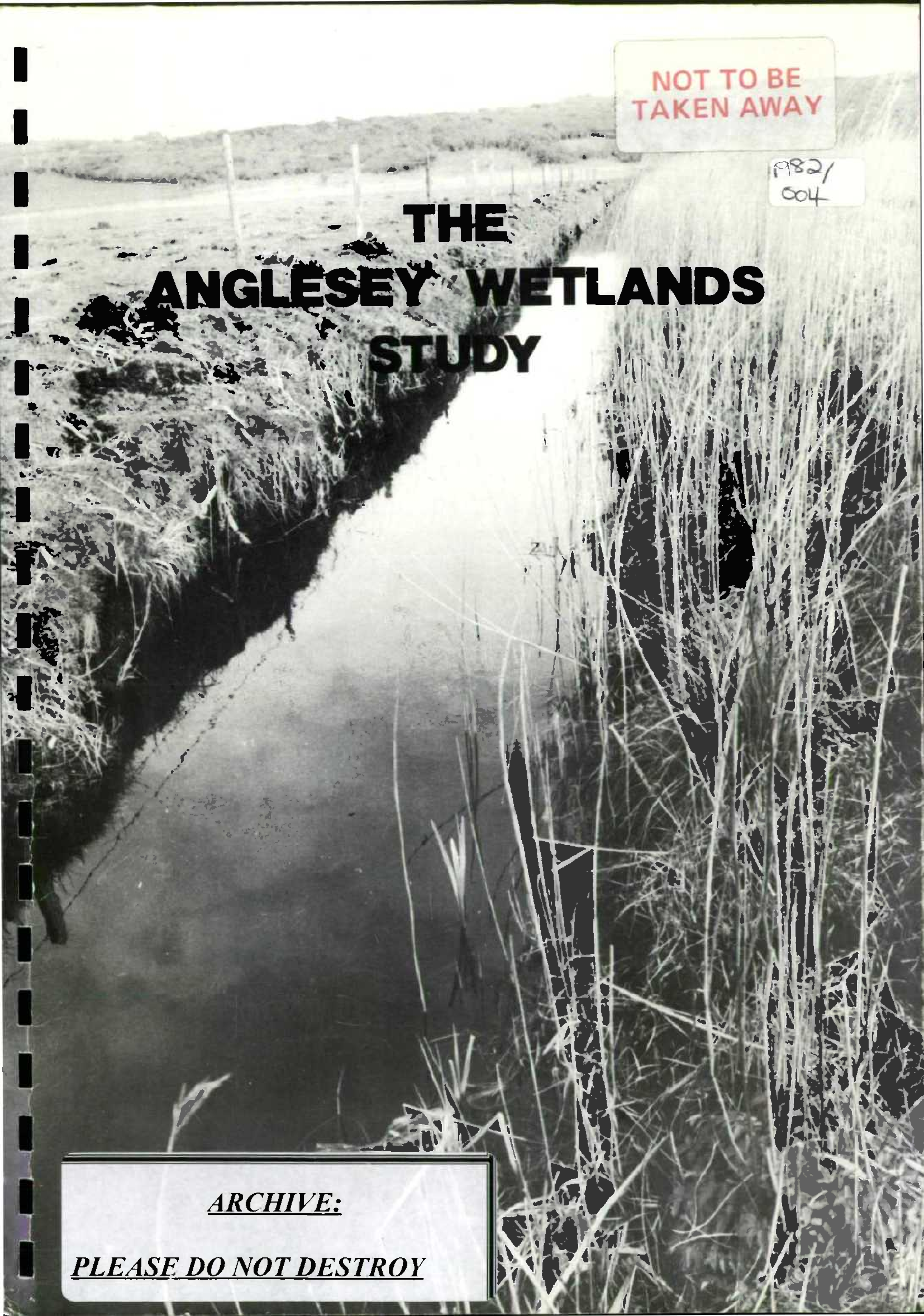
THE
ANGLESEY WETLANDS
STUDY



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ANGLESEY WETLANDS
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THE ANGLESEY WETLANDS STUDY

The Final Report of a three-year study
by the NERC Institute of Hydrology,
commissioned by the Nature Conservancy Council.

It has long been recognised that the conservation of wetland sites cannot be achieved merely by enclosure and protection from direct interference, but requires an active management based on scientific principles, and aimed at mitigating the indirect influence of the management of surrounding land and controlling the natural succession inherent in many wetland ecosystems.

The scientific principles for the active management of a wetland are largely hydrological: for this reason the Nature Conservancy Council commissioned the Institute of Hydrology (IH) to investigate the hydrological aspects of the conservation of one special wetland type, and to explore the more general problem of wetland conservation and its relationship with modern agriculture.

The four Anglesey fens, Corsydd Erddreiniog and Goch, y Farl and Bodeilio, were recognised by the Nature Conservation Review as deserving Grade 1 (Erddreiniog and Goch) and Grade 2 (y Farl and Bodeilio) status. All are subject to potential or actual threat from agricultural activity. Cors Erddreiniog is partly designated a National Nature Reserve (NNR), the remainder of the site being in agricultural use, while Cors Goch is partly reserved by a local Naturalists' Trust. Cors y Farl is privately owned and reserved for shooting, while Cors Bodeilio is used for rough grazing.

The immediate problem at Cors Erddreiniog is that land adjacent to the NNR, formerly used as rough grazing, is now being improved for more intensive use. Among the possible future management options, IH was asked to examine the compatibility of agriculutral and conservation uses of adjoining land.

Hydrological measurements at Cors Erddreiniog, compared with similar measurements at Cors Goch, taken as a 'control' site, show that there is sufficient water to maintain healthy wetland communities at Cors Erddreiniog, even in association with pastoral use, but the water supplies need to be redistributed to maintain winter and spring flooding of the reserve area.

This report is the third in a series; reference is made in the text to material, especially data, contained in the reports of the first and second years of the project.

CONTENTS

THE CONTEXT

> *"SEMI-NATURAL: Hitory of previous land-use often complex. Several factors modifying the environment. The effects of these must be determined. The choice of habitat pattern and species diversity determined by the land manager in relation to surviving flora and fauna and prior condition of area. The environment can be manipulated according to the conservation interests and objectives."*
>
> *(Duffey, 1971)*

PREFACE

This investigation has attempted to give the science of hydrology a new application; since hydrologists most often work in the context of civil engineering the major applications of hydrological study have been towards keeping society dry, or rather, just wet enough! Peat hydrology has been a neglected aspect of the subject for many years. This neglect is out of proportion to the area covered by the peatlands of Britain, especially in view of the conservation interest of those which are still wet enough to provide remnants of a typical British habitat. It is no accident that the British Ecological Society's Mires Research Group has consistently advocated more effort on peat hydrology. At this late stage of deterioration in our wetlands the project reported here has attempted to bring the available hydrological techniques to bear on an extremely complicated area of fen peat. It is clear that certain simple techniques should be applied on a much broader basis in future; it is also clear that new and specially adapted techniques will be necessary to achieve a breakthrough in key areas.

However, it must be admitted that the investigators were both inspired and humbled by a study done exactly half a century before this one: Godwin's hydrological investigation of Wicken Fen in the late 1920's set a model which has been much overlooked. Another East Anglian fen, Woodwalton, provides the hope that, with careful management, wetlands can recover from their long period of neglect and that in the future the conservationist will be able to offer "restoration" as a positive approach to set against the "reclamation" beloved of progressive agriculture.

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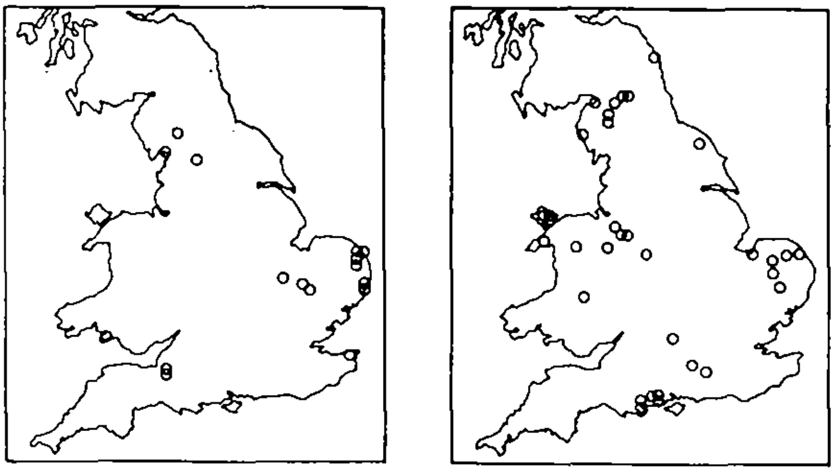
Acknowledgements

The authors would like to record their warm appreciation of the help accorded to them by N.C.C. staff, especially the Warden at Cors Erddreiniog, Les Colley, who quickly mastered hydrological fieldwork and maintained a good flow of data, even under adverse conditions. Haydn Williams and Stephen Ward first perceived the need for the study; Brian Ducker, Tim Blackstock, David White, Roger Meade and John Ratcliffe helped us finish it off. Whilst farmers around Cors Erddreiniog clearly have different perceptions of the need for conservation, we are indebted to them for a cheery approach to our activities: Messrs Williams (Nant Isaf), Jones (Rallt) and Morgan (Bodgynda).

THE CONTEXT

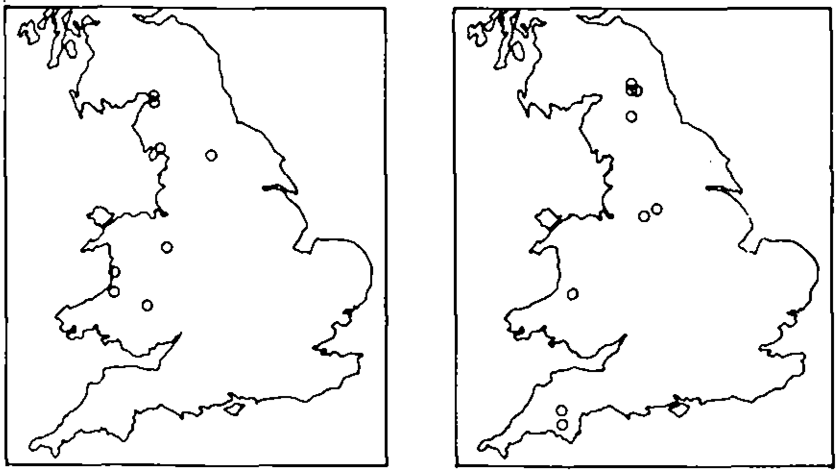
1.1 Wetland conservation in Britain

As recently as medieval times, the land surface of Britain was dominated by three types of terrain: upland moor and scrubland, forested slopes and valley wetlands. Of these wilderness types, only scattered remnants of wetland preserve their original state: moorlands are grazed and burned, forests are managed or replaced by agricultural crops and plantations. Wetland areas in Britain offer a wide range of habitat, this diversity arising from the varied geology of Britain, from the climatic gradients of the continental margin and from varied management practices. In addition to floodplain marshes and saltmarshes, Britain encompasses the spectrum of temperate mire types, from fen basins in the east to raised bog and blanket bog in the north and west. (Figure 1). Between these extremes lies a variety of mires acid and alkaline, base-rich and base-poor, each distinct mire site having its place in the matrix of varying oceanicity, nutrient availability, pH and climate.



Floodplain mires

Valley and basin mires



Raised mires

Blanket mires

FIGURE 1 Distribution of key peatland sites in England and Wales *(Ratcliffe 1977)*

Up to the time of the agrarian revolution, wetlands were an integral part of the common land, and were used relatively freely by the whole community for wildfowling, eeltrapping, grazing, fuel and building materials. Where wetlands were managed, it was to maximise yields of traditional wetland crops such as reeds, willow and sedge. With enclosure came the demand for land improvement, and wetlands were obvious targets for the new water management technology. Over the last two centuries, the threat to the remaining wetlands has intensified. With the recent availability of machinery and subsidies for drainage and improvement, and the rapid dissemination of results and information, agricultural drainage still remains the chief threat, but a phenomenal increase in the demand for horticultural peat has led to exploitation with dire result for wildlife and landscape.

The problem of conservation of wetland sites should be seen against a background of public distaste for wetlands - how many times for instance have the words slough and morass been used in the negative sense in English literature and speech - and the agricultural view of them as unproductive wastelands. (see also 1.2). The appearance of many wetlands is one of dereliction, with rank growth of 'weed' species and untidy carr vegetation, and it is this appearance that can lead a local authority, for instance, to regard convenient wetlands as likely sites for dumping of refuse. Overcoming this antipathy, or at best apathy, will require positive effort and an active policy of management if wetlands are to be appreciated as a useful, indeed essential, part of the land-use mosaic.

An aspect of the general decline in area of wetlands in Britain is that each of the remaining wetland sites has some feature which distinguishes it from its fellows. The Nature Conservation Review (Ratcliffe 1977) enumerated no fewer than 107 peatland sites in Grades 1 and 2 and 22 sites in the wetter categories of grassland (marshes, watermeadows etc.). None of these sites can be considered dispensible in the sense that it duplicates some other site. There is a climatic gradient from south to north, and many species are present at their northerly or southerly limit. There are temperature and moisture gradients from east to west, coupled with changes in the underlying geology. In addition many sites owe their interest to past or present management practices (Haslam 1973b) which differ regionally, while others have been the subject of long and detailed study and are distinguished by the volume of scientific information that is available on all aspects of their history and ecology.

The flora of wetlands are of interest ecologically on two grounds: specialisation and succession. Nowhere is succession in time and space better demonstrated than in the mire surrounding and advancing on a lake - the deposition of material either organic or inorganic leads inevitably to a rise in the ground surface or bottom relative to the water level and to the inward march of the vegetation zones. All mire flora are specialised to some degree, and it is only this specialisation that enables them to survive anaerobic conditions in the root zone, but none have taken this specialisation further than the few insectivorous species, all of which are confined to mires.

Another important aspect of wetland conservation, and one which has been useful in ensuring public interest and support for many reserves, is the attractiveness of wetlands to birds, as feeding grounds and breeding sites and as rest stations for migratory species. Meadows which flood in winter are particularly important in this respect, but open water is a necessary feature of peatlands which are to be used as bird reserves.

Chemically reduced conditions in peat impose severe restrictions on the rate of decomposition of organic material. Apart from the steady buildup of organic material that adds to the matrix of the peat itself, many recognisable fragments such as seeds, rhizomes and pollen are preserved, and can be used to assemble a picture, not only of plant communities on the mire surface, but of the composition of surrounding forests. In Britain peat stratigraphy can be used to follow the development of the flora since the end of the last glaciation, and in some cases the history of previous interglacial periods. The value of the stratigraphic record depends on the maintenance of reasonably wet conditions at the surface, to prevent wastage of the peat. Thus peatland reserves have a value as repositories of information about the past ecology of Britain, which, as the science of palaeobotany develops, is far from being exhausted.

All wetland sites are threatened, if not directly by reclamation works then indirectly by peripheral drainage, a general decline in water levels or the natural processes of vegetational succession. Climatic fluctuations also have an effect on wetland communities, particularly those dependent upon a limited range of variation of the water table, and Green (1978) drew attention to decreasing annual rainfall and its effects on shallow groundwater. The corollary to this statement is that all wetland reserve sites will require a serious effort at active conservation if they are to survive in their present form, let alone to be restored to some former healthier condition. Cases of active conservation are not numerous: the problems of land acquisition and protection from immediate threat have absorbed most resources to date. Nature Conservancy Council have done valuable ground work with the Nature Conservation Review (Ratcliffe 1977), the Welsh Wetlands Survey (in preparation) and a bibliography on British peatlands (Field and Goode, 1981), but the pages of the Nature Conservation Review disclose only three cases of active reserve management of wetlands. Two of these are very old-established reserves which have been the subject of intensive investigation for many years, and were described in detail by Godwin (1978). Wicken Fen was the first Fenland nature reserve to be established, and is owned by the National Trust. Wicken is important for its contribution to the understanding of the nature of the Fenland succession and its modification by cropping practices. The water level is controlled by sluices, and the Fen is used as a flood catchment area, thus securing high winter water levels in spite of the continually-lowered lode levels in surrounding land. In Godwin's words

> 'It was soon realised by the management committee that their task amounted to much more than controlling access, preventing disturbance and simply leaving nature to itself .... Anything but active management is out of the question and this evidently must rest upon as good scientific knowledge as can be acquired.'

Another of the Fenland reserves, Woodwalton Fen, requires careful manipulation of sluices to maintain a high water table, and is also used as a flood storage area.

Also in East Anglia, at Minsmere, the Royal Society for the Protection of Birds has recovered a reedmarsh area from what was formerly grazing marsh by judicious control of water levels and cutting of the reeds to prevent the formation of unbroken reedbed, which would have less appeal to bird populations. The reserve is divided by embankments into several compartments which can be managed independently. The artificial creation of meres for birds has been a feature of the management of both Minsmere and Wicken Fen (Plate 1).

Two features of the active conservation efforts made outside the prestige cases have been that it is easier to create open water than to create water level conditions for specific flora (i.e. birds are easier to please than plants!) and that only low-cost, ad hoc hardware need be involved, a point recently highlighted by the British Trust for Conservation Volunteers (1981).

PLATE 1 (a) Titchwell, north Norfolk, where RSPB have used simple water level controls

(b) Simple flap sluice in use by RSPB at Minsmere

(c) "Squash-bottle" valve in use by RSPB at Minsmere

1.2 The drainage threat: philosophy, design, benefits

Because of the frequency with which the threat of further agricultural improvement has occurred during the three-year Anglesey study it was thought worthwhile to spend a lengthy section in describing the background to the major alternative land management on wetlands,drainage for agriculture.

Very little of the land area of the British Isles has no drainage "problem" in the natural state, and the virtual disappearance of wetland has been a corollary of the preparation of the land surface for modern agriculture by land drainage. Land drainage comprises field drainage, mainly underdrainage in pipes, and arterial drainage, the preparation of rivers and surface water courses to conduct the field drainage water away.

The post-war era of planned agricultural economics has been set against the loss of cheap colonial sources of food and has resulted in considerable pride amongst British farmers that they have produced increasing amounts of food despite loss of land to urban expansion. There is consequently a strong drive to bring into production land which is apparently, to farmers, of no other value and which the continual bombardment of technical material they receive tells them can be improved. Land drainage is an obvious example: wetland areas are residual, apparently "waste" and have attracted a concentrated application of mechanized techniques without parallel development in the guiding scientific framework of hydrology and crop physiology.

The cost of the highly mechanized drainage techniques has been borne by society via grants to farmers, and it is at this point that the scene is set for conflict between the farmer and the conservationist, the former with a firm economic basis which is mainly artificial and the latter with no economics but a much greater application of scientific survey and, it must be said, a longer view of future values. With a few notable exceptions, the conflict is not resolved analytically and the conservation interest is forced into predicting how to mitigate the effects of the drainage scheme; unfortunately it is often hydrologically ill-equipped to do this and the provision of routine advice has been a major part of the present study. The long-term aim has, however, been that of giving management guidance which will turn wetland conservation into an active process, a change which will tend to even up the conflict with intensive, technological agriculture and provide scope for far more flexible compromises in land management.

> "Manipulating the flow of water is one of the most seductive and rewarding of Man's enterprises, and throughout history the drainage and reclamation of wetlands, speeding the flow of water even more rapidly and elusively to the sea, has been second only to forest clearance among the major human impacts on the environment."
>
> Bryn Green (1981)

By putting land drainage in its historical perspective (above) Green correctly identifies the element of heroic obsession which has been much of its momentum more recently. The full story of wetland landscape change is now being pieced together for several regions (e.g. Oxford University, 1981) following the pioneering study of the Fens by Darby (1956). Darby also deals with the heroic aspect of man's desire to drain and quotes this doggerel:

I sing no Battels fought, nor Armies foil'd,
Nor Cities raz'd, nor Commonwealths embroil'd,
Nor any History, which may move your tears,
Or raise your Spleens, or multiply your Fears;
But I bespeak your wonder, your delight,
And would your Emulation fain invite.

I sing Floods muzled, and the Ocean tam'd,
Luxurious Rivers govern'd, and reclam'd,
Waters with Banks confin'd, as in a Gaol,
Till kinder Sluces let them go on Bail;
Streams curb'd with Dammes like Bridles, taught t'obey,
And run as strait, as if they saw their way.

From a poem at the end of *The History of Narrative of the Great Level of the Fenns, called Bedford Level,* attributed to Samuel Fortrey (1685).

Darby also deals with opposition to drainage by local people to whom conservation was a shorter-term case of life-and-death than it is for the modern environmental lobby: fish, fowl, rush and osier produce of the wetland was obliterated in the face of the "improvement", which was invariably associated with enclosure.

It is possibly the success of the grand schemes of drainage in the past which has produced the momentum for continued drainage, even though prevention of inundation from watercourses was the major triumph of the Fens. Modern imitators are largely attempting to reduce soil water levels by arterial drainage and underdrainage.

> "The direct aim of a drainage operation is to lower the moisture content of the upper layers of the soil, which is commonly achieved by lowering the water table. As a result, air can penetrate into the soil more easily and become available to the roots of plants. At the same time, carbon dioxide produced by these roots, by other organisms, or by chemical reactions in the soil can diffuse through the air-filled pores to the surface."
> (Wesseling and van Wijk, 1957)

This difference has implications for the whole field of land drainage in the modern age. Green (1981) points to the inherent incompatibility of draining land so effectively that natural watercourses need protection against erosion by the larger volumes of flow and both agricultural and urban communities require costly flood protection. Yet these added tasks appeal further to the heroic aspect of the work and the incompatibilities only become obvious when costs and benefits are evaluated (see below) or when administrative structures force collaborative action between all sides involved with the use and disposal of water. The modern water authorities are examples of such structures and it is seen as no accident that agricultural interests put up a spirited fight for autonomy within them (Richardson, *et al* 1978). That agriculture largely won the fight suggests an impressive body of facts supporting the national good achievable by drainage; this, however, is untrue - the fight for autonomy of land drainage within water authorities was based largely upon fears by M.A.F.F. that it would lose prestige to D.o.E. and that the latter Ministry might well stress environmental impacts.

Plant/water relationships: the case of crops

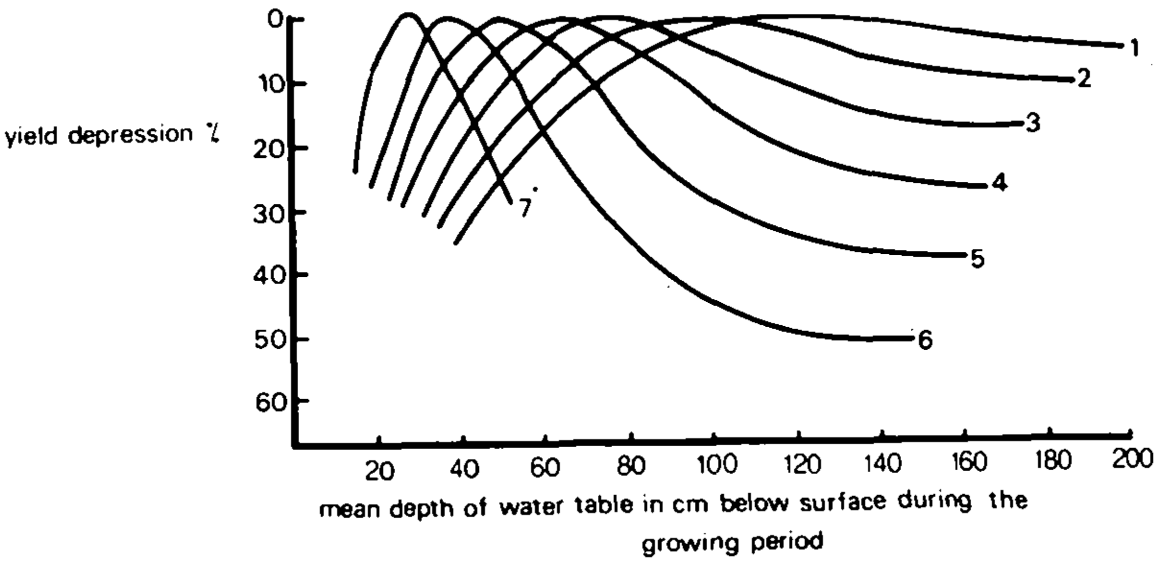
Our major interest in this study was to advise on the creation of suitable moisture conditions for a certain range of plants: those to be conserved on the Anglesey fens. It is therefore obvious that the management of water levels by agriculture to suit crops should fall under scrutiny. However, even reviews by drainage researchers point to the sparsity of published work of relevance to the U.K. (see Trafford, 1974, Berryman, 1975).

The most specific work of relevance was done at Cambridge just after the war (Eden *et al*, 1951; Nicholson *et al*, 1953; Nicholson and Firth, 1958) These authors also point to a lack of information, quoting only:

"The net yield of permanent pasture is inversely proportional to the elevation of the groundwater, and green feed is all the more nourishing when the level of the groundwater is low".

The conclusions of their own experiments were similar: water tables within 40 cm of the surface retarded root development and negatively affected microbial provision of nutrients. However, draw-down to 60 and 100 cms did not indicate a progressive advantage of drainage. Whilst yields were almost doubled, dry matter was optimum at 60 cm but crude protein at 100 cm. These results were proved valid for both dry and wet years (see Nicholson *et al*, 1953). In the later paper Nicholson and Firth quoted 24 inches (61 cm) as being the optimum water table depth for grass production. It is interesting that these early papers did not mention the effect of drainage on soil compaction by vehicles or livestock, a prominent feature of more recent work (see below).

The literature is still relatively sparse with experimental results on crop production and drainage in Britain, though certain reports from abroad are useful. Kramer (1940) linked the poor performance of waterlogged plants to a reduction in water uptake consequent upon carbon dioxide accumulation: he did not investigate different levels of drainage. There are many more papers dealing with physiological mechanisms than with crop yields. Bon (1968) dealt with the problem of artificially raising water tables in the sandy soils of S.E. Netherlands. Also in the Netherlands Visser (1958) collected water table depths for 2.2 million ha and compared them with crop yields. He found peats to be the most sensitive soils to water table depth (see Figure 2).



SOIL TYPES:

1	heavy river and sea clay
2	loamy humus-rich sand
3	light river and sea clay
4	old sandy cot-over peat soils
5	coarse sandy reclaimed heath soils
6	clay overlying peat
7	peat soils

FIGURE 2 Crop yield depressions as a function of water table depth during the growing season *(Visser, 1958)*

Williamson and Kriz (1970) advocated closer liaison between land drainage engineers and crop physiologists. They considered the dangers of waterlogging to vary with crop, stage of development and air/soil temperatures. They also reminded agriculturalists that there is a lower limit to water levels for successful crop growth. Two tables of results from the U.S.A. linked yields to water table depth; there were no results however for peat. The authors stressed the extremely local validity of the results and the consequent need for research, especially on the main risk - that of short-term waterlogging during the growing season.

Whilst work such as that by Visser and Williamson and Kriz appears useful in applying to land drainage, and its impact on wet soils in Britain, it can be so in only the most general way. The land drainage industry here has not adopted the experimental outlook and has applied maps and tables for the U.K. only to the choice of a suitable pipe (Bailey *et al* 1980).

We may describe the approach in which a given crop and soil are drained in a specific way to achieve the desired yield as rational drainage, yet Bouwer (1974) sounded a warning about hopes of such an approach.

> "Considering the capital investments in drainage systems that are made each year .... a more rational design of the systems to ensure maximum economic return would be highly desirable. The limited use of rational design procedures can be attributed to the complexity of crop yield versus soil-water content relationships, to the difficulty in predicting soil-water content profiles in relation to drainage system intensity and to the cost of field investigations for rational design in relation to the cost of the drainage system".

A very recent set of experiments by the Ministry of Agriculture, Fisheries and Food's (MAFF) Field Drainage Experimental Unit and the Agricultural Research Council's Letcombe Laboratory has made some progress towards the goal. Clay and sandy loam soils have been studied in both lysimeters and field plots. Indications are that, for cereals, water tables should not be less than about 50 cm below the surface; if they rise above this limit the excess should be removed in five or six days. Results are most comprehensive for winter wheat (e.g. Cannell *et al*, 1980) and they include those from research into fertilizer "cures" for waterlogging injury to crops (Trought and Drew, 1981). The prospect of manipulating soil chemistry as well as or instead of soil water levels to achieve better yields is a possibility; Drew and Lynch (1980) and Cannell and Jackson (1981) provide reviews and bibliographies.

It would therefore appear that drainage is not the only answer to the physiological effects of high water tables. Another indication of a slight change in emphasis in U.K. drainage philosophy is that the Field Drainage Experimental Unit has begun to promote the reduction of "poaching" (damage to grass and top soil by trampling) and the increase in the number of field work days (with machinery) as two major aims of drainage (Armstrong, 1977, Kellett, 1978). The conservationist might be entitled, therefore to judge drainage as an aid to the farmer who is overgrazing or over-mechanized! However, the ground is less secure to argue against drainage when it is promoted as part of campaigns to reduce disease and pests or to increase the length of the growing season (Plate 2).

Water levels and wild plants

Can ecologists claim to have a more coherent body of experimental results in relating the growth of wild plants to various soil water levels? Conway (1940) provided a review of the effects of reduced oxygen availability to waterlogged

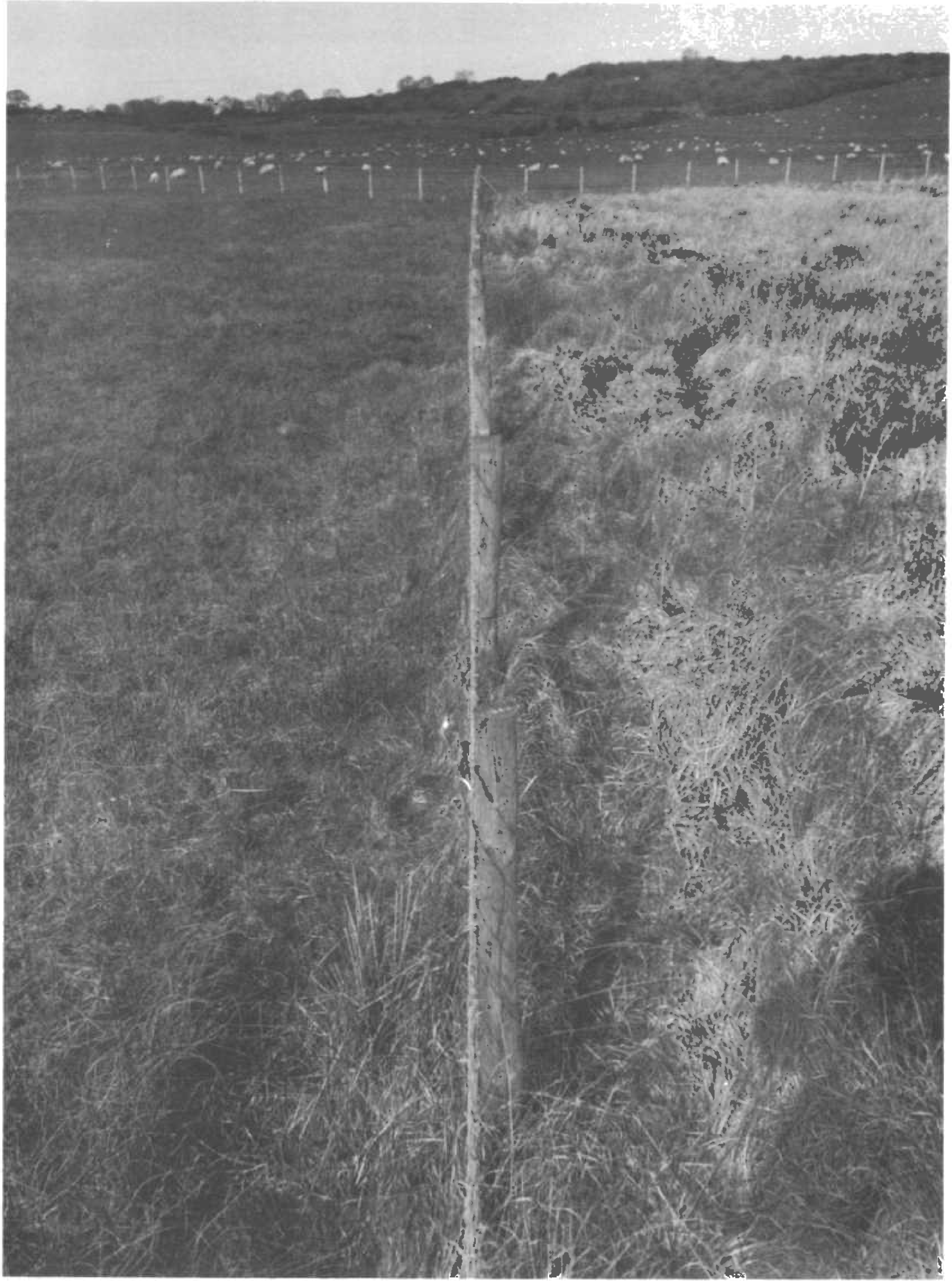


PLATE 2 The common face of wetland conservation: enclosure of livestock following land purchase (right, foreground) at Cors Erddreiniog. Note the density of sheep grazing on the reclaimed pasture in the distance.

plants, stressing the role of aerenchyma tissue in conducting oxygen from leaves to roots, notably in *Cladium*. However, the paper did not relate to water tables at various depths below the surface. Rutter's (1955) observations of *Molinia* were more hydrologically based, and referred to the benefits of a fluctuating water table, but to a plant which is not generally a candidate for conservation. Armstrong and Boatman's (1967) detailed study of oxygen under flushed and stagnant conditions also refer mainly to *Molinia*. One of the surest conclusions in wetland conservation came from such work, but on the negative side: inundation may be used to kill *Molinia* (Meade, personal communication).

More recent studies have pointed to more complex matabolic responses to waterlogging; the paper by Crawford and Tyler (1969) is in similar vein to the agricultural studies reported above in stressing that lack of oxygen is not the single cause of stress in flooded plants. However, such papers offer no results on varying water table levels which would be of relevance to conservation in the face of a drainage threat. The type of approach which would be of most use is that of Haslam (1970), working on *Phragmites* under a wide range of water tables. She concludes that nutrient status determines the tolerance of the plant to water stress, almost certainly a vindication of the conclusion that complex metabolic reactions around roots are involved.

As might be expected from its background of classification and mapping, plant ecology derives many conclusions from a geographical approach. The most recent detailed survey of rich fens in England and Wales (Wheeler, 1980(a), (b), (c)) produces several conclusions of relevance to conservation management (see Table 1 below).

TABLE 1 INTERPRETATION OF WHEELER'S (1980) SURVEYS FOR CONSERVATION OF FEN COMMUNITIES

Community	Water requirements	Nutrient/chemical requirements
TALL SEDGE & REED		
Scirpo-Phragmitetum	swamp	optimum in nutrient rich condition but widely tolerant
Cladietum	" + little flow + little variation of level?	prefers high pH? (6.5-8) low nutrients - can suppress *Phragmites* thus.
Potentillo-Caricetum	*Carex nigra* tussocks = strongly fluctuating water table.	transitional to poor fen
Peucedano-Phragmitetum	open water	more related to mowing/grazing
Angelico-Phragmitetum		high nutrient and mowing/grazing
Cladio-Molinietum	low summer water level	

CALCAREOUS MIRES		
Schoeno-Juncetum	water movement across upper soil. Tussocks become oligotrophic	soligenous (pH 6-7.5) relatively low in nutrients esp phosphorus.
FEN MEADOW,GRASSLAND, WOODLAND		
Molinia-Myrica	better drained areas	pH 4.3 - 5.6

Although Wheeler's study included both the Anglesey sites studied here, discussions with NCC concluded that an overlapping detailed survey of the plant communities and hydrology of Cors Erddreiniog and Cors Goch would add an experimental aspect not present in Wheeler's ecological conclusions. The report of the study (Meade, 1981) does not make direct use of the IH data because of the difficulty in relating water levels at the hydrologically determined borehole sites to plant growth at the botanically key sites. Some reorganization of boreholes followed (Figure 10) but Meade did take his own soil samples for moisture and mineral analysis. Summary diagrams are included here (see Figure 26) when the topic is returned to below in the light of the IH data.

It is clear from the above review that our knowledge of the optimum conditions of water level (above surface) and water table (within the soil) for the successful growth of both crops and wild plants is incomplete. So is our knowledge of the unique hydrological properties of peat during and after drainage.

Special problems of draining peat lands

Notwithstanding the success of large-scale schemes in preventing inundation of peat lands by arterial ditches, the record of underdrainage of peats is not so auspicious. Initial optimism has often been followed by disappointment, while the need to continually lower ditch levels to follow a falling ground surface requires an increasing outlay, particularly where pumping becomes necessary. The problems of peat drainage arise from the very nature of the medium and its mode of formation: they have no permanent solution, only temporary 'fixes'.

The farmer attempting to underdrain peat may or may not encounter a particular problem, that of slurry, at a very early stage. Under unfavourable conditions the blocking of entry slots or gaps in tile or plastic pipe drains by a slurry of fine peat particles and humic material can render a drain useless in a very short time. Prediction of slurry problems seems to be difficult, although they relate to the initial waterlogged state of the peat: the MAFF recommendation (Belding, *et al* 1975) is that pre-drainage by ditches be carried out before pipe drainage to allow a preliminary dewatering.

At a later stage, after drainage has been completed and the water table has fallen to its design level, two long-term effects, shrinkage and wastage, make themselves evident by a fall in the ground surface relative to datum, and, unfortunately, relative to the ditch water level. Wastage and shrinkage are often confused, and for many years the nature and causes of the lowering of ground level in the East Anglian Fens were not recognised (Godwin 1978). Shrinkage is a compaction of the peat caused by removal of the water above the new water table, while wastage is an actual loss of peat from the ground surface by wind erosion and biological and chemical oxidation processes.

Peat in its natural state is in a static equilibrium in which a balance exists between the weight of solid material and included water and the buoyancy exerted by the water and gases in the peat (Ivanov 1981). When water is removed from the upper horizons by, for example, a ditch or tile drain, the most important component of the buoyancy forces is removed, and the upper layers begin to compact under their own weight. It is less generally realised that peat below the water table will also undergo compaction due to the increased weight above it: thus the drain will also sink, and if this sinking is not uniform the gradient of the drain may become unfavourable or the drain may become discontinuous (Prus-Chacinski 1962). Prus-Chacinski reports and amplifies a method devised by Ostromecki (published in Polish) for predicting the amount of shrinkage in various peats. Ostromecki's formula can be used to predict the subsidence along the line of a tile drain for instance so that a drain with an initially well-designed gradient will not be adversely affected by compaction. Given a drain depth of 1 metre and a ratio of dry to wet densities of 0.143 obtained for peat samples from Rallt Bridge, Prus-Chacinski's modification of the formula gives the values presented in Table 2 for the final shrinkage of the ground surface of Cors Erddreinog subjected to drainage.

TABLE 2 PREDICTED SHRINKAGE OF CORS ERDDREINIOG PEAT AFTER DRAINAGE

Initial depth of peat, m	Shrinkage predicted by Prus-Chacinski formula, m
1.0	0.15
1.25	0.16
1.50	0.17
2.0	0.19

Thus a drainage scheme for the '40-acre' field at Cors Erddreiniog would involve a degree of ground lowering caused by shrinkage. Another effect of compaction is the decrease in permeability of surface horizons: Ivanov (1981) explains that two opposing effects are involved. Compaction of the peat layers tends to reduce pore space, while dehydration tends to reduce particle sizes and hence to increase pore space. Permeability may reduce by between 17% and 99% on drainage, depending on the peat type and its initial state (Ivanov 1981). Ivanov quotes a formula by Lundin, which relates the permeability after drainage to time elapsed since draining and the depth of the water table. Lundin's formula would predict a fall in permeability of Cors Erddreiniog peat to 1% of its present value on draining to a depth of 1 metre. By contrast, Belding *et al*, (1975) present a diagram by Eggelsmann which suggests a fall to 12% after drainage. However the actual lowering of water level in this case may be less: a half metre lowering of the water table would result in this figure from Lundin's formula. In any event it is clear that a drainage scheme for Cors Erddreiniog would need to be designed on a permeability of one tenth or less of its present value.

More serious than shrinkage - because it is less predictable - is the wastage of the peat surface by loss into the atmosphere. Peat accumulates in saturated conditions where aerobic processes are inhibited; the deliberate creation of aerobic conditions at the surface which is the aim of drainage (Wesseling and van Wijk 1957) cannot but result in increased rates of breakdown of organic matter and the loss of peat. Additionally the exposure of a dry peat surface to winds results in erosion and loss of material. These combined effects led to the loss of 1.4 metres of peat by wastage and shrinkage from Holme Fen, Cambridgeshire, in a mere twelve years (Godwin 1978). Wastage rates are not normally so fast: the range is between 11 mm and 120 mm per year (Belding *et al* 1975).

At least one formula exists for the prediction of wastage rate. Ivanov (1981) quotes a formula devised by Maslov, which embodies results from the USSR, the USA, Norway and other countries. Maslov's formula for the rate of wastage of a peat deposit is

$$\varepsilon_p = 0.08\,H\,\frac{\alpha_p^{1.4}\,h_p^{\frac{1}{2}}}{\exp(\beta T)}$$

where ε_p is the rate of wastage expressed in m per year

H is the average depth of the water table in m

α_p is a climatic parameter equal to the ratio of the mean annual temperature of the atmosphere (°C) and the annual precipitation (mm), multiplied by 100

h_p is the initial thickness of the peat deposit (m)

β is a coefficient $\beta = 0.1 + 0.02\,\alpha_p - 0.0025T$

and T is the time since drainage in years

Applied to the climate of Anglesey, Maslov's formula predicts a 77% reduction in the thickness of peat deposits at the centre of Cors Erddreiniog over a period of 20 years if the water table is maintained one metre below the surface. The rate of loss is proportional to the lowering of the water table, hence the need for careful management to prevent rapid wastage (Figure 3). Coincidentally the predicted initial rate of wastage is 120 mm per year. The wastage rate can be controlled by wise husbandry; Prus-Chacinski and the 'ameliorators' of Eastern Europe believe that it can be prevented altogether. However the price is high; the water table must be maintained close to the surface, the land must be kept in permanent pasture or hay meadow and grazing density must be kept low. The USDA Yearbook of Agriculture lends support to this conclusion: "The most practical way now known of reducing the loss of peat and muck soils is by controlled drainage that holds the water table as high as crop and field requirements permit" Stephens (1955). In the Byelorussian Polesie, an extensive drainage scheme to provide arable land ran into problems on peat soils (Komarov 1978): the problem of overdrainage having been recognised, experimental results suggested that the water table be kept high, and that pasture mixtures include such grasses as *Phalaris arundinacea*, the reed canary-grass, a wetland species. Effectively the only suitable land-use for peat even after drainage is wet meadow!

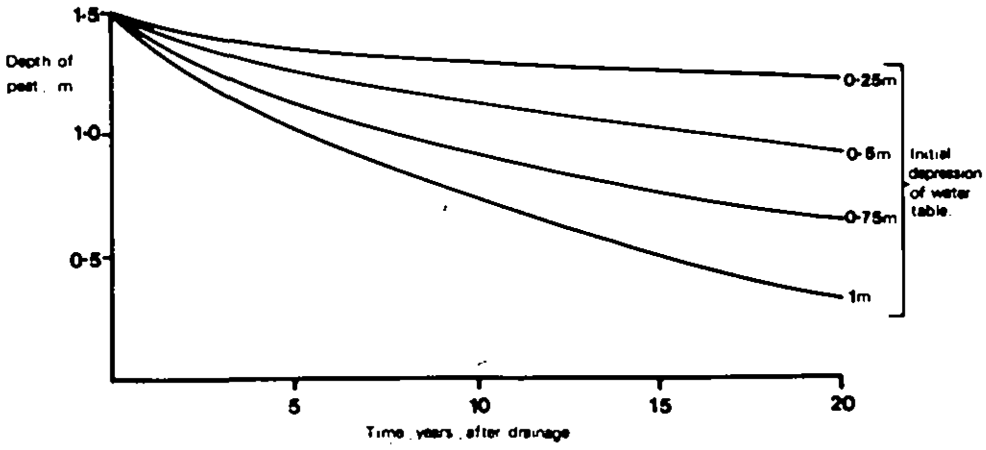


FIGURE 3 Rate of peat loss, in relation to initial lowering of water table, predicted by Maslov formula *(Ivanov, 1981)*

Drainage as practised: costs and benefits

Field drainage, or underdrainage, in the U.K. may be described as "partly rational". As outlined above, it has moved from a confused relationship with the prevention of surface inundation, to an often unspecified role in increasing yields, to a firmer role in reducing the effects of high stocking rates and mechanized agriculture on soil structure. Before considering the costs and benefits of current practices what are the major ones likely to be of threat to Anglesey fens? Some difficulty arises in that published research and actual practice, particularly in underdrainage on farms, are likely to differ.

The common U.K. practice for underdrainage is to remove the excess rainfall during the wettest 5-day period which occurs every year or two years (Parker, 1972); mole drains and piped ditches are designed around the wettest single day. For example, underdrainage on Anglesey would be designed to cope with 14 mm of rainfall per day for 5 days or 32 mm in a single day. There are many other variables involved, the principal of which is soil permeability - a difficult property to measure (See Section 2.3 here). In practice average values for whole soil series are used (Armstrong and Tring, 1980). Once a value is derived the depth, spacing and use of ancillary drains can be fixed for the scheme. Commonly, simple diagrams are used to guide the ADAS drainage advisor; text books abound with them (e.g. Hudson, 1975, and Luthin, 1957), as do the Technical Bulletins of the Field Drainage Experimental Unit (e.g. Bailey *et al* 1980).

Underdrainage cannot work unless the surplus water can leave the drained area efficiently. Consequently arterial channels often need improvement too and there are examples in the literature of comprehensive drainage schemes involving peat, e.g. Prus-Chacinski and Harris, 1963, Hall and Prus-Chacinski, 1975. The biggest change in design practice at larger scales is not merely the scale factor itself, as it influences rainfall and runoff intensity, but the chosen level of protection, for example against the one in 15-20 year runoff in the Lancashire pumping scheme reported by the two papers above (cf one in one or two years in underdrainage). It is at this point we begin to take bigger precautions against damage to life and property than against damage to crops. This incompatibility in the aims of land drainage, i.e. that water removed from agricultural land threatens land downstream under the worst combinations of circumstances, has forced those assessing the benefits and costs of land drainage to go beyond the economic balance sheet as applied to one farmer's fields. Economic analyses have, therefore, mainly centred on the larger, more comprehensive schemes.

The application of formal cost-benefit analysis to drainage is a recent phenomenon. The first well-published example of its use was the study of Amberley Wild Brooks, Sussex (Penning-Rowsell, 1978). At first sight it appeared easy to derive a financial figure for the changes in farming enterprise as a result of drainage; in fact agriculture zones itself sensitively to the threat of inundation and so there is normally a marked change to a more intensive land-use after a scheme is carried out, even if the change is rather slow to come about. The major difficulty, as became clear at the Public Enquiry into Amberley Wild Brooks, is that the uptake of the improved opportunities for agriculture is variable and is highly supported by public money when it occurs. There is thus a further cost to the public purse which attends the benefit (Penning-Rowsell, 1980). The difference becomes one between financial analysis, the narrow treatment of a single entity, which shows drainage to be profitable to farmers as early as 1½ years after installation and economic analysis which is concerned with the resources of society as a whole (Mann and Green, 1978). These two authors propose the fusion of a hydrological model with an agricultural model as a sound basis for cost-benefit analysis. They mention calculating the benefits to nature conservation of not draining only briefly, suggesting they may not actually need to be formalized. Wallace (1976) suggests that the wildlife interest should be judged against the benefit-to-cost ratio once the benefits have been compared with other investments; this at least gives a figure to work on. Roome (1981) agrees that forcing nature conservation benefits to fit conventional economic criteria may prove impossible. He concludes that the major research need is to elaborate the precise way in which conservation is of benefit to society.

Perhaps the best 'last word' is that of Penning-Rowsell, "It may not be worthwhile for the nation to contribute to draining land only for crops to be grown which are subsequently bought at intervention prices and disposed of at a loss!"

Clearly, if this were invariably true there would be little need to consider the formal benefits of conservation!

To summarise:

The philosophy of drainage in the U.K. has often been based on enthusiasm rather than science. Whilst research is now available which points to benefits in terms of soil physical properties after drainage it is still not a fully rational operation and is being increasingly questioned on cost-benefit grounds. Peat drainage is often only partly successful in its aims.

Nevertheless, the conservation interest will not win many wetland battles on cost-benefit analysis and the original aims of the Anglesey Wetland Study are still crucial: to improve knowledge of plant/water relationships and then manipulate them to the advantage of conservation.

1.3 The Anglesey wetlands

The island of Anglesey formerly had wide expanses of wetland. In 1810, W Davies was able to write: 'the commons, or waste lands, in Anglesey amount to between twelve thousand and thirteen thousand acres; whereof about nine thousand are level and highly improvable.' The main wetland areas were Cors y Bol, in the northwest of the island, an acidic valley fen, Cors Ddaugae (Malltraeth Marsh) and the area known as Talwrn Mawr, which comprised the four calcareous fen sites. Much of Cors y Bol has disappeared beneath the reservoir Llyn Alaw, and the Malltraeth Marsh was reclaimed for grazing between 1788 and 1812.

The four calcareous fens of Anglesey (Figure 4) have a botanical interest deriving from their position in the west of Britain with its relatively high rainfall and maritime climatic and chemical influences. The Carboniferous limestone and gentle topography of this part of Anglesey have given rise to a number of mires of the 'rich fen' type, with a diverse flora having a wide range of pH tolerance. Situated midway between the fens of East Anglia and those of Northumbria, the sites support a mixture of northern and southern floristic elements. The supply of carbonate-rich water from the limestone is counteracted on a local scale by water from the contiguous sandstone and boulder clay, and by rainwater, so that the slight elevation of hummocks and tussocks above the general groundwater level provides acid conditions.

Two of the four fen sites were selected for investigation: the largest basin, Cors Erddreiniog, which is partly scheduled as a National Nature Reserve (NNR), and Cors Goch, partly owned and maintained as a reserve by the North Wales Naturalists' Trust (NWNT). They are shown in Figure 5 and Plates 3 and 4.

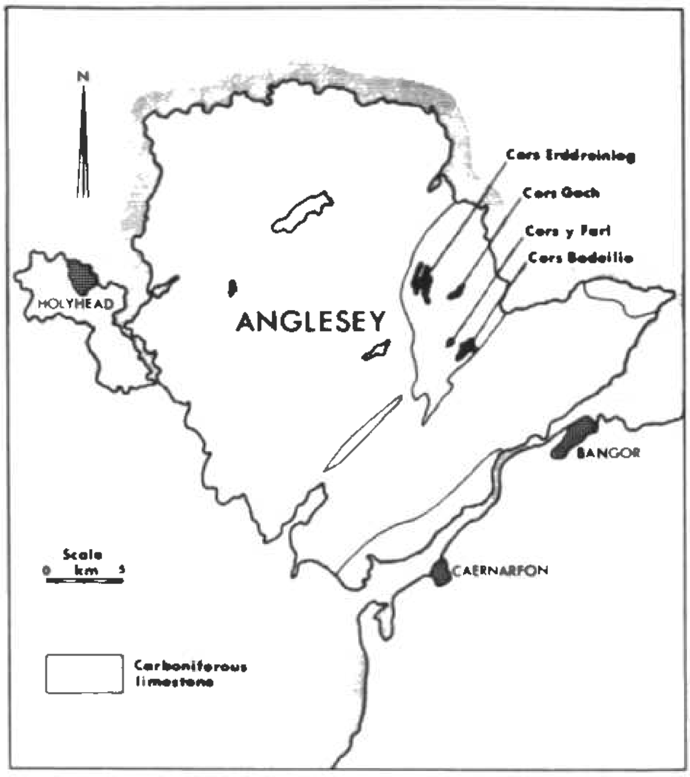


FIGURE 4

Calcareous fens of Anglesey

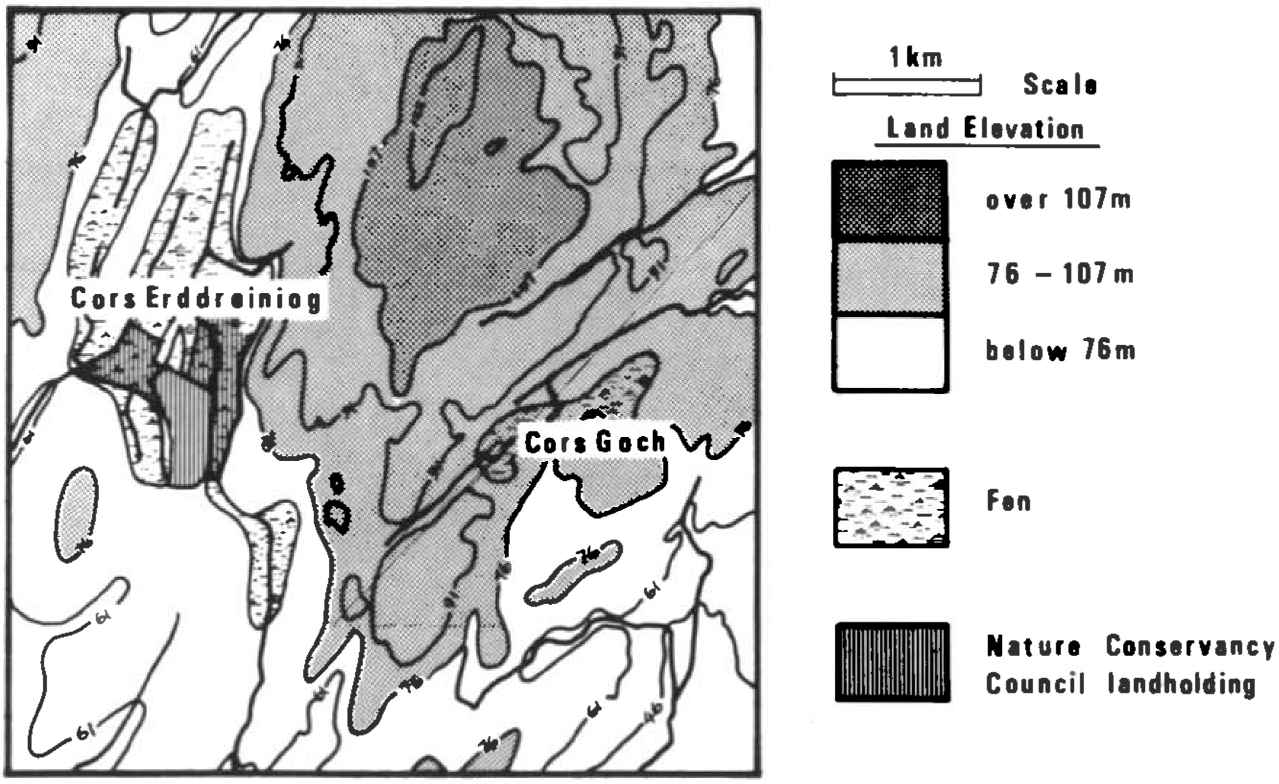


FIGURE 5 Cors Erddreiniog and Cors Goch

PLATE 3 Cors Erddreiniog from Nant Isaf (from the north east)

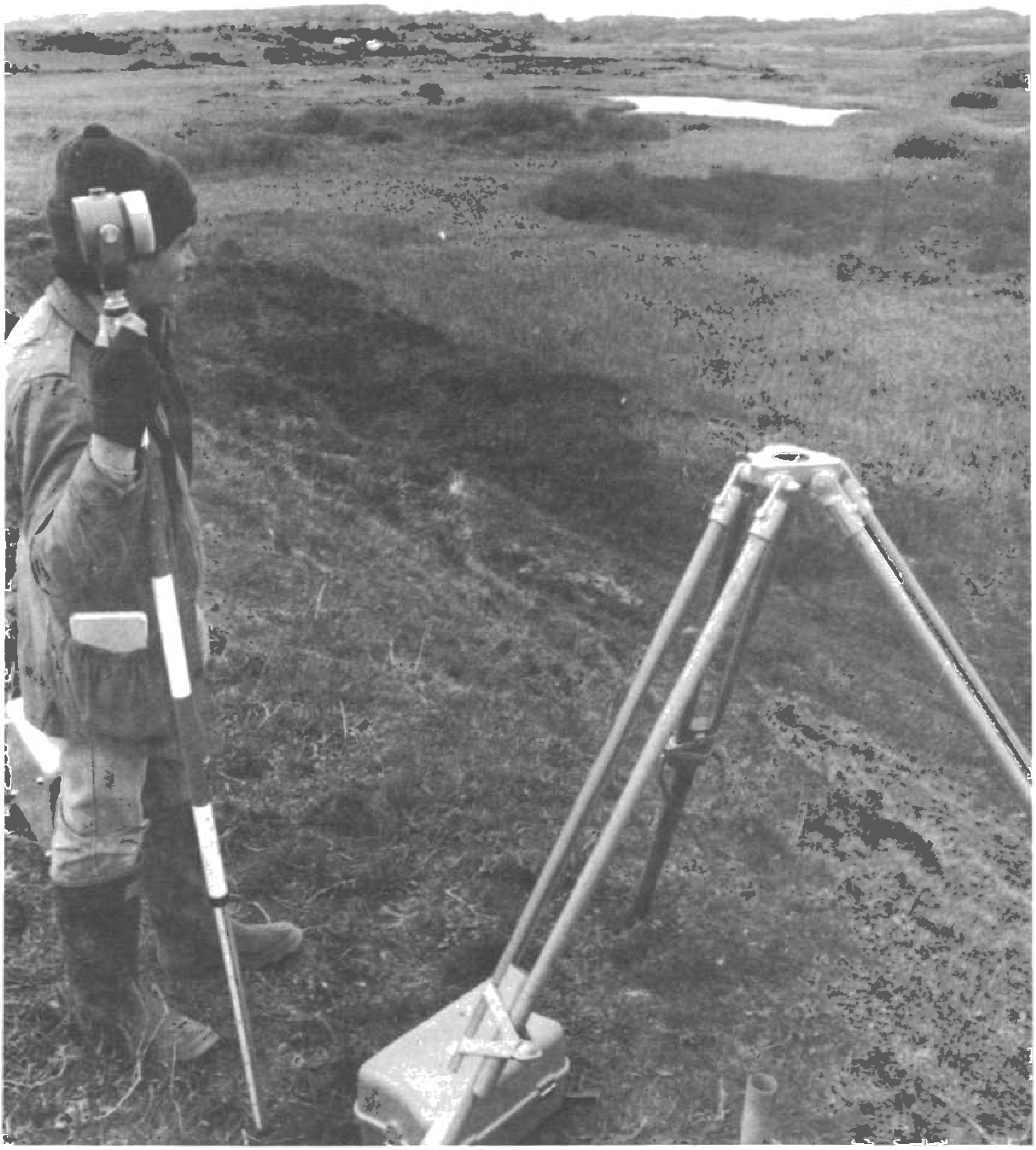


PLATE 4 Cors Goch from the limestone ridge (from the east)

Cors Erddreiniog, in a shallow valley on the sandstone beds of the Carboniferous limestone series, is separated by diffuse drainage divides into three subunits. Of these three parts, only the largest, the main basin, was given detailed attention during this study. Limestone outcrops as an escarpment on the east side of the valley, and it is from this ridge that the water supply of the main basin is provided by several discrete springs and probably also by diffuse seepage. The most significant springs occur in a field at Nant Isaf. An elliptical lake in the main basin, Llyn yr Wyth Eidion, is the remnant of a calcareous lake or lakes that formerly covered much of the site. Cors Erddreiniog is much dissected by drainage ditches of the nineteenth and twentieth centuries.

Cors Goch is also in a former lake basin at the foot of a limestone scarp. An elliptical remnant of the lake, Llyn Cadarn, survives at the western end of the basin, and shallow open water occurs in the form of ponds of irregular outline. Springs from the limestone are diffuse or submerged in the mire. Drainage, though it has been attempted, has not been effective, and the water level is kept high by the restriction of the outlet.

Both Cors Goch and Cors Erddreiniog are over-deepened basins hollowed out by the ice sheet, and the basal boulder clay is overlain by a sequence of lake sediments and fen peat. The first of the lake sediments is a plastic clay, which settled out of a turbid lake fed by runoff from the surrounding hills: the hilly ground was still mantled by till at this stage (in the late-Glacial and pre-Boreal periods). As the till was removed and redeposited in the lake the limestone surface was exposed and precipitation was able to percolate into the limestone. Carbonate-rich water from the limestone springs became the chief source for the lake, as it is now, and the clay was superseded by a finely-divided carbonate deposit laid down in the littoral zone. For about 7000 years up to the present, the carbonate marl and the succeding fen peat have been advancing inwards from the margins of the basin, the rate of advance in deep water being much slower. At Cors Goch a variation on this theme has resulted in at least one pocket of gyttja, a peat-like deposit formed entirely of organic fragments. At both sites fen vegetation has covered the marl with a layer of fen peat varying in depth from 1.5 metres to 4.5 metres and formed chiefly from *Phragmites* and *Cladium*.

The vegetation of the fen expanse clearly demonstrates the succession from aquatics to carr. However, this natural succession has been deflected by drainage (Godwin, 1929), so that *Molinia* has become dominant over a large area of the fen. The main aim of active management must be to protect those communities on the unmodified hydrarch succession and to reverse the reduction in diversity that has resulted from drainage activities.

The conservation problems of Cors Erddreiniog and Cors Goch stem from attempts to improve the arterial drainage of the sites. These were only partly successful at Cors Goch, but in the case of Cors Erddreiniog, the recent efforts of one zealous improver who owns land adjacent to the National Nature Reserve have caused a great deal of concern. This juxtaposition of opposing interests has led to the consideration of the possibility, or more likely impossibility, of compromise where there is no buffer zone. In addition, because the neighbouring farmer's activities place demands on the arterial drainage system that are incompatible with the maintenance of high water levels, the NNR is also under threat along that part of its periphery which lies along the main drainage ditch.

Clearly the solution to the problems will only be found in a careful and sensitive management of the hydrology of the fens, and this in turn will depend on detailed knowledge of present behaviour and accurate prediction of future trends consequent on change. The acquisition of hydrological data and its interpretation for the future management of Cors Erddreiniog National Nature Reserve, has been the task set for the Institute of Hydrology in this study.

THE ANGLESEY WETLANDS STUDY

2.1 Routine hydrological studies, 1980-81

The first annual report of progress (Gilman & Newson, 1979) outlined the concept of water balancing by means of comprehensive measurements of rainfall, flow, storage and evaporation. Figure 6 here summarizes the circulation of water in an Anglesey fen and the measurements made by the Project. Techniques of measurement are described in the first and second reports of progress and shown here in Plate 5.

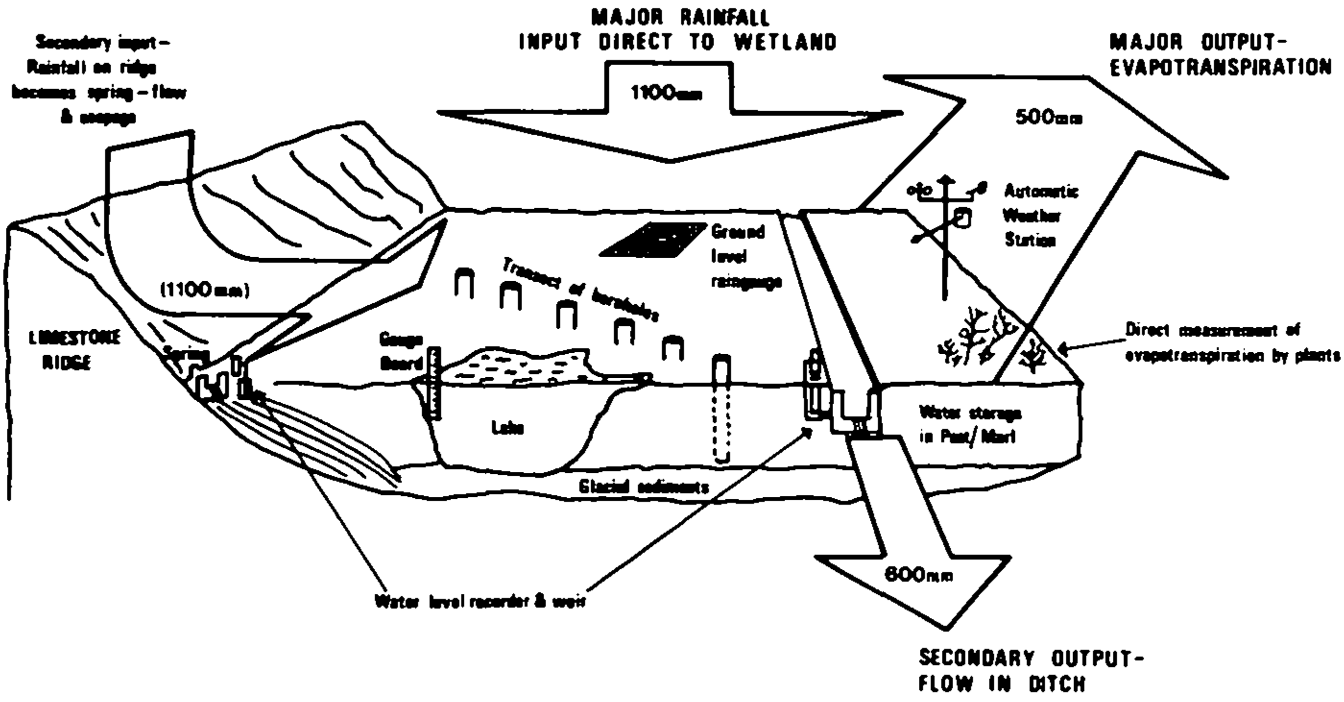


FIGURE 6 The hydrological cycle in an Anglesey fen basin: points of measurement

Apart from the assessment of an overall water balance on a catchment area, routine hydrological measurement provides the basis for seasonal and annual comparisons. Previous reports have presented a short review of the rainfall, evapotranspiration and soil moisture deficit for the year in question; the situation for 1980-81 is shown in Figure 7. The most characteristic feature of the Project's third year was that moisture stress (as indicated by soil moisture deficit) built up slowly to peak in August and September. The spring drought, a feature of 1980, was replaced by a late summer drought. Since the 1981 drought occurred during the height of the vegetation cover it is possible that actual moisture deficits were greater than those

PLATE 5 Techniques used in the Anglesey Wetlands study:

(a) Automatic weather station Rainfall is also recorded at this site

(b) Simple weir and water level recorder on in-flowing stream

(c) Borehole and recorder

(d) Gaugeboard for lake level measurement

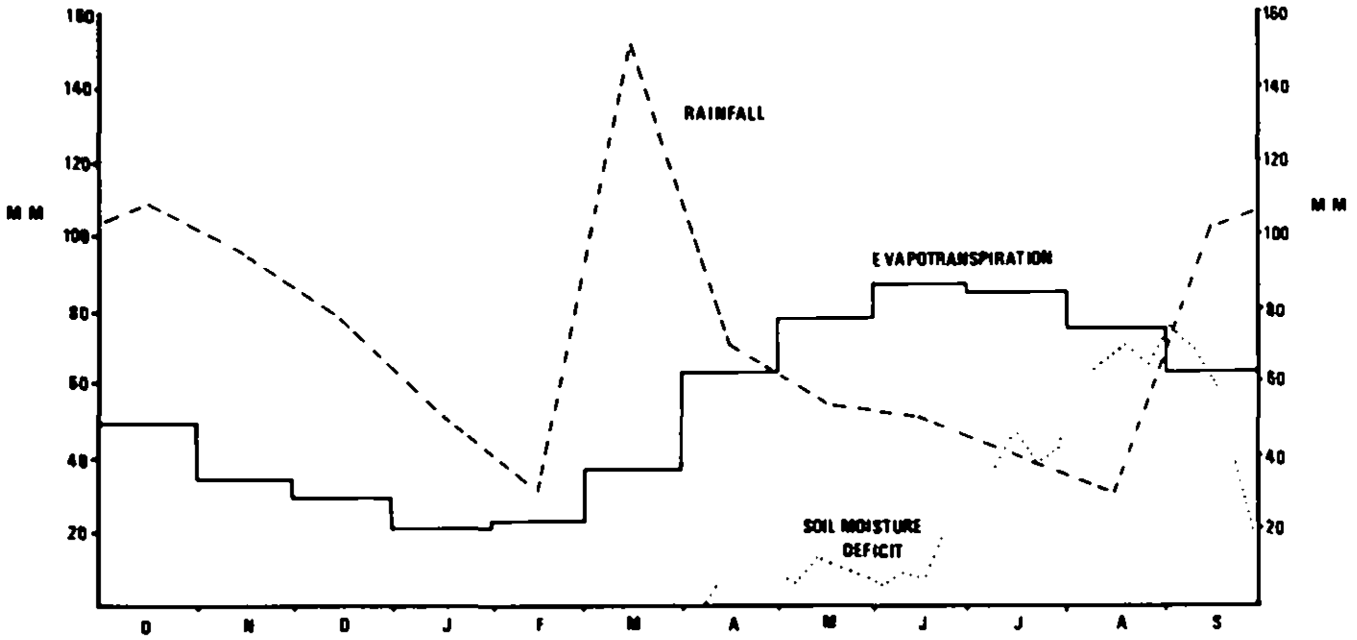


FIGURE 7 The balance of input from rainfall and potential losses by evapotranspiration for Anglesey, 1980-81 (based on monthly figures at RAF Valley). The soil moisture deficit is that calculated by the Meteorological Office for Gwynedd.

TABLE 3 RAINFALL TOTALS OF 20mm OR MORE RECORDED IN A RAINFALL DAY DURING THE *ANGLESEY WETLANDS STUDY*

	20-30mm	30-40mm	40-50mm	50-60mm
28.2.79		32.5		
11.12.79		37.0		
3.1.80	21.0			
30.1.80	20.0			
12.2.80	22.5			
11.3.80	23.0			

TABLE 3 (contd)

14.6.80	20.5			
20.9.80	20.5			
26.10.80		39.5		
19.12.80			40.5	
8.2.81	22.0			
21.3.81				60.0
19.9.81	20.5			
23.9.81	23.0			

Classification of heavy falls of rain at Valley, Anglesey
(Kindly supplied by Mr Ivor Maclean)

	DURATION					
	1 hr	2 hr	3 hr	6 hr	12 hr	24 hr
FREQUENCY						
Once in 10 yrs	18 mm	23	27	33	41	51
Once in 40 yrs	25	32	37	46	56	68
Once in 160 yrs	34	44	51	63	75	90

calculated from rainfall and potential evapotranspiration. In fact water management on the wetlands in a year like 1981 would require reference to research on net rainfall (i.e. the rain which penetrates the vegetation cover to reach the ground surface) and actual transpiration rates (see below), if the true requirement for raising water levels were to be known.

1980-81 was a wetter year than its predecessor with 1382 mm of rain falling at Cors Erddreiniog (cf 1111.2 for 1979-80). Distribution of the rainfall was more seasonally equable (60% winter, 40% summer) but there was a notable storm on 21st March which produced the worst flooding on Anglesey for some years. Mr Ivor Maclean, the Met. Observer at RAF Valley, has estimated that the 60 mm which fell during 24 hrs has a frequency of only once in 40 years. The daily falls of more than 20 mm during the Study are listed in Table 3. This shows that such falls can be expected every 6 months, with falls over 30 mm once a year and so on; the record is too short for probability analysis, and Valley records are tabulated for this purpose.

Streamflow response to the March storm, and the time distribution of the rainfall, are shown in Figure 8. It is of value to future water management schemes to consider such events in some detail since pumps or sluices would need to be manipulated to obtain maximum benefit from inundation or prevent damage. Figure 8 illustrates that, even with its system of ditches for drainage, Cors Erddreiniog is still comparatively slow to react to rainfall; the Nant Isaf hydrograph combines slow response of springs with the "flashiness" of surface runoff on a sloping catchment. Only a kilometre lower down the system, the individual peaks of the

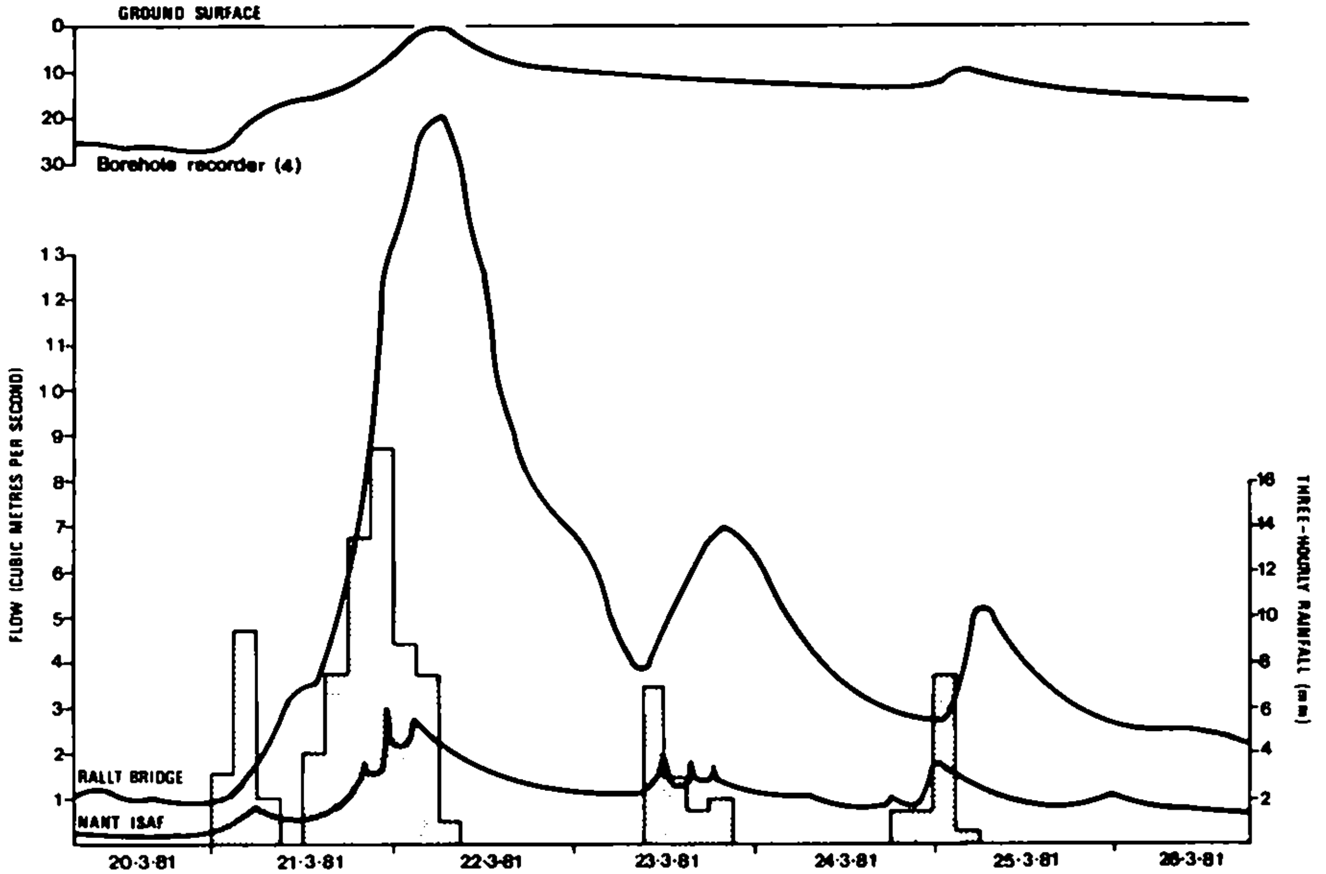


FIGURE 8 Rainfall and flow hydrographs at Cors Erddreiniog for the flood of 21st March, 1981

Nant Isaf record are seen to be smoothed and a delay of 6-8 hours introduced between peak rainfall and peak flow. A management system which sought surface inundation of the fen could easily provide a more voluminous if not a more rapid flood response; sluices would need to be opened, either before the flood to create storage or during it to prevent damage. The former is preferable since it enhances the natural flood-retaining role of wetlands. Complete agricultural drainage of the basin would, in most conditions, be detrimental to this role.

The annual plot on Figure 9 confirms the relative contributions to total outflow made by the various sources of water on Erddreiniog (Gilman and Newson, 1981). During dry weather the constancy of a small spring source (e.g. Nant Uchaf Spring) is important, but as flows increase sources which include some surface catchment, like Nant Isaf, contribute more, and for the highest floods the whole surface of the main portion of the fen becomes active via drains.

It will be obvious from Figure 9 that the hydrological instrument network on Erddreiniog has been less successful in the year 1980-81 than previously; deliberate damage was suffered by two flow gauges - Nant Uchaf Spring and Nant Isaf. Flow figures are therefore estimated. The Automatic Weather Station could not be maintained in the careful way IH has learned to be necessary, and data recovery fell to only 62% (from 90% in the previous year and 77% in 1978-79). In future, more extensive servicing and quicker data processing must be budgeted. Maintenance to the Nant Isaf water level recorder site necessitated by siltation also proved a problem. No hydrological investigation ever provides a truly continuous record, but future wetland studies will need to be carefully planned with the possible influence of the elements and vandalism in mind.

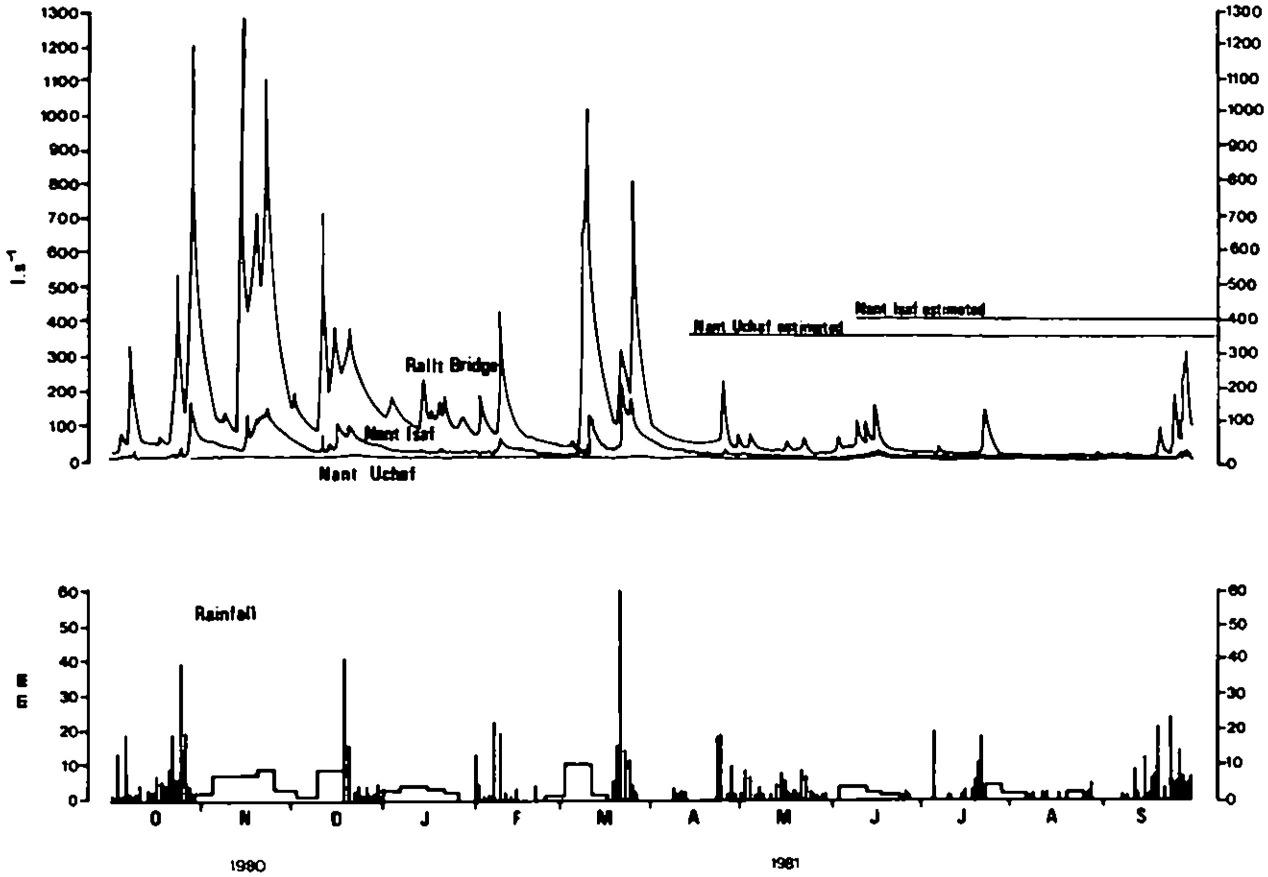


FIGURE 9 Annual records of rainfall and flow at Cors Erddreiniog for 1980-81. Periods without daily rainfall data are blocked together to show the average daily catch by a storage gauge.

Turning to measurements of storage from the borehole networks of the two fens, instrument problems were also encountered here; the Cors Goch recorder breaking down in January 1981 and that at Erddreiniog being redeployed in May 1981. The redeployment was to a site on the "ditch transect" of boreholes at Erddreiniog; at the time it was felt that deepening of the ditch was imminent. Both recorders are at present (March 1982) working on the ditch transect site but excavation has been delayed by NCC's obvious objections.

As for the remaining network of weekly-read boreholes (see Figure 10), those at Cors Goch were reduced to monthly readings during the summer of 1981 to allow the warden more time at Erddreiniog. Only records for sample boreholes are graphed (a sub-sample of those used in the paper by Gilman 1981), here in Figure 11 as illustrative of wetland status. Cors Goch (2) is representative of the type of site at which *Cladium* is most successful, with water levels standing above the surface all year. No boreholes in the Cors Erddreiniog (1) Transect show such high levels, though Erddreiniog (1) where *Cladium* is present but not dominant has standing water in winter. Erddreiniog (3), with water level below ground all year, is typical degraded fen.

The remainder of the records have been tabulated, together with previous data, so that seasonal levels, fluctuations and relationships with plant cover can be calculated. Clearly mean water levels relating to the local surface vary very little (Table 4)*, especially in winter. Summer levels vary more from year to year but not directly in accordance with seasonal rainfall; the timing of this rain may be the crucial factor. Range of water levels relative to local surface

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in Appendix II

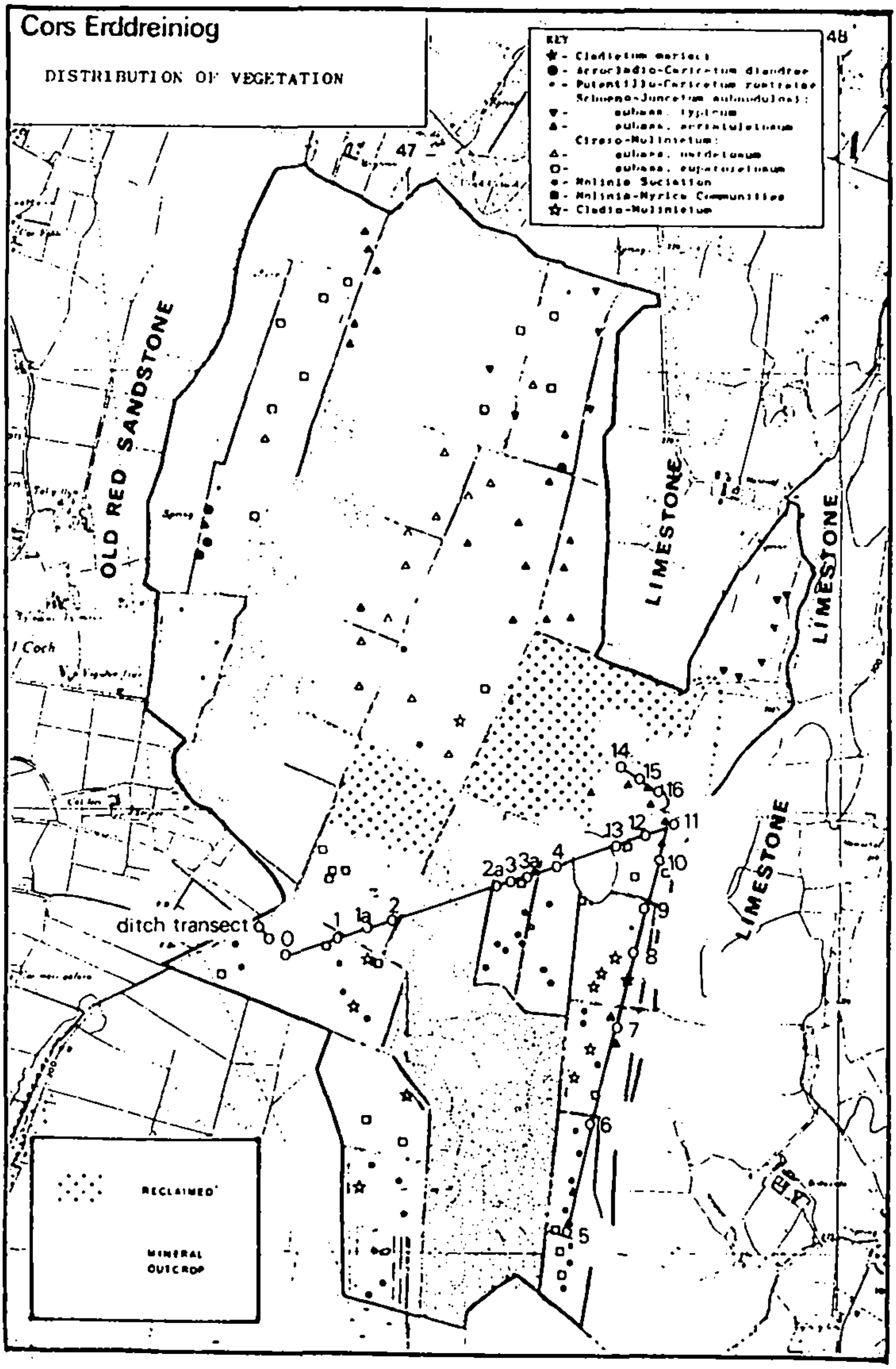


FIGURE 10 The location of boreholes, plotted on the botanical survey of Meade (1981)

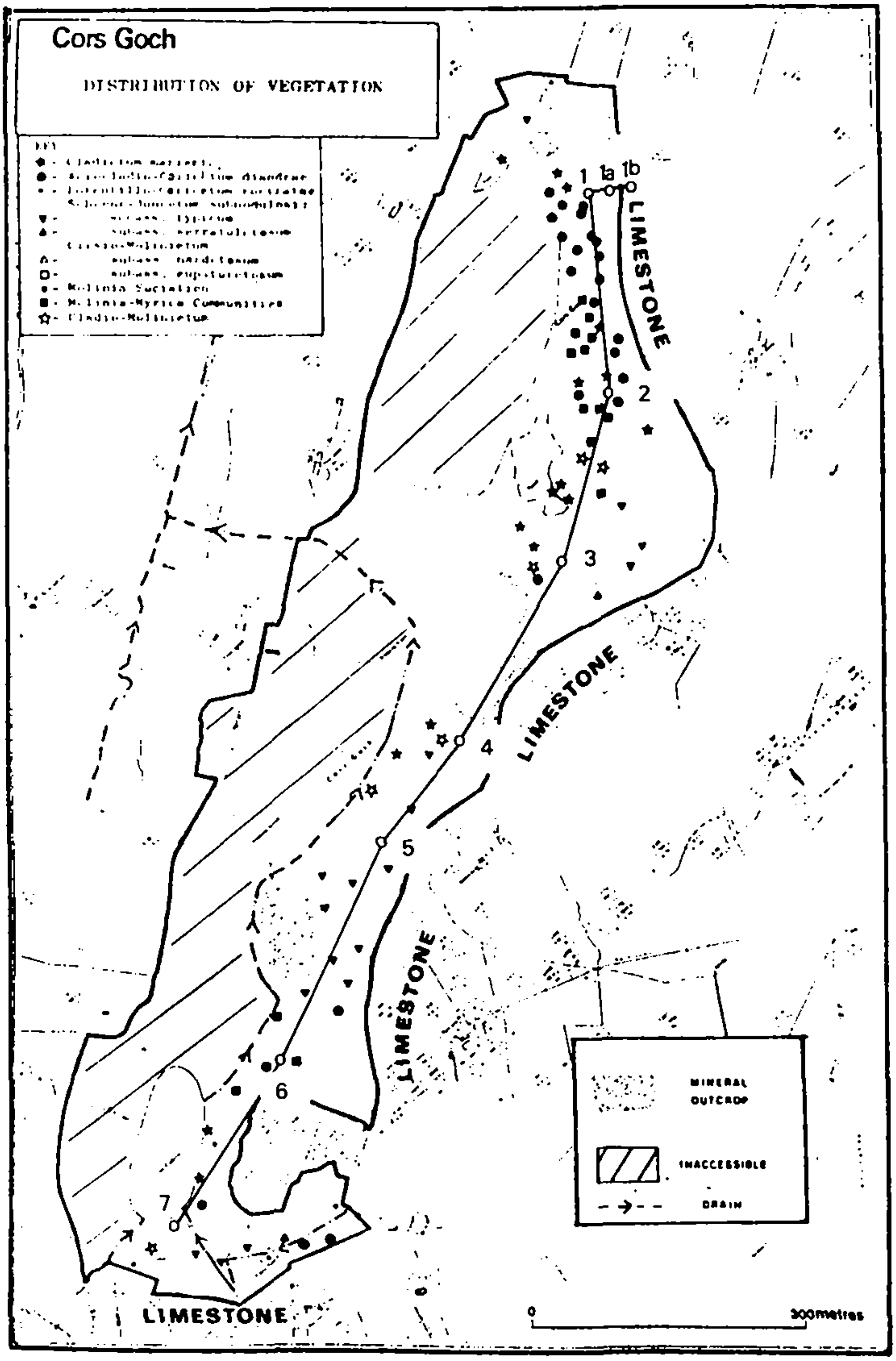


FIGURE 10 The location of boreholes, plotted on the botanical survey of Meade (1981)

varies, more especially the summer range: the wetness of April and September is the sensitive factor. During the study as a whole there has been no evidence of progressive change at any site on the two fens as a result of climatic change or continuing drainage influence; however the record is very short. Many of the basic recording positions are still set up at both sites and the long-term monitoring of key points is one recommendation which has been made informally to local NCC staff.

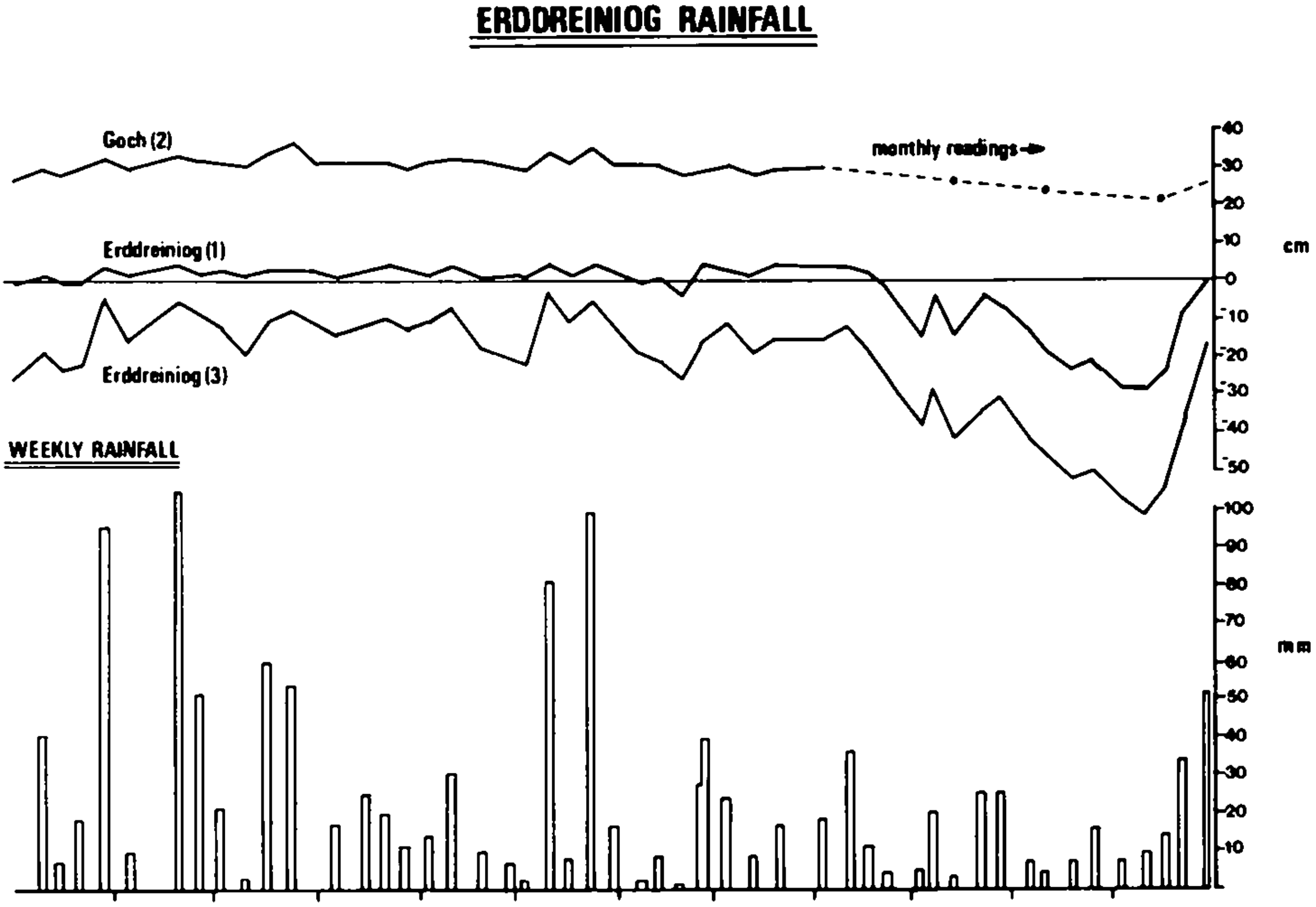


FIGURE 11 Weekly rainfall for Cors Erddreiniog and plots of water levels in a sample of boreholes at Corsydd Goch and Erddreiniog, 1980-81.

2.2 Studies of hydrological processes above ground

There are signs from water balance studies that around half of the rainfall input to the Anglesey wetlands is lost back to the atmosphere as evaporation and transpiration. This loss has a marked summer maximum (80% of the annual loss occurs April - September) and since rainfall shows a summer minimum, runoff is even more seasonally biassed (95% winter; 5% summer). During the summer, therefore, we may consider the fen to be participating mainly in vertical exchanges of energy and moisture above ground level.

Interception/evaporation

Since much of the fen vegetation is deciduous, the influence of a luxuriant plant cover during summer must be considered. The hydrologist needs to answer two major questions in respect of the canopy of vegetation:

(a) does less rainfall reach the fen surface beneath the canopy of plants; i.e. is rainfall circulating vertically by evaporating from *interception* storage before reaching the ground?

(b) is that water which reaches the ground used more or less efficiently in *transpiration* by wetland plants than by other species?

The simplest way to measure interception is to measure gross precipitation in an area clear of vegetation (or above the canopy) and net precipitation beneath the canopy; the major problem is to make both measurements representative and there is a particular difficulty with net precipitation resulting from the very variable cover produced by any plant canopy. At Corsydd Erddreiniog and Goch a very tentative approach has been made to representative net precipitation measurements by selecting sites at each location beneath the major fen plants. Each site is instrumented with a standard raingauge funnel set at ground level and feeding its catch into a carefully sunken collector. The collector was emptied regularly and the contents compared with the catch from a standard raingauge in the same area. Results are presented in Table 5. "Sky-shots" taken from the rim of the funnel at typical sites are shown in Plate 7 and illustrate the reason for interception.

TABLE 5 NET PRECIPITATION/INTERCEPTION MEASUREMENTS, ANGLESEY WETLANDS

CORS ERDDREINIOG

		Net rainfall (mm)						
Date	**Gross rainfall (mm)**	**Mixed herbs (a)**	**Mixed herbs (b)**	**Cladium (a)**	**Cladium (b)**	**Molinia**	**Salix**	**Phragmites**
13.7.81	2.8	.25	.25	1.2	.1	.8	.4	.1
22	26.3	11.5	5.95	8.1	2.15	15.3	6.1	5.1
28	28.4	11.8	11.6	5.6	8.6	12.8	10.1	18.2
6.2.81	7.3	2.0	1.2	4.3	1.9	10.1	2.7	3.2
11	4.1	1.8	1.2	1.0	1.0	2.8	1.2	1.5
19	7.3	1.0	.9	3.6	1.5	6.6	1.6	1.1
26	15.4	4.0	5.1	8.0	1.9	19.4	5.8	6.0
11.9.81	9.8	2.7	3.5	6.4	.8	8.9	2.5	4.8
17	14.3	2.5	6.1	8.6	1.7	15.9	4.7	2.5
22	36.4	9.7	13.8	27.9	5.8	35.7	12.4	19.5
29	50.6	24.6	19.9	29.0	6.2	51.6	18.1	20.9
8.10.81	85.2	52.9	48.2	24.3	10.5	75.2	47.5	48.7
Mean % throughfall		32	31	47	15	87	32	37

CORS GOCH

		Bracken	**Myrica**	**Schoenus Juncus (a)**	**Schoenus Juncus (b)**	**Cladium (a)**	**Cladium (b)**	**Salix**
21.7.81	**15.5**	**3.9**	**6.0**	**8.35**	**2.95**	**.6**	**.3**	**9.0**
12.8.81	**30.3**	**20.6**	**28.3**	**7.8**	**11.0**	**5.6**	**19.0**	**23.8**

TABLE 5 (contd)

1.9.81	32.1	16.0	24.4	18.2	12.7	8.05	8.5	15.2
17.9.81	28.8	21.3	16.2	18-5	7.0	1.6	12.7	20.4
Mean % throughfall		54	66	50	30	13	24	64

Because of the tentative nature of the sampling no attempt is made to analyse these data in the sophisticated ways used at IH for interception data from conifer plantations. The general conclusions are:

(a) only around half the rainfall which occurs during the period of dense plant cover (June - October) reaches the fen surface as "throughfall",

(b) *Cladium* reaches very high percentages of interception (very low percentage throughfall)

Since general throughfall is not the only route for rainfall to the ground surface, a selection of plants was instrumented to measure any water flowing down their leaves and stems (Plate 6). Stemflow was measured on only two occasions, after one week and after six months. Only in the latter case did it reach significant volume. However, when corrected for the spatial coverage of the *Cladium, Phragmites, Pteridium* and *Myrica* shoots so equipped, the proportional contribution of stemflow to total throughfall became less than 5%, i.e. around 2% of rainfall input. This is much less than occurs as stemflow in trees, possibly because of size but mainly because of the flexibility of the wetland plants which allows water to be blown from the leaves before it is channelled down the stem.

The major conclusion of the work is that just over half the rain falling on these fens during summer may not reach the fen surface; however, while the plant canopy is wet transpiration rates will be low so this is not a total loss to the fen hydrology. The balance between the processes requires further study.

Evaporation/Transpiration

Clearly, before any further attempt to assess the relative influence of the summer plant canopy on net precipitation input and transpiration output some method of measuring the latter is required. Whilst the major function of the automatic weather station on Cors Erddreiniog was to allow calculations of evapotranspiration via the Penman and Penman-Monteith equations, it should be remembered that these calculations refer to *potential* rates under a set of ideal conditions. Debate abounds as to whether wetland plants deviate from predicted rates of transpiration (because of abundant water availability or different physiological controls) and about the relative importance of open water evaporation in wetlands. The published work is now reviewed; most of it refers to plants of open water and compares rates of hydrophyte transpiration with the rate of evaporation from open water.

Many large wetland plants are accorded very high rates of transpiration with little experimental verification. For example Haslam (1970) quotes 1000 - 1500 mm p.a. for *Phragmites* in East Anglia. Thatcher (1921) quotes peat as promoting higher rates of transpiration from a range of plants than do mineral soils at the same water content. It is fair to say that only recently have plant physiologists and hydrologists been equipped to study rates of transpiration *in situ* without disturbance to the plant. No matter what precautions are taken, severing plants or parts of plants is likely to influence the measured rate of transpiration (Willis *et al* 1963) and even the construction of tanks and lysimeters can lead to

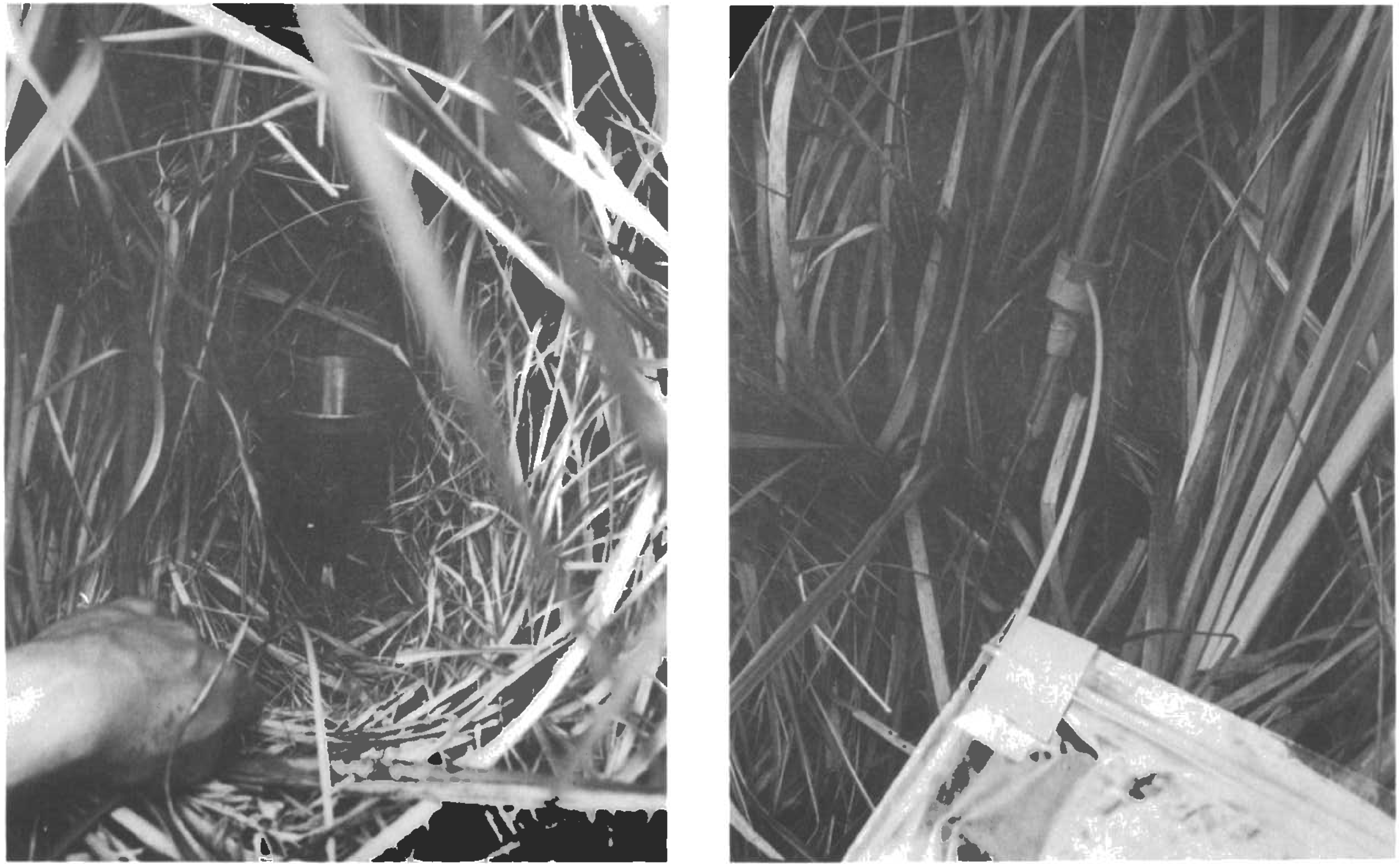
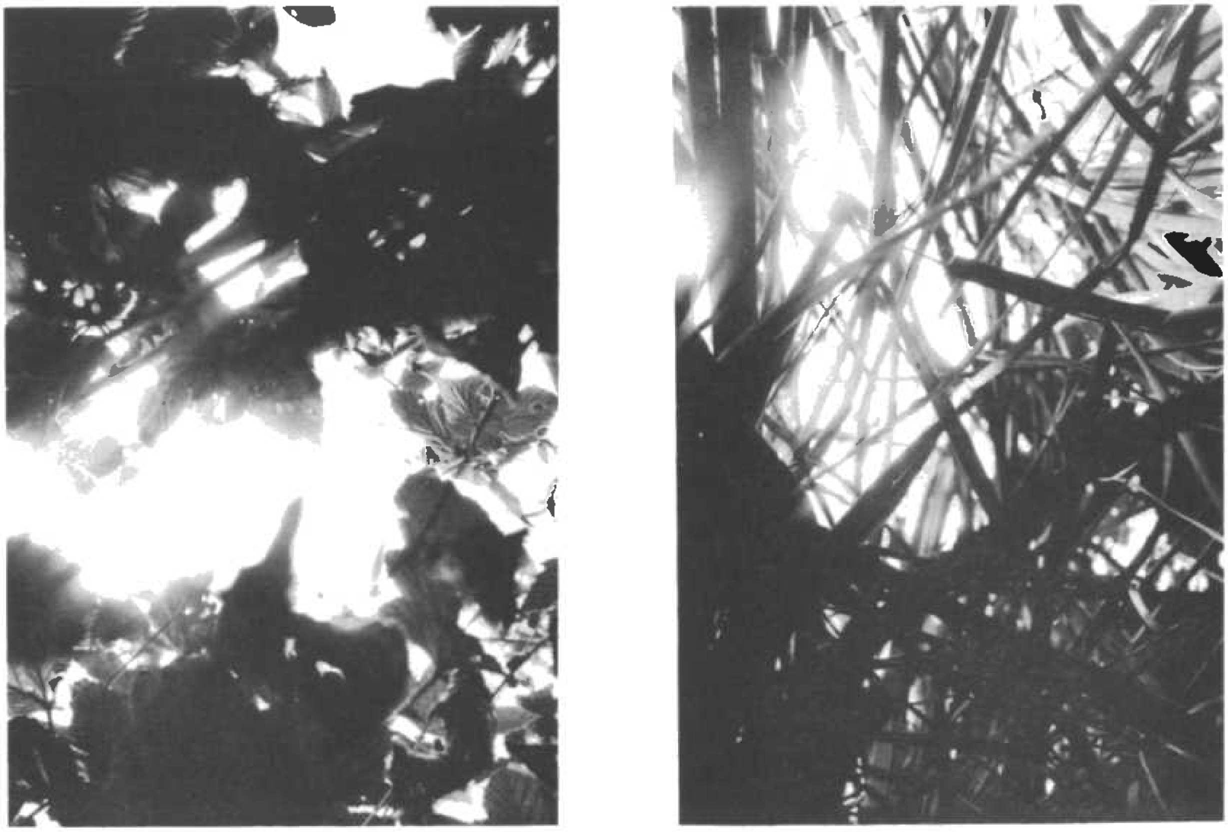


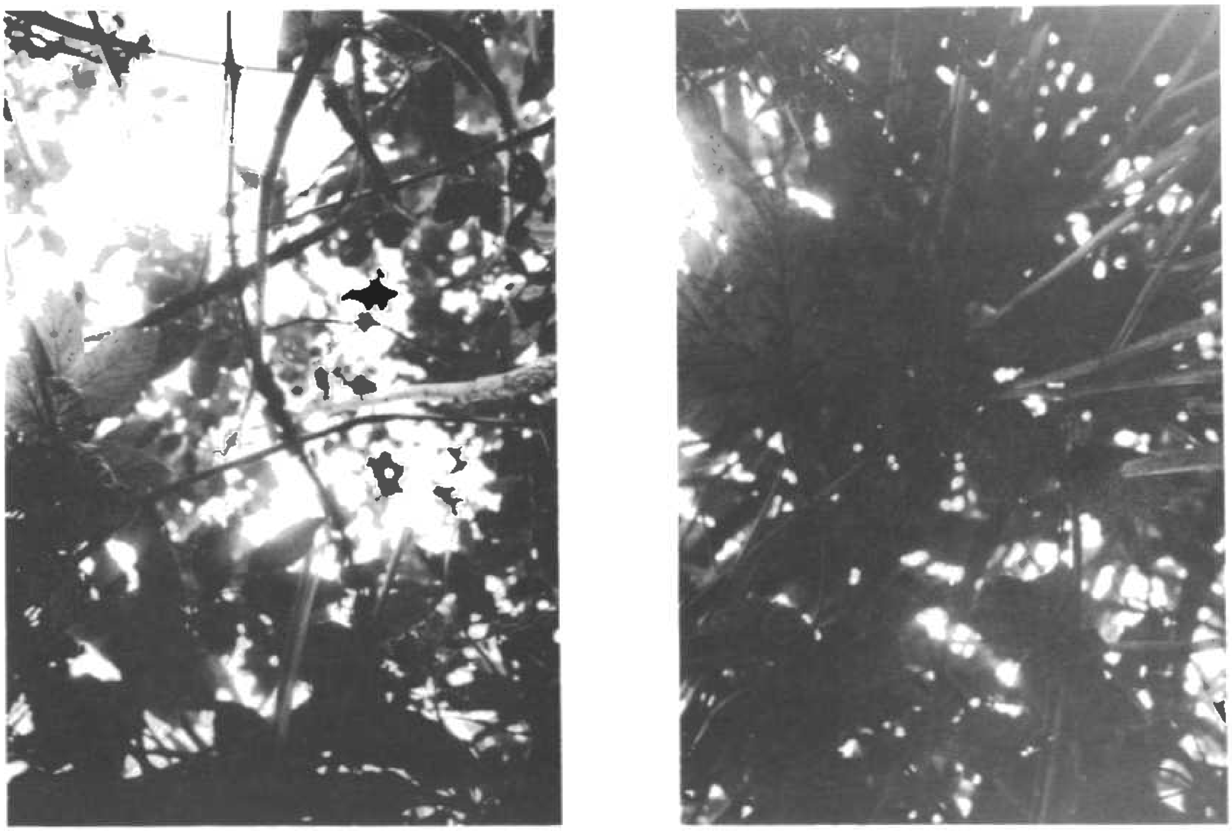
PLATE 6 Measurements of net precipitation beneath fen plant canopies, both pictures from *Cladium* sites

(a) Throughfall funnel/collector (b) Stemflow collar, tube and bag collector



Mixed herbs

Cladium



Salix/herbs

Phragmites

PLATE 7 Sample "sky shots" from beneath the vegetation canopy at Cors Erddreiniog "oasis effects" (see below). On the whole, the faults in these techniques will tend to exaggerate the rate of transpiration they measure.

It is not surprising, therefore, that the more recent papers are more conservative in their estimate of the transpiration rates (of hydrophytes especially). Eisenlohr (1966) suggests that, in vegetated prairie potholes in the USA, the water balance during the growing season sees the transpiration loss gaining on the open water evaporation as the latter is suppressed by the cover of plants. The effect is sufficient to reduce the gross loss of moisture from vegetated potholes when compared with unvegetated ones. *Linacre et al* (1970) confirms this result in Australia, using the eddy correlation method of measuring vapour flux. Linacre's (1976) review presents these results in the context of available methodology and climatic variables. Too often, he says, studies involving individual plants or lysimeters have been at the edge of a wetland where drying winds have produced the "oasis effect" and high rates of loss, or have been performed on tall specimens which are subjected to a similar "clothes line effect" by protruding from the general microclimate of the wetland. With regard to climate Linacre makes the point that his work and that of Eisenlohr refer to dry climates and standing surface water. Idso's (1981) review uses mainly examples from similar climates in concluding a water-conservation role for hydrophytes.

In view of the rather restricted geographical range of the above examples, the work of East Europeans is more likely to be of relevance to Anglesey; it also has the advantage of referring to shorter plants, grasses and sedges and a range of wetness conditions. For example Rychnovska *et al* (1972) compares the transpiration of grass/sedge communities in dry, mesotrophic and wet conditions and finds the ratio of transpiration to open water evaporation to be at a maximum (2.38) in mesotrophic conditions, a minimum in dry (0.33) and intermediate in wet (1.04). However, standardized by dry weight of biomass, these rates were similar (around 13 g.g^{-1}.d^{-1}).

Two papers by Priban and Ondok (1978, 1980) emphasize the importance of micrometeorological measurements in addition to direct studies of evaporation and transpiration; they calculate rates of loss between 2 and 6.5 mm d^{-1} for marsh stands of grass and sedge, very similar to the rates for wet grassland. Smid (1975) records relatively low rates of transpiration from a dense *Phragmites* stand in Czechoslovakia.

Despite the thoroughness of the East European studies it is their stress on micrometeorology which leads us to believe that only the order of their findings may be relevant to Anglesey (for a full treatment of wetland microclimate see Smid and Priban, 1978). A major characteristic of the oceanic, temperate UK wetlands is that summers are not as hot or dry as in East Europe. *Linacre et al* (1970) report a relevant result in this context; after a fall of rain their vegetated swamp site lost more moisture than the open water nearby. The Anglesey wetlands experience a large number of rain inputs during the growing season; it may therefore be that the transpirational component of loss is highly affected by this climatic fact, especially in view of the efficiency with which the plant canopy intercepts rainfall (see above).

Because the literature left little option but to make direct measurements it was decided to investigate the transpiration of two species *Cladium* and *Phragmites* at a single site at Cors Goch and another at Cors Erddreiniog. At first only direct techniques of disturbance were used, plants being excavated and installed in buckets or bags for successive weighings during a dry, warm day or single plants **being placed in measuring cylinders of fen water (Plate 8). The latter technique** was also used in the laboratory. However, there were clearly damaging effects of these treatments to roots and signs that transpiration was affected (leaf curl in

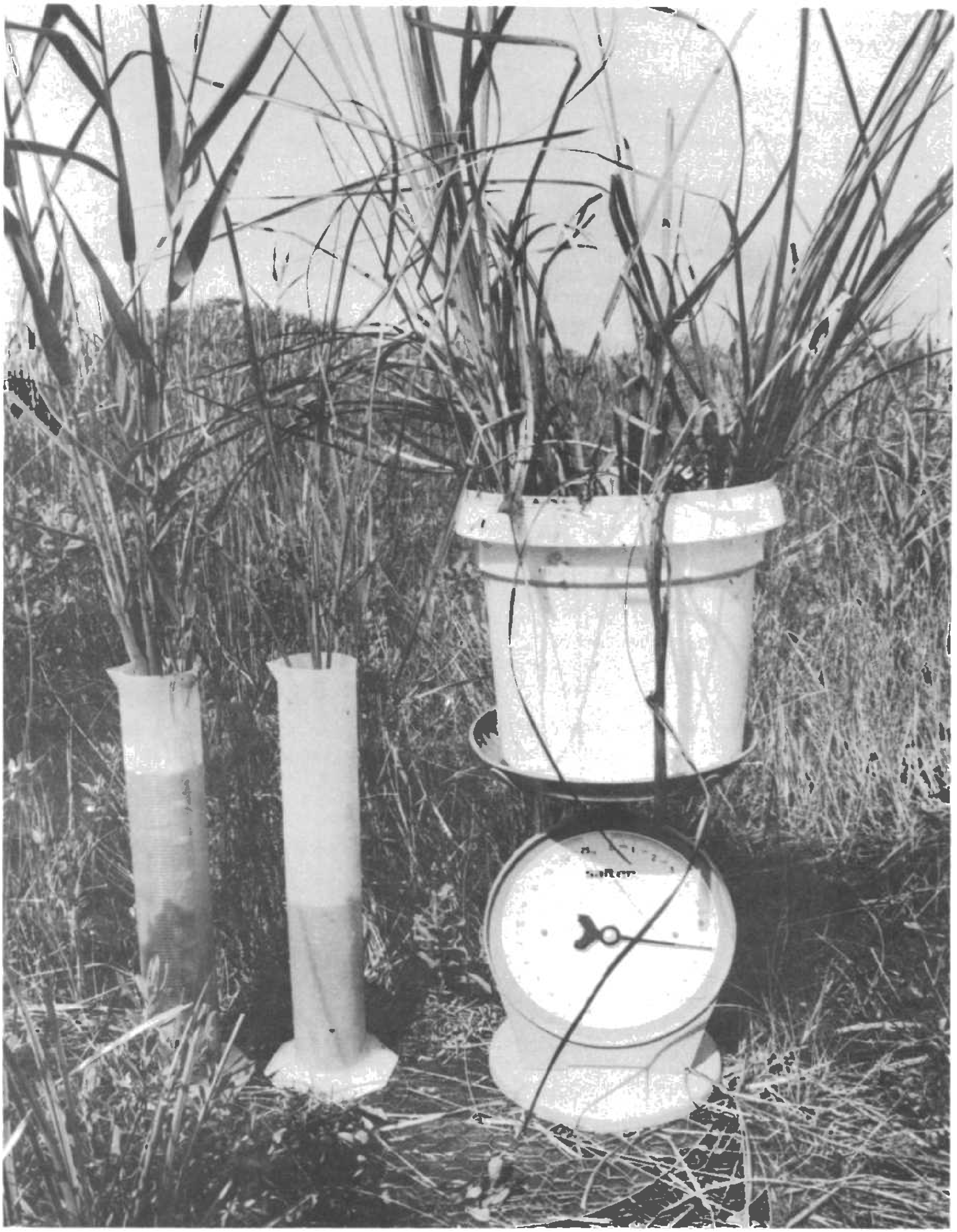


PLATE 8 Simple direct water-loss measurements on disturbed plants at Cors Goch. The equipment is 'nested' in the natural plant stand between measurements for more representative results.

Phragmites for example). Consequently Dr J Roberts of IH Wallingford agreed to use a porometer at the two sites. The principle of porometry is described by Weatherley (1966); it enables the conductance of moisture from leaves to be estimated from the opening of the stomata. Since only a sample of leaves can be measured the technique requires the measurement of leaf areas on individual plants (see Kvet and Marshall, 1971) and ground cover areas for that species.

Dr Roberts used a portable porometer (see Plate 9) on each leaf of the sample plants, both upper and lower surfaces, and at three positions up the leaf. Repeat measurements were made throughout the day. *Cladium* proved extremely difficult to study by virtue of its triangular leaf section; substantial variation in conductance resulted and the mean of the two maximum values in any set of measurements was taken to apply to both leaf surfaces. The lower surface of *Phragmites* leaves have higher conductance than the upper surface.

To reach a figure for canopy conductance it is necessary to calculate the area of plant leaves per unit ground area. Two methods were used to calculate this projected leaf area index (LAI), one gravimetric, the other geometric. The gravimetric technique uses small sections of dried leaves, cut to standard surface areas and weighed to give a graph of weight v area. Whole plants, or harvested quadrats, can then be weighed to gross up to an LAI. The geometric method idealized the leaf as an outline shape in which area is related to a measurable dimension like length or width, e.g. Ondok (1968) treats *Phragmites* leaves as a series of trapezia; we used an oblong surmounted by a triangle. Table 6 shows the LAI results and the resulting values of transpiration. Data for the other variables in the Monteith form of Penman's equation were obtained from the Cors Erddreiniog automatic weather station.

TABLE 6 RESULTS OF DIRECT MEASUREMENTS OF TRANSPIRATION BY POROMETER

A Leaf area indices (projected)

	Phragmites	*Cladium*
CORS GOCH		
gravimetric	0.23	0.71
geometric	0.25	0.47
CORS ERDDREINIOG		
gravimetric	0.27	1.33
geometric	0.27	1.14

B Porometry results

Estimated transpiration rates (mm d^{-1})

	Phragmites	*Cladium*
CORS GOCH (1.9.81)	0.09	0.64
CORS ERDDREINIOG (2.9.81)	0.15	1.14

PLATE 9 Portable porometer to measure stomatal conductance of transpired water (inset shows detail of use on a *Phragmites* leaf)

Clearly, *Cladium* transpires more, due to its larger LAI, but neither plant disposes of the potential evapotranspiration total for the days in question (1.53 mm 1.9.81, 1.79 mm 2.9.81). Either transpiration by shorter herbaceous species accounts for the differences or wetland plant covers act to conserve water under the conditions in Anglesey. The LAI figures for both species are low; Eisenlohr quotes 1.7 - 3.4 for *Phragmites*, whilst Daniels' (1975) data can be converted to LAI's of 0.1 - 2.8. Clearly the LAI of *Cladium* is crucial since the relatively luxuriant stand measured at Cors Erddreiniog (atypical of the area as a whole) almost reached potential rates.

Results from the more direct techniques are very variable and give cause for concern when, for instance, successive weighings of bucket tanks occasionally show an increase or the treated plants appear to be suffering leaf curl. However, they are of the same order of magnitude (see Table 7) as those achieved by porometry and meteorology

TABLE 7 RESULTS OF SIMPLER DIRECT MEASUREMENTS OF WATER LOSS ($mm\ d^{-1}$, standardised by leaf area)

	Phragmites	*Cladium*	Open water	Penman-Monteith E_t
Cors Goch 21.7.81				
Bucket tanks (wet)	-	1.20	1.50	1.65
Measuring cylinder	.01	.02		
Plants hung to dry	.10	.80		
Lab expts (14 days hanging)	.01	.10		
Cors Erddreiniog 26.8.81				
Bucket tanks dry	.40	5.10		2.50
wet	.60	2.70		
Measuring cylinders	.41	.09		
Plants drying	.56	1.70		
Cors Goch 1.9.81				
Bucket tanks (wet)	.60	1.75		1.53
Measuring cylinders	.11	1.18		
	(.09)	(.64)		
Cors Erddreiniog 2.9.81 Period from 26.8.81				
Bucket tanks dry	.15	2.02		1.97
wet	.30	.85		(average)
Measuring cylinders	.74	3.60		
2.9.81				
Bucket tanks dry	.20	1.76		1.79
wet	.10	.90		
Measuring cylinders	.05	.92		
Plants drying	.17	.74		
	(.15)	(1.14)		

Figures in brackets are porometer results for the same site on the same day on the days when both were carried out, and the greater transpiration rates of *Cladium* are pointed to by even the simplest measuring cylinder tests. There is also an intrinsic value of such tests when combined with simple meteorological measurements in the crop stand (Figure 12). These show how the water demand of the crop canopy builds up diurnally and the influence of wind movement over the crop surface.

Perhaps the most striking thing about the porometry and similar techniques is that, using the leaf area indices prevailing at the sample sites, transpiration rates are very low. However, the leaf area indices, themselves are low and when converted to the higher indices which would prevail in a pure stand the rates more closely approximate the potential rate from the Penman-Monteith equation. Unfortunately no published LAI's have been found for *Cladium*, neither is it possible to make accurate comparisons of the ground cover/production of this plant at the Anglesey sites and elsewhere. Only Godwin (1941) has published figures, for Wicken Fen, against which those of dry matter production at the sampled sites at Corsydd Erddreiniog and Goch appear moderate and low, respectively. *Phragmites* appears more abundantly in the literature (Buttery and Lambert, 1965, Haslam, 1972, Smid, 1975, Mason and Bryant, 1975), in every case with denser shoots and higher productivity than at our sampling sites. If we select a multiplication of ten times our measured transpiration rates to bring the Anglesey *Phragmites* sites into line with the LAIs of Daniels (1975) they are more reasonable and especially those measured by porometry are relatively close to the potential rate for the day of the measurements (around 60 - 80% of potential). This is still low and raises the question of stomatal control and leaf curling by *Phragmites* at these two sites. Roberts illustrated a fall in leaf conductance during the day at both sites and Plate 10 shows how the attitude of *Phragmites* leaves can change on a warm, dry, windy day between conditions at dawn and mid afternoon. Smid (1975), working on *Phragmites* in standing water recorded no stomatal control. One must conclude that the measurements described above yield interesting insights into the use of water by the plant species of the Anglesey fens but only two were treated and at sites where many other herb species are transpiring. Possibly the shelter of the taller plants inhibits high rates of loss from these. Of *Phragmites* and *Cladium*, one is best suited to porometry and the other to simpler direct techniques. Grossing up to simulate the transpiration by pure stands is difficult because the controlling variables of microclimate would be different in such a pure stand. The measurements made of temperature, humidity and windspeed to accompany the Anglesey experiments (Figure 13 is a sample plot) show that a more complete statement of the transpiration of rich fen communities will require much more comprehensive instrumentation and a much better geographical sample of conditions in each basin: the determining variables clearly operate the complex control system the East Europeans have been claiming. Plant vigour and phytosociology need study too; Rakhmanina and Molotovskii (1979) report *Phragmites* transpiration rates much lower outside a monocenosis. We may summarize the Anglesey results in this way:

(1) In most of the measurements, *Cladium* has transpired more than *Phragmites*. Since the Cors Erddreiniog stand sampled is not atypical of successful *Cladium* elsewhere its mean transpiration rate there (all techniques) of nearly 2 mm per day may be reasonably accurate (though imprecise).

(2) These *Cladium* results and those from *Phragmites*, when grossed up to simulate a denser stand (2.6 mm per day) are at or below the potential rate, indicating a measure of transpiration control by these plants under dry soil conditions. They are of a similar order of magnitude to those reported by Godwin (1931) at Wicken Fen. In management terms, therefore, plants are unlikely to suffer from desiccation; irrigation water if applied, might be transpired at high rates. Under present conditions transpiration is controlled before excessive soil tensions build up (see Section 2.3).

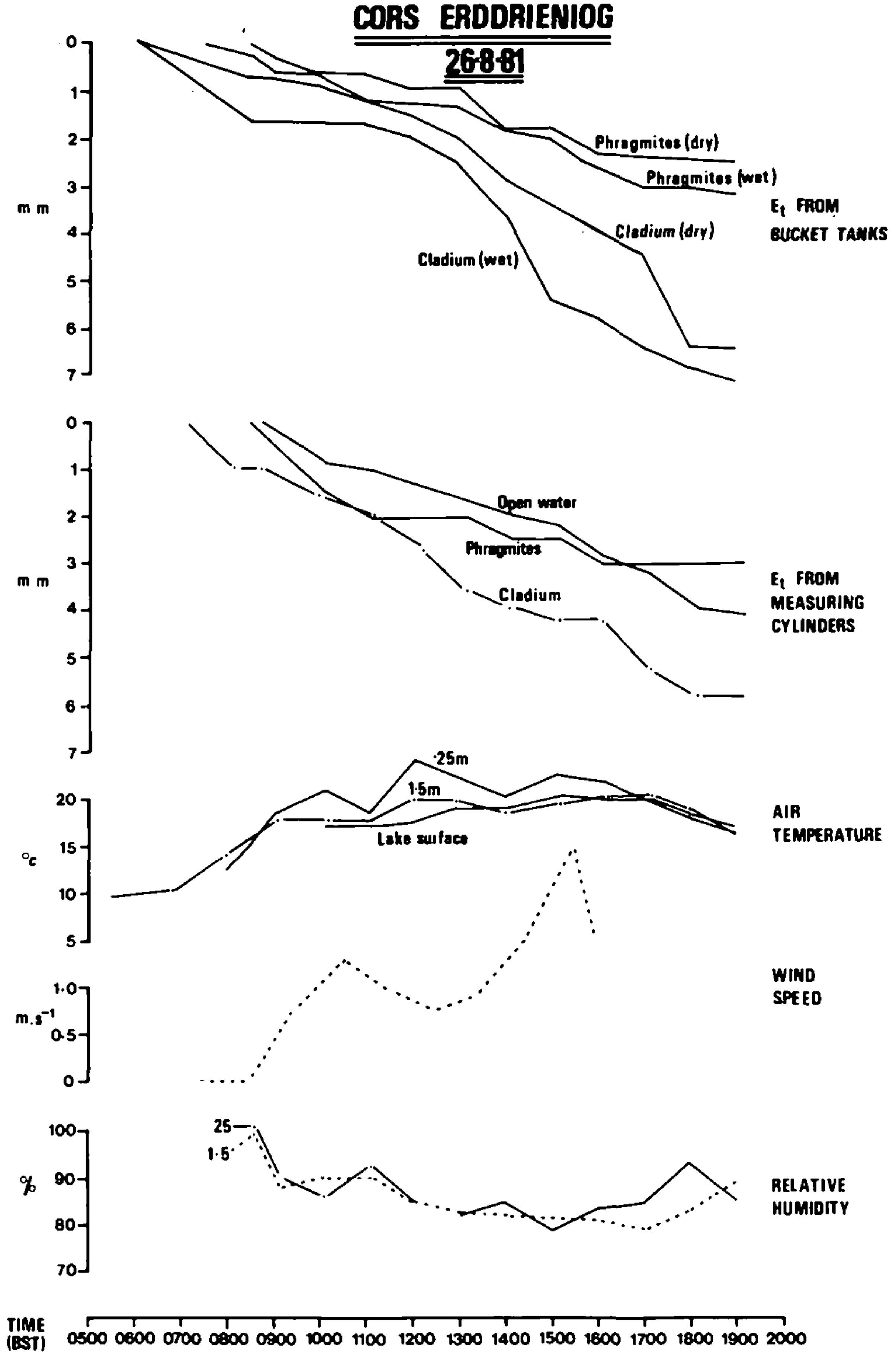


FIGURE 12 Simple direct measurements of water loss from plants, Cors Erddreiniog 26.8.81. Diurnal variation in air temperature and relative humidity are shown at levels of between .25m and 1.5m above ground. Windspeeds were measured at 1.5m. E_t = evapotranspiration

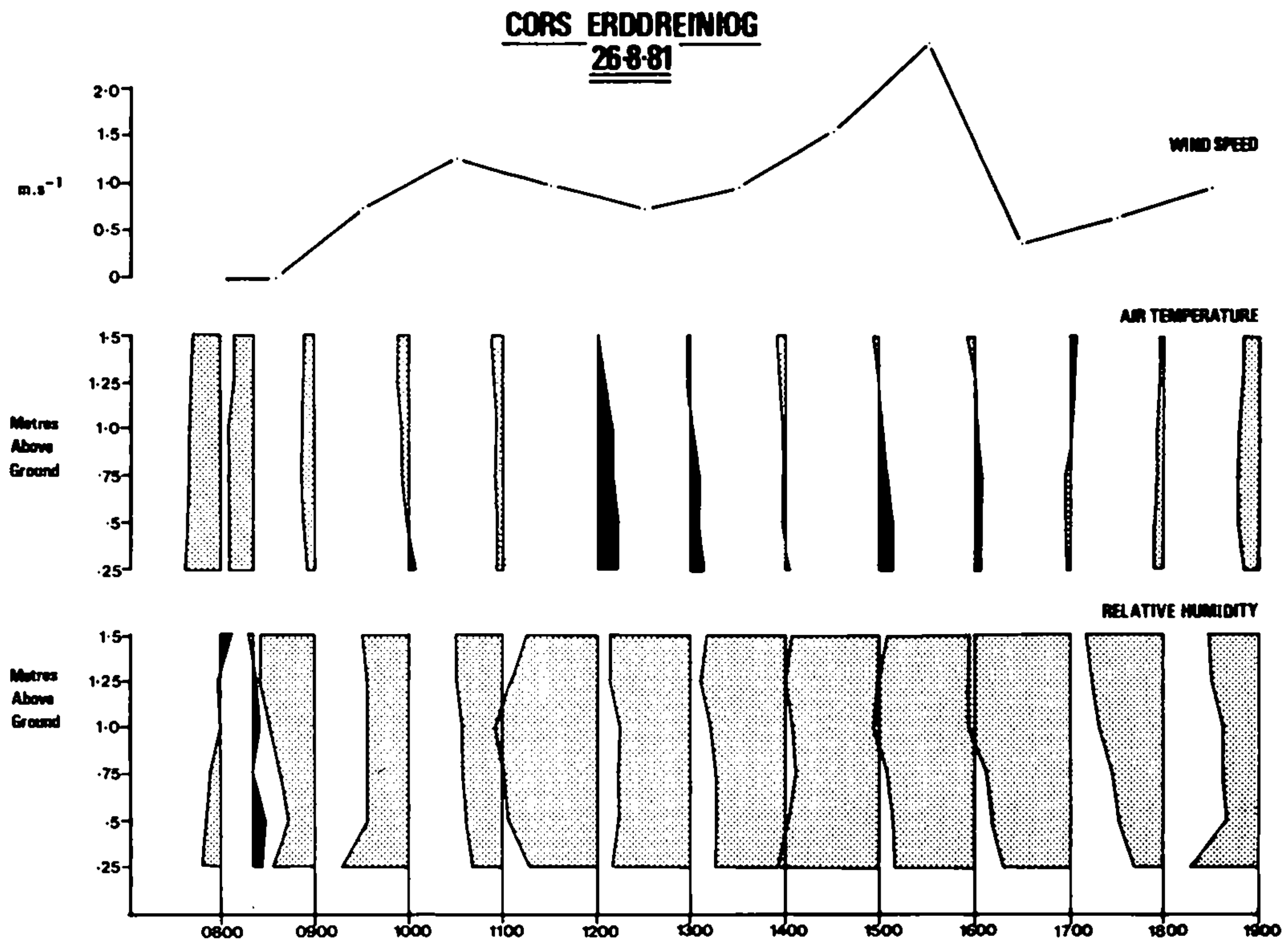


FIGURE 13 Microclimate within a 2 m stand of *Phragmites* and *Cladium*, Cors Erddreiniog, 26.8.81. Air mixing, air temperature and humidity vary appreciably diurnally and at levels within the crop.

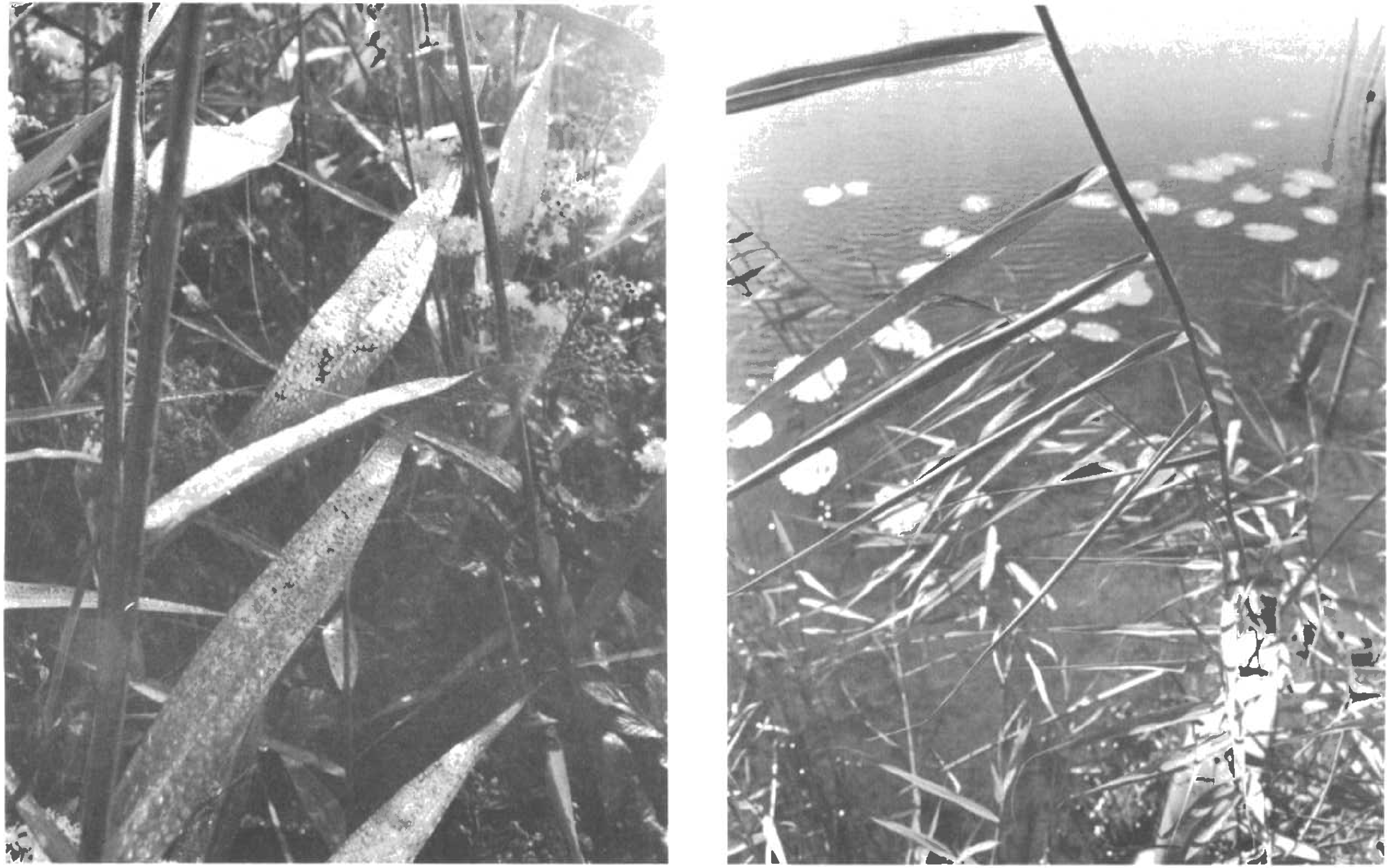


PLATE 10 Changes in the attitude and shape of *Phragmites* leaves between dawn (left) and mid-afternoon (right)

(3) Both sets of figures are low when compared with those in the above literature review, illustrating that results from hot summers and standing water elsewhere in the world cannot be extrapolated to Anglesey or even any UK wetland. The results indicate that interception and evaporation from plant canopies can account for more than half the summer input of moisture under our cooler, rainier conditions.

(4) Conditions of microclimatology and soil moisture/standing water need to be understood in detail for any wetland before we can be more precise about transpiration.

2.3 Studies of hydrological processes below ground

Below the fen surface, water stored in superficial deposits, primarily in the peat, moves mainly by saturated drainage, a process that is almost everywhere horizontal in direction. The storage zone for water is separated by the water table into an upper, unsaturated zone and a lower, saturated zone. In the unsaturated zone water movement is vertically upwards to satisfy transpiration needs of the plants, or vertically downwards conveying excess water to the saturated zone. In the saturated zone a potential gradient corresponding to the slope of the water table conveys water horizontally towards ditches and outflows; where standing water is present on the surface, the unsaturated zone is absent, and transport of water takes place by free surface flow above the ground and the slower saturated groundwater flow below the surface.

Soil water in the unsaturated zone

Unsaturated soil is a remarkable medium that can permit the concurrent movement of both water and air through its interconnected system of pores. Above the water table both air and water are present in soil pores, and the physical behaviour of the soil depends on the combined properties of the soil/water/air system. In this case, the potential gradients leading to the movement of water are generated by surface tension forces at the interfaces between the air and water components. Capillary forces depend on the curvature of the interface, so at low moisture contents, when only the smallest pores are water-filled, surface tension forces are very high, and the water component exists under tension rather than hydrostatic pressure (Figure 14). To withdraw water from the soil, a plant root must be able to overcome these tensions: the removal of water from the soil requires even higher tensions in the plant tissues, and in extreme conditions these tensions become insupportable and the plant wilts.

The entry of other forces complicates this simple picture of the unsaturated zone. The free energy of the system is the resultant of

(i) a force field emanating from the soil particles and their affinity for water (a)

(ii) the hydrostatic pressure (h)

(iii) osmotic pressure caused by dissolved salts (o)

(iv) external pressure (generally atmospheric) (e)

and (v) surface tension (t)

In humid conditions, the osmotic pressure component is generally small, and the absorptive forces of the soil particles are insignificant. The most important components under these conditions are hydrostatic and atmospheric pressures and surface tension.

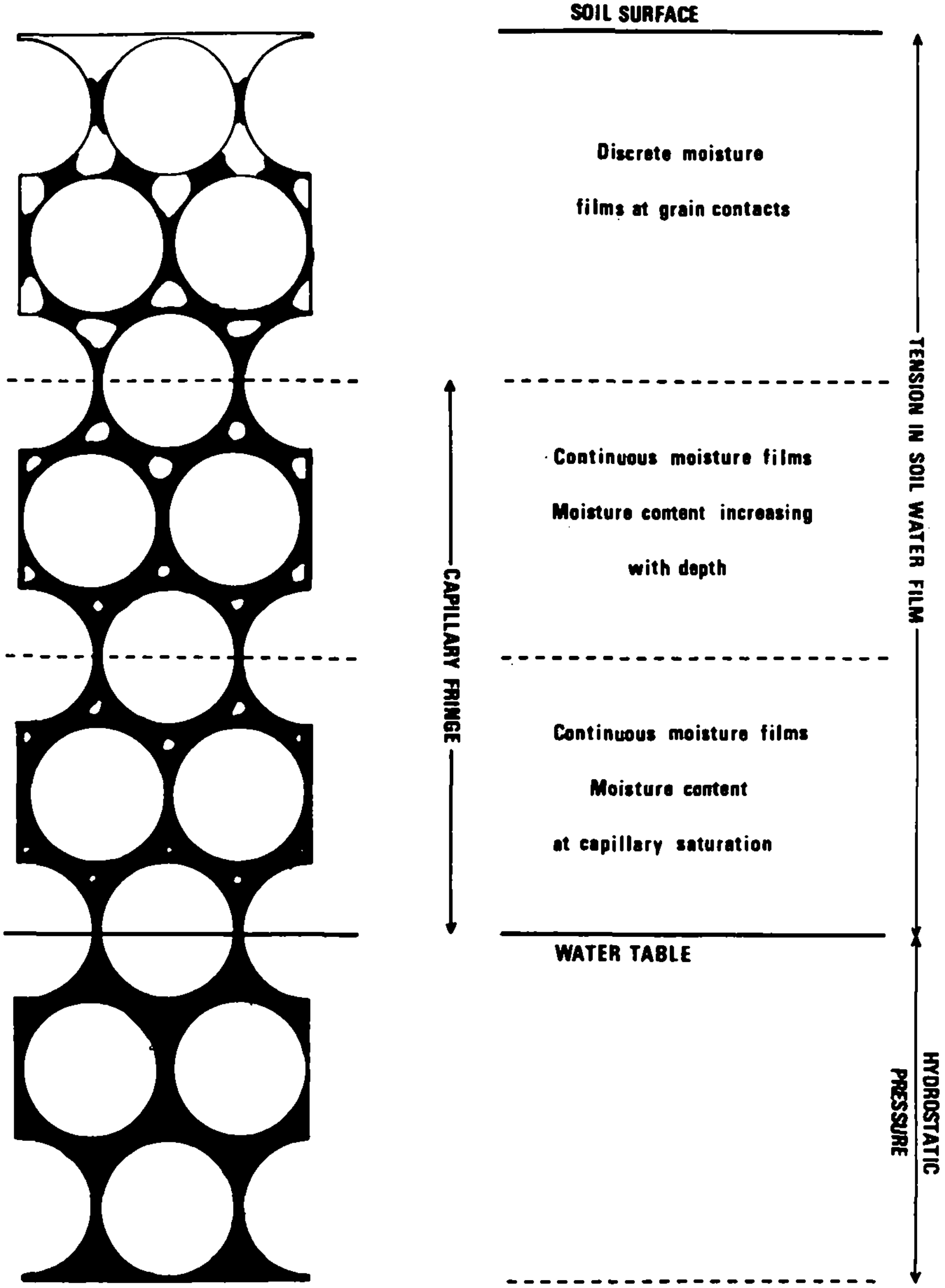


FIGURE 14 Forms of moisture in the soil

The soil water available to plant roots is determined by the gradient of free energy towards the roots. If subscripts p and s denote plant and soil respectively

$$f_p - f_s = (a_p - a_s) + (h_p - h_s) + (o_p - o_s) + (e_p - e_s) + (t_p - t_s)$$

(Black 1957)

In the plant the osmotic forces <u>are</u> important, and by controlling these the plant can manipulate the energygradient to continue withdrawing water from a drying soil. Thus over a wide range of soil moisture tensions many plants can obtain a constant flow of water to replace the transpiration losses.

Plant roots tend to grow towards moister soil, and root extension can further supplement the available water, but the increasing resistance to flow of longer and longer root pathways eventually limits the water supply. Effects of drought are more serious at times of growth: for example cereals are sensitive to a water deficit at the time of maximum growth, but not at other seasons.

With the exception of osmotic pressure, the sum of tension forces in unsaturated soil may be measured using a mercury manometer tensiometer. The principle of the tensiometer is the equilibration of a volume of free water with the water in the unsaturated soil. The tension in the water column necessary to sustain the equilibrium is measured by a mercury manometer. A porous ceramic pot contains the free water, and where a pore of the pot contacts an air-filled pore in the soil, the meniscus adjusts its radius of curvature so as to oppose exactly the tension in the water. Where contact is with a water film there is equilibration of tension between the soil water and the water in the pot. The maximum soil moisture tension that can be accommodated is 2T/r, where T is the surface tension of water and r is the radius of a pore of the pot, but a practical limit is a tension of about 1 bar, at which the water column cannot be sustained.

Figure 15 and Plate 11 show the equipment in a field installation. Flexible tubes are led from each tensiometer to a manometer board and readings are taken of the

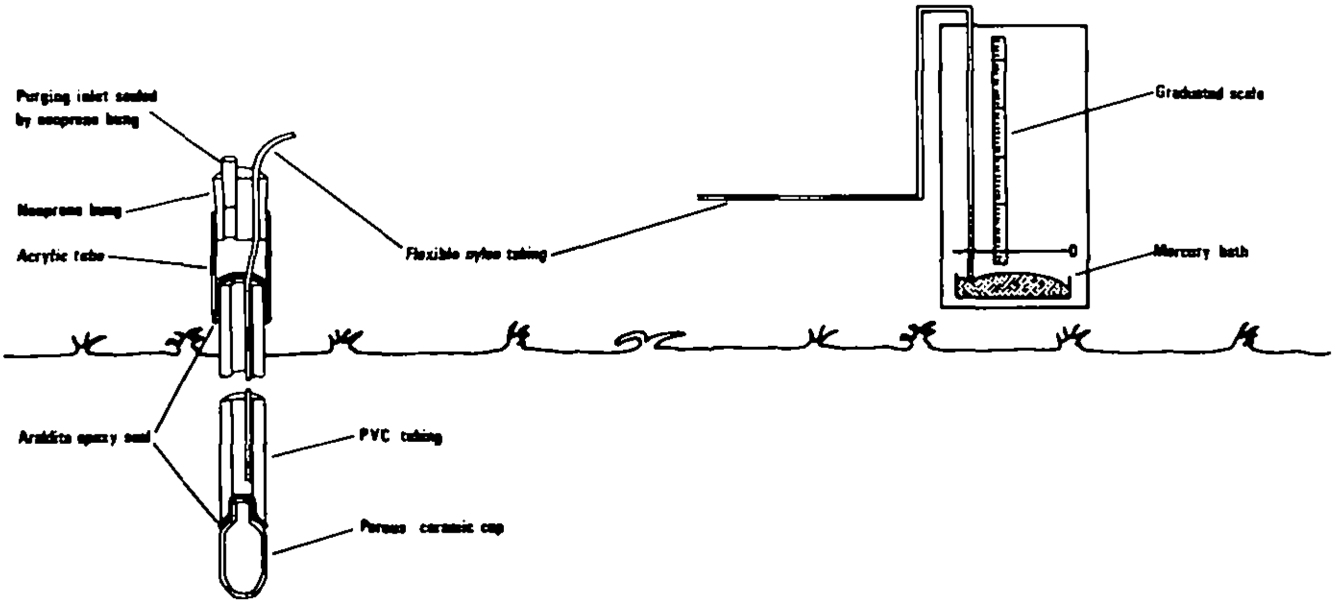


FIGURE 15 Idealized diagram of mercury manometer tensiometer as installed at Cors Erddreiniog. Plate 11 shows an actual installation.

PLATE 11 Tensiometers (left) and mercury manometer board (right) shown in proximity to covered borehole (foreground) Cors Erddreiniog, 2.9.81

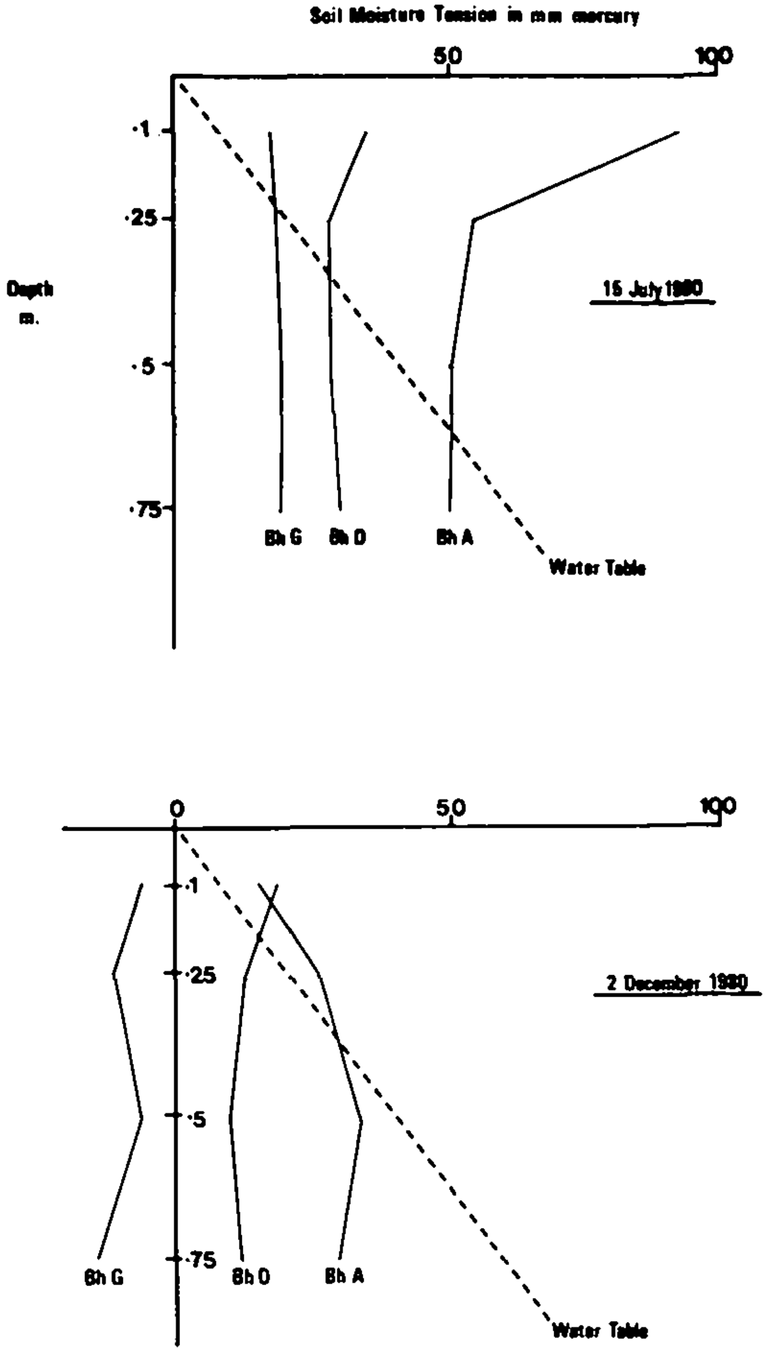


FIGURE 16 Tensiometer results at four depths, for two dates at three locations along a transect of boreholes normal to the main ditch near Rallt Bridge, Cors Erddreiniog. The 'water table' line joins the points where tensiometer results indicate saturation.

During summer 1980 tensiometers were installed at two stations on Cors Erddreiniog: at borehole Erddreiniog (1a) on the extended main transect and at the ditch transect at Rallt Bridge. Tension measurements were taken on the weekly borehole round from July 1980 to January 1981, and from May to October 1981. Measurements were discontinued during the winter because of the liklihood of frost which would invalidate the results and possibly damage the above-ground parts of the instruments.

The station at borehole 1a, on the fen expanse, yielded no measurable soil moisture tension. Indeed the results indicated water levels at or above the ground surface for much of the period of observation. At Rallt Bridge, tensions were highest at borehole A, two metres from the ditch, while at borehole G, 14 metres from the ditch, tension was rarely evident (Figure 16). The highest tension encountered was equivalent to 1170 mm of water, which is a much lower tension than would be expected in summer in an agricultural soil. Appreciable tensions only occur more than about 300 mm above the water table: this suggests the conclusion that moisture stress on the wetland community will only begin when the water level falls more than 300 mm below the surface, and will be even less evident for species with significant rooting depths. These include *Phragmites* and, unfortunately but inevitably, *Molinia*. The relationships between soil moisture and plant communities will be explored in more detail in section 3.1.

Flow of groundwater in the saturated zone

Below the water table, in the zone of saturation, the flow of groundwater is horizontal, and is governed by the permeability, which is a property of the soil which depends upon the type and size of pores, by the hydraulic gradient, which is the gradient of the water table, and by the depth of permeable deposits. The form of the water table will be discussed below under the heading of ground survey; the depth of deposits will be the subject of the section on stratigraphy (Section 2.4). The remainder of this section deals with the permeability of the fen peat which forms the topmost deposit everywhere on the fens, and with groundwater flow towards the main drain.

The permeability of soils and sediments varies widely, from 0.0001 metres per day for silt and loam soils to 100 000 metres per day for clean gravel. Peat has permeability generally in the range 0.1 to 10 metres per day (Bear 1972). This wide range of possible values quoted in the literature is sufficient justification for attempting to measure the permeability of the particular sediments encountered on the Anglesey Fens. The problems of obtaining and testing "undisturbed" samples in the laboratory are such that an *in situ* method is preferred.

The simplest *in situ* method for measuring permeability below the water table was developed by Diserens (1934) and Hooghoudt (1936) and refined by Kirkham (1945) and Luthin and Kirkham (1949). In its original form the method involved drilling a vertical hole in the soil, pumping or baling out the water and observing the rate of rise of water in the hole. A relationship between rate of rise and depression of the water surface below the water table (drawdown) was used to determine the permeability. There were numerous disadvantages to the field method, not least the problem of sloughing of the sides of the auger-hole in unconsolidated deposits. Kirkham's modification was to line the hole, restricting the open portion of the hole to a cylindrical cavity at the foot of the hole. This "piezometer" method has been used widely, and has become a standard method in land drainage work. (A piezometer is an observation well open over a confined region, and used for the measurement of hydraulic head at a point, rather than averaged over the depth of the hole.)

Figure 17(a) is a definition sketch for the piezometer method. The permeability k is given by the formula

$$k = \frac{\pi a}{(S/a)} \quad \frac{\ln (y_1/y_2)}{t_2 - t_1}$$

where a is the radius of the cavity

y_1, y_2 are drawdowns from the initial water level at times t_1 and t_2 respectively

and S/a is a dimensionless shape factor which depends on d and w

On Cors Erddreiniog it proved impossible to use the simple piezometer method, as the cavity in the peat did not stay open, and a modified technique was used. The simple tube of the Kirkham method was replaced by a tube perforated over a 150 mm length and tipped with a conical plug (Figure 17b).

Many methods have been proposed for the determination of the shape factor S/a. Luthin and Kirkham (1949) used an electrical analogue model to investigate the behaviour of the shape factor for varying d and w, and also the effect of an impermeable layer at a depth s below the cavity. Hvorslev (1951) derived a formula for S/a based on the assumption that the potential surfaces around the cavity were ellipsoidal. Hvorslev's formula, valid for w/a greater than 4, is

$$S/a = 2\frac{w}{a}/(\frac{w}{a} + \sqrt{1 + (\frac{w}{2a})^2})$$

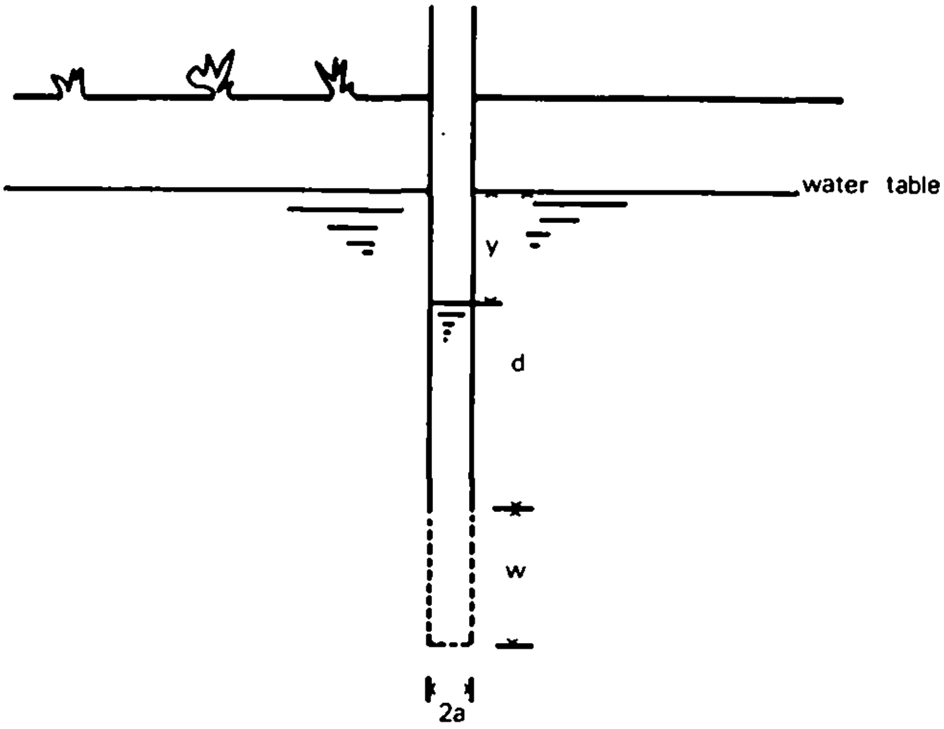
Youngs (1968) used an electrical analogue model to extend the range of values of S/a and to investigate the effects of an impermeable or infinitely permeable horizon below the cavity. Youngs' results showed a moderate degree of dependence on d, which is not expressed in the Hvorslev formula.

A comparison was made, for the piezometer dimensions used for the Cors Erddreiniog tests, between the available tables and formulae and a Bessel series solution. The results, in Table 8, show that even the simple formula of Hvorslev gives a consistent result, and all values, by any method, lie within plus or minus 6% of the mean value. In view of the relative simplicity of the Hvorslev formula, shape factors derived from this formula were used in the calculation of permeability.

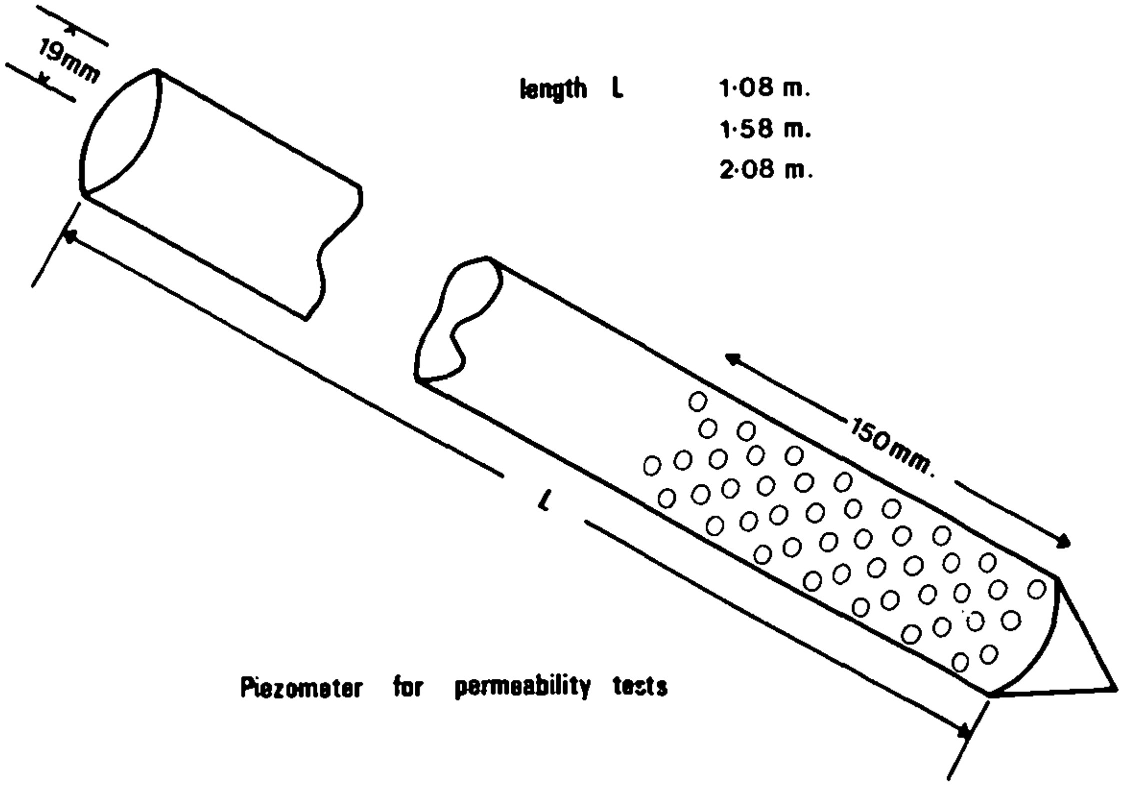
TABLE 8 PERMEABILITY TESTS: COMPARISON OF VALUES OF SHAPE FACTOR S/a

w/a = 7.89			
s/a = 100			
d/a =	90.5	34.0	26.7
Bessel series	23.6	23.3	23.4
Luthin & Kirkham	24.6		
Hvorslev	23.8		
Youngs (extrapolated)	23.0	25.4	25.9

Sites chosen for permeability testing on Cors Erddreiniog provide a reasonable sample of the fen surface within the NNR; they are Rallt Bridge, boreholes Erddreiniog (1) (6) (8) and (12) and the Automatic Weather Station site. Piezometers



Definition sketch for piezometer method A cavity of length w and radius a is augered out from the soil below the base of the tube The drawdown y of the water level in the hole is measured from the initial (water table) level



Piezometer for permeability tests

FIGURE 17 The *in-situ* method of permeability measurement were sunk at each site to depths of approximately 0.5 m, 0.75 m, 1 m, 1.25 m, 1.5 m and 2 m below ground level. The piezometers were then baled repeatedly to remove any smears which could have blocked the perforations during installation: this process is known as development. After development the water levels were left for about 24 hours to stabilise. The actual testing was carried out by pumping each piezometer to a level of about one metre below the water table, then recording the depth to water level every half minute for a period of between 5 and 25 minutes.

Permeability test data were analysed using linear regression to derive the best value for the ratio $\ln(y_1/y_2)/(t_2 - t_1)$ and the shape factor determined from the Hvorslev formula. All the data showed a markedly nonlinear behaviour, departing from the expected straight line graph in a very similar fashion (Figure 18). This type of behaviour was noted by Ingram *et al* (1974) in permeability tests in peat: the explanation would appear to lie in the elastic properties of the peat deposits, but a complete theoretical model has not yet been developed (H.A.P Ingram pers. comm. 1981). Meanwhile it is possible to use permeability values as measures of at least the relative permeability of various peat horizons. Table 9 shows the values obtained at the six sites and the depths shown. At four of the six stations there is a decrease in permeability with depth: of the two exceptions, borehole Erddreiniog (8) is in a tufaceous peat while borehole (6) is in an area that has been grazed. It is not known whether these distinguishing features can explain the departures from the norm.

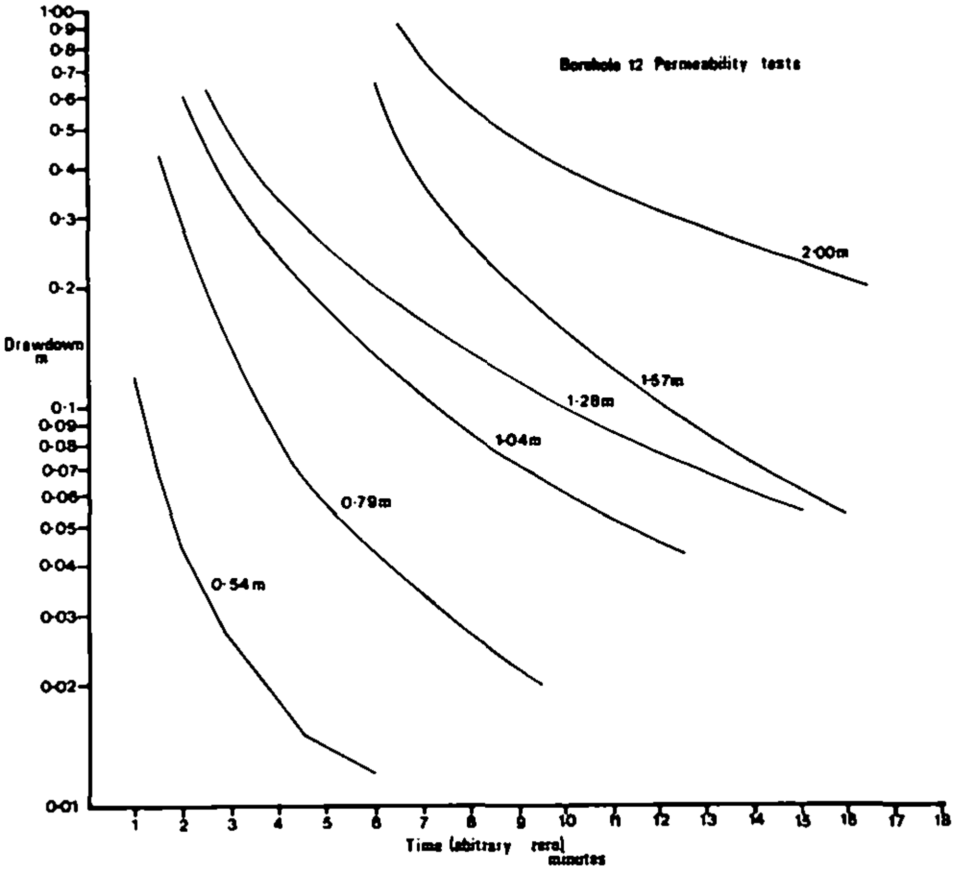


FIGURE 18 Plots of draw-down against time for a set of permeability tests, Cors Erddreiniog. Simple theory predicts that the plots will be linear but the behaviour of the peat does not accord with this.

TABLE 9 PERMEABILITY MEASUREMENTS AT CORS ERDDREINIOG

Site	Depth m	k md^{-1}	Depth m	k md^{-1}	Depth m	k md^{-1}	Depth m	k md^{-1}	Depth m	k md^{-1}	Depth m	k md^{-1}
Rallt Bridge	0.55	1.42	0.78	1.05	1.04	1.27	1.22	1.03	1.54	0.80	2.00	0.39
AWS	0.60	2.95	0.79	3.21	1.12	1.31	1.29	1.32	1.57	1.15	2.00	1.02
Borehole 1	0.79	0.96	0.93	0.88	1.21	0.97	1.38	0.81	1.67	0.55	2.00	0.46
Borehole 6	0.59	0.39	0.83	0.36	1.11	0.41	1.38	0.53	1.62	0.50	2.00	0.45
Borehole 8			0.83	0.47	1.07	0.41	1.33	0.51	1.60	0.57	2.00	0.56
Borehole 12	0.54	1.85	0.79	1.29	1.04	0.83	1.28	0.65	1.57	0.74	2.00	0.50

High permeability towards the surface is a characteristic used by Ingram (1978), following Soviet telmatologists K.E. Ivanov and V.V. Romanov, to distinguish two main layers of a peat mire, the upper *acrotelm* and the lower *catotelm*. Where these layers are distinct, the permeability varies over up to four orders of magnitude in the acrotelm, and it is in this layer that most of the groundwater and surface flow takes place. It is not clear that the layers can be distinguished so readily in fens as in oligotrophic bogs, but the trend in permeability values suggests the possibility of much higher permeabilities in the near-surface zone, where the piezometer method cannot be used.

Groundwater flow towards the main drain may be estimated by deriving an estimate of the transmissivity of the saturated thickness of peat adjacent to the drain. Transmissivity is the integral of permeability over the depth, and when multiplied by the hydraulic gradient gives the total groundwater flow per metre along the water table contour.

At Rallt Bridge, the water table between boreholes A and C is at an average depth of 0.55 m below the fen surface, and the gradient of the water table is 0.06. Dividing up the peat profile below the 0.55 m depth into three layers 0.55 to 1.22 m,, 1.22 m to 2 m, and deeper than 2 m, the transmissivity is obtained by the trapezium rule for the upper two layers, and by extrapolation of the rate of decrease in permeability for the third layer. The transmissivity of the full peat profile is the sum of $T_1 = 0.953\ m^2d^{-1}$ for the upper layer, $T_2 = 0.574\ m^2d^{-1}$ for the second layer and $T_3 = 0.09\ m^2d^{-1}$ for the lowest layer, i.e. the total transmissivity is $1.617\ m^2d^{-1}$.

Groundwater flow per metre along the water table contour is $1.617 \times 0.06 = 0.097\ m^3d^{-1}$. Inspection of the summer and winter water levels in the ditch transect shows that the hydraulic gradient remains essentially constant, while the water table may vary between 0.3 m and 0.75 m below the surface, corresponding to variations in transmissivity between 1.218 and 1.957, and a variation in flow between a summer minimum of 0.073 m^3d^{-1} and a winter maximum of 0.117 m^3d^{-1}. *Thus* groundwater flows are 60% higher in winter than in summer, or put in another way, the annual groundwater flow may be divided into 60% during the winter and 40% during the summer. This is very different from the distribution of surface runoff.

The average flow of 0.097 m^3d^{-1} corresponds to the draining of the excess rainfall from an area 89 m wide along the side of the ditch, the excess rainfall on Cors Erddreiniog being of the order of 400 mm per annum. That this is considerably less than the width of the field adjacent to the ditch testifies to the effectiveness of surface flow in removing the excess. Surface flow contributions to flood flows at Rallt Bridge have been assessed using conductivity measurements and field gaugings (Gilman and Newson, 1981). They point to the fact that nearly three quarters of flood runoff in winter comes from surface flow.

2.4 Flow from the fens at the basin scale - basic controls

Whilst process studies such as those reported above can point to the dynamics of water movement at a site, interpretation of both groundwater and surface water flows from the fen basins as hydrological units involves a much larger scale investigation of surface topography and stratigraphy.

Ground surveys of Cors Erddreiniog and Cors Goch

The most pressing need for information on lowland wetland nature reserves is, that for topographic survey. Because of their low relief and the importance to their ecology of surface, or near-surface, drainage even the shallowest of relief amplitudes can facilitate or obstruct drainage. Consequently, conventional cartographic surveys are only of restricted use and there are few benchmarks from such survey in wetland areas. Clearly, the disposition of water bodies and the direction of flows during wet conditions if mapped in the field can give a qualitative picture. However, the type of active water management advocated in the concluding sections of this report demands quantitative survey to a high standard of accuracy. Topographic survey data for Corsydd Erddreiniog and Goch have been obtained in a variety of ways:

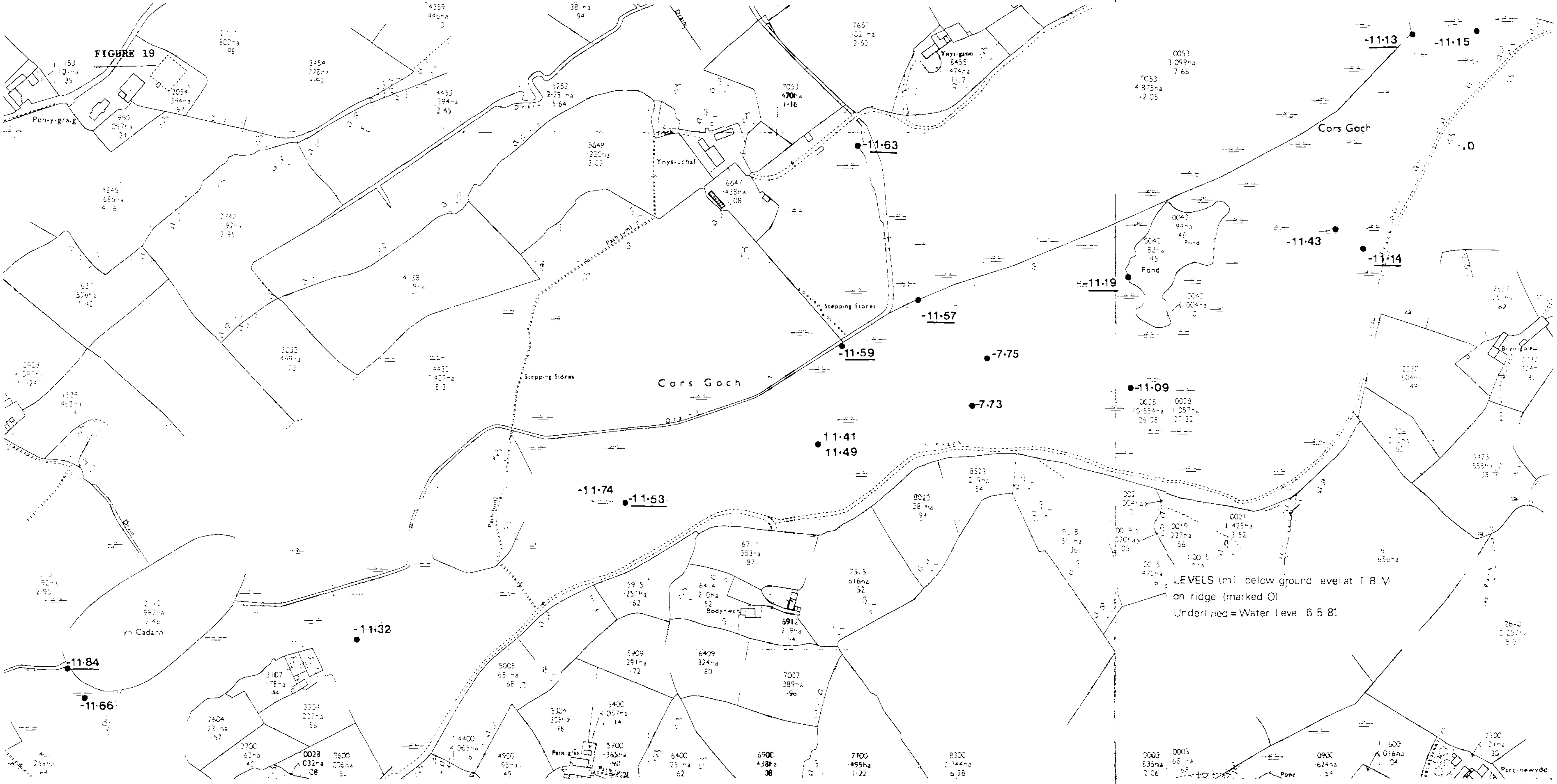
(a) *Simple levelling was used to choose transects for boreholes and to* accompany stratigraphic coring

(b) Intensive levelling was carried out to aid NCC's negotiations on drainage proposals by Mr Morgan at Cors Erddreiniog

(c) Full tacheometric survey of water and ground surfaces was carried out during summer 1981 at both sites using E.D.M. (Electronic Distance Measurement).

Since the surveys were performed under a variety of conditions, from heat haze to heavy rain, and involved a variety of operators and long-distance sighting, the accompanying plans are drawn up with levels accurate to 1 cm. Closure errors in level have been up to 8 cm but these have been distributed. With vegetation hummocks up to 30 cm high and an over-all relief of under a metre on much of the survey area, the surveyor is forced to compromise between the need for great accuracy and the hopeless complexities of the resulting survey. Consequently, we have concentrated on standing water levels, firm topographic features and hydrological instruments as survey points (Figures 19 and 20) some of the temporary bench marks used can only be pointed out in the field and a datum for these can be obtained from I.H. Previous survey datums (Gilman and Newson, 1979) have been revised and should be ignored.

FIGURE 19



LEVELS (m) below ground level at T B M on ridge (marked O)
Underlined = Water Level 6 5 81

CORS ERDDREINIOG TEMPORARY BENCH-MARKS

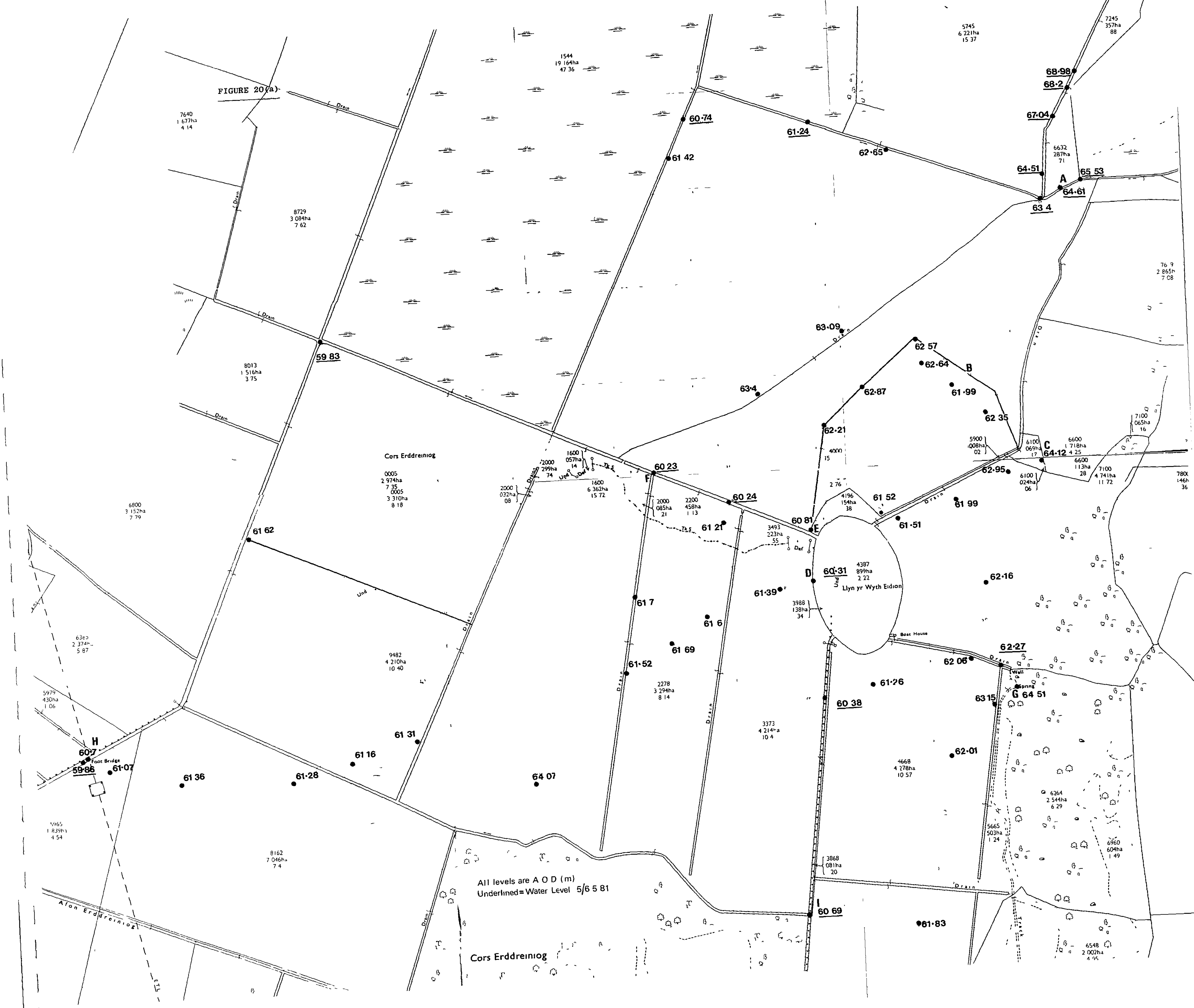
See letters on Fig. 20

(Elevations tabulated here where not shown on survey)

A	Sleeper bridge, Nant Isaf boundary ditch
B	Top of hinge-end NNR gate post: 64.41 m AOD
C	Yellow marker peg on NNR fence boundary (top)
D	Top of Llyn yr Wyth Eidion gauge board: 60.92 m AOD
E	Top of fence post at lake outfall: 62.09 m AOD
F	Top of clasp-end NNR gate post: 62.72 m AOD
G	Top of Nant Uchaf spring retaining wall
H	Top of N.E. bridge post, NNR side of footbridge: 61.90 m AOD
I	Top of northern NNR gate post: 62.75 m AOD
J	Top of southern NNR gate post 63.34 m AOD
K	Bridge parapet, Boddynda lane

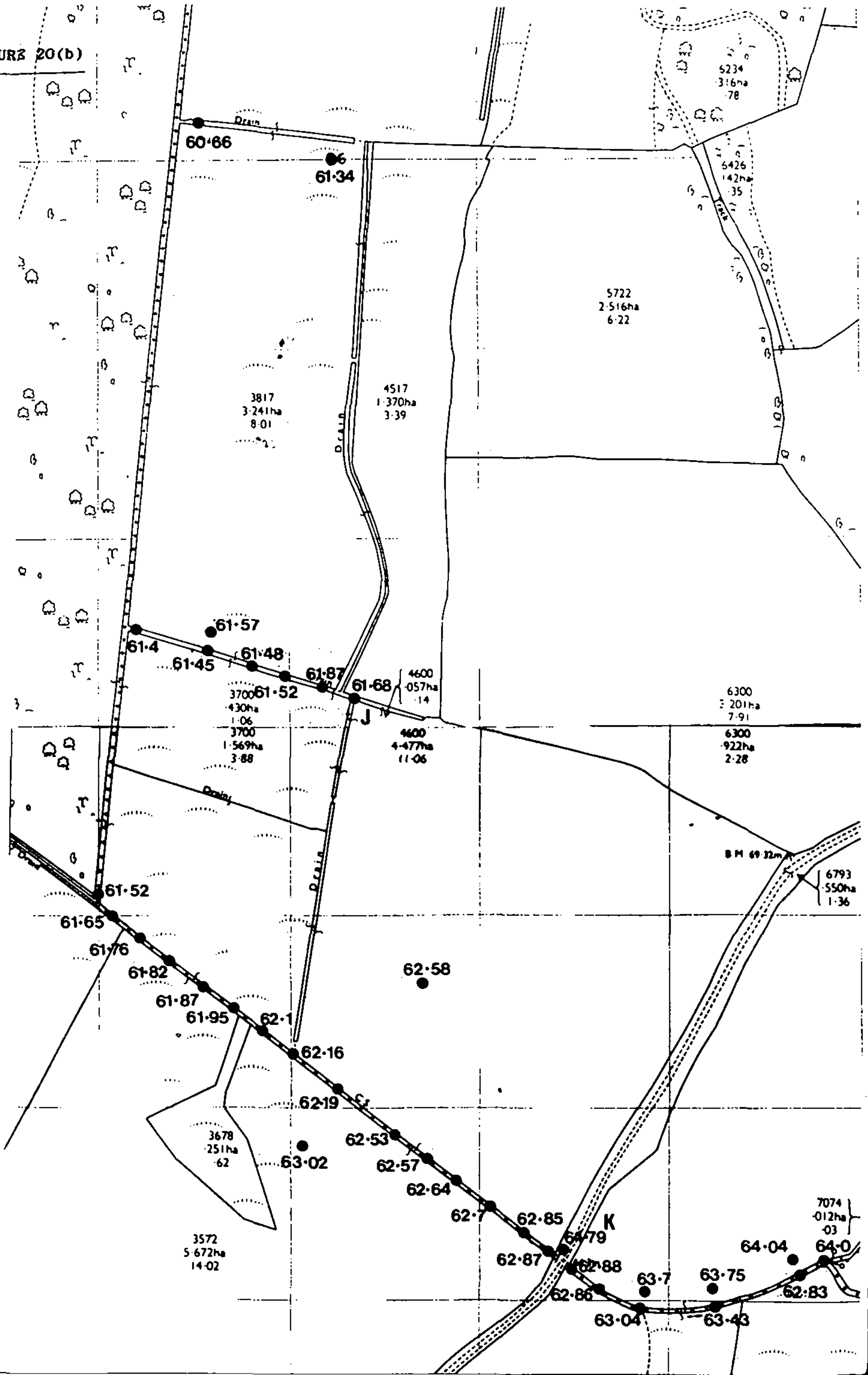
(In addition, all remaining boreholes have adjacent ground level shown on survey; tops of boreholes were used as short-term bench-marks.)

FIGURE 20(a)



All levels are A O D (m)
Underlined = Water Level 5/6 5 81

FIGURE 20(b)


60·66
Drain
61·34
Drain
5234
·316ha
·78
6426
·142ha
·35
Track
5722
2·516ha
6·22
3817
3·241ha
8·01
4517
1·370ha
3·39
61·57
61·4
61·45
61·48
61·87
61·52
61·68
J
4600
·057ha
·14
3700
·430ha
1·06
3700
1·569ha
3·88
4600
4·477ha
11·06
6300
3·201ha
7·91
6300
·922ha
2·28
Drain
Drain
B M 69·32m
6793
·550ha
1·36
61·52
61·65
61·76
61·82
61·87
61·95
62·1
62·16
62·58
62·19
62·53
3678
·251ha
·62
63·02
62·57
62·64
62·7
62·85
K
64·79
62·87
62·88
3572
5·672ha
14·02
62·86
63·7
63·04
63·75
63·43
64·04
64·0
62·83
7074
·012ha
·03

Since management of water levels on Cors Erddreiniog may involve spreading water from the two main discrete sources of spring water, the position of these springs is considered first. Fortunately the springs which comprise the Nant Isaf source rise considerably above the fen surface and it would be feasible to use their water from as little as 100 m upstream of the IH Nant Isaf weir. From such a position gravity feed could supply most parts of Cors Erddreiniog for the investment in some hundreds of metres of pipe and the achievement of access across Mr Morgan's intervening land. The position of the Nant Uchaf spring, only 2 m above the fen surface at its source is less practical in terms of distribution, expecially as it falls steeply through a hydraulic ram into the N.C.C. land holding. Only a renovated ram could pump the water around the eastern part of the N.N.R.

Over the rest of Cors Erddreiniog relief is half a metre or less with the exception of the central ridge which stands 2.5 m above the surrounding fen and a 2 - 4 m rise eastwards on to slope deposits at the foot of the limestone escarpment. The low relief means low water surface gradients. That of the Nant Isaf stream from the IH recorder to Rallt Bridge is .2%, much of which fall is achieved in the first section; from Llyn yr Wyth Eidion to Rallt Bridge water level slopes .05%. The "South Ditch", which also feeds Llyn yr Wyth Eidion slopes 0.12% from the tarmac road at the southern end of the main basin but by only .06% over the last half kilometre to the lake. There are, therefore, rather fewer opportunities for using this water, even if the quality were right.

At Cors Goch, it has not been possible to calculate reduced levels based on Ordnance Datum; a temporary bench mark on top of the limestone ridge forms the basis of the survey. Apart from the 11 m high escarpment the other main relief feature on Goch is the grit ridge which rises 3.5 m to divide the fen into north/east and south/west basins. Over the rest of the fen only a 65 cm relief was measured with the lowest-lying area being former peat diggings to the south-west of the ridge. Both major standing-water bodies are at the same level, under half a metre above the basin outlet, to which surface water gradients slope at .13% (Pond) and .05% (Llyn Cadarn).

Whilst the above summary of survey results does little directly to increase our knowledge of natural water movements in the fen basins there is one direct conclusion; with gradients so low especially in channels, surface drainage is not a rapid process particularly during the period of dense vegetation cover. To some extent this allows the fen vegetation to regulate its own water supply.

The second use of the surveys is to assess the records of underground water levels from boreholes in terms of the true ground surface. Accordingly, the transects of boreholes across Corsydd Erddreiniog and Goch have been drawn up to reduced level, showing their relationship with the surface (Figure 21). At Cors Goch water levels are clearly higher in the north-eastern section of the basin. Surface flooding in the south-western section appears to be mainly the result of topographic depression, exacerbated by peat diggings. The north-eastern section is also saucer shaped but standing water levels are apparently increased as a result of a less direct connection with the basin outlet. At Cors Erddreiniog water levels follow the surface faithfully except in the neighbourhood of drains. The surface flooding west of the ridge in a shallow depression is of interest; similar flooding to the east of the ridge is prevented by a drain. The fall of ground and water levels from boreholes 8 to 6 is more apparent than real - the transect forms a diagonal to a fall of land towards the South Ditch.

Stratigraphic surveys of Cors Erddreiniog and Cors Goch

An essential part of an investigation aimed at outlining the possibilities and strategies for management of a wetland site is the exploration of the nature and

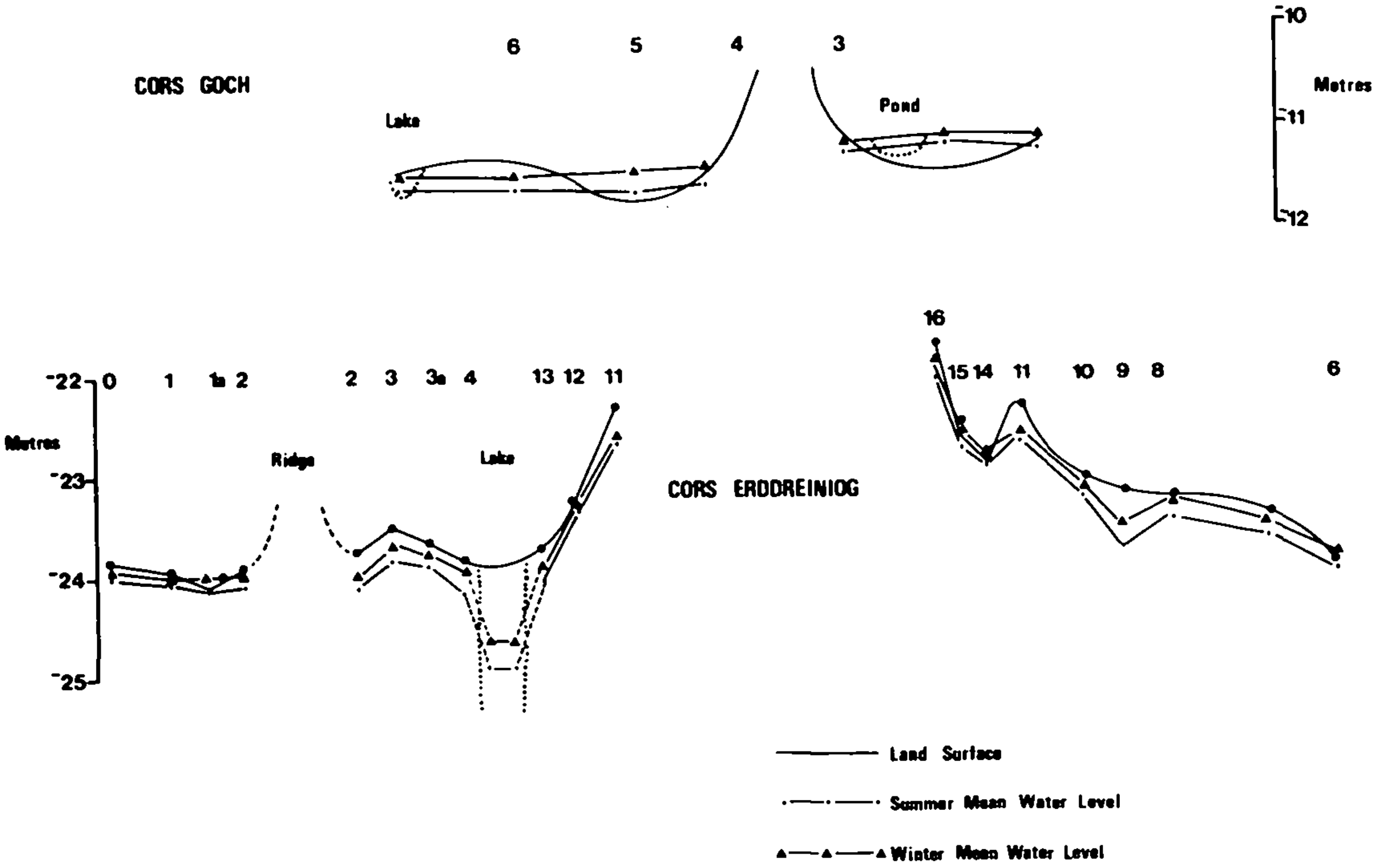


FIGURE 21 Reduced borehole water levels for the main transects across Cors Goch and Cors Erddreiniog. Convenient plotting scale only permits summer and winter mean levels to be shown.

depth of the soil and sediments. The storage of water that is necessary for survival through drought periods, and the resistance to peat wastage, depend upon the thickness of peat; the transport of water across the mire expanse is also influenced by the depth and type of the deposits.

Stratigraphic survey of Cors Erddreiniog and Cors Goch took a simple form, aimed at presenting a picture of the broad shape of the fen basins and the distribution of the lake sediments and peat. Three transects were laid out across Cors Erddreiniog, radiating from the spring east of the lake (Figure 22), and one broken-line transect, following the line of the observation boreholes, was set out down the length of Cors Goch (Figure 23). Additional data are available for Cors Goch in the form of a palaeobotanical study by Seddon (1957), who had obtained stratigraphic information on three cross transects of Cors Goch, and a pollen profile at one point.

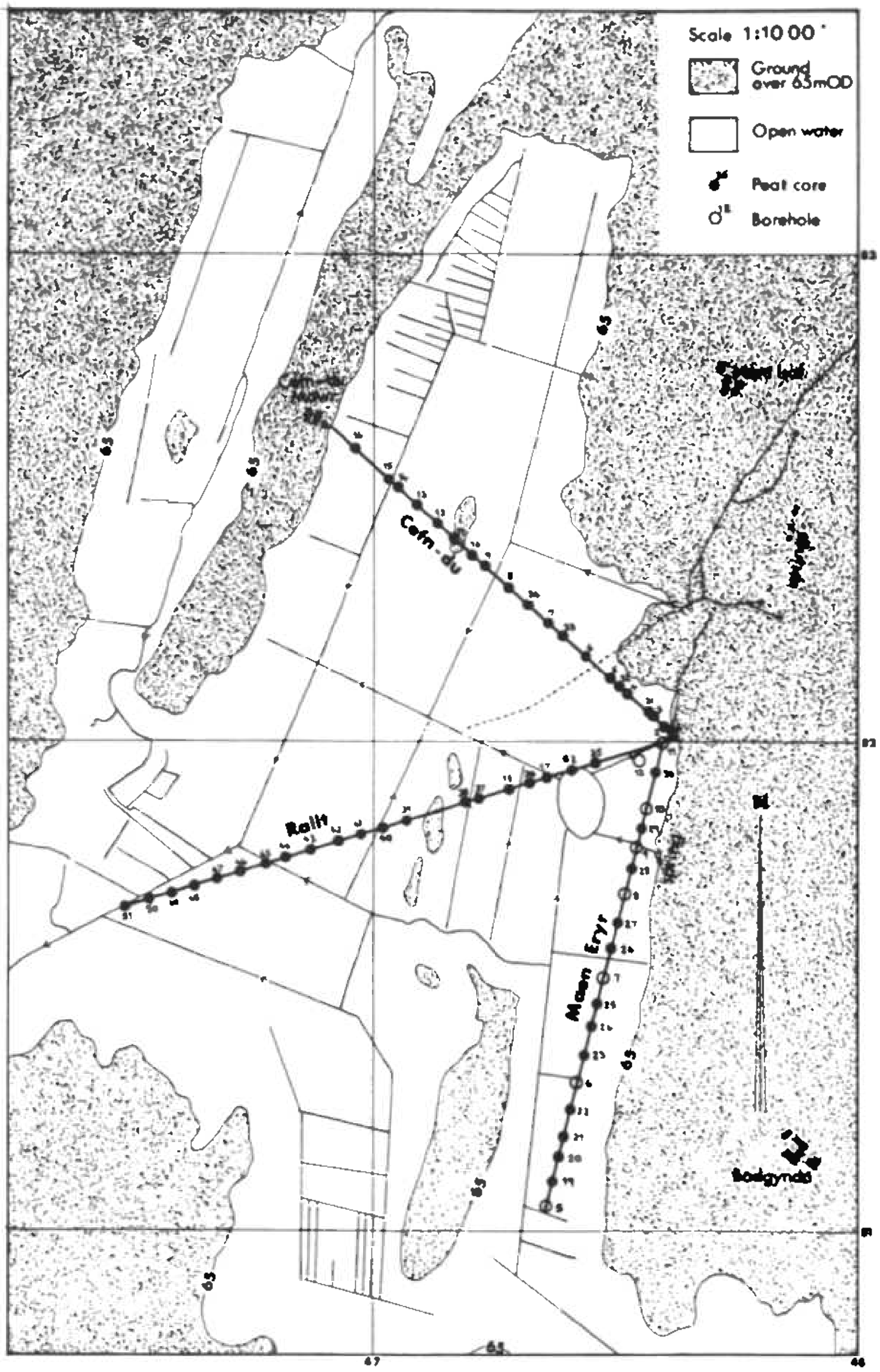


FIGURE 22

Stratigraphic core sites at Cors Erddreiniog

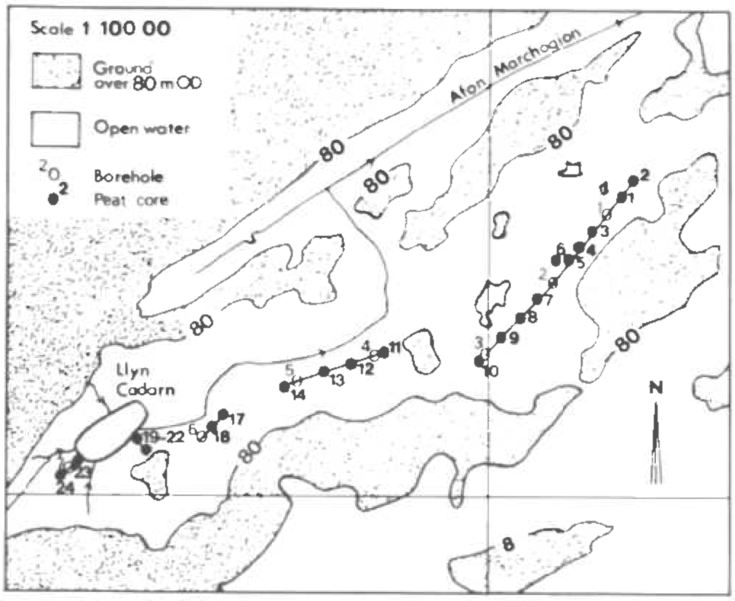


FIGURE 23

Cors Goch: Sites of stratigraphic coring at the eastern end of the fen

Along the four transects, at about 50 metre intervals, core samples were taken from the full depth (where the material was penetrable and its thickness did not exceed 9.5 metres, the available length of the corer) with a Russian type corer (Plate 12).

PLATE 12 Field use of the 'Russian' peat corer, showing insertion (left) and the resulting core (right), both at Cors Erddreiniog

For most 0.5 m lengths of core, details of stratigraphy were noted in the field, but samples were taken from interesting horizons for examination in the laboratory. Appendix I summarises stratigraphic information.

The results of the stratigraphic survey (Figures 24, and 25) confirm the origin of both fens as lake basins, with the deepest points more than 9.5 metres below the present ground surface. The basins have been filled mostly by lacustrine sediments, capped by fen peat up to 4.5 metres thick. The subsurface form of the basins is more complex than would appear from an examination of the fen surface, and Cors Erddreiniog is dissected by hidden ridges of bedrock which are now obscured by the fen peat.

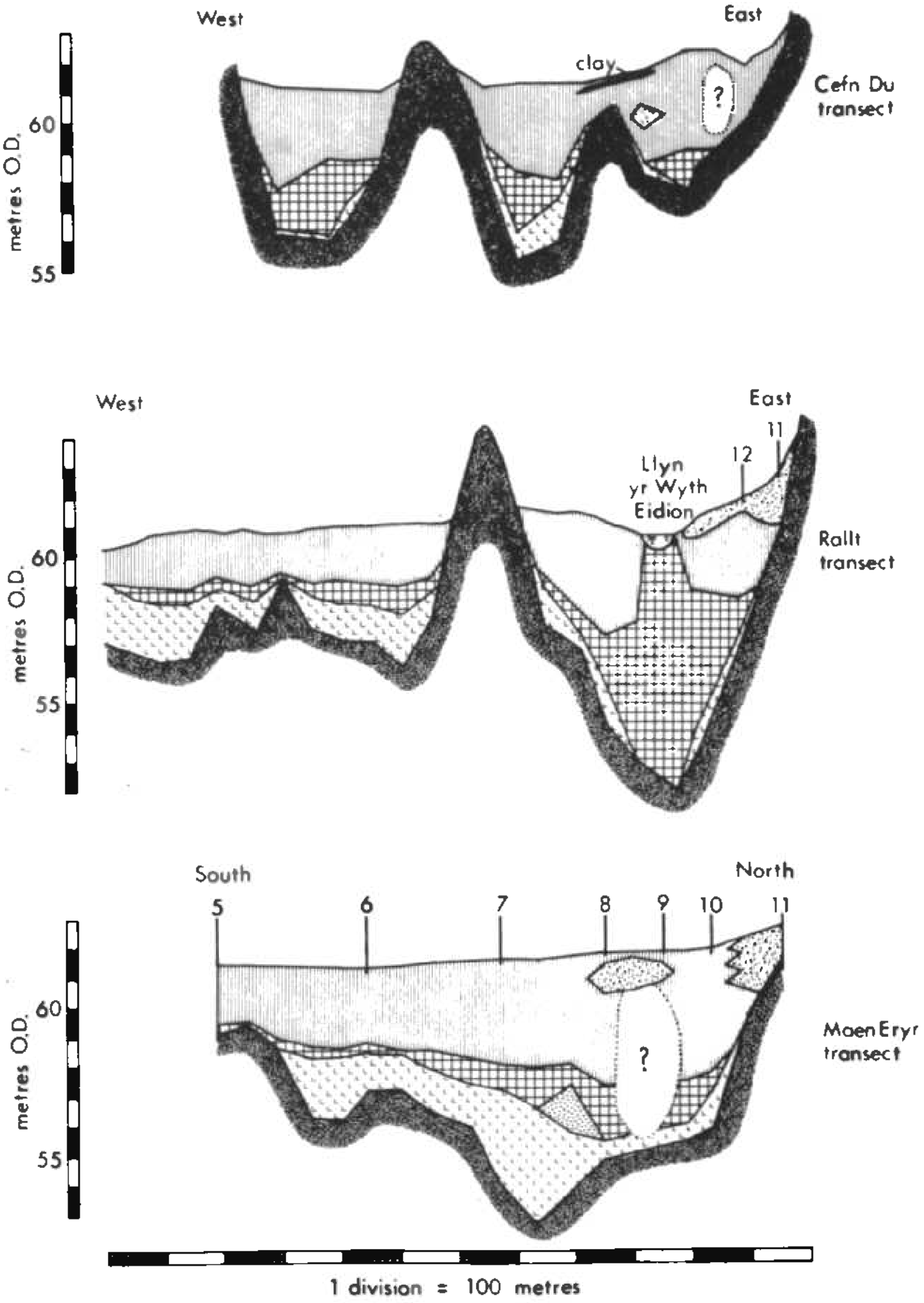


FIGURE 24 Stratigraphic section of Cors Erddreiniog

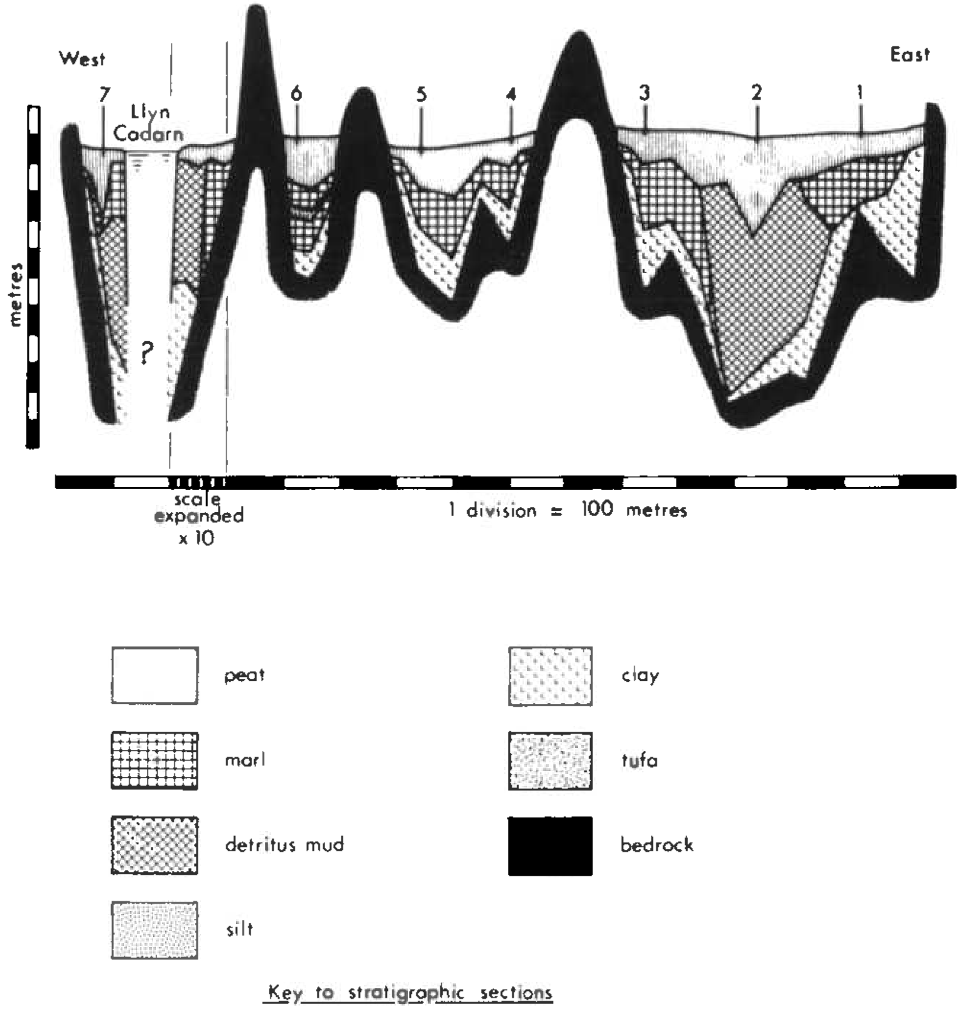


FIGURE 25 Stratigraphic section of Cors Goch

At the base of the profile, presumably on a foundation of boulder clay, is a layer up to 0.5 m thick of mauve-grey plastic clay, varying in colour from pink to neutral grey, and containing no macroscopic organic remains. Above this is a thicker (up to three metres) deposit of steel-grey clay, more or less silty and containing significant quantities of moss remains. Seddon (1957) identified these as belonging to the hypnoid group. The clay gives way to a carbonate deposit, varying in colour from greenish grey through pure white to buff, and containing linear leaf fragments presumably deriving from a reedswamp community. Moss fragments are much less common in this marl layer. Gastropod and bivalve shells are abundant, especially in the upper horizons of the marl, where it grades into the fen peat. The gastropod population is similar to that existing today in the littoral zone of Llyn yr Wyth Eidion on Cors Erddreiniog, with one notable exception. The commonest species is *Lymnaea peregra* (Wandering snail) comprising about 50-60% of the population. *Valvata piscinalis* (Valve snail) comprises about 30%, and *Planorbis laevis* (Smooth ramshorn) about 10%. *Valvata macrostoma*, a snail now restricted to Southern England and East Anglia (Macan 1977), is present in marl deposits but probably not in the present-day littoral zone. (Plate 13). Non-aquatic genera such as *Vertigo* and *Succinea* are also represented but uncommon, while the semi-aquatic *Lymnaea truncatula* occurs in the marl and in the present littoral zone. The witness of these snail shells, and the continuing formation of carbonate on the littoral shelf of Llyn yr Wyth Eidion, points to a littoral origin for the marl.

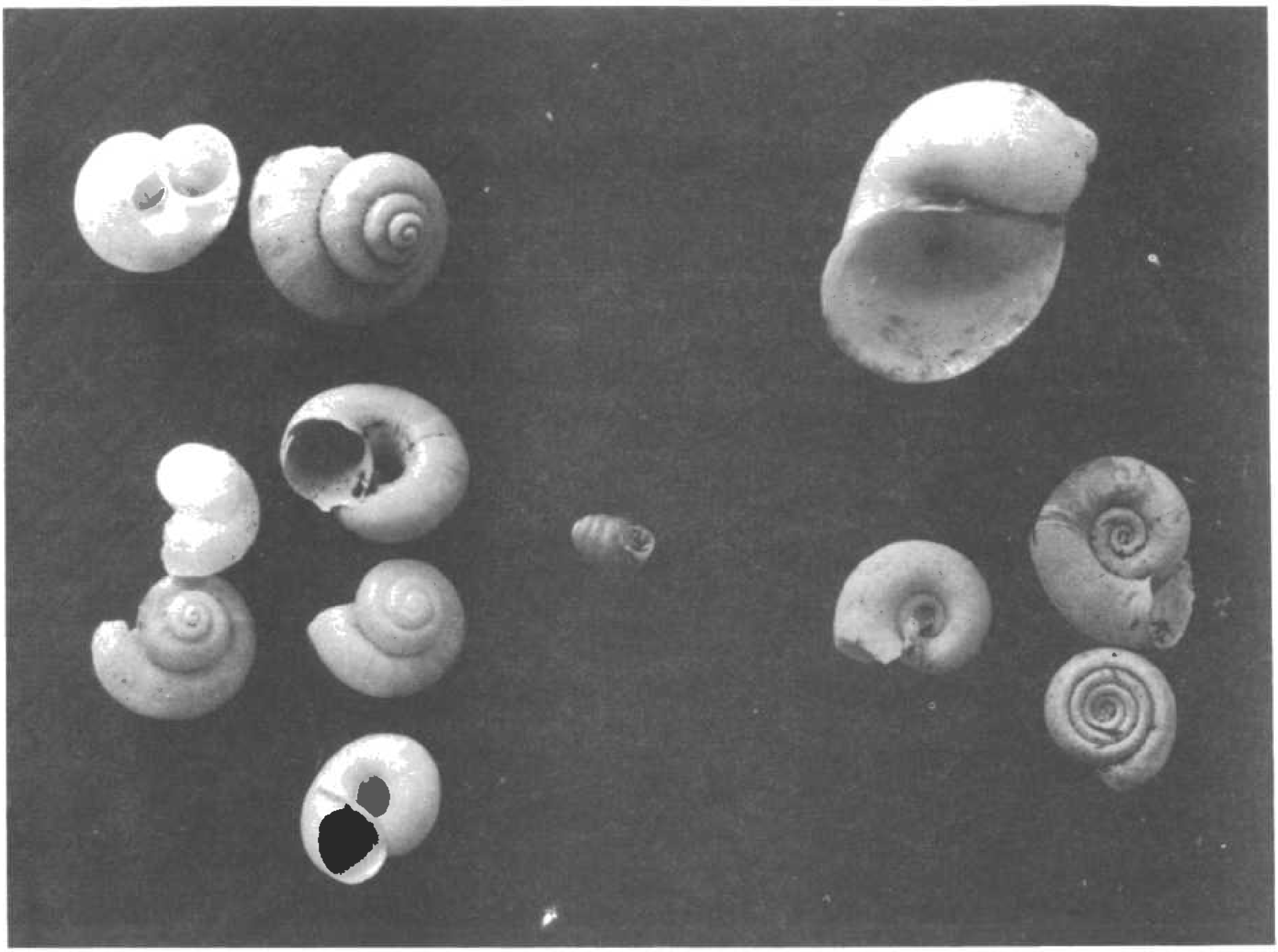


PLATE 13 **Gastropods from the former littoral zones of Llyn yr Wyth Eidion and Llyn Cadarn (av. size = 4 mm)**

Top right: Limnaea peregra
Centre: Vertigo
Bottom right: Planorbis laevis
Left: Valvata piscinalis, Valvata macrostoma

The marl is succeeded by fen peat, often containing shells in its lower horizons, and also containing recognisable *Cladium* and *Phragmites* remains. Near the springline tufaceous fragments are also present in the peat, sometimes in sufficient quantity to make the deposit impenetrable.

Another organic deposit that is represented locally at Cors Goch is a loose detritus mud or gyttja, which is formed of organic particles with little or no humic colloidal material. Gyttja is a lacustrine deposit which could have formed here under a floating mat of fen vegetation where the photosynthetic production of marl was inhibited.

The late-Glacial and post-Glacial history of the fen basins can be deduced from the stratigraphic records obtained during this study, from Seddon's (1957) manuscript thesis, and from observation of modern deposition processes.

Sedimentation in the lake basins began after the last (Devensian) glaciation, with an inflow of clay and silt in runoff from surrounding high ground. Although intense weathering would have provided abundant mineral nutrients, the water was probably too turbid to support much vegetation, levels too variable and shores too unstable for growth of a littoral community. The plastic clay at the foot of the profile contains 10 to 25% of calcium carbonate, but the succeeding silty clay is much lower in carbonate, around 1 to 5%. Textural variation noted by Seddon suggests that the upper clay, at least at Cors Goch, is derived from the dip slope to the north: although the bedrock on this slope is limestone it could be expected to have been mantled more deeply by boulder clay and to have contributed a suspended sediment load for a longer period than the limestone escarpment. Inflow from the limestone escarpments at both sites would have initially been surface runoff carrying a carbonate-rich suspended load to contribute to the lower clay, then as the weathered mantle was removed the inflow would become groundwater carrying dissolved carbonate but no suspended material.

The transition to marl or detritus mud began in the shallows at the periphery of the basins, as the quality of the water supply changed. Marl is produced by photosynthesis, usually of algae, which remove carbon dioxide from the water and cause the precipitation of calcium carbonate. *Chara* is one important example, but even single-celled algae may be responsible. The calcium carbonate content of marl samples from the Anglesey Fens ranges from about 60 to 99%, the balance being organic or siliceous material. Tufaceous particles are found in the littoral zone of the modern Llyn yr Wyth Eidion, often of a tubular form that arises from deposition of carbonate on reed stems (Plate 14). These tufaceous particles also occur at depth near the lake, but at other stations the marl is fine in texture. It may be that wave action was more vigorous in the larger ancient lake, resulting in abrasion of tufa particles and shells. Marl deposition is not a simple process: after initial production on the littoral shelf, wave action moves the particles outwards and down an inclined 'marl slope'. Final incorporation into the marl body could take place anywhere on this slope. Marl slopes with angles up to 40 degrees have been reported in the USA by Eggleston and Dean (1976). The slow encroachment of the marl slope and the littoral shelf out towards the centre of the lake results in a break in the continuity of sedimentation in deep water. Marl lake waters are usually clear, and there should be little deposition in deeper water beyond the marl slope. Llyn yr Wyth Eidion is reputed to be less clear than typical marl lakes, and this is attributed to influx of peaty water (Ratcliffe 1977). However this may be an effect of relatively recent drainage. The presence of this gap in the sedimentation sequence means that a full profile, for instance for pollen analysis, cannot be obtained from a central site. A similar result will hold for gyttja deposition, with a smaller slope angle. This may be the cause of the interruption in the pollen profile illustrated in the second annual report of this project (Gilman and Newson, 1981) and attributed by Seddon (1957) to a fall in lake level.

Towards the landward edge of the littoral shelf, a reedswamp community marked the front line of the advancing fen, prevented by wave action from encroaching more quickly. In the denser reeds to the rear, fen peat was laid down and the *Verlandung* process begun. In places where wave action was inhibited, for example in the central narrow channel of Cors Goch (Seddon 1957), the fen vegetation could advance as a floating mat, and marl formation would be succeeded by the deposition of detritus mud. The steady buildup of fen peat at the basin outlet resulted in a slow rise in the fen water level and in the deepest lacustrine deposits' being towards the centre of the fen, for example the deep marl deposit around Llyn yr Wyth Eidion.

The stratigraphic survey, in addition to pointing out the palaeobotanical interest of the Anglesey Fens, can be used to support arguments about hydrological management. The fen peat which supports the present plant communities is on average about

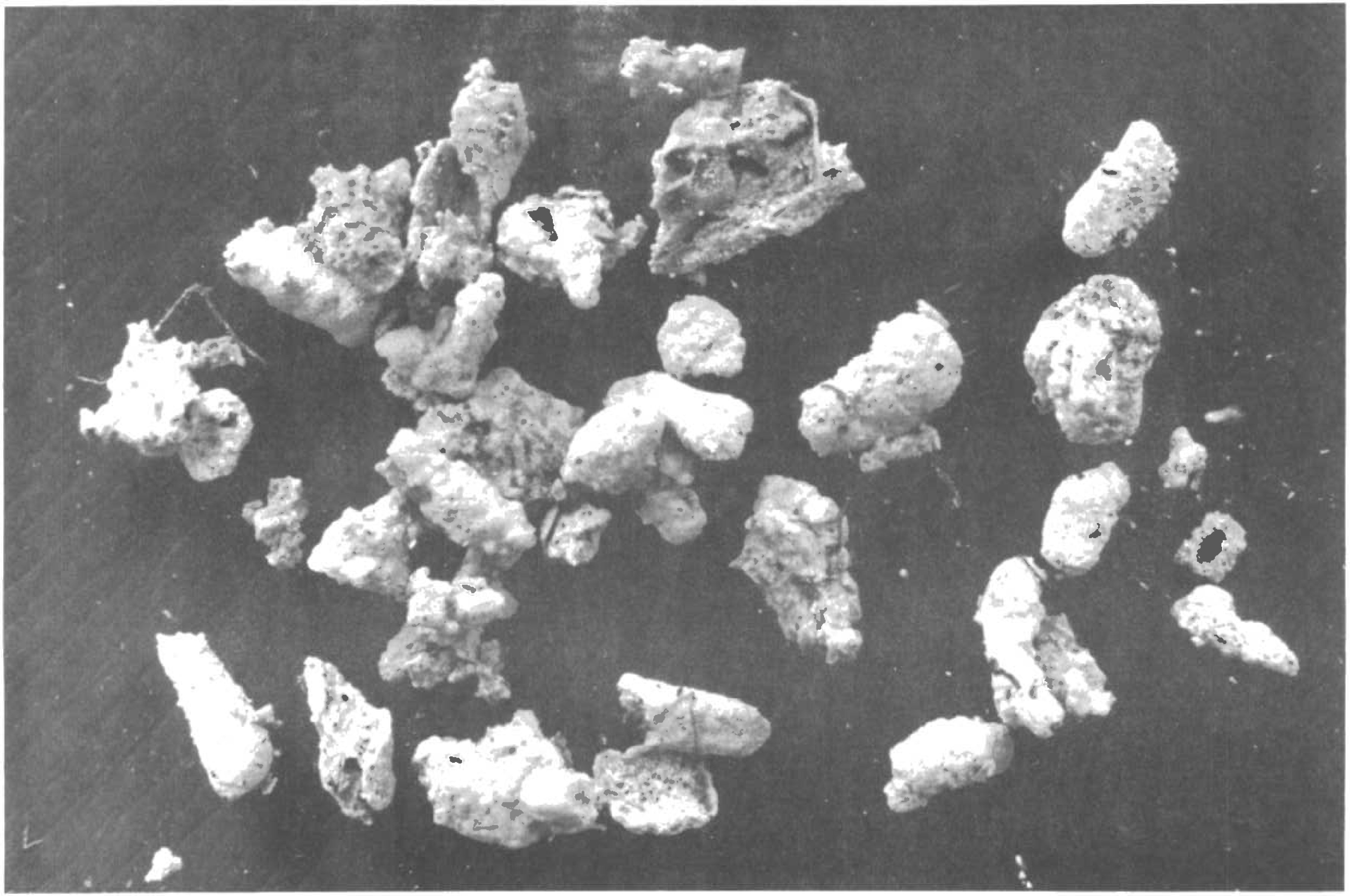


PLATE 14 Tufa fragments, one origin of the marl deposits

1.5 to 2 metres thick, sufficient to provide drought storage for fen vegetation but insufficient to provide a substrate for agriculture of the type practised in the East Anglian Fens for more than thirty to forty years if peat wastage is allowed to occur (see section 1.2).

The particle sizes present in the lower deposits lead to the conclusion that permeabilities are very low, and that most groundwater flow occurs through the peat. Given that there is no likelihood of deep flow or vertical percolation, there is reason for optimism about the prospects of surface and near-surface water management.

BUILDING A CONSERVATION STRATEGY BASED ON WATER MANAGEMENT

Before drawing together the conclusions from all the hydrological studies into recommendations it is helpful to, once again, consider the central conservation issue in the Anglesey fens - the continued vigour of their flora. It is clear that the present distribution of plant communities on the Anglesey Fens, and the prospects of manipulating them to restore former interest and diversity, are intimately bound up with local hydrological conditions. Detailed predictions about the response of the fen system to changes in management are impossible to make; Section 1.2 has already pointed to the unlikely prospect of fully quantitative plant-soil-water management but the requirements of several of the species present are well documented in qualitative if not quantitative terms. Instead of taking plant tolerances against specific water levels as a guide it is essential to fall back to the concept of wetland plant succession, which also implies changing water level and quality.

3.1 Specific plant-water relationships

The fen succession takes a well-defined course, from the first emergent plants to colonise open water, through peat-forming communities which raise the land surface sufficiently for bushes and finally trees to succeed. This succession may be accelerated, or retarded or temporarily reversed by climatic or hydrological events, or deflected by agricultural practices (Godwin 1929). Four plant species are worthy of close attention on the Anglesey Fens: three of these are phases in the fen succession, the fourth, *Schoenus nigricans*, is present in the marginal soligenous fen areas.

1. *Phragmites communis*, the common reed, which is most vigorous in the littoral zone of the lakes and in ditches, persists almost indefinitely as a minor element in the fen community. *Phragmites* is one of the first emergent colonisers of the open water habitat, although it is sensitive to wave and ice action, and to scour, so that it tends to avoid high energy shorelines (Haslam 1970). In swamp conditions, *Phragmites* competes successfully by shading, and forms monodominant stands with a closed canopy (Haslam 1973a). As the ground surface rises relative to water level, either spatially or temporally, the number of potential competitors increases, and the density of *Phragmites* shoots decreases. Competitors which are able to lay down quantities of litter, for example *Molinia* or *Cladium*, can suppress reed growth by reducing the number of shoots. *Phragmites* can withstand competition in areas which are permanently or intermittently flooded, and cutting or burning increases its dominance, but *Molinia* is also favoured by cutting and burning on drier land. An important fact with regard to management is that *Phragmites* is harmed by too rapid

an adjustment of water level, either towards drier or wetter conditions (Haslam 1970). The period of stress appears to last about four years after a sudden change in water regime. The performance of *Phragmites* is improved by an increase in the concentration of inorganic nutrients, particularly where this concentration is normally low (Daniels 1975), but in healthy stands nutrients are not limiting. In such conditions as those at Cors Erddreiniog, reduction in the performance of *Phragmites* is due entirely to the effects of competition.

2. *Cladium mariscus*, the giant sword-sedge, thrives where water levels are above or at the surface for much of the year, although it can tolerate a summer water level of 0.15 m below the surface and short periods with even lower levels. *Cladium* is the successor to *Phragmites,* in that it will flourish in shallow water, suppressing competitors by a dense mat of litter. *Cladium* has the advantage over *Phragmites* where there is abundant calcium but the water is poor in other nutrients (Haslam 1973b), but unlike *Phragmites, Cladium* cannot persist in sparse stands or in shade, so it is easily killed out by competitors such as bushes which can obtain a foothold (Godwin 1978, photograph on page 153). Aeration of the roots of *Cladium* occurs through the old leaves which have the most open pathways to the stock. Flooding to depths in excess of 400 mm prevents aeration and is unfavourable; however there is more available oxygen when the water level is above the surface and in motion, hence the preference of *Cladium* for shallow flooded conditions. Rooting in *Cladium* is shallow, about 0.15 m (Conway 1942), and this may be an indication of the inefficiency of the aeration process, compared for instance with that of *Phragmites,* which can root to 2 m (Haslam 1973a).

3. British wetlands in decline are invaded by *Molinia caerulia,* the purple moor-grass, a plant that will tolerate a wide range of soil conditions and tends by its growth habit to exclude other species. The lowering of the water table below the optimum for such species as *Phragmites communis* and *Cladium mariscus* improves the aeration of the upper peat and allows the entry of *Molinia*. Although *Molinia,* like other wetland plants, is adapted to carry on internal gas exchange to supply its roots with oxygen, this mechanism is not completely effective (Webster 1962). Thus *Molinia* could be regarded as one of the first of the dry marsh plants to colonise the fen surface. However there is good reason, at least in the case of East Anglia, to place *Molinia* off the main sequence of the hydrosere, as the conditions for its establishment are the same as those for bushes such as *Rhamnus*. *Molinia* cannot compete with bushes, and bush growth was prevented in the East Anglia Fens by management. *Molinia* should therefore be regarded as part of a deflected succession (Godwin 1929, Godwin and Bharucha 1932). At Cors Erddreiniog and Cors Goch *Molinia* has apparently been successful in its invasion because of the comparatively rapid drying out of the fen following drainage. The natural process of *Verlandung* caused by peat accumulation could have led to the establishment of carr rather than *Molinietum*. Once established, *Molinia* maintains its dominance through a dense litter mat, an early start into growth from its bulbous basal internodes (Jefferies 1916) and possibly by the promotion of fire (Dawkins 1939). Tussock formation is also important in ensuring survival through flood conditions: the spaces between tussocks form an interconnected network of drainage channels through which surface water can flow without inundating the tussock crests. It is certain that flooding that does inundate the tussocks is harmful to *Molinia:* Meade (1981) cites cases at Danes Moss, Macclesfield, and Risley Moss, where large areas of *Molinia* have been deliberately killed by flooding.

4. *Schoenus nigricans,* the bog-rush, occupies the soligenous margins of the Anglesey Fens, where it receives seepage water rich in calcium. Unlike the other species mentioned, *Schoenus* is a plant of soligenous fens and spring-fed areas, where water is flowing rapidly over or through the soil (Sparling 1968). The tussock habit helps in resisting erosion and preventing inundation, and incidentally is of ecological value in providing a habitat for acidophilous species above the

general level of base-rich water. Conditions are most favourable for *Schoenus* when the water table is at or near the surface of the soil, but the species can withstand a large temporary drop in water table associated with drought. Although *Schoenus* tussocks are resistant to burning, recovery after fire is less rapid than that of *Molinia*. Thus *Schoenetum* that has been infiltrated by *Molinia* is vulnerable to fire, and *Molinia* is able to achieve dominance by exploiting the drier conditions on the *Schoenus* tussocks. In some conditions, such as abandoned peat cuttings, *Schoenus* naturally gives way to *Molinia* and bushes in the course of time, although colonisation by the latter is retarded by the fire factor (Dawkins 1939).

Wetland plants are adapted, not to the direct effects of an excess of water, but to secondary effects, notably the lack of available oxygen in waterlogged soil (Gosselink and Turner 1978). These adverse conditions lead to the dominance of species adapted for agressive competition, with the tendency to establish mono-dominant stands nder natural conditions (Haslam 1973b). With human interference, mixed stands occur, such as the "litter" and "mixed sedge" communities at Wicken Fen (Godwin 1929), but such mixed stands are inherently unstable (Haslam 1973a) and it may be difficult for one species in such a stand to recover from a temporary setback.

At Cors Erddreiniog, and in the drier parts of Cors Goch, interference has taken the form of drainage, and has given rise to the present ascendancy of *Molinia*. Natural succession would occur through the *Molinia/Myrica* association to carr communities, and the first signs of these stages are present at both the Anglesey Fen sites. This succession can only be accelerated by the effects of drainage, although some retardation could be caused by frequent fires. What is needed at both sites is the tipping of the balance in favour of the wetland communities which preceded the *Molinia* invasion.

Using as a basis the classification of rich-fen vegetation presented by Wheeler (1980 a b and c), the Wales Field Unit of NCC embarked on a study of the distribution of vegetation on the Anglesey Fens. This study was designed to fit in with the hydrological work of IH, and to provide botanical information to assist in the preparation of management plans for Cors Erddreiniog. As in the case of the hydrological study, Cors Goch was envisaged as a control site where the effects of drainage were less marked.

The results are presented in a detailed report (Meade 1981); it is proposed here only to summarise and bring out some of the points made in the full report.

Seven main associations were identified on the Anglesey Fens. Three of these could be described as desirable rich-fen communities, the remainder were the product of *Molinia* invasion. Predictably, the best rich-fen vegetation was at Cors Goch, and it was only at Cors Goch that the wettest community, *Cladietum marisci*, could be found. At Cors Erddreiniog, it was suggested that the place of *Cladietum* had been taken by *Cladio-Molinietum*, where *Cladium* remained dominant, but in association with much *Molinia*. Much of Cors Erddreiniog is covered by a *Molinia*-dominated grassland, *Cirsio-Molinietum*, which in places could have developed from a wetter community dominated by *Phragmites*. The report indicates clearly the extent of the soligenous *Schoeno-Juncetum subnodulosi* along the limestone margins of the fens. Other communities, notably *Acrocladio-Caricetum diandrae* and *Potentillo-Coricetum rostratae*, occupy sites intermediate in wetness, and are likely to benefit from measures designed to favour *Cladietum* and *Schoenetum* at the expense of *Molina*.

The importance of water quality was emphasised by the results of performance measurements and water analyses (Figure 26) *Cladium* favours very wet conditions, and in this respect shows an opposite behaviour to *Molinia*. *Cladium* and *Schoenus*

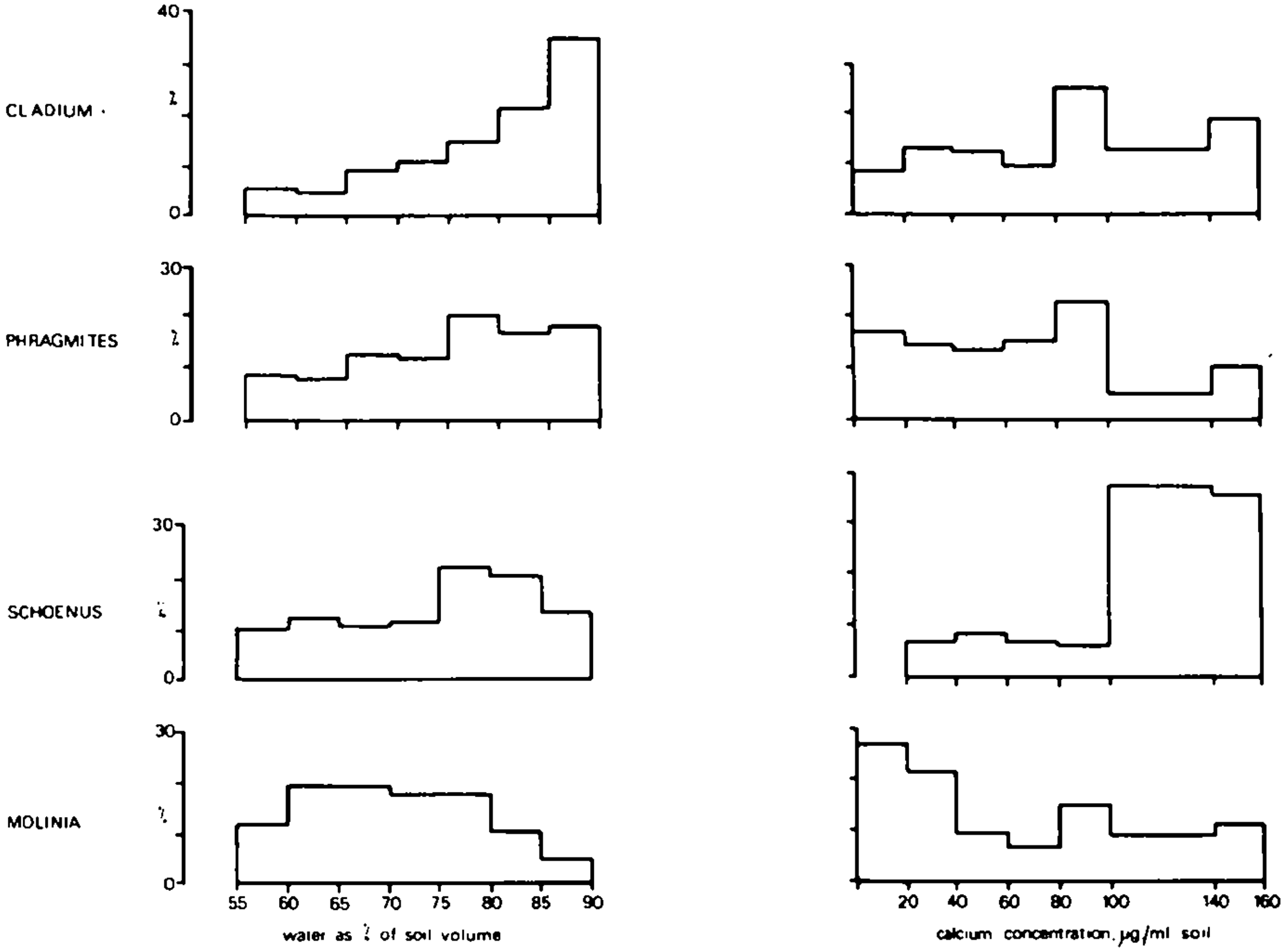


FIGURE 26 **Meade's plots of the relationship between plant communities and water content, water quality.**

tend to prefer soils with higher mineral contents, while *Phragmites* and *Molinia* perform best on organic soils. *Molinia* and *Schoenus* are opposites in their response to calcium: *Schoenus* is strongly favoured by concentrations in the soil in excess of 100 mg/l. The conclusion is clear when these performance data are related to the present distribution of vegetation at Cors Erddreiniog: not only have drainage works led to a general drying out, but the ditches have diverted calcium-rich waters that were necessary to maintain the competitive advantage of *Cladium* and *schoenus* over the invader *Molinia*.

The Wales Field Unit's report concludes with a number of recommendations for management and predictions of their floristic consequences. The central topogenous area should be flooded to kill *Molinia*, and a high-water-table regime maintained to discourage recolonisation. The soligenous margins are relatively healthy, but any further drainage, which might interrupt the supply of calcium-rich water, should be resisted. Around the lake and in the topogenous areas, new communities would develop in a pattern that depended on the inundation regime.

When the boreholes of the observation networks on Cors Goch and Cors Erddreiniog are classified in terms of the vegetation around them, it is possible to draw conclusions about the relation between the plant community and the seasonal variation in the water table. Table 10 summarises the vegetation environment of each borehole. The behaviour of the water table is best seen in a plot of range

TABLE 10 A SIMPLE VEGETATION KEY TO THE OBSERVATION BOREHOLE NETWORKS (by inspection)

CORS ERDDREINIOG

0	*Cladium, Filipendula, Epilobium*
1	*Molinia, Myrica, Succisa, Cladium*
1a	*Molinia, Phragmites, Epilobium, Juncus subnod., Carex elata*
2	*Myrica, Phragmites, Molinia, Potentilla erecta, Lysimachia*
2a	*Molinia, Myrica, Serratula, Phragmites*
3	*Phragmites, Myrica, Molinia, Rubus*
3a	*Myrica, Molinia, Succisa*
5	*Myrica, Molinia, Erica tetralix*
6	*Juncus effusus, Myrica, Molinia*
7	*Molinia, Myrica, Juncus subnod.*
8	*Molinia, Juncus subnod.*, rich in sedges
9	Pasture
10	*Molinia, Myrica, Phragmites, Rubus, Potentilla erecta*
11	*Serratula, Molinia, Festuca*
12	*Cladium, Molinia, Myrica, Schoenus, Juncus subnod.*
13	*Cladium, Filipendula, Rubus, Phragmites*
14	*Juncus subnod., Schoenus*
15	*Schoenus, Erica tetralix, Carex lepidocarpa*
16	*Juncus subnod., Molinia, Festuca*

CORS GOCH

1	*Schoenus, Carex lepidocarpa, Phragmites, Myrica*
1a	*Juncus subnod., Carex lepidocarpa, Schoenus, Cladium, Phragmites*
1b	*Myrica, Molinia, Ulex*
2	*Cladium*
3	*Cladium, Rubus, Mentha, Juncus subnod., Myrica, Filipendula*
5	*Cladium, Schoenus, Phragmites*
6	*Molinia, Myrica, Juncus subnod.*
7	*Molinia, Myrica, Juncus subnod.*

In summary, at Cors Erddreiniog the wet fen species, *Cladium* and *Phragmites*, are always accompanied by species more tolerant of drier conditions, and *Molinia* is present at almost all sites. Mean water levels are everywhere at or below surface. At Cors Goch there is good representation of wet fen communities, and invasion by *Molinia* is restricted. Water levels are generally higher than at Cors Erddreiniog.

versus mean elevation relative to ground surface. Figure 27 shows an annual plot, i.e. the range and the mean are taken over a year. Figure 27 also shows plots for winter (October to March. Figure 28 is a similar plot for the more distinct variations in summer (April to September). In the annual plot it is easy to see the differences between the two fens. Cors Goch (2), the only borehole in *Cladietum*, has a high water level that varies little over the year. Boreholes Cors Goch (1), (1a), (1b) (2) and (3) in the eastern end of the basin, have a small range in water level, compared with the other boreholes in the western basin. The tendency in Cors Erddreiniog is for medium to large ranges and water tables

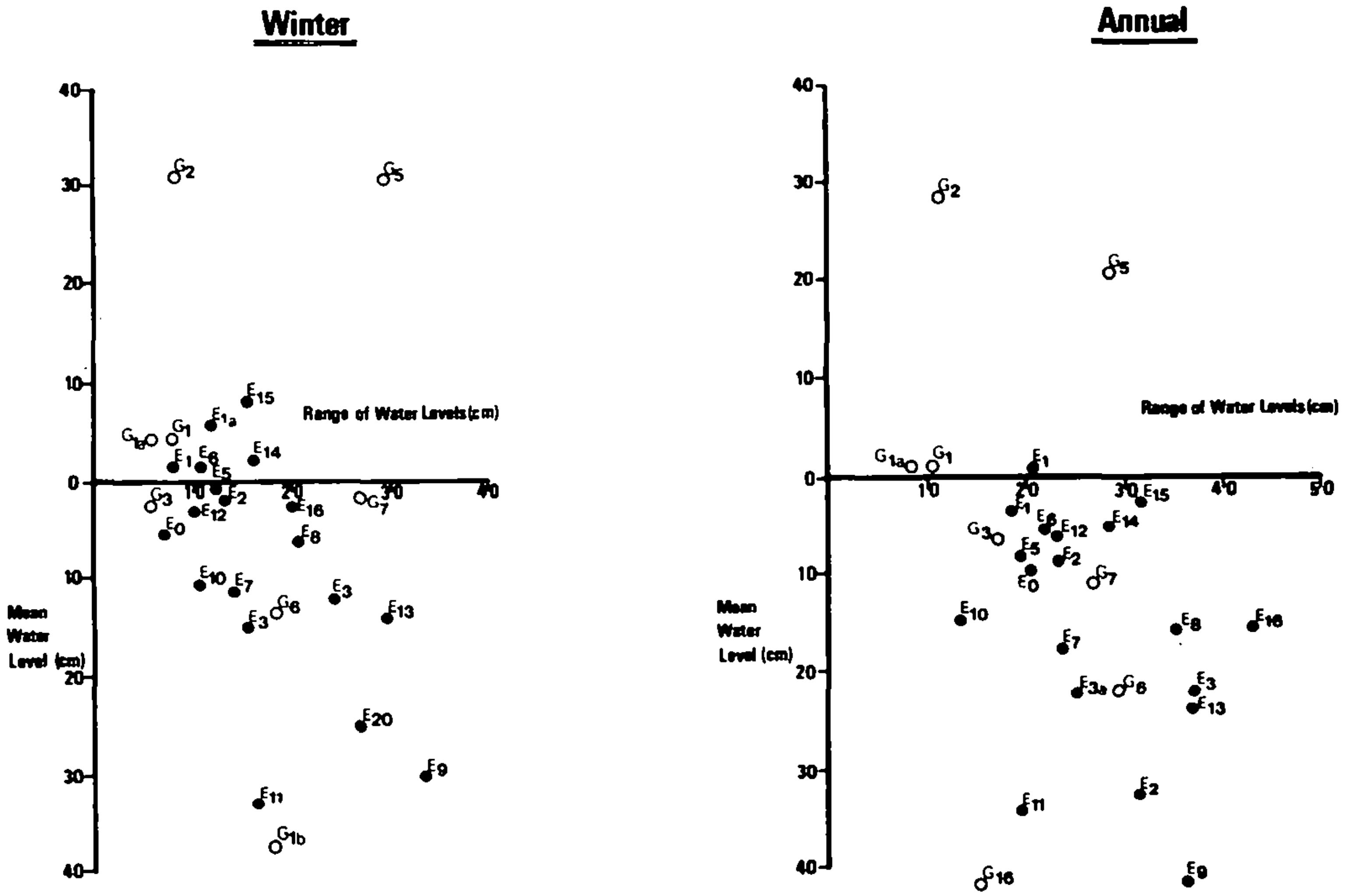


FIGURE 27 Mean water levels in observation boreholes at Corsydd Erddreiniog and Goch, plotted against the total range of water levels in the same borehole on an annual basis and for the winter half-year

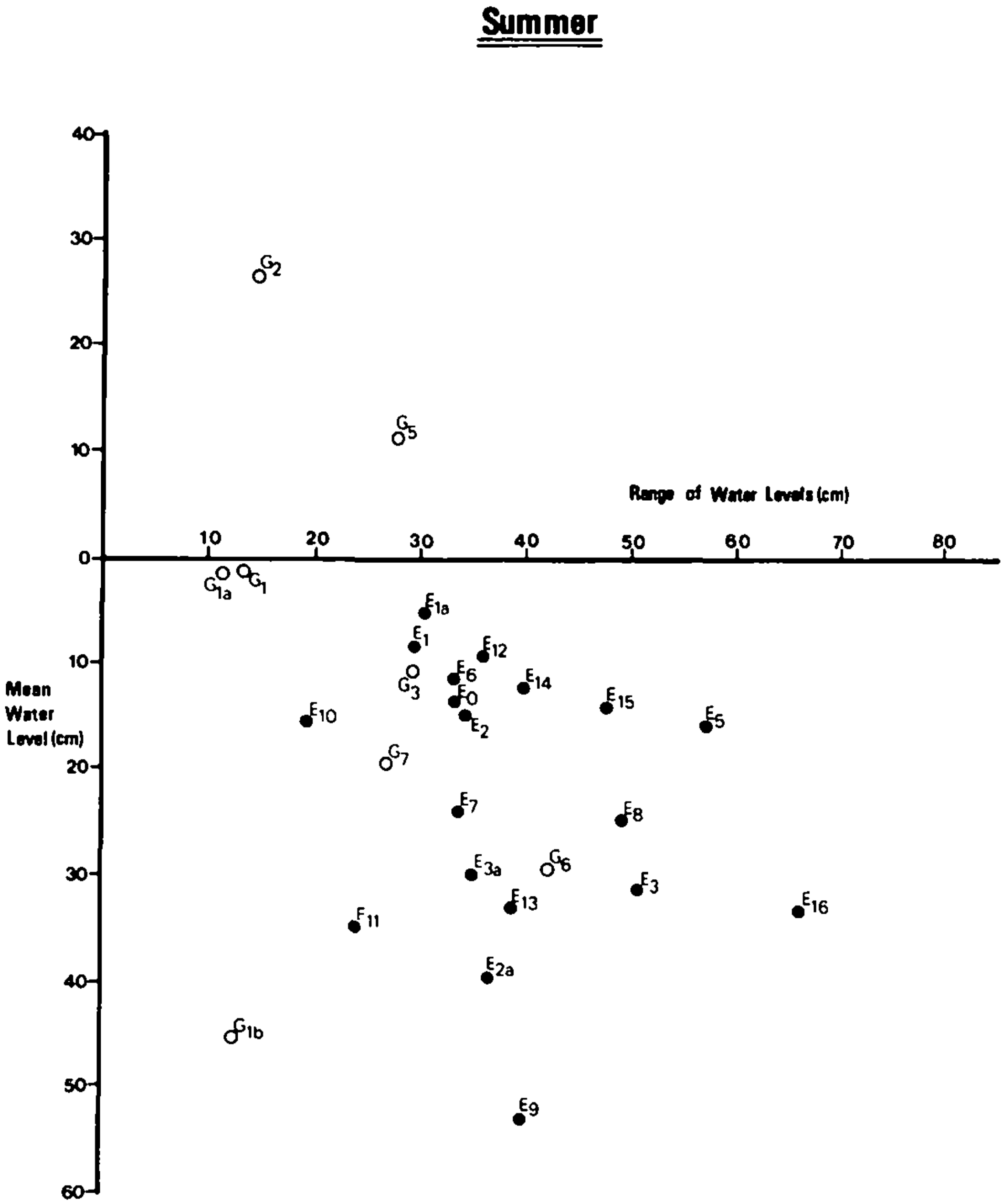

Summer

FIGURE 28 Mean water levels and range for the summer half-year below the surface, with the wettest conditions near Rallt Bridge and the lake. In winter the majority of boreholes at both sites have water tables near the surface and small ranges of variation, and in summer there is a trend towards falls in mean water level and increases in range. However, those boreholes exhibiting water levels considerably above or below the surface do not increase their ranges in summer to a great degree: very wet sites are subject to fluctuations caused by rainfall in winter and evaporation in summer, while sites with a deep water table are not controlled by surface drainage in winter.

From consideration of the plots it is possible to confirm that the soligenous *Schoeno-Juncetum* community can accept large ranges in water level, provided that the quality is right: several boreholes at Cors Erddreiniog, (3), (5) and (8) have similar marginal positions to the *Schoenus* boreholes, and similar water levels and ranges, but do not receive as much calcium-rich water and are overrun by *Molinia*. For the topogenous communites, *Cladietum* and *Phragmitetum*, only a high water table will provide suitable conditions.

3.2 A hydrological picture of Cors Erddreiniog and contrasts with Cors Goch

In a pioneering study of groundwater levels in Wicken Fen, Godwin (1931) set out to establish the nature of hydrological controls on wetland ecosystems. His instrument network was designed along what have now become familiar lines: a large number of observation pits for periodic measurements of water levels, and a very few equipped with continuous recorders. At Wicken Fen, as in the Anglesey Fens, the water levels in ditches or 'lodes' were important, and transects of observation pits were excavated to observe the attenuation of the effects of ditch levels with distance into the fen, and the levels to be found in different vegetation communities.

The result of Godwin's experiments was the separation of the short-term effects of rainfall events, and the localised effects of manipulated ditch levels, from a general trend of groundwater levels which was best observed in the central zone of the fen and derived solely from the annual cycle of evaporation and transpiration. Depression of groundwater levels in the summer was mainly due to the rise in evaporation, and the rise detected in autumn was due to the combined effects of the decline in evaporation and the onset of the winter rains (Figure 29).

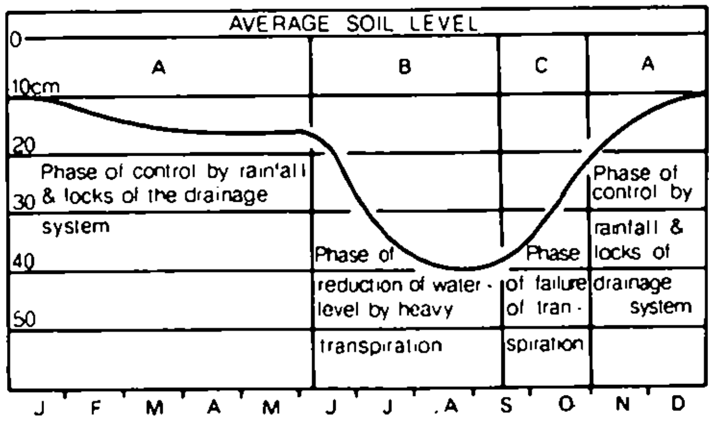


FIGURE 29 **The yearly behaviour of groundwater at Wicken Fen** *(Godwin, 1931)*

Godwin's annual trend of water level is a useful point to begin a survey of wetland hydrology, and data from Cors Erddreiniog and Cors Goch tend to support this simple scheme.

Rainfall, the primary input to the fen system, though quite evenly distributed throughout the year, generally fails for a period each summer. This summer drought can occur any time between April and September, and the project has been fortunate in covering drought periods in early, mid-and late summer. The impact of the rainfall deficit varies according to its timing. An early summer drought is scarcely felt, as transpiration and evaporation are still very low. In midsummer and late summer, temperature and radiation inputs are high, and the water table, unsupported by rainfall, drops rapidly. Thus in summer, the distribution of rainfall in time is a factor tending to modify the form of the water level curve. Figure 30(a) from Wicken Fen for the years 1928 to 1930, can be compared with data from a borehole on Cors Erddreiniog for the years 1979 to 1981, presented as Figure 30(b). In both cases the rainfall in July and August, when temperatures are highest, exerts a strong effect on the drop in water level.

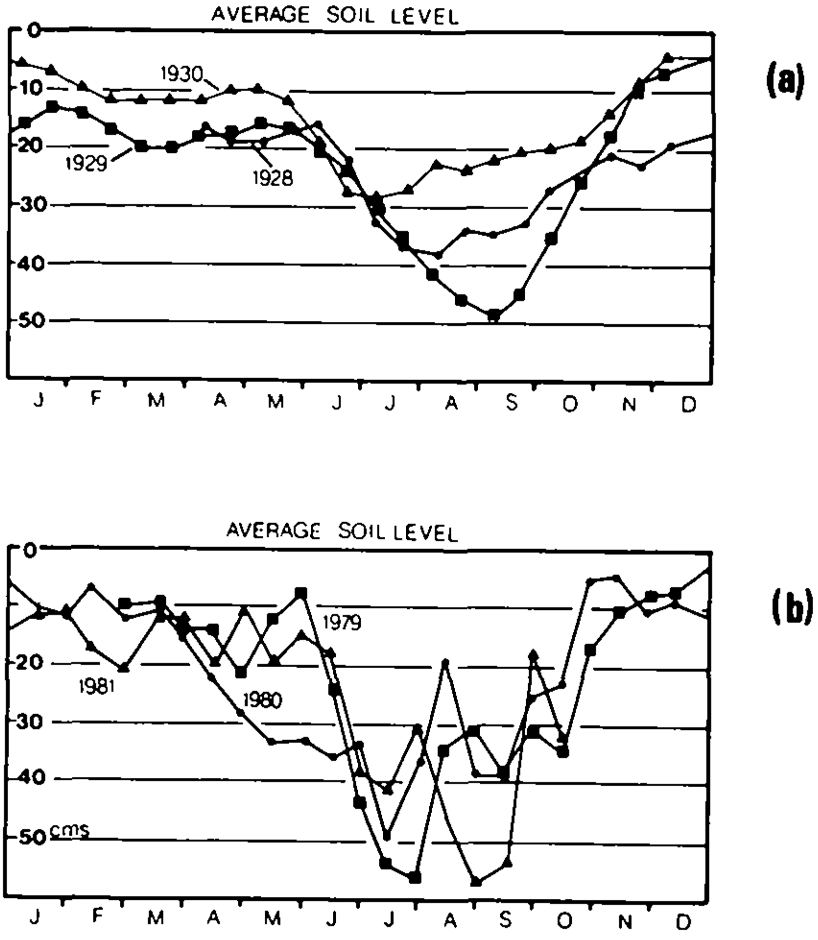


FIGURE 30 **Variation of the seasonal level of groundwater for differing rainfall conditions, with emphasis on summer**
(a) For Wicken Fen, 1928, 1929, 1930 *(Godwin, 1931)*
(b) Cors Erddreiniog borehole (3), present study

However, deficits arising from evaporation are never eliminated by the summer rainfall pattern. With Cors Erddreiniog in its present state, even high rainfalls can be disposed of by the ditch system, so winter flooding is an infrequent occurrence. During the period of study only the flood of March 1981 resulted in widespread surface water. In a restored fen basin, inundation would be more frequent, and would tend to favour the wetland communities at the expense of invading *Molinia* and bushes.

Of secondary importance to the balance of water quantity in Cors Erddreiniog is the flow of springs and surface inflows. The constant discharge of the Nant Uchaf spring, and probably the diffuse springs along the springline, is a steadying influence on water levels near the lake, while the more flashy input from Nant Isaf is canalised into the main drain, and does not have the influence on the hydrology of the fen that it would have had in the past before drainage. This diversion of the spring inflows has important consequences for the quality of the fen water supply, and this point will be discussed later.

The factor that exercises most control on the water level in the fen is the annual cycle of evaporation. Depending as it does on net radiation and on humidity deficit, which increases with temperature, the potential evaporation occurs almost entirely in the six summer months, from April to September, and peaks in midsummer. Transpiration of plants is later to start as it depends on the leaf area and on the rate of growth. Leaf area also has an influence on the interception of rainfall, a highly efficient process when summer showers alternate with drier spells, given the air movement so typical of Anglesey. The joint effect of evaporation and transpiration is to begin a steep lowering of the water table in May or June, corresponding with the period of maximum growth, and a reduction in the outflow from Cors Erddreiniog which is displayed as a fall in the level of the main drain. The amount of water taken up in cell tissue might be considered large in wetland plants: in fact it is not, seldom exceeding a millimetre on the ground. In late summer and early autumn the wetland plants begin to die back or ripen, and water levels are raised by the joint effect of the cessation of rapid transpiration and the increase in rainfall. This summer lowering of water levels could not be entirely eliminated even if constant water level could be maintained in the main drain: in any case the important objective is the raising of the winter water levels.

Another aspect of Godwin's (1931) study of Wicken Fen was the examination of continuous records from observation pits towards the centre of the fen expanse. In summer these records showed not a smooth decrease in water level, but a stepped decrease, with steeper falls during the day and sometimes a slight rise in the night. Godwin concluded that here he was observing the effects of the daily cycle of transpiration of the wetland plants. The daily fall, when corrected to allow for drainage, matched the actual evaporation measured in a lysimeter, with a 10% storage coefficient for the peat. That is, a 1 cm fall in the groundwater level was caused by a 1 mm loss by evaporation. At Cors Erddreiniog it was possible to perform a similar exercise on the records from the instrument on borehole 4 (Figure 31). For this period in July 1980, neglecting the 7th, when some other effect was in operation, and the 10th, with unknown potential evaporation, the falls in groundwater level were on average five times the evaporation, implying a 20% storage coefficient. An open water surface, subjected to no other influences, would of course have fallen by an amount equal to the evaporation. This difference in behaviour between water table and standing water level explains an effect noted at Cors Goch: at the eastern end, where there are large areas of standing water, fluctuations are small, whereas the western end of the basin shows large annual fluctuations.

A feature of the hydrological system at Wicken Fen is the flow of groundwater from

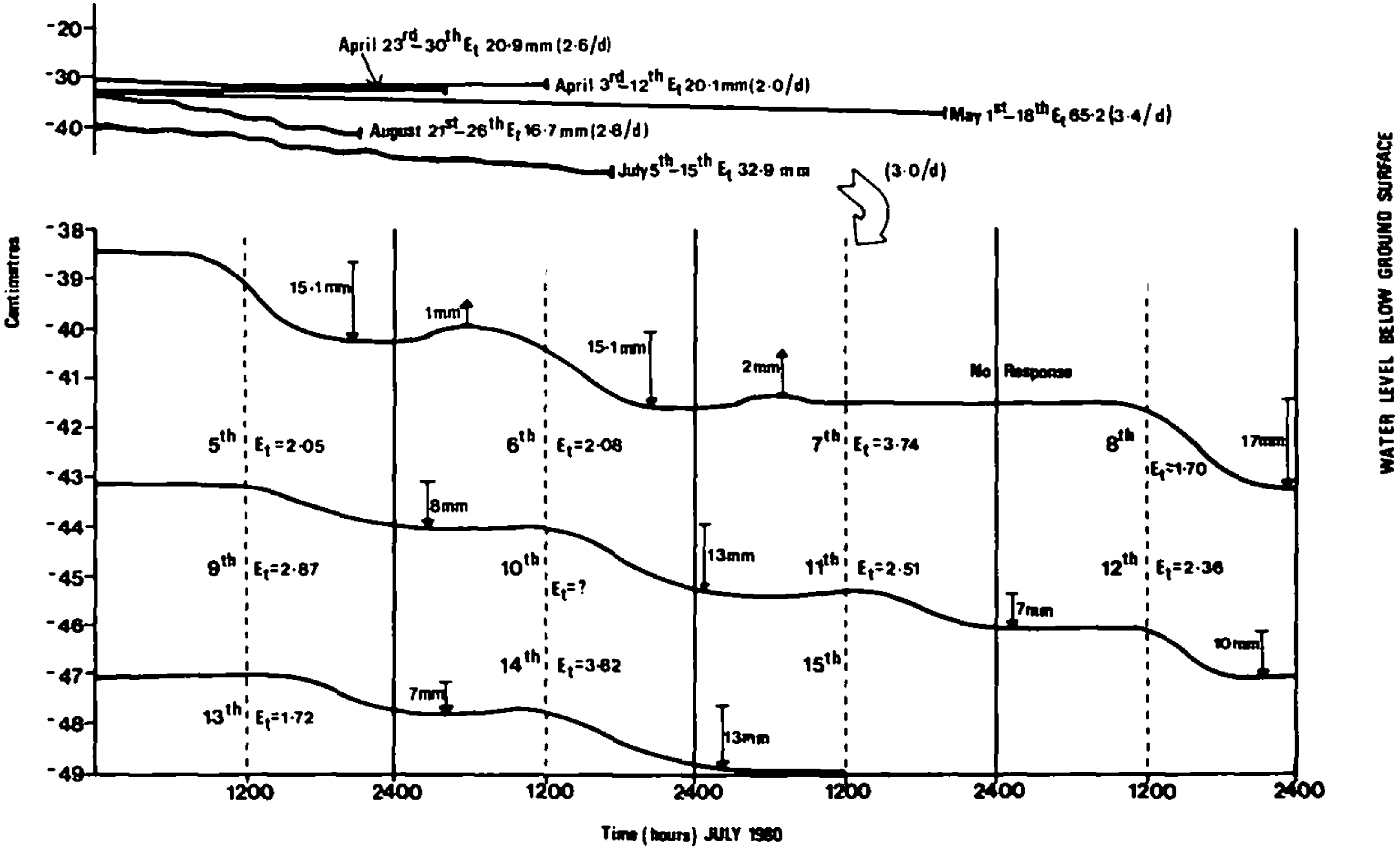


FIGURE 31 Water level fluctuations over short periods of moisture stress in the centre of Cors Erddreiniog showing (top) the difference in the rate of fall during dry spells before and during the growing season and (bottom) detail of diurnal variations in July 1980 with the potential evapotranspiration for comparison

the ditches into the fen expanse during the summer. At Cors Erddreiniog the depressed water level in the ditches appears to be lower than the fen water table, and there should be no relief of the summer lowering by influx from the ditches. However, without some sort of control of summer water levels, they would be expected to fall much farther. At Wicken, for instance, with evaporation rates in excess of 3 mm per day, the annual range of water level was about 300 mm, in spite of a low storage coefficient of 10%. At Cors Erddreiniog the evaporation exceeded rainfall by 192 mm over the four months from April to July 1980, and without supplementation from some source the water level would have been expected to fall by 0.96 metres. The actual fall was about 0.45 metres in borehole 3 and less in more favoured sites such as borehole 1. Clearly water levels are being sustained here as at Wicken Fen, however the mechanisms need not be the same. Firstly it may be unwise to consider potential evaporation as actual, particularly in the early part of the year when the ground is covered by a mat of dead litter and there is little or no transpiration; later in the year, when the wetland plants have built up a canopy and are transpiring freely the actual evaporation is more likely to equal potential, with evaporation from intercepted rainfall taking over when the vegetation is wet. Secondly water levels may be controlled by the base level in the main drain, which is itself subject to control by the growth of aquatic and emergent vegetation in it over the summer. In this case the main drain acts not as a source of water, but as a 'hinge' about which the inclined water table turns as the quantity of groundwater seepage reduces over the summer. The supplementation to the groundwater body that enables it to supply evaporative demand without excessive lowering of level comes actually from the groundwater flow entering the fen as diffuse springs along the bedrock contacts. This spring flow should behave in a similar way to the Nant Uchaf spring, and have a more or less constant discharge over the year. Springs could be expected from the sandstone facies of the Carboniferous limestone series in addition to the more obvious limestone beds.

A conclusion that emerges from a consideration of the wetland plant communities and their growing conditions is that there is no appreciable soil moisture control over transpiration; stomatal control may well be used to guard against storage problems within the plant (see Rychnovska, 1978) and the result is transpiration at or just below the potential rate when growing in soil. An increase in summer water levels to the stage of standing water would cause an increase in evaporative losses. The outflow from the fen, a valuable input to the Cefni reservoir, must be maintained and therefore this course of action is not recommended. Summer flooding can also harm fauna (Duffey, 1971). Since the flora of Cors Erddreiniog shows few apparent harmful effects of some slight limitation on transpiration, whereas it does show signs of losing out to competition, winter and spring flooding is the major option. In the case of *Cladium*, performance is certainly better in the wetter parts of Cors Goch, with summer flooding, and flowering is more common here. However such conditions would be difficult to achieve over wide areas of Cors Erddreiniog. Godwin and Bharucha (1932) concluded that the fen succession was unaffected by summer drought. The portion of rainfall and incoming runoff that is evaporated or used in transpiration is a third to a half. The remainder leaves the fen in the main drain. The storage of this excess on the fen expanse, maintaining high water levels in winter and early spring, is needed to tip the competitive balance in favour of valuable wetland species. At present the surface drains at Cors Erddreiniog are effective in removing the excess: even the very shallow field drains are capable of eliminating standing water from the level or gently sloping fen expanse. The result of active fen management would be to increase the amount of water going into storage on the surface and in upper soil horizons during the winter, and particularly during storm events. Once the fen surface was flooded to capacity, runoff response to rainfall would be more rapid than at present, so the hydrological effect of the fen would be to absorb summer and autumn rainfall more effectively than at present, but to transmit winter floods without loss, but with some delay.

For the botanical communities on the fen, water quality is as important as quantity. The differing requirements of the main plant species have been described above: it is clear that a management plans must take account of the variation of water quality across the fen in its present form and its future, managed, state. The limestone ridge to the east of Cors Erddreiniog is a rich source of calcium, and springs at its foot have given rise to an interesting community based on *Schoenus*. This soligenous fen community is not appreciably stressed, although its quality and extent could be improved by careful control of the spring outflow and some spreading of the spring water. Elsewhere on the fen, the calcium-loving *Cladium* community is in retreat, and it is possible that this decline is due in part to the acidification of its water supply. As groundwater levels fall, the supply of calcium is diminished, and rainwater becomes the principal water source. This condition is acceptable to *Phragmites* and to *Molinia* but not to *Cladium*, and the balance is tipped against the latter. To maintain a healthy *Cladietum*, it would be necessary not only to raise water levels by impoundment, but to provide a supply of calcium-rich water. This water is available in quantity only in the Nant Isaf spring field and down the length of the main drain.

Cors Goch has been regarded throughout the study as a 'control' site, a healthy fen which embodies the ideal state to which the restoration of Cors Erddreiniog should aspire. This is true in part: Cors Goch is certainly wetter than Cors Erddreiniog, and the *Cladietum* in particular could be used as a standard for comparison. However, Cors Goch is not without its problems.

At the eastern end of Cors Goch, conditions are very wet, with standing water throughout the year and healthy *Cladium* and *Phragmites* communities. *Molinia* is restricted to the margins and to a few 'islands' where acidic conditions have become established. Variation in water level is about 0.1 metres over the year, the reason for this small fluctuation being the large proportion of standing water. The same evaporative demand would result in five or more times this fluctuation if the water level were within the peat.

At the western side of the central bedrock ridge, conditions are very different. Some wet communities exist, but the amount of fluctuation is much greater, and there is no standing water in summer. The reason for the lower water level is the central ditch linking Llyn Cadarn with the outflow into Afon Marchogion. There are marked similarities between this area of Cors Goch and Cors Erddreiniog, although the *Molinia*-dominated communities do not have such a hold at Cors Goch. In both cases lake level fluctuations follow the general course of groundwater level changes, and the lake is clearly controlled by the groundwater level and the amount of outflow, both fundamentally determined by the seasonal cycle of evaporation. The lake area is too small for it to have a controlling influence on groundwater levels, by acting as a source of water in summer, and it may be that the only transfer of water is from the groundwater into the lake (Figure 32). The lower level of Llyn yr Wyth Eidion in the winter of 1980-81 was caused by excavation, by a neighbouring farmer, of part of the ditch leading from the lake.

The only course of action which could improve the status of the western part of Cors Goch is the artificial control of the level at the outflow. This would free the lake from its dependence on the quantity of outflow, and, if levels could be raised sufficiently, would make the lake act as a storage reservoir to supplement the water supply to the fen in the summer, thus reducing the fluctuation in groundwater levels. Setting aside the issue of ownership and access to the entire basin (it has been said many times that a secure future for Cors Goch depends upon ownership of the entire basin) it is vital for hydrological reasons that the outlet, which controls the base water level, must be under the management of the conservation interests, and not of a peat extractor!

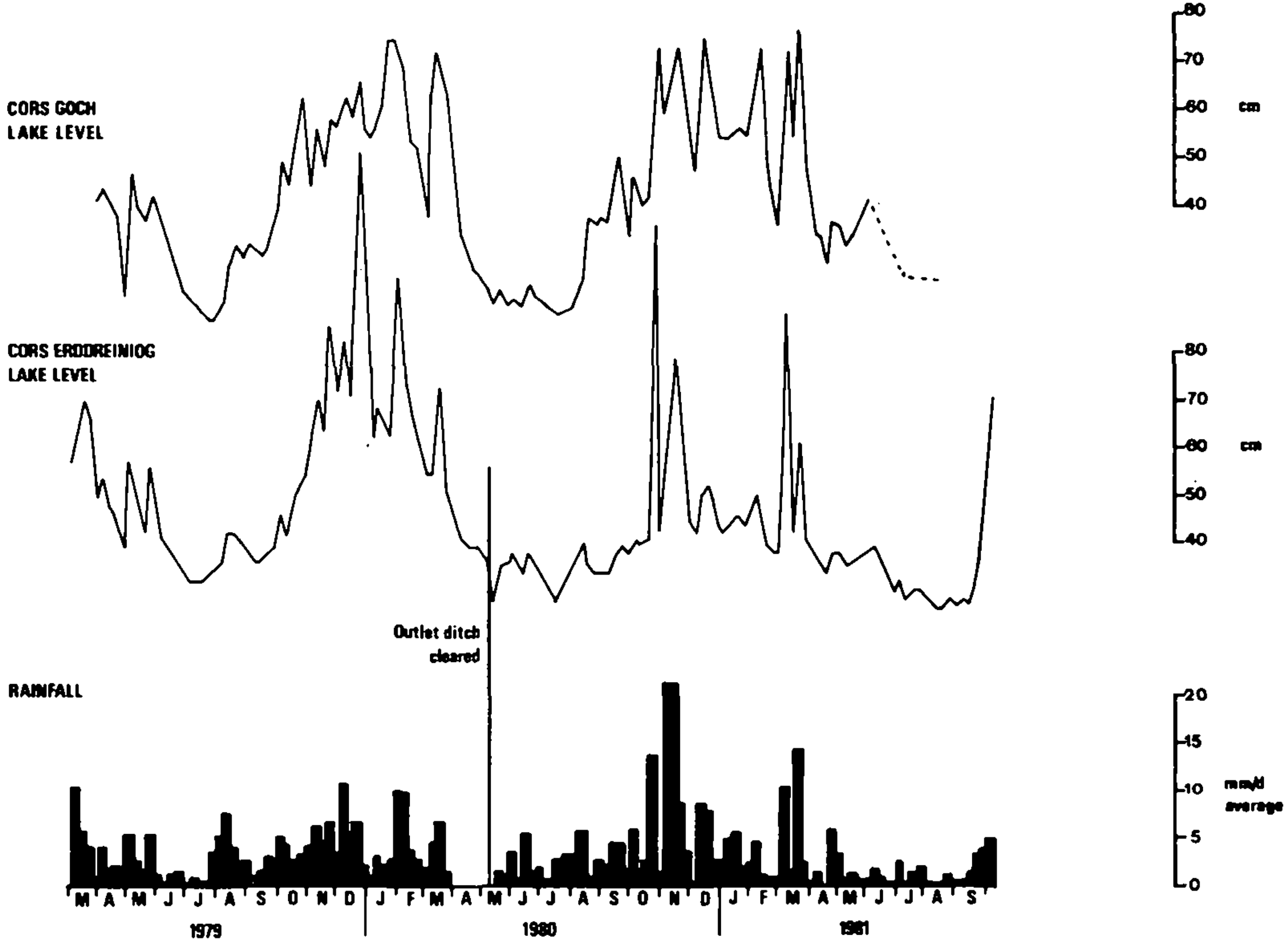


FIGURE 32 Lake water levels at Cors Goch and Cors Erddreiniog during the study period

3.3 Points at which extrapolations can be made to other wetland areas

There are a number of reasons for the possibility of extrapolation from Cors Erddreiniog to other British wetlands, i.e. the use of results obtained here with modifications based on local knowledge. Firstly, there can be few British freshwater wetlands in an unmodified state: the fever for land reclamation left few areas untouched by speculative drainage works. The actual gain in agricultural productivity, in those cases where wetlands still survive, must have been minimal, but the effect on the wetland communities in many cases has been marked. The road to recovery, where resources are available, must follow a similar course to that proposed for Cors Erddreiniog. However, the details of restoration and management plans will depend on local circumstances, in particular where water quality is a problem.

Secondly, British wetlands are constrained in their development by a similar climatic background. While rainfall varies from west to east, and the relationship between rainfall and evaporation may differ greatly, the seasonal fluctuation of temperatures and the role of ice and snow are a constant factor. Further, while plant communities exhibit changes from north to south, there is a tendency for certain ecological niches to be common to all sites, although they may be occupied by different species. For example, the water regime which favours *Cladium* at Cors Erddreiniog promotes *Carex rostrata* at Sunbiggin Tarn. One species which seems to be ubiquitous is the reed, *Phragmites communis*, with a wide range of tolerance of pH, nutrient status and climate.

A wetland is an area which has a high enough water table, or is flooded frequently enough, so that the roots of emergent vegetation are forced to exist for a significant proportion of the time in an anaerobic environment (Gosselink and Turner 1978). Invariably this condition results in the selection of a wetland flora that is adapted to live and compete successfully in this environment. Any modification of the wetland environment which reduces the effects of excess water will reduce the competitive advantage of the specialised plants and initiate a succession to more xerophytic communities. In many wetland types, some such succession is inherent even without outside interference, but in general it is not considered desirable in nature reserves to allow this succession to proceed unchecked. The aim is to maintain subareas representative of as many stages of the succession as possible, and to prevent the loss of early stages. In this way the scientific and education values of the reserve are maximised. From the point of view of the conservationist:

> the problems of wetland management derive from human interference, either deliberate or unintentional, with the fundamental water regime that distinguishes a wetland from other environmental types, or from natural succession allowed to proceed unchecked. Only sensitively-directed, active management can halt or reverse the decline or development of an affected wetland.

The natural resilience of wetland flora can result in the gross decline of a wetland community's being delayed for a considerable time. The details of the community structure may be sensitive to a change in the water regime, for example bryophyte populations can disappear from a *Phragmites* community, but the larger species have a 'biological inertia' which enables them to survive for a long period under conditions that are less than optimal (Gorham 1957). *Phragmites* is a particularly good example: an apparently healthy stand can conceal the fact of a fen's slow but inevitable decline. Natural succession to drier communities is accelerated by modification of the hydrology, and in some cases only a fall in water level of some centimetres is required to initiate bush growth and succession to carr (Godwin and Bharucha 1932).

> The natural state of a wetland is diffuse drainage with frequent surface inundation: a wetland divided by a drainage ditch or with its natural inputs canalised is certainly in decline and cannot be rescued without restoring its natural water regime.

Wetland sites are typified by one or both of excessive water input or impeded drainage. Raised bogs and blanket bogs owe their continuation to relatively high rainfall, although it is possible for bog conditions to develop on fen expanses where a degree of elevation above base-rich groundwater can be secured. All wetlands are sensitive to improvements in the drainage system, which result in a lowering of the local base level which controls the wetland water level. This local base level may be that of the lagg fen around a raised bog, of the bed of a channel in a blanked bog, or the drainage outlet of a fen. A fen relies on water from outside for its supply, and is vulnerable to changes in this supply.

> In any wetland area, control of the water regime hinges on the control of the point or points which establish the local base-line level, and in the case of fens the control of the points of inflow, both in quantity and in quality.

With caution it is possible to use the dominant species as an indicator of the condition of a wetland, or of particular areas within it. This procedure has its hazards, as for example in the case of recent drainage works, and it is difficult to compare different sites where the biotype may vary, but the trained botanist may be able to draw useful conclusions when botanical survey techniques are combined with other methods. The key to the use of this approach is the assembly of a body of data and experience on the performance and environmental requirements of the main species.

> The problem of providing environmental requirements for the range of communities present in a wetland site may be simplified to that of ensuring the continuance of optimum conditions for those communities whose needs are extreme (usually at the wetter end of the spectrum) and of maintaining a smooth continuum of conditions between the extremes. It is unlikely that management can provide, as a matter of deliberate policy, the ideal conditions for the minor floristic elements at a particular point on the site, but the establishment of a range of conditions across the site offers a better chance of survival than would neglect.

SPECIFIC RECOMMENDATIONS

4.1 Specific solutions at Cors Erddreiniog

Cors Erddreiniog has been directly damaged by the effects of past agricultural activity and is peripherally threatened still by zealous pasture improvement. No unaffected areas of the original rich-fen communities survive. Is it then worthwhile to devote NCC resources to the saving of this site, when a richer site exists nearby at Cors Goch?

The importance of Cors Erddreiniog derives from its potential rather than from its present state. While about half of Cors Goch, including the vital outlet into

Afon Marchogion, remains in unsympathetic ownership the site cannot be regarded as secure; the Marchogion would be much cheaper to deepen and grade than the Cefni, since it drains steeply to the sea. Additionally there are no sources of water at Cors Goch that could practicably be used to buffer the reserve against the effects of drainage along the northern fence. At Cors Erddreiniog spring supplies do exist, and the water level in the main outlet ditch is unlikely to be lowered further in other than temporarily-effective cleaning exercises. It is therefore possible to suggest short-term management schemes for Cors Erddreiniog that could maintain communities and perhaps start to reverse the degradation of the past.

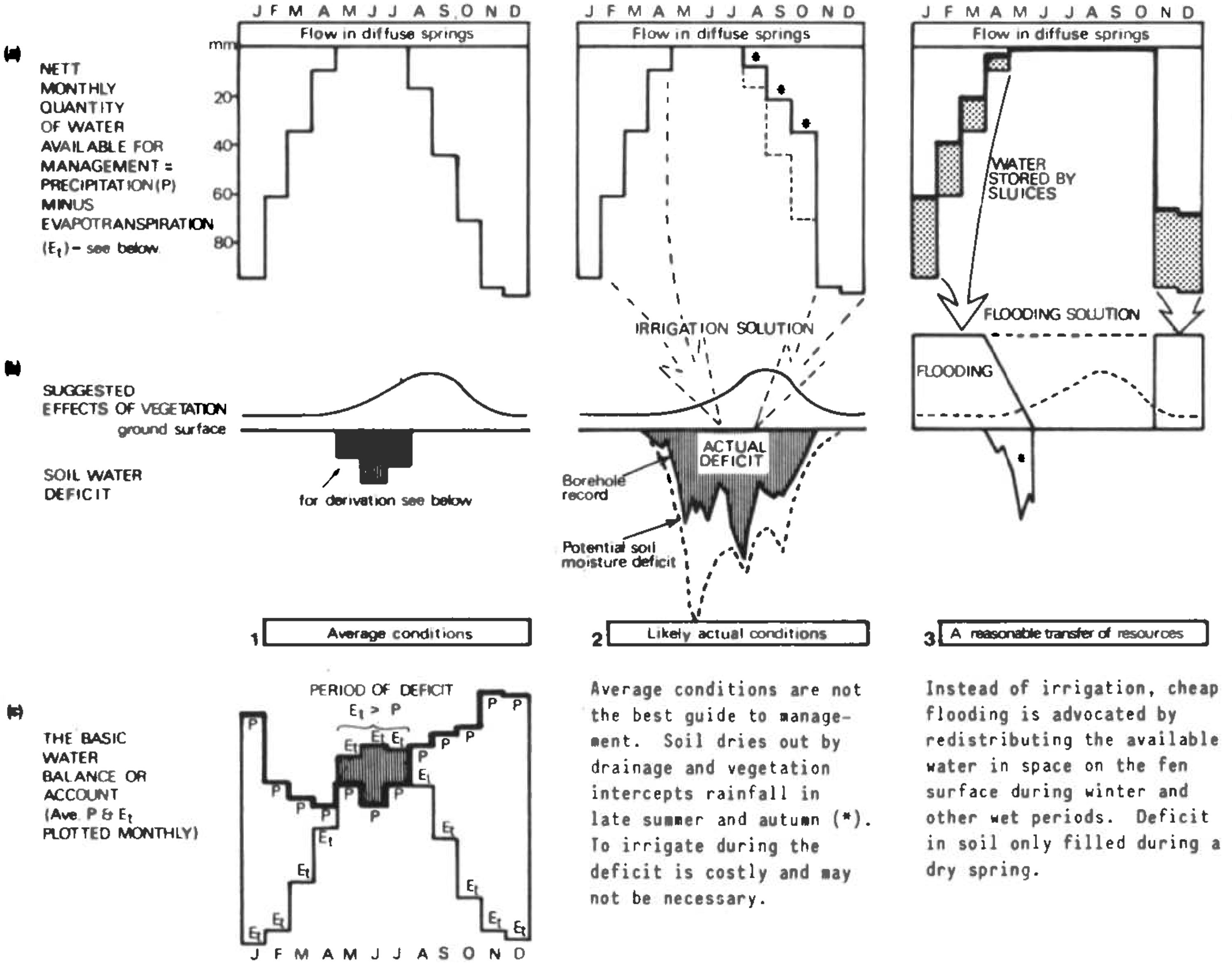
The problems to be solved at Cors Erddreiniog and Cors Goch are the consequence of a variety of drainage works attempted by landowners over more than a century. The clear aim of the works was to reduce flooding by surface water, perhaps as the precursor to more intensive drainage and reclamation. To ensure the continued success of arterial drainage away from the sites of agricultural effort the lower parts of these ditch systems became part of the "main river" designation under successive Land Drainage Acts (for an insight read Wisdom, 1979). In addition to the network of deeper ditches for arterial drainage at Cors Erddreiniog, a few shallow field drains were dug, which have been effective in reducing flooding but have not lowered the water table significantly below the surface. Only the central '40-acre' field at Cors Erddreiniog has had the next phase of reclamation, intensive grazing, and there are plans for tile drainage there. Other land holdings around the NNR have failed to take up the more modern methods of underdrainage; Anglesey agriculture is traditionally less intensive than that in East Anglia or the Somerset levels.

One aspect of the main drainage networks at Cors Goch and Cors Erddreiniog is therefore that, while frustrating the aim of conservation, they are not serving any very useful agricultural purpose. At Cors Goch the lowering of the levels at the western end is of benefit to the peat extractor: at Cors Erddreiniog, flooding by waters from the Nant Isaf springs is prevented, but further drainage and improvement has not been pursued. Only one farmer is keen to press his rights to underdrain because there is arterial drainage and then to improve the latter because of the former - a legitimate farming attitude under the present system.

At Cors Erddreiniog the main ditch as far upstream as the outlet from the 'spring field' at Nant Isaf is designated 'main river' and subject in principle to maintenance by the water authority under its permissive powers. Potentially this ditch could be cleared, and its level lowered, in response to the needs of agriculture. In fact, because the ditch is tributary to the Cefni Reservoir, wholesale re-grading is unlikely because of water quality deterioration whilst it was carried out. Nevertheless, in the short term any management measures should take account of the present level of the ditch and the unhappy prospect of further 'improvement'.

With or without control of the level in the main drain, the objective of management proposals must be to procure flooded conditions on a large part of the fen expanse, at least during winter and spring. This would promote the growth of *Cladium* where calcium was plentiful and *Phragmites* in less base-rich areas. Parts of the fen which could not be flooded should be allowed to develop in a controlled fashion into carr and fen woodland.

Any short-term proposals must be confined to the area currently comprising the NNR, and here the immediate problem is the dissected form of this reserve, a fact long recognized by the NCC. The fen reserve consists of two completely separate portions, divided by the sandstone ridge west of the lake. The eastern portion has



Average conditions are not the best guide to management. Soil dries out by drainage and vegetation intercepts rainfall in late summer and autumn (*). To irrigate during the deficit is costly and may not be necessary.

Instead of irrigation, cheap flooding is advocated by redistributing the available water in space on the fen surface during winter and other wet periods. Deficit in soil only filled during a dry spring.

FIGURE 33 A graphical hydrological indication of water quantities and management options at Cors Erddreiniog access in principle to abundant spring water which could be used to revitalise the topogenous communities around the lake. The western portion is also topogenous, but there is no available supply of water in the quantity required, without pumping up from the main drain.

In the long term the restoration of Cors Erddreiniog depends on NCC control of the whole of the main basin, and hence of the all-important level in the outlet ditch and of the spring inflows. With this area of control it would be possible to maintain a complete range of communities from aquatic to carr. The resulting reserve area would be both large and compact, would be viable in the long term and would be valuable to wildlife from the surrounding region, providing a refuge, nesting and feeding grounds. Acquisition of such an area is currently being attempted by NCC.

It is less than easy to obtain flooded conditions given the present condition of Cors Erddreiniog. Water sources have been diverted, and an easy route exists for drainage water from the fen. However, even with the present pattern of land ownership, the management strategy should be put in hand, and this effort would not be wasted should the objective of NCC control of the whole fen be achieved.

Before considering the most beneficial system of water management in geographical detail it is appropriate to re-state the hydrological data for Cors Erddreiniog, whose collection has been a major aim of this Project. It is often considered convenient to express the hydrological cycle for an area in terms of a bank balance, with deposits of precipitation being drawn out to "spend" on river flow and evapotranspiration. Much of Britain's irrigation scheduling is based on the simple quantitative picture of a temporary overdraft being covered by timely deposits. The Met. Office's calculation of Soil Moisture Deficit (S.M.D.) is used by growers to decide when and how much to spray. Whilst eventually deciding against irrigation philosophy for wetlands, Figure 33 sets out to compare the resources available for making Cors Erddreiniog wetter, with the demand the dry months impose.

Figure 33 develops, in three stages, the most economical way of managing the moisture account at Cors Erddreiniog. In the first column (1) the overdraft is shown to be small in that, on average (Smith 1976), evapotranspiration exceeds rainfall only in May, June and July, at the start of the main season of vegetation growth (the curve is based on Mason and Bryant's 1979 figures for *Phragmites* growth. The "account" is a lot healthier than a similar one for eastern Britain would be (e.g. only 546 mm of rain per year at Woodwalton Fen). This portion of the diagram indicates that a wetland is climatically viable under average conditions and that the problem of management is that of reducing the temporal (and spatial) inequalities in water distribution - this is at the core of British water supply technology.

However, Figure 33(1) is unreal in two respects, not dealing with the variability of summer rainfall (which often fails for extended periods) and not incorporating the drainage of water from the soil. Therefore, in column (2) the soil water deficit has been plotted in terms of an actual S.M.D. record (showing climatic variability) and an actual Erddreiniog borehole record, converted to water depths via a storage coefficient of 20%. The borehole record is the better guide since it records the actual, not the potential deficit in a sample year. Column (2) also illustrates the much longer season of deficit occasioned by the late summer/autumn plant growth maximum. Whilst the transpirational component of this growth season is covered by the actual deficits in the soil we have also illustrated a halving of the "available water" columns to represent interception losses. (The "available water" columns result from a subtraction of evapotranspiration from rainfall - simple moisture accounting; they are crucial to the next line of argument. Flow in the diffuse springs is essentially constant and comes from outside the main area).

Column (2) is unrealistic in water management terms in that it shows all the available water (runoff) being saved to irrigate during the period of deficit. There is little evidence that this "growing carrots" rationale will promote the recovery of *Cladium,* however, and column (3) shows two major changes. Only the earliest part of the soil deficit period, when fen plants are in competition with other species, is now irrigated and there is a major use of water in winter too - to flood the fen to an overall depth of 40 mm. Also shown is the source of the water from the "available water" store, with preference given to spring-fed runoff on water quality grounds. The graphical method shows that sufficient water is available to meet this aim but that storage might need to be provided to meet the needs of a dry spring or, alternatively, pumps could be used to re-use water from the ditches under such conditions. It should be remembered that some water must still flow down the river - especially in a reservoir catchment - and that much of what would be "supplied" at Erddreiniog would only, in fact, be in temporary storage, not used as such.

Since Figure 33, column (3), concludes that spatial redistribution of water is a better method of management than temporal redistribution, we need a spatial illustration. Accordingly, the general recommendation on hydrological grounds is converted into specific terms using the map of Cors Erddreiniog shown in Figure 34.

In both parts of the Cors Erddreiniog NNR, water levels are constrained by the presence of the ditch and the need to maintain a low ditch water level to satisfy the drainage requirements of the neighbouring farm land.

The eastern area around the lake. Attention should be restricted to the northern part of the area: the two most southerly fields have little immediate conservation interest except as a buffer zone and less prospect of recovery because of the need to maintain the "South Ditch" along its upper reaches where it is the collector of field drainage. The most radical management suggested for these fields has been excavation of peat to create an open water body. The two fields immediately south of Llyn yr Wyth Eidion are more hopeful: *Cladium* is present and the South Ditch is only a carrier at this point. Two lines of work are proposed:

(a) the blocking (by board sluices) of the South Ditch where it flows into the lake, at the corner of the woodland and at as many points upstream as are necessary. The ditches carrying water to the lake from the two springs should also be blocked. Closing ditches will not raise the water level above the ground surface; to achieve this aim over as wide an area as possible we advise

(b) the excavation of two contour ditches from the west of the lake round to the east, to confine the water made available by (a). The spoil from these ditches would be made into a low bank, 0.5 metre high by 2 or 3 metres wide, after compaction, along the downhill side of each ditch. There would probably be no need to provide structures to handle overspill.

Management of the area around the lake is made more difficult by agricultural ownership of the salient reaching towards the lake at its northern edge. If this triangle of land were owned by NCC, the lake level could be raised by between 0.5 and 1 metre using an adjustable sluice, to give a more natural base level and a larger area of littoral zone. As the boundaries stand, the ditch immediately downstream of the lake restricts any move to raise groundwater levels in the area west of the lake. All that can be done at present within the NNR west of the lake is to block the northward-flowing ditch that bisects this area. This has already been done with a board sill (see below). North of the lake is a soligenous area which has recovered well from the effects of grazing. As this area abuts on

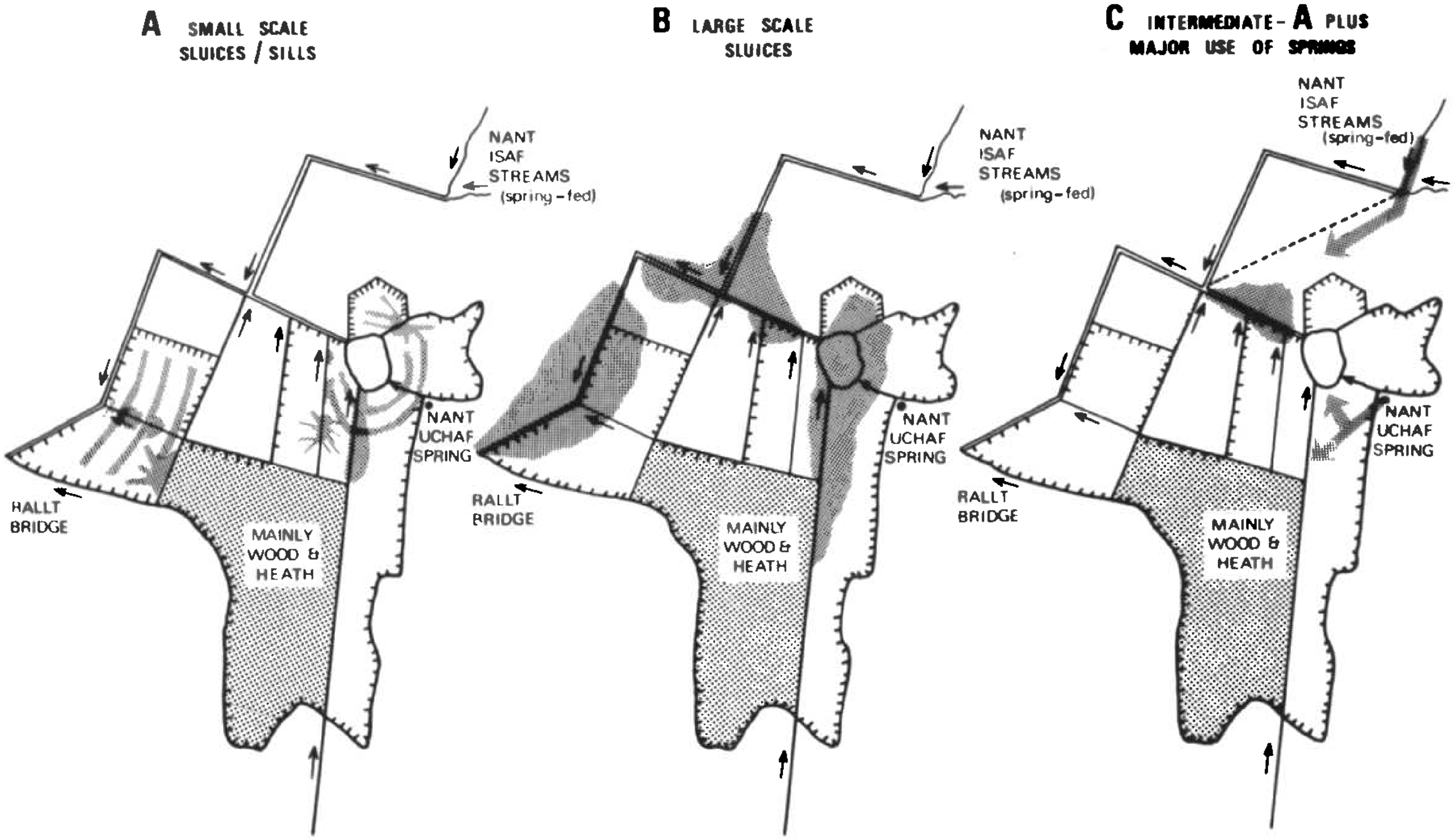


FIGURE 34 Maps indicating spatial management options at Cors Erddreiniog

improved pasture, it would probably be necessary to control water levels along the periphery of this area by sluicing the ditch leading southwestwards into Llyn yr Wyth Eidion from some small springs along the eastern margin of the reserve. One such board sluice has already been built.

The area west of the sandstone ridge. On the west wide of the sandstone ridge the peat surface slopes gently down towards the main outlet ditch. There is little supply of water to the upper edge, and the groundwater here must owe its origin largely to rainfall on to the fen surface. This is corroborated by the low concentrations of calcium found in the soil in this area. Water rich in calcium does exist in the ditches flowing westward, and this water could be spread out on to the fen surface. However it looks as if this area will remain poorer in calcium than that east of the ridge, and *Phragmites* may be more successful than *Cladium* here. Again there are two stages to the work of restitution:

(a) blocking of all ditches carrying water westwards across the site. It may be necessary to keep the western end of the southern peripheral ditch open for the benefit of the neighbouring farm land, but the inflow of water into this ditch should be diverted northwards on to the fen.

(b) as in the area east of the ridge, three contour ditches and associated spoil banks should be sufficient to confine surface water and provide waterlogged conditions to favour *Phragmites* and *Cladium* at the expense of *Molinia*.

It may be possible to install a pump to remove water from the main ditch to supply this area, but in any case the expense of purchase and operation is not justified until the earthworks required to restrict surface flow are in place. The aims of management here will always need to be set lower than east of the ridge because of the general absence of spring supplies; they will largely be to create local stretches of each individual plant succession: "habitat grabbing" in the face of some very degraded wetland under present conditions. At Woodwalton Fen (Duffey, 1971), strips of excavated ground 4 metres wide and .25 metres deep have been found effective in creating a wide spread of diverse wetland conditions. Experiments have also been conducted by NCC at Cleddon Bog, to investigate on a small scale the effects of various clearance and excavation options (Plates 15a/b). The above description is illustrated on Figure 34(a). However, two major opportunities presented by the geography of Cors Erddreiniog have not been grasped. One is that the low gradient across the entire site would make water management across the basin as a whole an option if ownership boundaries could be made to fit hydrological boundaries. Far more intensive topographic survey would be necessary before such a job was undertaken and there would be the difficult choice of deciding to build and operate one major sluice on the "main river" section of the ditch or several smaller ones for greater flexibility (see Figure 34(b)). The more likely land tenure changes might bring into play the important spring sources of Nant Isaf and the Nant Uchaf Spring. Despite their obvious utility as displayed in the graphical analysis above and on quality grounds they have, so far, not been used in the water management plan developed in this section. The major reason is that they currently lie outside the ownership of NCC. In some senses, therefore, Cors Erddreuiniog's trump card is in a dead hand. Figure 34(c) shows what could be arranged if they were to be purchased or governed by agreements. Fortunately Nant Isaf water can be supplied under gravity; that from the Nant Uchaf spring would need purchase and renovation of the ram pump at the site, or use of a portable pump on the ditch nearby.

Passing reference has been made above to the hardware of water level manipulation:

PLATE 15 Experiments at Cleddon Bog, Gwent, to investigate regeneration of flora after excavation of open water areas (this page) and bare peat areas (opposite)


2

sluices (which allow a variable control of the level of spill) and sills (which spill at a constant level but can sometimes be removed entirely). Both are effective on low gradient channels which also tend to have the "sluggish" streamflow response in floods which gives time for their operation before opportunities to divert water are missed or damage done.

The recent publication of revised practical guidance on the field construction of dams, weirs and sluices (British Trust for Conservation Volunteers, 1981) provides a basis for management initiatives at Cors Erddreiniog. Obviously the warden should be provided with the necessary materials and tools; access should be improved for their delivery or a special vehicle provided. Site storage for materials and tools is also advisable. At a slightly more expensive and sophisticated level, there are a number of engineering firms producing smaller water control structures and a small library of their brochures has been assembled by IH. A major implication of installing such equipment is that it places NCC in a responsible position vis-a-vis neighbouring land owners and the water authority. In all but the least sensitive sites (e.g. where installations have already been made) there must be regular monitoring and, if necessary, adjustment of water levels. Such practices are often fixed by bye-law in areas like the Somerset Levels. Any installations on "main river" would, in any case, need the agreement of the Water Authority. A corollary of both the installation and running of all but the smallest structures would therefore be easier access (preferably by vehicle in all weathers) and a new scheme of duties for the warden. It is no accident that at nature reserves like Minsmere which have made a success of simple water management techniques there is a generous On Site staffing. Nevertheless, recent developments in electronic control systems could help make the regulation automatic.

The reaction of neighbouring farmers to the proposals will depend on their farming system and its tolerance to winter flooding (assuming that on the reserve gets out of hand, or the basin-wide scheme is adopted only by agreement). Since summer flooding (i.e. during the growing and flowering season) is of most danger to any crop there is likely to be little justifiable antipathy to a well-designed scheme. The plan is similar to that in the traditional water meadow systems of the South of England. Mr Tony Lester-Card of MAFF/ADAS, Salisbury, has kindly supplied details of a semi-automatic "border irrigation" method of flooding a Wiltshire pasture in a recent attempt to re-introduce the water meadow system to improve grassland yields without the labour intensity of the traditional method. His results show that a sward of ryegrass/Timothy and White clover can benefit from both higher temperatures and better nutrition under the system; it does, however, require a form of grazing management which farmers might need to "re-learn". In the specific case of the farmer at Bodgynda there seems little likelihood that his grazing system can now be changed, having stocked up to cover all the land improved at Cors Erddreiniog.

This report cannot judge the reaction of the Welsh Water Authority to the more ambitious of the above proposals, except that their obvious statutory responsibility is to the riparian land owners. However, the drainage from Cors Erddreiniog also enters the important Cefni Reservoir. WWA would be keen not to reduce runoff for this reason; a summer irrigation strategy might well upset the yield of the reservoir but a winter flooding strategy could aid water management by smoothing the runoff pattern. As already mentioned above, land drainage operations can cause quality problems in drinking water supplied from Cefni reservoir; in fact any intensification of drainage or agriculture in a reservoir catchment causes problems. Welsh Water may, therefore, look favourably at the conservation interest.

If NCC gain control of the main drain and build sluices on it they may need to manage the growth of vegetation in the ditch under the new flow conditions. Simple clearance using a dyke or muck rake will be needed for efficient sluice operation but there are opportunities for creative management of the open-water habitat too.

4.2 A general statement on wetland acquisition, access and manipulation

The ideal in wetland conservation is to obtain control over all the hydrological influences on the site:

> 'it is necessary to have management control over the entire catchment before its survival as a reserve can be guaranteed. A small raised bog must be preserved in its entirety, complete with its unmodified peripheral lagg stream. A small swamp must be reserved together with its water supply, otherwise very expensive works will be necessary at some stage to keep the swamp alive." (Thompson 1979).

Even in New Zealand, where Thompson was writing, this ideal can rarely if ever be attained: in intensively used lands such as Britain it is difficult enough to designate the central area of a wetland for conservation. In practice an uneasy compromise at best must be reached with the owners of surrounding land, whose interests often conflict with nature conservation.

There are circumstances in which such a compromise can be extremely difficult to reach: these usually result from the separation of the wetland core from its water source, or from the extended and dissected form of the reserve, which maximises the length of the disputed boundary and minimises the distance between sensitive wetland communities and agricultural activity.

The pattern of land tenure on wetland nature reserves should always be related to the ideal of a hydrologically valid unit. The hydrologically valid unit will generally be compact in shape, to reduce edge effects, and will incorporate access to and control over its water supply and the outlet point that controls its base level.

As the Anglesey Fens study progressed it became clear that, despite the presence of a high water table and a large capacity for storage of water, mire hydrology is dominated by flows of water (Gosselink and Turner 1978). The dominance of mire species depends initially on chemically reduced conditions in the soil, resulting from the slow drainage of soil water and permanent or near-permanent saturation. Fens can show a gradation in species composition which derives from the balance between groundwater inflow and rainfall. In the case of soligenous mire, the dependence on a sufficient flow of water is obvious, while even ombrogenous mires require a sufficient flow of water to prevent either desiccation or the ingress of base-rich waters.

This consideration of the importance of flow leads to the formulation of three demands which must be met in active conservation of a wetland site:

(i) impeded drainage - the maintenance of high water level at the outflow

(ii) a sufficient water supply to maintain the hydraulic gradient

(iii) the right water quality at every point of the mire.

The management of a wetland to meet these three demands must depend upon an accurate hydrological appraisal of the site. Few sites are immune to natural hydrological change, to encroachment by the effects of peripheral activity or the long-term consequences of earlier attempts at 'reclamation', and it would be unreasonable to expect to devote detailed research attention to each site in turn. The following guidelines may be helpful in the planning of active management:

(i) climatological information available for a nearby station can be used to identify the factors leading to the development of the wetland. This type of data has usually been collected for a long time and will enable the investigator to discount, or to take full acount of, extreme conditions which may be encountered in a short-term study.

(ii) if reasonable maps of the site already exist, the only topographic survey required will be accurate levelling of all watercourses and areas of open water, and the plotting of locations of springs and other input points. Published maps prepared from aerial survey are usually accurate in their placing of ditches and water courses, but not in the direction of flow or the relative importance of springs. It is worthwhile to site staff gauges on major ditches and important areas of open water and to level the zeros of these gauges.

(iii) stratigraphic information can be useful in assessing the survival potential of mires, but it is not essential to go into detail.

(iv) much information can be obtained on a brief field outing by the use of simple measuring instruments. For example the presence of groundwater inflow is easy to detect in spring and early summer by the difference in temperature between it and the air or shallow standing water. At other seasons the daytime air temperature may be close to the groundwater temperature, and the difference is obscured. Electrical conductivity is another valuable indicator of groundwater inflow. An attempt should be made to visit the site in both dry and wet conditions, as the results of a single visit may be misleading.

(v) when a site is being managed, actively or otherwise, it is as important to monitor the hydrological behaviour of the site as it is to keep records of the species present. Measurements of soil/ground water level at key points are in general sufficient.

In Britain the demands of agriculture for the reclamation of marginal lands are on the increase, and it is no longer possible to set aside the 'buffer zones' which are desirable to separate intensive agricultural activity from wildlife conservation. As a result of the continuing erosion of these buffer zones, and especially their improvement by drainage, active management of wetland reserves is essential if these are to survive in useful form, and if conservation is to appear as a type of land-use rather than land wastage.

Management of water levels by sluices, pumped irrigation on sloping areas, or by vegetation control will require a new kind of attitude to wardening wetland reserves; supplies of materials and access will need to be improved, and where sophisticated controls are too expensive it will be for the warden to operate controls manually. Active management of this type is thought to have the added advantage of being more akin to farm management, making NCC's landholding a more active involvement in the countryside. Basic hydrological measurements are essential to this management, as is ground and botanical survey. Woodwalton Fen is often held up as the example of this type of management: there are many less costly schemes, for example those operated by the Royal Society for the Protection of Birds.

The attitude of conservation bodies towards schemes for drainage of adjacent land requires careful thought: on peat land, with a reserve that is hydrologically robust there is little need to resist small-scale land drainage solely on the grounds of conservation interest. Ditching will seldom lower water levels in fen peats over long distances, although it is very damaging if the conservation interest is in surface water. The use of relatively simple control structures will quickly reverse the drainage influence within a hydrologically coherent land holding (Plate 16).

Because of the study's findings on the likely efficiency of agricultural drainage of peats there are, however, grounds for a more active opposition to many drainage schemes on cost/benefit grounds. As well as being backward in hydrology, the land drainers lack a basic body of research to illustrate the crop or livestock tolerance to various levels of soil water.

Opportunities should always be considered for the use of drainage water from neighbouring property where its quality and timing suit the regime of the wetland. Such collaboration has value in public relations and helps to convince agriculture that conservation is an active, not inactive, use of the land. Collaboration is easiest where the conservation interest can be served by gravity flows or deliberate spilling of flood waters on to washlands; it is more difficult where rival interests share very flat land.

4.3 Research requirements

No research project comes to its conclusion without a list of topics which would repay further investigation: this list includes the side issues that were excluded through lack of time or resources and the mainstream problems that remain unsolved. What is lacking in the results from this study is an adequate basis for extrapolation to other sites (of anything but principles of wetland conservation). In other words, our solution is for one Anglesey Fen only, and it is not clear how a plan for water management at other sites could be developed without a replicate Anglesey Wetlands Study. Obviously it is not possible to devote the same time and effort to every wetland in turn, but there is a need for observations at a network of sites, representing different wetland types, which could show up the similarities and contasts between those types, and provide a better foundation for management decisions. We have proposed the type of "self help" hydrological investigation which would be the basis for simple management in Section 4.2 (above). It would be helpful to add to the stock of simple techniques; one has to admire the prescience of Godwin (1981) in developing the "insert phytometer" - a truly portable lysimeter would be a major breakthrough. A part of the necessary generalisation process to allow more detailed extrapolations would be investigations of the hydrological behaviour of the basic wetland substrate, peat, and the dominant wetland species. The aim here would be to assist with estimation of water flow through peat, for example towards ditches, of the amount stored in the peat, and of evaporation and transpiration, which have been shown to control the seasonal fluctuations in water level. Colleagues at I.H. who have worked on forest hydrology for over a decade are impressed at the chance to use hydrometeorological techniques on wetland vegetation.

With the results of these extended investigations, it would be possible to work from simple observations at a given site towards a fuller understanding of the hydrological behaviour of the site with and without active management, and of its relationship with surrounding land. The compendium of numerical techniques envisaged, when matched with the practical steps listed in Section 4.3 and knowledge of specific plant water requirements put the conservationist in a much stronger position than the local drainage officer!

It is proposed that a network of wetland sites, if necessary restricted to Wales, should be instrumented for hydrological monitoring. IH would be responsible for

PLATE 16 Creation of small areas of open water (grading to saturated peat) at Cors Erddreiniog by means of plank (left) and board sluices (right)

site selection, in consultation with NCC, for initial survey and interpretation of the data, and for intensive 'process' studies of peat and of the water relations of wetland plants. The workload of data collection and routine visits could be taken on by NCC wardens, resulting in considerable savings in travel and expense.

There is also a need to continue with the recording network at Corsydd Eddreiniog and Goch. Rainfall, open water levels and borehole water levels observed monthly will be sufficient for the detection of major natural or artificial influences on fen hydrology (including those of management). To accompany a major management initiative on the whole basin such a small network of instruments would need to be made more extensive and records taken more intensively.

Finally, the greatest single scientific contribution which NCC could make to the drive for active management of wetlands would be topographic survey, which is the basis for all hydrological interpretation of the site, its past history and present trends, and is essential for planned management. This is a task for which NCC is admirably well-equipped, and nowhere is the survey team more needed than on wetlands.

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APPENDIX I

STRATIGRAPHY OF THE ANGLESEY FENS

Cors Erddreiniog - Cefn Du transect

Station	Stratigraphy	Horizontal distance from base peg
Core 1	0.45 m peat Limestone or hard tufa	16 m
Core 2	Peaty loam too hard for corer	42 m
Core 3	2.00 m peat Bedrock	77 m
Core 31	2.00 m peat Bedrock	92 m
Core 4	0.20 m peat 0.30 m silt with shells Further penetration impossible.	143 m
Core 32	3.17 m peat and tufa 0.16 m peat with wood 0.17 m white marl 0.15 m peaty marl 0.15 m white marl Bedrock	167 m
Core 5	3.25 m peat and tufa or marl 0.75 m white marl 0.40 m peaty marl Bedrock	193 m
Core 6	0.10 m peat 0.10 m liver-coloured clay 1.15 m peat 0.80 m peaty marl 1.15 m peat 0.40 m grey clay Bedrock	261 m
Core 33	0.10 m peat 0.10 m liver-coloured clay 0.80 m peat 0.10 m grey silt 0.10 m yellowish-grey silt Bedrock	318 m
Core 7	0.20 m peat 0.10 m liver-coloured clay 1.20 m peat 0.10 m silt (weathered gritstone) Bedrock	356 m
Core 34	3.25 m peat 0.65 m cream marl 0.05 m grey silt 1.50 m grey clay, becoming pinkish in lowest 0.12 m Bedrock	413 m

Station	Stratigraphy	Horizontal distance from base peg
Core 8	3.00 m peat 0.05 m peaty marl 1.45 m cream marl 0.50 m marl, grading from cream to dark grey, with 15 mm white band at 250 mm 1.00 m grey clay Did not reach bedrock	476 m
Core 9	2.00 m peat 0.25 m cream marl 0.70 m grey clay with silty bands 0.05 m pinkish-grey clay Bedrock	530 m
Core 10	0.15 m peat 0.08 m grey clay with pink bands Weathered gritstone	566 m
Core 11	Less than 0.2 m peaty soil	621 m
Core 12	0.10 m peat 0.20 m orange-grey clay Bedrock	664 m
Core 13	2.30 m peat with wood 0.10 m peaty marl 0.35 m white marl Bedrock	722 m
Core 14	2.30 m peat 0.25 m dark grey silt 1.20 m white marl 0.25 m marl grading from white to grey 0.50 m grey clay banded with dark grey Bedrock	771 m
Core 15	2.40 m peat 0.10 m peaty marl 2.00 m cream marl 0.50 m marl grading from cream to grey	803 m
Core 16	3.40 m peat with wood below 1 m 1.40 m cream marl 0.20 m grey clay	893 m

Cors Erddreiniog - Rallt transect

Station	Stratigraphy	Horizontal distance from base peg
Borehole (11)	0.14 m peat	39 m
	1.16 m peaty tufa	
	0.50 m tufa becoming too hard to penetrate	
Borehole (12)	0.18 m peat	99 m
	0.16 m peat and tufa	
	3.01 m peat	
	1.40 m cream marl	
	0.25 m silt	
Core 35	0.60 m peat and tufa	177 m
	1.80 m peat	
	3.10 m cream marl	
	0.50 m marl grading from cream to greenish	
	0.50 m marl grading from greenish to greenish-grey	
	0.50 m transition from greenish-grey marl to dark grey silt	
	0.80 m stiff dark grey silt	
Core 52	2.20 m cream marl with shells and tufaceous fragments	196 m
	4.50 m brown marl	
	1.50 m greenish silty marl	
Core 17	3.10 m peat	269 m
	4.90 m white marl becoming stiffer with depth	
Core 36	3.90 m peat	319 m
	0.05 m peaty marl	
	0.55 m cream marl	
	0.50 m marl grading from cream to greenish	
	0.50 m marl grading from greenish to dark grey (silt) at base	
	1.35 m very dark grey silt	
	Too stiff to penetrate further	
Core 18	3.45 m peat	369 m
	0.05 m peaty marl	
	0.60 m cream marl	
	0.25 m grey silt with fibrous remains	
	0.25 m grey clay	
	Bedrock	
Core 37	2.20 m peat	429 m
	0.10 m peaty marl	
	0.30 m greenish-cream marl	
	0.05 m grey silt	
	1.20 m grey clay with pinkish tinge	
	Bedrock	

Station	Stratigraphy	Horizontal distance from base peg
Core 38	0.25 m peat 0.25 m greenish-yellow clay	457 m
Core 39	0.60 m peat Bedrock	584 m
Core 40	1.92 m peat 0.05 m peaty marl 0.33 m cream marl 0.005 m dark grey silt 0.695 m pinkish-grey clay Bedrock	633 m
Core 41	2.10 m peat 0.80 m cream marl 0.12 m grey silt 1.50 m grey clay 0.40 m pinkish-grey clay Bedrock	684 m
Core 42	1.95 m peat 0.05 m peaty marl 0.70 m cream marl 0.10 m grey silt 0.20 m pinkish-grey clay 1.00 m grey clay with bright pink band at 0.8 m Bedrock	734 m
Core 43	1.90 m peat, wood at 1.8 m 0.05 m peaty marl 0.65 m cream marl 0.05 m dark grey silt 1.25 m pinkish-grey clay, gritty at base	784 m
Core 44	1.90 m peat 0.45 m cream marl 0.05 m cream marl grading to dark grey silt 0.05 m dark grey silt 0.55 m grey clay 0.40 m pinkish-grey clay	834 m
Core 45	1.30 m peat 0.05 m peaty marl 0.05 m cream marl Bedrock (confirmed by second boring)	884 m
Core 46	1.65 m peat 0.05 m peaty marl 0.65 m cream marl becoming more greenish with depth 0.10 m greenish-grey silt 0.55 m pinkish-grey clay 0.30 m grey clay, lower 0.13 m banded pink and dark grey Bedrock	934 m

Station	Stratigraphy	Horizontal distance from base peg
Core 47	1.35 m peat 0.05 m peaty marl 0.45 m cream marl 0.30 m grey clay, with pink band at 0.20 to 0.25 m Bedrock	985 m
Core 48	1.90 m peat 0.10 m peaty marl 0.50 m greyish-cream marl 0.05 m grey silt 1.75 m pinkish-grey clay, banded at base with dark grey Bedrock	1037 m
Core 49	1.75 m peat 0.05 m peaty marl 0.20 m cream marl 0.35 m greenish-cream marl 0.05 m greenish-grey silt 1.95 m pinkish-grey clay, with bright pink band at 1.65 to 1.75 m	1087 m
Core 50	1.45 m peat 0.05 m peaty marl 0.35 m greenish-cream marl 0.05 m greenish-grey silt 1.85 m pinkish-grey clay, with bright pink band below 1.6 m	1137 m
Core 51	0.50 m ditch spoil 0.70 m peat 0.10 m greenish-grey sil 1.75 m pinkish-grey silty clay 0.15 m pink clay	1192 m

Cors Erddreiniog - Maen Eryr transect

Station	Stratigraphy	Horizontal distance from borehole (11)
Borehole (11)	0.14 m peat 1.16 m peaty tufa 0.50 m tufa becoming too hard to penetrate	0 m
Core 30	0.20 m peat 0.25 m tufa 0.05 m peat 1.50 m tufa with peat 0.70 m peat Too hard to penetrate further	59 m
Borehole (10)	4.25 m peat with wood 0.65 m cream marl 1.30 m grey clay becoming impenetrable	118 m
Core 29	4.42 m peat with wood 0.02 m peaty marl 1.46 m cream marl 0.60 m grey silt, becoming impenetrable	160 m
Borehole (9)	0.45 m peat 0.60 m peat and tufa 0.15 m tufa	198 m
Core 28	0.20 m peaty loam 1.05 m peat and tufa	248 m
Borehole (8)	0.40 m peat 0.50 m peat with tufa 0.10 m tufa 0.40 m peat with tufa 3.15 m peat 1.45 m cream marl 0.50 m marl grading from cream to grey 0.50 m grey silt becoming impenetrable	303 m
Core 27	3.45 m peat with wood 0.05 m peaty marl 0.60 m cream marl with shells 1.65 m grey silt 0.25 m pinkish-grey clay 0.50 m grey clay 1.50 m pinkish-grey clay	364 m
Core 26	3.73 m peat 0.77 m cream marl 0.60 m greyish-cream marl 1.90 m pinkish-grey clay 0.50 m grey clay becoming pink at base 1.50 m grey clay Bedrock	421 m

Station	Stratigraphy	Horizontal distance from Borehole (11)
Borehole (7)	3.64 m peat with wood	482 m
	0.94 m cream marl	
	0.42 m grey clay	
	2.00 m pinkish-grey clay	
	0.70 m dark grey clay	
	Bedrock	
Core 25	3.27 m peat with wood	533 m
	0.02 m peaty marl	
	0.45 m cream marl	
	0.06 m grey silt	
	0.33 m cream marl	
	1.37 m pinkish-grey clay	
	0.15 m grey clay	
	Bedrock	
Core 24	2.95 m peat	587 m
	0.02 m peaty marl	
	0.03 m cream marl with shells	
	0.62 m greyish-cream marl	
	0.88 m pinkish-grey clay	
	0.50 m dark grey clay	
	Bedrock	
Core 23	2.85 m peat	647 m
	0.04 m peaty marl	
	0.11 m cream marl	
	1.15 m grey clay	
	Bedrock	
Borehole (6)	2.63 m peat	707 m
	0.14 m greyish-cream marl	
	0.06 m yellowish fibrous material	
	0.11 m yellow-grey fibrous marl	
	0.56 m grey clay	
	0.50 m pinkish-grey clay	
	0.25 m grey clay	
	Bedrock	
Core 22	2.75 m peat	757 m
	0.12 m peaty marl	
	0.22 m cream marl	
	2.05 m grey clay	
	Bedrock	
Core 21	2.72 m peat	815 m
	0.10 m brownish-cream marl	
	0.30 m greyish-cream marl	
	1.93 m grey clay	
	0.05 m pinkish-grey silty clay	
	Bedrock	
Core 20	2.50 m peat	860 m
	0.30 m greyish-cream marl	

Station	Stratigraphy	Horizontal distance from Borehole (11)
Core 19	1.92 m peat 0.08 m grey silt	909 m
Borehole (5)	2.00 m peat 0.25 m cream-buff marl Bedrock	960 m

Cors Goch - long transect

Station	Stratigraphy	Horizontal distance from east wall
Core 2	0.75 m peaty silt 0.10 m grey sand 0.15 m silt banded cream and grey 3.00 m grey clay 1.30 m grey silty clay becoming dark grey at base	19 m
Core 1	0.93 m peat 0.07 m peaty marl 1.00 m cream marl 0.20 m greenish-cream marl 1.80 m grey clay 0.15 m pinkish-grey clay Bedrock	69 m
Borehole (1)	0.90 m peat 0.10 m peaty marl 1.15 m cream marl 0.18 m dark grey silt 0.32 m cream marl becoming greenish grey at base Bedrock	119 m
Core 3	1.3 m peat 0.20 m peaty marl 1.35 m cream marl, becoming greenish at base 0.65 m grey silt 1.00 m cream silt-marl 0.75 m greenish-grey silt 1.65 m dark grey clay with pinkish banding Bedrock	169 m
Core 4	1.45 m peat 0.05 m peaty marl 0.30 m greenish-grey marl 0.40 m dark peaty marl with shells 1.60 m detritus mud 2.60 m shelly detritus mud 0.35 m greenish-grey silt 1.75 m pinkish-grey clay with dark grey bands 0.10 m grey clay Bedrock	219 m
Core 5	1.50 m peat 0.50 m detritus mud 0.70 m shelly detritus mud 3.80 m detritus mud 0.60 m shelly detritus mud 0.10 m greenish-grey silt	249 m

Core 5 (Contd)	1.10 m pinkish-grey clay with dark grey bands	
	Bedrock	
Core 6	2.00 m peat	252 m (off transect)
	0.20 m detritus mud	
	0.50 m shelly detritus mud	
	1.55 m detritus mud	
	1.55 m shelly detritus mud	
	0.45 m greenish-grey silt	
	0.75 m greyish-cream marl	
	0.10 m greenish-grey silt	
	0.90 m pinkish-grey clay with dark grey bands	
Borehole (2)	3.50 m peat	307 m
	4.50 m detritus mud	
Core 7	1.80 m peat	357 m
	0.90 m shelly detritus mud	
	6.60 m detritus mud	
	0.20 m greenish-grey silt with high organic content	
Core 8	2.00 m peat with wood	407 m
	0.05 m peaty marl	
	0.45 m shelly cream marl	
	0.55 m greenish-cream marl	
	0.25 m tough greenish-grey silt	
	1.60 m greenish-cream marl	
	0.10 m dark grey silt	
	1.25 m grey clay with dark grey laminations	
	0.15 m pinkish-grey clay	
	Bedrock	
Core 9	0.95 m peat	457 m
	0.55 m shelly cream marl	
	0.50 m cream marl grading to greenish and more silty	
	0.50 m laminated cream marl	
	0.60 m greenish-cream marl	
	1.85 m grey silty clay	
	0.17 m pinkish grey clay	
	Bedrock	
Borehole (3)	1.20 m peat	511 m
	0.92 m cream marl	
	0.18 greenish-grey silt	
	0.20 m cream laminated marl	
	1.00 m greenish-cream laminated marl	
	2.15 m grey clay	
	0.15 m plastic grey clay	
	Bedrock	
Core 10	0.70 m peat	531 m
	0.90 m cream marl	

Core 10 (Contd)	1.40 m grey clay 0.20 m pinkish-grey clay Bedrock	
Core 11	0.50 m peat 0.50 m cream marl becoming greenish towards base 1.00 m grey clay 0.40 m silty grey clay Bedrock	726 m
Borehole (4)	1.05 m peat 0.05 m peaty marl 0.40 m cream shelly marl 1.05 m marl, laminated buff and grey 0.45 m greenish-grey clay 1.30 m grey clay with dark grey bands 0.10m pinkish-grey clay Bedrock	751 m
Core 12	0.50 m peat 0.05 m peaty marl 0.20 m cream marl with shells 0.60 m cream marl 0.60 m greenish-grey clay 0.05 m pinkish-grey clay Bedrock	801 m
Core 13	1.70 m peat 0.30 m shelly cream marl 0.60 m cream marl 0.12 m dark brownish-grey silty marl 0.28 m cream marl 0.93 m greenish-cream laminated marl 1.42 m grey clay with dark grey bands 0.10 m dark grey clay 0.05 m pinkish-grey clay Bedrock	851 m
Borehole (5)	1.35 m peat 0.10 m peaty marl 0.35 m cream marl 1.00 m greenish-brown marl 0.05 m cream marl 0.25 m grey clay 1.00 m pinkish-grey clay 0.20 m dark grey clay Bedrock	905 m
Core 14	0.35 m peat 0.05 m peaty marl 0.45 m cream marl 0.10 m dark brown marl with plant remains 0.75 m grey clay 0.25 m plastic grey clay Bedrock	935 m

Core 17	1.30 m peat 0.20 m peaty marl 0.40 m greenish-cream marl 0.08 m dark greenish-grey silt 0.47 m cream marl laminated cream to brownish-green 0.05 m blue-grey silty clay 0.50 m greenish-grey clay 0.60 m laminated grey clay 0.15 m plastic grey clay Bedrock	1073 m
Core 18	1.80 m peat 0.10 m peaty marl 0.60 m cream marl 0.40 m stiff brownish-green silt/marl 0.60 m cream marl 0.55 m marl grading from greenish-cream to grey 1.03 m grey clay Bedrock	1103 m
Borehole (6)	1.55 m peat 0.05 m peaty marl 0.80 m cream marl with laminations varying from brownish-grey to grey 0.45 m stiff greenish-brown silt 1.10 m cream laminated marl 0.55 m grey clay 0.25 m grey clay with dark grey bands Bedrock	1131 m
Core 19	0.75 m peat 1.00 m detritus mud Bedrock	1249 m
Core 20	0.50 m peat 2.85 m detritus mud 0.15 m shelly detritus mud 0.20 m silty detritus mud Bedrock	1252 m
Core 21	0.70 m peat 2.80 m cream marl 1.90 m brownish-cream marl 0.15 m greenish-grey silt Bedrock	1254 m
Core 22	0.55 m peat 2.20 m brownish-cream marl 2.00 m cream marl 0.75 m stiff brown silt/marl To stiff to penetrate further	1256 m
Core 23	0.50 m unhumidified *Cladium* remains 1.85 m marly detritus mud	1386 m

Core 23 (Contd)	4.00 m brownish-cream marl with shells 0.40 m dark grey silt/marl 0.50 m stiff detritus mud with shells 0.05 m dark brown silt/marl 0.20 m brownish-cream marl 0.25 m very dark grey silt 0.40 m stiff brown detritus mud Too stiff to penetrate further	
Borehole (7)	0.10 m peat 0.10 m shelly marl 2.30 m peat with wood 0.55 m shelly detritus mud 1.02 m cream marl 0.05 m greenish-grey silt 1.48 m pinkish-grey clay 0.30 m grey clay Bedrock	1409 m
Core 24	1.00 m peat 0.55 m cream marl 0.05 m dark grey silt 1.10 m pinkish grey clay with dark grey bands 0.45 m plastic grey clay 0.10 m silty grey clay Bedrock	1429 m

APPENDIX II

SUMMARY OF BOREHOLE WATER LEVEL DATA

(Tables 4(a) and 4(b))

TABLE 4(a) MEAN WATER LEVELS IN WEEKLY READ BOREHOLES

ERDDREINIOG

	0	1	1a	2	2a	3	3a	5	6	7	8	9	10	11	12	13	14	15	16
Summer 1979	-	-100	-	-191		-318	-	-141	-102	-226	189	-503	-143	-351	-77	-	-	-	-
(RAINFALL 411)																			
Summer 1980	-183	-71	-70	-139	-414	-315	290	-174	-132	-253	-306	-580	-189	-385	-119	-345	-171	-195	-427
(RAINFALL 331)																			
Summer 1981	-91	-77	-35	-113	-382	-309	-299	(-11)	(-2)	(-148)	-248	-511	-142	-314	-84	-320	-71	-87	-245
(RAINFALL 568)																			
Summer Mean	137	83	53	148	398	314	295	158	117	240	248	531	158	350	93	333	121	141	336
Winter 1979-80		+6		-28		-121		+9	+4	-120	-61	-313	-110	-348	-26				
(RAINFALL 780)																			
Winter 1980-81	-58	+19	+55	-17	-253	-129	-154	-18	+18	-109	-65	-291	-108	-327	-14	-143	+18	+77	-23
(RAINFALL 814)																			
Winter Mean	58	+13	55	23	253	125	154	4	+11	115	-63	302	109	338	20	14	+18	+77	-23
Annual Mean	98	-35	+1	86	-326	-220	-225	-81	-53	178	156	417	134	344	57	238	-52	-32	-157

GOCH

	1	1a	1b	2	3	5	6	7
Summer 1979	-12	-	-	+275	-129	+107	-318	-193
(RAINFALL 401)								
Summer 1980	-35	-25	-464	+248	-105	+81	-328	-221
(RAINFALL 360)								
Summer 1981	(-2)	(-8)	(-453)	(+270)	(-87)	(+146)	(-250)	(-181)
(RAINFALL 647)								
Summer mean	16	17	459	+264	107	-111	299	198
Winter 1979-80	+36			+321	-25	+321	-141	+2
(RAINFALL 671)								
Winter 1980-81	+38	+38	-379	+295	-29	+293	-150	-38
(RAINFALL 707)								
Winter Mean	+37	+38	-379	+308	-27	+307	146	-18
Annual Mean	+10	+10	419	+286	67	+209	223	108

TABLE 4(b) RANGE OF WATER LEVELS IN WEEKLY READ BOREHOLES (mm)

ERDDREINIOG

	0	1	1a	2	2a	3	3a	5	6	7	8	9	10	11	12	13	14	15	16
Summer 1979		330		458		663		762	387	399	558	486	254	408	496				
Summer 1980	274	223	261	260	315	348	287	378	281	273	437	340	202	87	307	335	481	539	634
Summer 1981	394	326	341	304	412	543	410	(105)	(99)	(69)	432	411	124	220	274	438	315	412	685
	334	293	301	341	364	506	349	570	334	336	498	397	193	238	359	387	398	476	660
Winter 1979-80		100		176		273		193	141	172	270	364	118	148	134				
Winter 1980-81	68	54	111	76	266	207	153	52	67	106	139	299	87	173	69	298	157	152	194
	68	77	111	126	266	240	153	123	104	139	205	332	103	161	102	298	257	152	194
Year	201	185	206	234	315	373	251	196	219	238	351	364	148	199	230	368	278	314	427

GOCH

	1	1a	1b	2	3	5	6	7
Summer 1979	178			233	478	300	649	345
Summer 1980	141	161	90	111	226	313	369	283
Summer 1981	74	69	160	90	181	218	251	180
	131	115	125	145	295	277	423	269
Winter 1979-80	75			79	55	312	216	261
Winter 1980-81	76	58	183	71	55	262	119	269
	76	58	183	75	55	287	168	265
	104	87	154	110	175	282	295	267

) only short runs of Spring data