1.2 The study area

Geology

Many of the features of the geology of North Wales can be related to a model of an ocean expansion - contraction cycle, including the patterns of sedimentation, igneous activity and tectonic events (Anderton et al., 1979).

In late Precambrian times, a change in the pattern of mantle convection led to the fracturing and separation of the North American - European continent to form an ocean basin. The line of separation of continental crust lies roughly from the Scottish border to Northern Ireland (fig.1.26). As the ocean began to open, tension in the diverging continental plates led to a series of NE-SW faults developing parallel to the continental margins. Vertical movements took place, with a block of crust sinking between the Aber-Dinlle and Church Stretton fault zones to form the Welsh Basin. Adjacent blocks were elevated as the Irish Sea landmass to the NW and the Midland platform to the SE. These fault blocks remained at or above sea level until Silurian times and are of major significance to the geology of North Wales.

The Cambrian in Wales was a period of quiet sedimentation. Sands, grits and muds were layed down in the fault bounded marine trough. Much of the coarse sediment of the Cambrian succession was provided by erosion of these bordering landmasses.

By Ordovician times the ocean basin had began to contract, with oceanic crust descending beneath Wales along a subduction zone. An important consequence of subduction was the initiation of volcanic activity from the Lake District in the north, through Snowdonia, to Pembrokeshire in the south.

Towards the end of the Ordovician period, volcanicity died out in North Wales, but normal marine sedimentation continued in the Welsh Basin until closure of the ocean was completed in the last parts of the Silurian period and the early Devonian. At this time, major compression, folding and faulting occured as the continental masses finally converged.

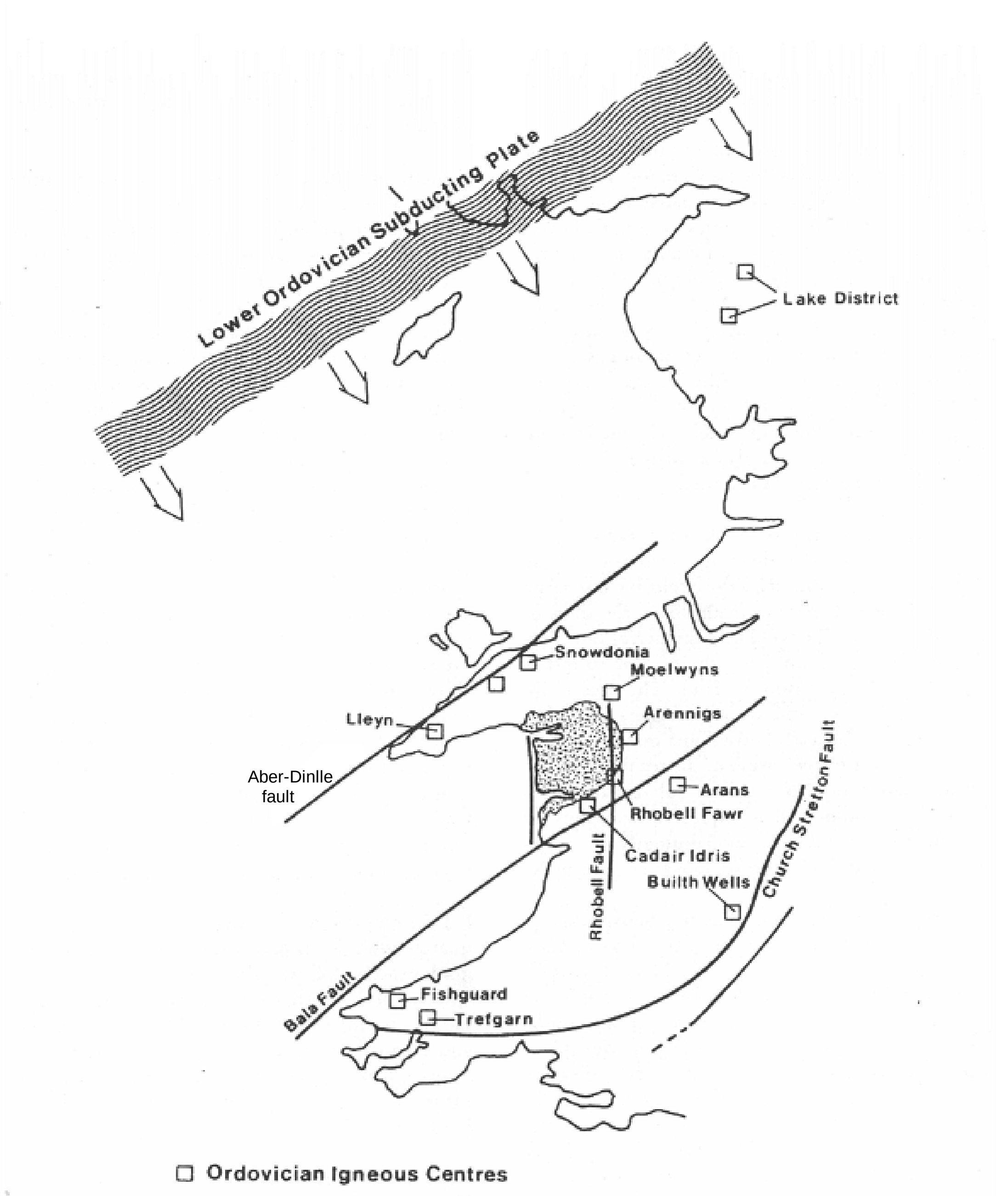

Figure 1-26: Volcanic centres and deep fracture zones related to Ordovician subduction in the Welsh Basin (after Hall, 1981)

The Mawddach catchment occupies much of the central, southern and eastern areas of a major anticlinal structure, the Harlech Dome (figs.1-27,1-28). Grits, sandstones and shales making up the Cambrian succession outcrop in the central area of the Harlech Dome (Matley and Wilson,1946). Surrounding the sedimentary outcrop is a circle of rugged mountains composed of Lower Ordovician volcanic rocks and associated igneous intrusions; these are the Moelwyn, Arennig, Aran and Cadair Idris ranges, rising to a height of around 800m.

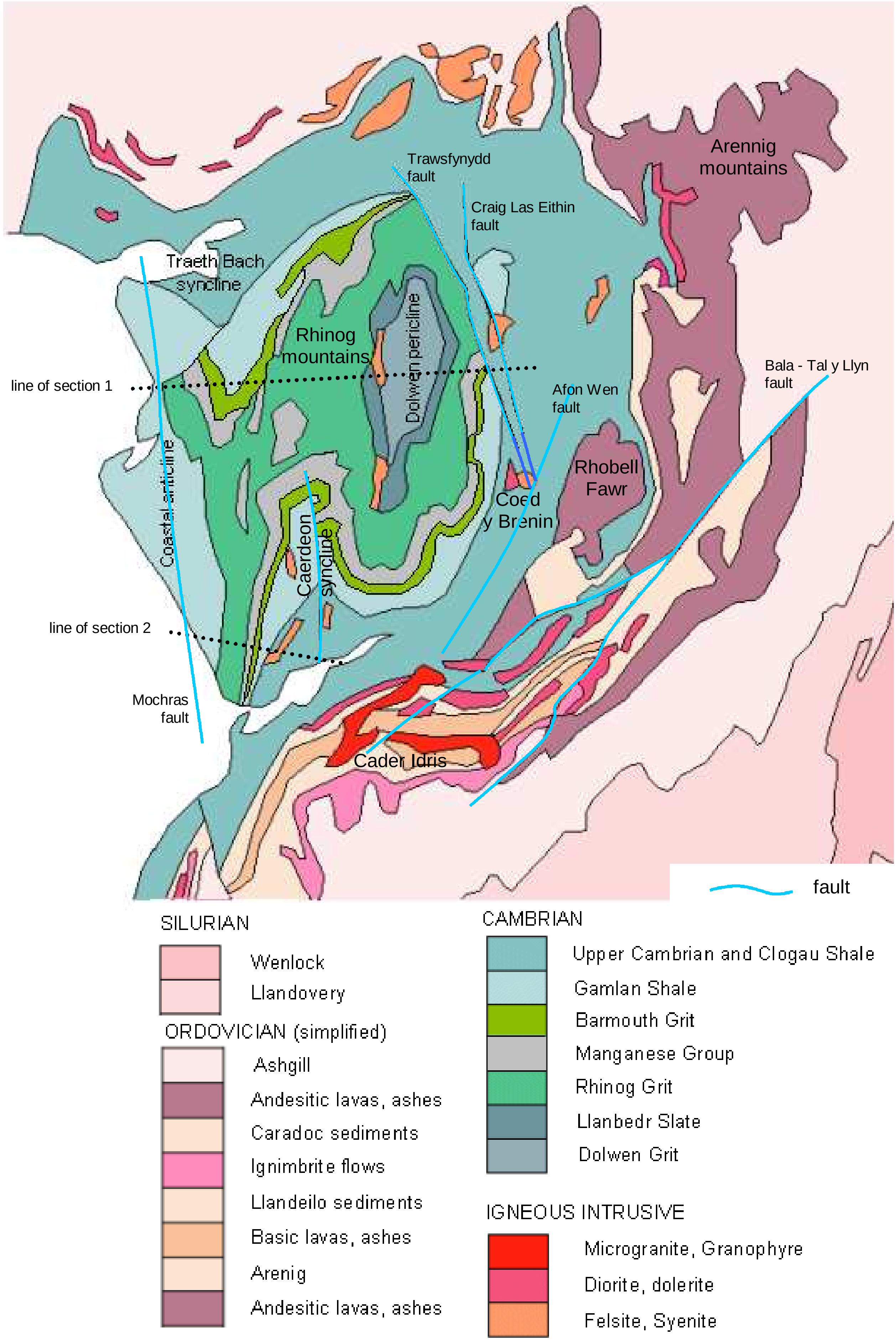

Figure 1-27: Geology of the Harlech Dome
(after Matley and Wilson, 1946; Rushton, 1974; Geological Survey, 1971)

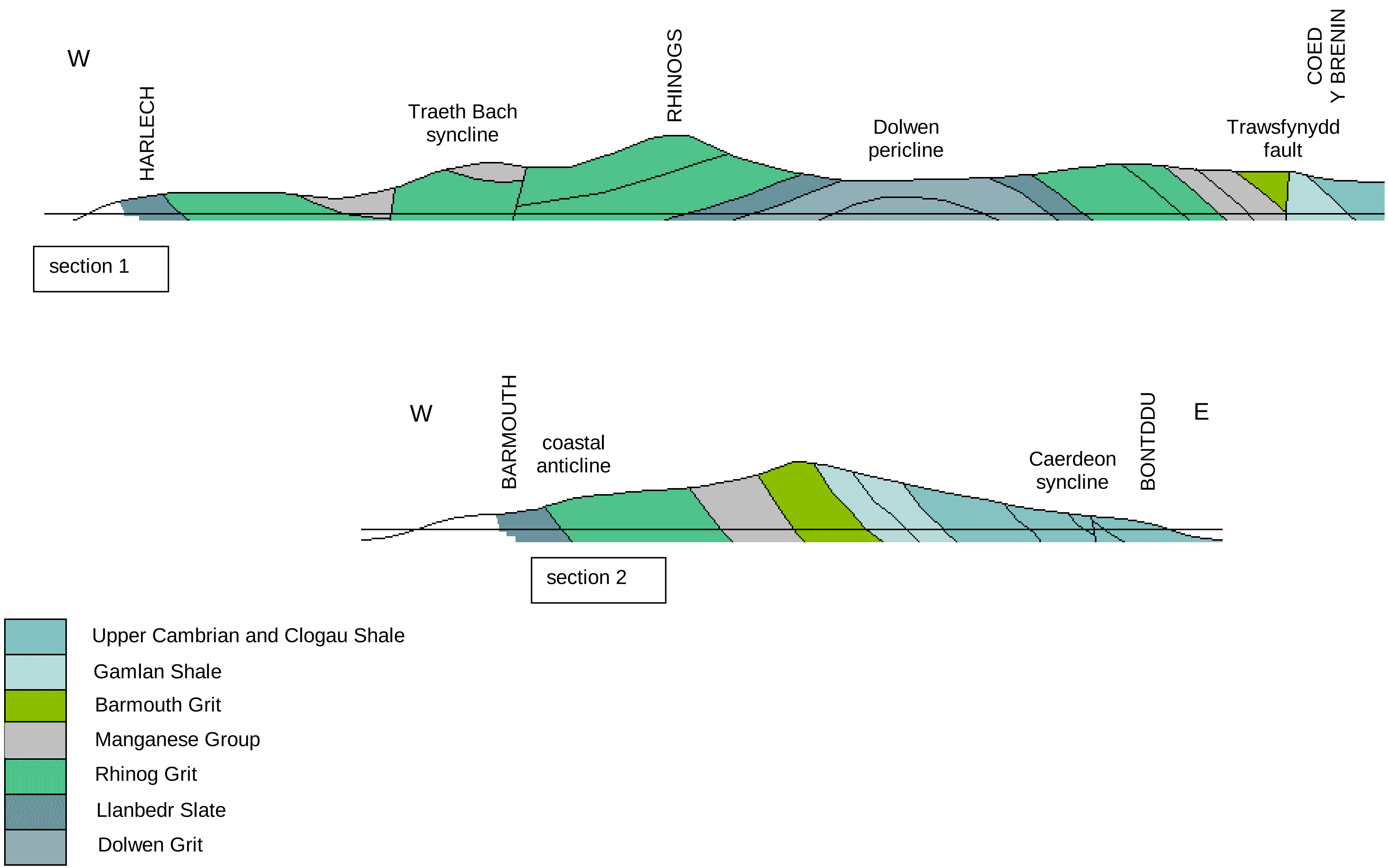

Figure 1-28: Harlech Dome geological cross sections

The lithological characteristics of Cambrian sediments in North Wales are summarised in fig.1-29 (Rushton, 1974).

The Cambrian succession in the Harlech Dome commences with the Dolwen Grit and Llanbedr Slate. These seem to indicate a period of deepening water. The Rhinog Grits represent a first phase of turbidite deposition. Coarse sediments released from the Irish Sea landmass spread across the floor of the deep water basin as a fan complex. Geological features of the Rhinog Grits are illustrated in fig.1-30.

Following the turbidite deposition, a pause in sedimentation took place, with a sequence of muds enriched in manganese accumulating on the basin floor. Near the base of this group is a bed of manganese silicate ore, which has been mined commercially in the Harlech Dome.

The subsequent deposition of the Barmouth Grits represents a return to turbidity current activity in North Wales. The geography of the Welsh Basin began to change, with the more distant Midland platform to the south-east rising above sea level whilst erosion reduced the elevation of the nearby Irish Sea landmass. By the time of the Gamlan Shale, sediment supply was predominantly from the Midland platform. Again, turbidite flows were discharged into the deep waters of the basin, but the distance of the North Wales area from the sediment source now meant that only finer shale sequences were deposited in this area. Similar conditions continued during deposition of the Clogau Shales and Maentwrog Beds (fig.1-31).

The Ffestiniog Beds of the Upper Cambrian mark another major change in the geography of the Welsh Basin. General shallowing of the water took place, and silts and shales were deposited in shallow water. Ripple marks are common on the surface of sandstone beds. In the closing stages of the Cambrian period, extensive deposits of mud were laid down in the Welsh Basin to form the Upper Cambrian Dolgellau and Tremadoc Beds.

<table>
<tr><th colspan="3">Lithostratigraphic unit</th><th>Lithology</th><th>Biostratigraphic unit</th></tr>
<tr><td colspan="3">Tremadog Slates Group</td><td>Slates and thinly bedded fine grained metasediments and siltstones (c.300m)</td><td>Tremadog</td></tr>
<tr><td rowspan="5">Mawddach Group</td><td colspan="2">Dolgellau Formation</td><td>Dark pyritous metashales and thin metasiltstones (c.50-100m)</td><td rowspan="4">Meirionydd (Upper Cambrian)</td></tr>
<tr><td colspan="2">Ffestiniog Formation</td><td>Interbedded strong metasiltstones and very fine metasandstones plus some slates (c.500m)</td></tr>
<tr><td rowspan="2">Maentwrog Formation</td><td>Penrhos Shales member</td><td>Rusty weathering dark pyritous metashales and laminated metasiltstones (c.300m)</td></tr>
<tr><td>Vigra Flags member</td><td>Interbedded grey metasiltstones, metasandstones and some metashales (c.300m)</td></tr>
<tr><td colspan="2">Clogau Formation</td><td>Predominantly dark metashales with minor metasiltstones</td><td rowspan="4">St David's</td></tr>
<tr><td colspan="3">Gamlan Formation</td><td>Thinly interbedded fine metasandstones and slates (c.250m)</td></tr>
<tr><td colspan="3">Barmouth Formation</td><td>Mainly massive greywacke sandstones (turbidite units) with intervening slates (c.200m)</td></tr>
<tr><td colspan="3">Hafotty Manganese Formation</td><td>Striped green and grey metamudstones and thin metasiltstones. Manganese bearing sandstone in lower part (c.200m)</td></tr>
</table>

Figure 1-29: Cambrian and lowest Ordovician (Tremadog) succession, after Rushton (1974)

Figure 1-30: Features of the Rhinog Grits, near Llyn Pryfed, Rhinog mountains.
(Upper photograph) Rocky terraces representing individual massive grit beds.
(Lower left) Conglomerate bed, composed of well rounded quartz pebbles.
(Lower right) Several fining-upwards sequences from grit to sand and silt layers, representing deposition from successive turbidite flows.

Figure 1-31: Vigra Flags member of the Maentwrog formation, Foel Ispri.

The softer sediments in the higher parts of the Cambrian succession produce less rugged scenery. Middle to Upper Cambrian rocks outcrop as the belt of hill country alongside the Mawddach estuary in the south, and the Vale of Ffestiniog in the north of the Harlech Dome, and follow the headwaters of the Mawddach inland into the Coed y Brenin forest. These outcrops produce the most productive areas of forest and agricultural land within the Mawddach catchment.

The Ordovician period saw the development of volcanic centres around the Harlech Dome (Wood, 1969) in response to the subduction of oceanic crust. Fault structures in the floor of the Welsh Basin controlled the distribution of volcanic centres around the Harlech Dome.

In late Tremadoc times, block faulting raised the central area of the Harlech Dome above sea level. Soft semi-consolidated beds of Upper Cambrian sediment were folded over the eastern edge of the fault block in the form of a monocline between Ffestiniog and Dolgellau, and erosion cut downwards into the sedimentary succession above the Dome. Rise of magma along the fault zone initiated volcanic eruptions in the area of Rhobell Fawr, with an accompanying phase of dyke and sill intrusion. At the close of the Rhobell volcanic episode the area again subsided below sea level, and marine sediments of early Ordovician age were laid down unconformably on top of the Rhobell lavas and folded Cambrian strata.

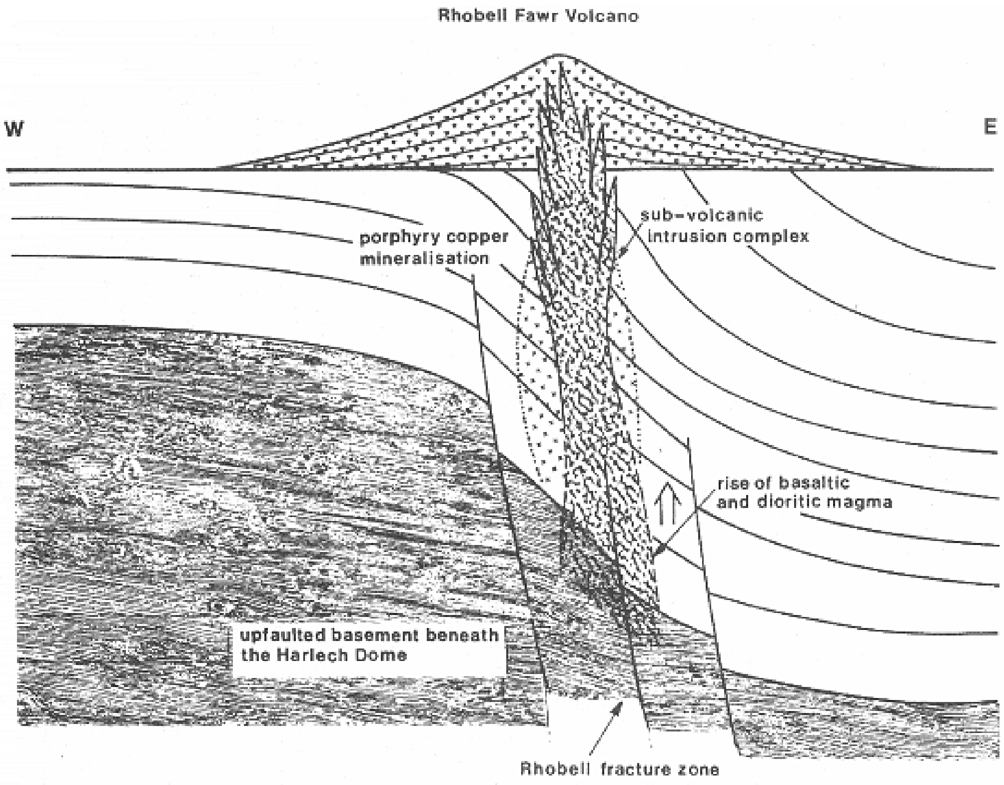

Figure 1-32: Structure of the Rhobell volcanic centre (after Kokelaar, 1977)

A feature of the Rhobell volcanic centre is disseminated copper pyrite within the sub-volcanic diorite intrusions and adjacent sediments in the Hermon area; this forms the Coed y Brenin porphyry copper deposit (Rice and Sharp, 1976). The copper was emplaced from hydrothermal fluids rising from the magma chamber beneath the volcanic centre in the late stages of crystallisation (fig.1-32). The hot hydrothermal fluids were also able to break down silicate minerals in the diorite to form clay minerals, in an analogous way to the formation of china clay around the Cornish granites. The area of copper emplacement around Hermon is now one of decomposed and easily eroded rock material with clearly visible green colouration of copper carbonate (fig.1-33).

**Figure 1-33:
Outcrop of decomposed diorite with disseminated copper carbonate mineralisation.
Coed y Brenin porphyry copper deposit, Hermon.**

Following the Rhobell volcanic episode, volcanic activity became more widespread along the southern and eastern margins of the Harlech Dome during the Ordovician period. Eruptions took place from various centres, and a thick succession of lavas, pyroclastic deposits, and interbedded marine sediments was built up, along with the emplacement of sub-volcanic and intra-volcanic intrusions. This complex succession is well exposed in the mountain ranges of Cadair Idris, the Arans, and the Arennigs. The complete volcanic succession extending from Arenig to Caradoc times is termed the Aran volcanic group (Ridgway, 1975), and has been divided into a series of nine smaller units (figs.1.34-1.36).

Craig y Llam formation	Thick and extensive rhyolitic ignimbrites deposited under sub-aerial conditions, representing a phase of widespread emergence. An eruptive vent has been identified at Mynydd Moel on Cader Idris.
Craig y Bwlch formation	Acid pyroclastics and ignimbrites layed down on emergent volcanic islands. Marine muds and water laid ashes, which may indicate subsidence below sea level after eruptions emptied the underlying magma chambers.
Pen y Gader formation	Basaltic lavas and ashes. Characteristics of both submarine eruption and accumulation on a land surface are found within the succession, suggesting deposition on and around low volcanic islands in a shallow sea area.
Nant Fridd Fawr formation	Acid ignimbrites and ashes. It may represent a localised eruption from an emergent volcanic island in the Rhobell area.
Llyn y Gafr formation	Basalt lava flows and associated ashes and muds deposited in submarine conditions, The basalts show pillow structures characteristic of eruption into water.
Cefn Hir formation	Acid ashes and coarser pyroclastic sediments. Volcanic mudflows are widespread, layed down from turbidity currents transporting loose pyroclastic debris down the submarine slope of the volcano.
Gwynant formation	Quiet sedimentation when muds were layed down on the sea bed. Occasional thin ash beds indicate continued volcanic activity.
Mynydd y Gader formation	Acid ashes and ignimbrites, deposited from pyroclastic flows under subaerial conditions. It is likely that the eruptions took place from the Rhobell igneous centre.
Pared yr Ychain formation	A sedimentary formation, composed variously of sands, mudstones and conglomerates, and represents a general submergence of the North Wales area at the beginning of the Ordovician period.

Figure 1-34: Formations within the Aran Volcanic Group

Figure 1-35: Cefn Hir volcanic mudflow, showing fragments and pebbles of rhyolite in a roughly stratified matrix of ash and mud.

Figure 1-36: Pared yr Ychain grey sandstones and mudstones.

Acid and basic magmas were erupted in alternate phases. Basic phases of volcanism were dominantly submarine. Clouds of basaltic froth would be ejected explosively from sea floor vents and would fall back to the sea bed as pyroclastic ash deposits. Quieter flows of magma would also radiate from the vents, with the hot basalt forming pillow structures on contact with the cold water. In the country rock beneath the submarine volcanoes, sheets of magma spread laterally to produce the vertical dolerite dykes (fig.1.37) or horizontal sills common in the area. Sill intrusions often follow weaker horizons of rock such as shales which would present less resistance to magma flow.

Figure 1-37: Dolerite dyke intruded through Upper Cambrian sediments, Moel Oernant

Acid magma was generated by partial melting of the granitic lower crust due to heat from basaltic magma above the subduction zone. This granitic melt would make its way upwards to a high crustal level, where it could form cylindrical intrusions or spread laterally to form domed sill-like magma chambers known as laccoliths.
The space for the intruding melt was created by lifting of the overlying rocks, and phases of acid volcanicity were frequently accompanied by emergence of volcanic islands. As crystalisation of the acid melt took place, gas pressure would build-up until explosive fracturing of the magma chamber roof occurred. Lava froth would

thrown into the air from the vent, to fall as pyroclastic ash or pour down the side of the volcano as a dense ignimbrite flow.

After the close of volcanic activity in the Harlech Dome, quiet deposition of marine muds continued for the remainder of Upper Ordovician times. Only occasional thin volcanic ashes from a distant source north-east of Bala appear within the sedimentary succession. Beyond the Harlech Dome area, however, major eruptions continued from centres in Snowdonia.

The varying lithologies of the Cambrian and Ordovician strata outlined above have an important effect on the hydrological response of the Mawddach catchement. Other geological factors which must be considered are folding and faulting within the region. Structurally, the Harlech Dome is more complex than its name implies. Within the encircling Ordovician outcrop occur several folds lying roughly on a north-south axis to form parts of the major structure (figs 1-27,1-28). South of Trawsfynydd reservoir is the Dolwen pericline, an anticlinal structure exposing Llanbedr Slate amid. Dolwen Grit at its core, The Rhinog mountains have the form of an escarpment, composed of resistant Rhinog Grit overlooking the western side of the pericline. Nearer the coast are two complimentary synclines; the Caerdeon syncline plunges south towards the Mawddach estuary and the Traeth Bach syncline plunges north towards the Vale of Ffestiniog. Beyond these structures, outcrops of Rhinog Grit and Llanbedr Slate form the eastern limb of the coastal anticline, which is terminated at this point by the shoreline between Porthmadog and Barmouth. Evidence from boreholes indicates that a downfaulted trough of Mesozoic sediments lies offshore in Cardigan Bay, with the N-S Mochras fault trucating the older rocks of the coastal anticline.

Faulting is very obvious on the geological map of the Harlech Dome, and has had considerable influence on the development of the landscape. The major estuaries to the north and south of the Harlech Dome have been eroded along fault zones; and the courses of several rivers, notably the Afon Wen north of Dolgellau, follow fault lines for parts of their courses. Faults in the Harlech Dome can be divided into several groups:

- Strong faults running in a general north-south direction along the inland and seaward margins of the Dome. To the east of the Dolwen pericline, these include the Trawsfynydd, Craig Las Eithin and Afon Wen faults, and in the coastal region around Harlech are the Moelfre and Mochras faults.
- Strong faults running in a general north-east to south-west direction. The principal of which is the Bala fault. These control the orientation of Wnion and Tal y Llyn valleys.

Both of these groups are related to deep fractures in the Earth's crust beneath North Wales. They were initiated as lines of weakness during plate motions associated with the opening and subduction phases of Iapetus, when they provided magma conduits for vocanic activity (fig.1-26). Once established as lines of weakness, these fractures have been reactivated at subsequent times during geological history.

- More minor and superficial are two sets of faults related to the Caledonian folding which produced the Dome in late-Silurian and Devonian times. One set radiate from the centre of the Dome, and are termed radial faults; they are well developed in the Coed y Brenin area. The second set run in arcs concentric with the dome margin, and are termed circumferential faults; these are well developed to the north of the Mawddach estuary around Bontddu. The radial and circumferential faults are of interest, as mineralisation along these fractures produced the gold bearing quartz lodes of the Harlech Dome (Gilbey, 1968).

Where a fault line has been reactivated on a number of occasions, a complex fracture zone of multiple sub-parallel failure planes can develop (fig.1-38).

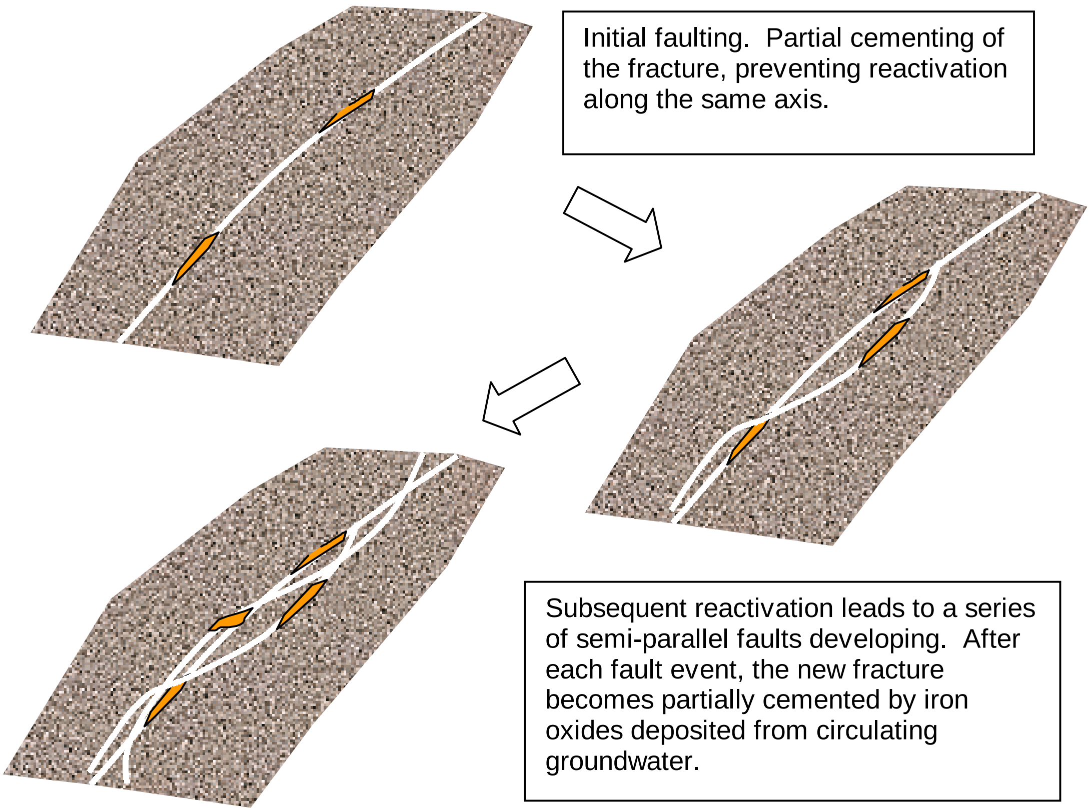

Figure 1-38: Evolution of a complex fracture zone by successive reactivation

Sections of early fault planes may become cemented by circulating ground water, so that subsequent movement takes place preferentially in softer country rock alongside. A wide zone of disrupted rock is produced, with high connectivity between fracture planes. Overall hydraulic conductivity in the fracture zone may be considerably increased in comparison to undisturbed country rock. Features of the Afon Wen fracture zone are illustrated in fig.1-39.

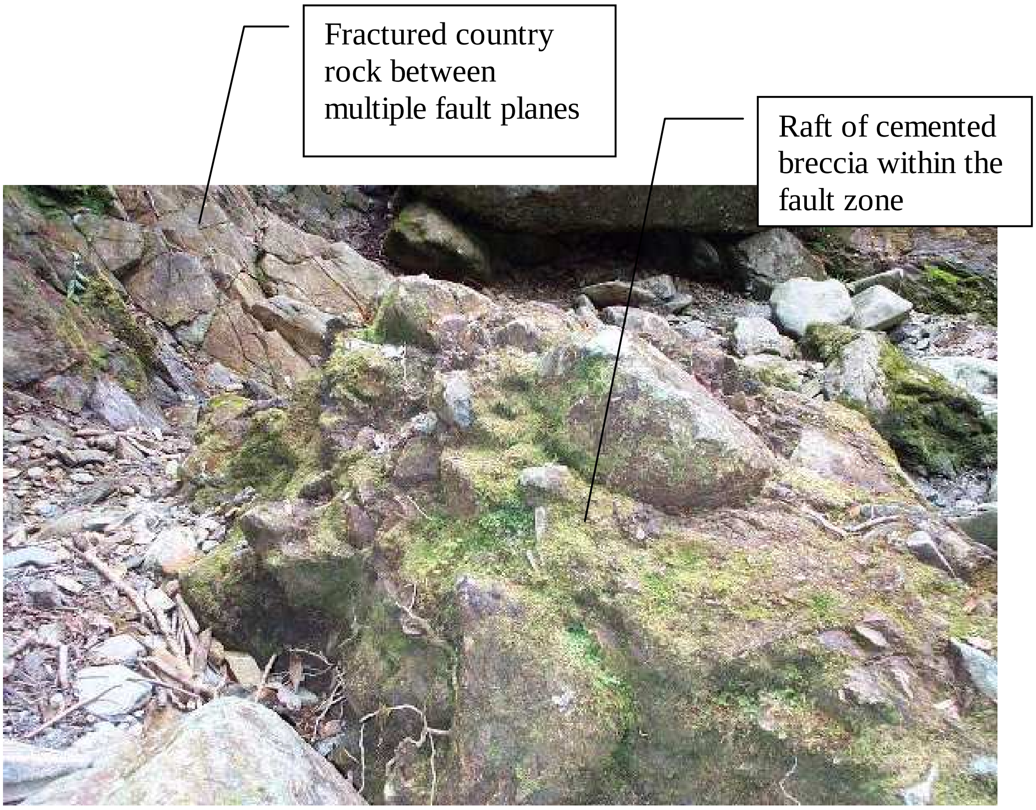

Figure 1-39: Afon Wen fracture zone, Hermon

Geomorphology

An important feature of the geomorphology of the Mawddach catchment is a well developed sequence of erosion surfaces developed in response to a pulsed uplift of North Wales during late Tertiary times. This uplift may be related to Alpine earth movements occurring to the south and east in Europe.

A prominent plateau surface extends across much of mid-Wales at an altitude of around 600m (fig.1.40). Deep valleys have been incised into this surface. The origin of the plateau surface is not known precisely, but is likely to be the result of prolonged river erosion reducing the land surface to a plain close to sea level during a period of crustal stability. Higher mountain summits such as the Brecon Beacons, Plynlimon and Cader Idris rise above this surface, and represent relict hills which were never reduced to the level of the surrounding plain.

Figure 1.40. View from Hyddgen across the Plynlimon mountain range, mid-Wales. The planar surface forming the skyline in the middle distance is a remnant of the 600m plateau. The summit of Plynlimon rises to 750m in the distance.

In the Mawddach catchment, erosional history is more complex. Miller (1946) has identified additional erosion surfaces at lower altitudes (fig.1.41).

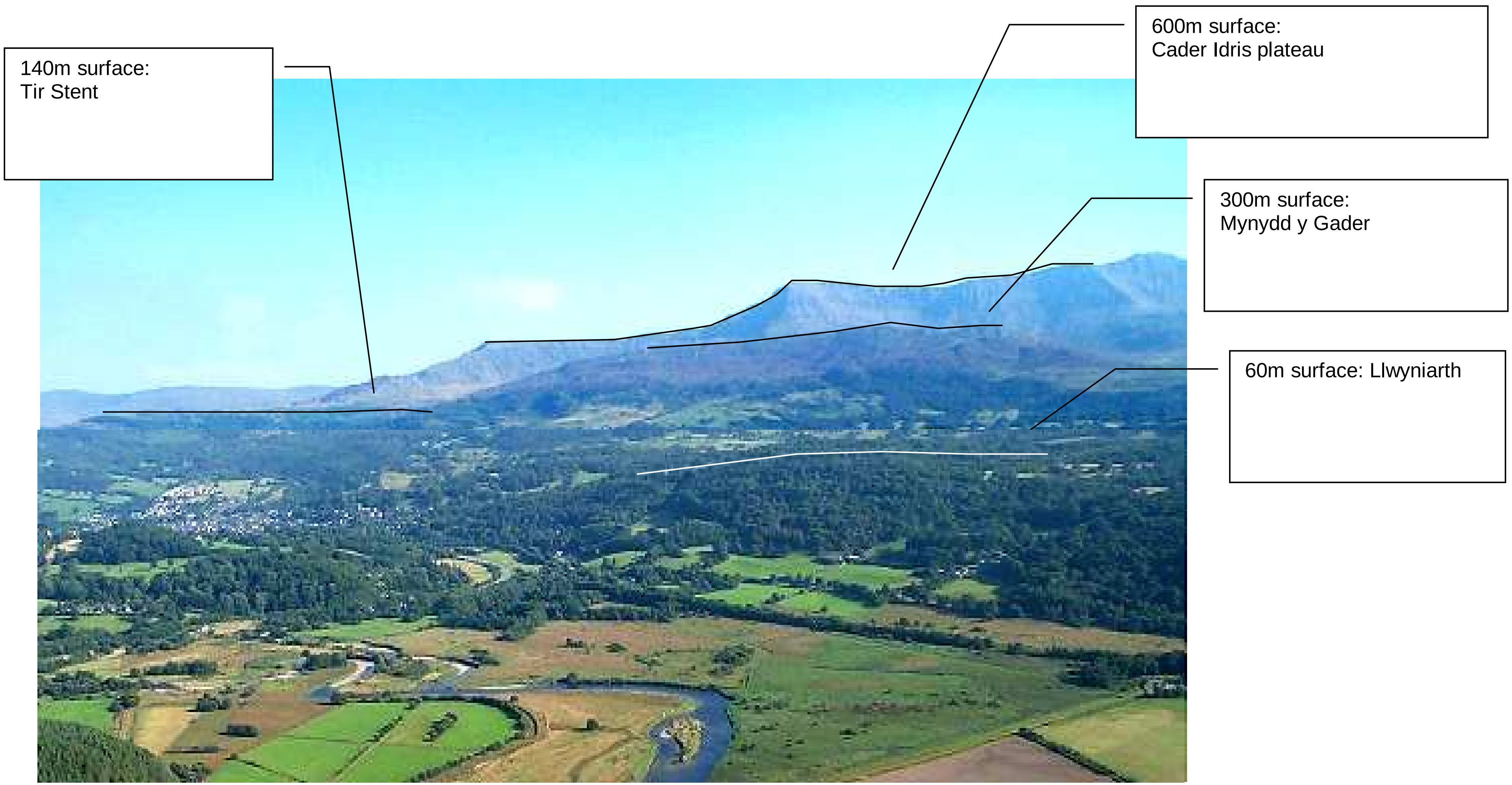

Figure 1.41. Erosion surfaces above the town of Dolgellau, looking south-east

Within the Mawddach catchment, the 600m plateau of mid-Wales is represented by the shoulders of Cader Idris, the summit of Y Garn, and the ridge of Llawlech. Initial drainage may have developed on that surface. Subsequent phases of rapid uplift, followed by periods of stability, have led to river rejuvenation and the development of polycyclic relief. Over a series of erosion cycles, major streams have become aligned to follow the outcrops of softer rocks or fault lines. Short tributaries, generally at right angles, drain the interfluve areas.

Miller named three lower erosion surfaces after localities around the Mawddach estuary where they are well developed:

- 300m surface: the Foel Ispri stage,
- 140m surface: the Rhyd Wen stage,
- 60m surface: the Ynys stage.

The origin of the surfaces is conceived as a combination of marine erosion near the coast and river erosion inland. The main north-facing scarp of Cader Idris may have originated as a sea cliff following fall of sea level to the Foel Ispri stage. Remnants of the 60m surface are prominent along the north and south shores of the Mawddach estuary (fig.1.42).

Each erosion surface may be expected to ascend as it is traced inland, following a graded river profile. Multiple rejuvenation is evident in the long profiles of the Afon Mawddach, and its main tributary the Afon Gain (fig.1.43). Graded reaches between knick points may be correlated with inland extensions of erosion surfaces of the Ynys and Foel Ispri stages.

Hayakawa and Oguchi (2006), in a study of Japanese mountain rivers, found that knickzones are more abundant in portions of rivers characterized by active erosion and rapid uplift, regardless of bedrock lithology, suggesting the dominant influence of fluvial hydraulics on location of knickzones. This finding is consistent with observations in the Mawddach catchment.

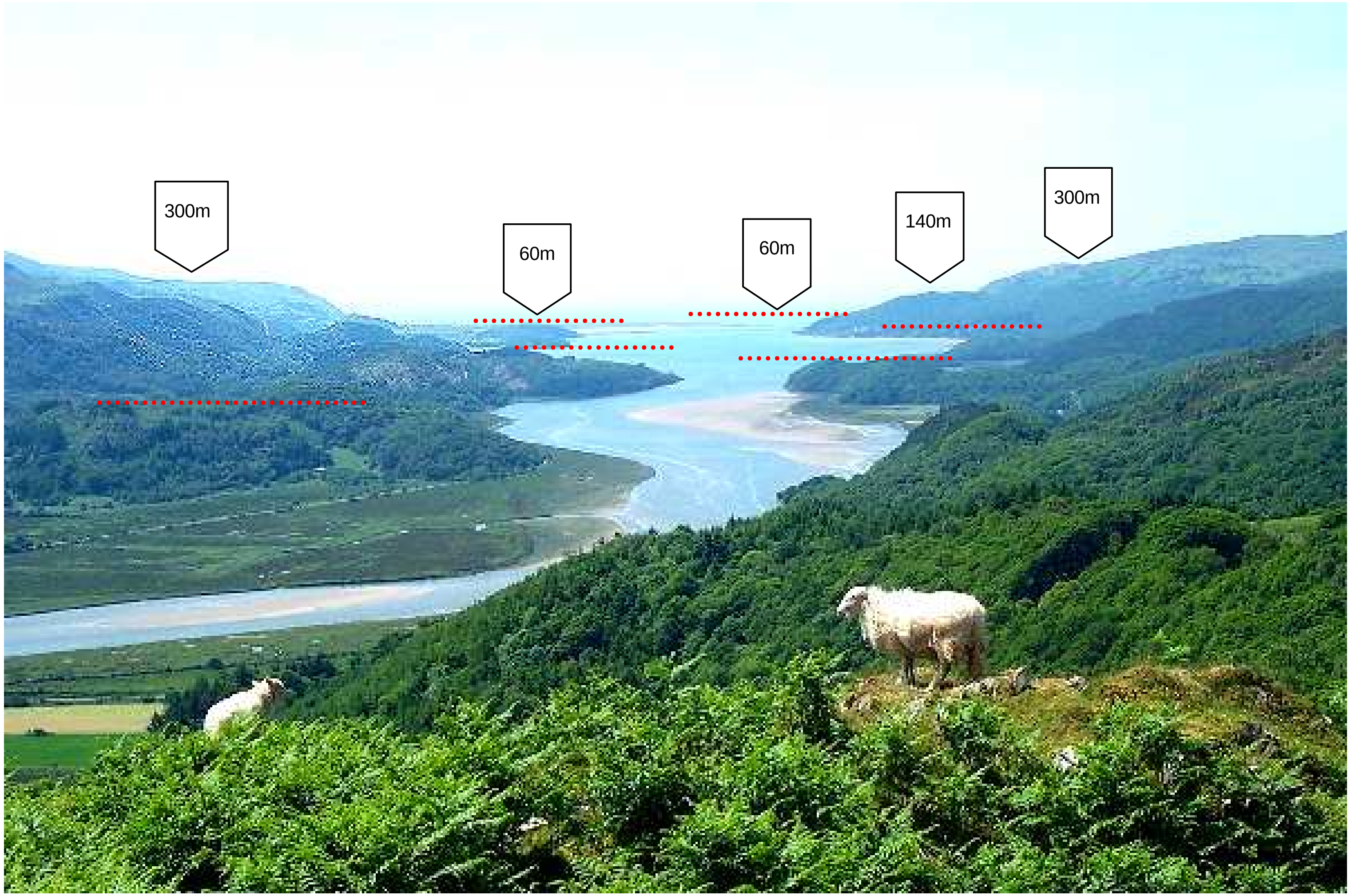

Figure 1.42. Erosion surfaces above the Mawddach estuary. Relics of the 60m surface are marked by red dotted lines.

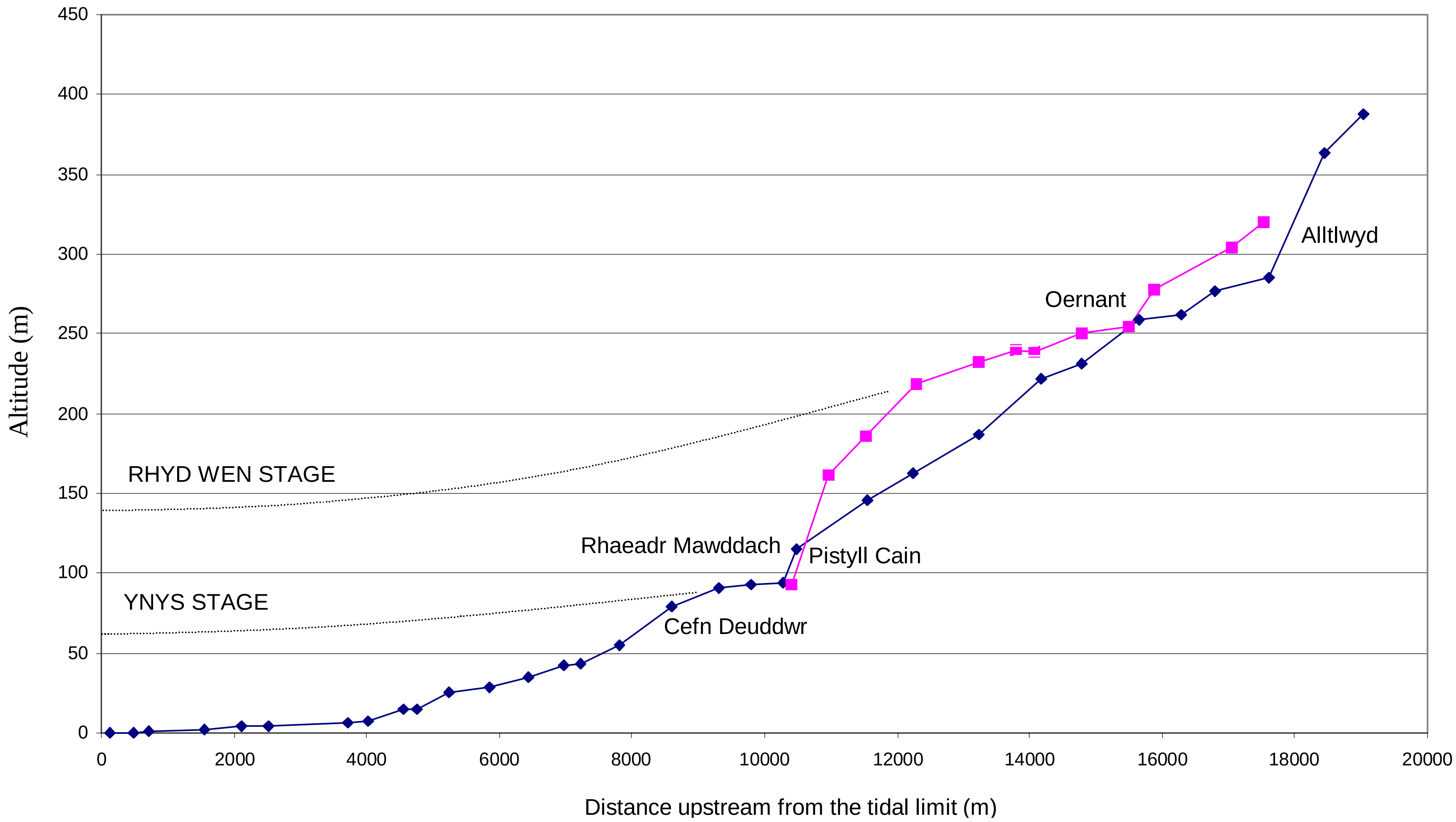

Figure 1.43. Long profiles of the Afon Mawddach (black) and Afon Gain (red). Sites of waterfalls and rapids associated with knick points are named: see fig.1.11

North Wales was extensively glaciated during Pleistocene times, and the landscape extensively modified as a result of glacial erosion, deposition, and subsequent periglacial sediment redistribution (Bowen, 1973) prior to the establishment of the present day Mawddach and Wnion catchments.

Local ice sheets developed over the Welsh mountains and flowed radially outwards (fig.1.44) during the three main stages of the Ice Age: the Wolstonian, Ipswichian and Devensian. Westwards flowing ice merged along the coast of Cardigan Bay with Irish Sea ice moving southwards from a source area in Scotland.

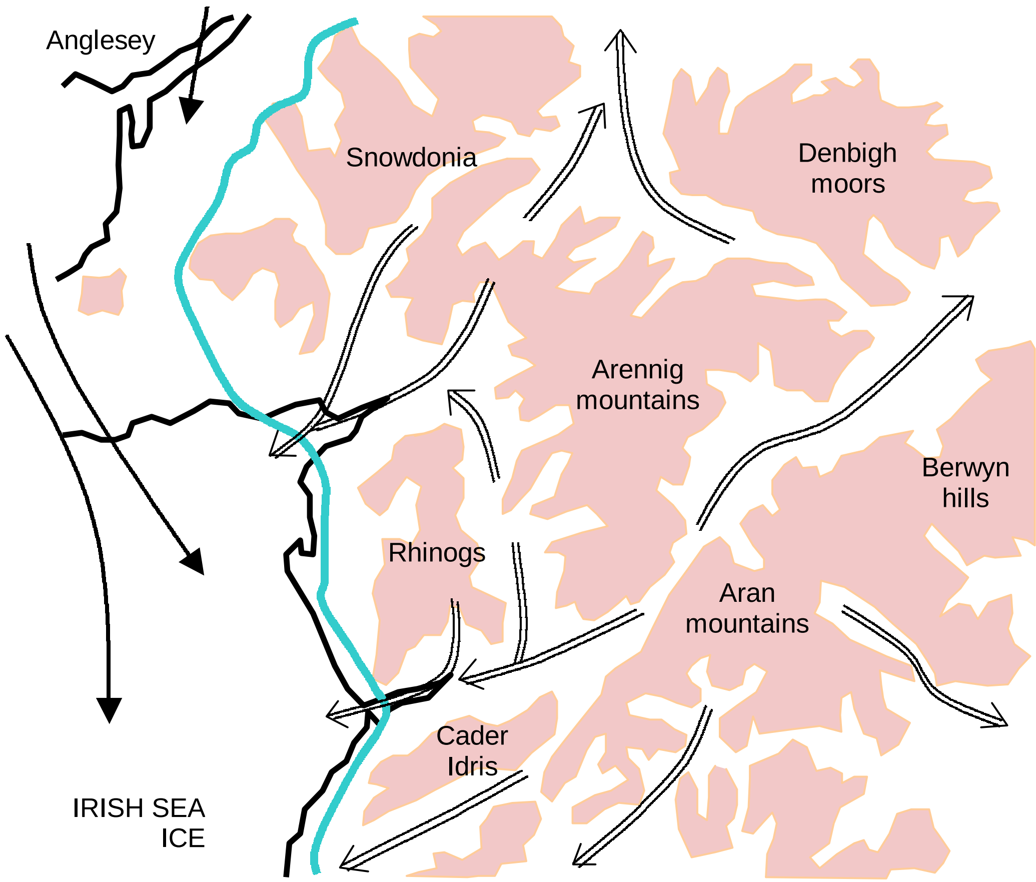

Figure 1.44. Main ice flow directions in North Wales (after Howe and Thomas, 1968)

Within the Harlech Dome region, a major ice cap was centred on the Arennig mountains, with the altitude of the ice reaching 1200m (Foster, 1968). Westwards flowing ice accumulated on the plateau surface around Trawsfynydd, from which it spilled northwards to the vale of Ffestiniog and southwards to the lower Mawddach valley. An extensive drumlin field developed around what is now Trawsfynydd reservoir. Mechanisms of drumlin formation are discussed by Price (1973).

Classical U-shaped profiles indicative of erosion by valley glaciers are shown by the lower Mawddach valley between Gelligemlyn and Llanelltyd (fig.1.45) and the lower Wnion valley between Bontnewydd and Dolgellau (fig.1.46).

Figure 1.45. The lower Mawddach valley

Figure 1.46. The lower Wnion valley

Figure 1.47. Llyn Aran

It is significant that the E-W oriented middle valley courses of the Mawddach, Gain and Afon Wen show no similar signs of glacier erosion, retaining deep V-shaped profiles, although boulder clay till is commonly present. The orientations of these valleys may have been such that they carried little ice flow in comparison to the main N-S oriented Trawsfynydd glacier.

Glacial cirque basins probably related to the late Devensian valley readvance (Watson, 1960; West, 1977) are seen along the north face of the Cader Idris escarpment. These may contain cirque lakes as at Llyn y Gader, Llyn y Gafr and Llyn Aran (fig.1.47). Cirques are also developed along the east facing escarpment of the Rhinog range above the Trawsfynydd plateau.

In the upper course of the Mawddach, features of valley glacier erosion are well developed at Allt Lwyd (fig.1.48). Downstream beyond Abergeirw, the River Mawddach descends into the steep gorge system of Coed y Brenin so it is unlikely that the main ice flow outlet from Allt Lwyd followed this route. Ice may have crossed low hills to reach the Trawsfynydd plateau directly, then merged with the main southwards ice flow towards the Mawddach estuary.

The Allt Lwyd valley is the possible site of a post glacial ribbon lake, dammed by a lobe of solifuction debris released from the steep south facing valley side. To investigate this theory, a geophysical survey was carried out in the area of the conjectured lake using the vertical electrical resistivity (VES) technique. Readings give a best fit (3% error) against a six layer model (table 1.1). Three layers with low resistivities in the range 44–196 Ω m occur at depths between 2m and 47m below the present ground surface. These resistivity values would be consistent with wet lacustrine clay, and show a sharp contrast with the high resistivity shale country rock beneath. An alternative interpretation is that one or more of the low resistivity layers represents glacial till of high clay content.

Figure 1.48. Allt Lwyd valley, looking SW. Site of the electrical resistivity sounding is marked in red.

Table 1.1. VES interpretation, Allt Lwyd

Resistivity (Ω m)	Modelled thickness (m)	Interpretation	Depth to base (m)
518	0.3	Topsoil	0.3
2015	1.8	Subsoil	2.1
149	18.9	Lake deposit	21.0
196	9.8	Lake deposit or glacial till	30.8
44	16.8	Lake deposit or glacial till	47.6
3465		Shale country rock	

It is likely that numerous additional lakes of various sizes existed within the Mawddach catchment in the immediate post-glacial period. The largest may have occupied the plateau east of the Rhinog mountain escarpment in the central area of the Harlech Dome (fig.1.49). Auger surveys have identified cream clay of probable lake origin beneath peat at both Cefn Clawdd near Trawsfynydd, and at Cefn Cam above Ganllwyd.

Figure 1.49. Site of conjectured post-glacial lake, Cefn Cam

A notable feature of the deeply incised river valleys of Coed y Brenin is a thick infill of glacial and periglacial material. The sequences are very varied in lithology, from freely draining gravel to sands, silts and clays of decreasing permeability (French, 1976; Clark and Small, 1982). Successions of up to 10m vertical extent are exposed in river cliffs in gorge sections of the Mawddach, Gain and Afon Wen.

To investigate the provenance of the sediments, grain size analysis was carried out on a series of samples from a river cliff succession at Pen Rhos in the Afon Wen valley (figs 1.50,1.51). The sediments may be divided into three groups:

- Very poorly sorted, with grain sizes reaching pebble grade or larger. Deposits falling within this group are identified as glacial till, and coarse river gravels with interstitial sand matrix.
- Very well sorted with finer grain sizes. Within this group were identified fluvial sands and silts, and a thin band of very clean, plastic yellow clay. The yellow clay is persistent downstream, and might represent lake bed material mobilised and carried down river after the failure of a glacial dam in the upper catchment.
- Materials exhibiting moderate sorting. These are interpreted as solifluction deposits, either in situ or emplaced within a short distance by river transport.

The sequence of sediments at Pen Rhos are interpreted as Boulder Clay of the Devensian valley readvance stage, overlain by periglacial deposits. The Late Devensian period has been subdivided into three Zones in North Wales (Howells et al., 1978), and it is during these Zones that the periglacial materials were produced:

- Zone I (Bølling) was a cold period after the final valley readvance. Solifluction processes would have been active at this time. Mass movement could occur on steep valley sides as periodic melting lead to saturation of the surface sediments above a permafrost horizon.
- Zone II (Allerød) was a warm period, during which larger volumes of meltwater would deposit fluvial sediments.

Zone III saw a return to cold conditions, with renewed solifluction activity.

		1. Forest brown earth
Zone III cold period	SOLIFLUCTION	2. Grey sandy clay
Zone II Allerød warm period	RIVER CHANNEL	3. Iron cemented cobble band
	LAKE FLOOR	4. Yellow clay
	FLUVIAL REDEPOSITION OF SOLIFLUCTION MATERIAL	5. Unstratified sandy gravel
		6. Fine gravelly sand
	FLUVIAL	7. Silty clay
Zone 1 Bølling cold period	SOLIFUCTION	8. Sandy gravel
Devensian valley readvance	VALLEY GLACIER	9. Boulder clay

Figure 1.50. River cliff deposits, Pen Rhos, Afon Wen

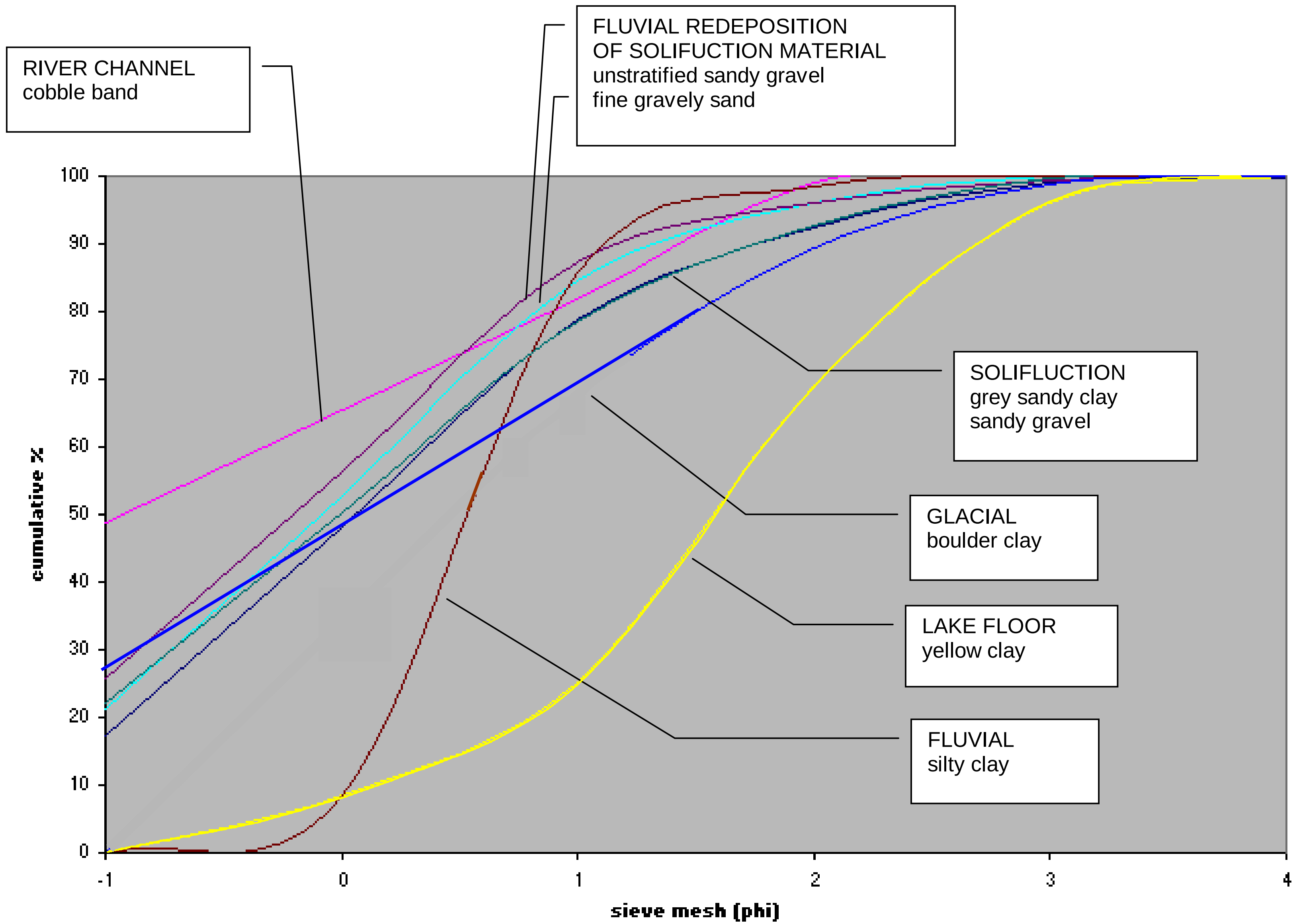

Figure 1.51. Sediment size distributions. River cliff deposits, Pen Rhos, Afon Wen.

When developing a hydrological model, the river routing function will be governed by characteristics of the river channels (Ward and Trimble, 2003). It is useful to carry out morphological classification of the river reaches within the Mawddach system. This will allow hydrological parameters to be assigned to reaches, based on measured parameters of sites with similar characteristics (Arcement G.J. and Schneider, 2003; Barnes, 1967).

Beechie et al. (2006) have considered river channel patterns and river-floodplain dynamics in forested mountain river systems of the Pacific Northwest USA. Straight channels are the least dynamic with relatively slow floodplain turnover. Braided channels are most dynamic, with floodplain turnover as low as 25 years and predominantly young floodplain surfaces. Island-braided and meandering channels have intermediate dynamics, with moderately frequent disturbances (erosion of floodplain patches) maintaining a mix of old and young surfaces. A threshold for the lateral migration of a channel occurs at a bankfull width of 15–20 m, as larger channels are deep enough to erode below the rooting zone of bank vegetation. Above this threshold, channels not confined between valley walls exhibit channel patterns distinguishable by slope and discharge, and slope–discharge domains can be used to predict channel patterns. The predicted spatial distribution of channel patterns reflects a downstream decline in channel slope, which is likely correlated with a declining ratio of bed load to suspended load.

Several morphological classification systems are available. The method chosen is that of Montgomery and Buffington (1997). This scheme has been developed for classification of mountain rivers, so it applies well to characteristics of the Mawddach drainage system.

The Montgomery and Buffington system defines seven basic categories of stream morphology, which represent in a general way a downstream sequence in response to decreasing stream gradient and increasing discharge. Reference reaches have been identified within the Mawddach-Wnion catchments which display characteristic stream morphology:

- Colluvial reach: Afon Ty Cerrig, Pared yr Ychain.

  Colluvial reaches occur as small first-order streams in the mountain headwaters of the river system. Stream gradients are typically greater than 20%, with much sediment movement occurring through debris flows from the steep valley sides (fig.1.52). Within the Mawddach catchment, colluvial reaches are associated particularly with slopes covered by Boulder Clay or periglacial deposits.

Figure 1.52. Colluvial reach. Afon Ty Cerrig at Pared yr Ychain, in the headwaters of the Afon Wnion.

- Cascade reach: Afon Ty Cerrig, Pared yr Ychain

  Cascade reaches are the next morphological type to appear as mountain rivers are followed downstream (fig.1.53). Typically they have boulder or cobble beds, and are narrowly confined by the valley sides. Slopes are in the range 10 - 30%.The large rocks within the channel are normally immobile, and are only transported during extreme flood events. More readily transported sand and fine gravel occurs within pools.

**Figure 1.53.
Cascade reach.
Afon Ty Cerrig,
Pared yr Ychain.**

- Step pool reach, Afon Mynach, Tai cynheaf

  Step pool reaches appear at gradients of 3 – 10%. Longitudinal steps form most of the elevation drops, with deep pools retaining sand and gravel bedload Fig.1.54). Step pool reaches may exhibit alternating supercritical and subcritical flow conditions between the steps and pools.

**Figure 1.54.
Step pool reach, Afon Mynach, Tai cynheaf.**

- Bedrock reach, Afon Gain near Gwynfynydd

  Bedrock reaches differ from the previous types in having no significant bed sediment present. Bedrock reaches are typically located where gradients are steep so the sediment transporting capacity of the stream greatly exceeds the sediment supply, even during normal flow conditions. Within the Mawddach catchment, bedrock reaches occur below knick points on the Afon Mawddach and Afon Gain (fig.1.55) where river rejuvenation is evident.

Figure 1.55. Bedrock reach, Afon Gain near Gwynfynydd.

- Plane bed reach: Afon Mawddach, Ty'n y Groes

  Plane bed reaches (fig.1.56) occur for gradients around 2-3%, and typically have a high bed roughness. They lack rhythmic bed forms such as steps, pools and riffles. Plane bed reaches are thought to form a transition between upstream channels where sediment movement is limited by supply, and downstream channels where sediment movement is limited by stream energy.

Figure 1.56. Plane bed reach. Afon Mawddach, Ty'n y Groes.

- Pool riffle reach: Afon Wnion west of Dolgellau

  Pool riffle reaches (fig.1.57) have a gentler gradient of around 1-2%. Pools occur at intervals of approximately 6 channel widths, with intervening shallow riffles crossing the channel. Flood plains are usually well developed.

Figure 1.57. Pool riffle reach, Afon Wnion west of Dolgellau.

- Dune ripple reach, Mawddach estuary upper basin, Penmaenpool

  Dune ripple reaches normally occur in sand bed channels with bed slopes less than 1%. These systems are very dynamic, with sediment movement occurring frequently and bedforms changing regularly. Dune ripple reaches occur in the upper basin of the Mawddach estuary, where fluvial processes are dominant.

Figure 1.58. Dune ripple reach, Mawddach estuary upper basin, Penmaenpool.

An additional category in the classification is the **forced pool reach**. This refers to step pools produced by non-fluvial processes, such as obstruction by fallen trees (fig.1.59) or the construction of weirs and fords. Wohl (2000) stresses the importance of woody debris and bank mass movement in controlling morphological changes in mountain rivers.

Figure 1.59. Fallen trees in the channel of the Afon Wen, Coed y Brenin.

Forced pool reaches are relatively rare within the Mawddach catchment, as timber obstructions in the main rivers of the Mawddach system are generally removed rapidly by the Forestry Commission, other land owners or the Environment Agency, to prevent flooding of riparian areas.

Soils

Classification

Soil type is related to a number of factors acting together at a locality
(Burnham, 1980):

- the physical nature of the bedrock or glacial and periglacial deposits affecting the mechanical breakdown and input of rock material to the soil profile.
- the chemical nature of the bedrock, affecting the input of plant nutrients, especially calcium.
- relief, affecting drainage and soil movement under gravity.
- hydrological conditions which affect the amount of water passing through the soil, and hence the degree of leaching or waterlogging.
- the agricultural history of the site, affecting the characteristics of the soil horizons.

Due to the seaboard location, southerly latitude, and relatively low elevation, the Mawddach catchment experiences an oceanic rather than montane climate. Typically, there will be high precipitation, high cloud cover and humidity, and low sunshine levels. Most soils are at least seasonally wet and show reducing chemical conditions with iron present as the ferrous ion . Locally the presence of steep slopes produce well drained soils, as do scree slopes and blockfields where drainage into cavities is rapid.

Fig.1.60 illustrates the distribution of the soils in and around the Mawddach catchment, simplified from the National Soil Map (Avery B.W., 1980; Cranfield University, 2004). The principal soil types found in the Mawddach catchment are:

Ranker. Ranker soils occur where the input of mineral material from the bedrock is almost negligible. The profile shows an organic A horizon, generally as a peat mat, lying directly on the solid rock surface (C horizon). Two types are distinguished within the Mawddach catchment:

- Revidge series: peaty humic ranker occurring mainly on Rhinog grit.
- Skiddaw series: more decomposed humic ranker, mainly on resistant igneous rocks (fig.1.61A).

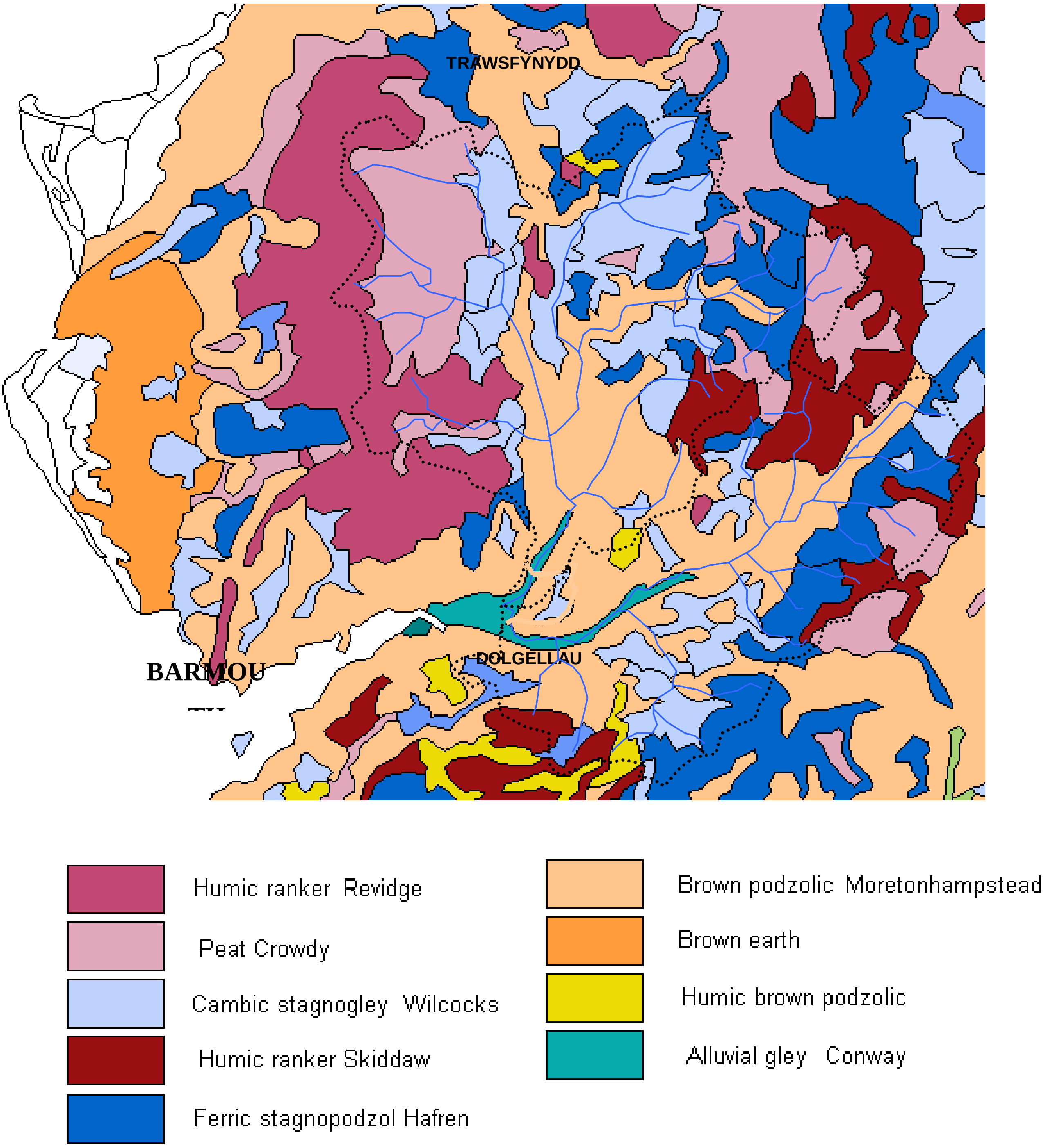

Figure 1.60. Soils of the Mawddach catchment (after Soil Survey of Great Britain)

A. Humic ranker on ignimbrite, Aran Fawddwy

B. Brown podzolic soil on diorite, Hermon

C. Stagnohumic gley on glacial till, Pared yr Ychain

D. Cambic gley on Upper Cambrian shales, Oernant

Figure 1.61. Soils of the Mawddach catchment

Brown earth. This soil type is deep, well drained and fertile. The A. horizon consists of mild humus of well-rotted plant material. Below is the B horizon composed of mineral particles, rich in iron and showing a brown colouration. The B horizon does, however, show a division into a sandy upper layer from which clay has been washed (E_b) and a lower layer where clay has accumulated (B_t); the layers are distinguished by their textures rather than colour or chemical nature. Brown earths are found in the coastal region of Ardudwy, west of the Mawddach catchment.

Podzolic soils. A podzol shows sharply contrasting soil horizons. The A horizon is dark brown or black and composed of acid humus. Below is a white or bleached horizon from which iron and other bases have been washed downwards by percolating groundwater. This removal of bases is called eluviation, and the horizon termed E_a. Below is a reddish horizon where iron has accumulated, termed the B_{fe} horizon.

If fluctuations in the water table occur during the year, the upper part of the B horizon may become aerated and an iron pan layer may form by oxidation of the accumulated iron. The C horizon consists of unaltered bedrock or glacial deposits forming the soil parent material.

The soils of the more fertile valley areas of the Mawddach catchment are brown podzolic soils, intermediate between brown earths and true podzols, showing a smaller amount of downwards leaching (fig.1.61B). A variety of brown podzolic soil with high humus content in the A horizon is found on volcanic outcrops around Cader Idris

Gley. Gley soils result from waterlogging. If water stays in the soil for a long period, the soil pores become filled and oxygen is excluded. Iron in the soil becomes reduced, giving a greenish colouration, although red mottles may be present where oxygen has been able to penetrate the soil along pores and structural cracks. Under conditions of gleying, the activity of soil microorganisms is prevented and plant material fails to decompose completely. This gives rise to peat accumulation if growth of vegetation continues fig.1.61C).

Alluvial gley soils subject to regular flooding are found in the lower valleys of the Mawddach and Wnion, and around the head of the estuary.

Cambic soils are poorly developed soils lying on bed rock at shallow depth. Where the bed rock is impermeable, gleying can occur. Cambic gley soils are found on outcrops of Cambrian shales and grits north of Coed y Brenin (fig.1.61D).

Peat soils. True peats occur in bogs and mires, where the peat reaches sufficient thickness to isolate the soil from any mineral substrate. Peat blanket bogs within the Mawddach catchment are discussed further in Chapter 3.

Hydrological characteristics of soils

The soil map above gives a general distribution, but wide variations in soil type can occur over short distances due to local conditions of slope, geology or vegetation (Pears, 1977). Typical soil sequences or *catenas* developed down hillslopes are shown in figs 1.62-1.63.

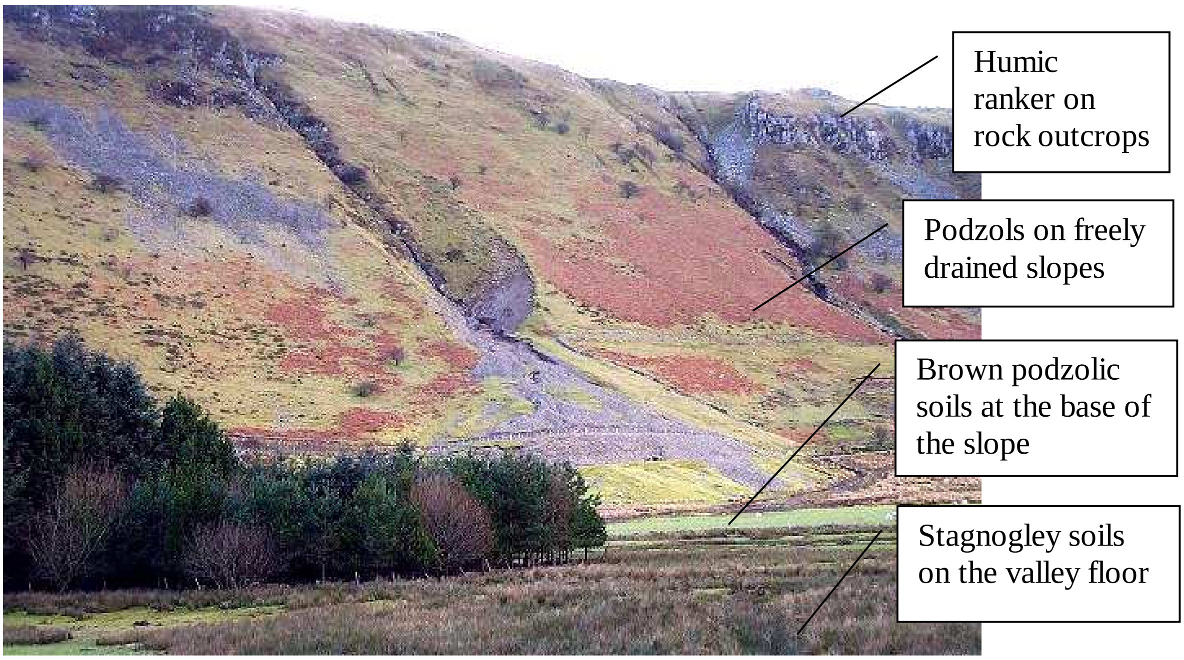

Figure 1.62. Soil catena, Allt Lwyd valley.

Ranker soils are formed on outcrops of resistant rock exposed by glacial erosion in upper mountain areas. Peaty gley podzols may develop on the gentler slopes surrounding summit plateaus where rain water runoff moves slowly towards the incised valleys.

Steeper valley slopes represent areas of rapid shallow throughflow, leading to leaching of soluble minerals and formation of podzols. Finer clay and silt particles carried down hill may accumulate on the well drained concave slopes of the valley floor to develop the thicker soil profiles of podzolic brown earths.

Flatter areas of the valley floor, especially near streams, may be subject to gleying due to a high water table for much of the year. In glaciated valleys, drainage is particularly impeded by boulder clay till or lacustrine clay deposits at shallow depth.

Gley soils of valley floors are potentially very fertile, and land drainage is commonly carried out within the Mawddach catchment to improve grass yield, both for hay and silage production and to bring forward the time in spring when grazing of the land may begin. Drainage techniques include construction of open ditches, and the installation of buried perforated plastic pipes. Agricultural modification of soil characteristics should be considered when developing a hydrological model for areas where land drainage has been carried out.

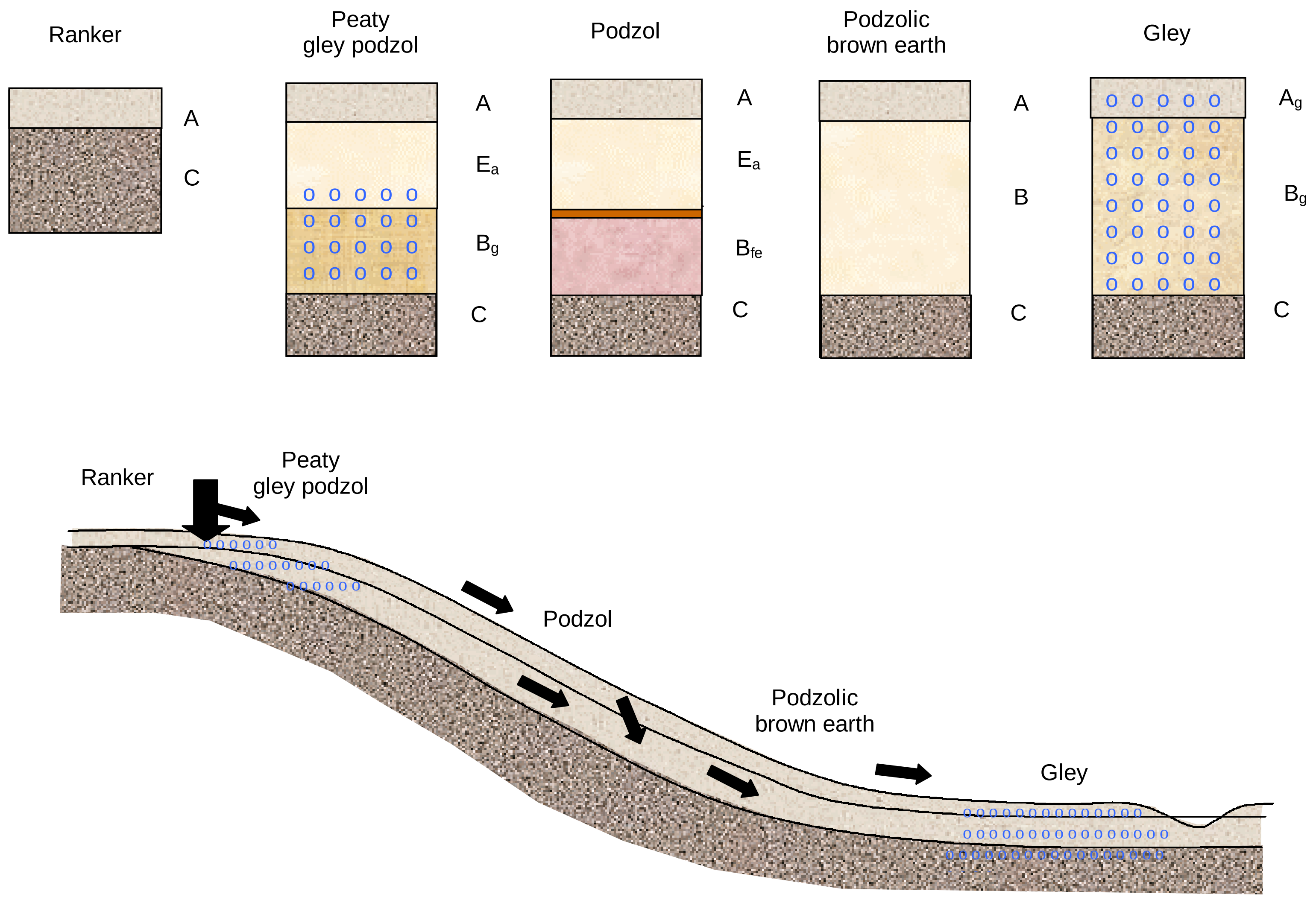

Figure 1.63. Soils in relation to slope and water movement

HOST classification scheme

The National Soil Classification system used in fig.1.60 has been developed for geographers, agriculturalists and ecologists, so does not directly address the hydrological characteristics of soils. An alternative classification known as HOST (Hydrology Of Soil Types) has been produced by the Institute of Hydrology (Boorman et al.,1995) and concerns itself primarily with the surface runoff and infiltration characteristics of soils. It is the HOST classification which has been used in the Mawddach research project.

The HOST system is based on a matrix of 11 hydrological response models identified by the letters A to K (fig.1.65). The three horizontal rows within the matrix represent the three basic hydrological pathway structures which may be present in soils:

1. Soils with a high permeability substrate in which the groundwater table is usually deep. Possible water pathways are: vertical infiltration, shallow throughflow and surface runoff. Vertical infiltration generally predominates, and surface runoff is uncommon.
2. Soils with moderate permeability substrate, so the groundwater table is generally near the surface. Possible water pathways are: addition to groundwater store, shallow throughflow and surface runoff. Shallow throughflow is predominant.
3. Soils with low permeability substrate. Possible water pathways are: slow infiltration to groundwater store, shallow throughflow and surface runoff. Shallow throughflow and surface runoff are predominant.

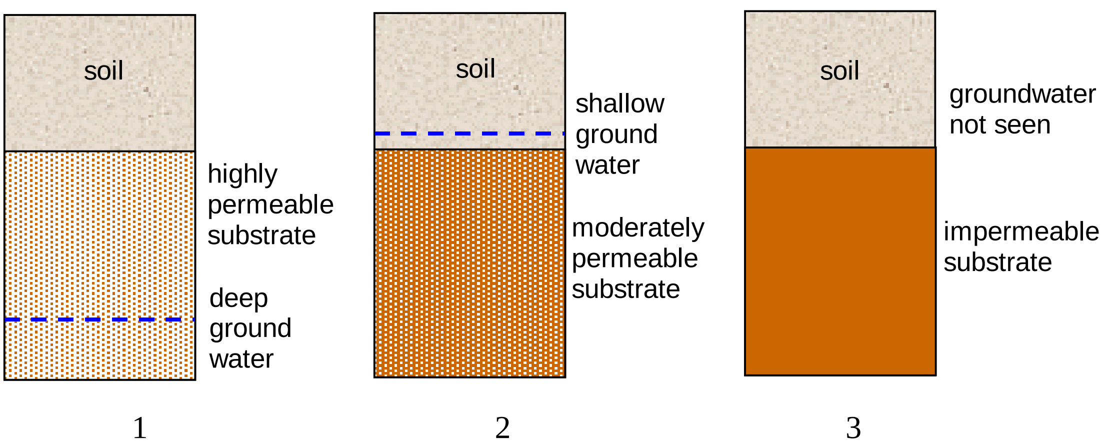

Figure 1.64. Basic hydrological classification of soils

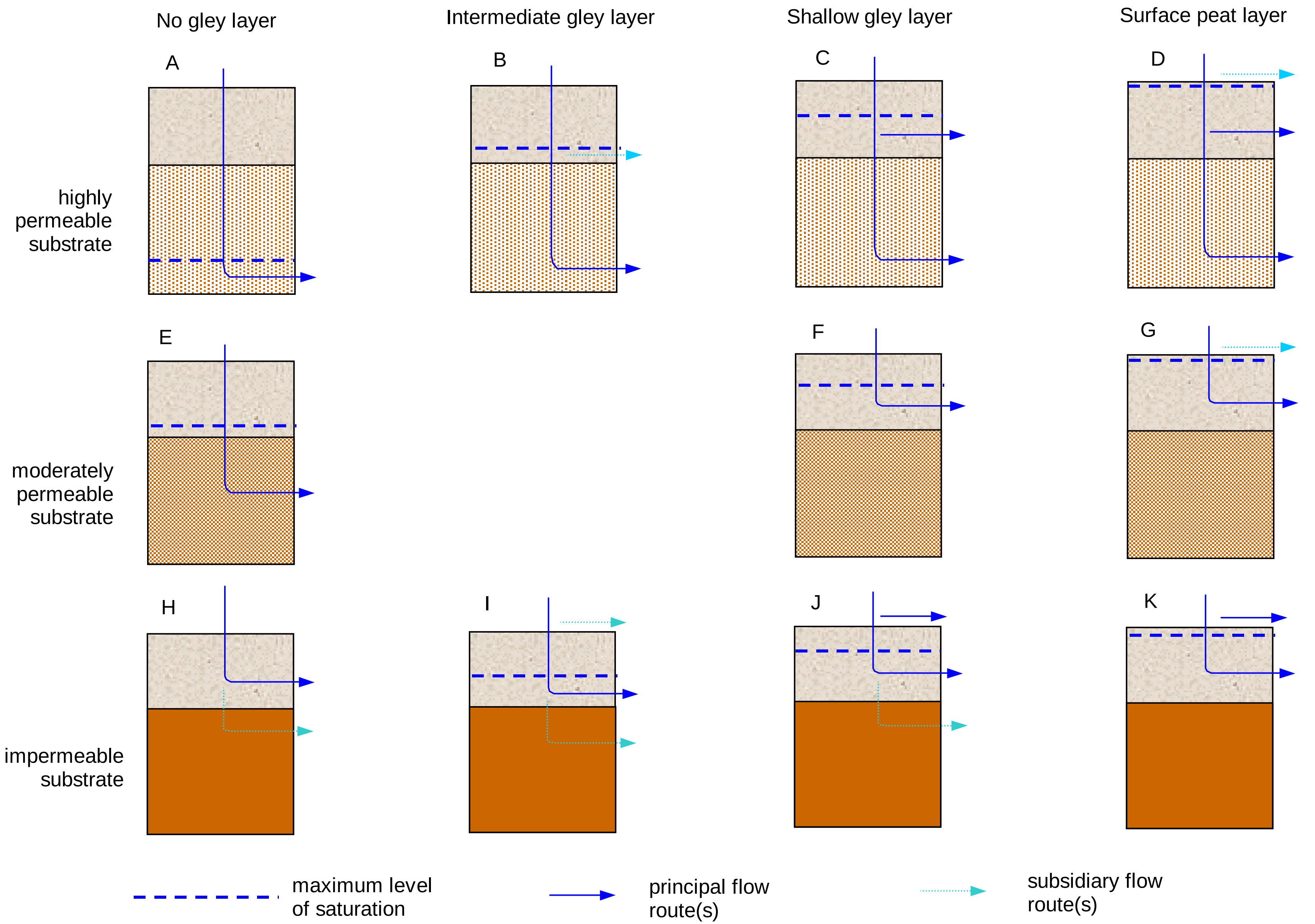

Figure 1.65. HOST hydrological response models (after Boorman, Hollis and Lilly, 1995)

The four vertical columns of the matrix of models (fig.1.65) represent progressively wetter sites within a soil catena. Column 1 contains situations with small volumes of water accumulation, allowing the level of saturation to be low in the soil profile. Columns 2 and 3 represent sites with larger volumes of water accumulation. Column 4 is the situation in which waterlogging is complete, and a surface peat layer is able to accumulate. Dominant and subsidiary water flow pathways are illustrated for the different models.

The HOST classification further subdivides the general models to distinguish a total of 29 hydrologically distinct soil classes which can be identified within Britain (fig.1.66). Only a subset of these classes is present in the Mawddach catchment.

Model A of highly permeable substrate with low water accumulation is subdivided into HOST classes 1-6 according to the substrate geology.

Integrated air capacity (IAC) is used to subdivide models F and I. This parameter is a measure of the amount of small pore space within the soil which is capable of holding water by capillary action. It is used as an indicator of saturated hydraulic conductivity for model F, and as a measure of soil water storage capacity for model I.

The HOST classification system is used in the Mawddach hillslope model as a basis for automated soil mapping and the allocation of hydrological parameters. This application is discussed in Chapter 4.

drier types **intermediate** **wetter types**

	SUBSTRATE HYDROGEOLOGY	MINERAL SOILS						PEAT SOILS	
		Groundwater or aquifer	No impermeable or gleyed layer within 100cm	Impermeable layer within 100cm or gleyed layer at 40-100cm IAC > 7.5	IAC <= 7.5	Gleyed layer within 40cm IAC < 12.5	IAC >= 12.5	Drained	Undrained
permeability increases downwards	Chalk	Normally present and at > 2m	1 A		B		C		D
	Limestone		2						
	Weakly consolidated, macroporous, by-pass flow uncommon		3	13		14		15	
	Strongly consolidated, non- or slightly porous, by-pass flow common		4						
uniform permeability	Unconsolidated macroporous, by-pass flow very uncommon		5						
	Unconsolidated microporous, by-pass flow common		6						
	Unconsolidated macroporous, by-pass flow very uncommon	Normally present and at <= 2m	7		E		F		G
	Unconsolidated microporous, by-pass flow common		8			9	10	11	12
permeability decreases downwards	Slowly permeable	No significant groundwater or aquifer	16 H	18	21 I	24	J	26	K
	Impermeable (hard)		17	19	22			27	
	Impermeable (soft)			20	23	25			
	Eroded peat							28	
	Raw peat							29	

Figure 1.66. Hydrology of Soil Types (HOST) classification system (after Boorman, Hollis and Lilly, 1995)

Vegetation

Most upland areas in the Mawddach catchment are underlain by rocks whose character is acidic or of intermediate acidity. This, combined with a normally high rainfall, gives soils that are mainly leached and podzolic (Edgell, 1969).

Most upland pastures have been formed from ancestral oak and birch forest. Pressure on this forest area began in the Bronze Age and continued until much had been removed by the fifteenth century. Associated with this change was an increase in pastoral agriculture and in the numbers of both sheep and cattle. In the 17th and 18th centuries, sheep increased more than cattle to create sheep farming in a form and on a scale similar to today. Thus, many areas have been grazed for at least 600 years, with large scale intensive sheep farming appearing in the last 200 years.

The variation shown by the present vegetation of the uplands of the Mawddach catchment is related to two main environmental gradients, soil nutrient level and soil drainage. Vegetation classes are summarised in fig.1.67.

Bogs and mires

Impeded drainage on valley floors leads to waterlogging and gleying of soils, often accompanied by accumulation of peat where the activity of decomposing microorganisms in the soil is prevented by anaerobic conditions. Waterlogged areas can be divided into bogs, which are mainly stagnant zones of water accumulation, and mires which have a constant throughflow of groundwater carrying plant nutrients in solution. Mires are more floristically rich than bogs as they present a less chemically hostile environment (Rodwell: 1991b, 1995).

Two types of bog site are common:

- Topogenous bogs with unhumified peat occur in level basin areas where ground water accumulates.
- Ombrogenous bogs occur on gentle slopes where waterlogging results from high rainfall in conjunction with slow run-off of ground water. The peat in such sites is humified as the water table is below the surface for much of the year.

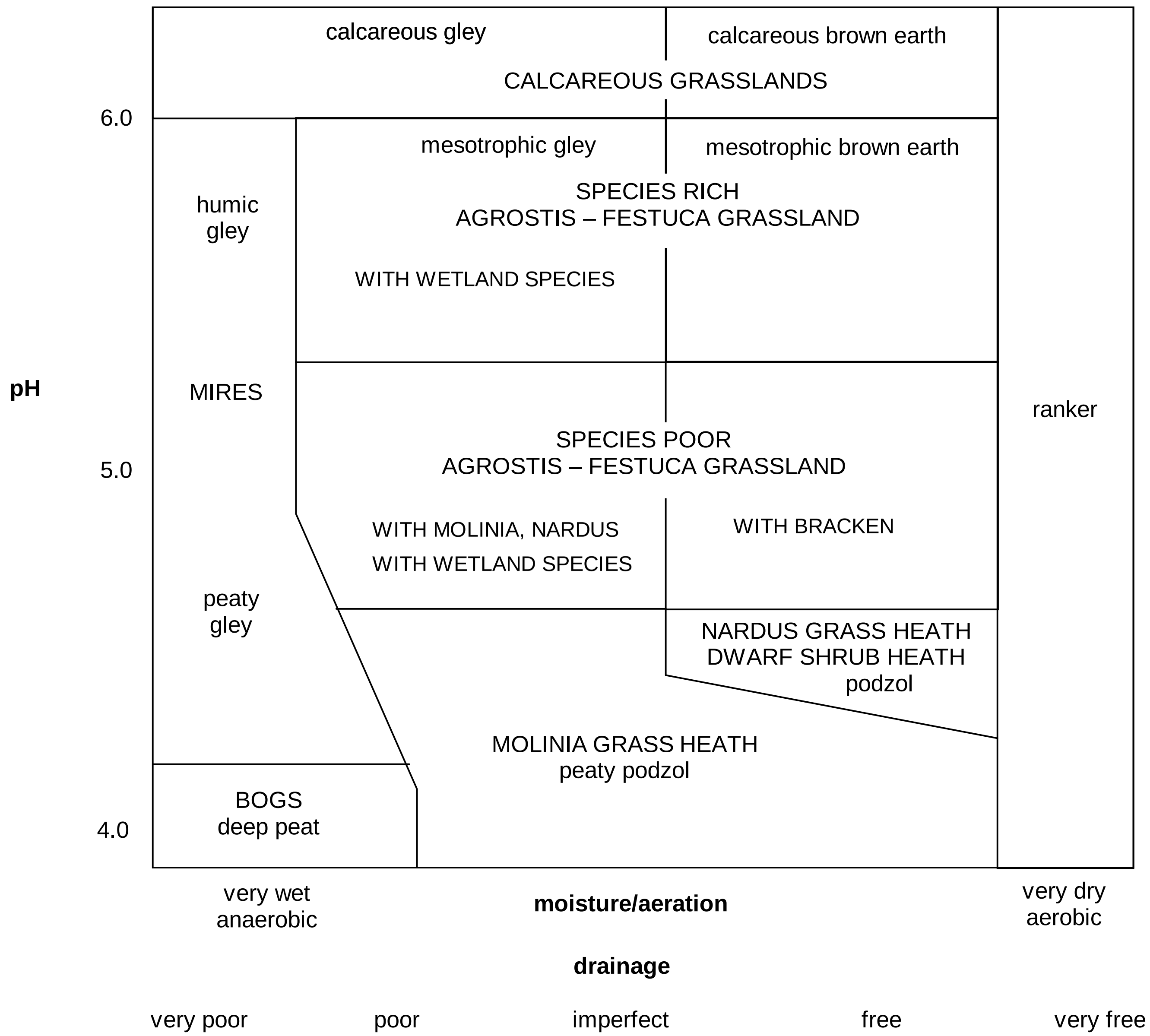

Figure 1.67. Vegetation classes in relation to soil nutrient level and drainage (after Edgell, 1969)

Topogenous bogs often occur initially around pools of open water. There will be a change in vegetation from true aquatic plants such as *Potomogeton* (pondweed) and *Nymphaea* (waterlily) to scattered plants of *Carex* and *Juncus*, and then a carpet of *Sphagnum* moss supporting *Carex rostrata* (bottle sedge). Basin sites may be covered by a community of *Sphagnum* and *Eriophorurn angustifolium* (common cotton grass) (University of Paisley, 2005).

Figure 1.68. Topogenous bog, Waen y Griafolen

Ombrogenous bogs are generally drier, and form a transition to heaths. *Eriophorum vaginatum* (hare's tail cotton grass) is often dominant, with heath dwarf shrubs in association including *Calluna, Vaccinium, Empetrum nigrum* (crowberry) and *Erica tetralix* (cross leaved heath). *Drosera*, the insectivorous sundew plant may be common.

Peat which is shallower and drier than in *Eriophorum* bogs may support a community of *Juncus squarrosus* (heath rush). *Luzula sylvatica* (woodrush) may also be important. A further species which may dominate ombrogenous sites is *Tricophorum* (deer grass).

Figure 1.69. Transition from topogenous to ombrogenous blanket bog, Waen y Griafolen.

Figure 1.70.
***Tricophorum* (deer grass) blanket bog,**
Waen y Griafolen.

Mires experience a constant throughflow of drainage water, in contrast to the more stagnant conditions of groundwater in bogs. This leads to a higher input of nutrient bases in mires, giving reduced acidity and a more favourable chemical environment for floristic diversity.

Figure 1.71.
***Carex echinata* (star sedge) mire, Llyn y Gafr, Cader Idris.**

Mires are most common on lower concave slopes which receive drainage water from the hillside above. The floristic richness of a site will depend on the rate of water flow and the geochemical nature of the surrounding area of the drainage basin. Mires range from acid sites closely resembling bogs, dominated by *Sphagnum* and *Eriophorum*, to sites with great diversity of flora including:

- *Calluna* (ling), *Erica* (cross leaved heath), *Vaccinium* (bilberry)
- grasses: *Agrostis, Festuca, Holcus, Molinia, Nardus*
- sedges and rushes: *Carex, Juncus*
- a variety of flowering plants: *Cirsium* (marsh thistle), *Galium* (heath bedstraw), *Potentilla* (tormentil), *Ranunculus* (meadow crowfoot), *Saxifraga* (starry saxifrage), *Viola* (marsh violet)
- mosses: *Hypnum, Polytrichum, Rhytidiadelphus, Sphagnum.*

Heaths

Heaths are dominated by dwarf shrubs (Rodwell: 1991b,1992). The soil is podzolic and nearly always with surface peat of pH 3.7 - 4.7. Heaths can be divided according to the dominant vegetation:

Calluna vulgaris heaths in which ling is the dominant species are widespread on well-drained scree of slope angles from 10º to 40º. In areas affected by water seepage, mosses can be important. *Hypnum cupressiforme*, however, is a moss which can dominate the ground layer even on excessively drained screes.

Figure 1.72. *Calluna* (ling) heath, Llyn Aran

On slopes of low angle where drainage is impeded, gley or pasty podzol soils develop. These support a heath vegetation dominated by *Erica tetralix* (cross-leaved heath). This damp heath can grade into bog and mire communities. Soil acidity is the factor favouring heath vegetation.

Vaccinium myrtillus (bilberry) heath is transitional between *Calluna* heath and acidic grasslands. *Vaccinium* is best developed on north-facing slopes of scree.

Figure 1.73.
***Vaccinium* heath, grading into grassland. Llyn Aran.**

Grasslands

In the upland areas of the Mawddach catchment, grasslands can be divided according to altitude into montaine and sub-montane types. These in turn are divided into communities with characteristics resulting from variations in soil moisture, soil acidity and grazing pressure (Rodwell, 1992).

- Sub-montane grasslands

  Nardus stricta grasslands (matgrass) are developed on flat plateau areas with gentle slopes where deep peat podzols and gley podzols are dominant. Wetter areas have *Viola palustris* (marsh violet) and *Cirsium palustre* (marsh thistle) present.

  Agrostis-Festuca grassland (purple moor grass - sheep's fescue) is widespread on slopes of 10º - 40º which are freely drained. The mosses *Polytrichum* and *Rhytidiadelphus* have a high cover value. *Agrostis tenuis* (brown bent) may be common.
- Montane grassland:

  Festuca-Juncus (Sheep's fescue - rush) grassland occur on the high summit plateaus where drainage is impeded.

  On drier sites, *Festuca* - *Cladonia* (sheep's fescue - lichen) grasslands develop.

The relationships between slope, soil type and the natural and semi-natural vegetation associations of the Mawddach uplands are summarised in fig.1.74.

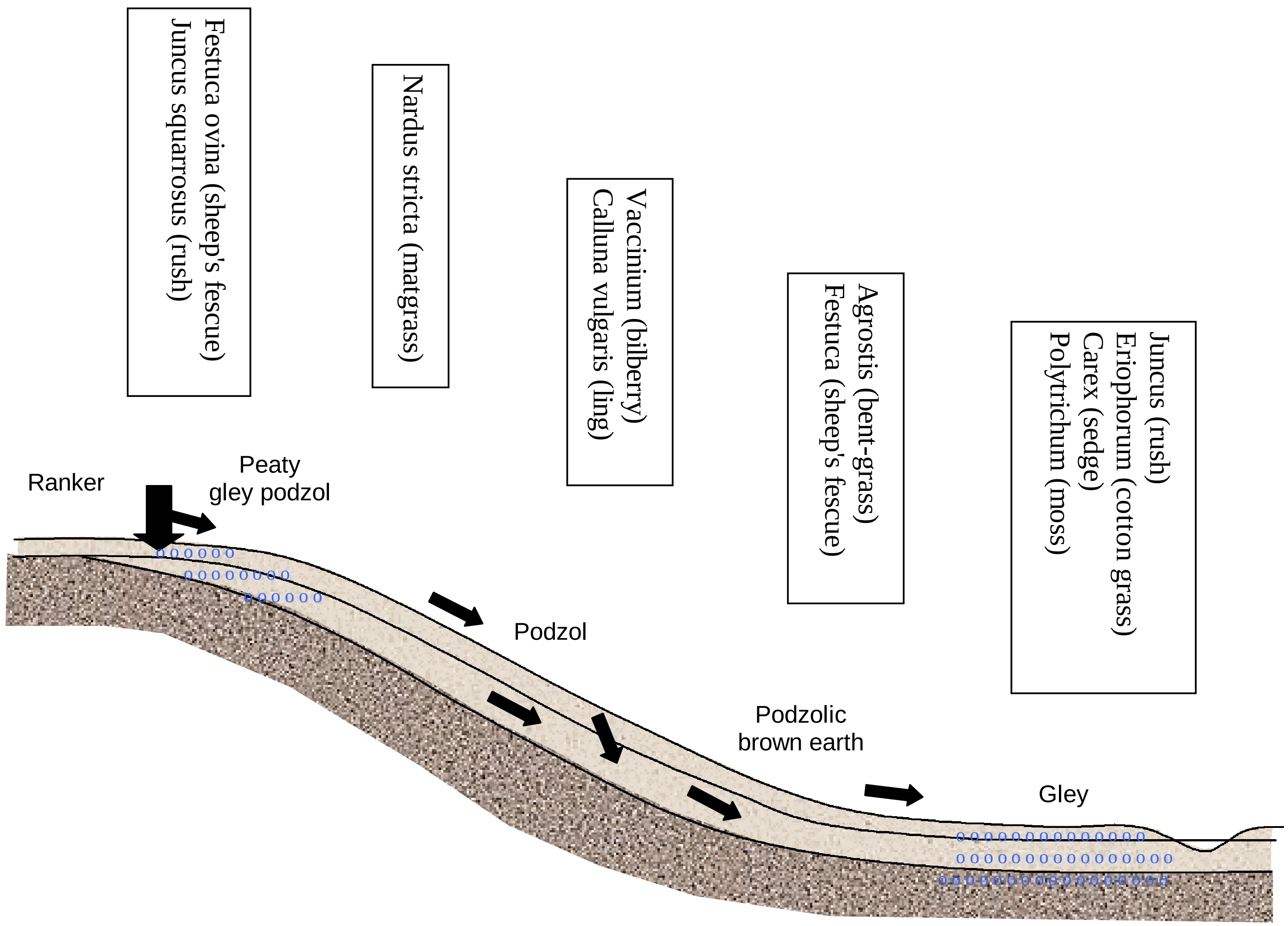

Figure 1.74. Typical vegetation associated with soil types, slope and drainage conditions

In the lower valleys of the catchment, grassland is mainly utilised for sheep and cattle grazing or production of hay and silage. Where grazing is restricted, species rich meadows can develop. Examples occur around the head of the Mawddach estuary (fig.1.75).

Figure 1.75. Species-rich water meadow in the upper basin of the Mawddach estuary, dominated by Rush, Sedge, the grasses *Agrostis* and *Deschampsia*, and a variety of flowering plants including: Clover, Marsh Thistle, Sharp Dock, Buttercup and Burnet Saxifrage.

Forestry

Relics of oak-dominated native woodlands survive in the Mawddach catchment, particularly in the gorge sections of the main rivers where their precarious sites have protected them from grazing pressures (fig.1.76). Mixed woodlands commonly occur across the riparian zones of the lower valleys, with wet woodland types dominated by willow and alder close to streams.

Commercial forestry has been developed extensively since the 1950's, establishing the conifer plantations of Coed y Brenin and the Wnion valley. In recent years, emphasis has moved from timber production towards recreational use of Coed y Brenin.

Figure 1.76: Mixed broadleaf woodland, Afon Clyweddog

Mountain bike trails around the forest are being extensively developed, in addition to encouraging use by walkers. The woodlands are increasingly being managed for their landscape and ecological value, with a move towards planting areas of broadleaves to replace conifers.

Figure 1.77:
Ground vegetation beneath a plantation of Douglas Fir, Hermon.
Mosses *Polytrichum* and *Plagiothecium* predominate.

An aspect of forestry practice which has implications for hydrological response is the age at which felling and replanting takes place. For commercial production, felling of Sitka spruce typically occurs after 34 years, with larch felled after 40 years. In areas of scenic importance, trees are being allowed to mature beyond this age, creating a higher canopy and more open forest structure. This encourages the growth of a prolific ground vegetation which may be dominated by mosses (fig.1.77).

To investigate the effects of vegetation on surface runoff production, a set of experimental sites were set up on hillslopes overlooking the village of Hermon in the Afon Wen sub-catchment. Three sites were chosen which were closely similar in slope angle and all underlain by a thick sequence of sand and gravel and clay periglacial valley infill deposits. The sites differ in land use: site 1 is a mature conifer plantation, site 2 is a clear-felled area of the same plantation, and site 3 is permanent grassland (figs 1.78-1.79).

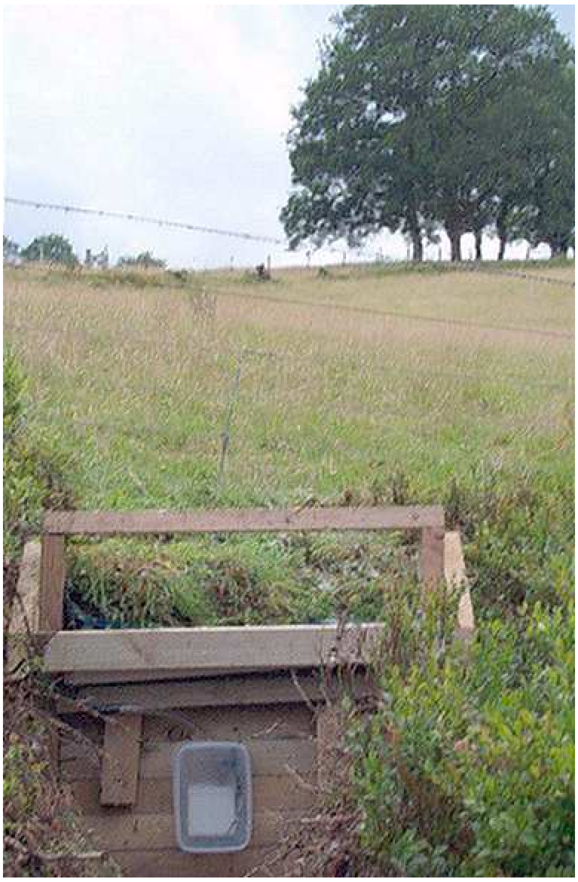

Figure 1.78: Surface runoff experiment, Hermon. (left) Site 1 beneath mature conifer plantation. (right) Site 3 beneath permanent grassland.

Figure 1.79: Clear felled hillslope at Hermon site 2

At each site, a collecting trough for surface runoff was installed, connected by tubing to a tipping bucket gauge and data logger. Runoff was measured for storm events during a period of six months from March to September 2003. Typical results are presented in fig.1.80 and redisplayed as cumulative curves in fig.1.81.

Runoff production is significantly higher from the clear felled hillslope in comparison to the forest and grassland sites. Whilst the mature conifer plantation and grassland generate approximately equal amounts of total runoff, the cumulative curves indicate that runoff initially increases more rapidly at the grassland site with the onset of storm rainfall. In fig.1.81 this effect is first observed for the rainfall event at 18 hours, but becomes progressively more marked with the events at 28 hours and 83 hours.

It is suggested that the difference in runoff rates for the forest and grassland sites can be explained by the nature of the ground vegetation. In the case of the forest, this is composed of deep and irregular masses of moss. With the onset of storm rainfall, surface water which cannot infitrate moves downslope through the vegetation cover. Dry mosses and grasses may provide similar resistance to flow, but the soft and flexible grass cover becomes progressively less resistant to surface flow with wetting. Moss colonies have a more rigid structure and maintain their resistance to surface water flow. Fast surface runoff from grassland increases in relation to moss ground vegetation for subsequent storms within a rainfall sequence.

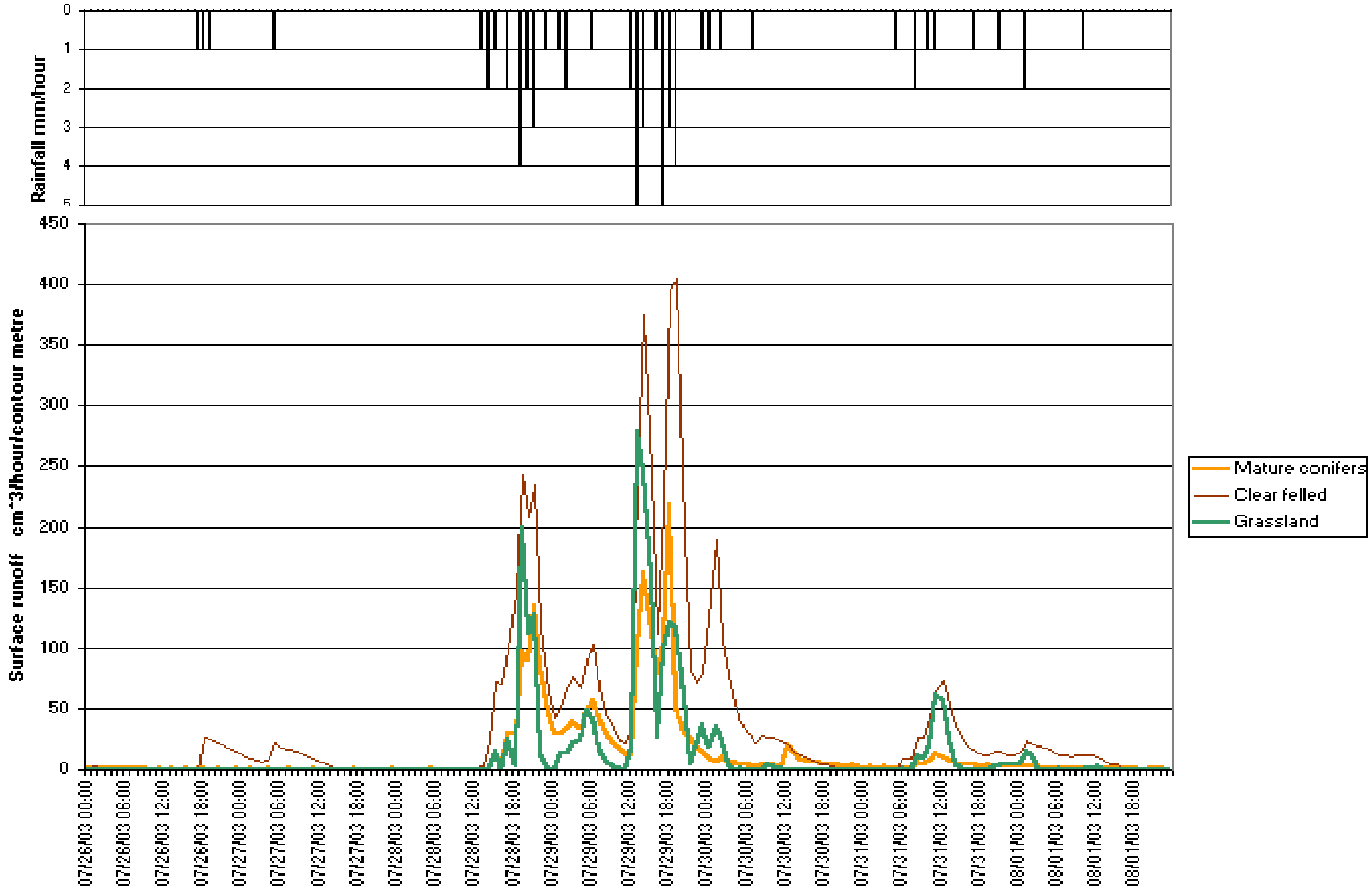

Figure 1.80: Surface runoff at experimental sites, 26 July – 1 August 2003

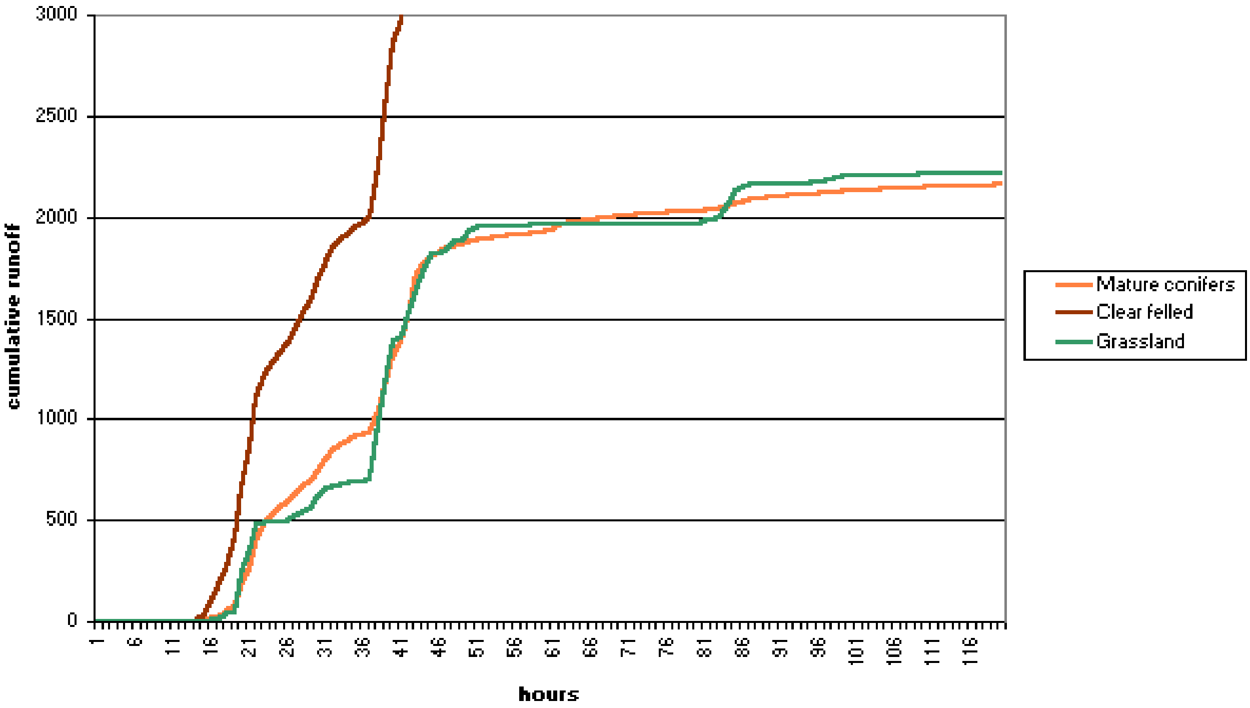

Figure 1.81: Cumulative surface runoff at experimental sites for the period 00:00h, 28 July to 00:00h, 2 August 2003

The moss cover beneath mature woodland appears to be playing a useful role in delaying surface runoff into river channels, and consequently has a moderating effect on flood peak generation downstream. It is therefore of interest to consider the conditions which encourage prolific moss growth beneath woodland in the Mawddach catchment.

A conceptual model has been developed, linking microclimate, vegetation and soil profiles developed beneath the sites (fig.1.82). Temperature and relative humidity at sites 1 and 2 have been monitored during the period of the soil runoff experiment, with example results shown in fig.1.83. Graphs of temperature are similar, but relative humidity is significantly higher within the forest, often remaining at 100% for much of the day during wet periods. The effect is to promote the growth of a prolific moss ground cover. This vegetation is able to trap slope wash sediment and adds organic material to the soil. The important role of high humidity for moss growth is discussed further by Clymo (1973).

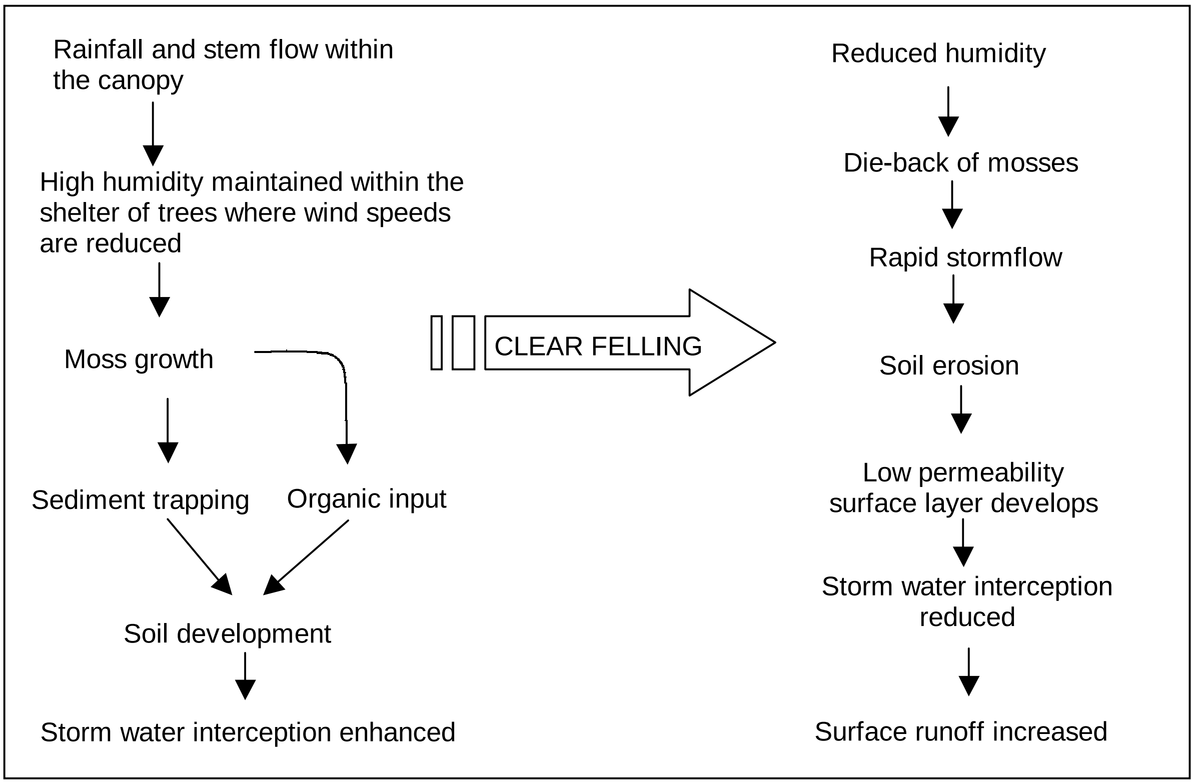

Figure 1.82: Summary of hillslope hydrology processes operating in the mature forest areas of Coed y Brenin

Figure 1.83: Humidity levels on hillslopes, measured at 50cm above the ground

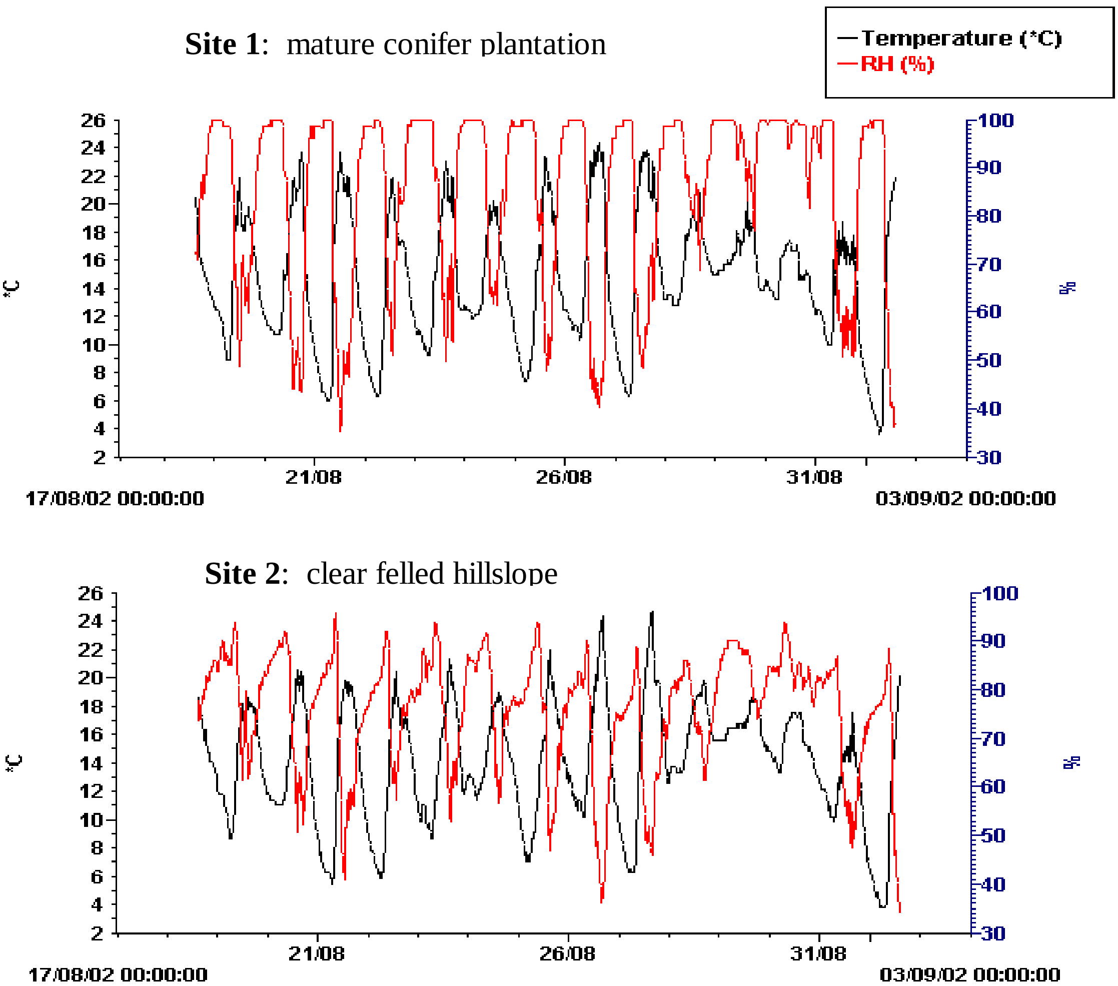

Fig. 1.84 illustrates soil profiles beneath sites 1 and 2. Over the 50 year period of forest growth, a deep soil profile of 140cm of brown earth developed at site 1. Within one year of clear felling, severe erosion removed over a metre of soil. 30cm of matted humus remains as a relatively impermeable hillslope cover.

Figure 1.84(a):
soil profile beneath forestry at site 1

Figure 1.84(b):
soil profile beneath clear felled hillslope: site 2

Soil development beneath the grassland has reached a stable profile depth of around 90cm. The limited depth in comparison to the conifer plantation may be due to less efficient trapping of downslope sediment wash by grasses.

A plot has been made of relative runoff rates for the three experimental sites, with time intervals sorted in order of increasing grassland runoff (fig.1.85). For low total runoff, the relative flow rates from the mature conifer plantation and from the clear felled hillslope can be very variable, but settle down to consistent ratios for moderate to high intensity rainfall events. Runoff is greatest from the clear felled site and least from the mature conifer site. Standardising to the runoff from grassland produces an average runoff relationship (table 1.2).

Land use	Relative runoff volume
Mature conifers	0.67
Grassland	1.0
Clear felled	2.0

Table 1.2. Relative rainfall runoff volumes from experimental sites with different land use, Hermon

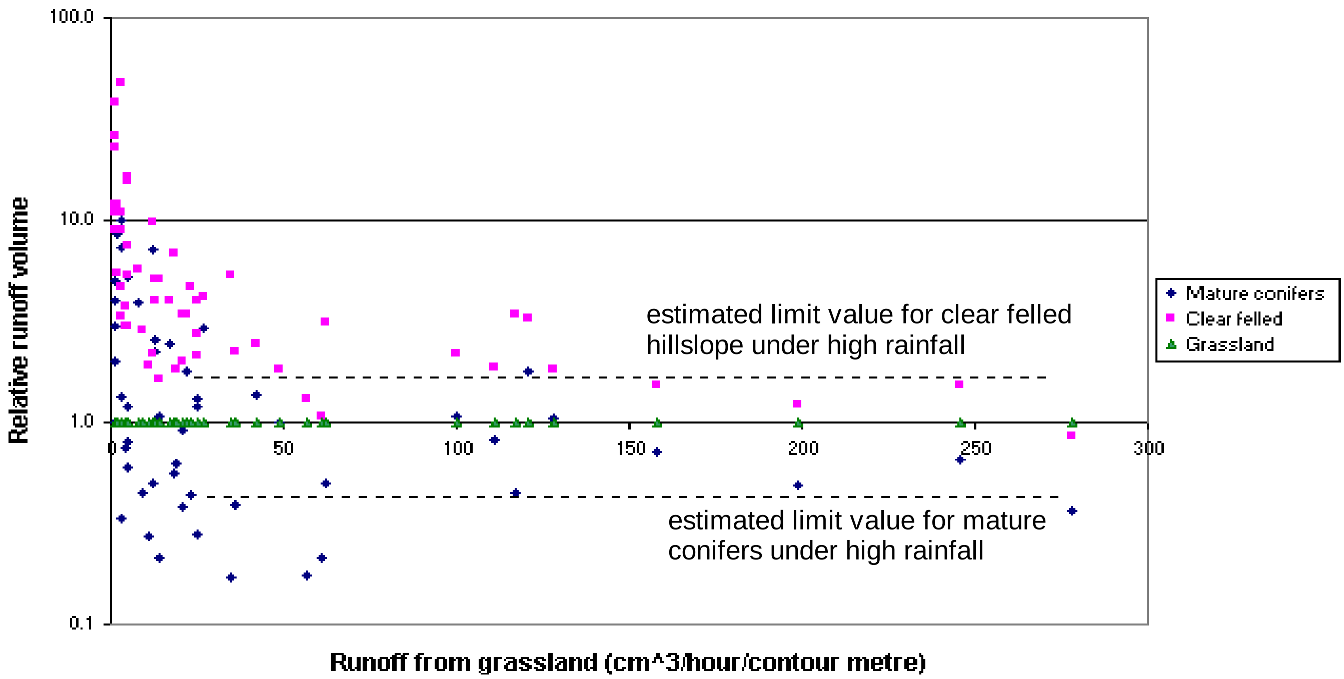

Figure 1.85: Comparative runoff rates for the three experimental sites

Within Coed y Brenin, forestry practice is moving towards continuous cover forestry with selective thinning and replanting replacing clear felling. However, extensive areas of coniferous woodland within the Mawddach catchment have been clear felled in recent years. Notable amongst these were plantations on the former Army artillery ranges in the Oernant area of the upper Afon Gain (fig.1.86). Further use of this land is hazardous due to buried unexploded munitions. Replanting with semi-natural broadleaf woodlands is planned, with wide riparian zones maintained around streams.

Figure 1.86: Clear felling of forestry plantations, Oernant

Preparing a vegetation and land use map

The hillslope hydrology models which are used in the Mawddach project require vegetation and land use data sets to be provided in both vector shape format and digital gridded format. Geographical Information System data sets of these types are available from various sources, but it was decided that a catchment vegetation and land use map should be prepared directly from field knowledge, supported by landscape photography, Ordnance Survey and Geological Survey maps, and colour air photographs at 1:25000 scale. This approach allowed greater flexibility for:

- editing land use data in response to agricultural and forestry changes within the catchment,
- developing modified data sets to investigate future land use scenarios.

The approach chosen involved two stages:

Vegetation and land use maps were prepared initially as vector shape files using the software package ***Mapmaker***. This program supports multiple layers, so that the land use map could be drawn as an overlay to an air photograph, topographic or geological map (fig.1.87). Background images in .BMP or .JPG format are registered spatially by entering Ordnance Survey grid coordinates for identified locations.

Map areas outlined as vector polygons could be assigned to land use and vegetation categories. The 17 class system of the Land Cover Map of Great Britain has been used (fig.1.88). *Mapmaker* provides convenient tools for editing; polygons may be easily merged or sub-divided, or the land use categories of polygons may be reallocated in response to land use changes in the catchment.

Vector shape files exported by Mapmaker in ArcView format are used directly in the Watershed Modelling System – HEC1 hillslope hydrology model. To use the land use map in the Mawddach integrated model, the shape file is first converted to 50m gridded data sets in ArcInfo format using ***SAGA-GIS*** software (Olaya, 2004). Very little loss of resolution occurs during the grid conversion process (fig.1.89).

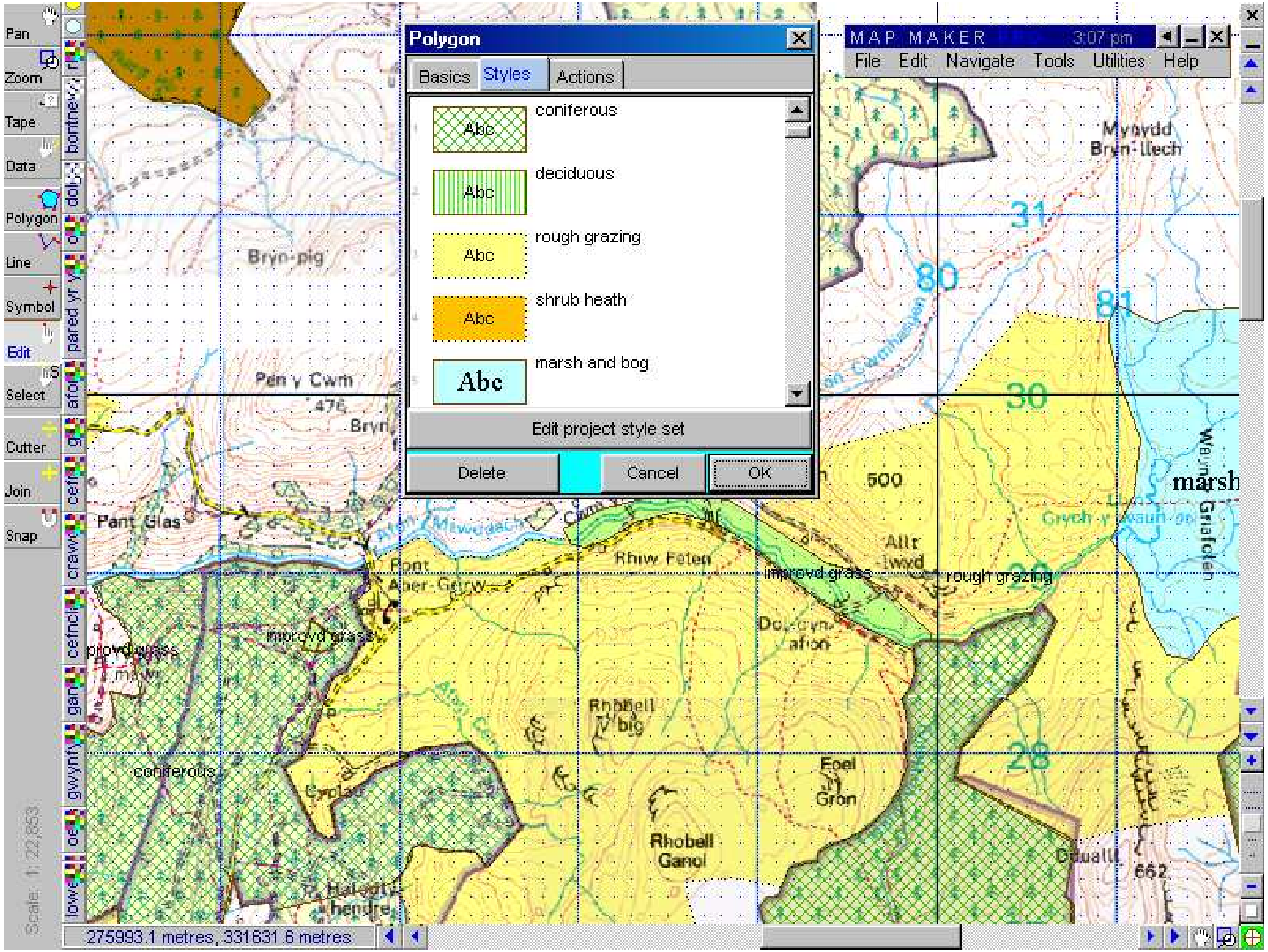

Figure 1.87: Preparation of a land use map for the Mawddach catchment using Mapmaker software

Category	Land use, vegetation
1b	Sea / Estuary
2	Inland Water
3	Beach / Mudflat / Cliffs
4	Saltmarsh
5	Rough Pasture / Grass Moor
6	Pasture / Meadow / Amenity Grass
7	Marsh / Rough Grass
8	Grass Shrub Heath
9	Shrub Heath
10	Bracken
11	Deciduous / Mixed Wood
12	Coniferous / Evergreen Woodland
13	Bog (Herbaceous)
14	Tilled (Arable Crops)
15	Suburban / Rural Development
16	Urban Development
17	Inland Bare Ground

Figure 1.88: Land Cover Categories, 17 class system
(after: Land Cover Map of Great Britain)

A simplified summary of the land use and vegetation map is shown in fig.1.90. Much of the hill land of the Mawddach and Wnion sub-catchments consists of rough grassland used for sheep grazing. Natural and semi-natural shrub heaths and blanket bogs are developed in higher mountain areas. Improved grassland is generally restricted to the lower and broader valleys and gentle hillslopes.

The extensive coniferous forest of Coed y Brenin occupies the middle course of the Mawddach, with other significant coniferous plantations on the slopes of the Rhinog and Aran mountains. Several large areas of clear felling exist at the present time. Broadleaf woodland is well developed around the lower Wnion valley, occurring as remnants of a larger area of forest. Broadleaf woodland also forms narrow riparian belts along the steep middle courses of many tributary streams, particularly where they descend in gorges incised into Tertiary erosion surfaces (cf. fig.1.76).

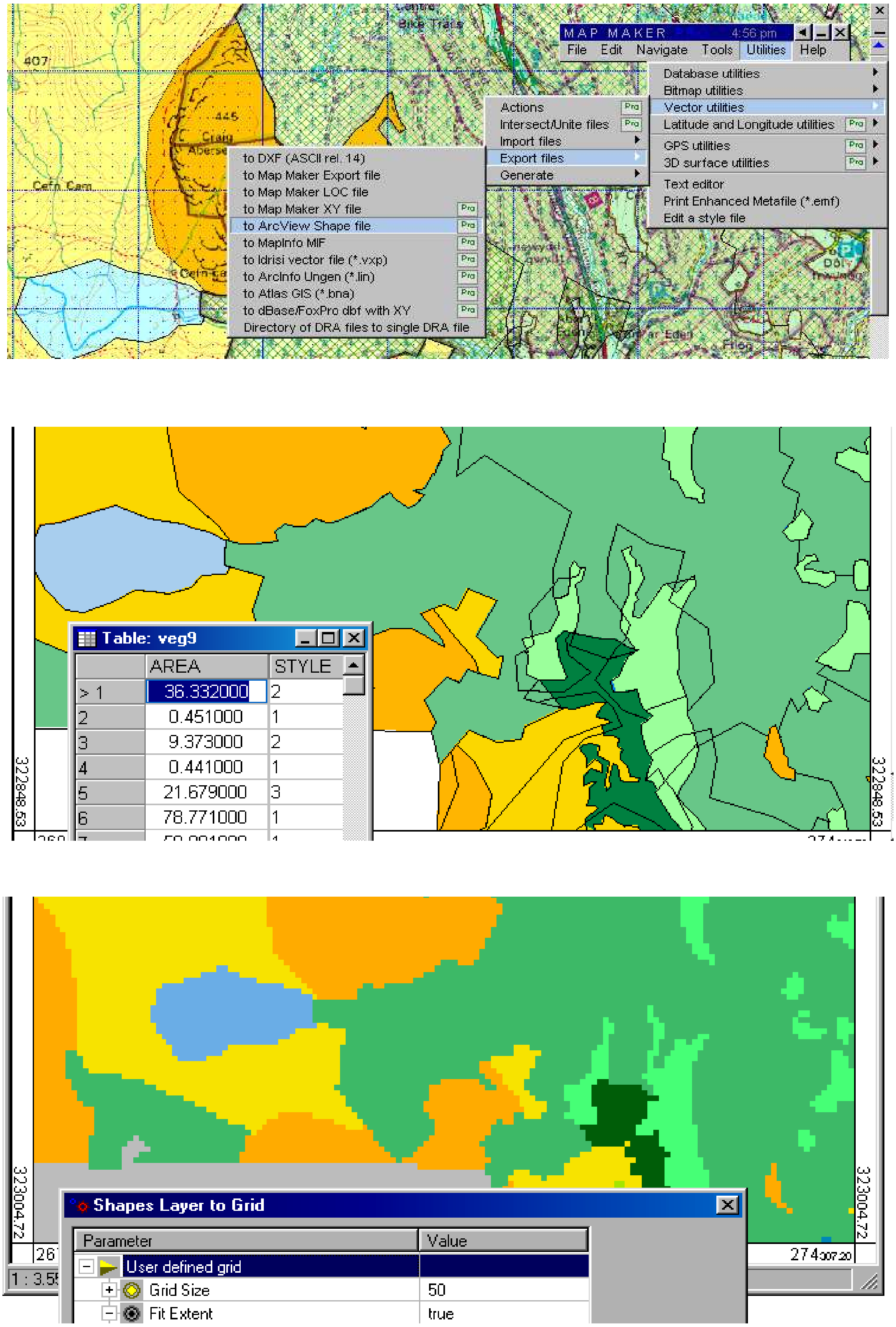

Figure 1.89: Preparation of land use data files for input to hydrological models.
Upper: conversion of Mapmaker overlay to ArcView shape file format.
Middle: shape file and corresponding database loaded into SAGA-GIS.
Lower: conversion of shape file to ArcInfo 50m gridded data using SAGA-GIS.

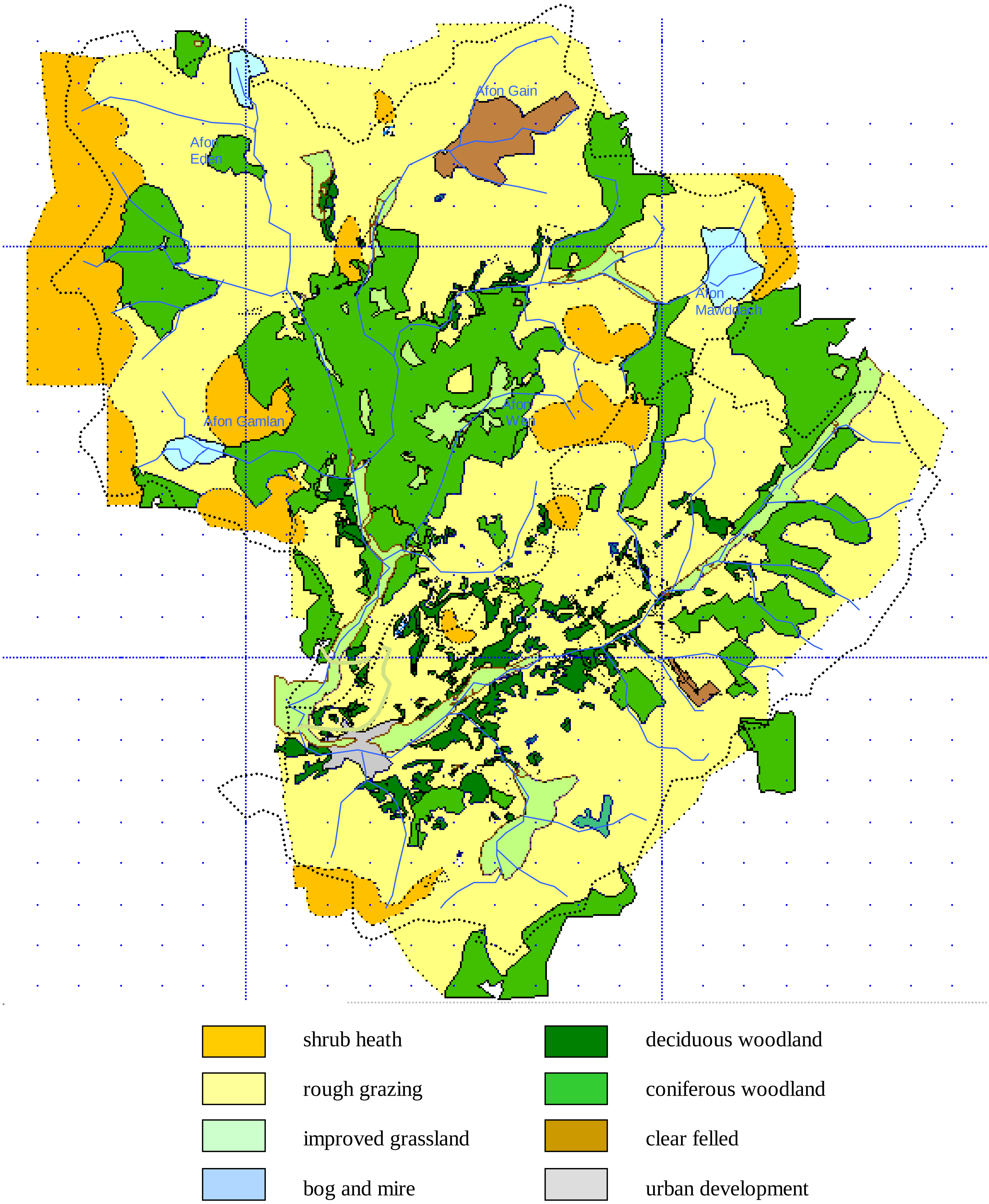

Figure 1.90: Summary of land utilisation for the Mawddach and Wnion sub-catchments

Industrial development

Metal mining

The Mawddach area is well known for metal mining, principally for gold and copper, which took place on a large industrial scale during the nineteenth and early twentieth centuries (Morrison, 1975). The Clogau and Gwynfynydd gold mines have been operated intermittently in recent years. Concerns have arisen about chemical pollution of rivers in the Mawddach catchment by drainage from mines and leakage from mineral processing operations. This issue is beyond the scope of the current modelling project. The main significance to hydrology is the presence of mine waste tips alongside rivers, where erosion during storm events can introduce large amounts of sand and gravel sediment into the river system.

Figure 1.91:
Gold mine waste tips extensively eroded during the July 2001 Mawddach flood.
(above) Gwynfynydd, (below) Bedd y Coedwr.

In the middle course of the Afon Mawddach, extensive waste tips are present from recent mining and reprocessing at Gwynfynydd, and at the disused Bedd y Coedwr and Tyddyn Gwladys mines (fig.1.91) in the Mawddach valley within Coed y Brenin. On the Afon Wen, waste tips remain from the large Glasdir copper mine. Much sediment forming the flood plains of the lower Mawddach may have originated from mining operations over the past 150 years, when little concern was paid to environmental issues (fig. 1.92).

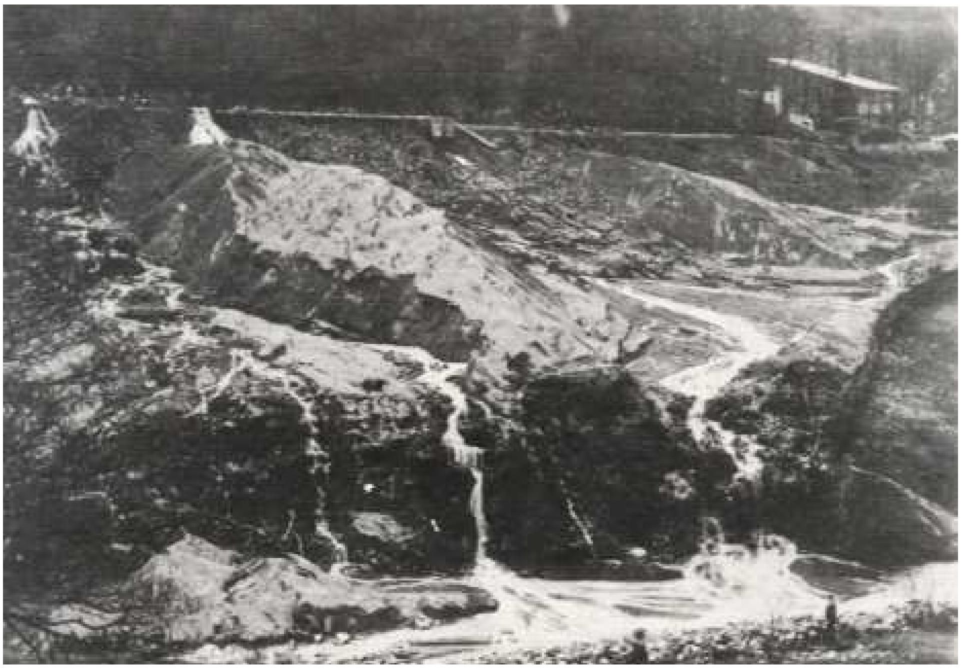

Figure 1.92: Waste tip from the ore processing mill, Glasdir, about 1900. photo: Meirionydd County Records Office.

Water supply

Two relatively small water supply reservoirs exist within the Mawddach catchment: Llyn Eithin occupies a shallow glacial basin on the slopes of Moel Oernant, and supplies the Trawsfynydd area. Llyn Cynnwch occupies a glacial basin on the interfluve between the lower Mawddach and Afon Wnion, and supplies the Dolgellau area.

Figure 1.93: Water supply reservoirs. (above) Llyn Eithin, (below) Llyn Cynnwch

Llyn Cynnwch is fed largely by groundwater from springs. Water from Llyn Cynnwch is piped to the Pen Cefn treatment works above Dolgellau. This works was re-equipped in the early 1990's. Lime is added to soften the water. The water is naturally clean, with no biological or algal contamination. Sodium hypochlorite is added as a precautionary measure. The supply for Dolgellau is gravity fed from a service reservoir at Pen Cefn. There is also a gravity supply to the main villages in the area, and down the estuary to Fairbourne.

Due to high rainfall, the levels of the two reservoirs are generally high for much of the year. In extended wet periods, the reservoirs overflow into streams. In the drought year of the 1970's there was a water shortage, so a pipeline was installed from Dolserau on the Afon Wnion to pump water up to Llyn Cynnwch. Abstraction is only permitted under Environment Agency licence when river levels are high, usually in the winter months. In practice, the pumped supply is rarely used.

The volume of water abstracted within the Mawddach catchment for domestic use can be estimated. Average per capita water use in Britain is 150 litres per day (OFWAT, 2008). The main centre of population in the Mawddach catchment is Dolgellau, with a total of 2,678 inhabitants at the 2001 census. The remaining area of the non-tidal Mawddach catchment is sparsely populated upland, so an upper limit for the total population may be taken as 5,000. Abstraction to meet the water needs of this population would be $750m^3$/day, representing a diversion of water from river flow of only $0.008m^3s^{-1}$. In a hydrological model, the amounts of water supply abstraction directly from Llyn Eithin and Llyn Cynnwch, or indirectly from the Afon Wnion, may therefore be considered negligible.

Ardudwy leat system

An engineering scheme having a significant effect on hydrology within the Mawddach catchment is the system of leats constructed to augment water supply to the Maentwrog hydro electric power station.

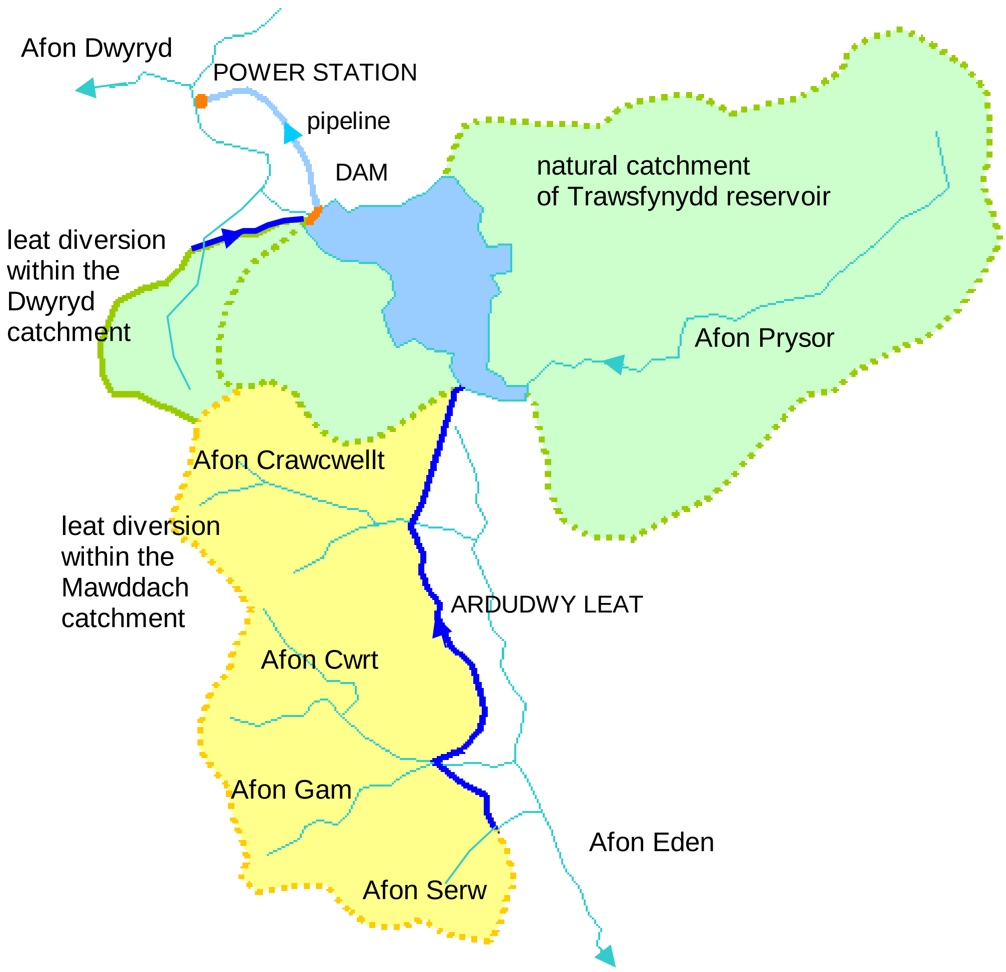

Figure 1.94: The Maentwrog hydroelectric power scheme

The purpose of the leat system is to divert water from the headwaters of three streams draining the eastern scarp of the Rhinog mountains, and carry the water into Trawsfynydd reservoir. The effect is to remove water from the Mawddach catchment and transfer it over the interfluve into the Glaslyn catchment.

Water abstraction occurs at a series of weirs, with water releases into the streams maintained at an agreed level to support fish stocks downstream.

Figure 1.95: Cwrt weir

Figure 1.96: Downstream discharge into the Afon Cwrt

Figure 1.97: Ardudwy leat, between Cwrt weir and Crawcwellt weir

The Ardudwy leat which discharges into the south west corner of Trawsfynydd reservoir intercepts flows from the headwaters of the

- Afon Serw - catchment area 2.5 km^2
- Afon Gam – catchment area 6.3 km^2
- Afon Cwrt (south Crawcwellt) – catchment area 8.2 km^2
- Afon Crawcwellt (north) – catchment area 8.5 km^2

The Ardudwy leat starts at Serw weir which is 7km south of Trawsfynydd reservoir. A 1.5km underground aqueduct connects the Afon Serw and Afon Gam, and a further 300m underground aqueduct links Gam weir to the Afon Cwrt. Between Cwrt weir, Crawcwellt weir, and Trawsfynydd reservoir, the Ardudwy leat is a concrete lined open channel (fig.1.97).

At Cwrt and Crawcwellt weirs there are sluice gates that can be opened to release all the water to the natural courses of the streams or to divert all but the prescribed flow into Ardudwy leat.

The design capacity of the Ardudwy leat increases from 0.8m^3/s at Serw intake, to 6.0m^3/s near Cwrt weir, to about 8.5m^3/s between Crawcwellt weir and the reservoir. When flows to the leat exceed the values quoted, the excess runoff spills to the River Eden, either over the spillweirs at the four stream intakes or from one of the small overflow structures which are spaced at intervals along the length of the open section. The maximum possible inflow to Trawsfynydd reservoir from the leat is calculated to be 10m^3/s.

The prescribed flows which must be maintained in the natural watercourses according to the North Wales Hydro Electric Power Act of 1952 are:

Afon Serw	6 litres/s
Afon Cwrt	41 litres/s
Afon Crawcwellt	248 litres/s

which amounts to a total discharge of approximately 0.3m^3/s.

Exact data on the operation of the Ardudwy leat during individual storm events is not readily available, but longer term statistical data is available (Binnie and Partners, 1985).

The average flow into the reservoir from the Ardudwy leat over the period 1963 to 1984 has been estimated as $1.77m^3/s$. During this period, the average total inflow to the reservoir was $3.94m^3/s$, so the contribution from the Ardudwy leat is approximately 50% of the total reservoir inflow.

Maximum monthly average inflows to the reservoir during the 1963-1984 period from its whole catchment were:

Month	inflow (m^3/s)
Dec 65	13.36
Oct 68	13.19
Oct 81	10.97
Nov 77	10.67
Dec 66	10.67
Nov 82	10.56

We may assume that the Ardudwy leat contributed 50% of the total monthly flows. The leat would have been operating at approximately 70% of maximum capacity during these high rainfall months.

Considering the available data, the following rules will be used to model the sub-catchment of the Ardudwy leat:

- During low flow periods with less than $0.5m^3/s$ discharge, all water flow will be directed into the Afon Eden.

- For discharges between $0.5m^3/s$ and $12.5m^3/s$, 75% of the flow in excess of the first $0.5m^3/s$ will be directed into the Ardudwy leat and lost from the Mawddach catchment. The remaining 25% of excess flow will be directed into the Afon Eden.

- Maximum flow on the Ardudwy leat is assumed to be 9 m^3/s. Once this flow is reached, all excess will be directed into the Afon Eden as spillway overflow at the weirs.

These rules are illustrated in the graph of fig.1.98.

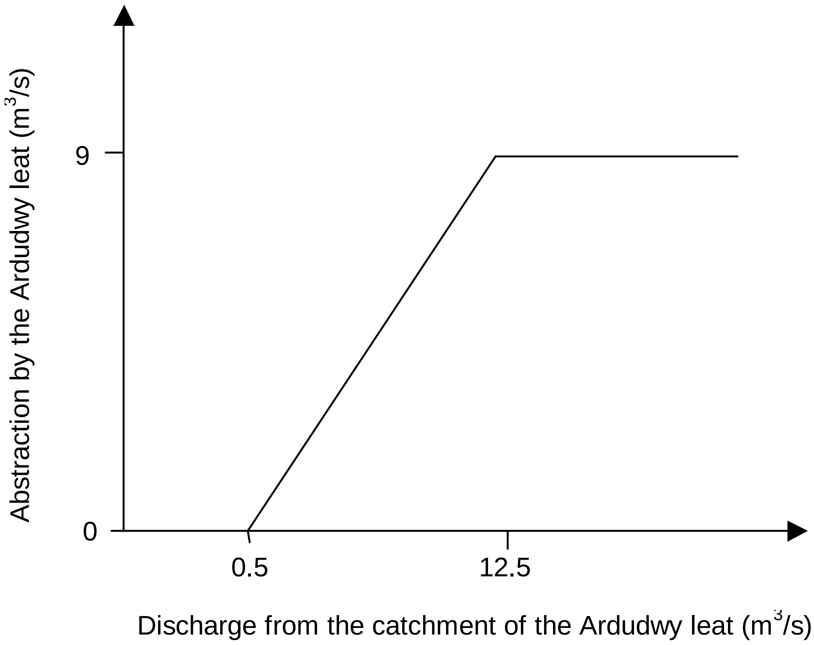

Figure 1.98: Assumed model for Ardudwy leat abstractions

Summary

The reconnaissance study carried out in the previous sections provides a conceptual basis for a hydrological model of the Mawddach catchment. The following characteristics of the catchment are considered relevant to the design of a model:

- The highest ground is formed by Cambrian grits and Ordovician volcanic rocks. Of these, the Cambrian grits generally have a higher permeability due to massive jointing. Higher mountain areas of Cambrian grit and Ordovician volcanics are covered by thin humic ranker soils.
- Less resistant sandstones, siltstones and mudstones occur in the Cambrian, particularly towards the top of the succession, and are also found interbedded with Ordovician volcanic rocks. These materials form valleys or lower ground on mountain flanks. Thin cambic soils often occur on the sedimentary outcrops, and may be gleyed due to low bed rock permeability.
- Glacial till, periglacial fluvial and solifluction deposits are common in the Mawddach catchment, particularly within deep valleys. These materials vary widely in hydrological properties. Boulder Clay impedes drainage, producing stagnohumic gley soils, whilst periglacial sands and silts encourage formation of better drained brown podzolic soils. Glacial and periglacial materials are readily eroded to provide river sediment during storm events.
- Major river valleys within the Mawddach system are aligned along geological faults. Reactivation of faults has led to zones of multiple sub-parallel fractures enclosing shattered rock. These fracture zones may facilitate river – groundwater interaction.
- Multiple phases of uplift during Tertiary times have produced a stepped landscape, with river rejuvenation and knick points evident on most main streams of the Mawddach system.
- River reaches within the Mawddach system exhibit a range of morphological characteristics within the general downstream progression of reach types: colluvial, cascade, step pool, plane bed, pool riffle, dune ripple. Classification of reaches can help in assigning appropriate hydrological parameters for river flow modelling.

- Natural vegetation within the catchment varies from bogs and mires, heaths and grasslands to broadleaf woodlands. Extensive conifer plantations are present, and some areas of grass land have been improved by drainage. Each of these vegetation zones has its own characteristic hydrological response.
- The presence of mature forest, whether broadleaf or coniferous, can lead to deepened soil profiles and reduced runoff. The development of prolific ground vegetation dominated by mosses may be important to this process.
- HOST soil classification can specify the dominant pathway(s): surface runoff, shallow throughflow, or infiltration to groundwater, at a particular hillslope site.
- The Ardudwy leat system is responsible for abstraction of water from an area of the Mawddach catchment. A model is given for abstraction rates in relation to sub-catchment runoff.
- Mining activities within the Mawddach catchment produce waste tips which are readily erodable sources of sand and gravel river sediment.