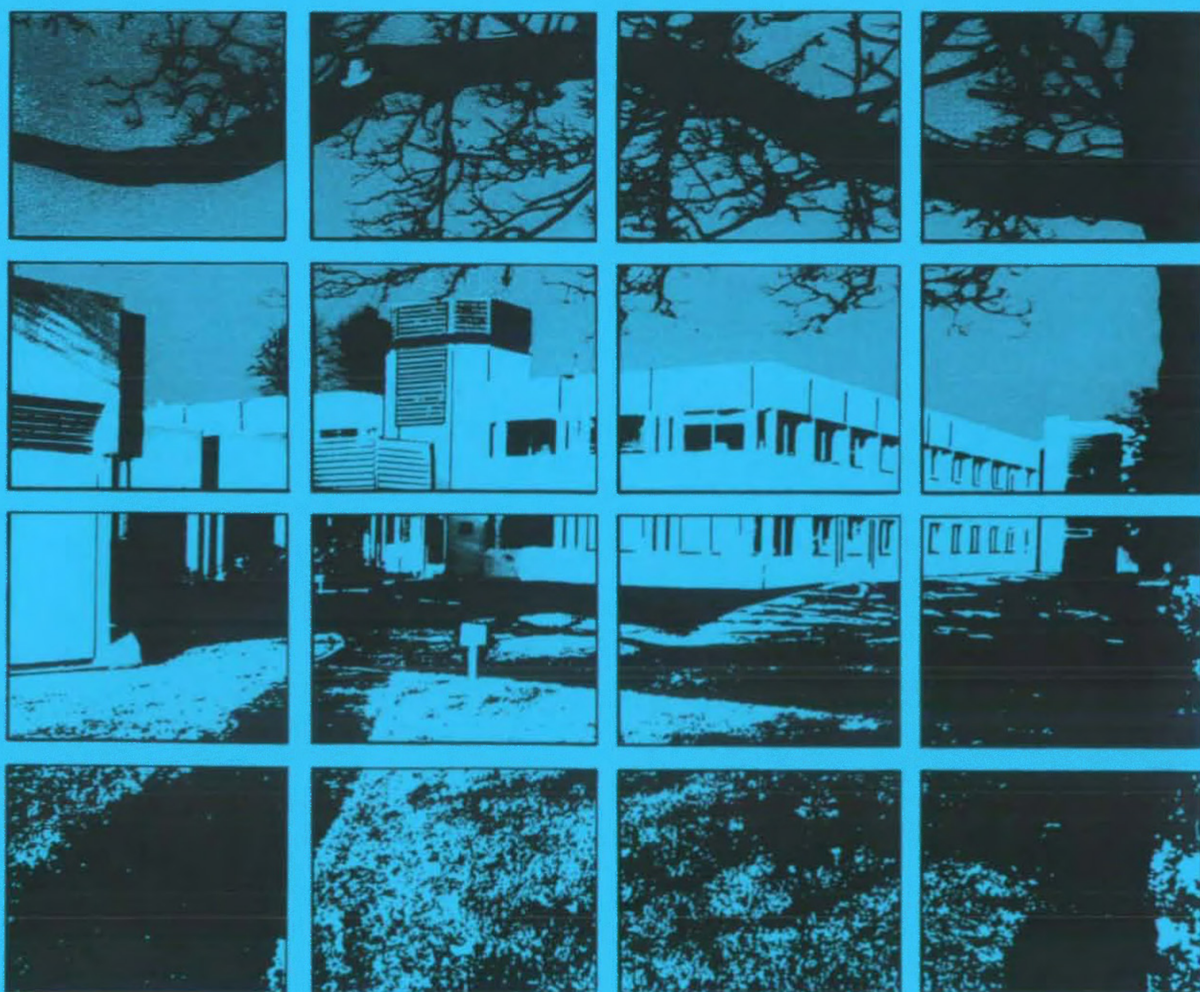
INSTITUTE of HYDROLOGY

The Soil Hydrology of the Plynlimon Catchments



Report No. 8

The author of this report, John Bell, was a Soil Hydrologist at the Institute of Hydrology from 1964 to 1993.

Published by the Centre for Ecology and Hydrology, research centre of the Natural Environment Research Council, UK

Institute of Hydrology Report No. 8

The Soil Hydrology of the Plynlimon Catchments

John Bell

Extensively revised 2005

Centre for Ecology and Hydrology

ISBN 1 903741 13 0

Published by the Centre for Ecology and Hydrology
Maclean Building, Benson Lane
Crowmarsh Gifford
Wallingford, Oxfordshire
OX10 8BB
United Kingdom

Tel 01491 838800
Fax 01491 692424
Internet http://www.ceh.ac.uk

Institute of Hydrology Report No. 8
Extensively revised and republished 2005

Contents

Author's preface to the 2005 revision

I carried out the Soil Hydrology Study of the Plynlimon catchments in 1968/69, during the early stages of the experimental programme, to provide some preliminary understanding of the soil hydrological processes that influence runoff. The findings were issued at that time as Institute of Hydrology (IH) Report No. 8, in a limited edition intended for internal use.

When the catchment experiments began, attention was mainly directed to measurement of the components of the water balance and to field process studies, but once the data collection system was working properly, the emphasis gradually changed to mathematical modelling. This was due to rapid developments in computer science and the increasing difficulty of obtaining the funding necessary for field studies. It is evident however that the need for basic information provided by process studies is no less now than it ever was. Unfortunately, much of the knowledge, data and experience of hydrological processes gained in the past are becoming inaccessible.

This revised and updated version of the original Soil Hydrology Study therefore aims at preventing the loss of the early soils work and, hopefully, will be of benefit to those working in the Plynlimon catchments today. The findings of the original work remain largely unchanged, although a few later ideas have been incorporated and the text has been extensively revised and re-presented. The publication of the original version of Report No. 8 was restricted to only a few copies, due to the high cost at that time of reproducing the large number of colour photographs on which it depended. This is no longer a difficulty, but other problems have arisen in the meantime.

Unfortunately the original colour photographs have deteriorated, but it has been possible to restore most of them digitally to something like their original state. However, digitisation has led to a new problem. The precision of the colour balance is very important in illustrating the sometimes subtle features of a soil profile, and colour balance, contrast, etc. can be adversely influenced by the means of reproduction, both on paper and on screen.

The original working field maps also have aged seriously and are now largely indecipherable, and the field soil map is beyond recovery. This is less serious than might be supposed because the mapping process had served to establish the relationships between soil and slope characteristics. The map of soil parent materials (Figure 3.01) represents the best attempt to resurrect the original version of that map. Although this is more generalised than the original, it illustrates well the distribution of the soil parent materials in relation to the topography.

It would, alas, be impossible to repeat the scope of the original field work because the original exposures provided by the newly cut access roads and drains are now slumped and overgrown.

Two important features of the work must be mentioned. Firstly, it is important to note that this was an entirely observational study and therefore subjective and untested at that time. Secondly, it was conducted specifically from a hydrological perspective, and although pedology, soil physics and geomorphology all played a part in it, these aspects have been kept to as basic a level as possible, avoiding complexities that are unnecessary in this hydrological context. The terminology used is that of the period but still serves well in this context. The meanings of the terms used are explained in the Glossary.

Many studies relevant to soil water processes in the catchments have been conducted and published in the years since this early work was done. A selection of publications, including an account of the overall experimentation is given at the end of this report.

I should like to thank my former colleagues: Mark Robinson, for his gentle but persistent encouragement (without which I should have given up long ago), Atul Haria, Cate Gardener and Brian Reynolds, for their support and advice, Emma Cowley, who digitised my maps, Jon Finch for help with the GIS Soil Parent Materials map and John Griffin for his cooperation in getting the work published.

Finally, I owe especial thanks to my wife Gill for her tireless and meticulous proof reading.

John Bell
June 2005

After graduating in geology, John Bell spent the next nine years mapping and evaluating the natural reserves of various minerals of economic interest before joining the Institute of Hydrology and becoming Head of the Soil Physics Section.

The Institute of Hydrology is now part of the Centre for Ecology and Hydrology.

Abstract

This soil hydrology study was carried out in the Plynlimon Catchment Experiment to provide an assessment of the influence of the soils in regulating the relationship between rainfall and runoff. It was an *observational* study, and therefore the findings are interpretive and subjective. Indeed, it could not be otherwise, being the essential precursor to the design and interpretation of the field experiments and modelling studies that were to follow.

One of the original criteria in the selection of this pair of catchments was that they should be watertight, with no possibility of ungauged inputs or outputs of groundwater between the catchments or sub-catchments that would invalidate their water balances. Of course this could never be proved completely, but the impermeable nature of the bedrock, coupled with several lines of indirect evidence was considered adequate to justify the assumption of water-tightness. Hence, the soil hydrology study was concerned only with the processes of water movement within and over the soils and in the weathered zone of the bedrock.

The principal findings were that there are three main soil types which may be considered to be hydrologically distinct – Podzol, Creep Brown Earth and Peaty Gley/Peaty Gley Podzol. Importantly, each of these occurs in different and specific topographic positions. The determinants of these locations are the aspect of the slope (north- or south-facing) and position on the slope profile (i.e. hilltop, upper convex, lower convex, upper concave and lower concave/riparian slopes). Each soil type is associated with its own set of soil hydrological processes controlling the transfer of rainwater via the soil system to the stream channels. Water storage in the regolith and its transmission downslope within an underlying shallow fissure system remains a possibility that cannot be entirely precluded, and this needs further study.

Field mapping of soils involves a great deal of subjective interpretation, relying heavily on intuition and experience in interpolating between exposures of the soil profile. A possible development would be to make use of modelling techniques, based on digitised topographic data in conjunction with parameters that define the different soil areas ("hydrological domains"), i.e. aspect, slope position and slope angle, thus producing a more accurate hydrologically-relevant soils map than is practicable by conventional field mapping techniques alone. If successful, the use of modelling techniques to define hydrological domains would be a potentially important aid to the improvement of physically-based models relating the hydrograph to rainfall.

1. Introduction

The uplands of Wales are a major source of water for the English Midlands. During the 1960s concerns began to emerge that upland forested areas might be yielding significantly less water than grassland, due to higher evaporative losses. There was also interest in the influence of upland land use both on flooding and on low flows lower down the river systems.

The Plynlimon experimental catchments were set up in the late 1960s by the Institute of Hydrology (IH), Wallingford, Oxfordshire, UK, a component body of the Natural Environment Research Council (NERC): the Institute has since become part of the Centre for Ecology and Hydrology (CEH).

Two adjacent catchments were selected to represent the two major land uses of upland Wales: coniferous forestry and sheep-grazed grassland. These catchments shared a common boundary and contained, respectively, the headwaters of the rivers Severn and Wye (see Figure 1.01).

These catchments were chosen because they were as similar as practically possible in all respects other than land use. They provided an extensively instrumented "outdoor laboratory" in which a wide range of hydrological experimentation would be undertaken over many years. The principal objective was to compare the water yields and hydrological characteristics of the catchments and to answer the question "do trees use more water than grass in high rainfall upland catchments?"

Matching criteria for the catchments included size, rainfall, soil type, geology, topographic characteristics, aspect, altitude above sea level and altitude range. The only major difference was land use. One catchment, containing the source of the River Wye, comprised traditional hill sheep pasture. The other, which contains the source of the River Severn, was occupied by the Hafren Forest, a Forestry Commission plantation of mixed coniferous species.

At the start of the project, topographic maps were produced from a specially commissioned aerial survey on a scale of 1:10 000 (and also 1:5000), with a contour interval of 2.5 m.

The two main catchments were each divided into sub-catchments and all were intensively instrumented with flow gauges, rain gauge networks, meteorological stations, neutron probe access tube networks etc. to provide basic water balance data. The Soil Hydrology Study, the subject of this account, was carried out during 1968/69 to provide a framework of information on the soils and their influence on the hydrological cycle.

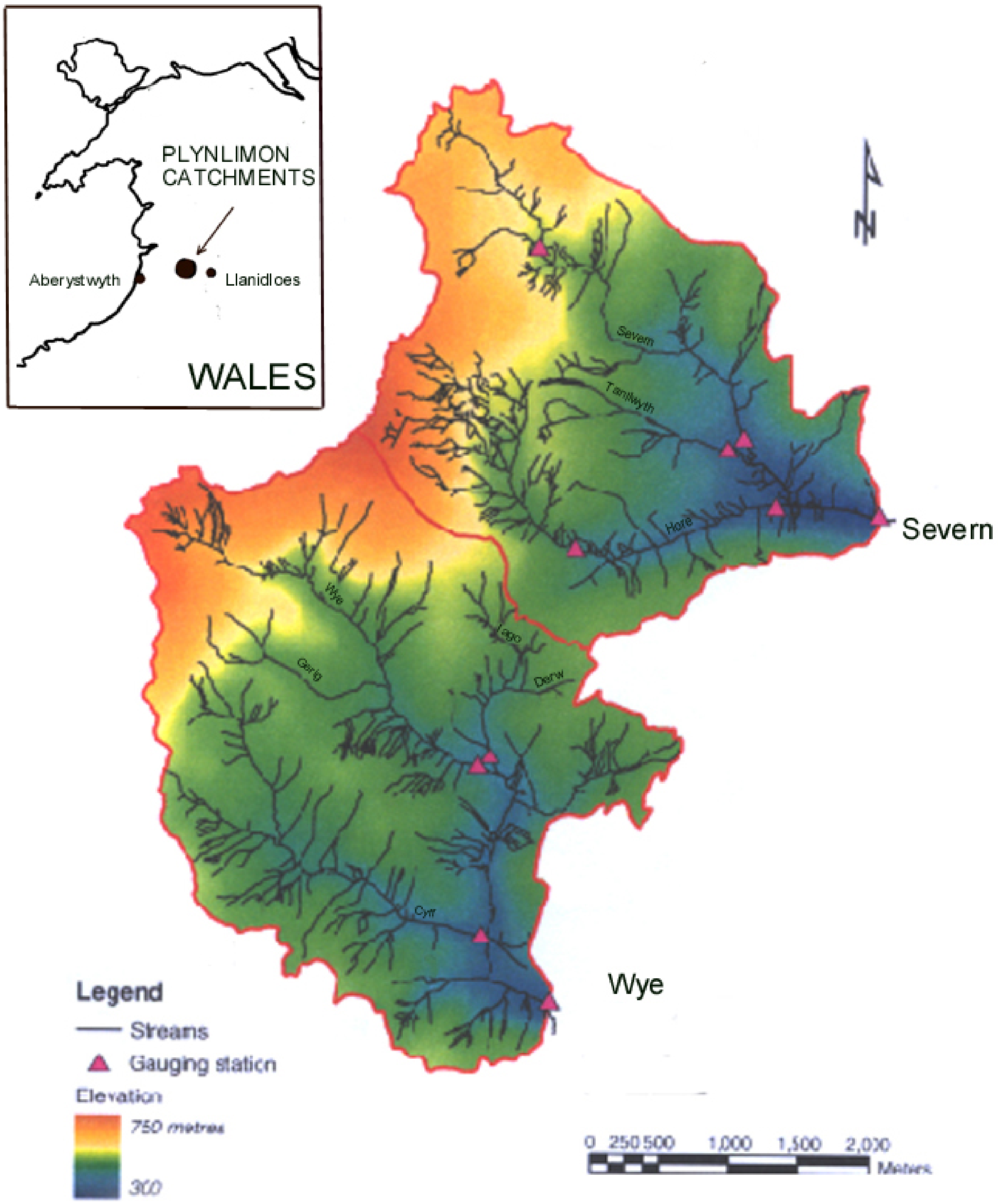


Figure 1.01 Topography and stream network of the Plynlimon catchments (based on a survey by Huntings for NERC, 1967)

The soil acts as a regulator in the relationship between rainfall and runoff, each flow pathway being subject to different impedances, gradients and storage characteristics. Physically-based mathematical models need to take account of these processes in as realistic a manner as possible, although inevitably a great degree of simplification is involved. Studies concerning water quality also need to be conducted with an appreciation of how the soil water system works.

A preliminary survey of the area suggested that a relationship might exist between slope characteristics on the one hand, and soil type and hydrological processes on the other. Thus, it became the main objectives of the soil water study to map the distribution of the soil types, to establish their relationships with topography and to elucidate the soil water processes. Of particular interest were the main pathways taken by the incoming rainwater in its passage to the stream channels. This would establish whether or not there was a consistent relationship that could be exploited for modelling and water quality research.

It became apparent that within the Plynlimon catchments there are several basic soil types, each exhibiting a degree of variability, posing the questions: “What factors are responsible for this and can any general rules be formulated to predict the distribution of the various soil types?” Variability in the lithology of the underlying rocks is usually one of the principal determinants of such variability, but not in this case, because the underlying rocks (lower Palaeozoic mudstones and slaty mudstones), are remarkably uniform in lithology.

It was necessary therefore to seek other explanations for the existence of the different soil types and their areal distribution. It became evident in the course of the study that the development and distribution of the three dominant soil types is closely related to topographical factors and that each soil type is characterised by its own set of hydrological processes.

2. Slope characteristics

Before the Pleistocene period, the outcrop of the hard Lower Palaeozoic mudstones and slaty mudstones of central Wales, being more resistant to erosion than the rocks of the surrounding areas, formed the mountains of the Plynlimon massif. Heavy rainfall, induced by the high land, created by erosion a system of V-shaped valleys, radiating out from the present-day Plynlimon, picking out any linear weaknesses afforded by fault lines, jointing or beds of softer rock.

During the Pleistocene, glaciers radiating out from the ice caps would have filled the valleys, at times covering the entire area to great depths, at other times leaving the higher ridges exposed above the ice. Glaciers moving down the valleys would have gouged them out into the characteristic 'U'-shape typical of any glaciated landscape. The last of the glaciers disappeared only about 10,000 years ago, leaving a wilderness of bare rock, Boulder Clay lining the valley floors and Head deposits developing on the ridges due to periglacial weathering. These conditions persisted long after the ice had retreated, and only comparatively recently did the climate become warmer, enabling vegetation to colonise the area. Soils began to be formed at this time, developing differently according to the different weathering processes pertaining in different positions on the slope and different slope aspects.

A paper by Dalrymple *et al.* (1968) entitled "An hypothetical nine-unit land surface model" is highly relevant to gaining an understanding of the relationships between the slopes of Plynlimon and the soils that formed on them.

The underlying principle is the recognition that all natural slopes potentially comprise a convex upper part and a concave lower part, the two being separated in the mid-slope position by a point of inflection.

Dalrymple *et al.* subdivide slopes into a maximum of nine "units" or "elements", the different elements being defined by criteria of slope angle and position above or below the inflection. A simplified version of this (Figure 2.01) represents very well the slopes of the Plynlimon catchments and surrounding areas. Not all elements are necessarily present, but the principles still apply. The type and extent of weathering, of soil formation, and hence of the hydrological processes, are all related to the slope element on which they occur.

The lowest two of the nine elements (8 and 9) are the riverbank face and the riverbed itself, so for the purposes of soil development these can be ignored and we are left with seven elements.

The upper part of the slope profile is the relatively level hilltop zone, i.e. the interfluvial area (element 1). An equivalent area at the base of the system is the virtually level riparian area that may border a river (element 7). The convex area is divided into upper and lower parts (elements 2 and 3), the lower being the steeper and extending downslope to the point of inflection where the convexity changes to concavity. The concave slopes below this are similarly divided into upper and lower parts (elements 5 and 6), the upper being the steeper.

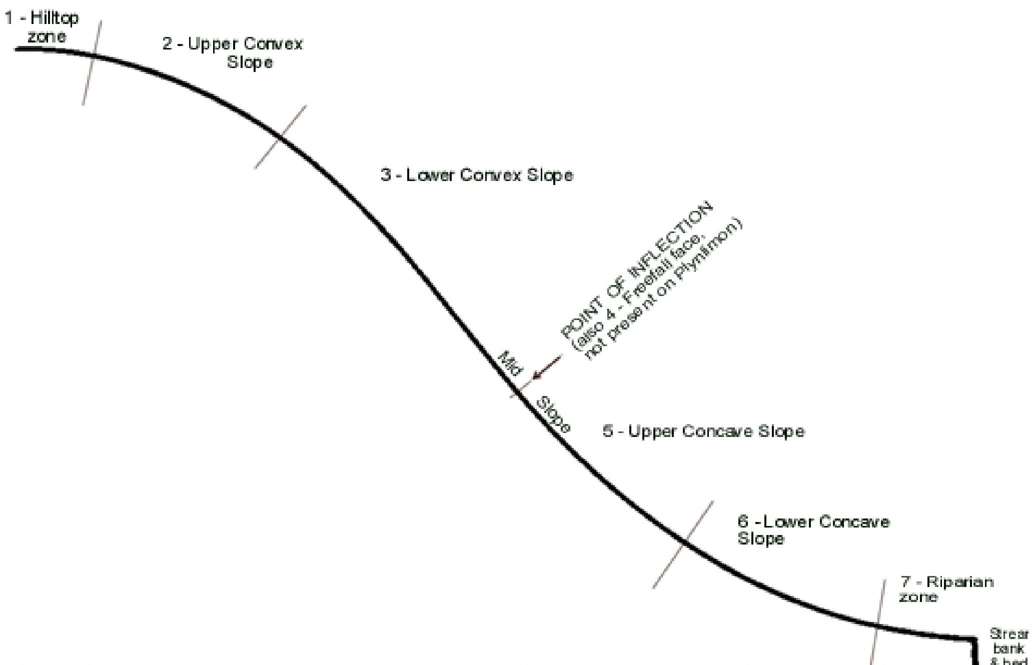


Figure 2.01 Typical Plynlimon slope profile showing relevant slope elements.

In the case of slopes that are very steep, the point of inflection occurs as a "free-fall face" (a rock face or cliff; slope element 4), but this is generally absent in the Plynlimon catchments.

Dalrymple *et al.* postulated specific slope angle criteria for defining the boundaries between the different elements, but these have been modified in this work and slope angle criteria are optimised to provide the best match with the field soil map.

3. Soil parent materials

A parent material is the rock or unconsolidated sediment from which a soil has been formed by physical and chemical weathering processes. The Pleistocene glaciation created not only the present landform but also the deposits that became two of the main soil parent materials of the area. All the soil parent materials were derived from a relatively uniform sequence of Lower Palaeozoic slaty mudstones and massive mudstones that underlie the catchments.

After the retreat of the ice, the parent materials were exposed to weathering by the freeze/thaw processes of periglacial conditions. Initially, conditions would have been the same on both sides of the valleys, but thereafter the higher angle of incidence of sunlight on south-facing slopes would have released them much sooner from the grip of the permafrost than the north-facing slopes. This major difference in exposure to sunlight would have created very different microclimates, with south-facing slopes subjected to the stripping of post-glacial deposits by various weathering processes for a much longer period and more intensively.

Slow climate change led, only a few thousand years ago, to a warmer, high rainfall climate, allowing vegetation to develop and the acid leaching soil-forming processes to start.

Within the Plynlimon catchments the three principal parent materials are Head, Boulder Clay (till) and Colluvium.

Head

Accumulations of frost shattered rock fragments on hilltops, formed in situ by late glacial freeze/thaw processes, further subdivided into:

- *Hilltop Head:* material still in situ on hill tops
- *Soliflucted Head:* Head that has been moved by post-glacial processes downslope onto the upper convex slopes
- *Bedded Soliflucted Head:* deposits of Head material moved farther downslope by annual cycles of slopewash and deposited as a sequence of thin graded beds on the upper concave slopes.

Boulder Clay (till)

A very compact and impermeable glacial deposit that originally filled the valley bottoms, sometimes to a considerable depth.

Boulder Clay and the various types of Head that remain today are mostly found on the north-facing slopes.

Colluvium

Warmer and wetter post-glacial conditions on south-facing slopes resulted in the removal of much of the Head and Boulder Clay, exposing the glaciated rock surface underneath to humid weathering conditions. This led to the formation of a layer of colluvial material, usually extending from hill top to valley bottom.

While all these parent materials share a similar mineralogy and chemical composition, they differ markedly in physical and hydrological properties such as hydraulic conductivity and porosity, leading to differences in soil formation and hydrological processes. Furthermore, each has been subjected to different hydrological and climatic environments by virtue of differences in their slope position and aspect; this has allowed different soils to develop. This is discussed in more detail in Part 5.

Figure 3.01 (below) shows the areal distribution of the main soil parent materials within the catchments, based on the original field map. The map shows how each parent material occupies its own characteristic position on the valley slope profile, defined in terms of altitude, aspect, steepness of slope and slope element (see Figure 2.01). Locally different microclimate and topographic features may lead to the formation of marginally different soils. Such differences will increase over time.

Traditional soil classifications are necessarily multi-purpose and tend to use generalised and easily recognised criteria. It was felt that it would be useful to classify the soils in a specifically hydrologically relevant manner.

The basic hypothesis therefore is that those parts of the catchments having the same slope characteristics would be expected to be characterised by similar hydrological processes, differing from other such areas. The term “hydrological domain” is suggested for such an area.

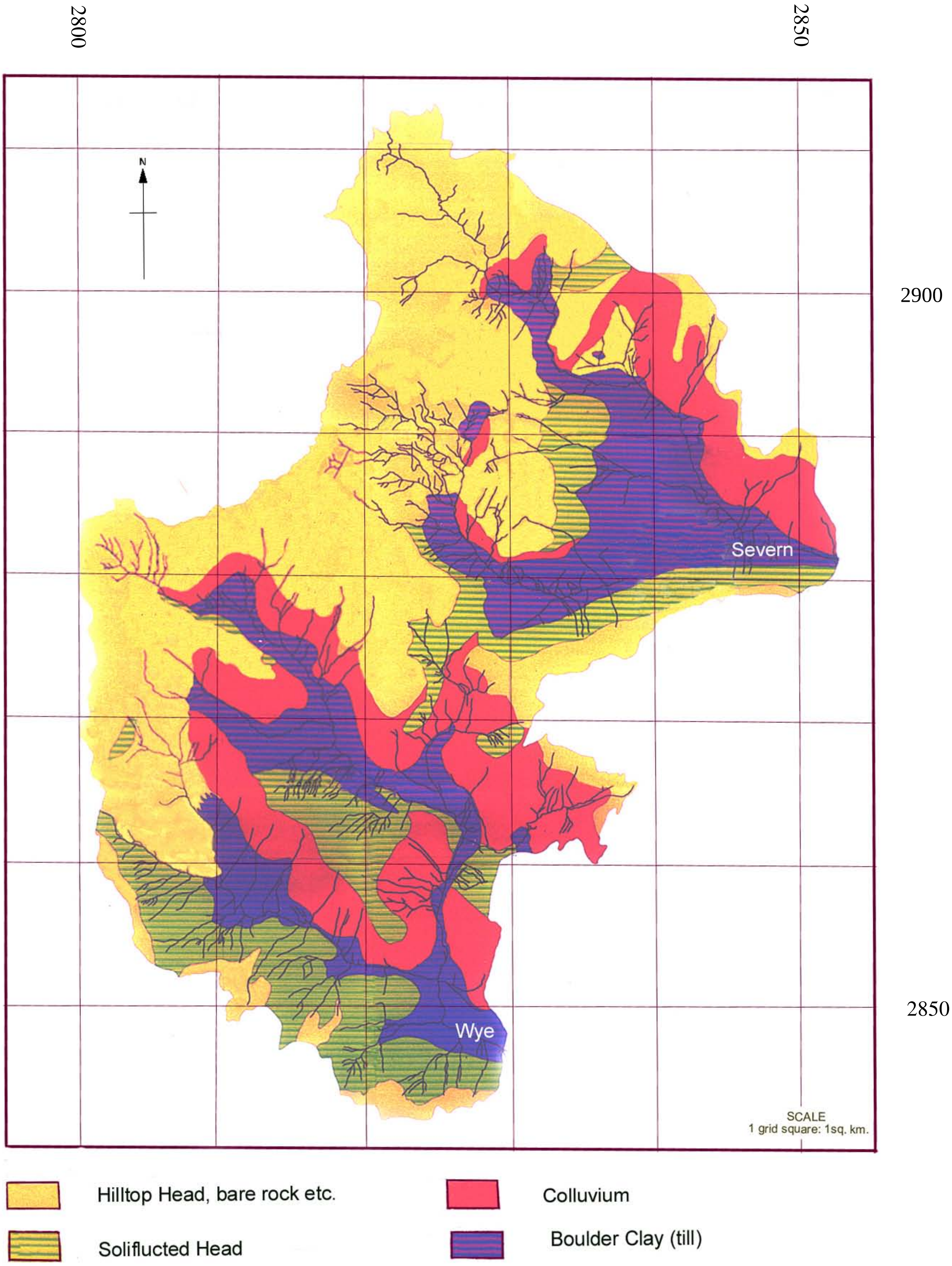


Figure 3.01 Distribution of soil parent materials in the Wye and Severn catchments (based on the original field mapping ca. 1968) with the National Grid overlay

4. The soils

The main soil types found in the Plynlimon catchments and surrounding areas are Podzols, Creep Brown Earths and Peaty Gleys/Peaty Gley Podzols (see Glossary).

PODZOLS

The high rainfall and the rock type of Plynlimon have provided the classic acid leaching conditions needed to produce a Podzol. A Podzol is a strongly layered soil which generally has, under its A/O horizon (in these catchments usually Peat or Peaty Loam), a pale grey clay/silt horizon (E horizon) representing all that remains of the original slaty mudstone parent material after it has undergone extreme chemical weathering by humic acids produced by the decay of the vegetation. Cations such as sodium, potassium, magnesium and calcium have been removed completely in solution, while less soluble cations such as iron, aluminium and manganese have been re-deposited at the base of the layer as a thin, usually well-defined, red-brown "iron pan", 1 to 15 mm thick.

Photo 4.01 shows the upper part of a typical podzol profile, in this case podzolised Colluvium lying on Boulder Clay. Valley Peat (A/O horizon) directly overlies the leached E horizon. Beneath this a 5-10 mm iron pan is seen (the B_{Fe} horizon) and below this the brown B horizon. This consists of variably weathered fragments of slaty mudstone mixed with oxidised, brown, silty-clay weathering products, with little or no organic material. This grades down into the C horizon, in this case Colluvium but more often fractured bedrock (not shown). See also Table 4.01.

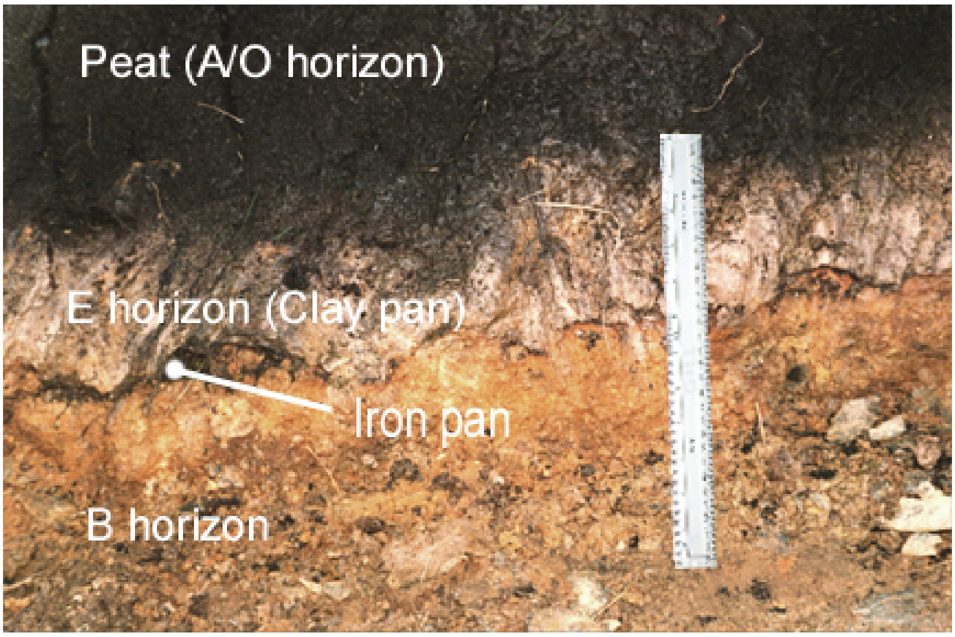


Photo 4.01 Podzolised Colluvium. A peat A/O horizon overlies the leached clay E_a horizon. Note the iron pan (B_{Fe} horizon) at its base and the absence of a B_h horizon.

Table 4.01 A typical Podzol soil profile on Plynlimon

Typical thickness (mm)	*Soil horizon*	*Soil description*
25 - 50	A	Mineral soil high in organic matter
50 - 200	E_a	Leached, pale ash-grey compact clay
0 - 150	B_{Fe}	Iron-pan: dark red-brown iron oxides
0 - 150	B_h	Black, secondary humus stained layer (manganese?) (often not present)
0 - 2000	B/C	Medium-brown, ochreous, silty-clay weathering product of slaty mudstone parent material
–	C	Slaty mudstone bedrock or Boulder Clay

The E_a horizon clay pan is important hydrologically because where it is well developed it forms a barrier to infiltration, deflecting water to run sideways as saturated downslope flow, either as laminar flow or as pipe flow (see later). In some areas the clay horizon is traversed by a network of fine cracks, probably due to shrinkage in dry summers: these may allow a proportion of water accumulating on the upper surface of the clay to percolate to the B and C horizons beneath.

Podzols are best developed on the flatter hilltop areas and grade laterally downslope into Creep Brown Earths.

CREEP BROWN EARTHS

In contrast to the Podzols, Creep Brown Earths are not strongly layered and do not have either an E_a horizon or an iron pan. The difference is due to their occurrence on generally steeper slopes than those where the Podzols form. Gradual movement downslope under gravity and better drainage (also due to the steeper slope) have led to more mixing and the formation of a soil composed of brown, oxidised fragments of weathered mudstone in a matrix of silty clay weathering products (Photo 4.02).

This is usually overlain by an A horizon comprising a 10 - 30 cm topsoil supporting grasses, bilberries, bracken etc.; this would probably have supported mixed deciduous forest until this was removed by early human populations. The B horizon is typically 20-100 cm thick and grades down into the weathered bedrock below. On steeper slopes traces of the cleavage planes of the rock can be seen curving downhill due to movement under gravity (Photo 4.03). It should be noted that the original bedding of these rocks has been largely destroyed due to the re-orientation of the clay minerals by metamorphism. This is the same process that, when more intense, leads to the formation of the true slates found to the north of this area. It is the cleavage (and jointing) that is usually opened by the weathering process in the shallow bedrock immediately below the strongly weathered surface zone.

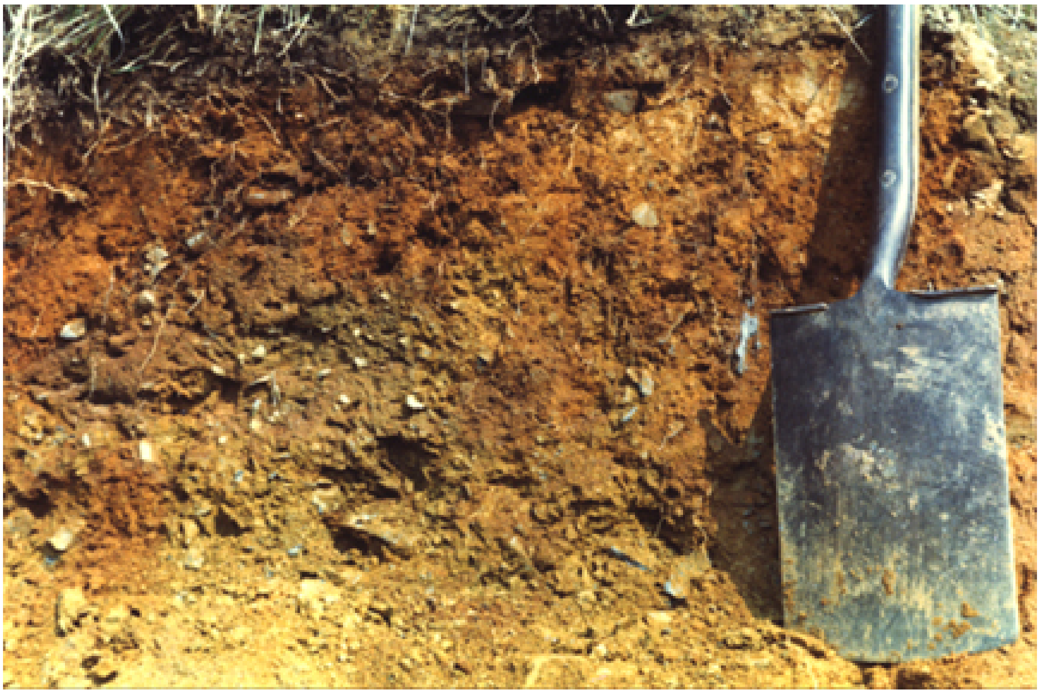


Photo 4.02   A Creep Brown Earth profile

Photo 4.03. Colluvium on a steep slope, showing the bedrock cleavage continuing upwards into the weathered rock C horizon and bending in the downslope direction due to soil-creep

Normal Brown Earths (i.e. Brown Earths formed in situ in flatter, well-drained areas, without the involvement of creep) occur infrequently in the catchments but are common in the lower surrounding areas.

PEATY GLEYS AND PEATY GLEY PODZOLS

Peaty Gleys are found on the less steep parts of the lower concave slopes bordering the rivers of the valley bottoms. Here the drainage is poor and runoff slow. The peaty layer (A/O horizon) at the top of the profile may be anything from 30 cm to 1.5 m thick, and sometimes more in localised hollows. The Peat may overlie either Boulder Clay or Colluvium mantling the Boulder Clay, the Colluvium having been mobilised from the slope above by freeze-thaw and slope-wash processes. Water tends to accumulate in this zone, thus creating reducing conditions, indicated by pale to dark grey or blue-grey soil colours.

In places where intermittent de-saturation occurs in the upper profile, for example close to a road or drainage ditch, or on top of a hummock, some brown and grey mottling (gleying) may be seen, indicating intermittent access of oxygen (Photo 4.04).

Photo 4.04. Weathered and partially leached Boulder Clay: note the grey mottling

The upper layers of weathered Boulder Clay can often be seen in an intermediate stage of chemical and physical breakdown; the shapes of the “boulders” are still visible but these are completely soft and degraded (Photo 4.05). The upper 10-30 cm of the Boulder Clay or Colluvium is often pale grey in colour and free of boulders, presumably indicating a greater degree of weathering and translocation of cations by acid leaching, and this may be described as a Peaty-Gley Podzol. However, the leached horizon is always more diffuse and less distinct than that of the Podzols of the upper slopes and any redeposited iron is usually well-dispersed and not obvious (Photo 4.06). It is likely that the podzolisation occurred here at a time when the climate was drier and conditions more oxidising. Tables 5.01 and 5.02 summarise the types of soil developed from each parent material and their relationship with slope position and aspect.

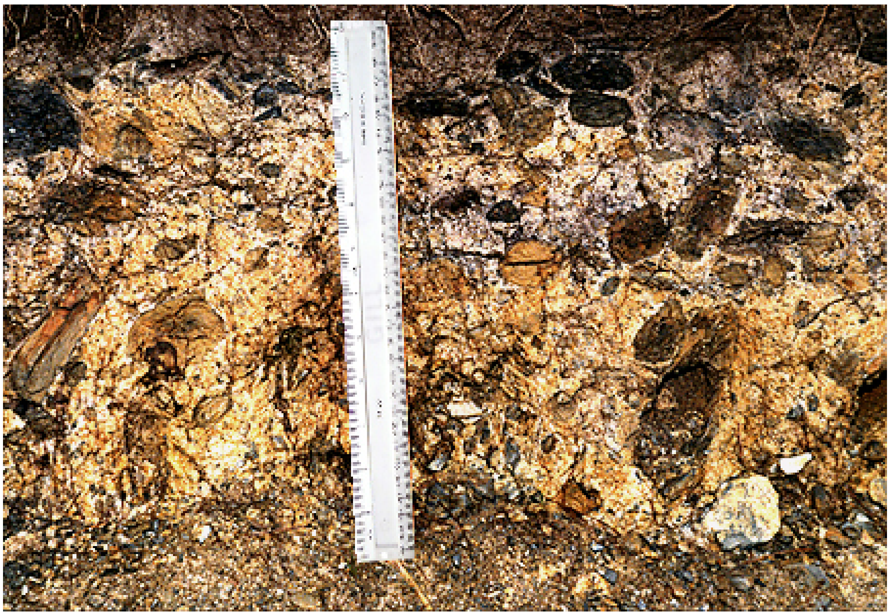


Photo 4.05. Weathered Boulder Clay: boulders have "rotted" and become soft, but retain their shape and colour

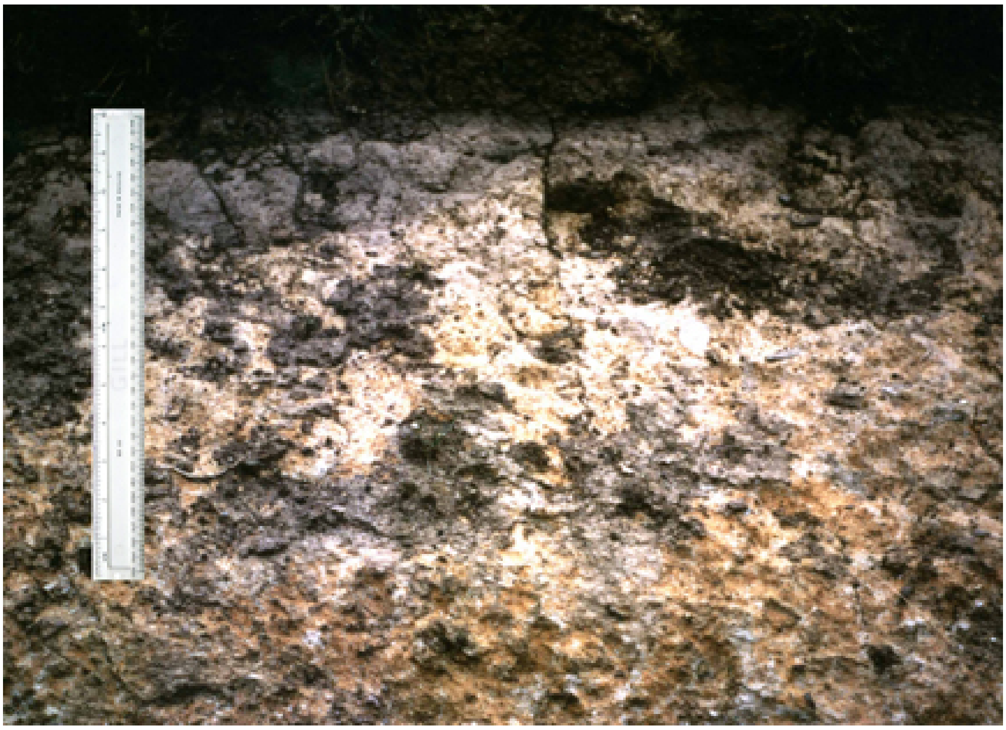


Photo 4.06. "Podzolised" Boulder Clay showing leached clay E-horizon and diffuse iron oxide staining beneath

5. Relationships between slope characteristics, soil parent materials and soils

Slope aspect and slope position have been important influences on the distribution of soil parent materials and the soils developed on them. These influences are closely inter-related and difficult to isolate, but it is convenient to divide the discussion in terms of the two slope aspect environments (north-facing and south-facing), and within these to subdivide on the basis of slope position on the slope profile.

The terms “north-facing” and “south-facing” are used to distinguish between two major soil environments. “North-facing” refers to slopes having a northerly component of aspect while “south-facing” refers to slopes having a southerly component of aspect. These definitions hold generally but, as with any natural system, localised anomalies always occur, in this case usually due to minor topographic irregularities.

THE SOUTH-FACING SLOPES

The south-facing slopes differ markedly from those that face north in respect of parent materials, soils and hydrology. Conditions are, and always have been, warmer on the south-facing slopes, enabling earlier and more rapid erosion of Head and Boulder Clay. The unprotected rock surfaces that then became exposed to humid and chemical weathering, developed a thin cover of Colluvium. The soil profiles that evolved on this parent material form a catenary sequence that extends from the hilltop watershed down to the valley bottom. The soil profiles are thinner than those of the north-facing slopes, usually less than one metre thick. The occasional deeper profiles found on the lower slopes are probably on isolated remnants of Boulder Clay or Head.

The Hilltop zone

The Hilltop zone has very low slope angles, albeit with a slight convexity that steepens away from the interfluve. The soil cover is thin and comprises a layer of podzolised Colluvium, which is rarely more than 20-30 cm thick, usually less and sometimes absent. Where there are only a few centimetres of Colluvium it is intensely podzolised, the podzolisation often penetrating the *in situ* fractured rock beneath. Hill peat probably covered the entire hilltop area, but most has now been removed by erosion and human activity. Where it remains it is usually 0.5 to 1.5 m thick, overlying Colluvium or directly on rock.

The Upper Convex Slopes

The soil cover starts to thicken away from the hilltop zone; the Podzol profiles found on it are well developed and also thicken downslope, but the entire profile rarely exceeds 1 m in total thickness.

The Lower Convex Slopes

Farther downslope, with increasing steepness, the Podzols may grade into the Creep Brown Earth that typifies the steeper mid-slopes. On the less steep mid-slopes Podzols remain, but may be discontinuous and patchy.

At the point of inflection the convexity of the upper slopes gives way to the concavity of the lower slopes. The vegetation here tends to be grass and bracken.

The Upper Concave Slopes

Creep Brown Earths (or sometimes Podzols) usually continue downslope below the point of inflection, becoming thicker as the slope becomes less steep.

The Lower Concave Slopes and Riparian Zone

Towards the valley bottom, as the slope becomes even flatter, the Creep Brown Earth (or Podzol) grades into Peaty Gley Podzol and then into the Peaty Gley of the riparian zone bordering the river. Isolated residual thin patches of Boulder Clay occur in the valley bottom and the Colluvium has usually spread across these as a thin layer between the Peat and the Boulder Clay. The valley peat is usually 1 to 1.5 m thick and generally saturated, except for the upper few centimetres that de-saturate during rain-free periods.

The south-facing slopes are traversed at fairly regular intervals by first-order and ephemeral stream channels (Photo 5.01) that have cut back from the valley bottoms at right angles to the line of the valley.

Photo 5.01. First-order drainage channels on south-facing slope: Boulder Clay terrace of north-facing slope in foreground

THE NORTH-FACING SLOPES

Unlike the south-facing slopes, which have only one important parent material (Colluvium), the north-facing slopes have two, namely Head and Boulder Clay. Each of these occurs on a specific slope position, and therefore so do the soils that have developed on them. This is analogous with the situation on the south-facing slopes i.e. soils are related to slope position and gradient.

The Hilltop zone

Most of the Hilltop zone to the north of the interfluve is thinly covered by Hilltop Head, consisting of loose fragments of slaty mudstone produced *in situ* by freeze-thaw processes at the end of the glacial period. This grades down into the fractured rock beneath. Being situated on fairly level ground, this parent material is stable, enabling it to undergo podzolisation. As with the Hilltop Colluvium (south of the interfluve), there are places where it has been removed by erosion, leaving patches of bare rock.

The Upper Convex Slopes

As the slopes steepen downhill, the Hilltop Head passes laterally into "Soliflucted Head", accumulations of Head material that have been moved downslope by processes of solifluction. Visually, there is little difference between this and the Hilltop Head above, but it seems likely that the deeper deposits on this part of the slope have been soliflucted. The upper part of this zone is podzolised and the entire profile is typically 1 m or more thick (Photo 5.02). At the base it grades into the fractured rock beneath. Further downslope the Podzol tends to be discontinuous. The soil is fairly well drained and hence there is grassy vegetation.

Photo 5.02. Podzolised Soliflucted Head

The Lower Convex Slopes

On these slopes the Soliflucted Head thickens to 5 m or more and, as the slope is steeper, the Podzol tends to be replaced by Creep Brown Earth. The Soliflucted Head is quite unstable. Removal of trees by human activity in the past, plus the more recent cutting of access roads, has added to this instability. This has produced a characteristic landscape of deeply eroded gullies (Photo 5.03) running normal to the contours. On the steeper, more eroded areas these gullies often lie close together (Photo 5.04). The underlying rock is usually exposed in the bottoms of these gullies.

Ephemeral flow in these channels washes the slaty mudstone fragments down onto the lower slopes, bypassing the mid-slopes to form outwash fans that locally mantle the Boulder Clay (Photo 5.05).

Photo 5.03. Soliflucted Head deposits on a lower convex slope overlooking the River Wye showing typical gully erosion

Photo 5.04. View across the River Wye showing gully erosion of Soliflucted Head deposits

Photo 5.05. Gully erosion of Soliflucted Head on north-facing upper slopes, with Boulder Clay in the foreground with covering of colluvium

The Upper Concave Slopes

Below the inflectional point are deposits of "Bedded Soliflucted Head". This parent material has been derived from the Soliflucted Head of the slopes above. The processes involved would probably have been a combination of frost-heave and surface runoff during the summer months.

Moving downslope, this material became more sorted into thin, laterally persistent beds, about 10 – 15 cm thick, dipping downslope typically at 10° – 25°. It is thought that each layer represents an annual cycle of slopewash, producing a remarkable sequence of these thin beds, each similarly composed of fine flaky fragments of slaty mudstone, with particle sizes ranging between 1 mm and 10 mm. Each bed is internally graded in grain size from top to bottom, so that the repetitive bedding pattern is clearly seen (Photos 5.06 and 5.07).

Deposits up to 5 m thick lie mainly on the inflectional and upper concave slopes. Bedding is less well developed further up-slope and the deposits are not so thick. More recent deposits of Colluvium sometimes overlie the bedded sequence.

Podzolisation is seen in most exposures (Photo 5.08), indicating that this material, having achieved its optimum angle of rest, is now stable and has been so for a long time.

This material probably occurs widely in both catchments but its extent and location have been difficult to determine due to paucity of exposures.

Photo 5.06. A 3.5m high strike face of Bedded Soliflucted Head in a roadside. View looking uphill: beds are dipping down towards the camera at about 25°. Note repetitive seasonal bedding.

Photo 5.07. Close-up of the Bedded Soliflucted Head seen in the exposed face in Photo 5.06. Particles range in size from 1mm to 10mm.

Photo 5.08. Podzol profile at top of a Bedded Soliflucted Head deposit

The Lower Concave Slopes and Riparian zone

The Lower Concave Slopes of north-facing aspect are dominated by Boulder Clay, which forms terraces along the right banks of the main rivers (Photos 5.09 and 5.10). The original deposits probably did not exceed 20 m and now are usually much reduced in thickness. The typical Boulder Clay of the Plynlimon catchments (Photo 5.11) consists of a matrix of green-blue-grey rock flour, which becomes pale buff-brown when oxidised (as sometimes occurs in its surface layer).

Photo 5.09. View of the north-facing slope of the Nant Gerig, showing gullies on the convex upper slope and the Boulder Clay terrace, with slumping, on the lower slope. Note contrast in colour to the near (south-facing) slope.

Photo 5.10. Remnant of a Boulder Clay terrace bordering the River Wye, above its confluence with Nant Iago

Photo 5.11. Fresh Boulder Clay exposed in slump face. Note blue-grey colour and "boulders".

Within the Boulder Clay are rounded, elongated pieces of hard, dark grey mudstone "boulders", which usually comprise about 5-10% of the total volume. These boulders (Photo 5.12) are usually about 5 - 15 cm in length and show the classic striations and plucking caused by the glacial processes. The Boulder Clay overlies a striated, ice-smoothed, fresh rock surface.

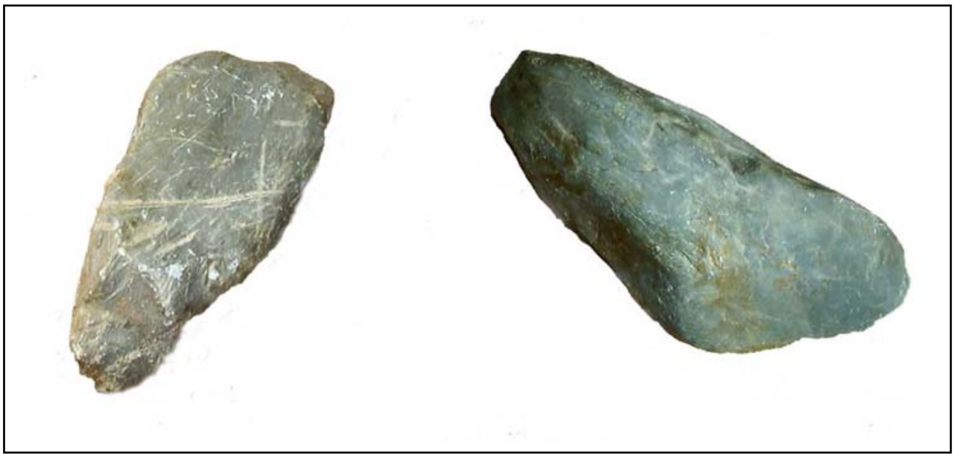


Photo 5.12. Typical mudstone boulder inclusion from the Boulder Clay, viewed from above and below. Note the smooth shape, striations and plucking.

The position of the Boulder Clay at the bottom of the slope, coupled with its impermeability, has allowed thick accumulations of peat to form, typically 1 to 2 m thick. This peat is one of the main water storages of the catchments. The peat and the mineral material beneath are almost permanently saturated, leading to the formation of Peaty Gleys. In some places the Boulder Clay extends somewhat upslope, and is therefore better drained. This has permitted intermittent oxidation and the formation of brown and grey mottled Peaty Gley Podzol.

The Boulder Clay terraces, being tough and impermeable, have resisted the development of ephemeral and first-order streams cutting back from the main river channel at the valley bottoms. This has not only protected them from much of the erosion that occurred on the south-facing slopes, but has also protected the Head deposits of the upper slopes from erosion.

Boulder Clay is not entirely confined to the valley bottoms and is sometimes found quite high up on the flanks of rounded spurs and in the 'V'-shaped valley heads. Thin smears of Boulder Clay (without the boulders) remain in hollows high up on the higher hilltop slopes above the heads of the main river valleys.

In the lower parts of the catchments, particularly in that of the Severn, the 'U'-shaped valleys merge and form relatively wide areas of low relief. Here, the distinction between north- and south-facing slopes is lost, and Boulder Clay forms the entire valley floor.

The upper surface of the Boulder Clay is often mantled by colluvial wash from the higher slopes. Podzolisation of the Boulder Clay (see Photo 4.06) and (where present) its colluvial mantle differs from that of the better-drained colluvial material of the slopes above. Podzolisation of the Boulder Clay tends to produce a diffuse zone of leaching (E horizon) up to a metre thick immediately beneath the peat cover, which often contains a small residual content of iron. The normal podzol iron pan (B_{Fe} horizon), where present, is represented by a diffuse, iron oxide rich zone, possibly better described as a B horizon. This soil is therefore perhaps not strictly a Podzol, because the much lower conductivity to water has inhibited the process of podzolisation. In this state the leached E horizon is often seen to contain soft, decayed "ghosts" of boulders (see Photo 4.05), although more extreme localised podzolisation in some places may have completely obliterated the original structure.

Typically, the Boulder Clay terrain is fairly level and slopes gently down towards the valley bottom. Minor slump features are common (Photo 5.13) and the Boulder Clay terraces usually terminate in a slump face at the riverside (Photos 5.09 and 5.14).

Photo 5.13. Early stage of a slump feature developing on the Boulder Clay terrace

Photo 5.14. Boulder Clay terrace on the Nant Iago left bank, showing recent slumping

In places where the Boulder Clay is mantled by colluvial material from the slopes above, both Colluvium and Boulder Clay may be much degraded by chemical weathering and decay, and in this state can easily be confused, particularly when gleyed. However, unless the rock fragments and/or boulders have been totally "digested", the Colluvium can be distinguished by the angularity of its fragments, which are very different in appearance from the Boulder Clay boulders (Photo 5.12).

This colluvial material has a more open texture than the Boulder Clay, is more conductive to water and hence is more susceptible to podzolisation. Its presence permits the formation of' subsurface drainage channels ("pipes", referred to later) which run downslope within this layer, beneath the E and B_{Fe} horizons of the Podzol, and directly on the impervious Boulder Clay beneath (Photo 5.15). This is in direct contrast to pipes of a different type on the south-facing slopes – see later in the report.

Tables 5.01 and 5.02 summarise the relationships discussed above and provide provisional estimates of the slope parameters that define the various soil type areas in terms of slope position and aspect.

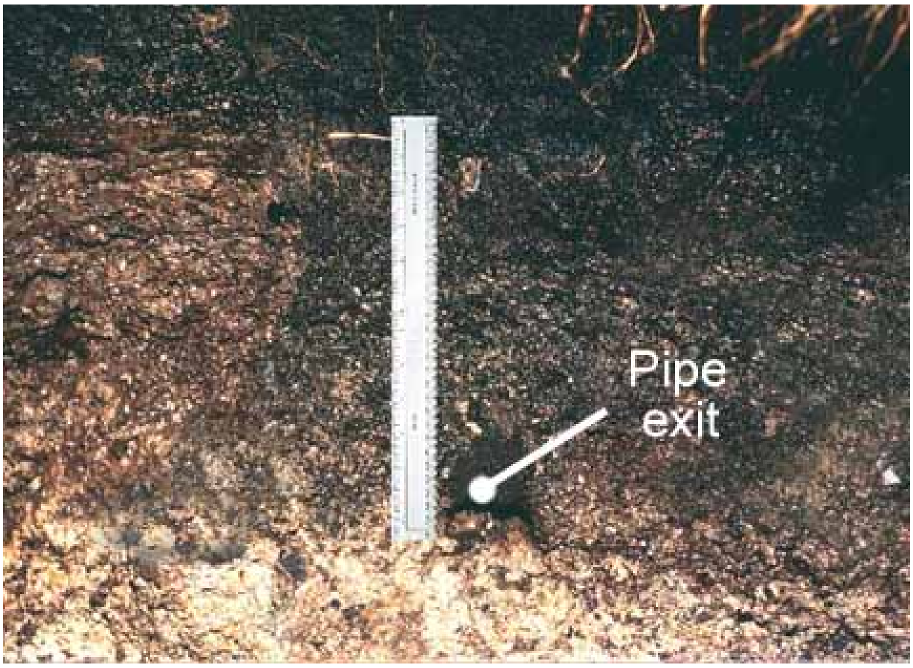


Photo 5.15. A small pipe emerging from within colluvial mantle on the surface of Boulder Clay

Table 5.01. Soil parent materials, soil types and topographic criteria controlling soil type location on south-facing slopes

Soil parent material	*Main soil types*	*Slope position*
Colluvium The dominant soil parent of the warmer, south-facing slopes, developed by weathering of exposed rock after removal by erosion of glacial and periglacial materials. The soils developed on this parent material tend to grade, one into another, downslope.	Podzol. Degree of podzolisation greatest on the higher slopes with a lower slope angle, where the soil profile is thinner. The B horizon comprises broken pieces and flakes of partially weathered mudstone/ slate in brown, silty ochreous matrix of weathering products. Overlain by peat hag or by thin peaty soil where peat hag has been removed.	Hilltop zone & Upper Convex slopes: can extend right down the slope if not too steep
	Creep Brown Earth. Instability on steeper slopes disrupts podzolisation. Vegetation is grass, bracken and gorse.	Lower Convex & Upper Concave slopes
	Peaty Gley or diffuse Peaty Gley Podzol beneath waterlogged valley peat. Easily confused with Boulder Clay, which it may overlie in places where isolated remnants of the latter still remain. Often highly degraded.	Lower Concave slopes
	Peaty Gley - gleyed blue/grey colluvium beneath waterlogged valley peat. Original structure often degraded.	Riparian zone
Boulder Clay remnants Most Boulder Clay has been eroded away from the south-facing slopes but remnants sometimes exist in the form of low mounds of boggy ground close to the rivers on the valley bottoms.	Peaty Gley Podzols and Peaty Gleys, usually overlain by up to 1 m of boggy peat	Lower Concave slopes & riparian zone

Table 5.02. Soil parent materials, soil types and topographic criteria controlling soil type location on north-facing slopes

Soil parent material	*Main soil types*	*Slope position*
Head - Hilltop Head (& rock) In places bare rock is exposed. Elsewhere remnants of hilltop peat overly thin deposits of Head, or sometimes thin smears of boulder clay (without boulders), typically less than 30 cm thick. Where the slope starts to steepen the Head deposits are thicker and these merge laterally, downslope, into Solifluceted Head.	Podzol. The Head deposits, where present, are very thin; therefore so is the soil profile and podzolisation is intense. Where superficial material has been removed the podzolisation can be seen to have invaded the partially weathered solid rock.	Hilltop zone
Head - Soliflucted Head Head that has moved down-slope due to periglacial processes (e.g. frost heave). The north-facing and, to a lesser extent, the east-facing upper and middle slopes tend to be dominated by this material, which is very liable to gully erosion when disturbed. This material is very evident on north-facing slopes (but has mostly been eroded from south-facing hillsides). Lower down the slopes this material grades into Bedded Soliflucted Head.	Usually well-drained and therefore supports grass rather than peat. This and its loose structure discourage podzolisation. Podzol on upper slopes tends to become discontinuous as slope steepens.	Upper Convex slopes
	Usually Podzol is poorly developed or absent here due to instability and free drainage. Soil profile usually comprises an A horizon directly overlying the C horizon, but Creep Brown Earth is present in some places.	Lower Convex slopes
Head - Bedded Soliflucted Head Results from annual cycles of freeze-thaw; stratified, well-graded 10 – 15 cm thick beds of shaly fragments, the beds lying at downslope angles typically of 10 °– 25°.	Usually Podzol, indicating that slopes have attained stability.	Inflectional mid-slopes and Upper Concave slopes
Boulder Clay (Glacial till) This is a very tough, compact, impermeable material, comprising a matrix of blue/grey rock flour containing ice-plucked and striated "boulders" of mudstone, typically 5 –15 cm long. Occurs mostly as valley infill remaining after the retreat of the glaciers. Although it has undergone erosion, extensive deposits remain on north-facing slopes where it forms terraces that are typically 10 to 20m thick. Lower down the rivers where the valley floor is wider, extensive areas of Boulder Clay occupy much of the valley floor. Very thin patches of Boulder Clay occur in minor hollows on the otherwise bare rock surfaces on the higher flat hilltops above the heads of the valleys.	Peaty Gley or Peaty Gley Podzols. Impermeability of the Boulder Clay and low slope angle create poor drainage and anaerobic conditions that favour development of Peaty Gley Podzols and Peaty Gleys, which are usually overlain by up to 1 m of boggy peat. Where oxidation has penetrated to upper part of the Boulder Clay it loses its blue-grey fresh colour and is mottled blue/brown (gleyed) or brown. Any Podzolisation is weak and diffuse.	Mainly on Lower Concave slopes & riparian zone, but locally extends up onto the Upper Concave slopes.

6. Soil water pathways

The main objective of the soil study was to provide information on the pathways taken by rainwater in its passage to the stream channels. This information would be available for modellers as an aid to the development of physically realistic models and to scientists studying the water chemistry of these and similar catchments.

One of the main features of the hydrology of the Plynlimon catchments is the dominance of saturated flow processes, a very different situation from most lowland areas.

Where an area is underlain by permeable rock such as the Chalk, most of the rain infiltrates vertically as unsaturated flow down to the water table. Only then does it move laterally, as saturated groundwater flow. Surface runoff is very unusual.

In contrast, in a hilly, hardrock, high rainfall area such as Plynlimon, infiltrating rain encounters one or more poorly permeable layers that are unable to accept the often high rate of input. Impeding horizons may be either at the soil surface, within the soil profile, or at the base of the regolith. During a rainfall event excess water can pond up on these layers and move downslope as saturated flow via a variety of different pathways.

THE MAIN PATHWAYS

There are several pathways by which saturated lateral flow reaches the stream system:

1. Overland flow – flow on the soil surface
2. Subsurface lateral (laminar) flow on impeding interfaces within the soil profile
3. Subsurface pipe flow on impeding interfaces
4. Lateral flow through the base of the weathered rock zone
5. Fissure flow through the fresh, unweathered bedrock

1. Overland flow – flow on the soil surface

In the grassland areas of both catchments there is significant overland flow when rainfall is intense enough (Photo 6.01) and these conditions occur quite frequently. A distinction has to be drawn between the overland flow generated on the convex upper slopes and that of the lower concave slopes close to the valley bottom.

a. Overland flow on the convex upper slopes

The stems of the grassy vegetation typical of the upper slopes in the Wye catchment tend to bend over in the downhill direction, which sheds and diverts some of the rain into overland flow; this is termed the "thatch" effect. An additional factor relevant to the generation of overland flow on the upper hillsides arises from the drying out of the topsoil during extended dry periods. Due to the humic content of these soils, they become quite hydrophobic at such times, and heavy rainfall following such a period can lead to a much higher proportion of overland flow than at other times. Most of the overland flow generated in this way feeds into ephemeral channels and thence to the valley bottom, without passing through the soil. This water can undoubtedly be regarded as "new" water that has just arrived as rainfall.

b. Overland flow on the lower of the concave slopes

Overland flow on the lower of the concave slopes may in part result from up-welling of water from pathways lower in the soil profile, and hence may have lingered in temporary storage prior to being displaced by new inputs upslope. This water may thus possess a different chemical identity.

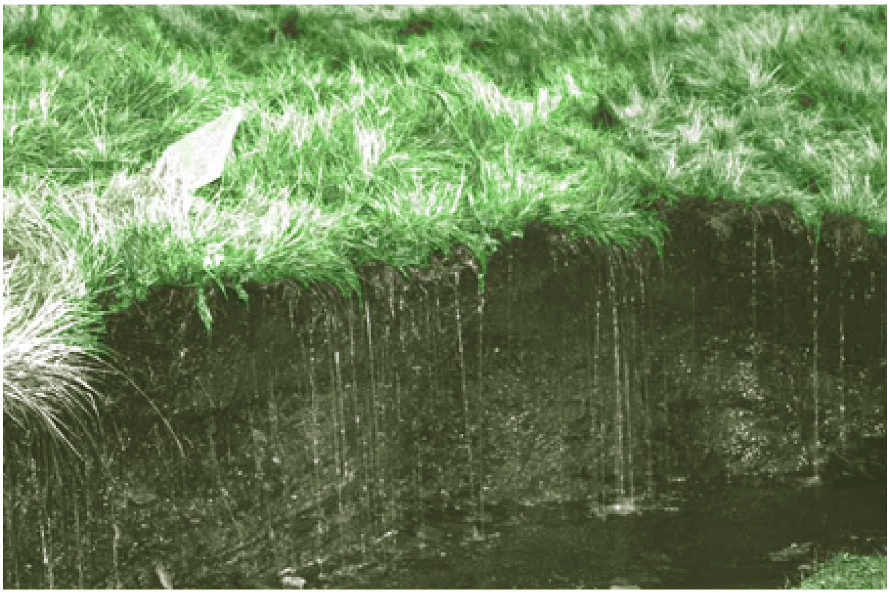


Photo 6.01. Overland flow cascading over a small slump face in Colluvium on a south-facing, lower convex slope during a moderate rainstorm

2. Subsurface lateral flow on impeding interfaces within the soil profile

This is relatively slow, lateral flow through the lower part of the A horizon where and when infiltrating water has ponded up over an impeding E horizon allowing lateral, saturated downslope flow.

3. Subsurface pipe flow on impeding interfaces

During a heavy rainfall event, one of the main routes for rapid downslope flow is via shallow systems of subsurface pipes that have formed on impeding interfaces. There are two types of subsurface pipe system in these catchments: the “valley-flank” and “valley-head” systems. Both owe their presence to a subsurface impeding horizon that forces water to flow laterally within the soil profile; preferential flow paths have developed, along which the pipes have been formed.

a. Valley-flank pipes

These consist of a network of small pipes (typically 50 mm in diameter) occurring on the slopes flanking the main valleys, usually overlying an E horizon clay pan (e.g. Photo 6.04). On the convex upper slopes or on inflectional mid-slopes the pipes usually occur within the Podzol profile on the A/E interface; on the concave slopes the pipes are larger and less numerous and rest within the base of Peat overlying Boulder Clay (e.g. Photo 6.03).

b. Valley-head pipes

These are found on the high hilltop areas above the valley heads where there is very little soil cover or regolith material. They run within the Peat, resting on the hard rock or thin deposits of Boulder Clay beneath. These pipes are much larger, forming extensions of the ephemeral channels of this area, feeding into these in periods of high rainfall. Once developed beyond a certain size they collapse and become an open channel.

Pipe systems probably constitute one of the main pathways that transmit flow quickly from the hilltops into the stream channels. Once sufficient rainwater has accumulated in the temporary hilltop storages, lateral flow feeds into these pipes and is very quickly transmitted to the lower concave slopes, where the pipe flow may sometimes be seen spurting upwards above the surface of the peat.

Thus, much of the rain that falls on the hilltops may reach the ephemeral and first-order streams or the main river channels ahead of rain inputs taking different pathways. Note that some of the water emerging on the lower slopes may be older water that has been displaced from storage.

4. Lateral flow through the base of the weathered rock zone

The main soil water storage in the catchments is in the peat and peaty soils, but this changes little and slowly. More important may be storage (as yet unproven) in the deeper weathered bedrock of the hilltop areas, which have been exposed above the ice for longest and are thus more deeply weathered. Water probably enters this material and accumulates at its base, mixing with later additions and moving sideways downslope as the phreatic surface rises, after rainfall, into the more conductive material.

5. Fissure flow through the fresh, unweathered bedrock

The existence of significant water-bearing fissures within the fresher bedrock below the weathered zone is difficult either to prove or to disprove.

Conducting fissure systems would probably follow tectonic joints in the rock, but, other than locally, they may not be open enough or sufficiently well connected to constitute a significant proportion of river flow. This topic is discussed later (see “Groundwater”).

The above flow pathways are shown diagrammatically in Figures 6.01 and 6.02. Being 2-dimensional, these cannot show flow paths via the gullies down to the lower slopes, nor those utilising ephemeral or first-order channels that discharge directly into the river. As flow moves down the slope, one route may feed into another. For example, laminar flow may feed pipe flow, which in turn may emerge onto the lower slope and become surface runoff. Different pathways dominate under different rainfall, soil and slope situations.

PATHWAYS OF NORTH-FACING SLOPES

The Hilltop zone

The Head on the upper convex slopes and flat hilltops, being relatively stable, has allowed the development of Podzols. As a consequence, there is an impeding E horizon immediately below the shallow peaty A horizon. This is also present beneath the remaining patches of hilltop peat. Ponding of water at this interface generates some lateral saturated flow that accumulates and eventually finds its way downslope, either as laminar flow or as rapid pipe flow. The clay E horizon on the flatter of the hilltop slopes is often traversed by a network of fine cracks, which probably allow some of the ponded water to infiltrate directly down into the weathered bedrock beneath, particularly following a period of drying out and shrinkage in the summer.

On the slightly steeper slopes lateral flow on the A/E horizon interface, once started, may continue right down the slope into the Boulder Clay area of the lower concave slopes.

Where thick hill peat still occurs, excess rain mostly runs off, feeding into gullies or into depressions that feed into ephemeral channels.

On the higher slopes, above the heads of the main valleys, peat is regenerating, infilling ephemeral stream channels and hollows; there are often water conducting pipes at the base of this peat.

The Upper Convex Slopes

The Soliflucted Head is a relatively free-draining material that lies on the north-facing convex slopes. The Upper Convex slopes have a gentle gradient, permitting the development of Podzol.

Apart from the possible small amount of leakage through the Podzol E horizon clay layer, most water infiltrating here ponds on the upper surface of this horizon and then flows laterally along it. Part emerges to feed runoff in the gullies; the rest continues as laminar or pipe flow downslope. When this encounters the downslope fringes of the Podzol area it is able to infiltrate further, down through the loose, fragmented C-horizon to its base. Here it ponds up and resumes downslope flow, through the weathered bedrock zone (Photo 6.02).

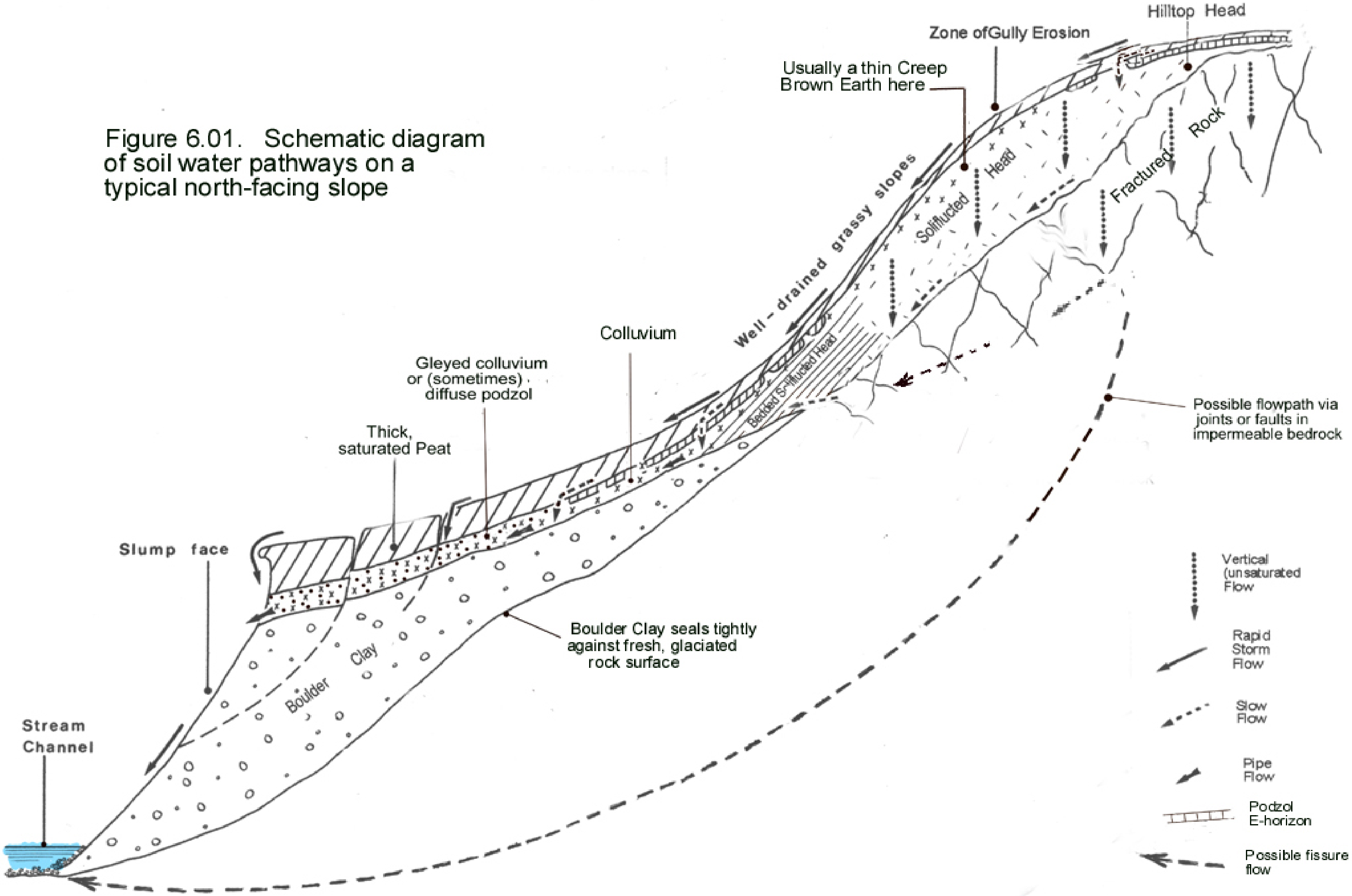


Figure 6.01. Schematic diagram of soil water pathways on a typical north-facing slope

Photo 6.02 View looking to the east from the west side of an eroded gully on the Wye-Cyff interfluve. 3m of Soliflucted Head is seen exposed in the east side of the gully (see also Photo 5.03). This material can be seen grading down into weathered bedrock. Grassy foreground forms pre-erosion surface.

This weathered and fractured bedrock is quite deep on the upper slopes, maybe as much as 7 m or more. This may constitute a perched aquifer, but the importance of this as a component of river flow is uncertain at present. There is also the possibility that such an aquifer might feed a joint and fissure system within the slightly deeper bedrock that might feed water directly to the beds of the rivers in the valley bottoms. At the time of writing there is no clear evidence to support this as a significant mechanism.

The Lower Convex Slopes

The situation here is similar to that on the Upper Convex Slopes, but as the slopes are usually steeper and unstable the Podzol is usually replaced by an AC-profile comprising a thin humic soil (A horizon) directly on the C horizon (Soliflucted Head parent material). The Soliflucted Head is thicker here, often 5 m or more.

Under conditions of heavy rainfall much overland flow is generated on these slopes, the thatch effect playing a part in this. The remainder of the rainfall infiltrates the grass cover and topsoil to accumulate in the weathered bedrock zone at the base of the profile, from where it probably flows mostly downslope through this layer. Some may enter the hypothetical deep fissure system mentioned above.

In heavy rainfall conditions a flow is generated in the gullies (see Photos 5.03 and 5.04), which at other times are mostly dry. These in turn feed into the surface runoff and peat bog of the lower slopes.

The Upper Concave Slopes

Bedded Soliflucted Head is the main parent material occupying this part of the slope profile. Having, by virtue of its mode of deposition, attained a stable slope profile, it is usually podzolised (see Photo 5.08), so infiltrating rainwater is partitioned. Some becomes downslope flow (on top of the E horizon). The remainder probably infiltrates down to the base where it meets either impermeable bedrock or impermeable Boulder Clay. In either case it is forced to move laterally downslope on this interface into the Boulder Clay zone.

The Lower Concave Slopes and Riparian zone

On the Lower Concave north-facing slopes, much of the original Boulder Clay infill of the valley floors still remains as terraces bordering the river. It is usually an area of low relief, sloping gently down towards the river, often ending in a slump face (see Photos 5.09 and 5.14). Elsewhere this has already gone and the surface of the remaining Boulder Clay is but little above river level: this can be seen in Photo 5.09, in the more distant part of the valley.

Pathways across and through this zone are quite different from those of the opposite side of the valley, where little or no Boulder Clay remains.

The Boulder Clay is a tough, impermeable material, which may be regarded as homogeneous in the mass. Due to its mode of genesis it always directly overlies a smooth, fresh, ice-worn rock surface so that in general there is no chance of significant flow beneath it via its interface with the bedrock.

In contrast to the south-facing opposite slope, first-order streams cross the Boulder Clay areas only infrequently and are usually small and carry little water. The reason for this is that the Boulder Clay tends to resist development of first order channels that might otherwise encroach upslope from the valley bottom. Usually the Boulder Clay lies directly beneath a metre or more of waterlogged valley peat (Photo 6.05), characterised by dense growths of sphagnum mosses. Where there are recent drainage ditches the surface is drier and supports the growth of grasses. The Boulder Clay of the upslope part of this area is, in some places, mantled by colluvial material from higher slopes. This is often in a gleyed (i.e. partly reduced) condition, mottled brown and blue-grey in colour. This suggests that there is little significant vertical infiltration of oxygenated water from the soil surface, but a degree of lateral flow within the gleyed part of the soil profile from upslope is not precluded. However, there is little observational evidence for this in newly dug soil pits.

The upper 20 cm or so of the Peat is a loose spongy mass of actively growing mosses and associated bog plants. Gravimetric determinations of water content and density of the peat have shown that this is almost entirely composed of water, the dry matter content typically being less than 5% w/w. Neutron probe water content measurements have shown that changes in profile water content are accommodated almost entirely by swelling and shrinking of the peat. The surface of the peat rises and falls, while the volumetric water content remains largely unchanged.

Most of the water coming down from the slopes above ends up here, irrespective of the routes followed, i.e. overland flow, discharge from ephemeral gullies in the Soliflucted Head, and subsurface flow out of the weathered bedrock (see Figure 6.01).

Irrespective of which route is taken by the water on its journey down from the hillsides above, it cannot pass through the impermeable Boulder Clay. Ultimately it has to flow either over the Peat, under the Peat, through the Peat, or via (hypothetical) fissures in the bedrock beneath the Boulder Clay. The first of these, i.e. flow through the surface layers of the Peat, is probably the main pathway, discharging straight into the river. Laminar flow at the base of the peat is unlikely to be significant for reasons mentioned above.

Some pipes do exist within the base of the peat and these probably carry water from the weathered bedrock beneath the Soliflucted Head during heavy rainfall conditions. They probably discharge straight into the river, although there is not much evidence for this as their exits are rarely seen other than in faces recently exposed by slumping. Such pipes may be up to 40 cm in diameter (Photo 6.03), although 5 – 10 cm pipes are more common.

PATHWAYS OF SOUTH-FACING SLOPES

The flow pathway system of the south-facing slopes (Figure 6.02) is far simpler than that of the north-facing slopes.

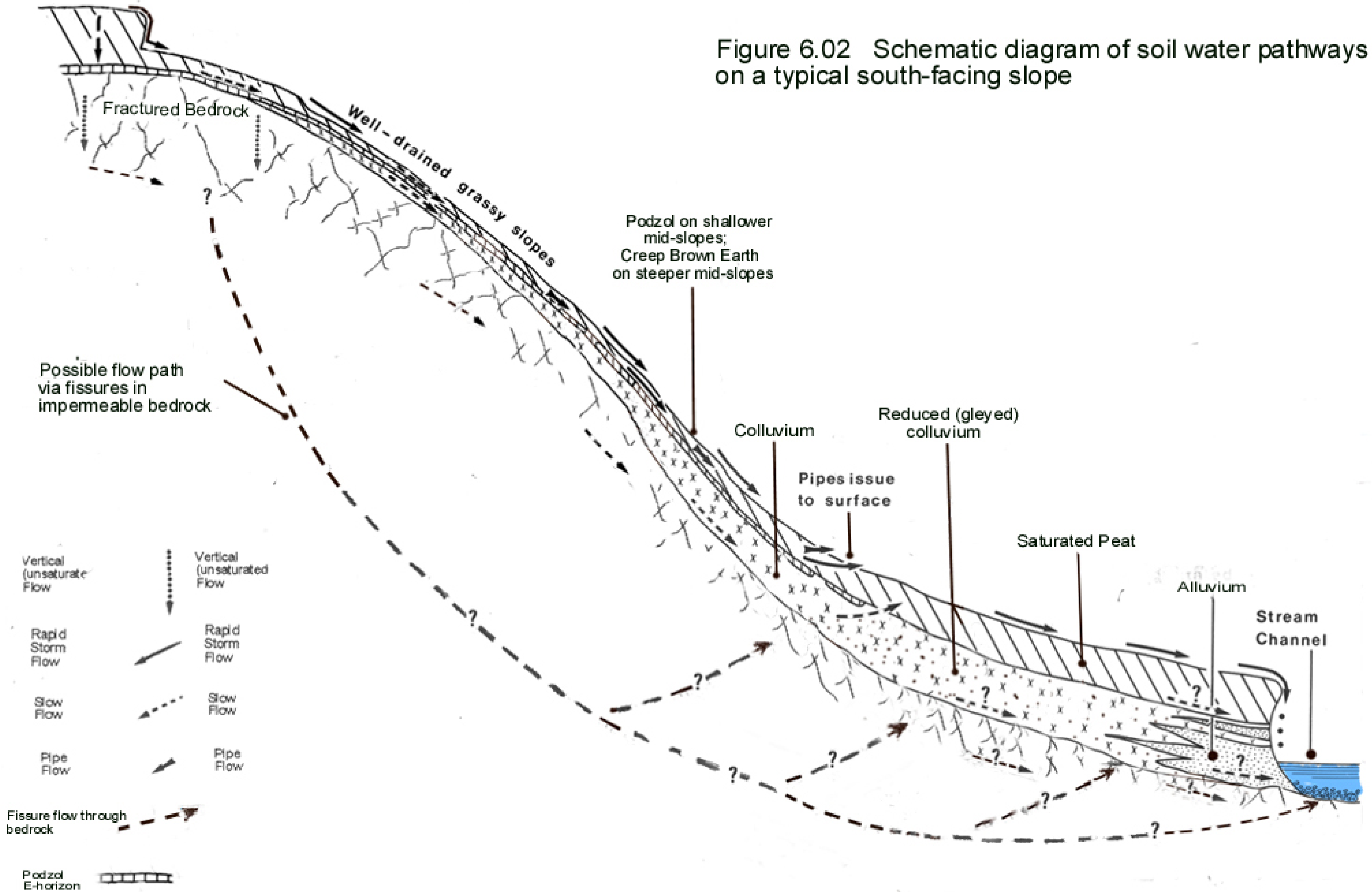
The Hilltop zone and Upper Convex Slopes

Most of the Hilltop area has lost its thick cover of Hilltop Peat, leaving only the underlying thin layer of Colluvium, with its condensed Podzol profile. In some places even this has been eroded away, leaving the bare rock exposed.

Rain falling on this area moves off laterally via a variety of pathways, either as overland flow (Photo 6.01), as laminar or pipe flow within the soil profile above the impeding Podzol E horizon, or through the lower zone of the C horizon (weathered slaty mudstone fragments and silty-clay weathering products). As with the Head deposits of the north-facing slopes, there is the possibility that water from this lower pathway may feed into fissure systems within the shallow bedrock.

In those places where Hilltop Peat still occurs, particularly in the more extensive Hilltop areas that occur above the heads of the main valleys, at the base of the Peat layer there is often a system of large diameter pipes, up to 50 cm across, similar in appearance to that shown in Photo 6.03. These lie on the impermeable clay pan of the Podzol E horizon, or sometimes on hard rock. The pipe system forms a collector network, draining the peat hags into ephemeral and first-order channels. These pipes grow in size until the Peat above collapses, thus extending backward the open channel.

Figure 6.02 Schematic diagram of soil water pathways on a typical south-facing slope



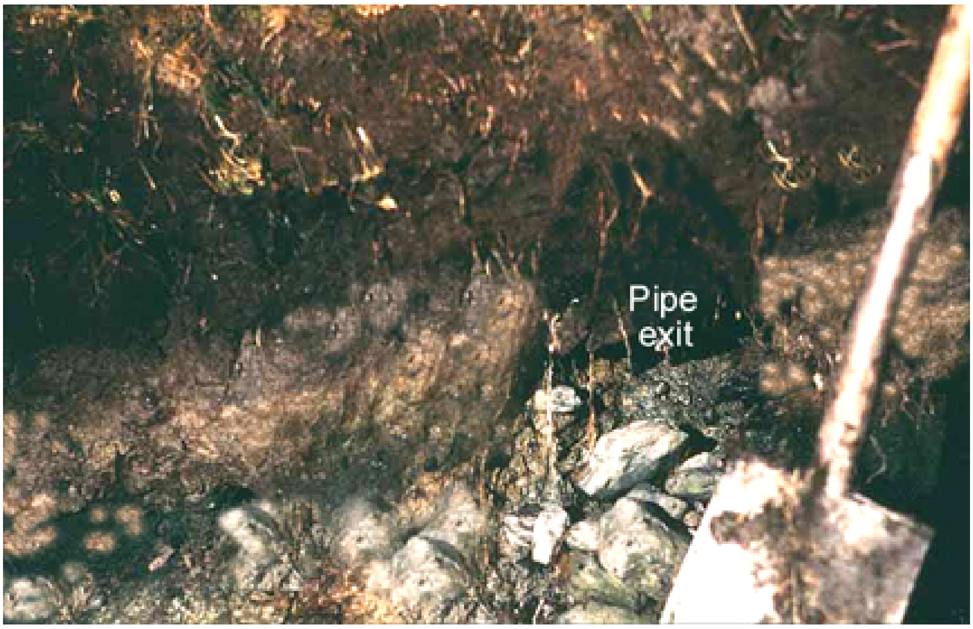


Photo 6.03 An example of a larger pipe in the E horizon below the Peat, resting on colluvium mantling the Boulder Clay

Starting on the Upper Convex Slopes, a system of smaller pipes such as that seen in Photo 6.04 runs downhill on the E horizon clay pan. Once a certain rainfall intensity and amount has been reached, these conduct rapid flow downslope. It seems probable that this water has infiltrated the thin A horizon of the upper convex slopes and entered the pipes as laminar flow above the clay pan. These pipe systems usually occur on hillsides flanking the valleys and should not be confused with the larger pipes found beneath the Peat on the high valley head areas.

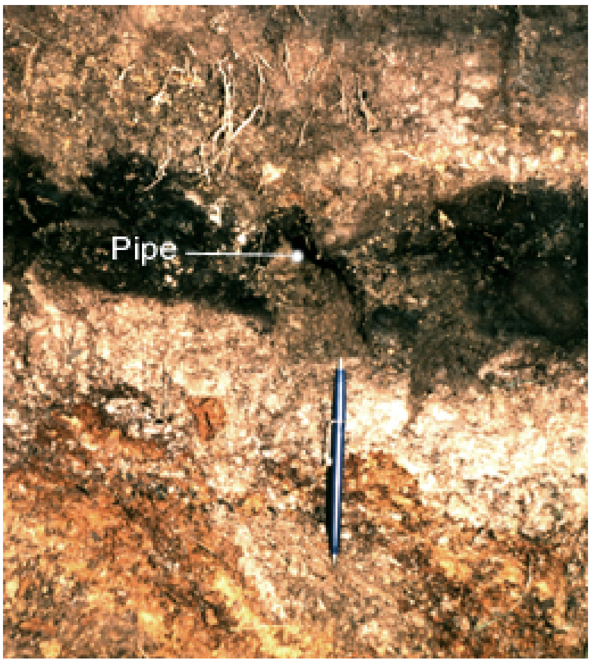


Photo 6.04 Double Podzol profile exposed in soil pit in Head, on Cyff-Wye interfluve, looking uphill. A second Podzol has formed above the first due to addition of late slope-wash. Shows pipe (above pen) on an E horizon clay pan of lower profile with iron pan beneath.

The Lower Convex Slopes and the Upper Concave Slopes

On shallower mid-slopes Podzols may extend downslope into this zone, and may even persist into the concave slope zones. Where this is so, the laminar flow and small pipe pathways of the Upper Convex Slopes continue into or through this zone as far as the Lower Concave Slopes.

In places where the slopes are steep enough to preclude Podzol development, Creep Brown Earth occurs. The absence of any impeding layer in this allows flow along the Podzol E horizon from the slopes above to disperse into the underlying B- and C horizons, thus feeding the flowpath at the base of the C horizon.

Creep colluvium slopes are generally smooth with a predominantly grassy cover, although lower down the valleys the mid-slope position tends to support bracken.

The Lower Concave Slopes and Riparian zone

The flattest areas of the valley bottoms are usually boggy, particularly where there are residuals of Boulder Clay, which appear as low rounded humps. Both the Boulder Clay and the Colluvium are generally in a partial or completely reduced state, with Peaty Gley Podzol or Peaty Gley profiles, indicating little or no passage of water through the material immediately beneath the Peat.

The oxidation state of the soil provides an indicator of water flow through it. In soils that conduct plenty of water the air in solution oxidises the ferruginous weathering products, and these impart rusty brown ochreous colours to the soil. Under the stagnant conditions of a peat bog, there is little flow of oxygenating water and anaerobic bacteria flourish, creating reducing conditions, in which iron compounds remain in a blue-grey reduced state. Gleying indicates an intermediate condition, usually brought about by seasonal drying of the profile by transpiration, allowing entry of some air or aerated water. This is essentially a vertical process, and does not imply any significant lateral flux of water through the system.

The Colluvium of this zone offers higher resistance to the passage of water due to its finer grain size and the lower slope angle, hence water arriving subsurface from the higher slopes is forced to the surface. It is not unusual during extended periods of heavy rainfall to see water spurting up out of the soil of the Lower Concave Slope area. This joins the water in the surface layers of the Peat and from there finds it way into the river channel of the valley bottom (Photo 6.05) where it trickles and drips out all along the bank.

Water moving downslope in the weathered surface of the bedrock, at the base of the C horizon, probably continues to follow this route into the base of the riverbank, but this is uncertain.

Photo 6.05 Valley peat (with thin alluvial lenses) exposed in the river bank. Water can be seen seeping through the vegetation and dripping into the stream.

First-order and ephemeral channels

The south-facing slopes are dissected both by ephemeral and first-order stream channels (see Photo 5.01). These tend to be more numerous and larger than those on the north-facing slopes. Flow is sustained in the first order channels mainly by the slow draining of the peat on the hilltops and of small peat basins on compound slopes.

7. Groundwater

When the Severn and Wye catchments were adopted for this long-term experiment, one of the main criteria for choosing them was that they were considered to be watertight, i.e. with no significant gains or losses of groundwater across the boundaries of the main catchments or their component sub-catchments. Such gains or losses would invalidate the water balances. The impermeable nature of the bedrock was assumed to preclude the existence of any conventional aquifer and any subsurface transfers of water across topographic divides. However, this underlying assumption has never been proved, and such proof would be very difficult if not impossible to obtain, although there are many indirect indications of its validity.

The following observations made during the course of the soils study support the view that the catchments contain no groundwater aquifers of sufficient size to make any significant contribution to the volume of river flow:

> 1. The rocks of the catchments and surrounding areas are predominantly hard, slaty or massive mudstones. When in a fresh, unweathered condition, these are totally impermeable and of such low porosity that water storage within the rock matrix is nil. Records from a 4 km long tunnel constructed for the Rheidol Hydroelectric Scheme nearby indicated that only in one place in the entire length of the tunnel was any water encountered. While this tunnel is several kilometres to the south west of the experimental catchments, the rock is similar. Any groundwater *storage* must therefore be looked for elsewhere. Neither was there any evidence of *pathways* in the form of joints or fissures bearing water in any significant amounts.
>
> 2. Numerous geological faults cross the catchments and often extend for many kilometres across country, but it is unlikely that these conduct or hold much water except perhaps in the weathered zone near to the surface. The reason for this conclusion is that it was these mineralised fault zones that were mined for lead and zinc in the 19th century, and although water can be seen today to flow from the horizontal drainage adits at valley floor level, no significant quantity has been observed to emerge from any of these workings.

The latter conclusion regarding the hydrological integrity of the catchment water balances does not preclude the possible existence of shallower, more open joints just beneath the hilltop regolith. Such joints might form connecting pathways between any (hypothetical) aquifer within the regolith and the river bed in the valley bottom, bypassing the soil system[1].

---

[1] *A running water balance calculation (Kirby et al., 1991) suggested that the magnitude of such non-soil (regolith) storage could be of the order of 120 mm, which is equivalent to about 5% of the typical annual catchment streamflow.*

If such a process of hillslope flow through jointing to the stream channels does occur, it is most likely to be on south-facing slopes. This is because on north-facing slopes the Boulder Clay protects the bedrock beneath from weathering, and hence the joints beneath would be tighter and less conductive. In these circumstances, fissure water might be forced up to emerge either as overland flow or as subsurface flow beneath the Peat.

To summarise, such evidence as there is at present, which inevitably is indirect, seems to support the view that in terms of *quantity*, contributions to river flow from groundwater are not likely to be of great significance. However, such contributions cannot be ruled out, and even if small, may be important in terms of their influence on water *quality*.

Further experimental work therefore needs to be done to establish the size and behaviour of any hilltop regolith aquifer and its relationships with water quality and quantity in the main river channels.

8. Some ideas on modelling the soil map

When the original soil study was carried out in 1968/69, modelling techniques were less advanced and the possibility of modelling the soil map did not arise. However, much has changed in the intervening years and it is suggested that it is now feasible to refine the field soil map by modelling, using criteria obtained from the original work.

Soil mapping is an inherently subjective procedure. Soil exposures, natural or man-made, are infrequent and hand-dug soil pits are not always practicable. Much informed guesswork has to be applied to the intervening areas. Soil types grade one into another in all directions, sometimes gradually, sometimes quite abruptly. Because of this, defining the position of boundaries between soil types is often highly subjective. Localised anomalies abound, resulting in small areas of soil that differ entirely from those of the area in general. If the scale of mapping is small enough, these may be ignored, but the larger the scale the greater the complexity and the more difficult it becomes to represent reality on a map. Thus, it must be accepted that a soil map is at best only a personal interpretation of reality, and two maps of the same area produced by independent surveyors would be unlikely to agree in detail. This poses the question: "How then is it possible to assess objectively the accuracy of a soil map?"

It is suggested that the results of the Plynlimon soil studies offer the prospect of a solution to this problem. On Plynlimon there is a strong correlation between the soil types, their position on the slope and the aspect of the slope, so that appropriate landform parameters representing these features might be assigned to each soil type. This offers the possibility that the digitised topographic data now available might be used together with information correlating soil types with slope position to model the soil map. Hopefully, this would avoid many of the subjective elements inherent in the field mapping process.

The procedure might be as follows:

1. The area would first be divided according to aspect. Areas having a predominantly north-facing aspect would be defined initially as those slopes facing between 280° and 100°; areas with a south-facing aspect defined as having aspects between 100° and 280°. Note here that although the terms "north" and "south" are used to describe these aspects, the orientation of the main valleys is ESE–WNW, so a degree of compromise is probably appropriate.

2. These would be further divided into areas of convex slopes and areas of concave slopes using the locus of the points of inflection in mid-slope where the transition between convex and concave slopes occurs.

3. Within the four divisions thus produced, further sub-divisions could then be made according to slope angle. Initial suggestions for this are:

- flat hilltop zone with upper convex slopes: from the interfluve down the slope until an angle of (say) 5° is reached;
- lower convex slopes: 5° down to the inflectional point;
- upper concave slopes: below the inflectional point, down to the point where the slope starts to flatten, say 5°;
- lower concave slopes and riparian zone: 5° and less.

The figures given above are merely examples and these parameters would initially need to be carefully estimated from field experience and the field map, and subsequently optimised to obtain the best agreement with the field map.

The question then arises: "How can the accuracy of the resulting map be objectively assessed?" There clearly needs to be a methodology to do this. A possibility could be to "score" the map on the basis of identifying the profiles in a number of randomly sited soil pits. The accuracy of the map would be defined by the percentage of these soil profiles successfully predicted by the map. This would still leave some unanswered problems such as "Who decides whether or not the pit profiles are in agreement with the map?" An element of subjectivity arises here again. There is also the question of how many soil pits are needed to give sufficient precision.

A further stage then would be to use the modelled soil map to define hydrologically similar areas ("hydrological domains"), on the assumption that the different soil types are indeed characterised by their own distinctive hydrological behaviour.

There is food for thought in all this, as it offers the prospect of some interesting research that would have value extending far beyond the Plynlimon experiment.

References and further reading

Brandt, C., Robinson, M. and Finch, J.W. 2004. Anatomy of a catchment: the relation of physical attributes of the Plynlimon catchments to variations in hydrology and water status. *Hydrology and Earth System Sciences* **8**: 345-354.

Dalrymple, J.B., Blong, R.J. and Conacher, A.J. 1968. An hypothetical nine-unit land surface model. *Zeitschrift für Geomorphologie* **12**: 60-76.

Gilman, K. and Newson, M.D. 1980. Soil pipes and pipeflow: a hydrological study in upland Wales. *British Geomorphological Research Group Monograph No 1*. Geobooks, Norwich, UK. 110pp.

Kirby, C., Newson, M.D. and Gilman, K. 1991. Plynlimon research: the first two decades. *Institute of Hydrology Report 109*, Wallingford, UK. 188pp.

Newson, M.D. 1976. The physiography, deposits and vegetation of the Plynlimon catchments. *Institute of Hydrology Report 30*, Wallingford, UK. 60pp.

Rudeforth, C.C. 1970. Soils of North Cardiganshire (Sheets 163 and 178). *Soil Survey of England and Wales*, Harpenden, Herts., UK. 153pp.

Glossary of terms

A horizon: The surface horizon of a mineral soil in which most biological activity occurs; minerals are lost from this horizon in solution and suspension by the process of eluviation.

ABC Soil: A soil with a complete profile, including an A, a B, and a C horizon.

AC Soil: A soil in which the B horizon is absent. Commonly such soils are young, like those developing from alluvium or on steep, rocky slopes.

Acid Soil: Generally, a soil that is acid throughout most or all of the plant root zone, having a preponderance of hydrogen over hydroxyl ions in the soil solution.

Anaerobic: Living or functioning in the absence of air or free oxygen. A reducing environment.

Aquiclude: A layer of rock or soil, which is relatively impermeable compared with other layers above or below.

B horizon: A soil horizon, usually beneath an A horizon, or surface soil, in which either:
(1) clay, iron, aluminium and organic matter have accumulated by receiving material from above either in solution or in suspension, or by clay development in place, or
(2) the soil has a blocky or prismatic structure, or
(3) the soil has some combination of these features.
In soils with distinct profiles the B horizon is roughly equivalent to the general term "subsoil".

Bedrock: The solid rock underlying soils and other earthy surface formations.

Boulder Clay (Glacial Till): A deposit formed by erosive action of a glacier on its rock floor, consisting of a finely ground rock flour matrix containing plucked, chipped and rounded boulders of country rock. This is left behind after the retreat of glaciers and often fills a valley floor to a considerable depth. Where the country rock is argillaceous the resultant Boulder Clay is usually very tough, resistant to erosion and highly impermeable.

C horizon: The unconsolidated rock material in the lower part of the soil profile from which the upper horizons have developed.

Catena: A sequence of soils of about the same age, derived from similar parent material, under similar climatic conditions, but having different characteristics due to variation in relief and drainage.

Clay pan: A compact, slowly permeable soil horizon rich in clay and separated more or less abruptly from the overlying soil. Clay pans are commonly hard when dry, and plastic or stiff when wet.

Colluvium: Mixed deposits of soil material and rock fragments which accumulated through soil creep, slides, and local wash on slopes under the influence of gravity.

Creep, Creep Soil: Slow mass movement of soil material down steeper slopes primarily under the influence of gravity, but aided by saturation and freeze/thaw processes

E horizon: A soil horizon that has been formed by the process of eluviation.

Eluviation: The translocation of material from one soil horizon to another, in the form either of solution or as a colloidal suspension. Soil horizons that have lost material through eluviation are said to be *eluvial*; those that have received material are *illuvial*.

Ferric Iron: An oxidised, trivalent form of iron, responsible in hydrated form for red, yellow and brown colours in soils.

Ferrous Iron: A reduced, bivalent form of iron, imparting a blue-grey appearance to some wet subsoils in which conditions are anaerobic.

Gley or Gley Soil: A soil in which intermittent waterlogging and periodic lack of oxygen have given rise to a mottled brown and grey colour. The term "gleyed" is applied, as in "moderately gleyed soil".

Greywacke: A poorly sorted sandstone containing silt and clay.

Head: The term "Head" is used mainly in Britain. It is applied to accumulations of rock fragments on hilltops, created in situ by the periglacial weathering processes of freeze/thaw and frost heave.

Hydrological domain: A part of a catchment having the same slope characteristics, expected to be characterised by similar hydrological processes, differing from other such areas.

Illuviation: An accumulation of material in a soil horizon through the deposition of suspended mineral and organic matter originating from horizons above. Since at least part of the fine clay in the B horizons (or subsoils) of many soils has moved into them from the A horizons above, these are called *illuvial horizons*.

Iron Pan: An indurated soil horizon in which iron oxide is the principal cementing agent.

Leaching: The removal of materials in solution by the passage of water through soil.

Pan: A layer or soil horizon within a soil that is firmly compacted or is very rich in clay. Examples include hardpans, fragipans, claypans and traffic pans.

Parent material: The unconsolidated mass of rock material from which the soil profile develops.

Peaty Gley: A semi-permanently saturated soil that is extensively anaerobic (reduced) and supports a growth of peat. Vertical infiltration of oxygenated water can be assumed to be negligible in these circumstances, although this does not rule out passage of oxygen depleted water that might ingress laterally.

Periglacial:
a. Relating to the zone immediately surrounding a glaciated area or ice cap, characterised by permafrost, and by freeze/thaw and frost heave erosion processes.

b. The term is also applied to the environment pertaining immediately after climate change has led to removal of permanent glacial conditions, prior to the onset of temperate conditions.

Podzol: A strongly layered soil produced under a temperate, excess rainfall climate supporting an acid vegetation and hence giving rise to acid leaching conditions. Calcium, magnesium, iron, aluminium and other cations are leached out of the upper part of the profile, together with clay minerals, leaving an ashy, pale-grey, silty clay horizon (eluvial E_a horizon) which in its extreme stage of development becomes an aquiclude, forcing much of the infiltration from above to drain off as lateral saturated flow. This leads to very wet conditions above the E_a horizon highly suitable for peat growth, culminating in saturated, anaerobic soil conditions (surface-water gley). Beneath the clay E_a horizon there may develop a very thin iron pan, rich in iron oxides and hydroxides (the B_{Fe} horizon), and perhaps also a similar secondary humus horizon (B_h). Beneath this is the B_s horizon, an oxidised, somewhat more permeable layer rich in sesquioxides and clay derived from above. This grades down into the parent material (C horizon) beneath.

Profile: A vertical section of the soil through all its horizons.

Regolith: The unconsolidated mantle of weathered rock and soil material of the earth's surface; the loose earth materials above solid rock. Only the upper part of this, modified by organisms and other soil-building processes, is regarded by soil scientists as *soil*.

Regosol: An azonal group of soils that includes those without definite horizons developing from deep unconsolidated or soft rocky deposits.

Riparian Zone: Land adjoining water channels or lakes that is subject to occasional flooding.

Solifluction: A type of creep in regions where the ground freezes to a considerable depth. As the surface layer thaws during the summer it moves as viscous flow downhill over the frozen layer. This can occur at slope angles of as little as 2° or 3°.

Till: see Boulder Clay.