3.65	5.65			
NOV	7.81	4.05	3.76			
DEC	7.45	4.13	3.32			
1981						
JAN	5.58	4.11	1.47			
FEB	2.53	2.38	0.15			

On the other hand, enhanced losses of nitrogen were found for almost all the months for which data are available. The pattern of these enhanced losses is similar for each of the three years studied showing high losses in the late summer and autumn as the demand for nitrogen by the pasture decreases. Reduced rates of evaporation and increasing rainfall at this time of year ensures sufficient moisture to leach the excess mineral nitrogen within the lysimeter. Peak nitrogen losses occur in November as field capacity is reached. The losses then decrease through the winter with a secondary peak in the spring and reach minimum values in July when the nitrogen demands of the growing pasture is greatest and drainage from the lysimeter is lowest. The spring peaks are presumably caused by leaching of the applied nitrogenous fertilizer before it can be utilized by the growing pasture. Annual nitrogen losses attributable to the improvement were greatest in the first year (52 kg/ha) and reduced progressively for the next two (34 and 22 kg/ha). Total losses for the three years were 108 kg/ha. This compares with a total nitrogen application of 225 kg/ha. Not all of the 108 kg/ha can be accounted for as applied fertilizer as some is due to the loss of indigenous nutrients following cultivation. It could be argued, however, that a loss of indigenous nutrients is a direct economic loss since they will have to be replaced in the long run if fertility is to be maintained. In effect, therefore, approximately 50% of the added nitrogen fertilizer is lost without being utilized by the improved pasture.

The results obtained from this study can be used, in conjunction with results obtained from undisturbed rough pasture (Roberts et al., 1983), to estimate the effects of the various agricultural practices on nitrogen and potassium losses as shown below:-

EFFECT OF DRAINAGE = LOSSES FROM DRAINED PASTURE - LOSSES FROM UNDISTURBED PASTURE

EFFECT OF GRASSLAND IMPROVEMENT = LOSSES FROM DRAINED AND IMPROVED PASTURE - LOSSES FROM DRAINED PASTURE

EFFECT OF DRAINAGE + GRASSLAND IMPROVEMENT = LOSSES FROM DRAINED AND IMPROVED PASTURE - LOSSES FROM UNDISTURBED PASTURE

The following section deals with the problem of extrapolating the results from the lysimeter study to a catchment scale and, using a schedule of pasture improvement typical of the mid-Wales region, predicts its effects on streamflow quality.

6.2 Extrapolating the results of the lysimeter study to the catchment scale.

Direct extrapolation of these results would be feasible only in the event of complete improvement in one season of a peat catchment overlying relatively impermeable clay. Real land improvement schemes are much more complex and, for a variety of topographic, management and economic reasons, would normally be applied only to selected parts of a catchment and phased over a number of years. The improvement would be implemented on a variety of land types eg. heaths, slopes and mires, and would often be accompanied by other land use changes such as afforestation.

An example of this is the Clywedog Reservoir catchment in mid-Wales run by the Severn-Trent Water Authority for river regulation purposes. This has seen dramatic changes in land use since completion of the dam in 1967 but it has still taken more than the last 20 years to improve 24% of the catchment and to afforest a further 32% (Newson and Hudson, 1976). More recently Collingwood, 1981 in his report on the present and future land use at Lake Vyrnwy, which supplies water to the Liverpool Corporation, predicted the possible effects of future land use change - pasture improvement and afforestation - on the quality of the water in the lake.

Ideally, such predictions require estimates of nutrient losses from all the contributing land types under undisturbed conditions and at different stages of the improvement and afforestation cycles. Although a great deal of information on the expected nutrient losses from different established land types and uses (Roberts et al., 1983) and, more recently, from changes in land use (Roberts et al., 1984) has been collected, it is not sufficient for a comprehensive prediction. However, to give some

indications of the possible magnitude of the effects on stream nutrients, such an approach has been attempted for a scenario involving the progressive improvement, without afforestation, of the Wye catchment. The data required have been extracted from this present study and from Roberts et al., 1983. The improvement is assumed to be implemented over a seven year cycle ie. one-seventh every year, superimposed on a twenty-one year tile drainage replacement cycle. A typical seven year cycle between reseeding would show:-

(i) In the first year the effects of drainage.

(ii) In the second year the cumulative effects of residual drainage, cultivation and fertilizer application.

(iii) In the third year just fertilizer application and rapidly diminishing disturbance effects.

(iv) In the remaining four years of the cycle an enhanced background level compared to unimproved pasture due to the residual fertilizer and drainage effects. This would be superimposed with a seasonal variation, especially for nitrogen, as a result of nutrient cycling within the grassland ecosystem. In some cases, the seasonality will be masked if fertilizer applications are made throughout the improvement.

The contributions of areas in different phases of improvement would have to be combined with contributions from undisturbed areas. On top of the seven year improvement cycle must be superimposed a typical twenty-one year tile drainage replacement scheme where this is part of the improvement procedure.

One aspect of upland development for which information is scarce and one which may affect a large percentage area of upland catchments, is the improvement of dry banks without tile drainage, either discharging directly into a water course or through a mire area. Modelling this situation is easy if the scheme involves direct discharge to stream channels, when it becomes simply a volumetric mixing exercise for waters of different concentrations. However slope runoff, as indicated earlier, is not normally channelled through tile drains but is a combination of surface runoff, interflow and pipeflow. Such nutrient-rich flow leaving an improved area of dry bank may feasibly be modified by take up of nutrient in areas downslope.

At present levels of knowledge, this type of scheme cannot easily be simulated. It is assumed, for simulation purposes, that if a slope is to be improved then it is done in its entirety. Furthermore it is assumed that blanket peat, slope areas and mire areas will have independent outfalls to surface channels and so will not interact. Such a scheme would require that the boundary between the slope areas and the valley bottom mires is delineated by a cut-off drain. This was proposed at the beginning of this lysimeter study in order to isolate the field plot surrounding the lysimeters from the slope above but was discounted because of the danger to stock. As a result, the nutrient concentrations in the drainage outfalls were depressed compared to the lysimeters because of the twin bias of dilution by upslope water and the greater drainage density, hence greater weathering volume, inside the lysimeter.

It must be assumed for the simulations that, in the absence at present of direct results from slope areas, the likely effects can be approximated by the "grassland improvement only" estimate of nutrient losses outlined in the previous section.

6.2.1. Modelling a progressive improvement of the Wye catchment at Plynlimon

The areal extent of each land type is shown in Fig.2 and their percentage coverage summarised in Table 10. The model used is as shown in Table 11. Basically, the model splits the catchment into an area that is improveable with drainage, A, improveable without drainage, B and unimproveable, C. No afforestation is considered. Improvement is assumed over a seven-year cycle i.e. one seventh is done each year. The annual total nitrogen loadings in the improved land decreases with years; in the case of the drained and improved land from D1 to D7 and for the improved only land from I1 to I7. Loadings from unimproved land are assumed to be constant (U). At the end of the seven year cycle, the process is repeated, but, in this case, drainage is not required and the loading values appropriate to improvement only are used. However, there will still be some residual from the drained areas. Similarly, at the end of the fourteen year cycle, improvement only is repeated but, in this case, the effects of the initial drainage are assumed to have ceased. At the end of the twenty-first year, the whole cycle including drainage is repeated.

TABLE 10 AREAL EXTENT OF LAND TYPE DOMAINS IN THE WYE CATCHMENT

Soils	Vegetation	% area
Peat (caron)	Heath	8.9
Podzol (Hiraethog)	Rough pasture	36.5
	Improved pasture	25.9
	Closed canopy conifers	0.3
Peat (Ynys)	Mire	28.4
Unimproveable		unknown assumed 0

Some difficulty in utilising the lysimeter results arises because the drainage work on the lysimeters was carried out in the year previous to the improvement. This was necessary because time had to be allowed for the construction and instrumentation of the lysimeters and a pre-improvement check made on the relative behaviour of the two lysimeters. This is not the usual practice as draining would normally be done in early spring and the improvement as soon as the ground had dried out sufficiently. On peaty ground however, where much drying and soil structure change takes place after draining, a suitable time would be left for the ground to settle before improvement. In such cases, the timetable of events on the lysimeters is probably realistic and, as a result, the first water quality effects noticed on any catchment would simply be equivalent to the losses from the lysimeters due to the drainage alone.

Unfortunately, measurements of the first year's loss were incomplete because after the drainage in June 1977, it took 3 or 4 months to complete the water quality instrumentation and to start recording in November 1977. At the onset of data collection, concentrations, of nitrogen in particular, were at their highest for the whole study period (up to 16mg/l). Although concentrations in the summer months would have been depressed, a significant proportion of the nutrient runoff for [illegible] would have occurred when the autumn rains started in September and [illegible]. Therefore an estimate is made of the nutrient loadings and concentrations for June 1977 to October 1977 by assuming that concentrations were low in the summer months rising to a peak in November. Extrapolating the mean concentrations between November 1977 and April 1978 backwards would seem to be the best estimate available of the effect of the drainage alo[illegible]

TABLE 11 A MODEL TO EXTRAPOLATE THE RESULTS FROM THE LYSIMETER STUDY TO THE WYE CATCHMENT

Weighted loadings

Years (n)	Drained + Improved Areas		Improved Areas		Unimprovable
1 → 7	$\frac{A}{7}\left(\sum_{i=1}^{n} D_i + (7-n)U\right)$	+	$\frac{B}{7}\left(\sum_{i=1}^{n} I_i + (7-n)U\right)$	+	C.U
8 → 14	$\frac{A}{7}\left(\sum_{i=1}^{n-7} I_i + \sum_{i=7}^{n-7+1} D_i\right)$	+	$\frac{B}{7}\sum_{i=1}^{7} I_i$	+	C.U
15 → 21	$\frac{A}{7}\sum_{i=1}^{7} I_i$	+	$\frac{B}{7}\sum_{i=1}^{7} I_i$	+	C.U
22 → 28	$\frac{A}{7}\left(\sum_{i=1}^{n} D_i + \sum_{i=7}^{n-21+1} I_i\right)$	+	$\frac{B}{7}\sum_{i=1}^{7} I_i$	+	C.U
etc.					

where $D_{1...7}$ = average annual loading for drained and improved land in years 1 to 7

$I_{1...7}$ = " " " " improved

U = " " " " unimproved = 10 kg/ha

A = area of catchment that is improvable with drainage

B = " " " " " without "

C = " " " " unimprovable

Values used for model application (kg/ha) May – April

Year	1	2	3	4	5	6	7
D	204.4	130.6	[illegible]	59.0	42.7	26.3 x	10.0
I	45.0	33.8	23.0	20.4 x	16.9 x	13.4 x	10.0

x Interpolation

A = 0.38 x Area of Wye B = 0.62 x Area of Wye C = 0

The problem is further complicated by having to decide which values of loadings are most representative of the pre-improvement phase. Results from the two lysimeters vary probably because the depth of the peat, and hence the weathering volume, is greater on the improved than on the unimproved. Furthermore, during this period, concentrations in both lysimeters were very much greater than in the samples extracted from either of the drains, because the drains were backfilled several months before the lysimeters and the drain samples were diluted by water off the slope. Since the depth of peat varies on the mire areas, the best estimate of drainage would seem to be an average of the results from the two lysimeters during the early period. At most, this should introduce an error of 0.5 to 1.0 mg/l in mean concentration which is equivalent to approximately 10% in loads.

Having established the characteristic loadings for various phases of the improvement cycle, the results of the model simulation in terms of the upward trend in losses and concentrations relative to background levels for the unimproved Wye catchment (Roberts et al., 1983) are shown in Fig.22. Both of these indices have relevance. Loadings are an estimate of

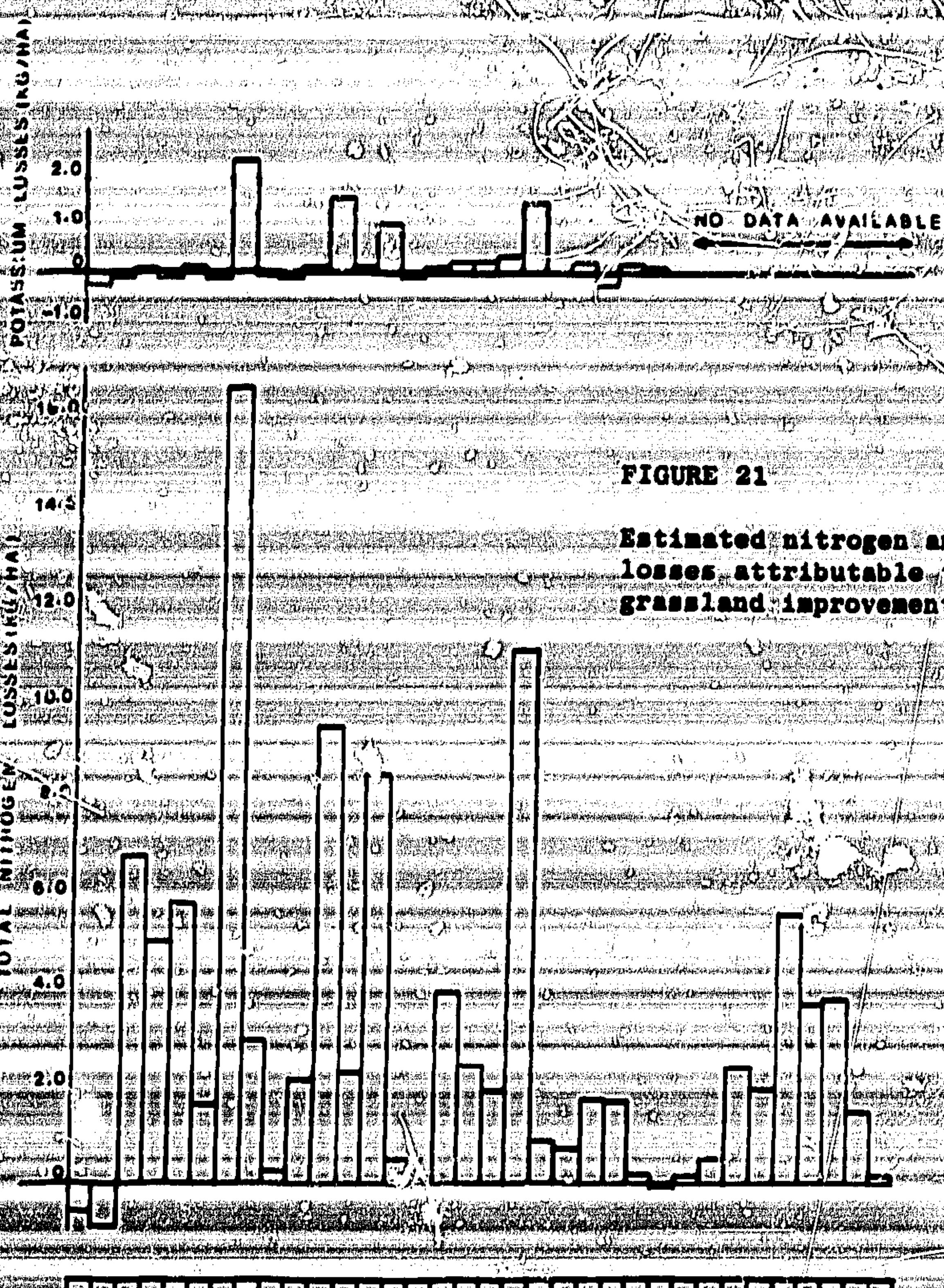


FIGURE 21

Estimated nitrogen and potassium losses attributable to the grassland improvement

the economic loss of nutrients to agriculture and the cost of replacement by artificial fertilizers. Both concentrations and loadings are of interest to the water industry, the former due to its control on potability and the development of aquatic ecosystems and the latter as a management tool when mixing supply waters of varying quality.

It must be remembered, however, that the results of the simulation model given in Fig.22 is site specific in terms of geography, geology, soil types, improvement practices and, perhaps most importantly, climate. As indicated previously, the Plynlimon region is very wet, with a mean annual rainfall of 2500 mm. As well as having a direct bearing on nutrient losses, this also has an indirect bearing on concentrations since leaching rates are high almost throughout the year. Therefore, great care must be exercised when comparing the results of this simulation model with those obtained for other studies.

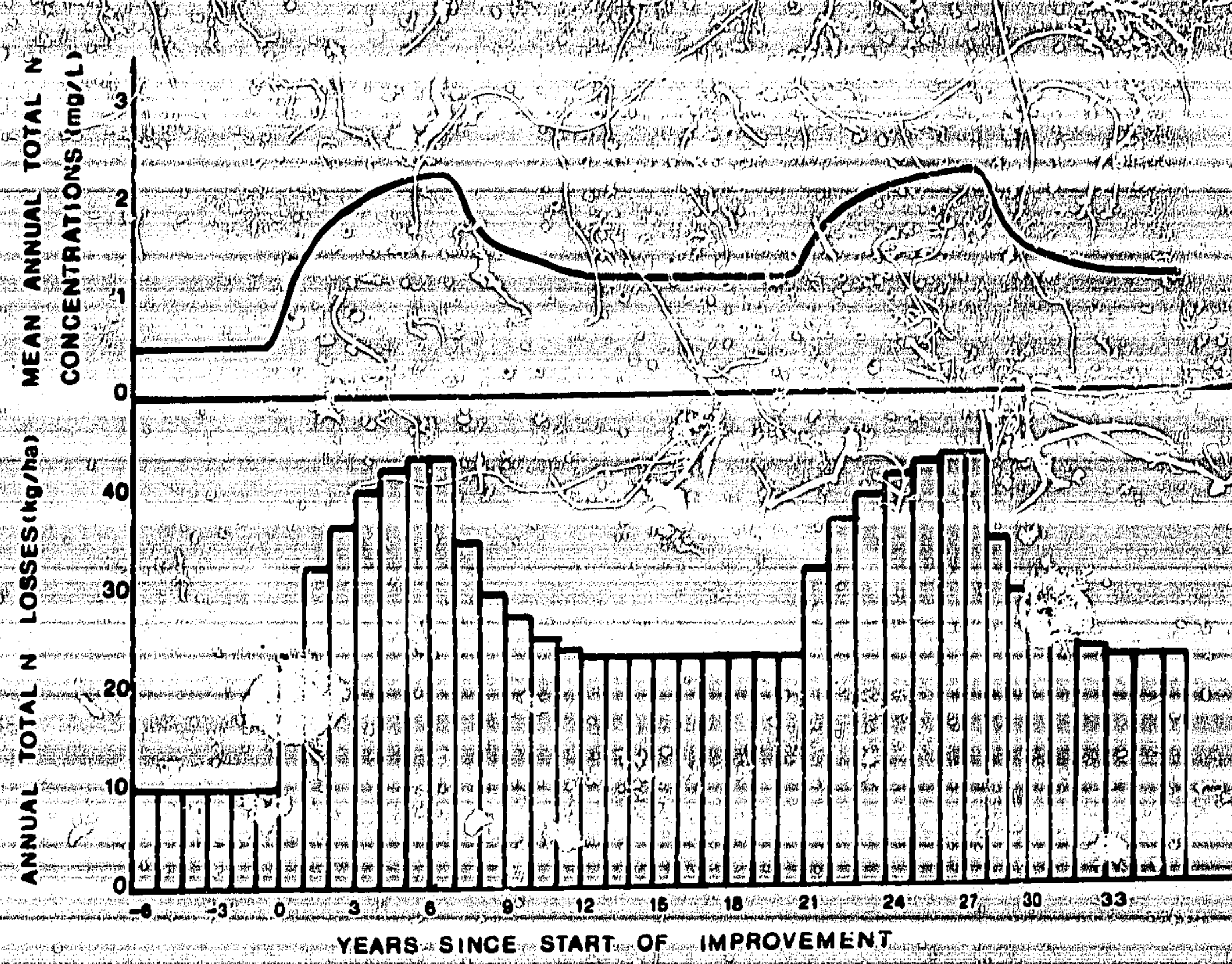


FIGURE 22 Model simulation of the effects of gradually improving the Wye catchment

7. DISCUSSION

The results of the model simulation, although subject to a number of assumptions, give a realistic estimate of the likely increases in total nitrogen concentrations and losses in streamflow from a catchment subjected to a typical intensive pasture improvement scheme.

Nutrient losses from cultivated land under "similar" conditions as reported in the literature vary a great deal reflecting the numerous controls affecting these losses. Seuna and Kauppi, 1980 in their study on a clay and silt cultivated area in Finland, observed large increases in nitrogen, notably nitrate-N, concentrations following sub-draining 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 2.0-17 mg/l. Increases in annual loads varied from 1.5 to 25 kg/ha for total N and from 1.7 to 24 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 and a fertilizer 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 fertilizer on runoff water quality could be detected for at least 5-10 years whereas the effect of potassium fertilization disappeared in 1-2 years (Kenttamies, 1980). Similar results have been found in other parts of Finland.

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

Duxbury and Peverly [illegible] found annual nutrient outputs which ranged from 0.6 to 30.7 kg/ha [illegible], 39.2 to 87.5 kg/ha for NO_3-N and 1.0 to 1.9 kg/ha for NH_4 [illegible] drained organic soils located in New York. Maximum observed concentrations were [illegible] mg/l for NO_3-N and 10 mg/l for PO_4^{3-}-P. Hortenstine and Forbes, 1972 found high concentrations of NO_3-N (up to 150 mg/l N) and [illegible] (up to 30 mg/l [illegible]) in soil solutions from unfertilized muckland adjacent to Lake Apopka in Florida. Erickson and Ellis, 1971 reported that 18.2 kg N/ha and 1.45 kg P/ha were leached from the Michigan State University experimental muck farm in 1969 and only 4.1 kg N/ha and 1.6 kg P/ha were collected in drainage water from the Holland Marsh, Ontario in the spring of 1971 (Nicholls and MacCrimmon, 1974).

Studies carried out in the upland areas of the UK also show enhanced nutrient losses from improved grassland. Newbould and [illegible], 1977 reported annual losses of 30 kg/ha of N from intensive sheep farming on grassland receiving 20 kg/ha of N at the Hill Farming Research Organisation. [illegible] nitrogen losses from a small (41 ha) catchment under permanent grassland receiving 284 kg N/ha annually (190 kg N/ha as fertilizer, 500 tonnes of farmyard manure and 182 cu.m of slurry) at the

Great House Experimental Husbandry Farm averaged 40 kg N/ha per year, (Webber and Wadsworth, 1975). On a number of occasions, NO_3 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 fertilizers. Losses of phosphorus, on the other hand, were very low, usually less than 1 kg P/ha per year.

Leeks, 1980 found higher concentrations of both NH_4^+N and NO_3^-N (0.11 and 1.6 mg/l) in streamflow from previously improved pasture receiving no fertilizers than from unimproved pasture (0.04 and 1.0 mg/l). Ortho-phosphate concentrations were also slightly higher in the improved pasture. Also, higher concentrations of chlorophyll 'a' and larger numbers of organisms and higher species diversity were found in streams draining the improved pastures.

Although the nitrogen concentrations predicted in this study in the simulation of the pasture improvement scheme (2.25 mg/l or 4-5 times those under undisturbed conditions) are well below the World Health Organisation recommended limit of 11.3 mg/l of nitrate-N, their persistence may seriously curtail the effectiveness of the role of upland water as a downstream dilution agency. This is at a time of great financial constraint and also when the water authorities are having to invest to comply with the new EEC guidelines on public water supply. As an indication of possible investments involved, the Anglian Water Authority has estimated that it will cost between £10 million and £15 million to comply with the new EEC standards in their region (Anglian WA, 1979).

On the other hand, substantial benefits have been observed as a result of upland pasture improvement. The work at the Pwllpeiran experimental husbandry farm in mid-Wales is particularly relevant to this study because of its close proximity to the study area and its similar elevation, climate, geology and soil (ADAS, 1979). In recent years, its production of lamb has more than quadrupled from 11.1 to 48 kg/ha/yr whilst calf production has increased from 2.4 to 39.3 kg/ha/yr (ADAS, 1980).

Clearly, therefore, serious consideration must be given to the conflicting demands of water resources, agricultural production, forestry and recreation in the upland areas of Britain. The results obtained from this, and similar studies, will prove valuable in determining land use policy in these areas.

CONCLUSIONS

The effect of upland pasture improvement on nutrient concentrations and losses was monitored in the drain outlet from a small 1.5 ha plot and in the discharge of a 100 sq m [illegible] lysimeter. The results obtained were compared with those from an adjacent undisturbed plot and lysimeter. It was found that:

(i) Nitrate-N concentrations were much higher in the improved plot than in the unimproved plot particularly during the autumn following the implementation of the improvement scheme. Concentration levels were greater than the World Health Organisation limit of [illegible] mg/l for some time during this period. However, the greatest increase in nitrate concentrations was as a result of the initial drainage. The effect on other nutrients was less pronounced.

(ii) Total nitrogen losses (in kg/ha) attributable to the improvement were found to be 62.4 and 18.0 in the first and second year, respectively, following the improvement. Similar values for potassium were 5/3 and 6.5.

(iii) A simulation model was used to predict the effects of a typical intensive pasture improvement scheme in an upland catchment. It was predicted that, following the improvement, total nitrogen concentrations would rise from a background level of 0.5 mg/l to [illegible] mg/l. Losses would increase from about 10 kg/ha/yr to 40 kg/ha/yr.

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ACKNOWLEDGEMENTS

The authors wish to acknowledge the immense amount of work carried out by the staff of the Plynlimon office of the Institute of Hydrology in constructing the two lysimeters used in this study. They would also like to thank the staff of the Soil Science Department of ADAS, Trawscoed for analysing the large amount of water samples collected during the course of this study.

APPENDIX I CORRECTING THE FLOWS

As a pre-requisite to hydrograph separation, general sub-surface recession curves were established for both lysimeters using a number of measured recessions obtained during periods of no rainfall. These are shown in Fig.23. The basis of the analysis is to split the general recession curves into their component parts (Ineson and Downing, 1964). In the relatively simple situation of sub-surface discharge from a lysimeter, two components, namely, interflow and base flow need be considered. (Surface runoff is disregarded in this analysis as it is measured separately). Interflow is considered as that part of infiltration which moves relatively rapidly in approximately horizontal directions, usually in the soil zone or immediately below it, but which does not penetrate to the underlying zone of saturation. These flows occur during and immediately following precipitation events and, because of the efficient nature of the tile drains in the backfill within the lysimeters, would be conveyed very rapidly to the flow measuring devices. Base flow originates from that part of infiltration which moves downwards under gravity to reach the main zone of saturation below the water table before moving laterally through the lysimeter blocks into the tile drains. Some delay would be expected before these flows reached the measuring devices but they would continue for a longer time period following the precipitation event than the interflow. If the supposition concerning the nature of the excess flows from the lysimeters is correct, then these two types of flows will be supplemented by the leaks through the boulderclay layer. Since these originate at points upslope of the lysimeters and have

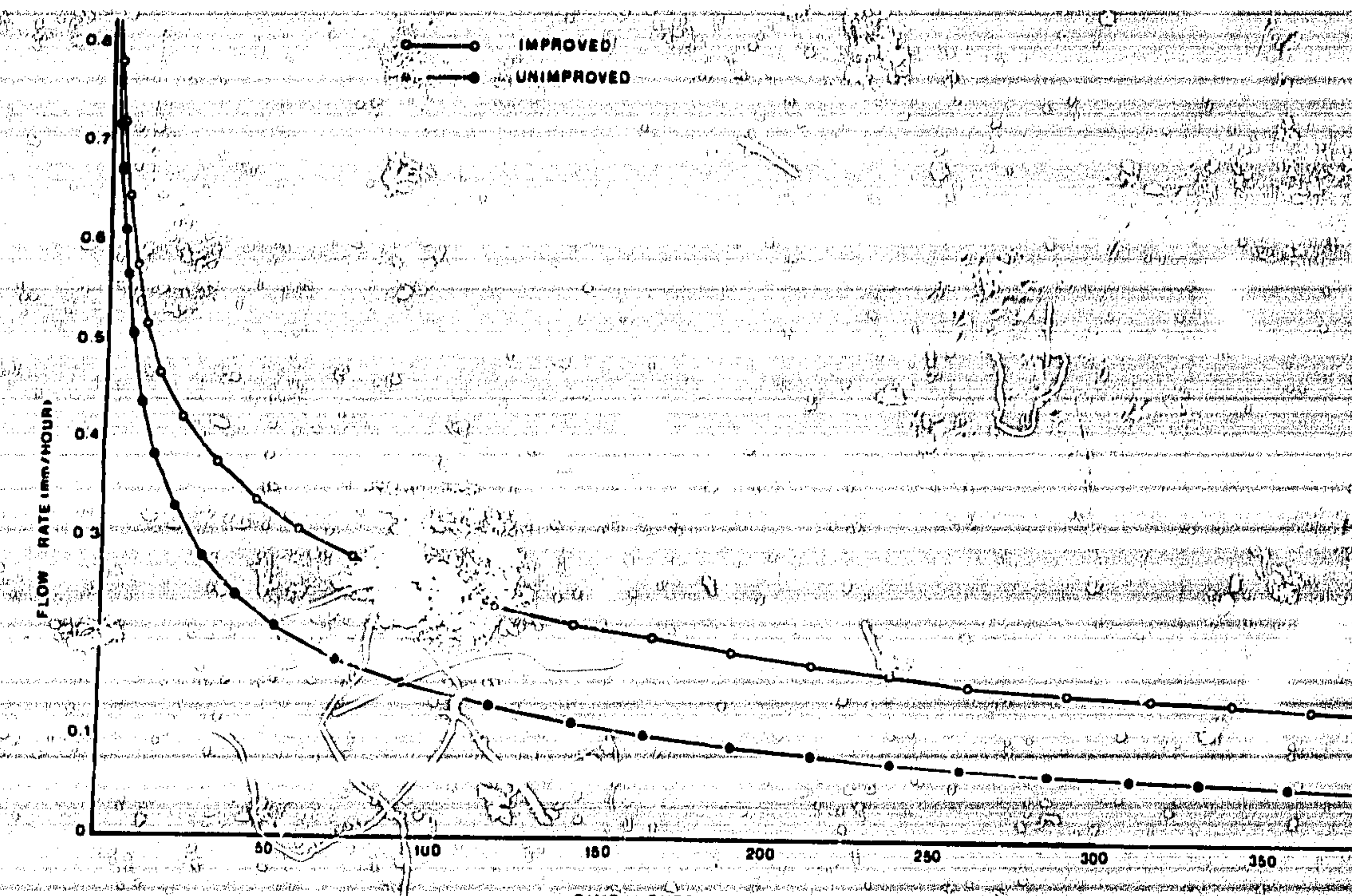

FIGURE 23 General recession curves for the Nant Iago lysimeters

to infiltrate underneath and through the boulderclay, it is likely that a significant time lapse would occur between the precipitation event and these leaks being manifest at the measuring devices. A schematic representation of the components of the sub-surface discharges from the Nant Iago lysimeters is given in Fig.24. The relative magnitudes and durations of the three components are not significant at this point.

In order that the duration and magnitude of the leak component be identified, it is assumed that its recession follows a simple expression. In practice, the most used expression is a simple exponential (Barnes, 1939) and it is also used in these analyses. The leakage rate, q_t, at time, t, is given by:-

$$q_t = q_o e^{-bt}$$

where q_o = initial flow rate,
e = the base of the natural logarithm,
b = a constant,
e^{-b} = the recession constant.

Two further studies were conducted to supplement the results obtained during the hydrograph analyses (which will be described later) to provide further insight into the nature of the leakages into the lysimeters.

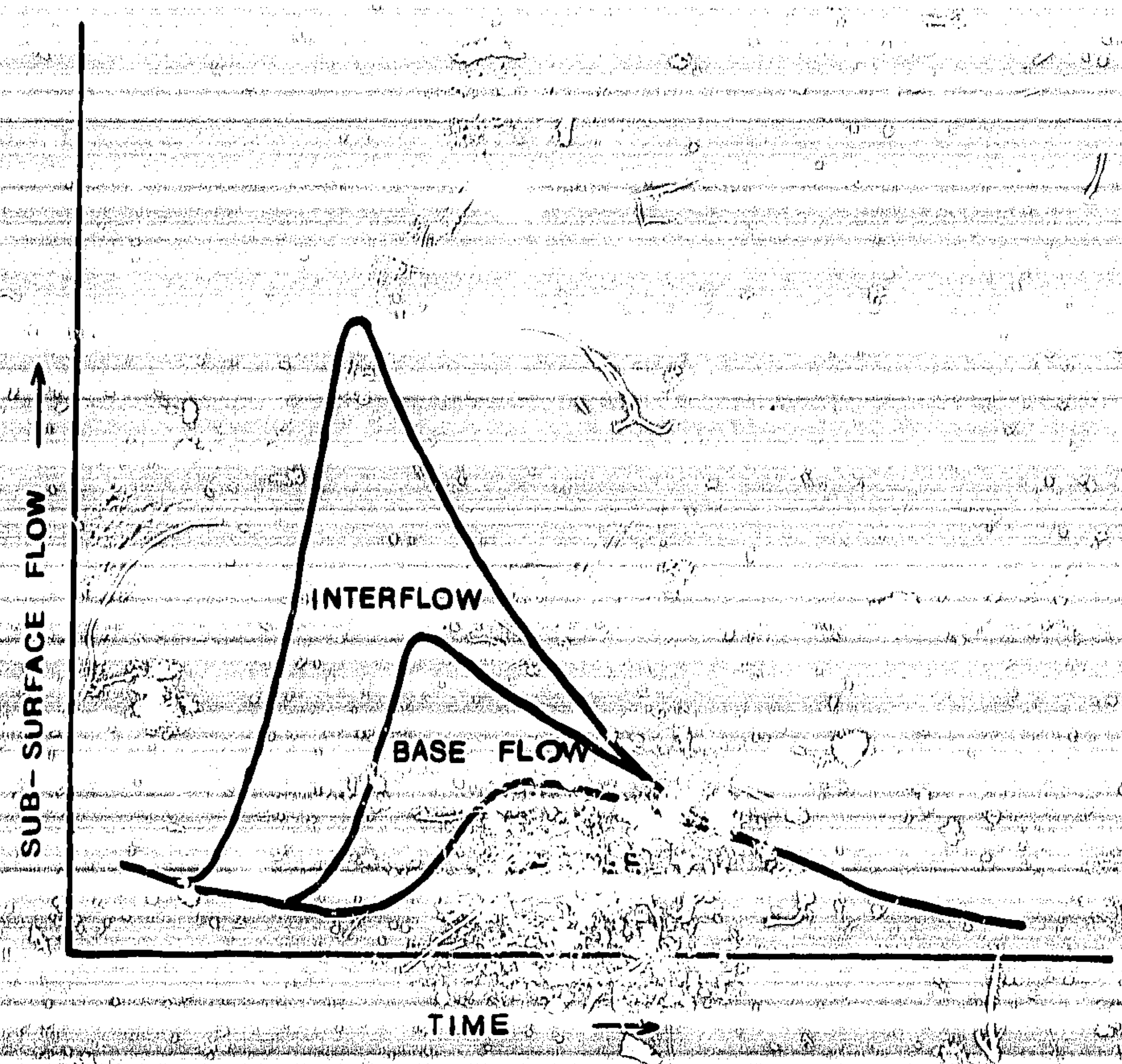

FIGURE 24 Components of subsurface flow from the Nant Iago lysimeters

COVERING THE LYSIMETERS

Both lysimeters were completely covered with heavy duty clear polythene sheets during the period 5.12.78 - 9.1.79. Surface runoff from each plastic sheet was channelled into the surface collectors and measured independently as before. By stopping any rainfall inputs directly to the lysimeters, it was hoped that any leaks through the boulderclay as a result of infiltration inputs upslope would be shown as discontinuities on what should have been the smooth recessions of the sub-surface flows. Also, by comparing rainfall totals and the surface flows from the two lysimeters, the efficiency of the plastic sheets in restricting the direct entry of rainfall into the lysimeters could be assessed.

The months December and January were chosen to conduct this experiment so that the effects of imposing virtual greenhouse conditions on grass growth would be minimal during the coldest months of the year. Also, the choice of these months would ensure sufficient precipitation for the experiment to be meaningful. On the debit side however, the period chosen was extremely cold and very windy. These conditions caused instrument malfunction and, more seriously, caused the polythene sheets to tear and allow rainfall into the lysimeters. The data collected are summarised as daily totals in mm per unit area in Table 12a. Because of the precise nature of the experiment, the flows shown and subsequently used in determining leak rates are restricted to those data collected using the tipping bucket discharge recorders.

TABLE 12a DAILY RAINFALL AND FLOWS (mm) FROM THE COVERED LYSIMETER

		IMPROVED LYSIMETER		UNIMPROVED LYSIMETER	
DATE	RAINFALL	SURFACE	SUB-SURFACE	SURFACE	SUB-SURFACE
DEC. 1978					
5	0.0	0.0	9.0	0.0	5.6
6	0.5	0.0	7.6	0.0	5.1
7	9.4	0.3	5.6	5.2	4.9
8	17.1	13.7	6.9	12.7	5.3
9	4.1	2.7	5.7	2.7	3.0
10	12.9	9.6	5.8	8.6	4.2
11	3.2	*	5.3	*	3.6
12	20.0	*	*	*	*
13	23.2	*	*	*	*
14	42.2	*	*	*	*
15	7.3	*	*	*	*
16	0.0	*	*	*	*
17	0.5	*	*	*	*
18	0.5	*	*	*	*
19	0.0	*	*	*	*
20	0.0	*	*	*	*
21	0.0	0.0	4.7	0.0	*
22	0.0	0.0	4.6	0.0	*
23	0.0	0.0	4.5	0.0	*
24	30.7	24.5	5.7	22.7	*
25	9.9	9.4	5.6	9.4	*
26	4.7	3.7	5.4	2.7	*
27	13.2	14.0	6.0	12.1	*
28	23.7	25.6	6.3	24.2	*
29	13.2	11.3	5.9	10.2	*
30	0.0	*	*	*	*
31	0.0	*	*	*	*
JAN. 1979					
1	0.0	*	*	*	*
2	0.0	*	*	*	*
3	0.0	0.0	2.3	0.0	2.1
4	0.0	0.0	*	0.0	*
5	0.0	0.0	*	0.0	*
6	27.5	[illegible]	*	*	*
7	49.5	45.3	6.8	45.7	5.2
8	9.5	8.0	5.3	7.5	3.6

* unreliable data

An inspection of Table 12a shows that reliable data were not collected for much of the period. Even when the tipping bucket flow recorders were operational, daily rainfall totals were invariably higher than daily surface runoff totals from both lysimeters, even allowing for open water evaporation from the plastic sheets. This suggests that the plastic sheets were not entirely satisfactory in stopping rainfall from entering the lysimeters directly. This is demonstrated in Fig.25 for the improved lysimeter for the period 23.12.78 to 29.12.78. Here, increases in the sub-surface flow occurred during each rainfall event though it is impossible to determine what proportions of the increases can be attributed to direct rainfall input through tears in the plastic sheets and to leaks through the boulderclay layer. The rapid response of the sub-surface flow to rainfall events suggests that large proportions of these increases are due to direct rainfall inputs.

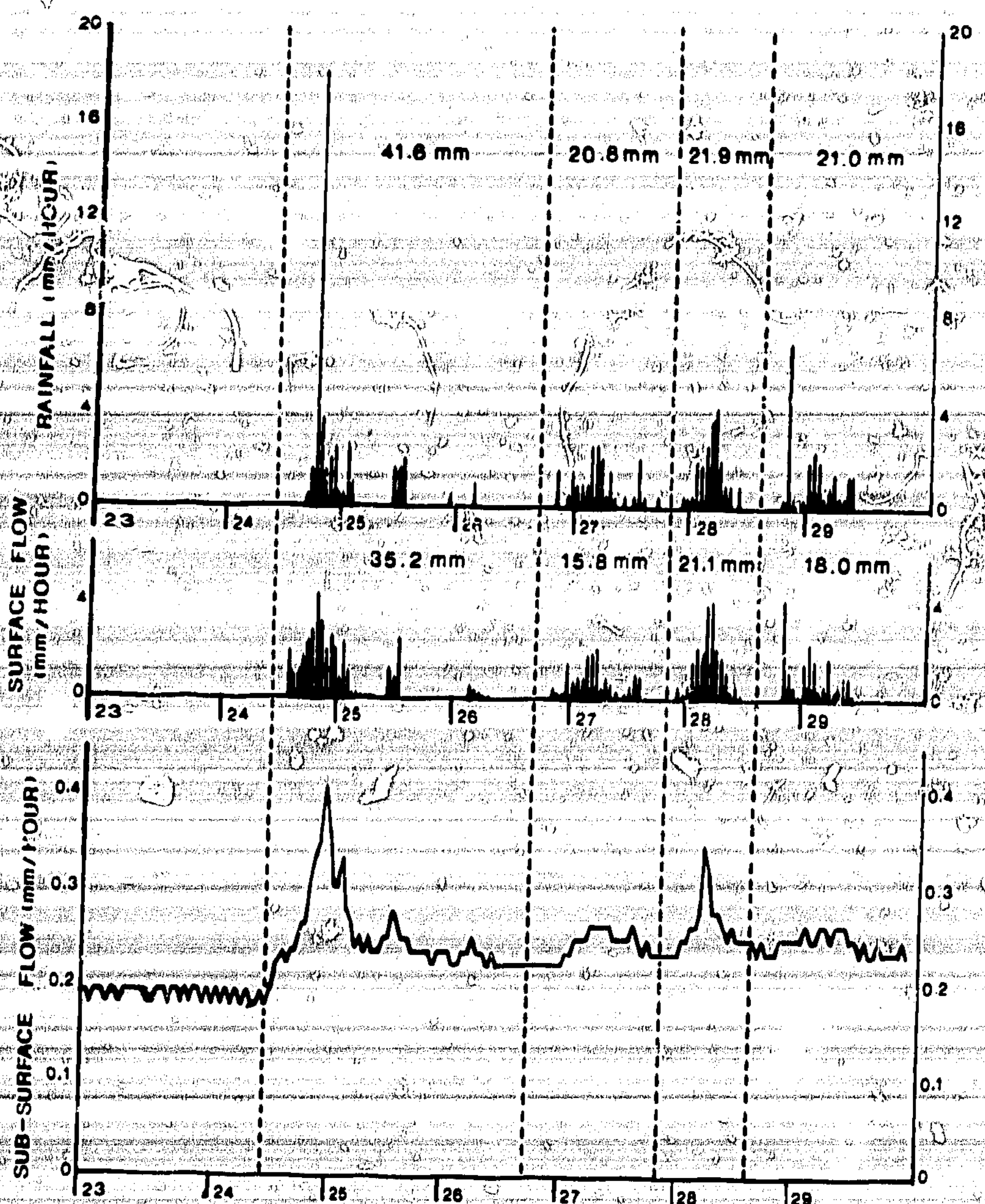

FIGURE 25 Covered improved lysimeter: 23.12.78-29.12.78

TABLE 12b DAILY RAINFALL AND FLOW TOTALS (mm) FROM THE COVERED LYSIMETERS

* unreliable data

MONTH	RAINFALL	IMPROVED LYSIMETER SURFACE	IMPROVED LYSIMETER SUB-SURFACE	UNIMPROVED LYSIMETER SURFACE	UNIMPROVED LYSIMETER SUB-SURFACE
NOV 1979					
23	0.0	0.1	10.7	0.0	7.4
29	8.5	1.0	8.5	0.9	5.4
30	4.5	5.3	7.5	4.7	4.5
DEC 1979					
1	5.0	3.1	6.8	2.3	3.9
2	15.0	17.2	6.3	16.3	3.6
3	1.0	1.2	*	0.9	3.2
4	20.5	11.8	*	22.0	3.0
5	57.8	37.6	*	55.3	[illegible]
6	3.5	2.1	*	3.4	2.3
7	15.0	10.4	*	14.7	2.6
8	12.5	3.3	10.3	12.5	2.7
9	24.0	17.1	6.9	24.7	2.2
10	12.0	9.6	11.1	11.4	2.5
11	26.0	20.4	13.7	24.1	2.6
12	37.0	14.1	13.9	16.3	2.4
13	11.0	7.4	*	9.3	*
14	15.5	10.7	*	14.0	*
15	10.0	7.9	[illegible]	9.3	2.3
16	2.5	1.6	6.6	2.1	2.1
17	0.0	0.20	[illegible]	0.0	2.1
18	17.5	11.1	7.7	14.0	2.1
19	5.0	2.9	6.6	3.3	2.2
20	1.5	0.0	5.3	0.0	2.1
21	2.0	0.0	5.2	0.0	2.0
22	0.0	0.0	4.7	0.0	1.9
23	0.5	0.0	4.4	0.0	1.9
24	7.0	0.1	4.2	0.7	1.9
25	6.5	2.6	4.7	3.3	1.8
26	21.0	30.7	10.3	30.1	2.1
27	39.0	32.3	10.2	35.5	2.7
28	6.0	4.5	6.3	4.3	2.4
29	6.0	1.1	5.6	1.2	2.4
30	9.5	2.4	6.0	3.5	2.2
31	1.0	0.3	5.1	0.2	2.0
JAN 1980					
1	0.5	0.0	4.3	0.0	1.9
2	0.5	0.0	4.5	0.0	1.9
3	53.0	59.4	13.4	60.3	2.5
4	10.0	3.9	7.5	9.6	2.2
5	10.5	3.6	7.3	9.3	2.3
6	1.0	0.5	5.6	0.5	2.3
7	0.0	0.0	5.1	0.0	2.1
8	0.0	0.0	4.9	0.0	2.0
9	0.0	0.0	4.0	0.0	1.9
10	0.5	0.3	4.5	0.1	1.9
11	0.5	0.0	4.5	0.0	1.8
12	3.0	3.8	4.5	3.5	1.7
13	0.0	0.0	*	0.0	*

Because of the disappointing return of reliable data and obvious leakages through the plastic sheets, it was decided to repeat the experiment during the period 28.11.79 to 15.1.80. The tipping bucket discharge recorders were much more reliable during this second period resulting in a high return of useable data (Table 12b). Also, comparisons between rainfall totals and surface runoff totals were better than in the previous period. However, surface flows from the improved lysimeter were generally lower than the rainfall totals particularly following the intense rainfall during the 5th December. This suggests that a tear developed in the plastic sheet on or about this date allowing some of the incoming rainfall to enter the lysimeter directly. This is supported by the fact that substantial increases in sub-surface flow occurred during subsequent rainfall events. These increases were much greater than would have been expected from an increase in the rate of leakage through the boulderclay layer. On the other hand, the surface flows from the unimproved lysimeter were generally greater than the rainfall totals, whilst the sub-surface flows reacted only slightly, but positively, to substantial rainfall events. Therefore it was decided to study the surface and sub-surface flows from the unimproved lysimeter during substantial storm events.

Hourly precipitation totals (mm), surface runoff totals (mm) and sub-surface flows (mm/hour) from the unimproved lysimeter for three selected precipitation events during December 1979 and January 1980 are shown in Fig.26. In each of the events illustrated, the surface runoff total exceeds the precipitation total by, on average for the three events, 10%. However, no real significance, in terms of the hydrological balance of the lysimeter, should be attached to this fact because the precipitation during these periods was often in the form of snow and the imbalance between rainfall and surface runoff totals may well have been due to different melt rates in the rainfall collector and on the plastic sheet. In fact, if the precipitation totals, corrected for open water evaporation, and surface runoff totals are calculated for the whole period (28.11.79 – 15.1.80), they are remarkably similar at 432.8 and 435.2 mm, respectively.

Each of the three precipitation events produced increases in the sub-surface flows, though the forms of the increases varied remarkably, being rapid and 'peaky' during 3-4.1.80, slow and of long duration during 25-28.12.79 and intermediate during 4-6.12.79. Since the antecedent sub-surface flows and rainfall totals were similar for the first two events, it can only be assumed that the shape of the sub-surface hydrograph is a reflection of the intensity of the precipitation input. In particular, the rainfall and surface runoff measured on 3.1.80 is a reflection of rapid snowmelt in the rain gauge funnel and on the plastic sheet, respectively. If a similar snowmelt occurred upslope of the lysimeter, then the rapid input of water into the peat profile and then underneath and through the boulderclay layer would explain the rapid increase and subsequent decrease in sub-surface flow. In contrast, the rainfall event of the 25th - 28th December was longer and less intense, producing a broader sub-surface hydrograph. The event of 4-6.12.79 is interesting in that, although the rainfall intensities were, as measured, higher than those of 3-4.1.80, the sub-surface hydrograph was less 'peaky'. This may have been due to the fact that the antecedent sub-surface discharge was higher on the 4th December.

Crude estimates can be made of the quantity of water entering the lysimeter as a result of these precipitation events. This is done by subtracting the expected recession flows (as given in the general recession curve) had the precipitation event not occurred, from what was actually measured. In this way, the effect of the precipitation event on the sub-surface flow may be split into two parts:

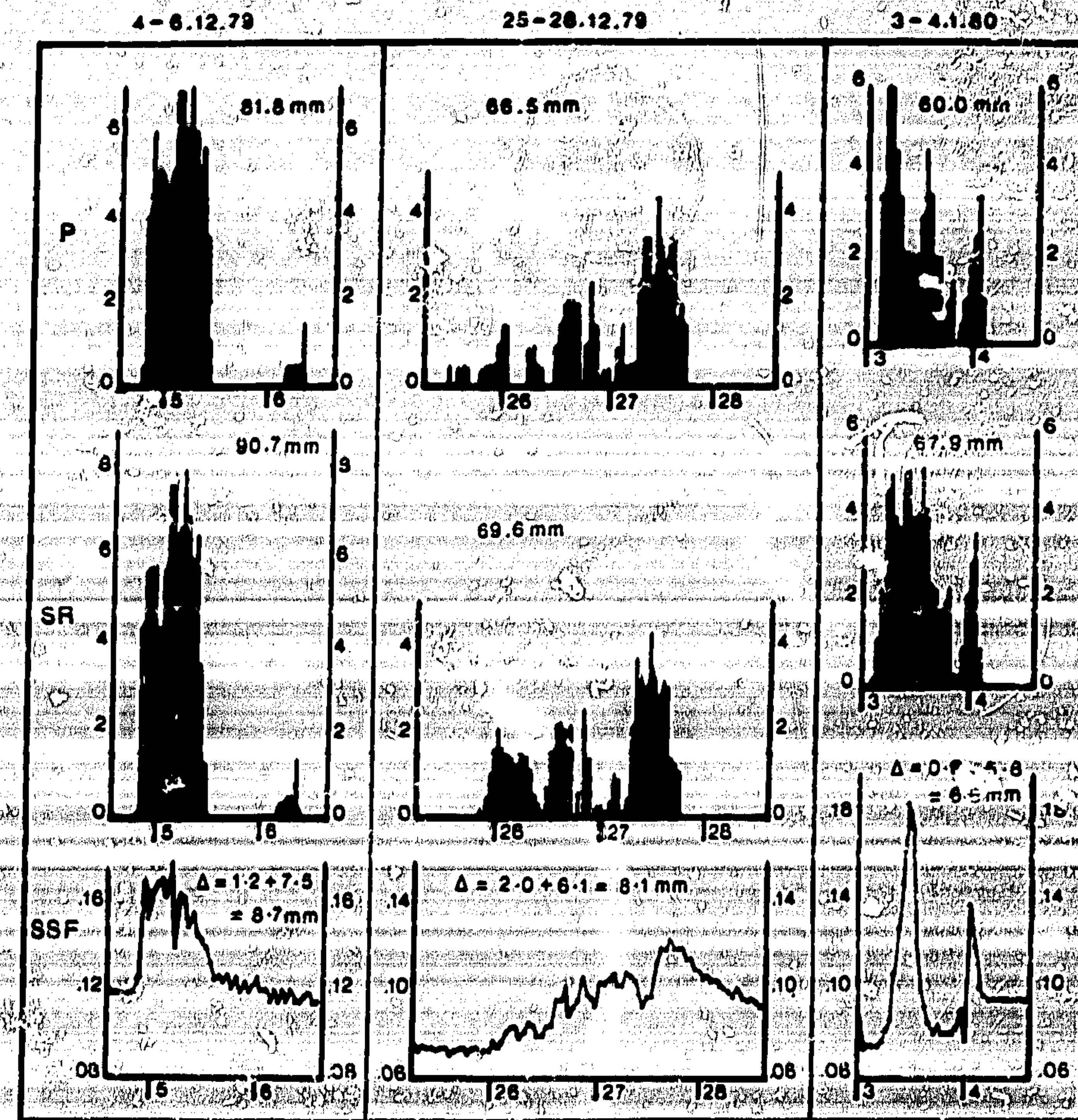

FIGURE 26 Rainfall (P), surface runoff (SR) and sub-surface flow (SSF) from the covered unimproved lysimeter (mm/h).

a) An immediate effect by increasing the sub-surface flows.

b) A residual effect manifest in higher recession flows, and hence, higher drainage totals, at the end of the precipitation event than had the event not occurred.

These two effects have been calculated for each of the storms studied and are shown in Fig.26, the immediate effect being the first, and lower, in each case. Although these calculations can only be regarded as crude estimates, they are remarkably similar for each of the events and follow closely the total amount of precipitation in each case. If the sum of the rapid and delayed effects are compared with the corresponding rainfall total, then the ratios of total effect to total rainfall are 0.11, 0.12 and 0.11, respectively, for each event. Interestingly, if these effects are extended over an annual basis for an average rainfall total of 2400 mm, then an estimated leak of 264 mm or 0.7 mm per day is obtained. This is similar to the figure obtained from a water balance. The significance of this will be discussed later.

Obviously, the data shown in Fig.26 are as a result of the three extreme events that occurred whilst the lysimeter was covered. Lesser events produced similar but less dramatic effects, the actual increase in the sub-surface flows being less apparent but, nevertheless, the 'topping-up' of the sub-surface flows was significant. Similar leakage estimations for all storm events that occurred whilst the lysimeter was covered are shown in Table 13. It is interesting to note from this that, as a percentage of the incoming precipitation, it is the minor events that apparently cause the greatest leakages into the lysimeter. This will be considered further when an attempt is made to distribute the leakage over the range of measured sub-surface flows.

If the above calculations are made for those two periods 28.11.79 - 12.12.79 and 15.12.79 - 12.1.80, when reliable sub-surface flow rates were obtained, then the following leakages are estimated:-

28.11.79 - 12.12.79

Total Rain = 213.3mm
Total Sub-Surface Flow = 52.7mm
Total Sub-Surface Flow expected from recession = 42.7mm
"Rapid" leakage = 52.7-42.7 = 10.0mm
"Topping-up" of recession = 15.2mm
Total leakage = 25.2mm = 11.8% of precipitation.

15.12.79 - 12.1.80

Total Rain = 210.5mm
Total Sub-Surface Flow = 60.6mm
Total Sub-Surface Flow expected from recession = 31.2mm
"Rapid" leakage = 29.4mm
"Topping-up" of recession = 23.0mm
Total leakage = 52.4 mm = 24.9% of precipitation.

Again, it is apparent that most of the leakage, in absolute terms and as a percentage of the precipitation, occurs during relatively low flow periods.

TABLE 13 EFFECT OF PRECIPITATION EVENTS ON SUB-SURFACE FLOWS FROM THE COVERED UNIMPROVED LYSIMETER

DATE	RAINFALL TOTAL (MM)	INCREASE IN SUB-SURFACE FLOW (MM)			
		RAPID	DELAYED	TOTAL	% OF RAINFALL
01-02.12.79	17.5	0.4	5.9	6.3	36
04-06.12.79	81.8	1.2	7.5	8.7	11
07-09.12.79	51.5	0.7	7.9	8.6	17
10-11.12.79	37.5	0.2	3.[illegible]	3.8	10
18-19.12.79	19.5	0.3	4.5	4.8	25
21-26.12.79	65.5	[illegible]	6.1	8.1	12
03-04.01.80	60.0	[illegible]	5.[illegible]	6.0	11

PERMEABILITY INVESTIGATIONS

The possibility of the existence of a leakage through the boulderclay layer under the lysimeter on the improved site was investigated by staff of the Institute of Geological Sciences during October to December, 1980 (Allen and Bird, 1981). Two basic approaches were employed:-

a) To find the water table configuration within the lysimeter and to study the variation of hydraulic gradient with depth.

b) To measure the permeability of the clay forming the base of the lysimeter so that a quantitative estimate of a possible leakage could be made.

A series of Cambridge drive-in piezometers were inserted to the peat/boulderclay interface on a 2m by 2m regular grid within the lysimeter. Daily water levels were measured in each piezometer and contour maps of water levels in the peat inside the lysimeter produced (Allen and Bird, 1981). These show the expected ridge of water across the lysimeter produced by the down-slope hydraulic gradient offsetting the dome shape found in lysimeters constructed in level surfaces. There was no evidence of local sources of leakage into the lysimeter.

Two lines of piezometers, each one at 3m outside an upslope edge of the lysimeter were installed into the boulderclay layer and a series of water level recovery tests carried out so that estimates of the permeability of the clay could be made. The results obtained from the various piezometers varied considerably in the range 0.002 - 0.2m/day, reflecting the diverse nature of the boulderclay layer.

A comparison of the water levels in piezometers installed into the boulderclay layer with those in nearby piezometers installed to the peat/clay interface gave some indication of the hydraulic gradient within the clay. This was done on five separate occasions between November 1980 and Februry 1981 and, on each occasion, a range of values was obtained. Using a mean value, together with the average permeability of the boulderclay, an attempt was made to calculate the leakage into the lysimeter using Darcy's Law:-

$$V = -K \frac{dh}{dl}$$

where V = Leakage Rate (mm/day)
K = hydraulic conductivity (mm/day)
$\frac{dh}{dl}$ = hydraulic gradient (-ve sign indicates flow in direction of decreasing head)

The results obtained are shown in Table 14. These will be used later to compare with leak rates obtained from recession analyses.

TABLE 14 LEAK RATES INTO THE IMPROVED LYSIMETER USING THE RESULTS FROM THE PERMEABILITY TESTS

Time/Date	Estimated leak (mm/hr)	Subsurface flow (mm/h)
1030/01.11.80	0.12	0.27
0950/10.12.80	0.16	0.23
1200/12.12.80	0.10	0.13
1030/13.12.80	0.05	0.23
19.02.81	0.24	0.17

Apart from the results shown in Table 14, the overall conclusions found from this series of tests were:-

a) Leakage occurred into the lysimeter from the underlying boulderclay, the head being available because of the proximity of a hillside and the semi-permeable nature of the clay allowing water movement to occur.

b) The leakage into the lysimeter was not by means of a single fissure but was probably fairly evenly distributed over the total sub-surface area.

c) The rate of leakage varies, being lower immediately after a storm when the ground is fully saturated than after a few days without rain. However, it is thought very probable that after longer spells without rain the rate of leakage would fall as the piezometric heads in the clay fell.

HYDROGRAPH ANALYSIS

The crude water balance employed on the flow data from the lysimeters suggested leakage rates of [illegible]mm/day and 1.0mm/day respectively, into the improved and unimproved lysimeters. Daily flow totals from the lysimeters during particularly dry periods were less than the leakage rates shown above. This suggests that the leakage rates into the lysimeters are not constant and must vary with flow rate.

Also, recession flow data from a $84m^2$ natural lysimeter within the Hafren forest at Plynlimon (Calder, 1976) suggests that, had the lysimeters been fully sealed, they would have ceased to drain well within the 380 hours of recession flows shown in Fig.23 (I.R.Calder, personal communication). This implies that the tail ends of the recessions shown in Fig.23 were as a result of leakages into the lysimeters at which time contributions of direct drainage of the lysimeters were negligible. This is particularly so since the tile drains on the inside of the lysimeters will ensure efficient and rapid drainage by maintaining steep hydraulic gradients within the peat.

In order to determine the points on the general recession curves shown in Fig.23 at which true flows cease, the recession curves of the leakages into the lysimeters are assumed to follow a simple exponential expression,

$$q_t = q_{o}e^{-bt}$$

such as normally used to describe such flows (Barnes, 1939).

Thus the measured flows from the lysimeters, MF, as depicted in Fig.23, are a combination of the true flows, TF, and the leakages, L.

$$MF(f(t)) = TF(f(t)) + L(f(t))$$

$$= TF(f(t)) + q_{o}.e^{-bt}$$

If the natural logarithm of the above expression is employed :-

$$Log_e[MF(f(t))] = Log_e[TF(f(t))] + Log_e q_o - bt$$

and the natural logarithm of the measured flow plotted against time, then it should become a straight line at the point at which true flow ceases and the measured flow is sustained by the leakage into the lysimeter.

This is done for the lower end of the general recession curves of the two lysimeters in Fig.[illegible]7. The values of leakages at time t=0, q_o, and

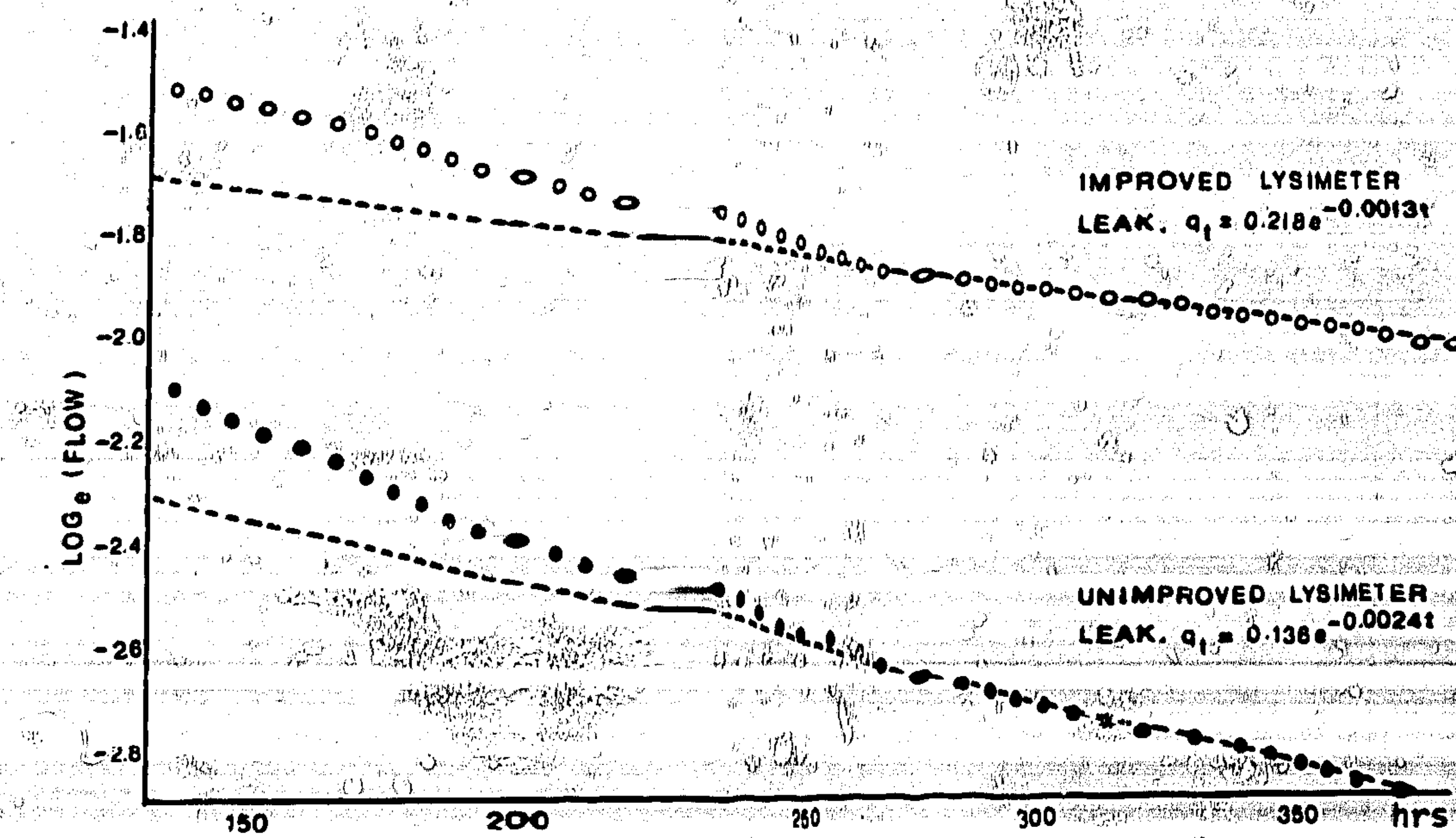

FIGURE 27 Natural log of measured flow (mm/h) vs. time for the Nant Iago lysimeters

the slope of the recession, b, were obtained using the least squares routine.

It is interesting to note that the general recession curves of both lysimeters when extended backwards as simple exponentials become non-linear at approximately the same time. This occurs at about 200 hours or approximately 12 days from the beginning of the recession. At this point the measured flows are 0.160mm/hour (3.8mm/day) and 0.075mm/hour (1.8mm/day) from the improved and unimproved lysimeters, respectively. It is assumed, therefore, that flows less than these values are due solely to leakages into the lysimeters and can be disregarded when computing true flows. These values are larger than the calculated average daily leakage rates.

Having determined the points at which true flows from the two lysimeters cease, it now remains to identify the timing and magnitude of peak leakage flows and the shape of the leak hydrographs during and immediately following precipitation events. If the leakages are due to the permeable nature of the clay seals and differences in hydraulic heads within and upslope of the lysimeters, then it would be expected that the leakages would be at their maximum when the differences in the hydraulic heads (hydraulic gradients) were greatest. This, in turn, depends on the relative rates of drainage of the lysimeters and the areas upslope of the lysimeters. Since the lysimeters, with their permeable backfill and tile drains, would be expected to drain more rapidly than the upslope areas, the hydraulic gradients and hence the leakages would be expected to increase following the cessation of rainfall. This hypothesis is supported by Allen and Bird, 1981 who concluded "the rate of leakage varies being lower immediately after a storm when the ground is fully saturated than after a few days without rain". They went on "however it is thought very probable that after longer spells without rain the rate of leakage would fall as the piezometric heads in the clay fell".

The results of the permeability tests (Table 14) show clearly that, over the range of flows studied, the estimated leak into the improved lysimeter is greatest at the low end of the flow range and decreases reasonably smoothly towards the higher end of the flow range (Fig.28).

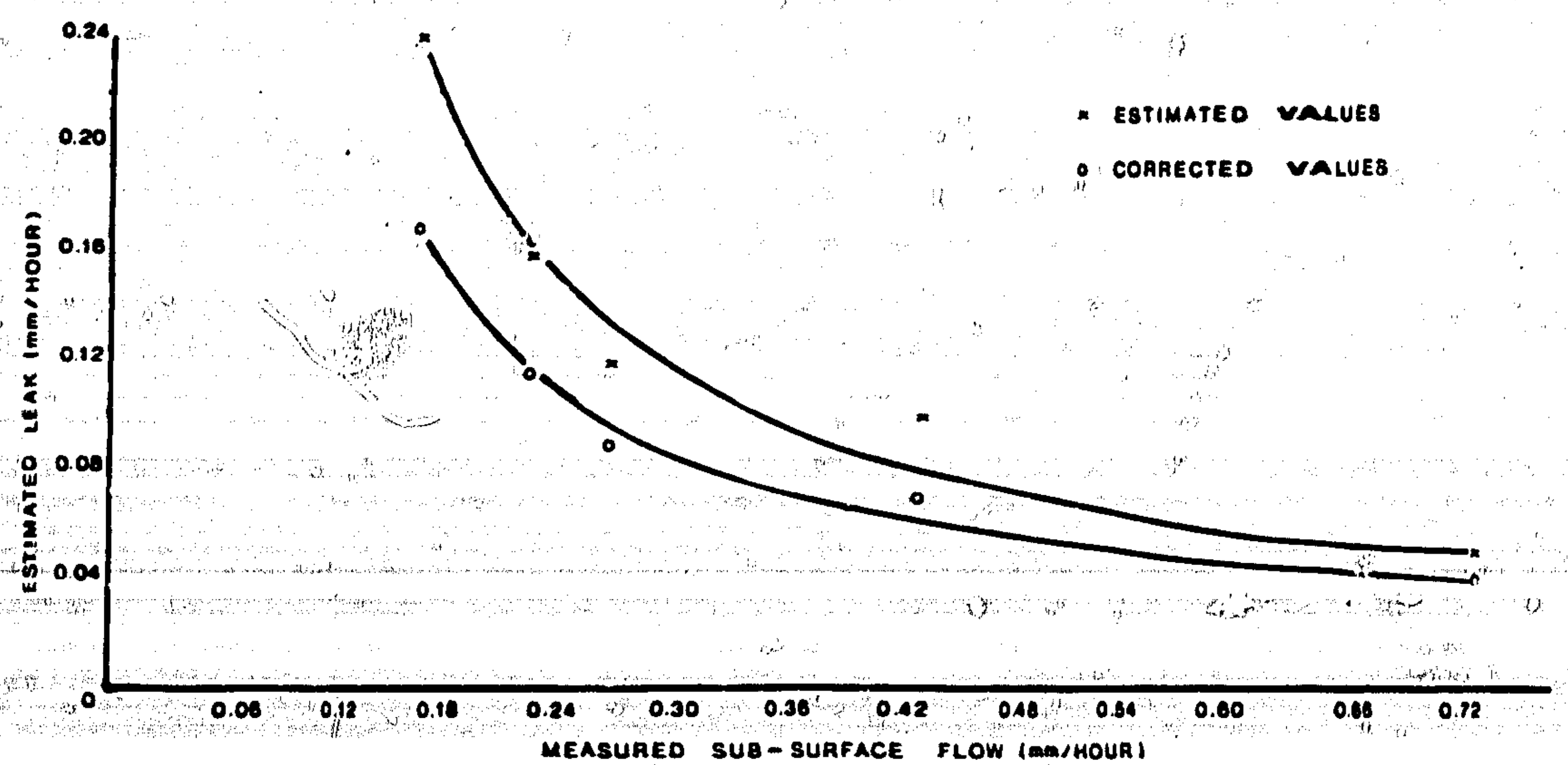

FIGURE 28 Leakage rates into the improved lysimeter estimated from the permeability tests

Although the actual estimates of leakage rate are obviously suspect (one estimate of leakage rate is greater than the measured sub-surface flow), there is no reason to suspect their relative magnitudes. The method of computing the leakage rates:-

$$V = -K.\frac{dh}{dl}$$

where K = saturated hydraulic conductivity (mm/day)

$\frac{dh}{dl}$ = hydraulic gradient

and the fact that the saturated hydraulic conductivity is a constant means that the variations in leakage depend only on variations in hydraulic gradient. The overestimation of leakage rate at the measured sub-surface flow of 0.17mm/hour suggests that the saturated hydraulic conductivity has been overestimated. This, together with the previous observation that true flow from the improved lysimeter ceases at about 0.16mm/hour further suggests that it is about this time that the leakage rate is at its maximum. Accordingly, the estimates of leakage rate obtained by Allen and Bird, 1981 (Table 14) have been adjusted assuming that the measured sub-surface flow at 0.16mm/hour is totally sustained by leakage. The corrected leakage values are shown as the lower curve in Fig.28. In the absence of any further information, these corrected leakage rates were used to estimate true flows from the improved lysimeter. Corresponding leakage rates into the unimproved lysimeter were simply estimated to minimize the differences between the two "true" recession curves. This resulted in an apparent leak that was not manifest until over four days following the beginning of the recession.

The estimated leakage rates and "true" hydrographs were shown earlier in Fig.13a and 13b. The natural logarithms of the "true" flows have also been plotted against time in Fig.29a and 29b. These have initial steep slopes followed by flatter linear portions. Finally, there is a further steep portion as the drainage ceases. This shape of curve is typical of ephemeral streams (Nutbrown and Downing, 1976). Assuming that the recessions of the "true" baseflows from the lysimeters are simple exponentials, then the divergences from the straight lines drawn on Figs. 29a and 29b at approximately 30 hours after the start of the recession presumably correspond to contributions from interflow.

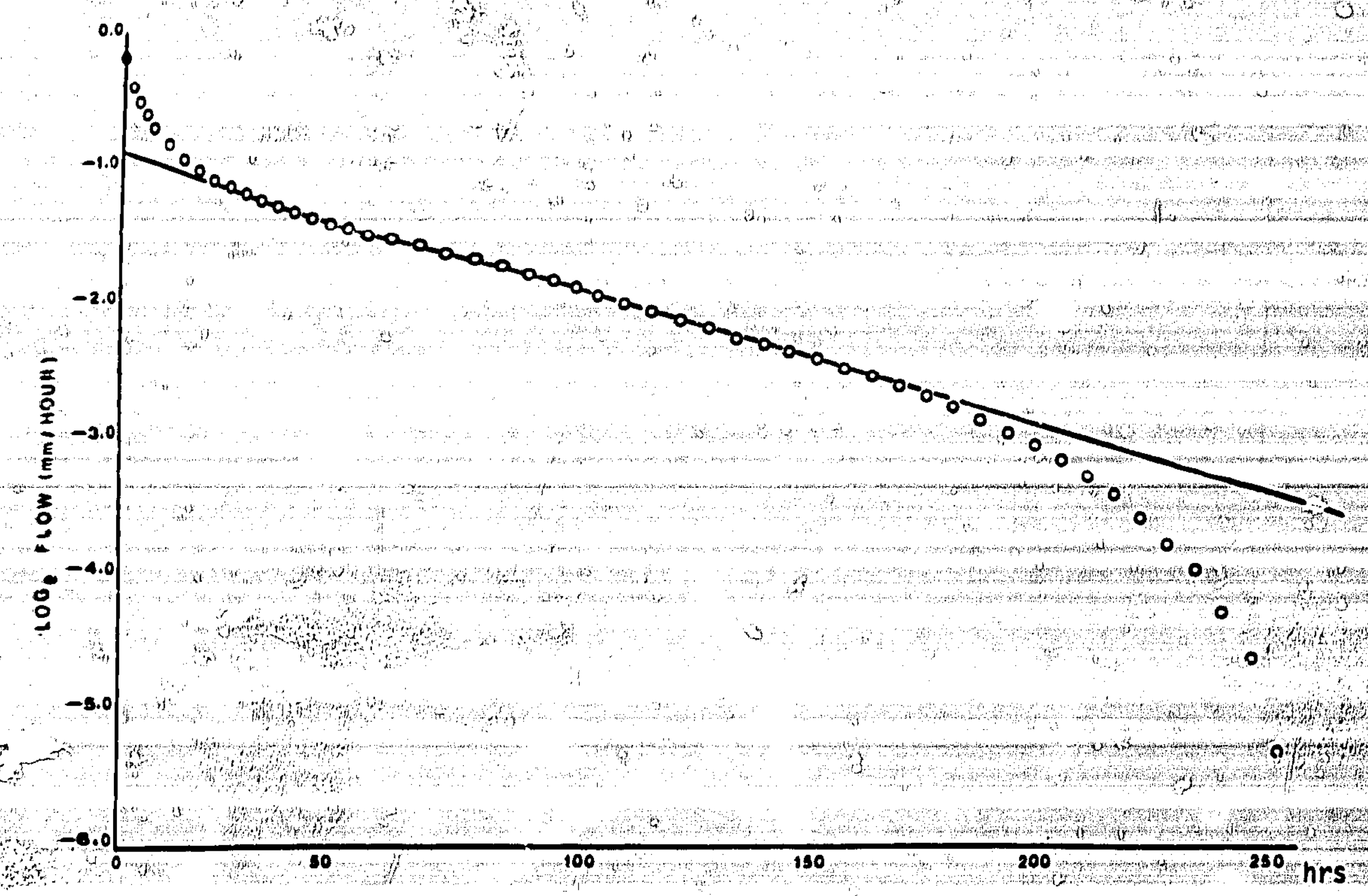

FIGURE 29a Log$_e$ ('true' flow) vs. time for the improved lysimeter

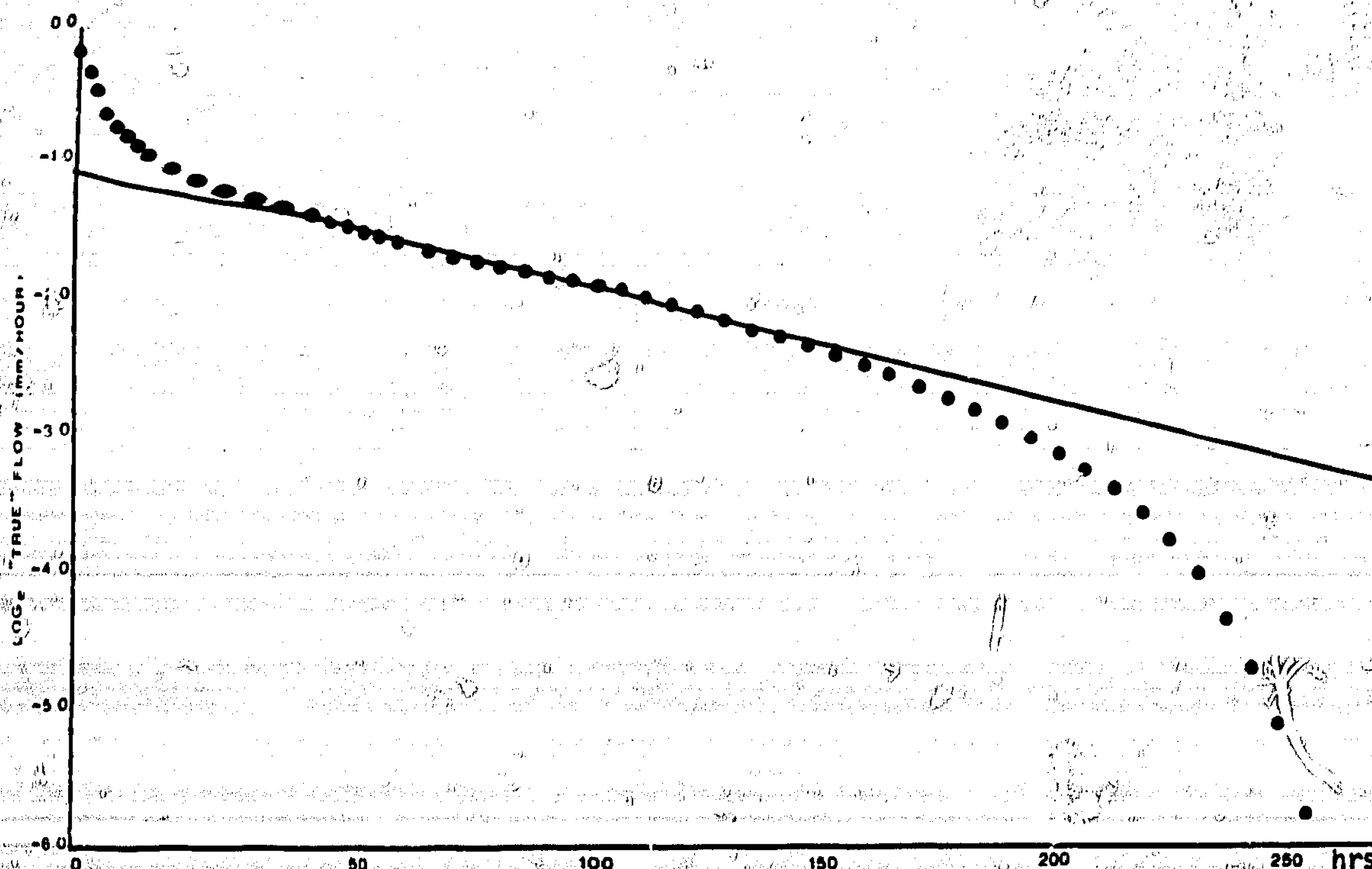

FIGURE 29b Log$_e$ ('true' flow) vs. time for the unimproved lysimeter

APPENDIX II LYSIMETER SOIL MOISTURE - ITS EFFECT ON THE ESTIMATION OF WATER AND NUTRIENT FLUXES AND THE IMPLICATION FOR FLOW ROUTING AND WATER RESOURCES.

The incorporation of soil moisture values, expressed in terms of changes in soil moisture storage in mm over specified periods, into the water balances of the headwater catchments of the Severn and Wye (IH, 1976) was shown to have a significant effect on within-year calculations of evaporation but to have little effect over an annual cycle, particularly when calculated on a wacer-year ba. s. Compared to the relatively stable soil moisture situation in the catchments as a whole, it was thought that the change in soil moisture over an annual period on the recently drained lysimeter plots could have an appreciable effect on the water balance especially on the within-year calculations. As a result, three soil moisture access tubes for neutron scattering soil moisture estimation (Bell, 1976) were installed in the main block of each lysimeter (Fig.30) in order to quantify the following effects.

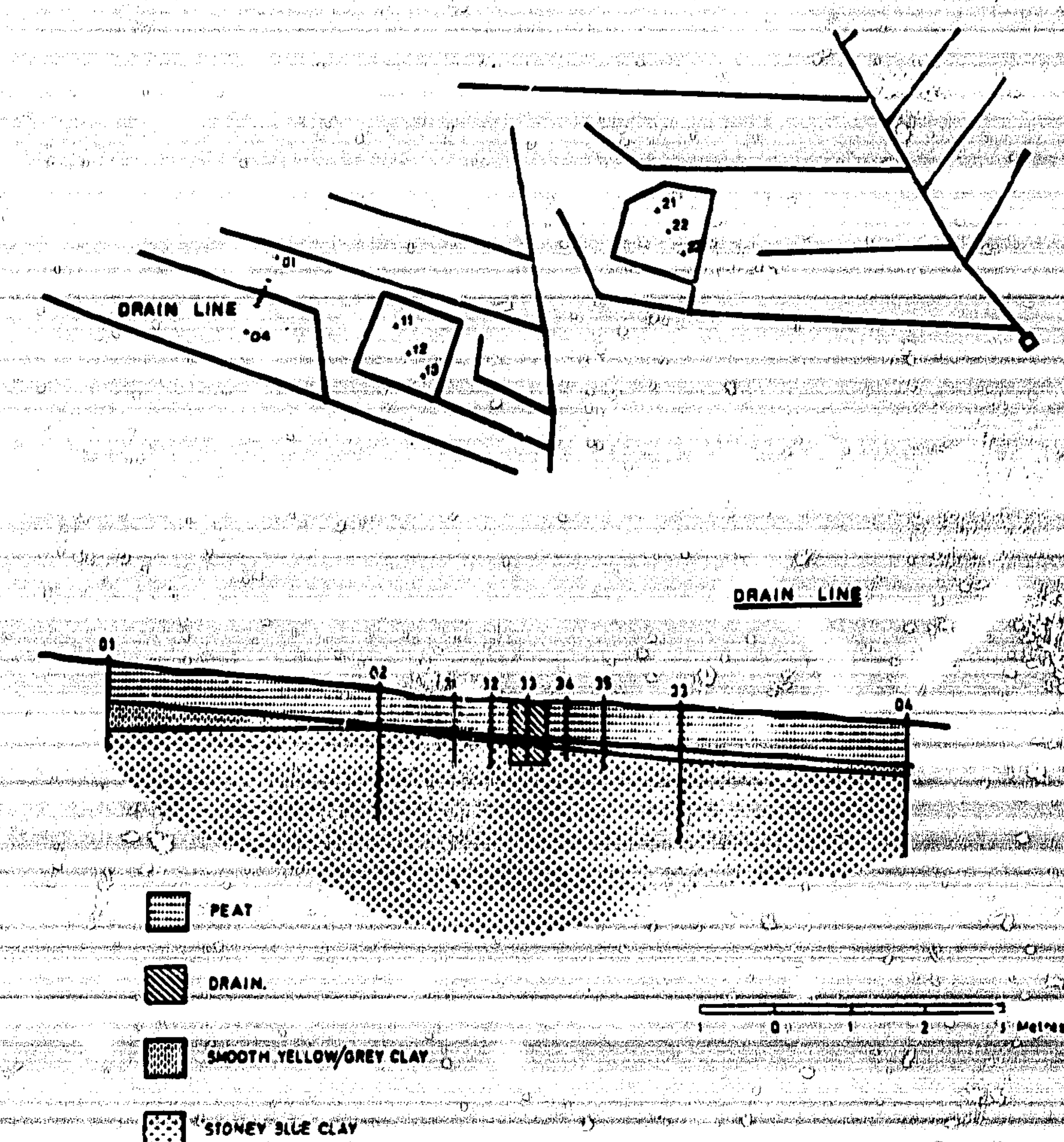

FIGURE 30 Position and numbering of soil moisture sites

(i) The contribution to the water balance.

(ii) To quantify the changes in soil moisture storage on drainage and their effect on total water resources especially during drought periods.

(iii) In conjunction with soil water sampling and chemical analysis, to estimate the quantities of and variation in free nutrients within the lysimeters with regard to defining changes in nutrient storage and pathways for routing of nutrients dissolved in soil moisture to the outfalls of the drainage system.

(iv) To estimate the effectiveness of the tile drainage system in promoting dry enough conditions for satisfactory root growth.

Because of the difficulties involved in defining the eventual positions of the lysimeters and the lack of a control period before their installation, item (iv) was studied separately across an outlying tile drain where nine tubes were installed symmetrically as shown in Fig.30. Readings were taken for a period prior to the extraction of the central tubes, the digging of the drain and the replacement of the tubes, the central one of which was replaced in the backfill of the drain. Subsequent readings were taken to assess the effect of the drain. The results (Hudson and Roberts, 1982) indicated that the drain had little effect more than 1 metre away from either side. Because neither of the lysimeters had tubes in or within a metre of the backfill, the secondary benefit of the soil moisture tubes outside the lysimeters, which were read on the same day in most cases, was to give a quantitative estimate of the drawdown in the backfill within the lysimeter. This would not be realistic in terms of absolute values of soil moisture because of the deeper nature of the peat in the lysimeters. However, it is probably reasonable for the estimation of change in soil moisture, particularly during the summer months when these changes are caused primarily by evaporation. In these cases, soil moisture change is dependent on rooting depth and is independent of total depth of peat, provided that this is not limiting. At times of maximum change when soil moisture has most bearing on the water balance, the soil moisture values from the drain tubes give a good estimate of the changes in the backfill and that volume of soil block in its close proximity within the lysimeter.

The contribution of change in soil moisture to the water balance is therefore calculated by weighting the soil moisture change of each tube with its approximate volumetric extent of representativity within the lysimeter. Each lysimeter is assumed to be a 10m by 10m square with a depth of 2m. Tube 33 from the drain site is assumed to be representative of the backfill which was cut by two sweeps of a V-bucket on a mechanical digger and given a representative volume of 46.8 cu.m (four sides of the lysimeters). Inspection of the pattern of drying out by a time series of total moisture content (Fig.31a,b) indicates that there is a gravitational wedge of soil moisture evident on both lysimeters, so that piezometric gradients in the soil close to the backfill will be greatest at the downslope boundaries of the lysimeters. Also, the lysimeters were orientated with one of their diagonals running downslope, affording a certain amount of symmetry. This means that the tubes (2, 31 and 32, see Fig.30) upslope of the external drain line can be used to represent the downslope drawdown for two sides in the lysimeter block. Conversely, the tubes (34, 35 and 3, see Fig.30) downslope of the external drain line represent the two upslope sides of the lysimeter. The soil moisture change in these volumes, extending 2m from the edge of the backfill into the soil block of the improved lysimeter, is calculated as the arithmetic mean of

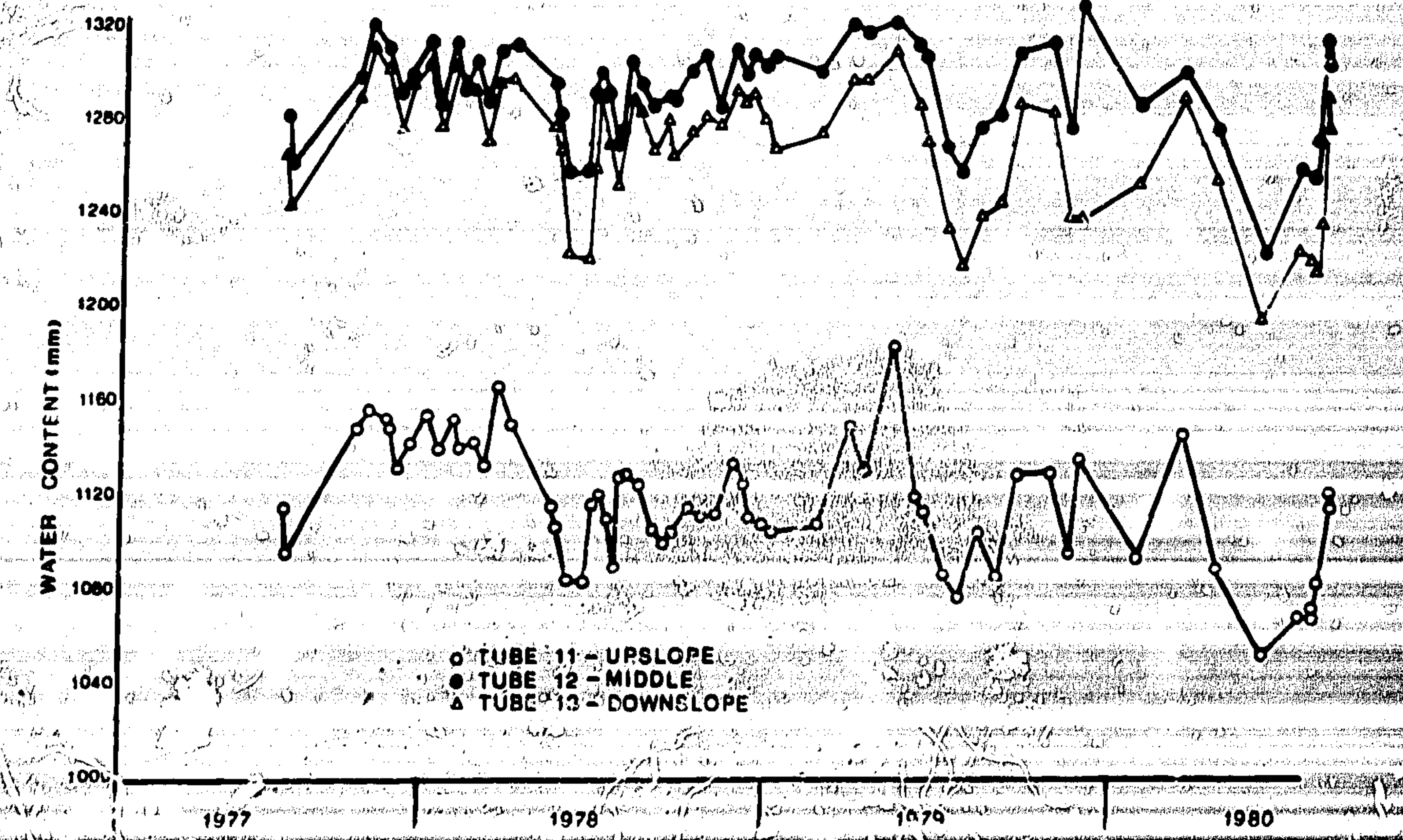

FIGURE 31a Total-profile water content - improved lysimeter

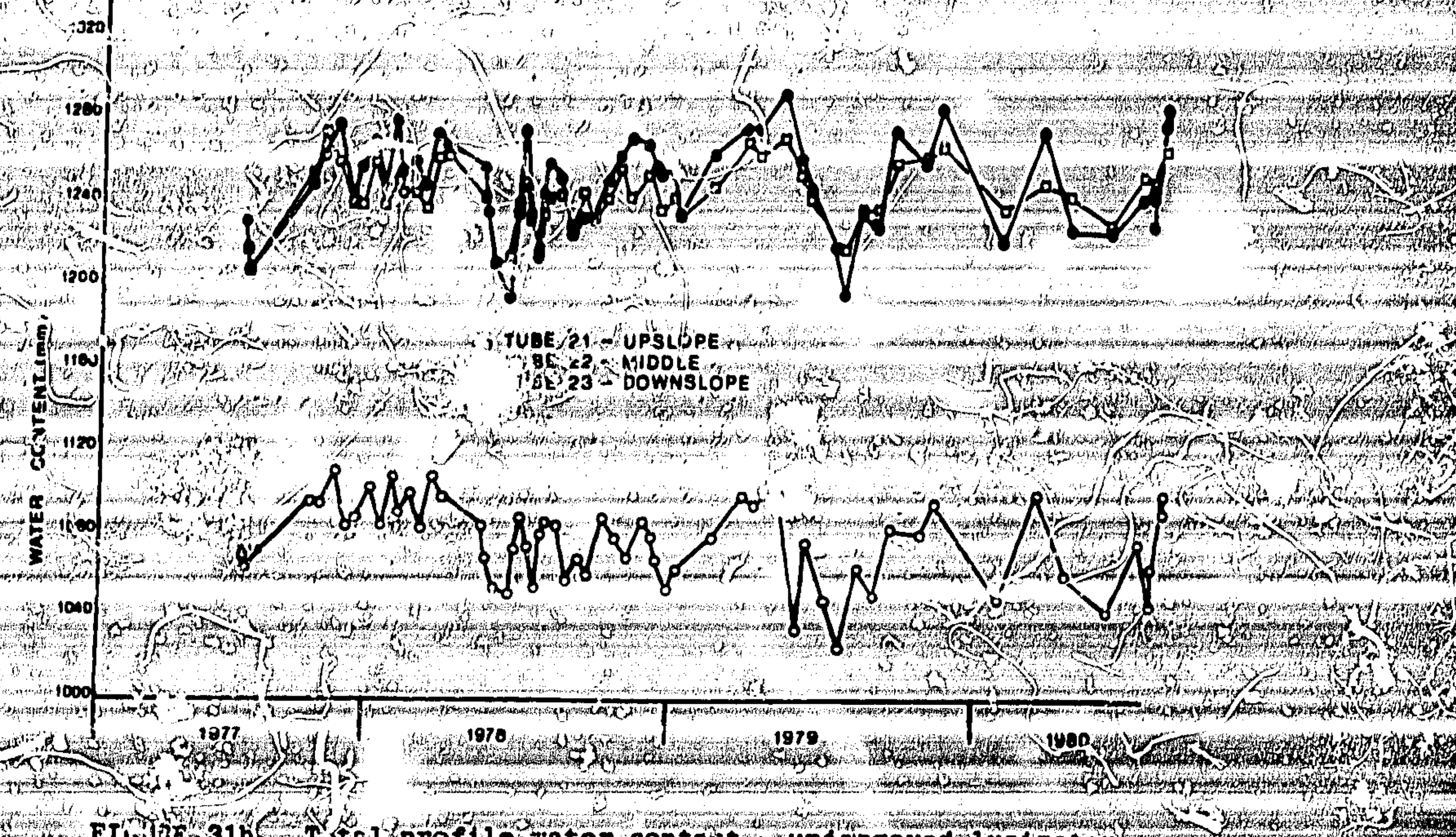

FIGURE 31b Total profile water content - unimproved lysimeter

tubes 2, 31, 32 and 13 for the downslope area and the arithmetic mean of tubes 34, 35, 3 and 11 for the upslope area. For the unimproved lysimeter, tubes 23 and 21 replace, respectively, tubes 13 and 11. The total volume represented above is 112.8 cu.m for each lysimeter. The remaining 40.4 cu.m is represented by the central tubes 12 and 22 of the improved and unimproved lysimeters, respectively.

Using this technique, changes in soil moisture storage between successive reading dates have been calculated for each lysimeter. These together with rainfall, runoff, potential evapotranspiration and water balance residual totals, defined as shown below, are summarized in Tables 15a and 15b.

Residual = Rainfall-Runoff-Potential evapotranspiration-change in soil moisture.

These residuals, together with rainfall totals, are shown graphically in Fig.32. The results from the two lysimeters are generally in very good agreement showing marked seasonal differences. During the wet winter months, large residuals, both positive and negative, are observed. These presumably are a reflection of the response rate of the lysimeters to precipitation inputs i.e. the bulk of the rainfall input during one period may not be manifest as output until the following period. Conversely, during the drier summer months, the residuals are much smaller but generally negative, perhaps a reflection of the fact that actual evapotranspiration is rather less than potential during these periods.

TABLE 15a PERIOD RAINFALL (P), RUNOFF (Q), POTENTIAL EVAPOTRANSPIRATION (ET), CHANGE IN SOIL MOISUTRE (AS) AND WATER BALANCE RESIDUAL FOR THE IMPROVED LYSIMETER

PERIOD	P(MM)	Q(MM)	ET(MM)	AS(MM)	RES. (MM)
19.06.78-28.06.78	68.8	29.9	17.9	39.9	-18.9
28.06.78-13.0[illegible]	173.3	158.9	25.8	-3.5	-7.9
13.07.78-20.[illegible]	3.8	3.4	17.8	-24.9	+7.5
20.07.78-28.07.78	67.5	18.8	20.3	25.0	+5.4
28.07.78-17.08.78	133.7	91.8	34.6	11.7	-4.4
17.08.78-01.09.78	25.7	62.7	29.6	-18.7	-47.9
01.09.78-12.09.78	25.8	0.1	17.3	4.1	+4.3
12.09.78-22.09.78	40.2	25.6	13.7	1.1	-0.2
22.09.78-11.10.78	193.3	158.6	17.7	10.6	+6.5
11.10.78-23.10.78	33.1	25.4	6.6	4.8	-3.[illegible]
23.10.78-08.11.78	40.1	44.5	6.8	-7.4	-3.8
08.11.78-27.11.78	267.0	311.5	7.3	15.2	-67.0
27.11.78-08.01.79	372.9	[illegible]04.7	3.3	-1.3	-33.[illegible]
08.01.79-21.02.79	182.[illegible]	110.0	2.7	-1.4	+71.1
21.02.79-28.03.79	477.6	424.9	20.1	12.4	+20.2
28.03.79-04.06.79	514.1	477.1	129.7	-10.2	+76.5
04.06.79-05.07.79	[illegible]	20.0	85.8	-36.7	+0.1
05.07.79-20.07.79	[illegible]	0.0	44.2	[illegible]	-0.9
20.07.79-10.08.79	[illegible]	6.8	51.4	[illegible]	+5.5
10.08.79-31.08.79	204.7	192.0	45.2	0.0	-32.5
31.08.79-20.09.79	114.2	44.3	35.8	[illegible]	+8.1
20.09.79-26.10.79	204.2	213.7	35.4	1.9	-46.8
26.10.79-12.11.79	273.7	266.0	8.7	-6.0	+5.0
12.11.79-29.01.80	621.8	826.7	24.0	-1.6	[illegible]
29.01.80-12.03.80	372.2	325.0	21.4	12.6	+13.2
12.03.80-15.04.80	156.7	207.0	38.7	-30.9	-58.1
15.04.80-04.06.80	47.7	1.7	161.1	-40.9	-56.2

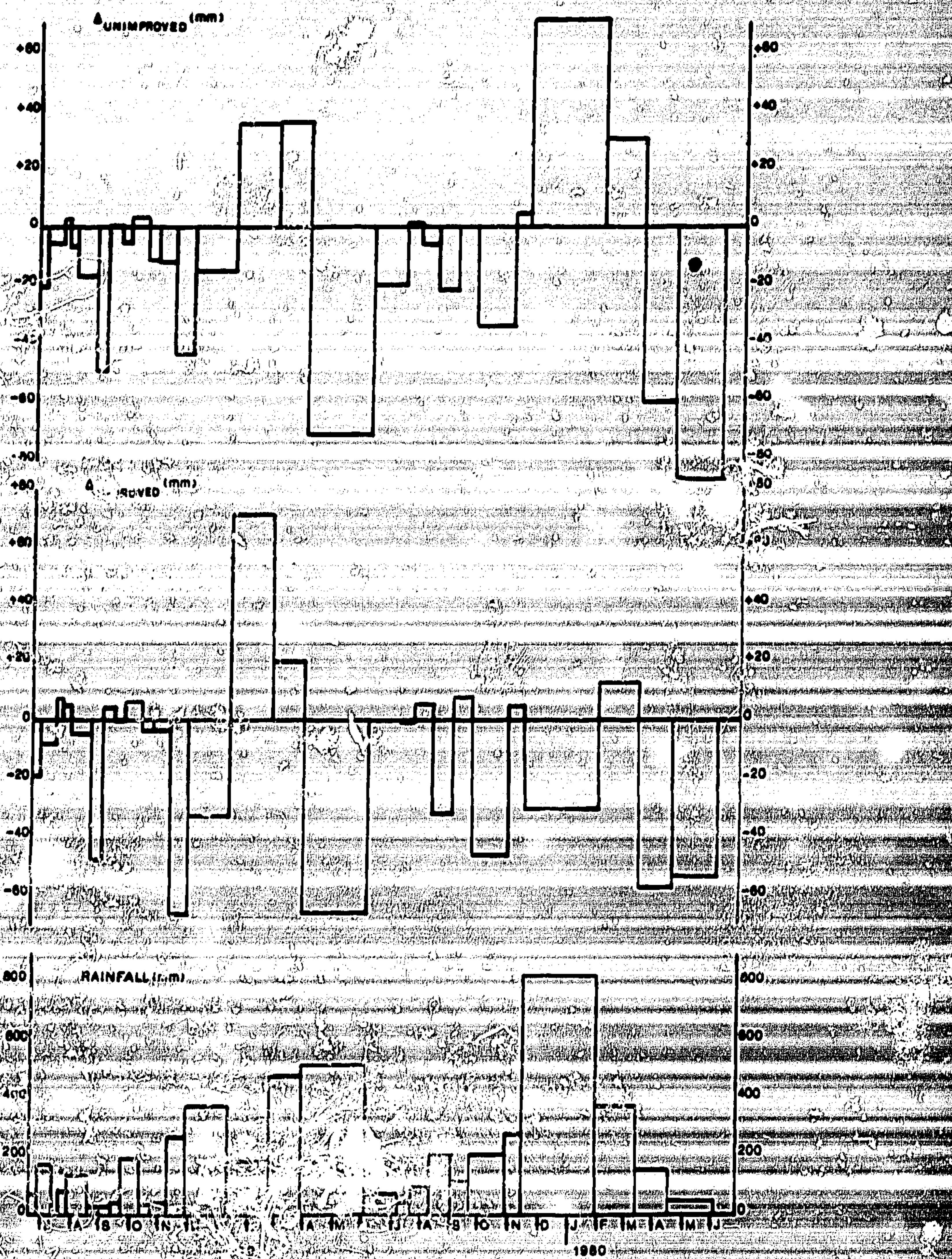

FIGURE 32 Period rainfall and water balance residuals.

TABLE 15b PERIOD RAINFALL (P), RUNOFF (Q), POTENTIAL EVAPOTRANSPIRATION (ET), CHANGE IN SOIL MOISTURE (AS) AND WATER BALANCE RESIDUAL FOR THE UNIMPROVED LYSIMETER

PERIOD	P(MM)	Q(MM)	ET(MM)	AS(MM)	RES. (MM)
19.06.78-28.06.78	68.8	31.3	17.9	40.0	-20.4
28.06.78-13.07.78	173.3	157.8	25.8	-4.7	-5.6
13.07.78-20.07.78	3.8	7.3	17.8	-24.1	+2.8
20.07.78-28.07.78	67.5	27.2	20.3	26.8	-6.8
28.07.78-17.08.78	133.7	106.5	34.6	9.5	-17.0
17.08.78-01.09.78	25.7	67.8	29.6	-22.5	-49.2
01.09.78-12.09.78	25.8	1.4	17.3	6.1	+1.0
12.09.78-22.09.78	40.2	31.6	13.7	0.3	-5.4
22.09.78-11.10.78	193.3	159.4	17.7	13.1	+3.1
11.10.78-23.10.78	33.1	30.9	6.6	6.9	-11.3
23.10.78-08.11.78	40.1	48.3	6.8	-3.2	-11.8
08.11.78-27.11.78	267.0	294.4	7.3	8.9	-43.6
27.11.78-08.01.79	372.9	391.2	3.3	-6.6	-15.0
08.01.79-21.02.79	182.4	137.8	2.7	6.3	+35.6
21.02.79-28.03.79	477.6	411.4	20.1	10.0	+36.1
28.03.79-04.06.79	514.1	475.6	129.7	-19.8	-71.4
04.06.79-05.07.79	59.2	35.0	85.3	-32.0	-19.6
05.07.79-20.07.79	33.5	0.0	44.2	-12.2	+1.5
20.07.79-10.08.79	90.0	13.6	51.4	30.7	-5.7
10.08.79-31.08.79	204.7	183.3	45.2	-2.4	-21.4
31.08.79-20.09.79	114.2	49.7	35.8	28.0	+0.7
20.09.79-26.10.79	204.2	204.5	35.4	-1.8	-34.0
26.10.79-12.11.79	273.7	247.0	8.7	13.5	+4.5
12.11.79-29.01.80	821.6	744.8	24.0	-17.4	+70.4
29.01.80-12.03.80	372.2	303.1	21.4	17.3	+30.4
12.03.80-15.04.80	155.7	210.0	38.7	-32.3	-59.7
15.04.80-04.06.80	47.7	19.3	141.1	-25.9	-86.8

The observed residuals in the water balances could be as a result of several factors. These include:-

(i) No correction has been made to the rainfall inputs during snow conditions. Although it is generally accepted that ground level rain gauges overestimate inputs during snow conditions, Table 5 showed that the snow estimate for November 1978 (367.2mm) is much greater than that given by the ground level gauge at the Nant Iago site (293.9mm). This could well have been the cause of the large negative residuals observed for both lysimeters during the period 8-27.11.78. Also, it is conceivable that precipitation inputs as snow to the two lysimeters were in fact much greater than estimated by the ground level gauge because of drifting into the shelter afforded by the walls of the lysimeters.

(ii) No allowance has been made for the different grass types when calculating evapotranspiration. The Penman estimate used is based on short grass and it is likely that the Juncus/Molinia vegetation on the unimproved lysimeter will transpire at lesser rates. In fact, Roberts (1983) did note greater transpiration rates from the improved then the indigenous pasture though, in this case, actual rates may have been less than potential during the drier summer.

(iii) The calculation of changes in soil moisture storage over the larger part of the area of the lysimeters was done using data from outside the lysimeter areas. This is compounded by the fact that these changes were by far the greatest experienced and do not take into account local conditions within the backfill surrounding the lysimeters.

(iv) The uncertainty in the flow data. Although the balances for the two lysimeters were generally in agreement, differences did occur. This is seen particularly during the period 12.11.79-29.1.80 when the improved lysimeter showed a deficit of 31.1mm whilst the unimproved lysimeter showed a surplus of 70.4mm. This particular period was very wet and it was at this time that cracks in the plastic sheeting surrounding the improved lysimeter became evident. It is conceivable that surface runoff could have entered the improved lysimeter through these cracks. Although some correction has been made for this by a comparison of very high flow rates from the two lysimeters, this may not have been enough.

Bearing these factors in mind, the balances obtained over the entire period are remarkably close in terms of the total flows. For both lysimeters, a negative total residual was obtained. For the improved lysimeter, the residual was -340mm, representing 7.6% of the total flow, whilst for the unimproved lysimeter a value of -299mm was obtained (6.8% of total flow). Whatever the cause of these imbalances, it is gratifying to note that they are small compared with the total flows and are similar in magnitude.

Item (ii) in the original specification for the soil moisture study, "the changes in soil moisture storage after drainage and their effect on water resources", has been covered by Hudson and Roberts, 1982 for the tubes around the external drain. The lysimeter soil moisture results are instructive, however, in that the time series shown in Fig.31a and b show, not only the obvious dryness of the upslope tube in each lysimeter, but also a trend towards greater variations in soil moisture ranges on the improved lysimeter compared with the unimproved. The upslope tube on the improved lysimeter also shows a tendency for winter soil moisture values to decline over the period. There is a hint of this also on the unimproved but it is not quite so obvious. If anything this suggests that the greater transpiration rates from improved grassland noted by Roberts, 1983 may be having the effect of increasing soil moisture deficits in summer relative to the indigenous Juncus/Molinia vegetation. This observation is supportive of the ability of improved pasture to "drain itself" and is implicit in the success of the spike rotavation method of improvement developed at Pwllpeiran E.H.F. which relies on the operation of this positive feedback mechanism. The declining winter levels may be a result of soil structural changes on drying and root foraging, the continued effect of the tile drainage or a combination of both. Whatever the reason, it is a good sign for the maintenance of suitable conditions for sward growth without any visual signs of stress occurring during particularly dry periods.

It is not feasible to use the lysimeter water balance results to assess the differences in hydrological response of the tile drained area before and after drainage because drainage installation was part of the lysimeter construction procedure. The best studies of this type rely on a high percentage of drainage occurring on an existing topographical watershed, e.g. Robinson, 1980 at Coalburn and Conway and Millar, 1960 at Moorhouse. However this study of soil moisture changes reported here is a secondary source of information that can give some clues to the likely behaviour of drained areas.

Various attempts have been made to assess the effects of tile drainage on soil moisture (Hudson and Roberts, 1982) and water table levels (Newson and Robinson, 1983) in soils in the mid-Wales region. Both studies indicate that extra storage capacity is made available in drained soils by the general drying out of the soil profile, though subsequent structure changes in soil on drying, particularly in peat, may lower field capacity to compensate. At the same time, the cracking and opening up of the upper soil horizons increases the infiltration capacity of the soil making these areas more receptive to storm rainfall. Though the total amount of storm rainfall that can be stored in the post-drainage profile may well be similar to the pre-drainage situation, benefit will be most noticeable during high intensity rain storms when there is greater likelihood of the total soil moisture storage capacity being utilized due to the increase in infiltration rates. In contrast, little benefit would be gained for long duration, low intensity storms where rainfall intensities are not sufficiently high to produce rapid surface runoff even in the pre-drainage period. Similarly, the latter portion of a long duration, high intensity storm would be little affected because, by this time, the soil store would be saturated.

This hypothesis was tested and partly supported by results from an infiltration survey carried out during the summer of 1978. Constant head infiltrometers were used on a network of points across the field plot surrounding the improved lysimeter to determine the variation in infiltration capacity into massive peat. Without even allowing for greater than "natural" heads in the infiltrometers, infiltration rates varied greatly (range 0.1mm/hr to 326.6mm/hr). The lower values could not explain the rapid response of the improved lysimeter to rainfall and were probably representative of pre-drainage infiltration rates into remnants of massive peat. Some of the sample points, however, displayed very high infiltration rates that could not easily be explained by surface cracking induced by cultivation. This suggests that sub-surface cracks caused by rotavation or dessication are capable of conducting water rapidly in a sub-surface channel network without the water ever becoming part of a true soil moisture store, however transiently. Surface evidence of a gradually increasing density of mole hills on the drained site over the study period suggests animal activity as an agent of enlargement for the sub-surface drainage network, if not the initiation of the network. Moles have also been implicated in soil pipe formation in other areas of the Wye catchment (Gilman, 1971).

For all its comparative efficiency in removing excess water from agricultural land, the tile drainage system, together with the effects of mole activity, is less effective in converting rainfall to streamflow than the rapid concentration of surface water in ephemeral channels over waterlogged soils in undrained situations. It follows therefore that the increase in resistance to flow afforded by the new drainage network will increase concentration times of flow and hence reduce flood peaks. With a greater volume of soil moisture store in some cases reducing the volume of flood flows at the same time, the net effect should be a noticeable reduction in flood hazards on the tile drained peat catchments.

Among other studies in the literature, Newson and Robinson, 1983 adopt the logical, but unusual in the upland context, approach of studying catchment average unit flood hydrographs before and after tile drainage of both peaty gley and clay soils. Their results confirm that the above hypothesis holds good for tile drainage systems though it is interesting

that pre-afforestation open drainage of moorland at Coalburn, Northumberland (Robinson, 1980) resulted in an increase in flood peaks. This suggests that the gripping and open arterial drainage network characteristic of afforestation schemes exhibits lower flow resistance than the undisturbed conditions where flows comprised mainly surface runoff in sheet form or in ephemeral channels.

The aim of drainage is to reduce waterlogging by encouraging the loss of water under the influence of gravity away from the rooting zone of the standing crop. This promotes aeration, mineralization of required nutrients and ultimately increased crop productivity. As suggested above, a reduction in flood hazard may also be a benefit of tile drainage but this must be balanced against the possibility of changing streamflows during drought conditions. All other factors being equal, the reduction in runoff volume during flood peaks must be compensated by a post-drainage increase in baseflow. The implication for dry weather flows in upland catchments is one of increased yields. Although the total soil moisture will have been reduced by drainage, that which remains becomes more available for baseflow as a result of the steep piezometric gradients set up around the drains. This hypothesis is supported by the soil moisture values from the lysimeters which show an increasing range after drainage.

This gain may not be particularly far reaching, however, as water resources may only benefit during moderately dry periods. Traditionally, it was thought that peat bogs and mires provided the bulk of summer baseflow in mid-Wales, but discontinuities in the baseflow recessions at Plynlimon during 1976 suggested that many peat sources had dried up about 20 days after cessation of rainfall. This compares with the estimate of 12 days for the lysimeter flows in this study. Beyond this period, baseflow yields from the catchments were sustained by perched shallow aquifers underlying peat deposits. These aquifers, usually of glacial drift or gravel deposits are not directly affected by the tile drainage of the overlying peat and provided that winter recharge has filled the groundwater store before the dry period, low flows in very dry summers should not be affected.

One further point regarding changes in flow routing concerns the behaviour of the underlying clay deposits of the valley bottom mires. It is clear from the measured flow data from the lysimeters that considerable fluxes of water move through the clay into the overlying peat as a result of hydraulic gradients. By implication, the further downslope on the mire, the greater the hydraulic head in the clay relative to the controlling height of the upslope extremity of the clay deposit (see Fig.12). If the hydraulic conductivity of the clay is constant, then fluxes through the clay will increase downslope. This is manifest in the increasing depth and wetness of the downslope peat on the mire and explains the corresponding increase in difficulty of the initial draining. The greater groundwater inputs to the peat at the lower end of the mire more than compensated for the increased piezometric gradients in the peat caused by the proximity of the abrupt discontinuity at the edge of the terrace area (Fig.3). The effect of the tile drainage was to increase relative hydraulic heads by lowering the water table in the peat and hence to cause more water to move through the clay than previously. Because the lysimeters were both fairly close to the top of the upslope extremity of the clay, it is entirely feasible that the flux of water into the lysimeters (the "leak") only started at that point in the post-drainage phase or at least was of much lower magnitude before hydraulic heads were increased. This could also explain why there was greater leakage into the improved lysimeter, being further down the slope than the unimproved lysimeter and therefore experiencing greater hydraulic gradient.

Item (iii) of the original aims of the soil moisture part of the study was investigated by collecting soil water samples from depths of 20, 40, 60, 80, 100 and 120 cm inside each lysimeter. Porous pots and drilled stainless steel tube vacuum samplers were used for this purpose. Both instruments proved inadequate, however, and provided only intermittent and small volume samples. Results from the study were scarce, therefore, and no comparison with flows, flow concentrations or soil moisture values was attempted. This sampling was abandoned in the autumn 1978.

Generally, the concentrations of the various nutrients in the soil water samples that were collected were of the same order as found in the streamflow samples taken in the Wye catchments (Robe-ts et al., 1983), i.e. N 0-1.0mg/l, K 0-05mg/l. However, there were some isolated occasions when very high values of, particularly nitrogen (up to 9 mg/l) and phosphorus (up to 0.3 mg/l) were found in both lysimeters. During these occasions, the higher values were obtained from the samples collected in the upper profile with concentrations decreasing with depth. These high nutrient concentrations were generally found in the summer months during high flow periods, though this may have been a reflection of soil moisture availability for sampling purposes. The high nitrogen concentrations were generally caused by organic nitrogen. Bearing in mind the problems caused by peat particles blocking the pores of the porous pots used to sample the soil water, this suggests that the weathering of these peat particles may well have been the cause of at least some of the high concentrations. However, the sparsity of available data means that the origin of these high concentrations can only be speculated upon.