3.5 Peat blanket bogs

Hydrology of blanket bogs

Peat may be deposited in various geographical situations. Blanket bogs typically occur on level or gently sloping hillslope facets with impeded drainage. Water enters the bog area by downslope *discharge*, and excess water may exit to provide downslope *recharge* (Mitsch and Gosselink, 2000).

Figure 3.184: Hillslope water flows within a blanket bog, after Mitsch and Gosselink (2000)

Peat deposits may be classified as ***acrotelm*** which is poorly decomposed plant material, and ***catotelm*** which is highly decomposed humified peat. Typically, a layer of younger acrotelm will overlie older catotelm.

The relative extents of vertical and horizontal water movement within a blanket bog depend largely on bedrock permeability. Reeve, Siegel and Glaser (2000) identify two contrasting flow models:

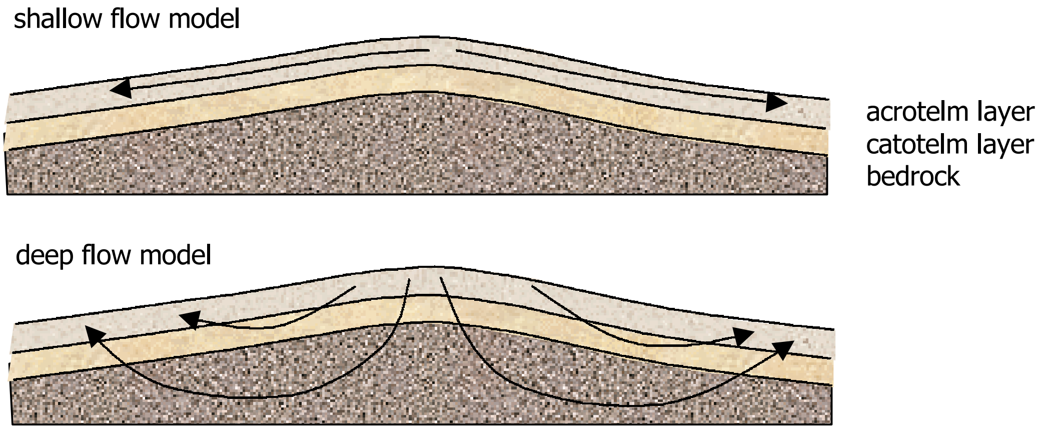


Figure 3.185: Models for water flow within a blanket bog, after Reeve, Siegel and Glaser (2000)

- In the deep flow model, the blanket bog is developed on a substrate with a higher hydraulic conductivity than the peat, for example (peri)glacial sands. Groundwater circulation cells penetrate into the underlying deposits.
- For the shallow flow model, the blanket bog is developed on a bedrock with low hydraulic conductivity. Typically the catotelm layer becomes saturated with almost immobile water, and significant lateral flow is restricted to the surface acrotelm layer.

In modelling experiments, Reeve, Siegel and Glaser have demonstrated that irregularities on the peat surface can produce local areas of water resurgence. This type of spring or seepage is commonly observed within large areas of blanket bog:

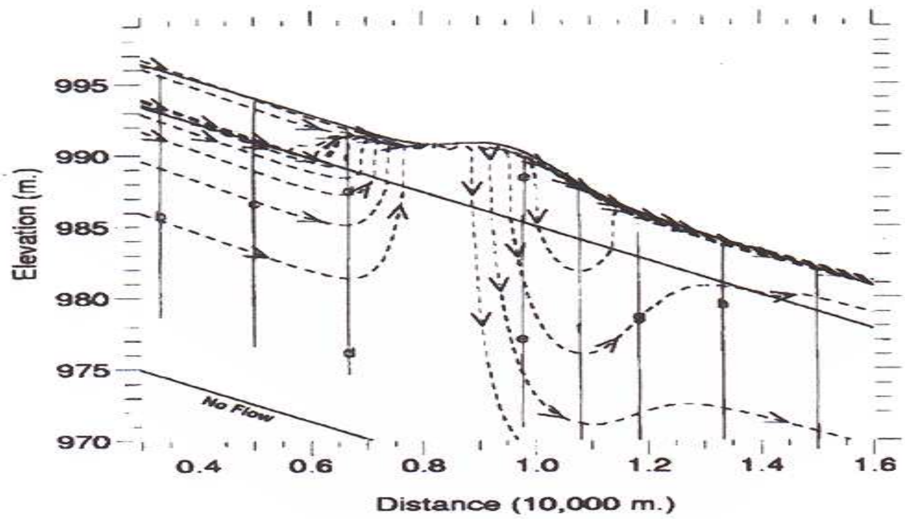


Figure 3.186: Model showing water flow pathways around a spring seepage area associated with a localised peat dome, after Reeve, Siegel and Glaser (2000).

Holden and Burt, (2003b) made a study of three peat blanket bogs in the Northern Pennines, occupying areas between 0.5km^2 and 11km^2. All had similar flash flood characteristics, producing storm discharge peaks between 2 and 3 hours after a rainfall maximum. Experiments were carried out to determine the relative importance of surface runoff and deep flows within the peat. It was found that approximately 80% of storm outflow occurs through a saturation excess overland flow mechanism. An additional 18% of storm flow occurs within the top 5cm layer of the peat, irrespective of the total thickness of the underlying peat. These results are consistent with the shallow flow model of Reeve, Siegel and Glaser.

During dry periods, the water level within a blanket bog would be expected to fall as a result of stream drainage. The pattern of the recession hydrograph will depend on the depth of penetration of the outlet streams into the normally saturated catotelm layers of the peat (Todd , 1980):

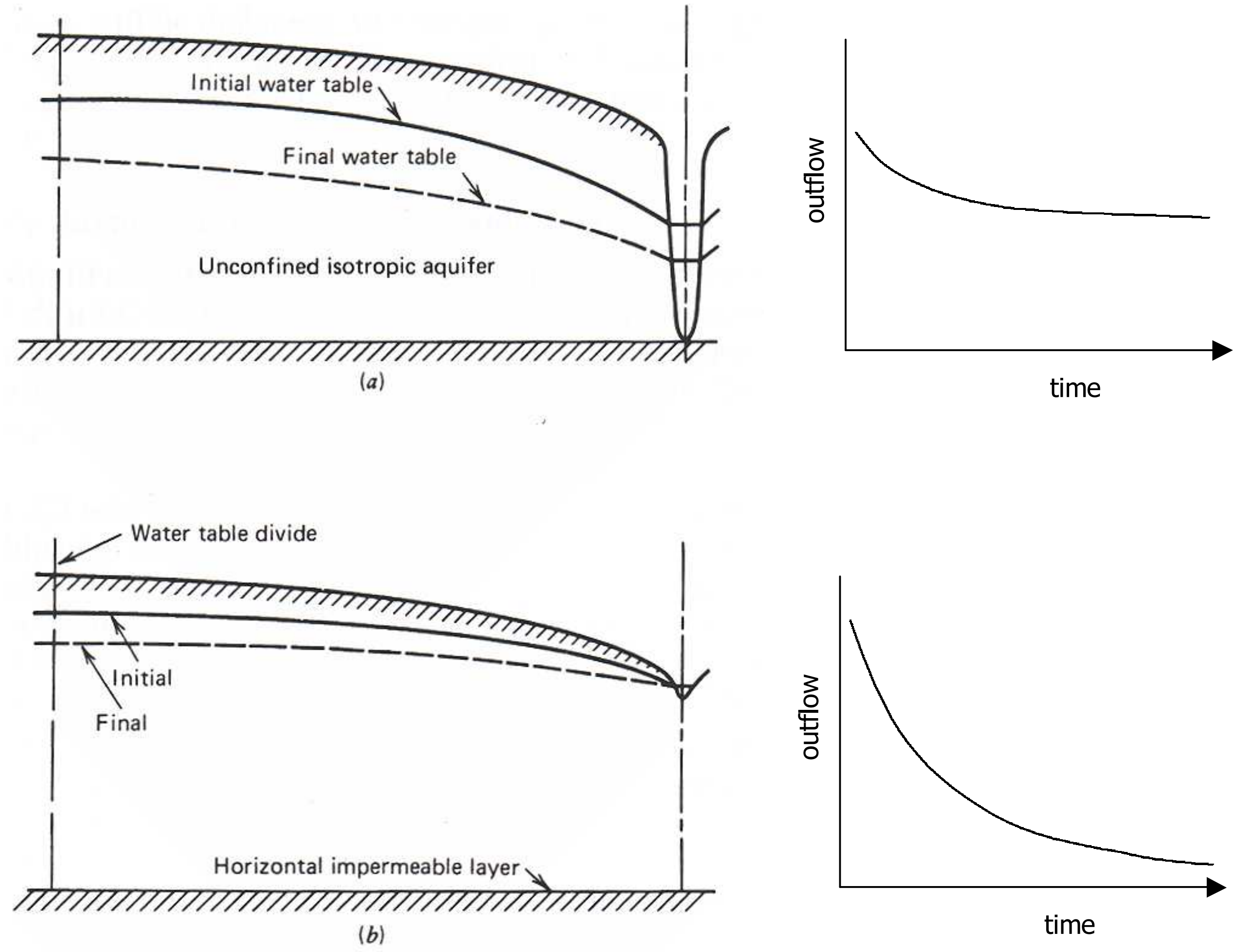


Figure 3.187: Models for stream penetration depth and outflow hydrograph patterns.

- Where streams are deeply incised into the catotelm peat (fig.3.187a), outlet stream flow can remain almost constant during long periods without rainfall. The limiting factor for stream flow is the low hydraulic conductivity of the humified peat.
- Where streams incision is shallow (fig.3.187b), outlet stream flow declines exponentially after rainfall. The limiting factor for stream flow is the volume of temporary water storage within the unhumified acrotelm peat.

Physical downcutting of streams may not be necessary for the deep penetration model to apply. Langhoff, Rasmussen and Christensen (2006) have made a study of stream flows in peat fenlands in north Denmark, where water flow can remain almost constant for long periods after rainfall. Experiments show that 50% of water entering the drains is moving upwards into the streambed from deeper peat layers. In this location unhumified acrotelm peat extends to considerable depth, and is underlain by glacial sands which can encourage deep groundwater circulation patterns.

On the surface of a blanket bog, evapotranspiration may cause significant water loss, particularly during dry summer months. The extent of this loss may be estimated by analysis of diurnal water table fluctuations, as in fig.3.188:

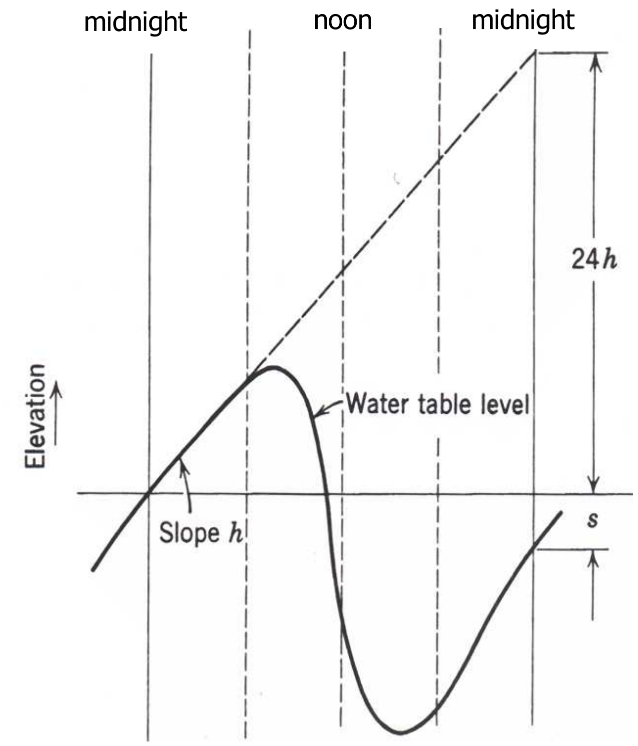


Figure 3.188: Features of a water table graph used in the estimation of evapotranspiration rate, after Todd (1980).

Evapotranspiration rate ET is estimated from:

$$ET = S_y(24h \pm s)$$

where:

S_y specific yield of the aquifer, which is approximately 1.0 for saturated peat.

h hourly rise in water level from midnight to 4am, when evapotranspiration is assumed to be zero.

s net change in water table level over the 1 day period .

Care needs to be taken when applying standard groundwater models to peat blanket bogs. According to Darcy's law, a constant hydraulic conductivity value can be assigned to porous geological materials such as sandstone. However, Ingram, Rycroft and Williams (1974) have shown that the hydraulic conductivity of a humified peat deposit may be variable. Experiments were carried out in which open tubes were inserted into catotelm peat, and an initial water level difference created between the tube and the surrounding peat. Tests were carried out with both an elevated water level in the tube (*depletion* experiment) or with a depressed water level in the tube (*recharge* experiment). Variants of the experiments either allowed the water levels in the peat and tube to equilibrate naturally, or maintained the initial head difference by adding or removing tube water. Results are presented in fig.3.189:

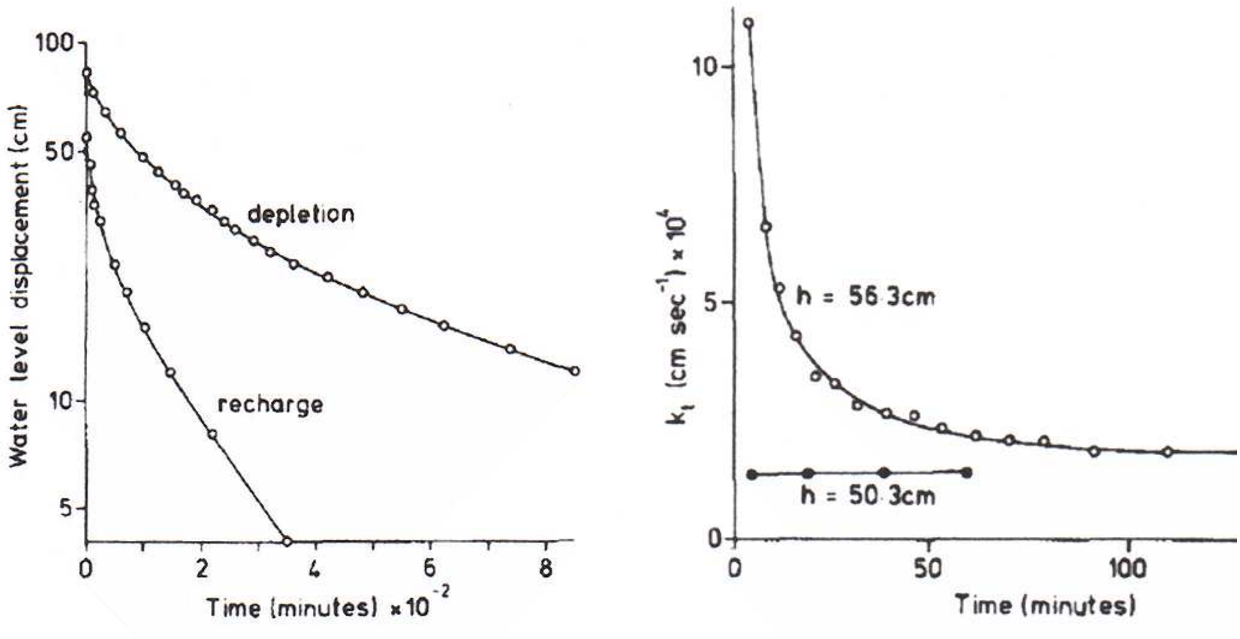


Figure 3.189: Peat hydraulic conductivity experiments by Ingram et al. (1974).
Left: water levels allowed to equilibrate.
Right: initial water level difference maintained.

It was found that in both sets of experiments that conductivities are initially high, but decline over a period of time to a limiting low value. The practical effects of this observation are that humified peats will saturate more rapidly than expected at the start of a rainfall event, but subsequently exhibit low permeability which can be correctly modelled by Darcy's equation.

Holden and Burt (2003a) have measured hydraulic conductivities in upland blanket peat from experimental sites in the Pennines. They have found that peat is a much more variable material than mineral soils, and large and unexpected lateral and vertical variations in hydraulic conductivity can occur over short distances. The general expectation that conductivity will decrease with depth is not born out by field evidence.

Blanket peat in the Mawddach catchment

Peat blanket bogs occur in a number of areas of the Mawddach catchment. Thick organic soil horizons are developed, which are saturated for a large proportion of the year. Acid anaerobic conditions prevent breakdown of plant materials.

Ince (1983) uses evidence from the pollen profiles of lake sediments in Snowdonia to outline the sequence of vegetation changes since the last ice retreat 10 000 years before the present. Initial grassland communities gave way to Juniper and Beech woodlands, and then to Birch, Oak, Elm and Alder woodlands in the uplands of North Wales. At the same time, increased precipitation led to soil leaching and acidification. Blanket bogs were able to develop where conditions of high water inflow combined with gentle slopes and impeded drainage on an impermeable substrate.

The most favourable sites for blanket bogs in the Mawddach catchment are the broad flat floors of glacial basins, where clay till impedes percolation to bedrock and waterflows are concentrated by convergent hillslopes.

Blanket bog development occurs:

- in the east-facing glacial basins below the Rhinog mountain range,
- on the flat floor of the Trawsfynydd plateau, in the area of dispersed drainage to the south of Trawsfynydd reservoir,
- on the north-facing slopes of the Aran mountains above the Wnion valley,
- on gently sloping mountain slopes and glacial basins to the south of the Arennig mountains.

Wetland habitats appear to be particularly sensitive to climate change. Bellamy (1986) documents a sequence of changes affecting the Irish boglands. Modification of the natural vegetation zones of blanket bogs may in turn lead to a change in hydrological characteristics, affecting flood generation downstream. Blanket bogs may consequently play an important role in flood management for the Afon Mawddach.

Two example areas of peat blanket bog have been investigated as part of the Mawddach study:

- Waen y Griafolen, in the source area of the Afon Mawddach, covering a plateau basin of approximately 6 km^2 in the Arennig mountains. This site has been designated a Special Area of Conservation due to the variety of wetland plants and fauna supporting Hen Harriers at the highest predator level.
  Field work was carried out at Waen y Griafolen in conjunction with the MSc Water Resources project of Feysal Awissa, Bangor University (Awissa, 2003), and has been followed up by computer modelling. Results are discussed later in this chapter.
- Cefn Clawdd, to the east of Moel Ysgyfarnagod in the Rhinog mountain range where extensive blanket peat is developed on a gently sloping glacial clay substrate in a broad open valley. Field work was carried out to measure water levels in the peat during 2003 using a borehole water depth recorder and data logger.

Figure 3.190: Valley of Cefn Clawdd, with the Rhinog escarpment in the background.

Cefn Clawdd peat blanket bog

Cefn Clawdd is typical of a series of eastwards-facing glacial basins developed in the Rhinog escarpment between Trawsfynydd and Ganllwyd. Cefn Clawdd is floored by a clean cream clay with the characteristics of a lake floor deposit. It is possible that this material was deposited in a lateral lake at a time that the Trawsfynydd plateau was occupied by slowly moving sheet ice. The low permeability of the clay, combined with a gently valley slope, has led to the development of a number of areas of deep blanket peat, with thinner peat soils covering much of the remainder of the basin.

Figure 3.191: Humified peat (1.4m) overlying cream clay with water-rounded pebbles, Cefn Clawdd.

A water depth recorder was operated in a borehole at Waen Fach for a period of three months during 2003. A section of the record is given in fig.3.192. This shows:

- Diurnal water table oscillations of approximately 10cm in response to evapotranspiration and recharge,
- Rapid water table rise by 60cm in a 3 hour period following rainfall of 24mm on 1 April 2003,
- Slow decline of the water table by 40cm in the subsequent 5 dry days.

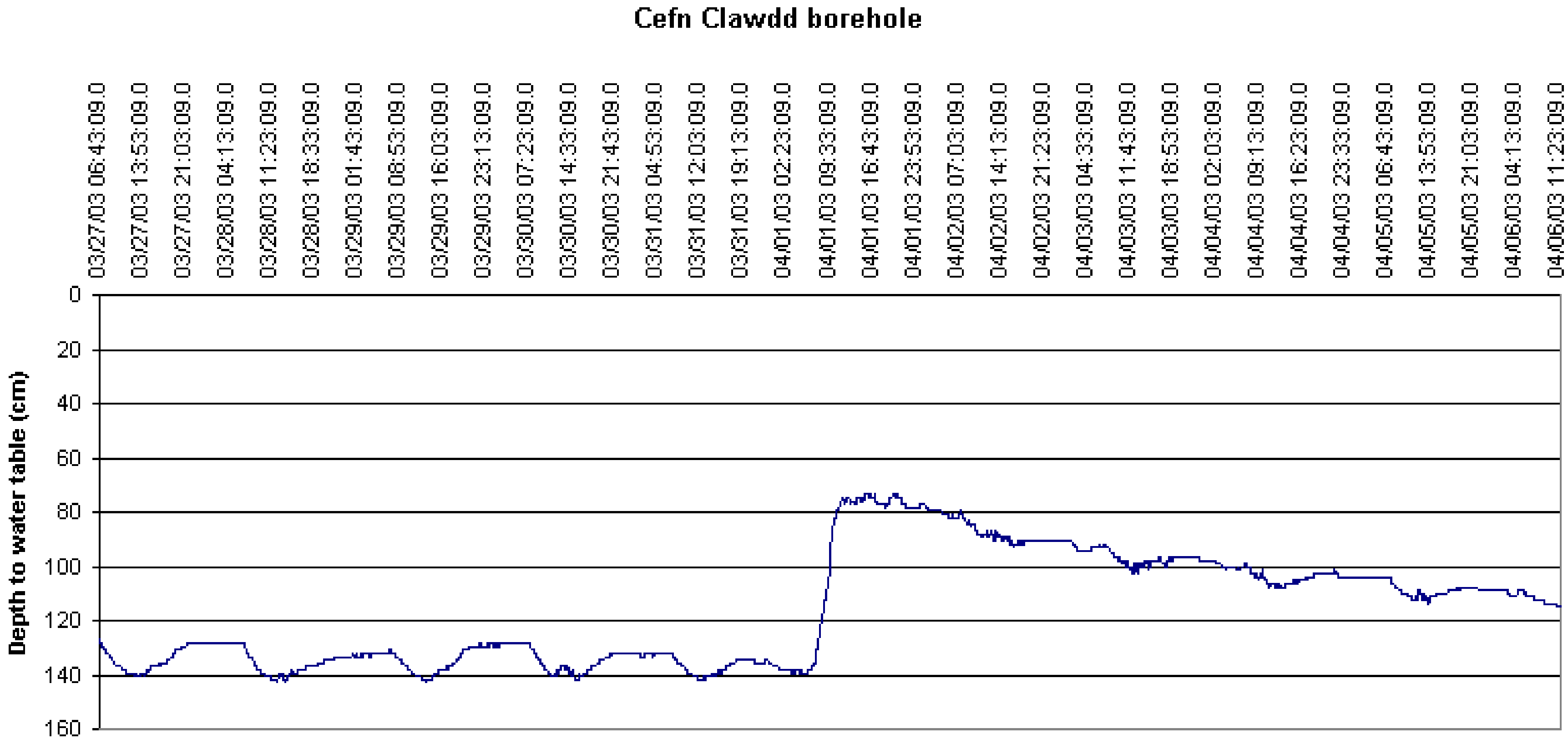


Figure 3.192: Example bore hole record for Cefn Clawdd, 27 March – 6 April 2003

Waen y Griafolen case study

Stratigraphy

Prior to undertaking hydrological modelling, surveys were carried out to determine the stratigraphy of the Waen y Griafolen blanket bog. It was found that a complex sequence of deposits are present, reflecting a number of stages of development from early post-glacial times up to the present day. A stratigraphic interpretation is presented in fig.3.195, based on evidence discussed in the paragraphs below:

Underlying bedrock

The plateau basin of Waen y Griafolen is largely underlain by Upper Ordovician mudstones of the Nant Hir formation, with older Ordovician ignimbrites of the Aran Fawddwy formation forming the mountain ridges which border the basin to the west and east. Nant Hir mudstone is exposed at only one location within the blanket bog, in the bed of an incised river channel (fig.3.193) where it is overlain by glacial till.

Figure 3.193: Ordovician mudstone bedrock exposed beneath glacial till, Waen y Griafolen

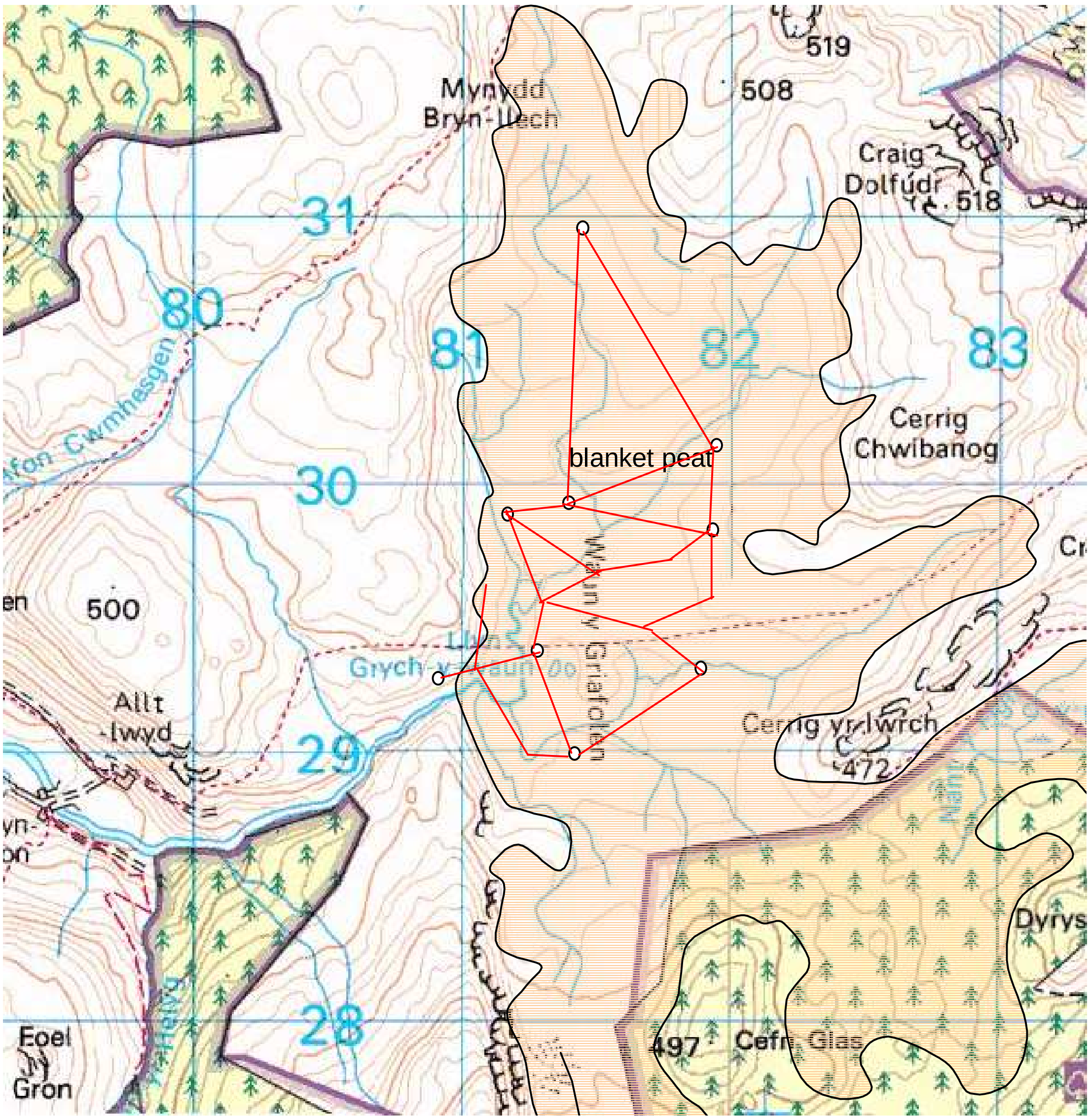


Figure 3.194: Waen y Griafolen, showing the extent of blanket peat. Red lines indicate the positions of the cross sections in fig.3.195.

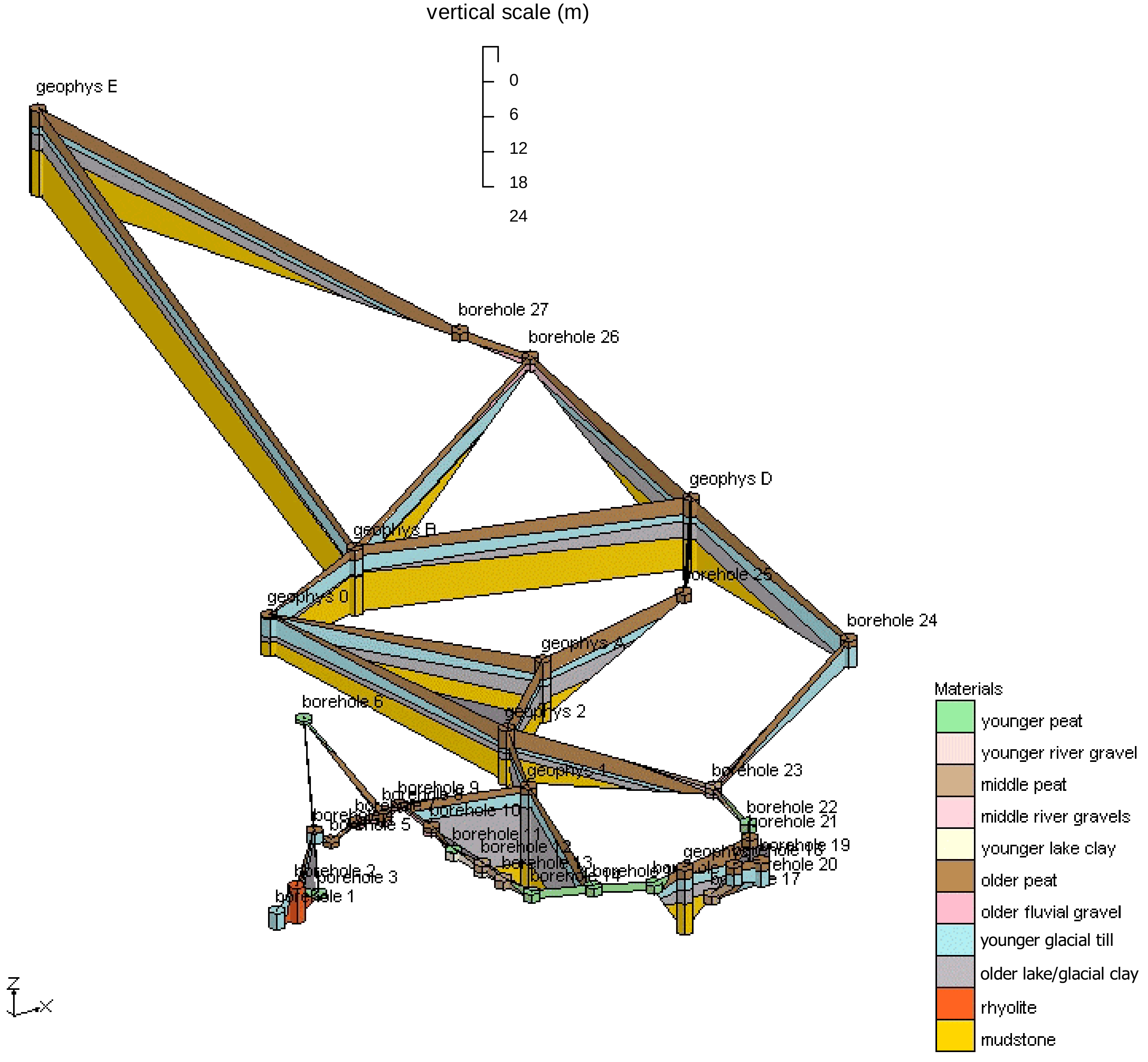


Figure 3.195: Summary of stratigraphic data collected from field surveys,

Waen y Griafolen. Positions of section lines are marked on fig. 3.194.

Geophysical survey

Bedrock and glacial deposits underlying Waen y Griafolen are generally hidden beneath thick peat, so geophysical investigations were carried out to provide evidence of the stratigraphic sequence. A combination of Electromagnetic and Vertical Electrical Sounding techniques were applied at eight sites across the bog, with data analysis carried out by DC RESI software. Example vertical section interpretations are given in fig.3.196.

For all sites, three distinct layers were detected above the Ordovician mudstone, and have been identified as: peat, sandy boulder clay drift, and a lower layer of high clay content - either a lake clay or older glacial drift (Table 3.7).

Layer	Average resistivity (Ωm)	Average thickness (m)
Peat	204.88	2.3
Sandy boulder clay	366.25	2.0
Clay	20.76	3.2
Mudstone	188.00	

Table 3.7. Summary of geophysical observations at Waen y Griafolen

Older peat deposits

Erosion at the western edge of the Waen y Griafolen basin has exposed the base of old humified peat (fig.3.197). At this horizon, a palaeosoil occurs with tree roots in growth position. A wood sample has been dated by Oxford University Radiocarbon Accelerator Unit as 8905 ± 45 years before the reference year AD 1950. This date represents the earliest return of forests to the uplands of western Britain following deglaciation (Bellamy, 1986). The roots are likely to be alder (*Alnus*) which is known to have been present in Ardudwy to the west of the Rhinog mountains at a time of 8700b.p. (Chambers and Price, 1985). At a slightly higher horizon within the peat are found samples of water-transported birch branches. It is conjectured that the Waen y Griafolen blanket bog developed on the site of an extensive shallow lake overgrown by wet woodland. Peat accumulation appears to have continued with little interruption for the past 9000 years, with mosses, heathers and other dwarf shrubs as the principle vegetation.

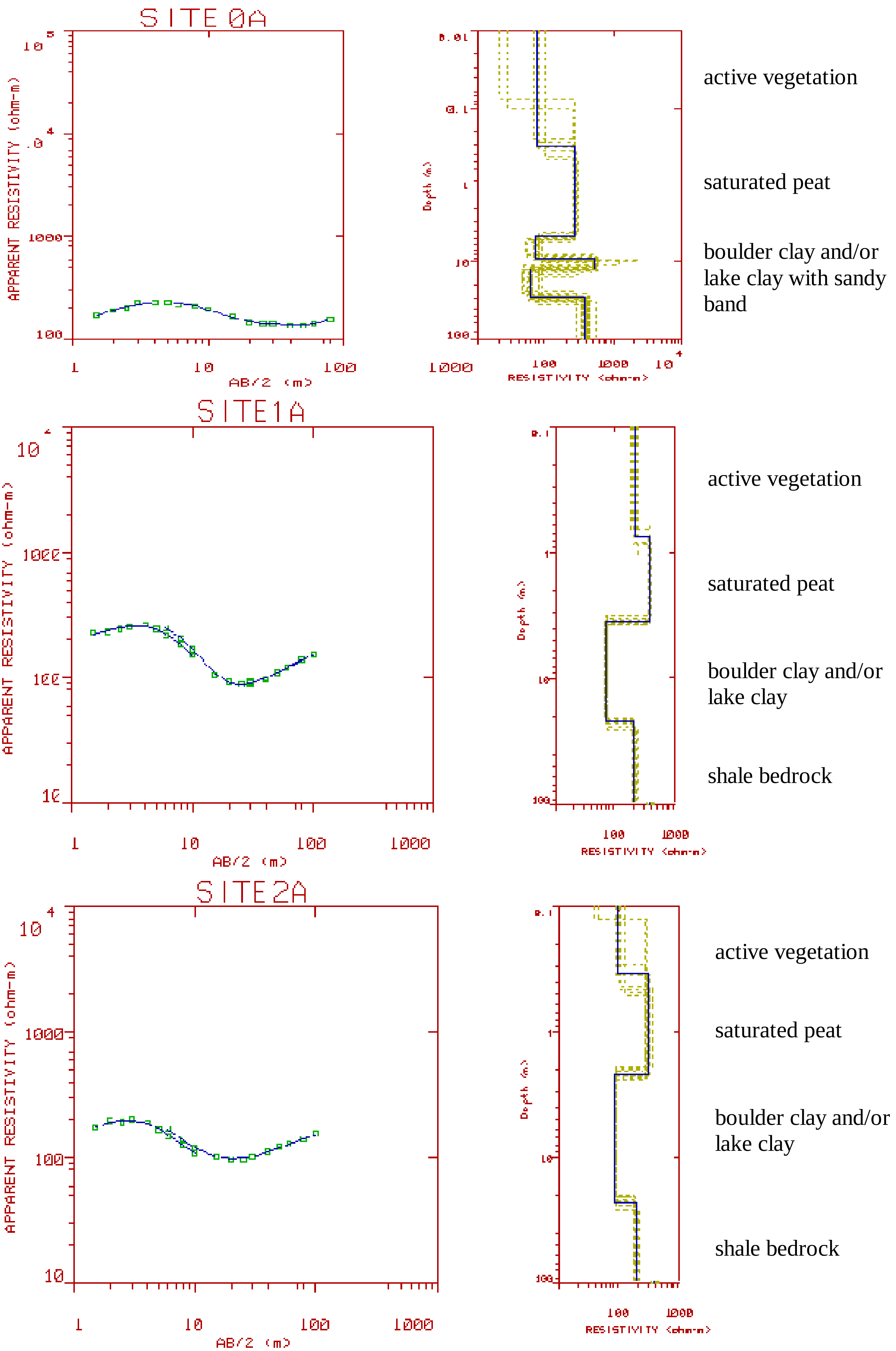


Figure 3.196: Geophysical survey and interpretation of sections

Figure 3.197: Older humified peat experiencing erosion near the plateau basin outlet stream, as a result of drying out in response to a fall in stream base level.

Surface layers of the peat bog

Preliminary inspection of Waen y Griafolen suggested that a complex sequence of superficial deposits may be present. An auger survey was carried out at 30 locations distributed across the bog to identify and determine the distribution of shallower deposits. Samples were obtained to a depth of 1.6m, with the recording of grain size, mineral and plant content of the layers extracted.

Vegetation quadrat surveys were carried out at eight sites representative of different plant communities across Waen y Griafolen. A 1m quadrat frame was placed randomly, and plants within the sample area were identified and percentage cover estimated.

Field surveys were followed up by analysis of colour air photographs, to provide further information about the distribution of vegetation zones, superficial deposits and the pattern of surface drainage.

Channel system and younger peats

Peat with active vegetation growth covers the bog, but horizons of river gravel and lake clay were found beneath peat in some locations, indicative of an earlier and more extensive surface drainage system eroded into the bog surface. The period of erosion represented by the buried river channels and lake bed might be linked to a period of increased rainfall identified across Europe at around 2800 years before the present (Bellamy, 1986). Edwards and Whittington (2001) have identified an increased sediment deposition rate in lakes in Britain and Ireland between 2980 and 2810 B.P. which is consistent with this high rainfall period.

The former river channel system is represented at the present day by meandering valley-like depressions within the surface of the blanket bog (fig.3.198), which increase in width towards the basin outlet. A small misfit stream is often present within the valley depression. Topographic sections were surveyed across three representative channels (fig.3.199).

Figure 3.198:
Relict drainage channels, Waen y Griafolen:

(top) *Juncus* community infilling a former river channel, incised into older peat covered by *Erica* community.

(middle) Area of peat hag erosion which is now actively regenerating .

section 1

section 2

section 3

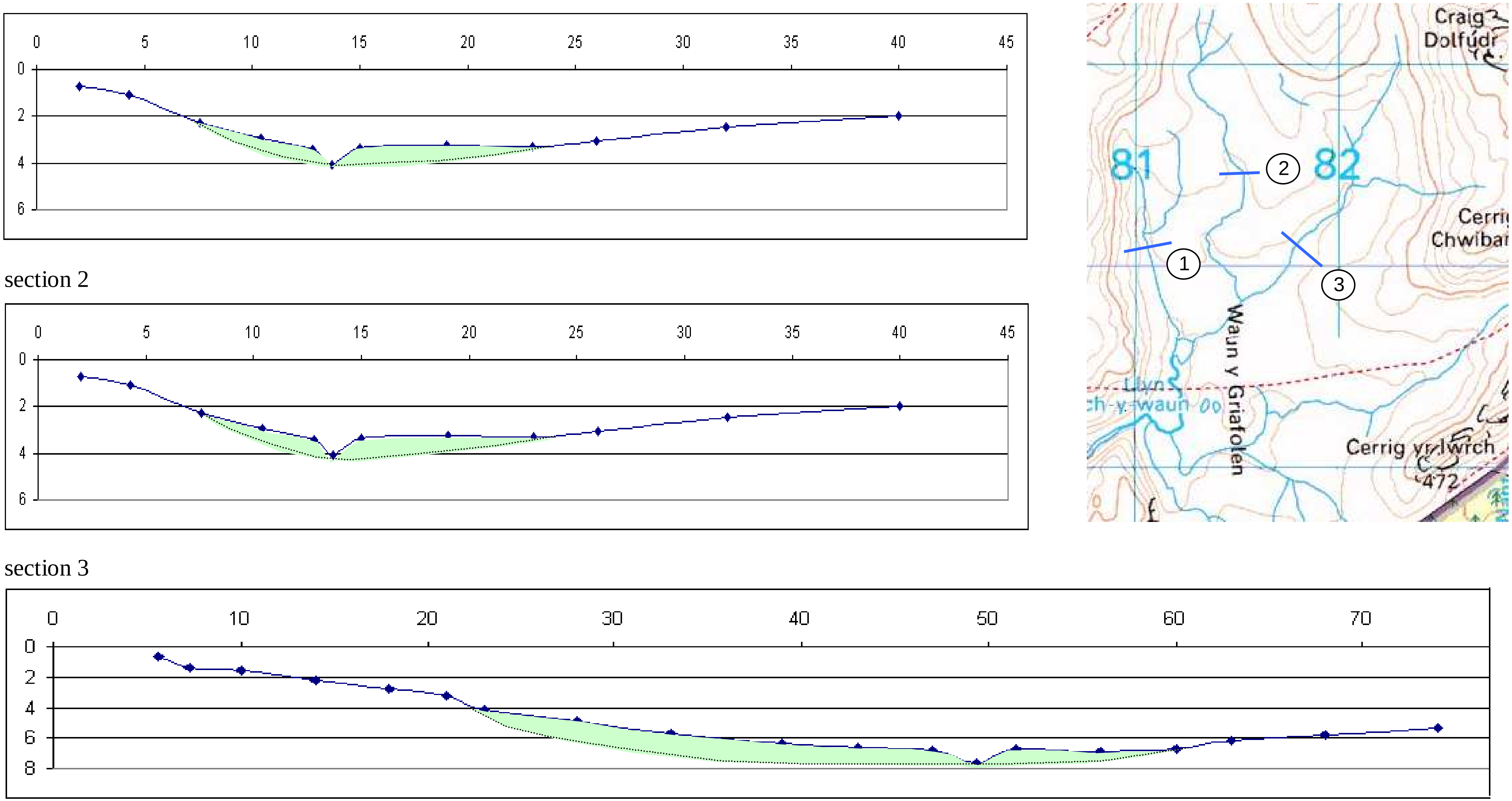


Figure 3.199: Surveyed cross sections of relict drainage channels, Waen y Griafolen.

Estimated extent of young peat infill marked in green. (inset) Location of sections.

Four vegetation communities are prominent within the blanket bog (Table 3.8). The *Erica* community occupies the central area of the blanket bog above older peat, whilst the *Trichophorum* community occurs towards the margins of the older peat area. *Juncus* and *Sphagnum* communities infill former river channels and are sites of development of younger peat.

Community	Dominant species	Subsidiary species
Juncus channel	Juncus effusus, Polytrichum commune, Eriophorum vaginatum	Rhytidiadelphus loreus, Sphagnum subnitens, Nardus stricta
Sphagnum channel	Sphagnum auriculatum, Carex nigra, Eriophorum vaginatum	Juncus effusus, Vaccinium oxycoccus
Erica moor	Erica tetralix, Cladonia portentosa, Trichophorum cespitosum	Vaccinium myrtilis, Sphagnum capillifolium, Empetrum nigrum
Trichophorum moor	Trichophorum cespitosum, Juncus effusus	Eriophorum vaginatum, Nardus stricta

Table 3.8. Vegetation communities within Waen y Griafolen

The surface drainage system of Waen y Griafolen begins as sphagnum pools within the relict channels. Flowing streams develop, and are often incised through the younger peat to the level of the older buried river channels (fig.3.200).

Towards the basin outlet, streams converge to produce larger gravel-bed channels. The present day drainage system largely conforms to the relict channel pattern. Near the basin outlet, a thick deposit of lake clay in excess of 6m thickness was identified by auger and geophysical surveys. This may mark the site of a large lake into which the relict channel system drained, with the small lake of Llyn Crych y Waen now representing a small remnant.

Figure 3.200: Surface drainage within Waen y Griafolen:
(top left) *Sphagnum* moss pool within a relict drainage channel,

(top right) Small misfit stream in a broad relict channel with *Juncus* and younger peat infill,

(bottom) Gravel stream near the basin outlet.

Some modification of drainage pattern on the *Erica* moor areas of the bog occurs as a result of a series of ploughed ditches approximately 0.5m wide and 1m in depth (fig.3.201). These were cut around the middle of the 20th century in an attempt to improve the pasture for sheep. Much of the drainage network is now overgrown, and there is no visible effect of modifying the natural vegetation in comparison to similar unploughed areas of the bog. The drains are generally dry, and probably only carry water at the peak of storms.

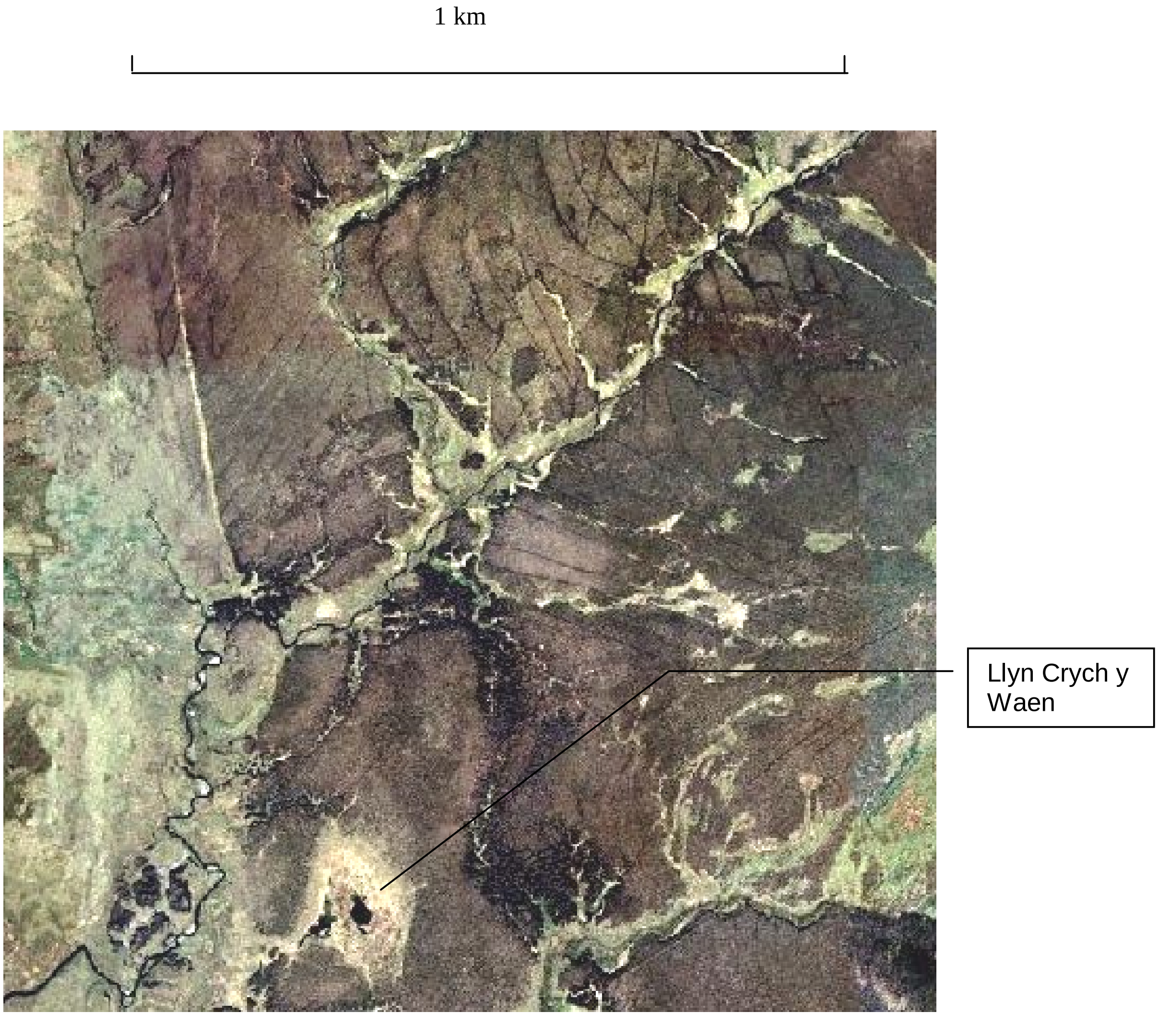


Figure 3.201: Vertical air photograph of the central area of Waen y Griafolen, showing the pattern of ploughed drainage ditches cutting across *Erica* moor on older peat.

A possible sequence of development of the Waen y Griafolen blanket bog can be deduced from field evidence and correlation with events elsewhere in western Britain:

- The Arennig mountains were extensively glaciated during the main Devensian advance, with southwards-moving ice scouring a plateau basin in soft mudstone to form the site of Waen y Griafolen. Glacial till blanketed the basin.
- During the final interglacial period, a lake may first have appeared within the basin. Clay would be carried in from the surrounding slopes to accumulate on the lake bed. Further glacial till was deposited during the late Devensian valley readvance.
- Forest and moorland vegetation returned to upland Wales around 9 000 years B.P. At Waen y Griafolen, the glacial lake gave way to wet woodland dominated by alder and birch.
- Perhaps as a response to colder and wetter conditions, the woodland deteriorated and became a focus for blanket bog development. Accumulation continued slowly over the following 5 000 years, with lower peat layers becoming increasingly compressed and humified.
- At around 2 800 years b.p., a change to a significantly wetter climate caused peat hag erosion and the growth of a dendritic drainage system. Large braided gravel channels were cut into the peat surface, draining into a substantial lake near the basin outlet.
- Reversion to earlier climate conditions caused a reduction in water flows within the channel system and allowed peat growth to resume. Heathers dominated on the drier surface of the old peat. The wetter valleys were colonised by mosses, rushes and sedges, with gravel channels progressively buried by younger peat. This peat is continuing to accumulate at the present day, appearing as a poorly decomposed mass of plant material with a more open texture than the older humified peat.

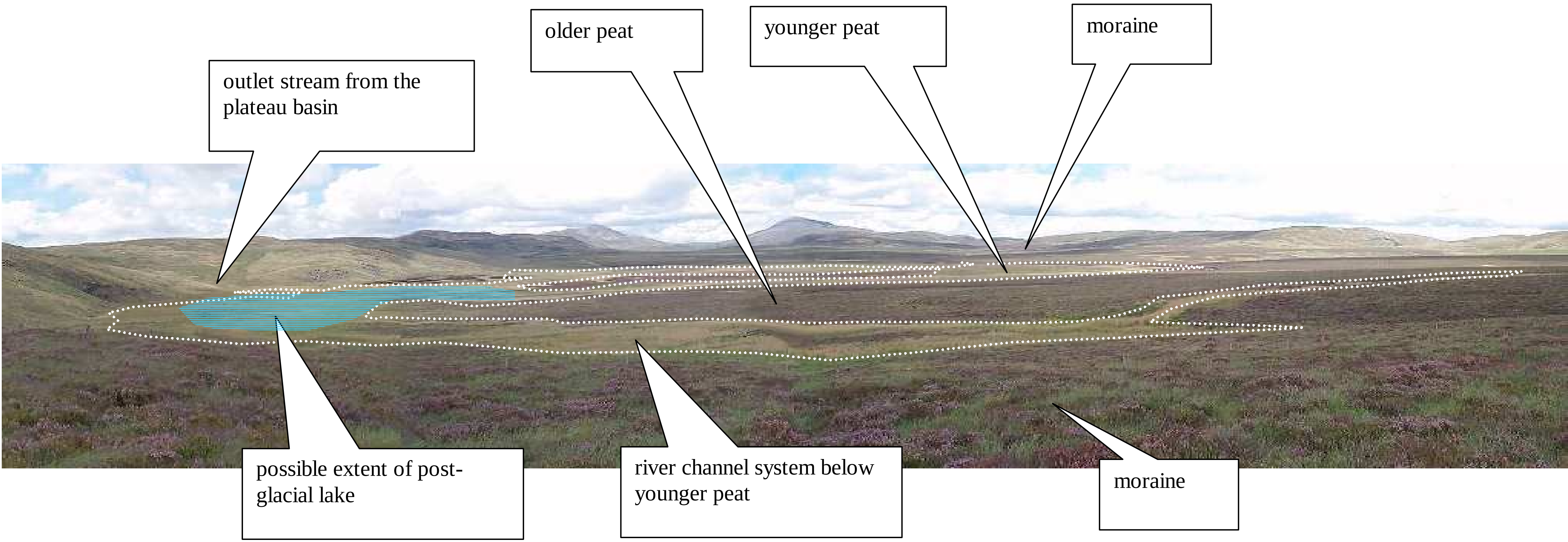


Figure 3.202: Superficial deposits and former drainage pattern, Waen y Griafolen

Hydrology

At the beginning of the hydrological study, it was assumed that the wide expanse of deep peat at Waen y Griafolen would have an important function in water interception and storage during storm events. It seemed reasonable that most, if not all, rainfall could be absorbed within the peat and would be slowly released over a period of days or even weeks. In order to test this hypothesis, a borehole with water depth recorder and an array of dip wells were emplaced in the blanket peat.

A borehole site was chosen at a location near the centre of Waen y Griafolen, on the low plateau surface between relict drainage channels. The site lies within an area of *Erica* moorland vegetation (fig.3.203) and is underlain by older peat. A perforated plastic pipe was sunk to a depth of 2.5m within the peat without reaching glacial deposits or bedrock. A barometric water depth recorder in the pipe operated continuously from May to September 2003. A raingauge was installed alongside the borehole. Rainfall and water table data are displayed in fig.3.204.

Figure 3.203: Waen y Griafolen borehole with water depth recorder

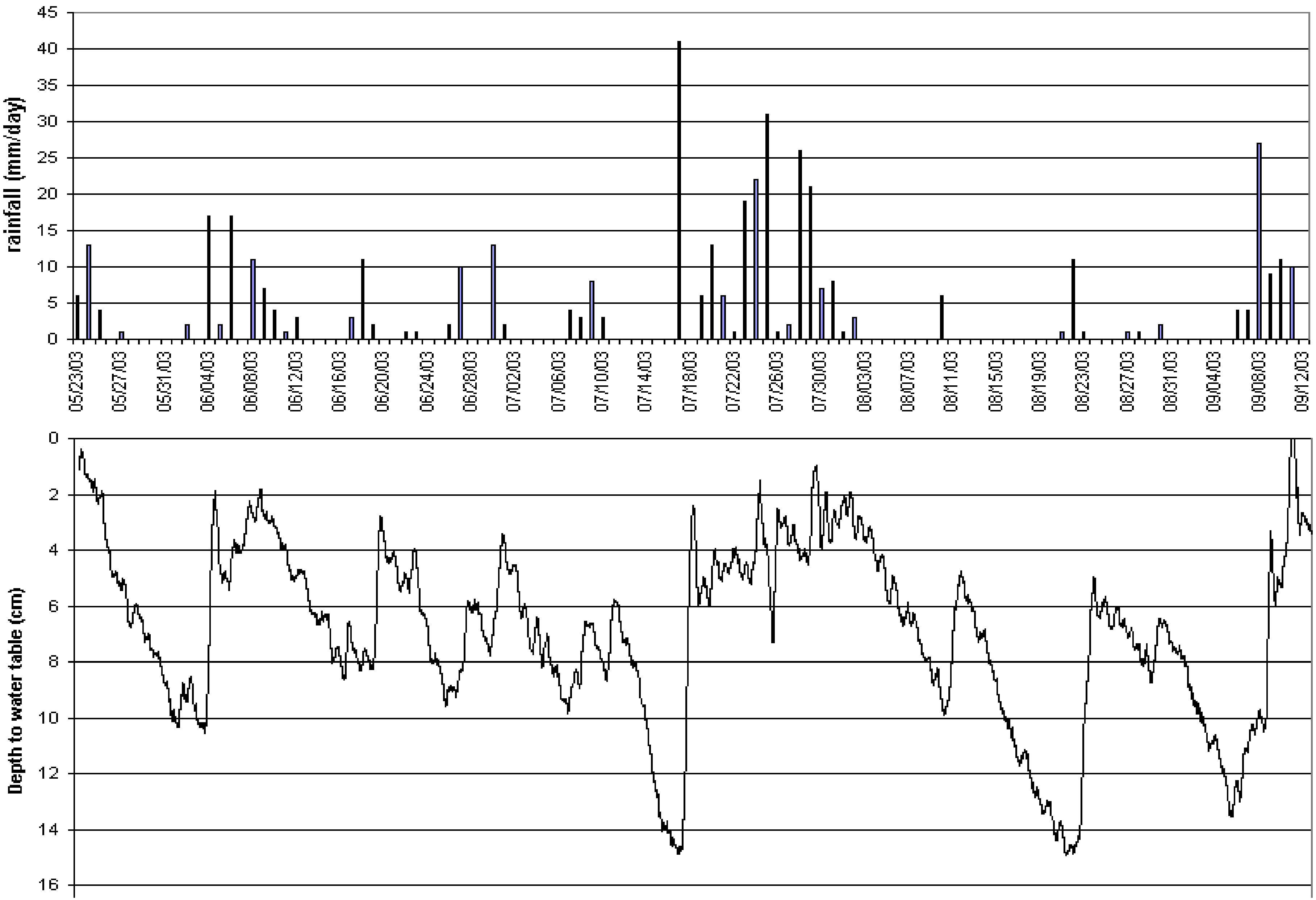


Figure 3.204: Rainfall and watertable records for the Waen y Griafolen borehole site

Examination of the borehole watertable data provides the surprising result that the storage capacity of the older peat is very limited. During a thunderstorm over Waen y Griafolen on 17 July 2003 the watertable rose by 12cm within a period of 3 hours, reaching within 2cm of the ground surface. It is likely that surface runoff was occurring from substantial areas of the older peat during this storm.

In a typical rainfall period, water level within the older peat rises by 8cm per day. In dry periods the fall in water level is at a fairly constant slower rate of 8cm per week. Thus the older blanket peat is likely to be close to saturation during the wetter winter months, and the recovered storage capacity in the summer can be rapidly expended by a few days of wet weather.

To obtain a more detailed picture of water movements within the peat, 6 dip well tubes were emplaced in a ring of approximately 500m radius around the borehole in areas of deep older peat. The array coverage was subsequently increased to 8 tubes (figures 3.205 and 3.206).

Results of manual readings of water depths in the dip-well tubes are given in Table 3.9:

> The first set of measurements were taken on 29 July 2003 during a period of heavy rainfall. All tubes show water levels close to the ground surface. This is consistent with the borehole data, and indicates widespread saturation of the peat.
>
> The sets of measurements taken on 5, 13 and 27 August indicate a progressive fall in groundwater level at all sites by between 10cm and 50cm. During the same period the borehole water level appeared to decline by 60cm, but it should be noted that these figures conceal a number of short term fluctuations in the water table which are apparent on the borehole graph. It is likely that similar but proportional fluctuations had occurred at all the dip well sites between readings.

Figure 3.205: Emplacing a dip well tube in older peat at site 7, Waen y Griafolen

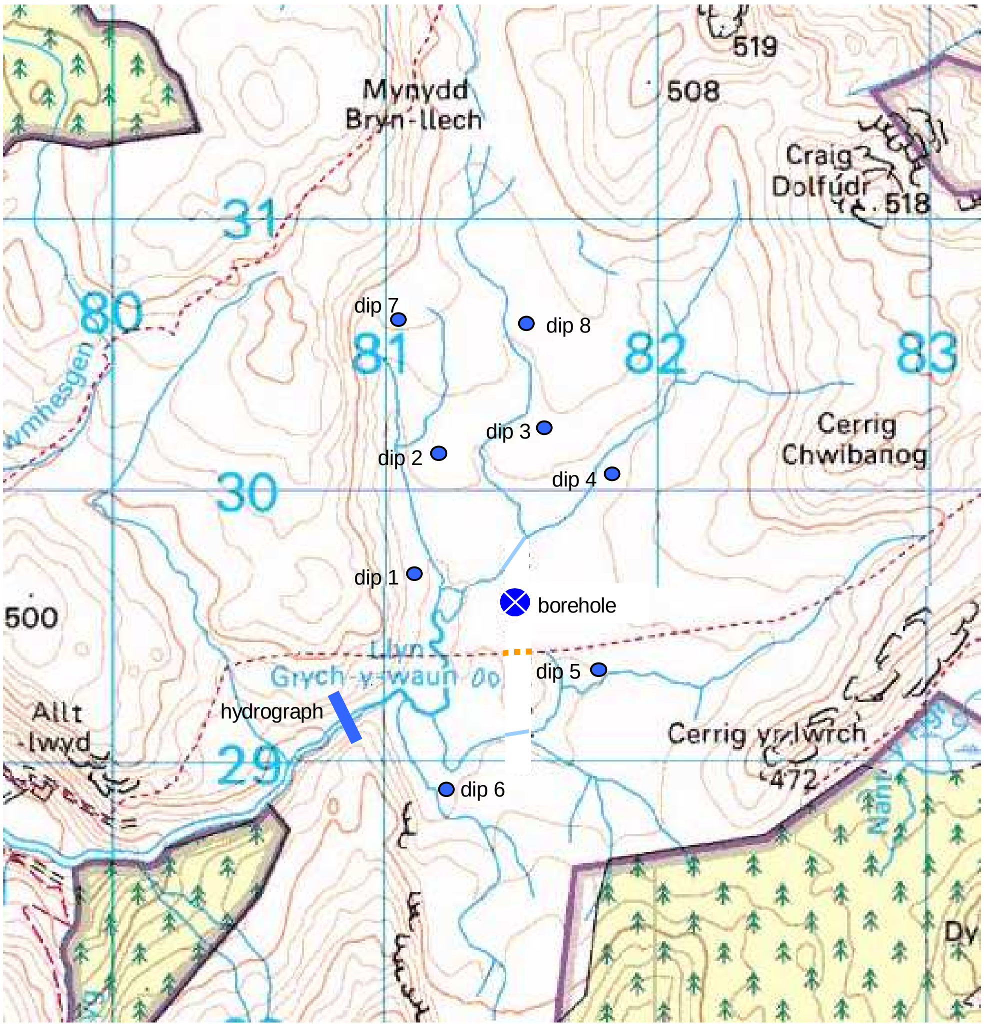


Figure 3.206: Locations of dip wells, borehole water depth recorder and hydrograph site, Waen y Griafolen

Dip well designation			**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**borehole**
Map reference SH			***81163 29638***	***81206 30113***	***81500 30210***	***81896 30053***	***81840 29303***	***81283 28855***	***81119 30615***	***81479 30748***	
Date	**Time**										
29/07/2003	*12:14 – 19:20*	**Water level(m)**	0.06	0.04	0.05	0.01	0.06	0.07	-	-	0.1
5/08/2003	*13:10 - 17:20*		0.29	0.11	0.18	0.06	0.20	0.17	-	-	0.4
13/08/2003	*13:35 - 18:30*		0.43	0.20	0.22	0.10	0.29	0.25	-	-	0.6
27/08/2003	*13:20- 15:40*		0.55	0.20	0.23	0.11	0.32	0.26	0.17	0.27	0.7

Table 3.9: Water level at different times measured from top of the dip wells (after Awissa, 2003)

Outflow from the Waen y Griafolen blanket bog

The outlet stream from Waen y Griafolen forms the headwater reach of the Afon Mawddach. A hydrograph recorder was operated on the outlet stream over the period July to September 2003 (fig.3.207).

Figure 3.207: Outlet stream hydrograph site, Waen y Griafolen. A barometric depth recorder is situated in the pool upstream of the V-notch weir.

Awissa (2003) produced a calibration curve for river dischage against river stage by measuring water velocity within the V-notch at low flow, and aditionally over the flat weir at high flow.

A record obtained for the sequence of rainfall events between 5 and 12 September is displayed in fig.3.208. Comparison with the rainfall and borehole watertable data (fig.3.204) indicates that the peak river flow during the period corresponds with the surface saturation of the peat on 11 September.

Water table depths and river hydrograph data collected during the 2003 period of field observations will be used in the calibration of a MODFLOW groundwater model in the section which follows.

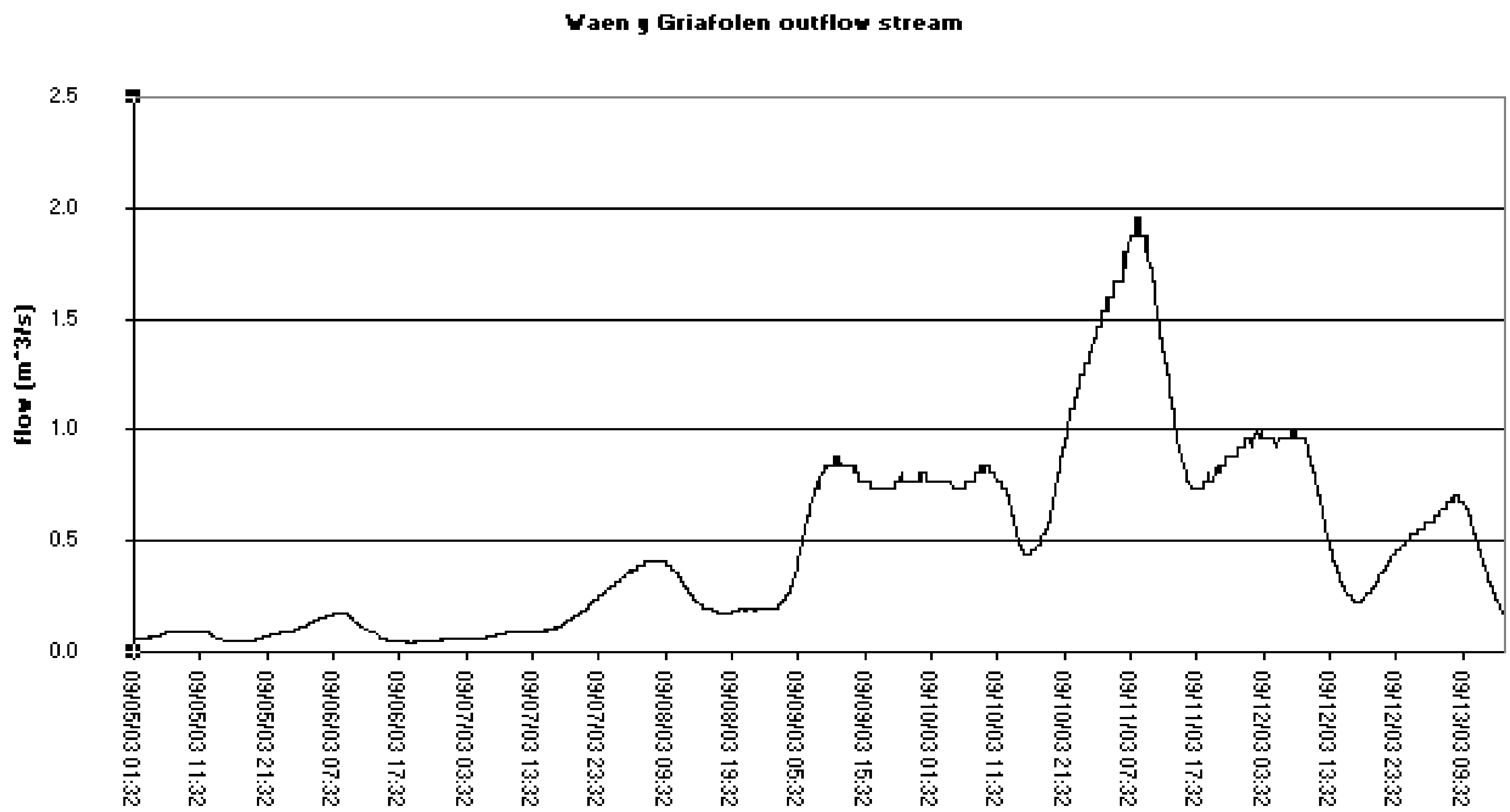


Figure 3.208: Hydrograph for the Afon Mawddach, Waen y Griafolen, over the period 5-13 September 2003

Waen y Griafolen groundwater model

The Waen y Griafolen MODFLOW model will first be used to simulate the sequence of peat saturation and runoff during the storms of September 8-13, 2003. River flow and borehole water level data were recorded during this period and will provide a basis for calibrating the model. The effects of the ploughed surface drains in increasing surface runoff from the older blanket peat can be examined.

The model will then be used to investigate the possible consequences of environmental change on river outflow from the blanket bog:

A majority of climate change models for western Britain predict an increase in winter rainfall coupled with drier and hotter summers, with a higher rainfall intensity for individual storm events (Arnell, 2002; Skaugen et al., 2003; Jones et al. 2005). The temperature and rainfall conditions responsible for peat growth or erosion appear to be very finely balanced. Minor climate changes may cause loss of vegetation from the relict drainage channels and reversion to gravel floodplain conditions over substantial areas of the current blanket bog.

The model will be run for the extreme storm event of 3 July 2001, with outflow determined for the current pattern of vegetation. Hydrological parameters will then be adjusted to simulate the loss of younger peat infill from the drainage channels. A re-run of the model will then provide an estimate of storm runoff under the modified surface conditions which may affect the blanket bog in future decades.

A geological map is used as a background image in setting up the MODFLOW model. An outer boundary for the model is taken as bedrock outcrop along the foot of the mountain escarpment bounding the basin to the west, and the upper extent of the peat and clay deposits around the eastern margins of the basin.

Geophysical data collected in conjunction with F. Awissa for eight sites are given in Table 3.10. For each site, three sediment layers have been identified above the mudstone bedrock: a deep layer of fine clay, overlain by clay with a higher sand content, and then the surface layer of blanket peat. These layers will be configured to produce the MODFLOW model.

		SITE							
		0	1	2	A	B	C	D	E
	SH	81195 29773	81278 29238	81308 29342	81444 29465	81370 29831	81292 28858	81808 29666	81490 30839
Layer Thickness	Peat	0.3	1.2	3.5	3.32	1.9	1.8	3.3	3.1
	Sandy clay	3.5	2.5	0.8	1.3	3	2.2	1.3	1.4
	Clay	1	11	1.3	3.4	0.3	2.6	3.2	3
	Mudstone	-	-	-	-	-	-	-	-

Table 3.10: Layer thickness at each site when curves from EM and VES are combined

Positions of geophysical measurement sites are located on the base map, and thicknesses of sediment horizons entered to produce a set of stratigraphic columns (fig.3.209).

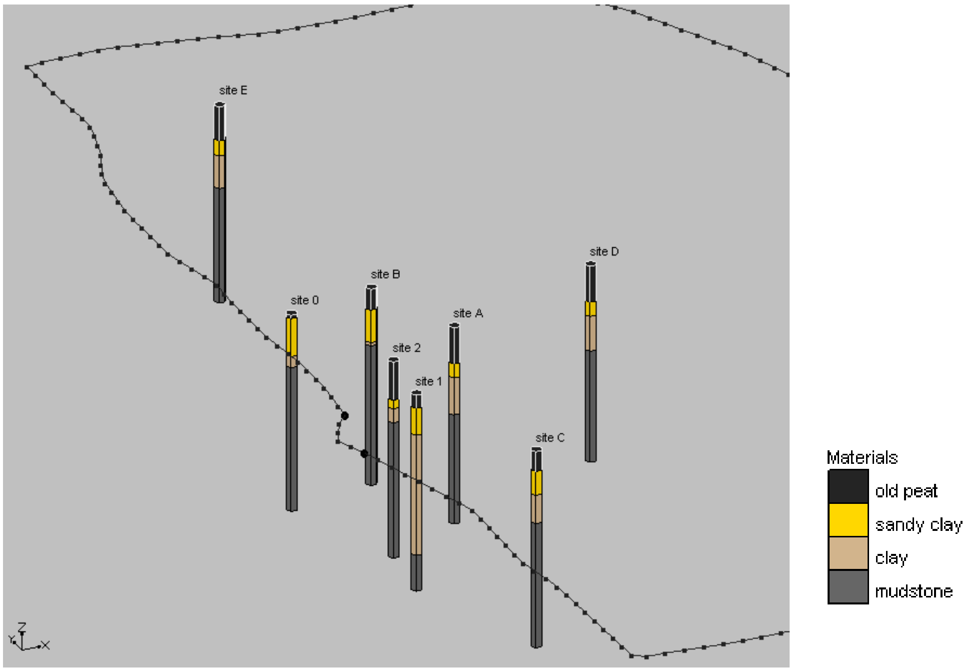


Figure 3.209: Stratigraphic sequences plotted on the MODFLOW model from geophysical data

Sediment boundaries are interpolated between measurement sites to generate a solid model (fig.3.210). Increased thickness of clay is visible in the area of the basin outlet where remnants of a glacial lake were identified. Thickening of clay is also evident in the area of moraine deposition in the north of the basin.

The final stage in setting up the MODFLOW model is to interpolate the layers onto the MODFLOW three-dimensional grid, offsetting layer elevations according to the ground surface heights derived from the Ordnance Survey 50m grid.

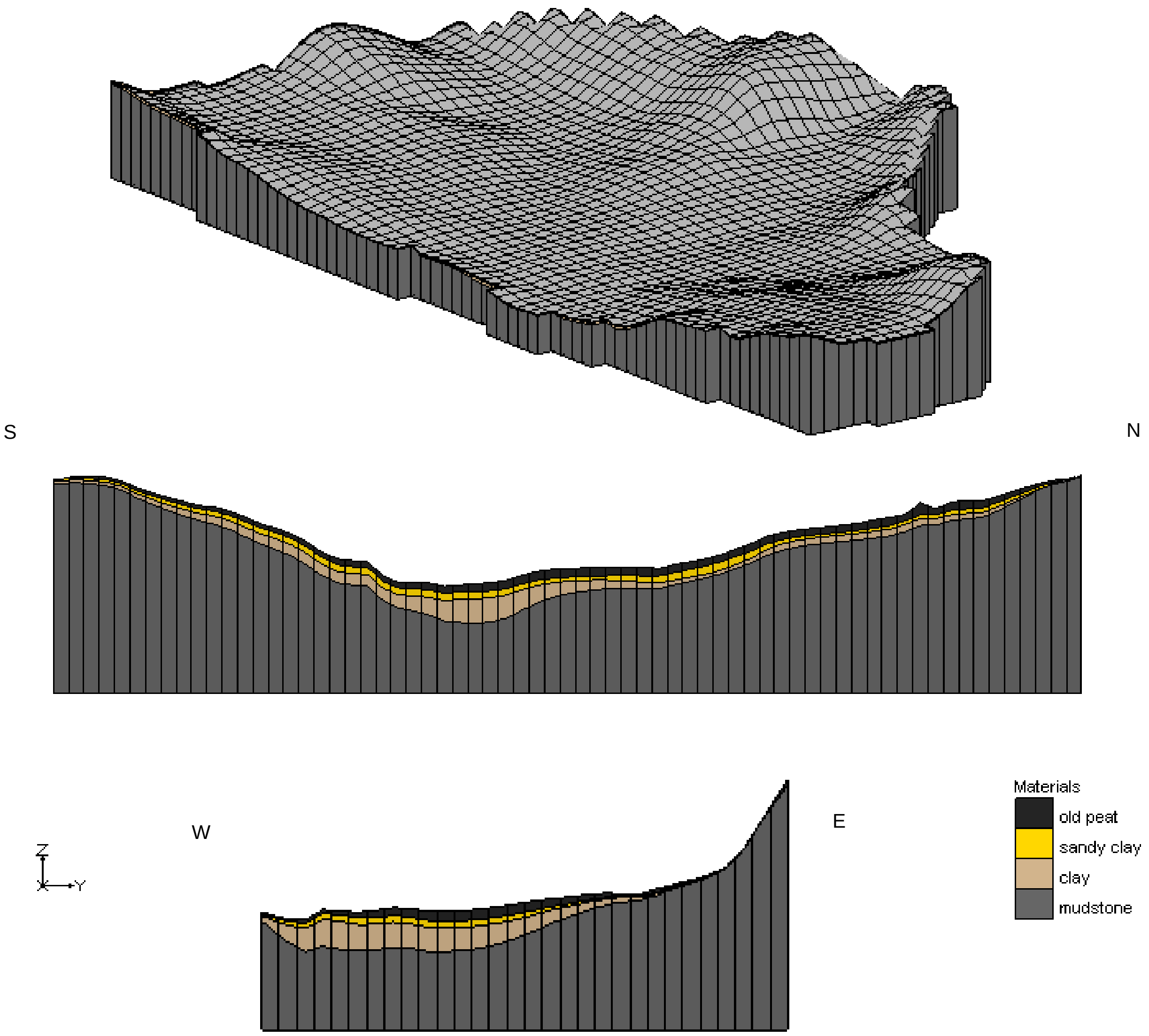


Figure 3.210: Waen y Griafolen MODFLOW three-dimensional grid, showing example South-North and West-East cross sections.

Configuring hydrological parameters

The patterns of river channels and ploughed drainage ditches (fig.3.211) were traced into the MODFLOW model using an air photograph overlay. Only those drainage ditches appearing as continuous lines of distinct colour on the high resolution air photographs were included. Additional relict ditches, now discontinuous and overgrown by heather, were considered to have negligible effects on the regional drainage and could be incorporated into a bulk hydraulic conductivity value for the older peat deposits.

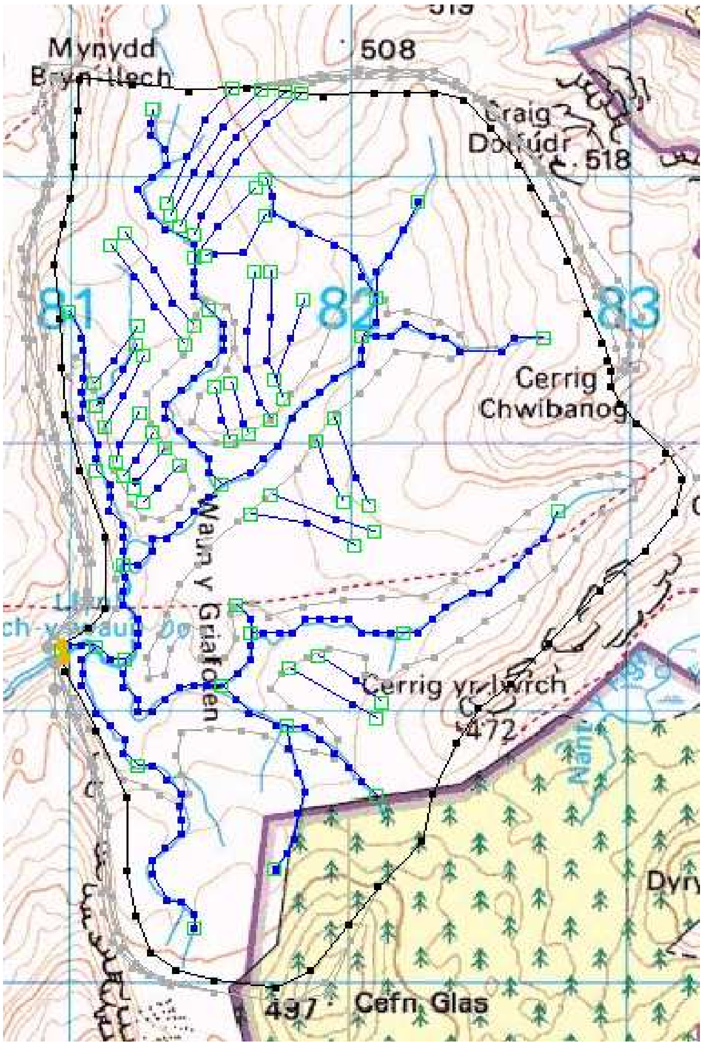


Figure 3.211: Pattern of river channels and ploughed drainage ditches incorporated into the Waen y Griafolen MODFLOW model

Both rivers and drainage ditches were modelled using the ***drain*** package in MODFLOW. This operates in a similar way to the ***river*** package, but ignores water loss through the channel bed during periods of low water table. From field observations, this is an acceptable simplification. The river channels are deeply incised into the blanket bog and flow even during dry periods. The ploughed drains, by contrast, cross the surface of the raised peat and are completely dry except for short periods of storm conditions. The river channels were given hydraulic connectivity to both the peat layer and the underlying sandy clay layer of the stratigraphic sequence. The ploughed drains were allowed a hydraulic connectivity only to the surface peat layer.

Areas of younger peat were differentiated from older peat within the upper stratigraphic layer, so that different hydraulic parameters could be assigned to the contrasting materials.

The model was run for calibration using the 8-13 September 2003 rainfall sequence. Initial hydraulic conductivity and channel conductivity values were chosen, then an automated procedure within the Groundwater Modelling System systematically adjusted these values for each stratigraphic layer, rivers and ditchs, to obtain a best fit with the measured outlet stream discharge (fig.3.208) and borehole water level (fig.3.204). Checks were made for the dip well sites, to ensure that water depths were consistent with the known patterns of water table movement in comparison to the central borehole.

Calibration values obtained for the model are given in Table 3.11:

		Horizontal conductivity K (m/h)	**Vertical conductivity K (m/h)**
layer 1a	old peat	0.1	0.01
layer 1b	young peat	50.0	20.0
layer 2	sandy clay	0.005	0.01
layer 3	clay	0.0005	0.001
layer 4	mudstone	0.00001	0.00001

	Hydraulic connectivity	**Bed conductivity $(m^2/h)/m$**
rivers	layer 1 to 2	20
ploughed drains	layer 1	20

Table 3.11: Calibrated hydrological parameters for the Waen y Griafolen MODFLOW model

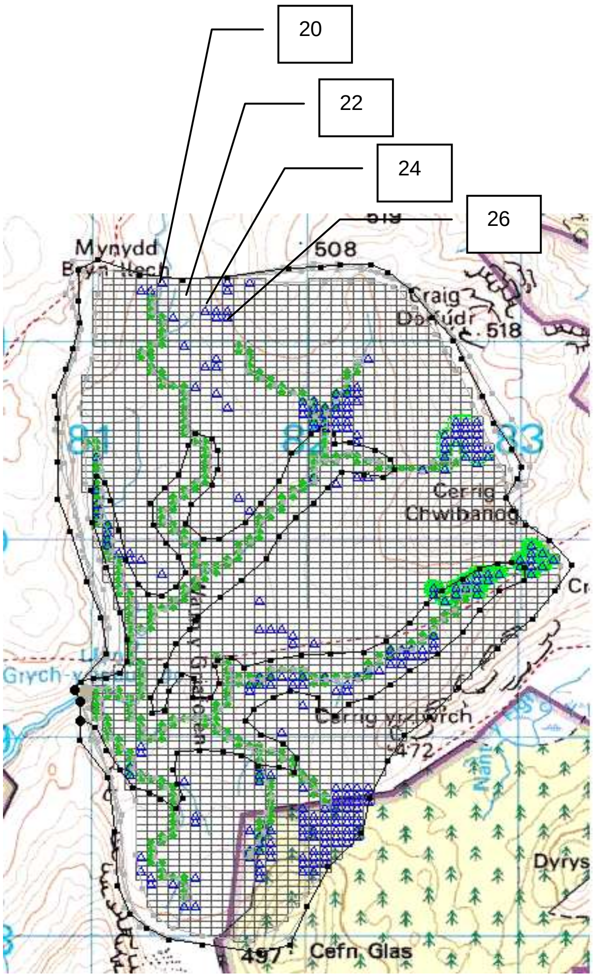
The older peat clearly has a low hydraulic conductivity to maintain the water table at the observed level close to the ground surface. By contrast, moderately high conductivity values must be allocated to the younger peat channels with their sphagnum and rush/reed bed infill, in order to provide the necessary timing delays for flood hydrograph peaks on the outflow stream. Hydraulic conductivities are low for the sandy clay layer, with the underlying clay and mudstone layers effectively impermeable.

The extent of surface saturation at times during the 8-13 September 2003 rainfall sequence are shown in fig.3.212, with north-south cross sections through the model given in fig.3.213 for 12:00h, 12 September. Zones of surface saturation are seen to develop in three principal situations:

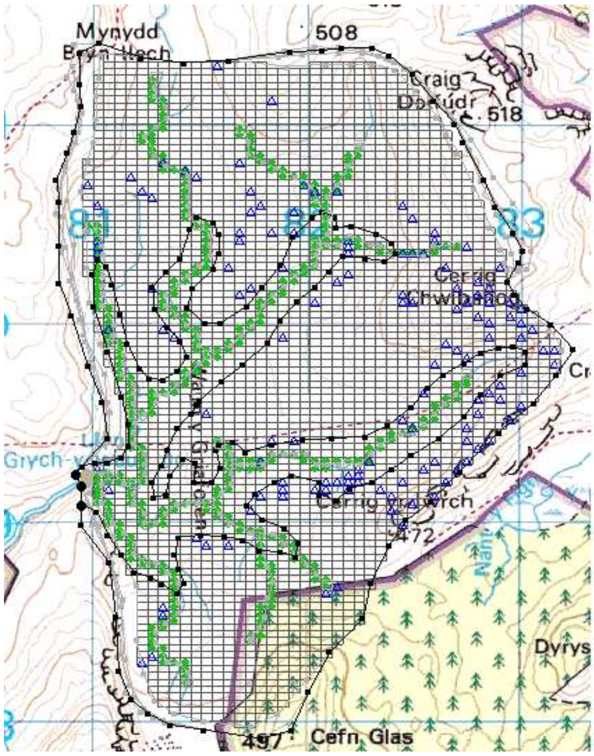
- on gentle slopes within the peat which have a large upslope contributing area,
- on flatter areas of the raised bog where lateral outflow is low,
- on the slopes surrounding the bog where bedrock outcrops, or where clay glacial deposits form the surface layer.

The incised river channels infilled by younger peat have a localised effect in lowering the water table in the adjacent older peat.

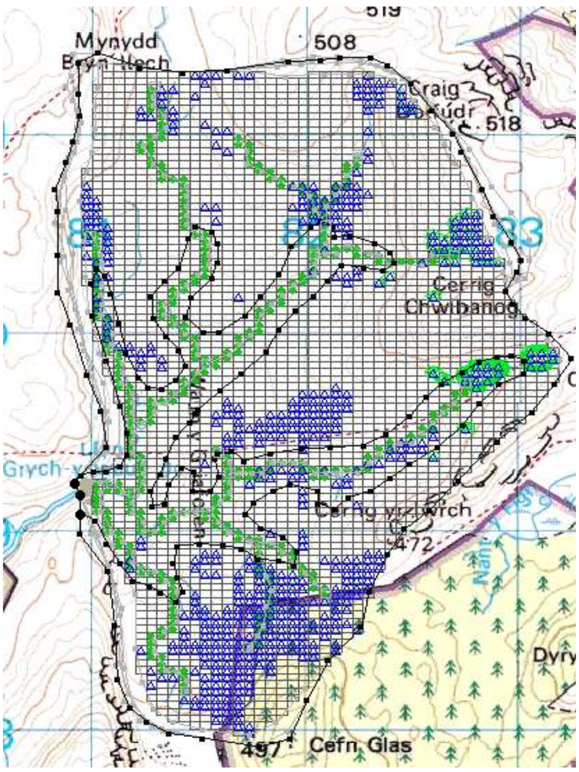
The ploughed drainage channels are found to be inactive except during periods of surface saturation of the surrounding older peat. Even at times of saturation, the drains carry a total flow of less than 1% of the flow in the overall river system. This appears to be a result of the low horizontal hydraulic conductivity of the old blanket peat, restricting groundwater flow into the drains.



12:00h, 8 September 2003



12:00h,10 September 2003



12:00h, 12 September 2003

Figure 3.212:
MODFLOW model for the rainfall sequence of 8-13 September 2003. Zones are surface saturation are marked by blue triangles.

Reference numbers in the top left diagram indicate the column numbers of cross sections in fig.3.213.

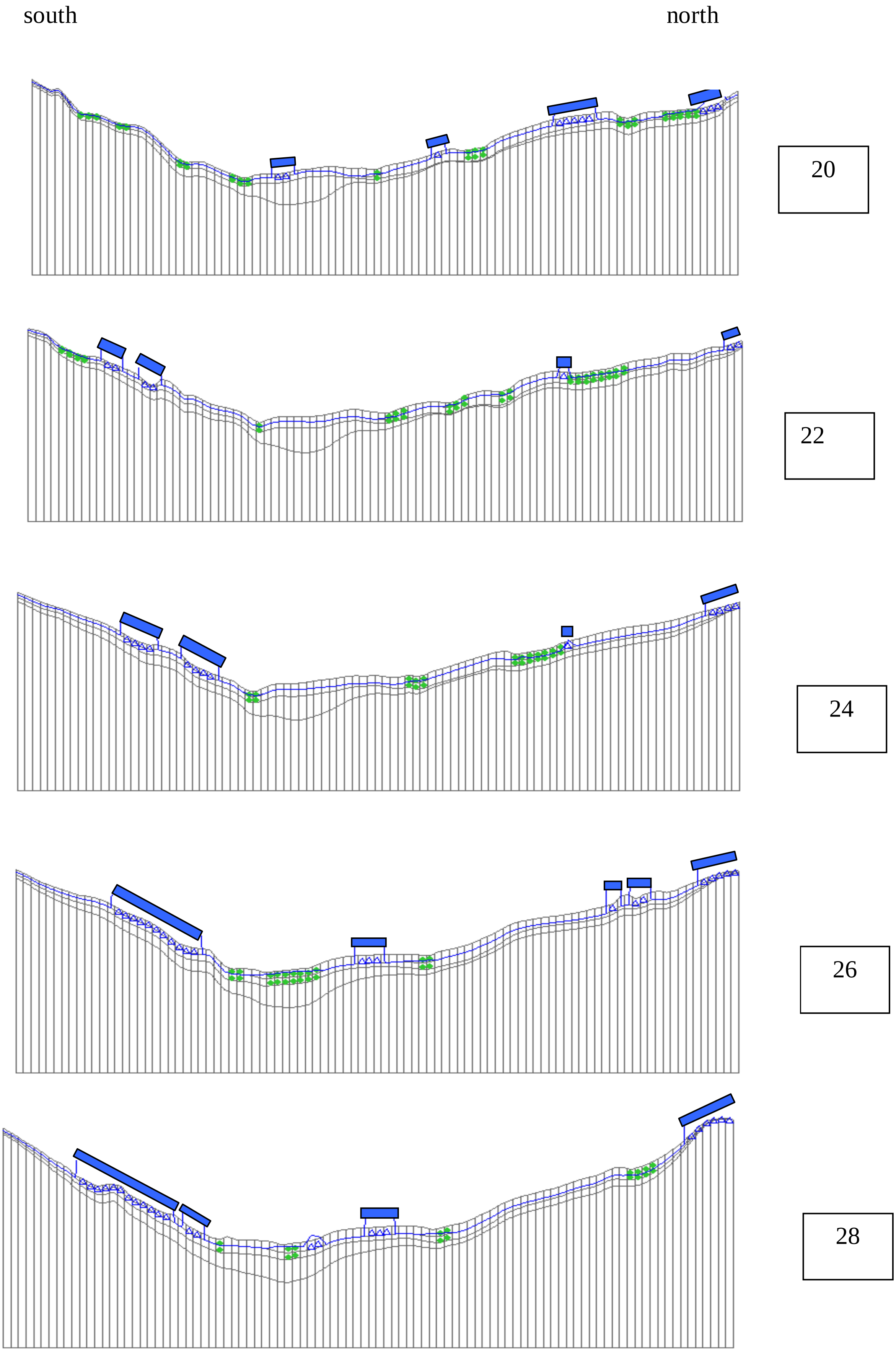


Figure 3.213: North-south cross sections through the Waen y Griafolen model for 12:00h, 12 September 2003. Areas of surface saturation marked by blue bars. River and drain locations are marked in green. Vertical exaggeration: 8.

In the next phase of modelling, a simulation of the 3 July 2001 storm event was carried out, assuming current hydrological characteristics for the older blanket peat and the younger peat filled channels.

A second model assumes removal of vegetation over the full width of *Sphagnum* and *Juncus* channels, and simulates waterflows in open river courses above a gravel bed

The stream system of Waen y Griafolen was divided into a series of reaches (fig.3.214). The volume of water entering each reach from the surrounding peat during the second hour of the storm event was estimated for the two MODFLOW models. Results are given in Table 3.12.

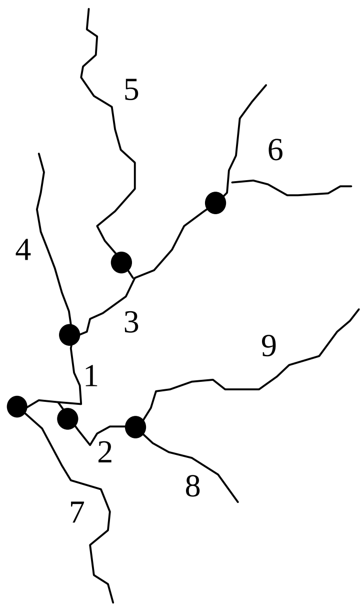


Figure 3.214: Key to numbered river reaches listed in Table 3.12

Modelling predicts that removal of younger peat in *Juncus* and *Sphagnum* zones would lead to an increase in the severity of flash flood responses due to the loss of temporary water interception capacity. In an extreme case of complete removal of younger peat from channels, peak discharge from the basin could be almost doubled.

The model suggests that loss of *Juncus / Sphagnum* peat would lead to a reduction in aerial extent of surface saturation within older peat during storm events. This could result in the drying out of *Erica* communities and the onset of peat hag erosion. Drier grassland and *Trichophorum* communities may then invade the *Erica* moorland.

Reach	*Sphagnum /Juncus* infilled channels	Open gravel bed channels
1	13 207	33 197
2	1 237	9 585
3	5 356	5 368
4	2 519	3 565
5	3 744	4 864
6	4 633	5 062
7	1 979	1 724
8	2 851	4 753
9	3 088	1 396
Total flow	38 614	69 514

Table 3.12 Modelled water flows (m^3) entering surface streams from peat during hour 2 of the 3 July 2001 storm event. Numbering of river reaches is given in Figure 3.214.

The *Juncus / Sphagnum* communities are seen as fragile. Management options to protect channel vegetation are recommended, which could include the blocking of surface streams to encourage a distributed water flow and maintain saturated ground conditions. A favourable area for *Sphagnum* bog regeneration would be above the low permeability lake clay deposits near the basin outlet.

Consideration should be given to stabilising the river course as it leaves the blanket bog through a boulder channel over glacial moraine. Increased fluvial erosion at this point would lower base levels and reduce the area of saturation suitable for *Sphagnum* ecosystems.

Summary

- Peat blanket bogs are developed in a number of areas of the Mawddach catchment, particularly within glacial basins floored by clay or impermeable bedrock.
- Groundwater levels have been monitored in blanket bogs at Cefn Clawdd and Waen y Griafolen. Both sites show similar hydrological responses. The water table in the peat rises rapidly during a storm event, followed by a very slow linear fall over the subsequent dry period.
- Small diurnal fluctuations in water level were observed at both sites, and are ascribed to evapotranspiration.
- Outflow from Waen y Griafolen remains almost constant for long periods between rainfall events, and may be attributed to deep penetration of streams into catotelm peat.
- Two contrasting peat types are present at Waen y Griafolen: older peat which is highly humified and gelatinous in texture, and younger peat which has an open texture of undecomposed plant material.
- The older peat forms the higher areas of the blanket bog, with the younger peat infilling a relict river channel system incised into the plateau surface of the bog.
- Older peat accumulation began around 9 000 B.P., shortly after the final ice retreat. It is likely that the channel system containing the younger peats was cut during a wet climatic period at 2 800 B.P.
- Field observations and modelling indicate rapid saturation of the older peat areas and surface runoff during storm events. Water enters the channel system infilled by younger peat, which acts as a reservoir and releases water gently into the river system.
- An array of shallow ploughed drainage ditches on the surface of the older peat appears to have limited effect on the hydrological response of the blanket bog. The ditches increase the rate of surface flow into the channel system, but flow through the younger peat controls overall discharge to the outlet streams.
- Loss of the younger peat and reversion to open gravel river channels would almost double the peak storm discharge from the blanket bog.