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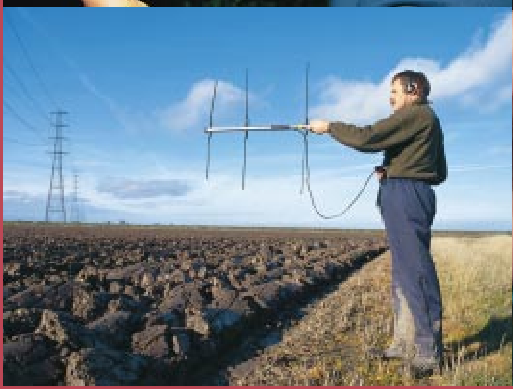


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Modelling the effect of land use change in the upper Severn catchment on flood levels downstream

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The appendices to this report and model files are available on a CD, on request from the Enquiries Service, English Nature (tel: 01733 455101)

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Executive summary

Land use is one of several significant factors affecting quantity and timing of flood runoff, and is arguably more accessible to human control than other factors such as climate, soils and channel hydraulics. Major changes occurred over the latter part of the 20^{th} century. For instance the area of rough pasture in the Cambrian Mountains declined from 78% in 1948 to 55% in 1983, the majority of this land being converted to coniferous forest. However there is little evidence of effects of extensive land use changes on the flood hydrology of catchments. Studies on the catchment scale, for instance the large networks of catchments used in the preparation of the UK Floods Studies Report and the Flood Estimation Handbook, have not turned up simple relationships between land use and flood hydrology, except in the case of urbanisation.

In the UK, impacts of afforestation on water resources have been demonstrated, and quantified in terms of the additional costs of developing reservoir storage, especially in upland areas. Forest practices, preparatory to planting and accompanying harvesting, have been blamed for increased and accelerated runoff, with local impacts such as erosion and sedimentation. The expansion of upland agriculture in the second half of the 20^{th} Century, through drainage and improvement of pasture, has not yet been investigated experimentally on a catchment scale as a possible contributor to changes in flood hydrology.

The economic strategy responsible for the expansion of pastoral agriculture in some regions is certain to change with a radical re-working of the Common Agricultural Policy. The economy of upland regions of the UK, where farmers and communities are tied to livestock production, will be slow to recover from the impact of outbreaks of disease. In future, there will be little pressure to increase or even maintain present grazing densities on moorland and hillslopes, and the hill farmer will be forced to reconsider the costs and benefits of grazing the uplands. Increased uptake of various agri-environment schemes can be expected, resulting in extensive changes in upland vegetation communities and habitats, and also in changes in soil properties, microclimate and hydrology.

The objective of this project is to understand the connections between upland land use and flood hydrology, through collation of existing information on the hydrological behaviour of the Severn headwater catchment and results of reported studies on a variety of spatial scales. This report explores the ways in which land use in the upper Severn catchment may affect flood response for small to medium-size events. Land use maps have been used to predict those areas where changes such as reduced grazing, reversion to moorland or scrub, or planting of forest on presently grazed hillslopes, might realistically be expected to occur.

Results of the investigation are incorporated into a hydrological model, in which the spatial dimension of this large catchment is taken into account. The model can be used to predict the consequences of possible land use changes in the upper catchment, especially those modifications to farming practice at high altitude that might be advantageous in terms of improvement of habitat and biodiversity.

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1 Background

The introduction of Catchment Flood Management Plans (CFMPs) represents an extensive multi-disciplinary approach to flood management, providing a framework for investigation of flood generation, the optimal design of hydrometric networks and strategic planning for flood warning and flood protection works. The CFMP also offers the opportunity to integrate concepts of optimal land use and the conservation of landscapes and habitats with the primary objective of reducing the damage caused by flooding. Like Catchment Management Plans and Local Environment Agency Plans, the CFMP is open to consultation with a wide range of interested people and organisations.

The River Severn, upstream of Gloucester, has been selected as one of five pilot CFMPs. Although the total catchment area is 9895 km^2, the flow of the River Severn at times of flood is dominated by contributions from the high-rainfall area of its 2025 km^2 headwater catchment upstream of Shrewsbury[1], which generates around 51% of the non-baseflow discharge of the Severn[2], and a larger proportion of peak flows. The mean annual flood at Shrewsbury is 59% of that at Gloucester, while the peak flows at Shrewsbury in the years 1990-1995 averaged 67% of those at Gloucester.

The uplands of the Severn headwaters (Map 1.1) reach a maximum altitude of 827 mOD, and the annual average rainfall at the source of the Severn exceeds 2500 mm, compared with around 750 mm for the lower parts of the catchment. As the floodplain widens and the channel gradient becomes less steep, inundation of riverside properties is frequent, especially at Shrewsbury and also at Bewdley, where the area of the Severn catchment has grown to 4325 km^2, more than double that at Shrewsbury. The component of the mean annual flood at Bewdley arising from the headwater catchment is around 80% of the total.

Land use is one of several significant factors affecting the quantity and timing of flood runoff, and is arguably more accessible to human control than other factors such as climate, soils and channel hydraulics. Major changes occurred over the latter part of the 20th century. For instance the area of rough pasture in the Cambrian Mountains declined from 78% in 1948 to 55% in 1983, the majority of this land being converted to coniferous forest (Parry and Sinclair, 1985). However, apart from the major influence of urbanisation, including road-building, there is little direct and incontrovertible evidence of the effects of extensive land use changes on the flood hydrology of catchments. Studies on the catchment scale, for instance the large networks of catchments used in the preparation of the UK Floods Studies Report (NERC, 1975) and the Flood Estimation Handbook (CEH, 1999), have not turned up simple relationships between land use and flood hydrology, except in the case of urbanisation. In the UK, the impacts of afforestation on water resources have been demonstrated, and quantified in terms of the additional costs of developing reservoir storage, especially in upland areas.

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[1] Catchment areas of Severn to Haw Bridge (upstream of Gloucester) and to Montford (upstream of Shrewsbury), from "Hydrometric register and statistics 1991-95", published by Inst. Hydrol. & Brit. Geol. Surv. (1998).

[2] Mean flow x (1 – Base Flow Index), using figures from "Hydrometric register and statistics 1991-95".

Forest practices, preparatory to planting and accompanying harvesting, have been blamed for increased and accelerated runoff, with local impacts such as erosion and sedimentation (Binns, 1979; Clarke and McCulloch, 1979). The expansion of upland agriculture in the second half of the 20th Century, through drainage and improvement of pasture, has not yet been investigated experimentally on a catchment scale as a possible contributor to changes in flood hydrology.

The economic strategy responsible for the expansion of pastoral agriculture in some regions is certain to change with a radical re-working of the EU's Common Agricultural Policy. The economy of upland regions of the UK, where farmers and communities are tied to livestock production, overwhelmingly cattle and sheep, will be slow to recover from the impact of two crippling outbreaks of livestock disease in recent years. In future, there will be little pressure to increase or even maintain present grazing densities on moorland and hillslopes, and the hill farmer will be forced to reconsider the costs and benefits of grazing the uplands. Increased uptake of various agri-environment schemes can be expected, resulting in extensive changes in upland vegetation communities and habitats, and also in changes in soil properties, microclimate and hydrology.

The objective of this project is to develop a better understanding of the connections between upland land use and flood hydrology, through the collation of existing information on the hydrological behaviour of the Severn headwater catchment and the results of reported studies on a variety of spatial scales. The results of the investigation are incorporated into a hydrological model that can be used to predict the consequences of possible land use changes in the upper catchment, especially those modifications to farming practice at high altitude that might be advantageous in terms of improvement of habitat and biodiversity.

2 The upland land surface and its effects on flood runoff

With the exception of operational or emergency discharges from reservoir storage, flood flow in the major rivers of the UK follows major rainfall events or, occasionally, rapid snowmelt[3]. Some of the largest Severn headwater floods this century, for instance in 1941 and 1947, have resulted from the combined impact of rainfall and an accumulated snowpack (Howe et al., 1967). However, the magnitude of the response to a flood-generating event differs between catchments, and even between events involving similar inputs of water. Other factors such as topography, soil type and land use combine to modify the rate of discharge to and through the river channels, and ultimately have influence on the flood peak and the duration of high flows.

Land use has most influence on the middle range of flow events (Figure 2.1). Those fortunate areas with a high level of flood protection may be almost unaffected by these modifying influences, but in a less well-protected area more prone to overbank discharges, even a small reduction in peak discharge may be significant, making the difference between a flow contained within the channel and widespread inundation of the floodplain.

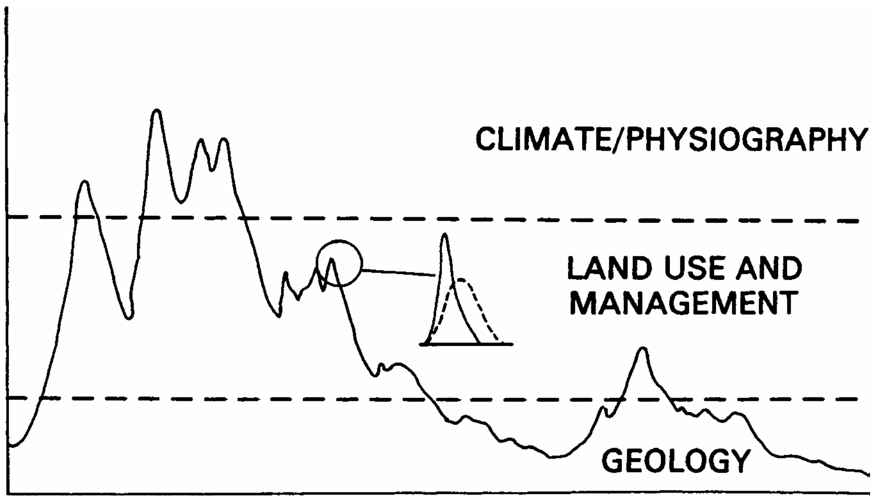

Figure 2.1 *The most significant impacts of land use on catchment hydrology lie in the mid-range of flows: the highest flows are defined by climatic events and catchment landform, while low flows are defined by geology, soil type and evapotranspiration rates - Newson (1997)*

Flood generation starts at the point of impact of rainfall, or the point of release of liquid water from snow, on vegetation or soils on the catchment flanks. From here the water moves through a cascade of vegetation surfaces and over or into the soil, before eventually reaching the stream, where channel characteristics control its passage to the lower parts of the

[3] Throughout this report, the term “flood” will be used in its hydrological sense, i.e. to indicate a high river discharge rather than inundation of the land surface outside the river channel.

catchment. At every stage of the cascade there is storage of water, and/or loss to the atmosphere, and there may be diversion of part of the input into faster and slower flow processes. What remains to fill the rivers is a fraction of the original input, delayed by resistances and temporary storages at every stage of its passage through vegetation, through the soil, and down the catchment flanks.

In the context of flood management, the time delays imposed on the flood peak by water passing through the soil may be as important as the losses: water reaching the river network after several hours detained in the soil may make little contribution to the flood peak, which is largely generated by the rapid runoff processes. This investigation is concerned with the impact of land use on both quantity and timing of runoff in the river network, and in particular with the effects of various potential changes in land use in the upland catchment of the River Severn.

At the catchment scale, the effects of the land surface and vegetation on the total quantity of runoff from a given event are summed up in a simple measure, the percentage runoff, more strictly defined in this context as the percentage of rapid runoff. For the Severn catchment to Montford, the gauging station just upstream of Shrewsbury, the annual outflow in the river is only 56% of the annual rainfall, but about half of this figure represents base flow resulting from slow release from the deeper horizons of the soil and from groundwater bodies in permeable rocks, sands and gravels, and regulated flow from reservoirs. For individual rainfall events, the percentage runoff varies, tending to be higher for larger rainfall inputs, and for those falling on wetted soils.

Though it is relatively easy to determine the percentage runoff for a given extreme event, by comparing the river discharge (after subtracting slow-response components making up the base flow) with the measured input from rainfall or snowmelt, it is not always a simple matter to interpret the range of percentage runoff figures obtained from various events. Much will depend on the antecedent conditions: for example under dry soil conditions, there is a substantial soil moisture deficit to be satisfied before the surface soil is saturated. Conversely desiccation cracking of soils and resistance to re-wetting (hydrophobicity) may permit rapid lateral movement of runoff water over unsaturated soils (Doerr et al., 2000), leading to flash flooding in summer from convective storms. The form of the event itself can have an impact: long-duration, less intense rainstorms contribute more water to the soil moisture store than heavy rain of short duration. Compaction or freezing of the surface soil allows little infiltration, and gives rise to a high percentage runoff.

Land use has an impact on the percentage runoff, through its effects on the partition of storm water between surface runoff and other flows and storages. There is more opportunity to make a significant proportional change in a low percentage runoff figure than in a high figure (Frost, 2000), and it is doubtful that land use change would have much impact on some of the most intense storms, for example those extreme UK events analysed by Acreman (1989), some of which produced flood flows in excess of 100 mm/hr from small catchments. This might suggest that in general the impact of land use would be felt more in relatively small events than in the extreme floods that cause the most concern. For example, for the exceptional Tay floods of February 1990, caused by catchment rainfall totals with return periods varying from 10 to 100 years, and rapid melting of snow that fell on high ground, it was concluded that afforestation, land drainage and changes in the river channel had insignificant impacts (Falconer and Anderson, 1993). Model studies of flood generation from catchments subject to alternative land uses also indicate that the more frequent floods are affected more by land use change than are the very extreme events (Naden et al., 1996; Price et al., 2000).

Land use practices can contribute to delaying the movement of slope waters, both by encouraging infiltration and by offering resistance to overland flow, in the form of vegetation and microtopography. For example, contour ploughing has been used widely in the USA as part of a toolkit of soil conservation techniques to prevent surface flow and soil erosion, while its converse, downslope or oblique ploughing with the intention of improving drainage of upland soils, has been shown to cause serious erosion in UK plantation forests. Poaching by animals, recreational trampling and off-road vehicle traffic are recognised as major causes of localised waterlogging on farmland, and of destructive runoff in the mountains.

Conversion of open land to forest has significant effects on the water budget, and its water resources implications have been researched thoroughly over several decades (Clarke and McCulloch, 1979; Kirby et al., 1991). However, its impact on the flood regime is less obvious, and may be confined to unregulated subcatchments such as the Severn upstream of Llanidloes, which is about 40% forested. In the Vyrnwy and Clywedog subcatchments, also heavily forested, the regulating effect of large reservoirs will tend to obscure the impact of the conifer forests (Plate 2.1).

Plate 2.1 *Lake Vyrnwy, constructed as a water supply reservoir for Liverpool in the 1880s, has an area of 4.45 km*^{2} *and now also has a role in regulating the flow of the Severn (Photo courtesy of Altered Light).*

Though modest improvement of upland pasture can be achieved by liming, fertiliser application and an appropriate grazing regime, it is not possible to change the sward radically without the precursors of drainage and ploughing. Impacts of these practices would be expected at two important stages of the rainfall-runoff response: the partition of incoming precipitation into rapid runoff, soil moisture storage, evaporation and slower runoff processes, and the routing of the resulting rapid runoff through various flow pathways to the rivers. Drained land might be expected to yield a rather smaller quantity of rapid runoff, because drained soil has a higher capacity to absorb water, but on the other hand the speed with which that runoff reaches the stream may be greater (Harris et al., 2000). Ploughing, undertaken at intervals of a few years for temporary leys, would tend to increase the storage capacity of the surface soil and impede the vertical movement of water towards underdrains by creating a more spatially uniform topsoil. Regular ploughing has also been found to reduce hydrophobicity, the tendency of soils to reject infiltrating water, usually when dry. Catchment and plot studies have confirmed that field or forestry drainage, and furrow ploughing for forest planting, usually result in a "flashier" hydrograph, though the problem is later compounded by interception losses in a maturing forest cover.

Reversion of improved pasture is a more complex process, involving changes in vegetation and soil properties and a decline in the effectiveness of drainage works. The end result cannot be the widespread restoration of pre-existing natural or semi-natural ecosystems, as other factors have changed, e.g. the loss of old wethers from flocks, and the degradation of blanket peats. Rapid leaching processes in the uplands would tend to reduce the duration of excess nutrient levels, another common problem of restoration of semi-natural systems. The various processes of reversion take place at different rates, with estimated timescales varying from decades to centuries (Ball et al., 1981), but the reduction in drainage density and the increase in interception of precipitation by heather and scrub would suggest a trend towards decreased total runoff and a lengthening of the timescale of the storm hydrograph, i.e. a less "flashy" hydrological regime.

2.1 Flood runoff from pasture and moorland

The process of infiltration into the soil determines the partition of net rainfall and snowmelt between rapid and slow flow towards the drainage network. Water that cannot infiltrate, for whatever reason, is channelled by the microtopography of the ground through an informal network of rills, shallow depressions and macropores close to the soil surface. Overland and rapid subsurface flow tends to merge into deeper surface flows less influenced by the roughness of vegetation and soil, and concentrates in the more significant rills and in field boundary ditches, which constitute a form of "dry valley" network integrated with the river network.

On reaching the river, accumulated surface and shallow subsurface flow ultimately forms the flood hydrograph, which is superposed on one or more hydrograph components associated with groundwater discharge (*baseflow*) or slow flow through the soil (*throughflow*). As the hydrograph, seen as the graph of total channel discharge against time, represents the integration of many processes operating on different timescales, it is often a smooth bell-shaped curve (Figure 2.2), though more frequently it is a superposition of several curves representing successive pulses of rainfall or snowmelt (Figure 2.3). However, some small research catchments have been found to respond even to short rainstorms with a double-peaked curve, resulting from the arrival of overland flow followed by slower throughflow in the soil (Nutter and Hewlett, 1971).

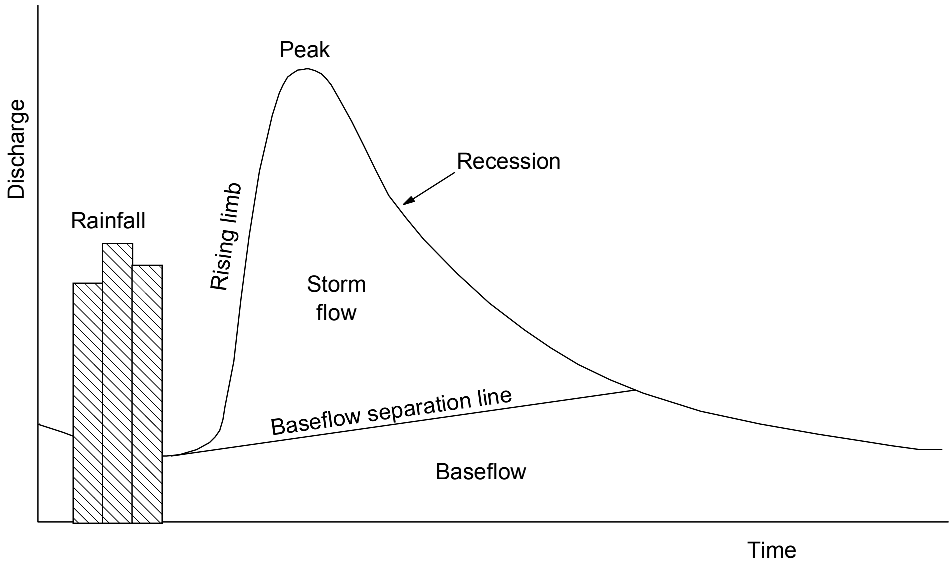

Figure 2.2 *A simple flood hydrograph produced by a pulse of rainfall. There are many different techniques for the construction of the baseflow separation line to isolate the rapid runoff contribution to the hydrograph.*

Following plot studies in the United States, where rainfall intensities are generally much higher, and soil erosion has always been a serious problem, the significance of overland flow to the flood hydrograph was perhaps over-emphasised in the hydrological literature. Failure to observe extensive overland flow in Britain led to detailed investigation of the mechanisms of shallow subsurface flow, usually in strongly layered soils such as podsols. Though throughflow in the soil matrix is much slower than surface flow, there is a multiplicity of larger passages, or *macropores*, caused by plant roots, burrowing animals and desiccation cracking, that can conduct water quite rapidly down hillslopes (Jones, 1997). In the uplands of mid-Wales, and other similar hill areas in the UK, such as the Pennines, natural pipes, either scattered over the hillslope or integrated into the stream drainage network, provide an intensive pattern of rapid flow pathways in headwater catchments, and contribute to the storm hydrograph (Gilman and Newson, 1980).

It would be unwise to assume that, even under extreme conditions, saturation of the surface soils, and consequent overland flow, will occur over the whole catchment. Flatter areas near stream channels, and surface depressions where the soil remains damp because of the convergence of slow throughflow from upslope, will reach saturation more rapidly during rainfall, and will act as *partial contributing areas* for the generation of flood flows in the river (O'Loughlin, 1981; Weyman, 1974; Weyman, 1975). Maps of partial contributing areas have been produced for intensively-studied catchments, and demonstrate a fingering pattern like the veins of a leaf, extending the channel network upstream, especially at times of heavy rainfall, when they take up a larger and larger proportion of the total catchment area. Some parts of the contributing area pattern may be disjoint under normal conditions, amalgamating with the network only occasionally or late in the storm event. Though individual contributing areas may originate from local drainage or impermeable soil horizons, the broad outlines are defined topographically. Using digital terrain models the contributing areas show up as isolines of the *topographic index* $\ln\left(A/\tan(\beta)\right)$, where A is the catchment area upslope of the given point, and $\tan\beta$ is the local ground surface gradient. The topographic index incorporates two important factors controlling saturation: the concentration of flow from uphill, and the effect of the local gradient on drainage.

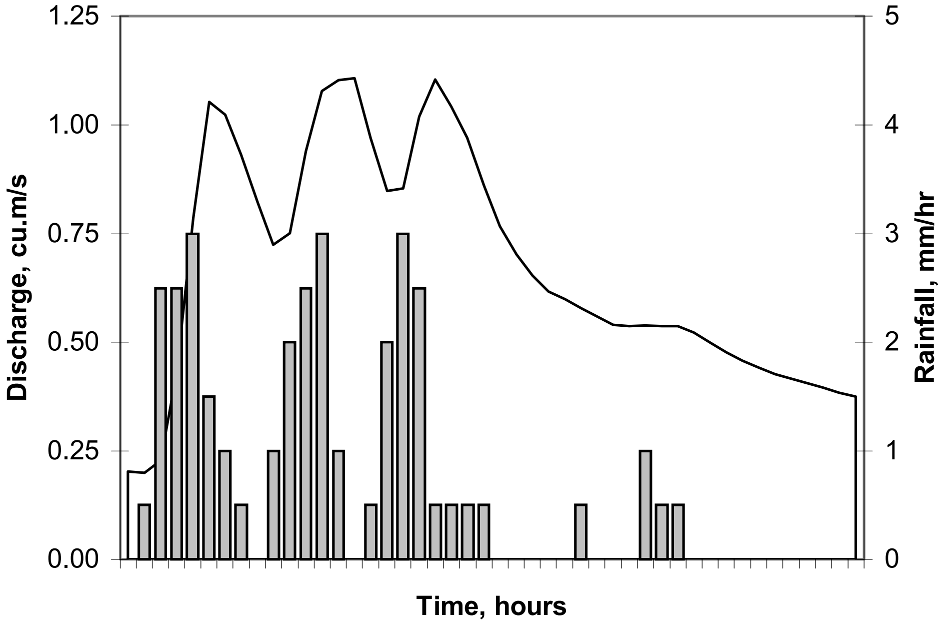

Figure 2.3 *A complex flood hydrograph arising from several pulses of rainfall, Dulas at Rhos-y-Pentre, 15 January 1999*

The extent of partial contributing areas waxes and wanes according to season: Harvey (1971) observed that summer rainstorms, which needed to be heavier to produce storm runoff from his clay catchment in southwest England, also tended to produce a quicker response and a shorter hydrograph, while winter floods were slower to rise and longer-lasting. He concluded that almost the entire catchment was responding to rainfall in winter, while only a small part, presumably close to the stream channels, was generating storm flow in summer.

There is evidence to show that a modest change in vegetation, for example pasture improvement or reversion, has more impact through altering the infiltration capacity of the soil than through modified interception of rainfall (Jones, 1997). Infiltration is a complex process involving gravity drainage through large soil pores and capillary flows through small pores, driven by soil moisture tension gradients. Macropores, with a diameter of between 1 and 10 mm, provide a quick and easy path for water to reach the deeper layers and sometimes to the water table (Beven and Germann, 1980). The quantity of flow induced by a soil moisture gradient is defined by the hydraulic conductivity, a measure of the resistance presented by soil pores. In unsaturated soils the hydraulic conductivity is moisture-dependent, while the hydraulic conductivity for saturated soils is determined mainly by the size and connectivity of the larger soil pores. During a rainstorm, vertical flow through the unsaturated zone, initially high due to the tension gradient from wet surface soil to dry deeper layers, decreases with time as the deeper soil absorbs water, and the gradients driving capillary flows decrease. Eventually the infiltration rate is entirely defined by gravity drainage, and depends on the saturated hydraulic conductivity (Saxton and Shiau, 1990).

The effective rainfall, which provides the rapid runoff component of the flood hydrograph, is the balance after infiltration has been subtracted (Figure 2.4), and the total effective rainfall over the catchment for a given event is equal to the total rapid runoff. In general, the proportion of rainfall that infiltrates is higher for drier soils. Small rainfall inputs, especially those in summer, may be lost entirely to the soil. Many different models can be used to estimate the infiltration rate and its variation over the duration of a rainstorm: at the simplest level, a constant infiltration or loss rate, estimated from the antecedent rainfall or the soil moisture deficit, is often used in flood prediction.

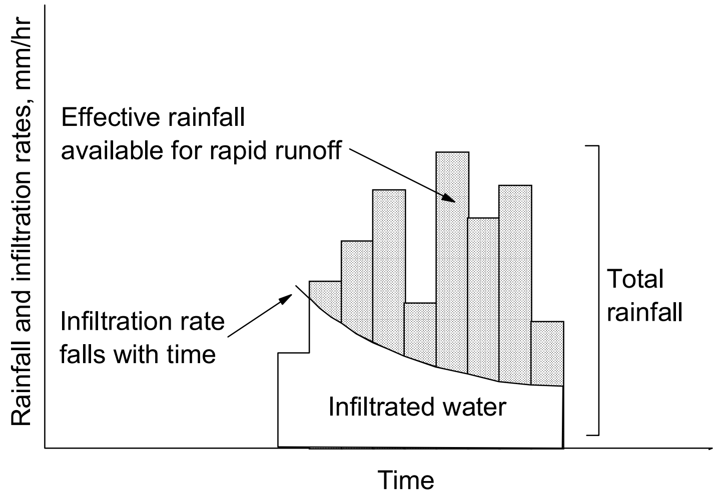

Figure 2.4 *The effective rainfall that generates flood flows is the balance of the actual rainfall after infiltration has been subtracted In this case the infiltration rate falls off exponentially. Note that early rainfall is lost to the soil, and does not contribute to rapid runoff.*

Deep-rooted plants tend to reduce rapid runoff by drawing heavily on soil moisture, creating a large soil moisture deficit that must be satisfied by infiltration before widespread surface runoff or shallow throughflow can occur. Trees and shrubby plants also reduce the proportion of rainfall reaching the ground, by intercepting water on the canopy. As an example of the variation in the proportion of rapid runoff generated by different land uses, Miller (1977) offers figures of 20% interception loss and 4% overland flow for oak/hickory forest, 20% interception and 31% overland flow for a forest without a litter or humus layer, and 76% overland flow for unimproved pasture. These figures, originating in North America where rainfall intensities are often much higher, cannot be applied directly in the UK, where overland flow is a rarer and more localised phenomenon.

There have been many studies of the hydrological processes taking place in the uplands of Britain. It could be argued that the unforested uplands offer the best opportunity to study natural hydrological systems relatively unaffected by man’s activities. However, this argument is somewhat misleading, as the uplands have been subject to management and change over many centuries, the present grazing regime reflecting a tradition that may have been evolving since Mesolithic times. Pollen records suggest a much wider original spread of deciduous woodland, and there is evidence to connect the leaching of upland soils with clearance by fire to improve hunting grounds (Curtis et al., 1976). Some of the familiar “natural” features of the uplands, such as extensive blanket peat, podsol soils and close-cropped grasses on the hillslopes, oak and birch woodlands and alder coppice confined to the valleys, have been created or modified as a result of human interference. Less obvious attributes of the upland environment, which may have major importance for hydrology, for instance the development of natural pipes carrying rapid runoff to the stream system, the erosion of blanket bog and the balance between grass and heather, show complex relationships with historical land use changes, and it is by no means clear to what extent natural systems can be restored by a simple reversal of past influences.

Some features of the semi-natural upland environment are very different from those of more intensively managed agricultural land. Drawing on a range of upland hydrological studies, Jones (1997) presents a picture of the complexity of the upland flow network, where runoff generated on blanket peat and exposed hillslopes is channelled to the river network by a variety of fast and slow processes, some of them disjoint and responding only occasionally (Figure 2.5). Simple theories of runoff generation are shown to be inadequate to describe the full range of hydrological behaviour. There is evidence of storage of water where rapid runoff would be expected, for example on hillslopes where disjoint and anastomosing drainage systems can spread water as well as concentrating it. Conversely there is rapid movement of water through natural pipes where overland flow is apparently absent. The process of throughflow in the soil not only gives rise to a delayed onset of the flood hydrograph, but it also has important water quality implications, as water detained in the soil has time to come into chemical equilibrium with its surroundings before entering the stream.

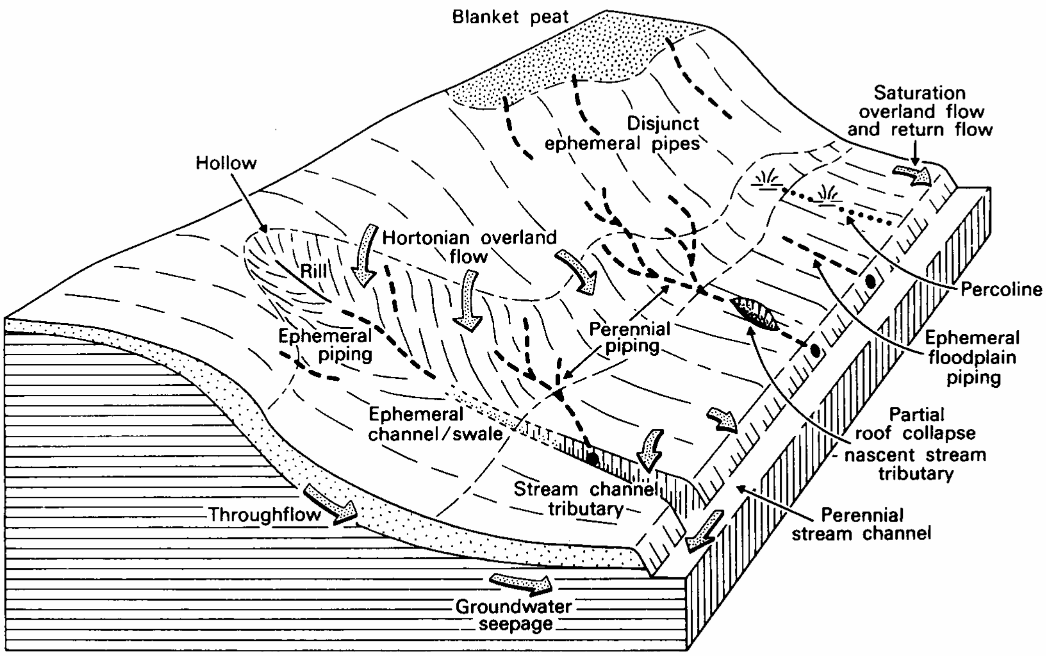

Figure 2.5 *Processes of runoff generation on an upland hillslope – Jones (1997)*

Agricultural drainage systems are never disjoint: there is always concentration of flow into larger and larger channels, though their efficiency may be degraded by low gradients, obstruction or lack of maintenance. It could be argued that one of the more significant agricultural consequences of expanding the artificial drainage network is the incorporation of formerly disjoint or poorly-connected wet areas such as springs, small wetlands and depressions. The most common reason advanced for proposals for land drainage schemes in Wales and southwest England in the 1970s was the alleviation of problems with spring water (Robinson and Armstrong, 1988). The impacts on natural habitats of drainage activity targeted in this way have been widespread and severe. In the uplands, the beneficial effect of field drainage in increasing the capacity of the soil to infiltrate and store water is probably overrated, and is almost certainly negated by the compaction of surface soils by intensified grazing.

2.1.1 Grazing

Grazing animals are an important modifying influence on the structure and composition of vegetation communities, and a change in grazing density amounts to a land use change that may in an extreme case be equivalent to ploughing and reseeding. Transformations resulting from a change in grazing can be surprisingly rapid: for instance exclusion of sheep from upland pasture has been shown to cause an increase in heather from 1% to 30% on a well-drained soil, and an increase in moorgrass from 55% to 80% on a wetter site, over a period of only two years (Jones, 1967). After fifteen years of exclusion, heather had reached 88% by weight, but it was reduced to 10% when sheep were allowed to graze for a further 12 years.

There is considerable variation in grazing intensity in the uplands: some valley bottom fields are close-cropped and poached, while the open moorland, used mostly for summer grazing at a relatively low density, supports a diverse sward including heather and bilberry. Grazing animals also exercise preferences, frequently leading to heavy use of areas where there is already bare ground or short grass, and within these areas there is excessive pressure on favoured species and the spread of unpalatable species. A study on the north Pennines showed that sheep allowed to graze freely had congregated at various intensities, from 5 ha^{-1} on *Agrostis/Festuca* grassland to 0.1 ha^{-1} on heather-dominated blanket bog (Rawes and Welch, 1969, quoted by Miles, 1987). Sheep grazing on moorland causes a decline in the cover of heather, which can withstand only a limited level of destruction of its growing tips, and it has been estimated that 43% of the heather moorland in Wales shows suppressed cover and/or growth forms associated with overgrazing, neglect and inappropriate management (Bardgett et al., 1995). The impact of grazing on heather or any other vegetation type is not simply related to the stocking density, but depends upon the detail of the vegetation community: for example heather is suppressed more where it is already only a minor component (Armstrong and Milne, 1995).

There are few quantitative studies on the hydrological effects of grazing, probably because of the difficulty of ensuring that catchment boundaries correspond with treatment boundaries. Accepting the usual caveats with regard to results from the US, where annual rainfall can be low but storm intensities are high, the results presented by Hanson et al. (1970) serve to demonstrate the potential impact of grazing intensity on the hydrology of grasslands (Table 2.1). In four out of five years of the study, the more heavily-grazed plots produced more runoff, though it is not made clear whether this was entirely due to differing infiltration capacities or changes in interception losses. Infiltration rates for various crop and grass covers were tabulated by Kirkby (1969), drawing on work in the USA by Musgrave and Holtan (1964): infiltration into the soils of old permanent pasture could be ten times that into bare soil, and more than four times the infiltration rate of heavily grazed pasture.

Some features of livestock grazing, for instance the creation of bare soil areas by poaching and the establishment of a network of sheep tracks, develop in proportion to stock density, and there is evidence that grazing at high intensities decreases the infiltration capacity of the soil (Gifford, 1975), through the very high pressure exerted by hoofs, increasing the bulk density of the surface soil and reducing its porosity (Smeins, 1975). Changes in infiltration capacity can be detected even in recently improved pasture by the spread of the soft rush, *Juncus effusus*, which takes advantage of poaching and wet surface soil (Miles, 1987), and is an early sign of the reversal of the hydrological effects of drainage and ploughing.

Table 2.1 *Annual precipitation (mm) and runoff (mm) from western South Dakota grasslands subject to various grazing intensities (Hanson et al., 1970). The impact of each grazing intensity was measured on four 0.8 ha plots.*

Year	Grazing treatment					
	Heavy		Moderate		Light	
	Forage utilisation > 55%		Forage utilisation 35 to 55%		Forage utilisation < 35%	
	Precipitation	Runoff	Precipitation	Runoff	Precipitation	Runoff
1963	308	46	305	40	320	35
1964	218	17	218	7	197	1
1965	275	3	281	4	277	3
1966	239	4	233	0	240	0
1967	279	31	284	20	277	14
Mean	264	20	264	14	262	11

Universally, grazing of the uplands inhibits tree growth and favours grasses over shrubby plants, though some taller species such as gorse and bracken can withstand grazing, and provide habitats with a considerable potential for interception of rainfall. Within established woodlands, notably oak woodland on the slopes, sheep grazing removes the understorey, reducing the interception capacity and gradually thinning the woodland canopy as replacement of senescent trees is prevented. Grazing of the most valuable floodplain land right up to the river's edge has been blamed for the loss of streamside trees and consequent damage to river banks in the Severn valley between Welshpool and Shrewsbury (Purseglove, 1989).

A recent steady increase in livestock numbers in Wales, part of a long-term trend that has seen the numbers of sheep in the uplands doubled since 1875 (Anon, 1978), with pronounced dips in the 1920s and 1940s, has led to modification of the traditional transhumance pattern. Increased use of lowland grasslands for hay and silage production, to support larger numbers of stock through the winter, and sheep housed at lambing time, has pushed more stock on to the hills in summer (Plate 2.2). Sheep are also kept on the hills for a longer period with the use of supplementary feeding, a practice which leads to concentration of stock around feeding stations, and trampling and destruction of heather, as well as erosion (Hudson, 1984). Improved access to the hills, following grant aid for roadbuilding, has extended the area of improved grassland well above its former ceiling, though these upland pastures are difficult and expensive to maintain at their maximum productivity.

Plate 2.2 *A modern upland farm in the Wye valley. Sheep farming is now heavily dependent on silage and concentrates for winter feeding, and improved access to the hill land has resulted in changes in the pattern of grazing.*

In recent years, there has been a 40% increase in the numbers of sheep in the Yorkshire Dales, and year-round grazing of the uplands has led to increased erosion, a short-cropped grass sward and the loss of heather in the 1000 km^2 catchment area of the Rivers Ure and Swale (Sansom, 1996). The conversion of the local economy from largely dairying and beef production to sheep has taken place since 1982, and this period has also seen a sequence of four severe floods in thirteen years, each exceeding the extremes recorded by 19^{th} century floodmarks. Sheep were traditionally wintered in the lowlands of the Vale of York, and cattle were housed in barns in the valleys, but winter feeding has made it possible to keep sheep on the hills throughout the year. Sansom's article concluded with a call for further investigation of the relationship between sheep grazing and flood runoff generation.

2.1.2 Drainage

Land drainage for agriculture, though not so extensive as forest drainage on the higher ground, has been an important factor in the development of pastoral agriculture in mid-Wales. Drainage of lower slopes and flat land, carried out by hand using ditches and grips, was aimed at improving the quality of the best grazing land close to the farm, in the first instance by diverting groundwater discharges and dealing with areas of surface water accumulation. Moorland was drained by shallow grips, open drains typically cut using a single mouldboard Cuthbertson plough to improve the quality of heather grazing for sheep and grouse.

Grazing of valley-bottom mires is improved by trenching to lower the water table, reduce the incidence of footrot and liver fluke and permit the peat to carry cattle without excessive poaching (Hudson, 1998). The improvement in soil aeration and productivity is small, but it is a precursor to modification of the vegetation community by more intensive grazing, and the additional nutrients made available by animal manure and the slightly drier conditions in the superficial peat.

Tile drainage, introduced in the 19th century and carried out by hand (Figure 2.6), made it possible to improve hay production and arable cropping, and a remarkably high percentage (over 75% in some parts of mid-Wales) of the land inspected in 1971-80 in relation to drainage proposals was found to have pre-existing field drains (Robinson, 1990; Robinson and Armstrong, 1988). The impetus for field drainage waned somewhat in the early years of the 20th century, when the cost of drainage might exceed the freehold value of the land (Adkin, 1933). Underdrainage of larger areas in mid-Wales had to wait for the arrival of specialised machines, and UK Government grant support for mechanised draining was at its height in the 1970s. Tractor-mounted backacter trenching machines facilitated work on irregular land, diminished the need to employ specialist contractors, and improved the maintenance of existing systems.

Underdrainage using tiles or plastic pipe is an effective method for improving pastures, without the inconvenience of open ditches, which are always a hazard to stock, and at close spacing prevent access by vehicles for sward management and hay cropping. In fortunate circumstances pipe systems can be long-lasting. However, few if any drainage systems are immune to damage by machinery, blocking by sedimentation or ochre formation, and disturbance by roots and burrowing animals, and replacement or repair will eventually be necessary. Tile drains paid in peaty soils change in alignment and profile with time, and may lose continuity. The cost of locating and repairing problem areas is usually disproportionate to the loss of productivity if the problem is ignored, and many drainage schemes installed under the generous grant aid available in the 1970s are likely to decline in effectiveness in the future (Hudson, 1998). After-treatments such as moling and subsoil ploughing, designed to create a secondary network of macropores at an angle to the main tile or pipe drains, were slower to catch on in Wales than in eastern England (Green, 1976; Green, 1977), possibly owing to the smaller profit margins inherent in the pastoral economy.

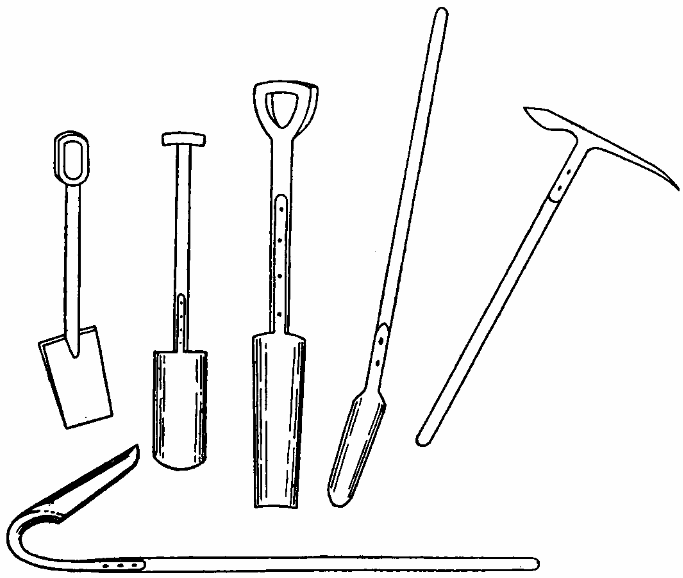

Figure 2.6 *Hand tools used for tile draining in the 19th century and at least up until the 1930s, when tractor-pulled mechanical devices were just being introduced. However, tile drainage was considered too expensive in the 1930s, and mole drainage, often using cable haulage from a static tractor, was becoming more popular* (Adkin, 1933).

The hydrological effects of drainage are a combination of effects on the response of runoff to rainfall, through changed hydraulic properties, and of changes in the antecedent conditions prior to runoff. In a thorough and detailed review of the topic, Robinson (1990) distinguished five ways in which the effect of drainage on hydrology could be manifested:

Tending towards higher peak flows

i) increased drainage density – an important parameter affecting the timing of flood runoff

Tending towards lower peak flows

ii) enlarged available soil water storage capacity – increasing infiltration into the soil and reducing the quantity of rapid runoff

iii) effects of storm characteristics and antecedent conditions – the runoff that would have been generated by small to medium sized storms can be reduced or eliminated

Complex or unpredictable responses

iv) different types of drainage systems – pipe drainage, partially isolated from the ground surface, is believed to delay the passage of runoff into streams, where an equally intensive network of open ditches would reduce the duration of runoff and increase peak flows

v) extent and location of drainage within a catchment – the changes in yield and timing of flow from a drained area interact with the main stream network within the catchment, sometimes with unexpected consequences.

Arguably the main function of drainage is to increase soil aeration by reducing the volumetric moisture content of the soil in the drier spells between rainfall events. This is achieved by tapping the groundwater body in the saturated zone of the soil to lower the water table, and by the creation of a fine network of channels to conduct storm water away rapidly during and after rainfall. In theory this provides the opportunity for storage of storm rainfall within the soil profile, hence delaying the onset of flow in the drains, perhaps to the extent that there is no rapid increase in discharge at all for small rainfall events (Richards, 1968; Robinson, 1990). This has been the main thrust of arguments aimed at proving that drainage reduces rather than increases peak discharges in rivers.

Soil aeration may not be so important for winter floods: for instance the increase in soil moisture deficit brought about by drainage is small in the Welsh uplands during the winter, when flood-producing rainfall events are most common, and soil moisture deficits can also be small in the summer. If the year is divided for land drainage purposes into a "winter" season when soil moisture is at or above field capacity (i.e. field drains are flowing), a "summer" season when there is a significant soil moisture deficit, and "spring" and "autumn" seasons when soil moisture is below field capacity but drying and wetting respectively (results from the Field Drainage Research Unit, quoted by Bailey and Bree, 1981), Welsh upland sites pass directly from spring to autumn without a summer!

Drainage of peat by regularly-spaced ditches can result in the creation of up to 130 mm of soil water storage in the upper peat (Hudson, 1998). Not all this storage is available to delay the onset of rapid runoff, however, because high intensity rainfall can bypass the soil water storage and induce immediate surface or channel flow, and drained peat becomes hydrophobic (Robinson, 1986). The network of cracks created in the upper peat after drainage, and the increased activity of burrowing animals, especially moles, enhances the hydraulic connection between the surface and the partially dewatered peat matrix, and at the plot scale there appears to be a longer delay in the conversion of rainfall to streamflow in tile-drained peat than in undrained peat (Roberts et al., 1986). Results obtained on a mole-drained clay plot in the Thames valley (Beven, 1980) indicated that cracks above mole drains provided an important mechanism to deliver water to the outflow, and there was little movement of water into the clay matrix. The free movement of water into the cracks decreased the incidence of surface saturation and overland flow, so that although the flow processes were very different, there was no net effect on the timing or magnitude of outflows.

Results obtained in the field often seem to be contradictory, perhaps indicating a variation with the type of drainage, the effects of arterial drainage improvements or a change over time after drainage. Results from an experiment on drained peatland in Scotland indicated that peak flows can be increased by 25-30%, with a shorter time-to-peak, as the very small increase in the storage capacity of the peat following drainage is insufficient to compensate for the increase in drainage density (Nicholson et al., 1989).

It is interesting to note that the quantity of available storage in the upper layers of drained peat is almost identical to that of natural blanket peat with an intact *Sphagnum* moss cover (Conway and Millar, 1960). In the 1950s Conway and Millar conducted a pioneering experiment on four small (3.8-8.8 ha) peat catchments in the Pennines, and showed that open drainage of blanket peat, whether by grips or irregular erosion channels, led to more rapid runoff, with higher and earlier peak flows. Moderate burning, without total destruction of the mire community or the heather, tended to produce a flashier hydrograph, but the effect was very much less than that of drainage. Subsequent analysis of the data obtained on the four catchments, including unpublished results obtained after the publication of the Conway and Millar paper, showed that the unit hydrographs[4] from the two undrained catchments had a time-to-peak twice that of the two drained catchments (Robinson, 1985). It may be that, in terms of control of runoff, only peat that is already modified by burning, grazing and the destruction of the moss and litter cover benefits from the increased storage created by drainage.

One of the first authors to attempt to reconcile the two opposing viewpoints on the drainage of peat, i.e. that it increases/decreases peak runoff, was McDonald (1973), who surmised that peats that carried a good *Sphagnum* moss cover, generally those that had escaped modification by burning or other compaction processes, tended to lose their storage capacity on draining, while peats that were already compacted or modified in some way responded to drainage by increasing the volume available for moisture storage. As Hudson (1998) remarked, not all the increased airspace in drained peat is available for storing water. Thus the flood control function of drainage is doubtful in the case of peat, while the effect of increased drainage density is well supported by the literature.

Land drainage is well covered by plot studies, though the usefulness of many of the results in the context of this report is limited because of the lack of measurements of surface flow in addition to drain flow, and commonly because of the lack of a "control" to record the outflows from an equivalent undrained plot (Robinson, 1990). Out of a wide range of reported drainage experiments, Robinson assembled results from six sites in the British Isles that met a range of scientific criteria, and derived the general conclusion that, perhaps contrary to expectations, field drainage appears to increase flood peaks generated on permeable soils, and to decrease the flood peaks from heavy clay soils at the field scale. He explained this conclusion on the basis that the hydraulic connection between the ground surface and the drains was better in the more permeable soils, but that drained clay soils developed a large soil moisture reservoir in the unsaturated zone, poorly connected to the drains. Surface saturation of clay soils, which in the undrained state would have led to overland flow, was virtually eliminated by drainage. It was recognised that such a small number of studies could not cover the wide range of drainage systems and environments in the British Isles, and that results obtained at other sites might be affected by such diverse factors as secondary treatment (e.g. moling and subsoiling) and compaction by heavy machinery or animals. Secondary

[4] The *unit hydrograph* is the hypothetical response of a catchment to a pulse input of effective rainfall, commonly 10 mm falling over a one-hour interval, and is computed from the measured response to a number of real rainfall inputs.

treatment gave higher discharge peaks than pipe drains alone, and open ditches gave higher peaks than subsurface drains.

Two of Robinson's six sites were within the upper Severn catchment at Club House, Tylwch, and Rhydyfeitty, Staylittle, and were the locations of a study of the effects of small tile drainage schemes on runoff from peaty gley soils at Rhydyfeitty and surface water gley soils at Tylwch (Newson and Robinson, 1983). Although neither site would have justified improvement unequivocally on cost-benefit grounds, the schemes were typical of such proposals throughout mid-Wales in the 1970s, representing a compromise between the costs of carrying out the works and the requirements to guarantee good drainage (very close drain spacing and a permeable backfill). On the peaty gley soil there was no permeable backfill or subsoiling, while on the surface water gley soil both a permeable backfill and subsoil ploughing were used. Both sites, which were slightly under 2 ha, were rotovated and reseeded at the end of the scientific study.

The effect of drainage at both sites, determined by comparison of unit hydrographs measured before and after drainage, was to lengthen the duration of storm runoff and to delay and reduce the peak discharge (Figure 2.7). Another significant effect was a halving of the proportion of the year for which the water table lay within 0.4 m of the ground surface, reducing the effects of poaching by grazing animals. Though the results for the surface water gley were in keeping with Robinson's conclusions for clay soils in the UK in general, the improvement in soil moisture conditions in the peaty gley was smaller, and one conclusion of the investigation, taking into account the results of other peat drainage studies, was that

> "it would therefore appear probable that the drainage of upland *peat* soils in this country will tend to have a limited effect on soil moisture conditions, which may not be sufficient to counter the effect of faster flows through the artificial drainage network, and so lead to increasing peak discharges" (Newson and Robinson, 1983).

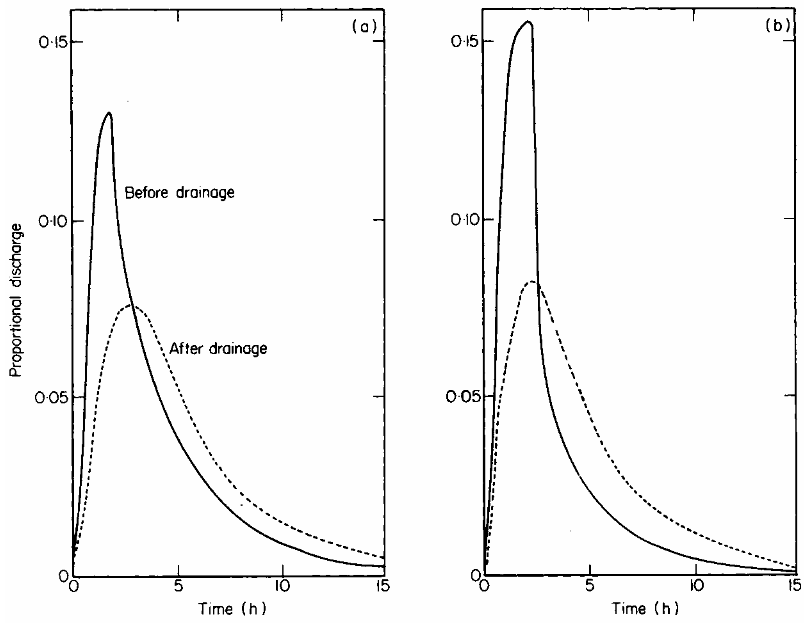

Figure 2.7 *Average unit hydrographs from uniform rainfall of 30 minutes duration, before and after drainage of (a) Club House (surface water gley soil) and (b) Rhydyfeitty (peaty gley soil).*

Robinson (1990) followed through his analysis of plot studies with modelling work which showed that drainage was more likely to reduce peak flows from plots in the high-rainfall north and west of the country, and to increase them in the drier east and south. In sites where natural drainage was predominantly over the surface or in the near-surface zone, outflows were delayed and/or reduced by drainage, whereas sites with a dominant subsurface drainage in the natural state would become flashier in their response to rainfall.

However, field drainage is commonly accompanied by improvements in the arterial drainage network, and the net effect is generally an increase in both peak flows and low flows, whether or not the peak flows are increased at the field scale (Robinson, 1990). Results of plot-scale studies are notoriously difficult to extend to catchment scale – this statement is highly significant in the history of hydrology, as it has been the justification for the setting up of expensive catchment-scale investigations all over the world. Nevertheless, the plot scale is useful for identifying processes, and neither the plot experiment nor the catchment experiment can stand alone as the sole means of predicting impacts on the drainage-basin scale.

The interface between land drains and the wider stream network (i.e. between plot scale and catchment scale) is not well researched. The nature of the catchment response to drainage depends on the distribution of the drainage effort within the catchment. In lowland catchments the uptake of drainage, though unevenly distributed, does not usually correspond with any physical characteristic of the catchment: in upland catchments drainage may take place in parts of the catchment defined by particular soils or gradients, and the net effect may be very difficult to predict. Robinson gives the example of forest drainage at Llanbrynmair, immediately to the west of the Severn basin, which was confined to the less steep areas of the catchment. These areas were located in the upper (formerly moorland) part of the catchment, where the effect of drainage was to expedite the passage of the flood hydrograph, and in the lower part of the catchment, where the impact of drainage on the catchment outflow hydrograph was much less.

Within a catchment of the size of that of the Severn at Shrewsbury, the physics of flow in the stream network, and even the spatial distribution of rainfall in an individual storm event, acquires as much significance as the processes generating flow in the headwaters. The evidence connecting land drainage activities to changes in hydrological behaviour in the upper Severn catchment is somewhat ambivalent, as there have been demonstrable and sometimes simultaneous changes in the frequency of heavy rainfall, so that it is impossible to conclude unequivocally that changes in flood frequency are related to land use. There is some evidence to indicate that the flood hydrograph of the Severn at Caersws became flashier and peak flood flows doubled between 1964 and 1983 (Figure 2.8), after 255 miles (410 km) of tile drains had been laid in the catchment over the four-year period between 1961 and 1965 (Howe et al., 1967). However, Robinson (1990) points out that the comparison between events in the 1960s and the 1980s is possibly unsound, as a different timebase was used for hydrographs in the two distinct periods.

The quality of mapping of the extent of land drainage within a catchment is variable. Even at the height of the drainage programme, when detailed information accompanied every application for grant aid, schemes could be mapped only at the parish scale, any records which could help to trace an individual farmer's receipts from government being confidential (or destroyed). As political boundaries rarely coincide with topographic ones, and upland and lowland drainage are not distinguished in the data, it is difficult to relate the extent of drainage within a hydrological catchment to the effects that may be detected at its outlet. The difficulty of establishing a spatial distribution and chronology of drainage activity within a catchment has been an obstacle to investigations that might have related land drainage to runoff characteristics at the catchment scale.

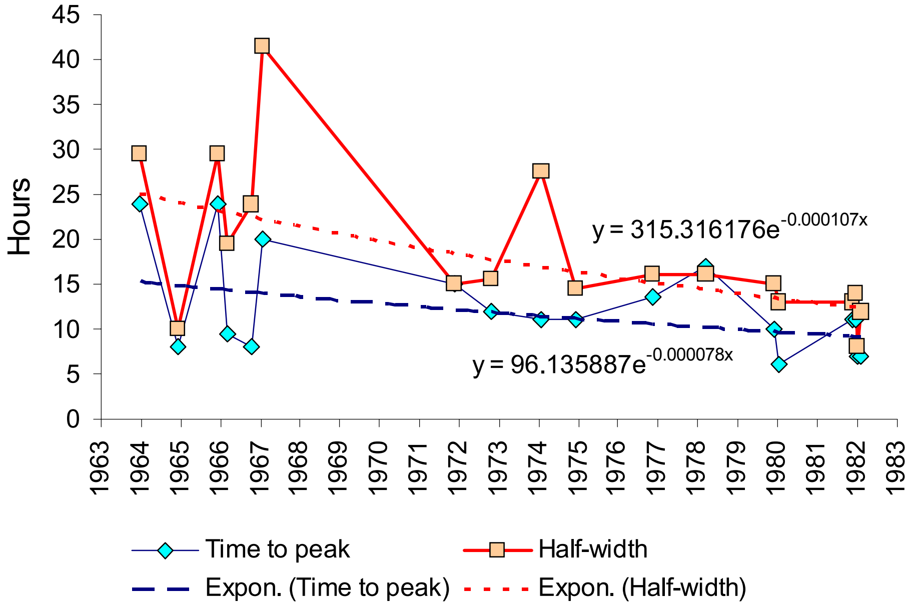

Figure 2.8 *Variation in time to peak and half-width[5] of unit hydrographs for River Severn at Caersws, between 1964 and 1983 (Higgs, 1987). Both parameters appear to have changed by about 3% each year on average, but note the caveat in the text above.*

2.1.3 Ploughing

Moorland will not support large numbers of grazing stock, and some species, though acceptable in spring, become unpalatable, especially to sheep, later in the year (Halley, 1982). Some improvement in grazing can be obtained by liming and fertiliser application, which usually favours grass at the expense of heather, but it has become a widely accepted practice since World War II to replace indigenous grassland and moorland species with more palatable and productive swards, based on perennial ryegrass (*Lolium perenne*) and clovers. Upland pasture, usually on the margins of moorland where gradients and access allow, has been ploughed and reseeded with mixtures specifically designed to thrive in the upland climate, but requiring on the whole better drainage and lower acidity than the indigenous grasses.

Ploughing is not just used a means of breaking up the surface soil to provide a seedbed: it can also be used to remove deeper obstructions to root growth and drainage, e.g. illuviated

[5] The half-width is the time interval over which the discharge exceeds half its peak value, and is regarded as a robust measure of the duration of the flood peak.

horizons, where clay particles have been deposited to form the impermeable horizon of a podsol, and iron pans where the downwashed clays have been accompanied by chemical precipitation. Improved grasslands, though they can survive the upland climate, are more productive on deeper soils, and need help to exploit the mineral nutrients available at depth. Ploughing is partially intended to improve infiltration by providing increased cracking and a generally lower bulk density. A study on heavy-textured soil demonstrated that underdrained land subject to minimal cultivation techniques can generate peak flow rates around 30% higher than those from ploughed and tine-cultivated areas, largely because of increased surface flow (Harris and Colbourne, 1979). Thus on land that is ploughed infrequently the full advantage of underdrainage is not achieved.

Negative factors associated with frequent ploughing of upland soils include compaction of the subsoil by heavy machinery traffic, eluviation that will tend to enhance the plough pan, and exposure of the soil surface to rainfall after the loss of the natural organic mulch. These factors can actually reduce infiltration, especially during winter and spring, and give rise to an increase in standing or flowing water at the surface (Jones, 1997).

2.1.4 Reversion

Once it has been created by drainage, ploughing, reseeding and fertiliser application, upland improved grassland has to be actively maintained: physical and chemical conditions of the soil change under the influence of the upland climate, particularly high rainfall, and succession will take place to a community that is less productive in agricultural terms unless the farmer intervenes. Semi-natural vegetation such as rough pasture, maintained mostly by an appropriate grazing intensity, also changes with time if grazing patterns change, or if regular practices such as moorburning are discontinued or neglected. Reversion is a complex process: though the direction of succession is well-known for some communities as a result of long-term exclusion studies, rates of change are uncertain, varying from a few years for the development of rushes as drainage deteriorates, to more than a century for the reversion of high-altitude grassland to shrubby heath. The timescale of the return to acid soil conditions after abandonment of liming is not well understood (Anon, 1978).

Abandonment of improved grassland is only likely to take place at high altitudes, where re-application of lime, slag and fertiliser is required frequently and at some expense. In these high-rainfall areas, a limited range of rough pasture communities can develop as a result of reversion. With the removal of the competitive advantage for improved grassland species such as rye-grass and clovers, the most likely change is a return to *Agrostis/Juncus* and *Festuca/Juncus* grasslands of the type found on steeper slopes in areas of high rainfall, with grassy heaths of the *Festuca/Nardus/Molinia* type dominating the less well-drained areas. Reversion to shrubby heath is slower and less predictable, and Ball et al (1981) considered that the wettest shrubby heath groups, *Nardus/Sphagnum/Calluna* and *Eriophorum/Calluna* heaths, restricted to sites suitable for peat formation and commonest above 427 mOD, would take a considerable time to reappear.

In the context of flood generation, the most significant aspect of reversion to a more ‘natural’ community is the development of a mulch or litter layer. This layer, absent from a heavily-grazed grass sward, protects the soil surface from puddling, thus increasing the hydraulic conductivity of the upper soil and the opportunity for infiltration. In grasslands the small storage capacity offered by the litter layer itself is probably negligible compared with a typical storm rainfall. However, the advantage to be gained by the effective restoration of blanket mire, with a significant storage capacity created by *Sphagnum* mosses, would be considerable.

Interception losses are not confined to forests, though the processes are more obvious in the forest canopy. The dwarf shrubs present in mires are also capable of retaining water on leaves and stems, and the interception loss can be a significant proportion of the precipitation. For instance, a lysimeter study by Eggelsmann (1963) recorded evapotranspiration losses well in excess of the potential rate on a raised mire in north Germany in spring and autumn. On a similar site converted to grassland, the seasonal changes in the actual evapotranspiration followed those of the potential rate. A lysimeter study in north Yorkshire (Wallace et al., 1982) showed that evapotranspiration rates from a pure heather stand (*Calluna vulgaris*) exceeded the potential rate on wet days but fell below the potential rate on dry days, a clear indication that interception of rainfall was significant. Hall (1985) showed that water was retained as a thin continuous film over the leaves and stems of heather, requiring the addition of nearly 30% more water before the canopy would start to drain. These are ideal conditions for evaporation of significant quantities of intercepted water, and the results suggest that heather moorland may evaporate considerably more water than grassland.

2.2 Flood runoff from forests

Forest hydrology has been an important topic for many years, its worldwide interest stemming largely from the extensive felling of natural forests, often in regions where high rainfall intensity can cause disastrous erosion of exposed soils. Deforested areas have shown immediate increases in total runoff, and a tendency for groundwater levels to rise, as water that would have been intercepted by the forest canopy becomes available for runoff generation and infiltration. The timing of runoff is also affected: removal of natural forest reduces the time of concentration of runoff, and tends to increase peak discharges.

In the UK, the emphasis has been on the extensive planting of coniferous trees in the uplands, sometimes in the early days associated with the development of reservoirs for water supply. Forests were favoured as a means of controlling soil erosion and as a *cordon sanitaire* to isolate reservoirs from contamination by people and farm animals. The impact of afforestation of gathering grounds on water resources was not appreciated until the 1950s, when the significance of evaporative losses from canopy interception was demonstrated by lysimeter studies in the catchment of the Stocks Reservoir in the Pennines (Law, 1956). Law's experiments showed an additional evaporative loss from spruce forest, relative to grassland, of 290 mm/a, a considerable drain on the water resources of the reservoir catchment. The small scale of Law's lysimeter investigation left it open to criticism, and the necessity for a catchment-scale study, involving a direct comparison between upland grassland and coniferous forest, led to the initiation of the Institute of Hydrology's long-running Plynlimon experiment around the sources of the Severn and Wye.

The Plynlimon catchment experiment was set up in the late 1960s, when the uplands of mid-Wales were one of the prime areas of conifer afforestation, as well as providing important public water supplies for Birmingham (from the Elan valley reservoirs in the headwaters of the River Wye and by abstraction from the River Severn at Bewdley supported by storage in the newly-constructed Clywedog Reservoir) and Liverpool (from the Vyrnwy Reservoir). The initial emphasis of the experiment was the investigation of the effects of conifer forest on water resources, and the main instrument network consisted of large numbers of raingauges, to obtain reliable measurements of areal rainfall despite the extreme variability of rainfall in the uplands, several high-quality river gauging structures, and a range of climatological instruments. Measurements continue to the present day, and the framework set up to achieve the original objective has also supported a range of “bolt-on” studies of hydrological processes in forests and upland grasslands, and water quality investigations, especially into the generation of acidity in surface waters as a result of atmospheric pollution (Kirby et al., 1991).

The results of the Plynlimon experiment have left no doubt about the magnitude and significance of interception losses from coniferous forests in the high-rainfall uplands of the UK. A follow-up study at Balquhidder in the Highlands of Scotland tackled the problem of the forest water budget in an area more prone to snow, and where the alternative to afforestation of hill land was heather moor. Plynlimon, Balquhidder and subsequent water budget studies have established sound principles for the prediction of evaporative losses from the three main upland land uses, grassland, heather moor and forest. Extension of process-oriented studies into broadleaved forests has produced comparable results for several important tree species, though the hydrology of the range of habitats lumped under the heading of broadleaved woodland is not yet fully understood, and extensive planting is taking place without a thorough understanding of its implications for water resources.

2.2.1 Native woodland

Native woodland can be regarded as a relict of the once widespread forest that covered the country before the Neolithic clearance for pasture began in earnest, though the continuity of the woodland habitat at any given spot is debatable. Native woodlands in the upper Severn basin are broadly of two types, oak/birch on steep slopes and alder along stream courses, and they are usually confined to the lower parts of subcatchments, up to about 350 mOD (Figure 2.9). The total area of deciduous and mixed woodland within the catchment is around 18 km^2, i.e. less than 1%.

Natural or semi-natural forests differ from modern upland plantations at ground level as well as in species composition. Plough furrows and ditching are absent, though there may be drains along boundaries, which are typically formed from hedge banks, though the hedges themselves have now mostly been replaced by wire fences or allowed to decay.

In comparison with open communities such as short grassland, woodland soils build up a considerable soil moisture deficit during the growing season, as a result of high evaporative losses. Transpiration from forests, both broadleaved and coniferous, is a relatively conservative process (Roberts, 1983), averaging 350 ± 25 mm/a across Europe: the similarity of annual totals between broadleaves and conifers in northern Europe implies that deciduous trees transpire more freely during their shorter growing season. There are important exceptions to this rule: for instance, poplars and willows are viewed as heavy users of water.

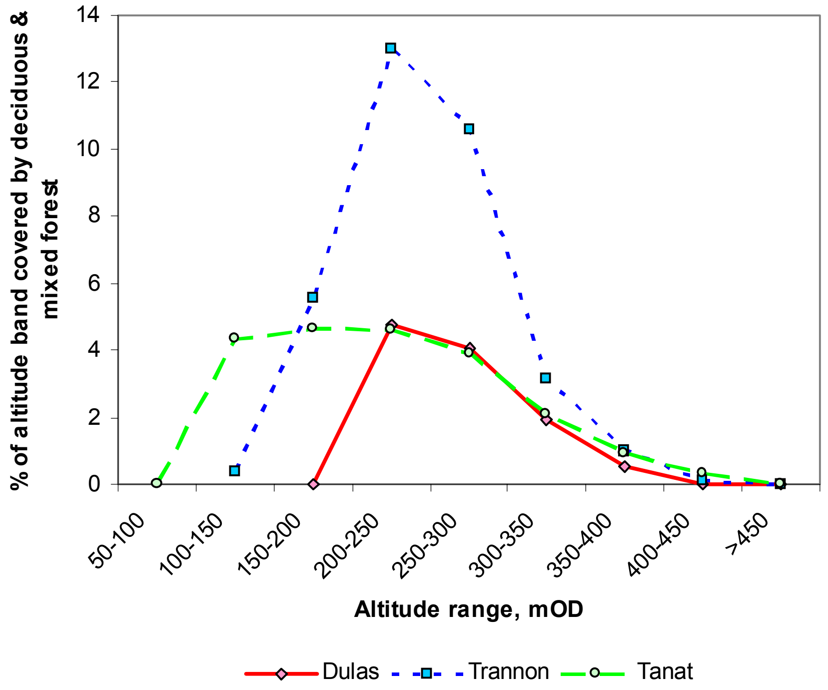

Figure 2.9 *Existing deciduous and mixed forest in three subcatchments of the upper Severn. The upper altitude limit is climatic, the reduction in forest cover at lower altitudes can be attributed to clearance for pasture, which has left woodland clinging to steeper slopes and in dingles in the mid-altitude range.*

The additional losses from woodland must be attributed to the evaporation of intercepted precipitation from the canopy. Interception is highly variable, according to species and climate, in particular the rainfall regime (Hall and Kinniburgh, 1994). However, it is the general rule that on the annual timescale interception by broadleaved trees is lower than for conifers, though growing season totals may be equivalent, at around 25% of precipitation. Interception losses from broadleaved woodland during the winter are surprisingly high, at between 7 and 12% of precipitation at UK sites, but it is thought that the branches and trunks, which receive little water in the summer, take over from the leaves in winter to act as effective intercepting surfaces. There are few experimental results from high rainfall areas like mid-Wales, but results obtained for oak in Cumbria (Carlisle et al., 1965) showed a growing season interception loss of 17% and a dormant season loss of 10%.

2.2.2 Coniferous plantation

Conifers are valued for their quick growth and relatively uniform size and growth habit. These properties, together with a tolerance of exposure and high rainfall, have led to the widespread planting of conifers in the uplands of the UK, especially at times of low prices for hill land (Plate 2.3). As coniferous plantation has often taken place on catchments that are important for water supply, much of the hydrological research on afforestation was directed towards establishing whether annual losses from forested catchments were greater than losses from the vegetation that the forest replaced. A series of investigations, both water budget studies at the catchment scale, such as Plynlimon and Balquhidder, and process studies measuring mostly the vertical movement of water beneath the canopy, by throughfall and stemflow, has shown that in UK forests there is a consistent loss of between 25 and 30% of incoming precipitation caused by interception on the forest canopy (Johnson, 1991). Interception losses are not wholly defined by the parameters of the evaporation process, energy input, wind and humidity, but depend on the time for which the canopy remains wet. Because of the increased exposure of intercepted water on the tree canopy, relative to water held in or on short vegetation, there can be significant evaporation even during rainfall, and it has been demonstrated that the annual interception loss is in proportion to the annual precipitation. A surprising result has been the fact that this applies both to trees and to heather, though the interception loss from heather is less than half that from conifers.

Plate 2.3 *The headwaters of the Afon Llwyd, a tributary of the Clywedog. Alternative land uses at this altitude (300 mOD) are rough pasture, improved grassland and coniferous forest.*

Another effect of interception losses, and to a lesser extent drainage, is to increase the soil moisture deficit that builds up between rainfall events, especially during the summer. Runoff percentages will be reduced for autumn storms as water infiltrates into the dry soil. The precise effect of increased infiltration rates on runoff from individual storms may be related to the magnitude of the rainfall event: the difference between runoff peaks from grassland and forested catchments would be expected to be more pronounced for small to moderate-sized flood events, while "in the truly hazardous flood it is unlikely that drier forest soils will be able to store sufficient moisture to mitigate flood damage" (Blackie and Newson, 1986). Other factors will tend to increase infiltration rates and reduce the quantity of water available for rapid runoff: Binns (1979) drew attention to the litter layer that builds up under trees, and the tendency for the upper soil layer to be more porous.

The response of afforested catchments to individual rainfall events is affected by the improved drainage that accompanies planting. Early stages of growth are subject to checking, and even failure, as a result of high soil moisture levels and competition with other plant species that also grow rapidly once stock are excluded. Forest drainage is aimed not only at lowering the water table and improving soil aeration, but also at reducing competition from established vegetation, notably heather, by creating a zone of bare soil, which takes time to recolonise, around the young trees. This is achieved in the first instance by the creation of the "plough drainage system" using a double-mouldboard plough to cut turves from a trench and invert them to create two drier ridges of bare soil into which the trees are planted (McDonald, 1973).

The plough furrows are linked by the deeper drains of the "main drainage system", crossing the ploughlines and forming an uphill extension of the natural drainage network. Some of the channels of the main drainage system may well be natural watercourses. Recent guidelines have emphasised the need to isolate the forest drains from the streams, using the riparian zone as a buffer to improve stream water quality and prevent a sudden flush of sediment into the river system. However, the riparian zone, forming part of the natural distribution of contributing areas, is usually saturated at times of flood, and the overall effect of the forest drainage system is to increase the drainage density of the catchment. Drainage density, theoretically defined as the length of flowing channel per unit area, but practically estimated from the number of stream junctions per unit area, is one of the principal factors determining the time-to-peak of the flood hydrograph, and it would be expected that forest drainage in an upland catchment would decrease the time-to-peak significantly.

The Coalburn catchment, in the headwaters of the River Irthing in Cumbria, was instrumented at an early stage before planting with conifers. The consequences of the initial ploughing and draining stages, in terms of water resources and storm runoff, were investigated using a gauging structure, a raingauge network and intensive climate instrumentation (Robinson et al., 1998). In 1972, the site was ploughed at 5 m spacing, and it was calculated that the drainage density was increased 60-fold by ploughing (Robinson, 1980). Ground preparation was found to increase the water yield, primarily by increasing low flows, and to increase peak flows, though the duration of high flows was not changed. The time-to-peak of the one-hour unit hydrograph was halved after drainage, and the peak flow increased by about 40%. As the trees grew, water yields, base flows and peak flows all declined, and as the forest neared canopy closure, peak flows were approaching the pre-drainage levels. By 1990, storm hydrographs were not statistically different from those before drainage. Twenty years after ploughing and planting, significantly lower soil moisture contents were being recorded in peat beneath the trees than in peat under grass. An increased seasonal range in soil moisture content suggested that the drier peat in the forest was acting as a store for rainfall, reducing the amount of rapid runoff (Robinson et al., 1998).

The Coalburn results are in keeping with Howe et al's (1967) assertion that peak flows are increased in the interval between ploughing and draining and canopy closure. Rutter (1958), quoted by Howe et al. (1967), expected that ploughing effects may take up to thirty years to dissipate, while McDonald (1973) estimated that the effect of ploughing would not extend beyond canopy closure, typically 15-20 years. Examination of the state of the ground beneath mature coniferous plantation in the Hafren Forest demonstrates that the hydrological function of plough furrows is spatially variable, with some downslope furrows still hydrologically active and retaining water, while others are dry and choked with needles. The deeper drains of the main drainage network remain active, and some have been eroded far below their original beds.

In recognition of the erosive potential of forest drains at high flows, guidelines set a 2° limit to the gradient of ditches, but it has not always been possible to adhere to this rule, and many early drains were steeper, causing severe erosion and sedimentation. Low disturbance techniques such as contour ploughing of valley-bottom soils and the screef planting method, in which trees are planted by removing a single turf, have been used in recent plantings such as that at Llanbrynmair Moor (Hudson, 1998).

Despite the environmentally-oriented drainage and planting practices used at Llanbrynmair, it was possible to detect significant changes in the hydrology of small catchments. An experiment based in two catchments on Llanbrynmair Moor, one forested in the 1980s, the other an upland grazing “control”, showed that the location of drainage, even within a small catchment, was highly significant. Drainage remote from the catchment outlet had little effect on the time-to-peak of storm discharge from the catchment: however it caused a 47% increase in the peak runoff for a given rainfall input (Robinson, 1990). More detailed examination showed that the drainage had reduced the time-to-peak of flows generated at the top of the catchment, so that the peak from the drained area now coincided with the floodwaters generated lower down the catchment. Later ploughing and drainage of land lower in the catchment made little difference to the timing or magnitude of flood peaks.

The Plynlimon experimental catchment network offers a good opportunity for the investigation of the effect of mature forest on flood magnitude and frequency, especially since the 8.7 km^2 headwater catchment of the Severn is 70% forested. Over 100 paired events (i.e. events for which simultaneous rainfall and flows for both the forested Severn and the grassland Wye were available) were compared, demonstrating that for larger storms, after allowance was made for the areas of the two catchments, there was no significant difference between the catchments (Kirby et al., 1991, p60). For very small storms, with a peak runoff of less than 1 mm h^{-1}, peak flows were consistently lower from the Severn than from the Wye. The effect of interception of rainfall is to reduce the total runoff, and this has most effect for smaller storms. For the larger storms, the more intense drainage network of the forest compensates for the lower total runoff and produces peak flows equivalent to those from the grassland.

A more detailed unit hydrograph study of 40 paired events on the Severn and Wye catchments, with return periods of less than five years, showed that there was no significant difference in the timing of the flood response between the two catchments, but the total rapid runoff, on average, from the Severn was 88 % of that from the Wye for the same storm (Kirby et al., 1991, p62). The Flood Studies Report presents a general equation relating the percentage runoff to a Standard Percentage Runoff defined by the soil type and factors defined by the antecedent conditions and the total storm rainfall (see Section 5.1.1). A similar equation developed for the Severn and Wye catchments predicted that the percentage runoff for standard design conditions (a wet catchment and 10 mm of rainfall) was 35.6% for the Wye and 27.4% for the Severn, suggesting that in this case, i.e. for smaller storms, the runoff generated on the Severn was about 75% of the runoff from the Wye.

One of the most significant flood events in the history of the Plynlimon catchment experiment took place in August 1973, when, unusually for summer, the soils were close to saturation. This convective rainstorm also gave rise to record discharges in the Tanat and Vyrnwy (see Table 3.6). The two-day storm, with a total rainfall of 143.6 mm and an intense core of 70 mm over a six-hour interval, was analysed in detail, making use of the intensive instrument network in the mostly forested headwaters of the Severn and the grassland headwaters of the

Wye, and of the capacity of staff at a manned field station to undertake post-flood surveys of river channels and erosion features (Newson, 1975). The streamflow hydrographs, interpreted through unit hydrograph theory, showed surprisingly little difference in timing between the two experimental catchments, despite the very different land use, though the Severn experimental catchment produces consistently lower peak runoff than the Wye, and did so on this occasion. The implication from this and other studies of flood generation in the Plynlimon research catchments is that any delay in runoff caused by interception of rainfall by the trees is more than compensated by the more efficient drainage network of the drained and naturally steeper Severn catchment.

Because conifer afforestation on the large scale in Britain is relatively recent, with large areas approaching the first harvest simultaneously, the hydrological impact has not been integrated over the years as it would have been with an even-aged forest (Binns, 1979). The effect of initial ploughing and drainage has been discussed above: future plantings are expected to involve smaller areas and less disturbance. Harvesting operations, requiring the use of heavy machinery, cause widespread disruption of the soil, and produce waves of sediment, in addition to puddling of the surface soil. Trucks are heavier than envisaged at the time of planting, and the construction of more and wider access roads is a feature of the harvesting stage. The environmental impact of both planting and harvesting processes should become less obvious as the forestry industry settles down into a period of stable management of existing forests, with operations carried out on smaller compartments and staggered in time. However, Blackie and Newson (1986) point out that a more rapid flood response will persist throughout the growth cycle, though flood peaks are reduced by interception losses once the canopy has closed.

2.2.3 Deciduous plantation

The planned expansion of deciduous woodland throughout England and Wales has still to make a significant impact on the uplands, and it is not clear what form this could take in an area dominated by small farms where the expense of fencing and protection are important considerations. There is no doubt that two general rules will apply, as with all new development in this area: uptake will be slow among more traditional landowners until a convincing economic argument can be advanced, and the upland climate will have to be taken into account if failures with conifer plantings on high-altitude land with poor soils are not to be repeated.

Consideration of the distribution of existing deciduous woodland would suggest that an upper limit of 300-350 mOD is realistic, and a rapid assessment of the likely sites for plantings indicates that steeper slopes, some of them formerly taken in-bye but now covered by bracken, will be preferred over land more suitable for pasture and hay-cropping. In view of these factors, it is unlikely that deciduous planting will require the same intensive drainage as the upland conifer plantations, so that initial effects on flood generation will be minimal.

Once deciduous plantation is under way, it is anticipated that the hydrological effects will be intermediate between those of native deciduous woodland and conifer plantation: spacing would be initially closer than in natural woodland, and as with coniferous trees later thinning will depend on the eventual market for the timber, while the canopy may also be thicker and more uniform than in natural woodland, and the understorey less well-developed. There is insufficient evidence from field experiments to predict water budgets with any precision, as most experiments to date have been undertaken in lowland managed woodlands. However, lowland experiments indicate that soil moisture deficits will increase, with a corresponding increase in infiltration rates and a decrease in the total runoff of up to 50%. The summer soil moisture deficit has been found to extend to 3 m below ground level at one lowland site. However, shallow soils on the steeper slopes most likely to be planted will limit the development of the deficit (Finch, 2000).

The effects of new plantings on flood generation are largely unknown, as no studies of responses to rainfall have been undertaken in high-rainfall areas of the UK. However, because of increased interception rates, the unevenness of the forest floor, the lack of intensive drains and the buildup of larger soil moisture deficits under woodland, it can be expected that flood peaks from wooded areas will be delayed, and peak flows reduced.

As deciduous woodland will inevitably be confined to the lower parts of subcatchments, relatively close to the main river channels, the impact of delaying flood hydrographs from this part of the catchment could be to synchronise peak flows with those generated higher in the catchment. There is therefore no guarantee that the modification of the flood peak by deciduous woodland will be an overall benefit to the larger catchment.

2.3 Summary

Land use change in a catchment can affect both the quantity and timing of flood runoff, though the effect on peak discharges may be confined to small to moderate-sized floods. The most important process limiting the total runoff from farmland and moorland is infiltration into the soil, and some mitigation of flood discharges is to be gained from those land uses tending to increase the capacity of the soil to detain water in its passage to the river, or to absorb it and return it to the atmosphere. Agricultural development of the uplands in recent years has depended on operations and management strategies that removed rainfall as quickly as possible, and there has been increased use of moorland and upland grassland, leading to conditions that favour the generation of surface runoff. Conifer afforestation, the other large-scale change over the latter half of the 20th century, involves a reduction in water availability in the long term, but the intensive drainage associated with planting provides a quick outlet for flood runoff, tending to increase peak discharges in the first instance.

There has been a significant increase in the number of sheep grazing the uplands, and an extension of the period over which high-altitude pastures are in use. This led to a campaign to extend the area of improved pasture into the moorland fringe, using drainage, lime, slag and fertiliser treatments and improved seed mixtures to create more productive grasslands: a successful, though unsustainable, strategy that owed much to substantial financial support. On both improved pasture and rough grazing, higher stock densities have led to closer cropping and poaching. Loss of vegetation cover and localised erosion have resulted from winter feeding of sheep and from the natural tendency of stock to congregate around feeding stations and in areas with a more palatable sward, while the increased pressure on moorland has led to a decline in the heather and other dwarf shrub component of the vegetation community.

While it is difficult to obtain confirmation of direct impacts of land use change on the flood response of a large and varied catchment, small-scale studies demonstrate the local influence of operations such as drainage, and the net effects of afforestation in catchments where the forest makes up a large proportion of the catchment area. The results discussed in this Chapter are presented in a concise form in Table 2.2.

Table 2.2 Impacts of land use change on flood generation in the uplands

Cause	Impact(s)	Typical magnitude	Timescale
Increased grazing by sheep	Decreased infiltration	No UK numerical data – US results show doubling of runoff for light to heavy grazing	More winter grazing of higher land since 1970s
	Reduction of heather and other dwarf shrubs – decreased interception losses	Can be reduced from dominance to 10%, depends on community structure. >40% of Welsh heather moorland affected. Heather interception losses about half those from tree cover.	Reduction within 2 years of exposure to increased free-range grazing
Field drainage	Higher peak runoff due to increased drainage density – effect also compounded by improvements in arterial drains	25% increase (Nicholson et al 1989) for peat 85% increase for moorland gripping (Conway & Millar 1960)	Immediate – persists for open ditch drainage, underdrains show decline in efficiency
	Lower peak runoff due to increased soil storage	40-45% reduction (Newson & Robinson 1983)	Immediate – see above
	Shorter time to peak	67% (4 hrs) reduction (Nicholson et al 1989) 46% (1.6 hrs) reduction (Conway & Millar 1960)	Immediate – see above
	Longer time to peak	25% increase (Newson & Robinson)	Immediate – eventual decline in underdrain efficiency results in increased surface flow
Ploughing	Increased infiltration	No numerical data	Probably limited to ~5 years
	Decreased infiltration	No numerical data	Related to afteruse

Table 2.2 *(cont.)*

Cause	Impact(s)	Typical magnitude	Timescale
Reversion to rough grazing	Increased infiltration due to lower grazing density, development of mulch layer	No numerical data	~10 years
	Increased heather/dwarf shrub component	Interception ~10-15% of precipitation	Up to 100 years for stable heather moor – depends on presence of plants/seeds
Conifer afforestation	Decreased total runoff due to interception loss	~30% of precipitation	Change occurs at canopy closure (15-20years)
	Increased infiltration due to drier soils	No numerical data – applies only in summer & autumn	Change occurs at canopy closure
	Shorter time to peak	56% (2.8 hrs) reduction (Robinson et al., 1998) No apparent decrease (Kirby et al 1991)	Short-lived impact following initial drainage. Compensating interception loss comes into play at canopy closure
Deciduous woodland	Decreased total runoff due to interception loss	~25% of precipitation in foliated season ~10% of precipitation in dormant season	Timescale depends on species
	Increased infiltration due to drier soils	No numerical data for uplands – soil moisture deficit developed to greater depth than under grass, runoff halved (Finch, 2000)	Timescale depends on species

3 The Severn headwaters

3.1 The catchment

The catchment of the River Severn to the Montford Bridge gauging station (Shrewsbury) has an area of 2025 km^2. The River Perry joins the Severn from the north, immediately downstream of the gauging station, and for resource management purposes the downstream limit of the upper Severn catchment is usually taken as the Severn/Perry confluence, increasing the total area to 2055 km^2 (Figure 3.1). The Severn headwater catchment extends from the source of the Severn near Pen Pumlumon Arwystli (741 mOD), one of the five peaks of the Plynlimon range.

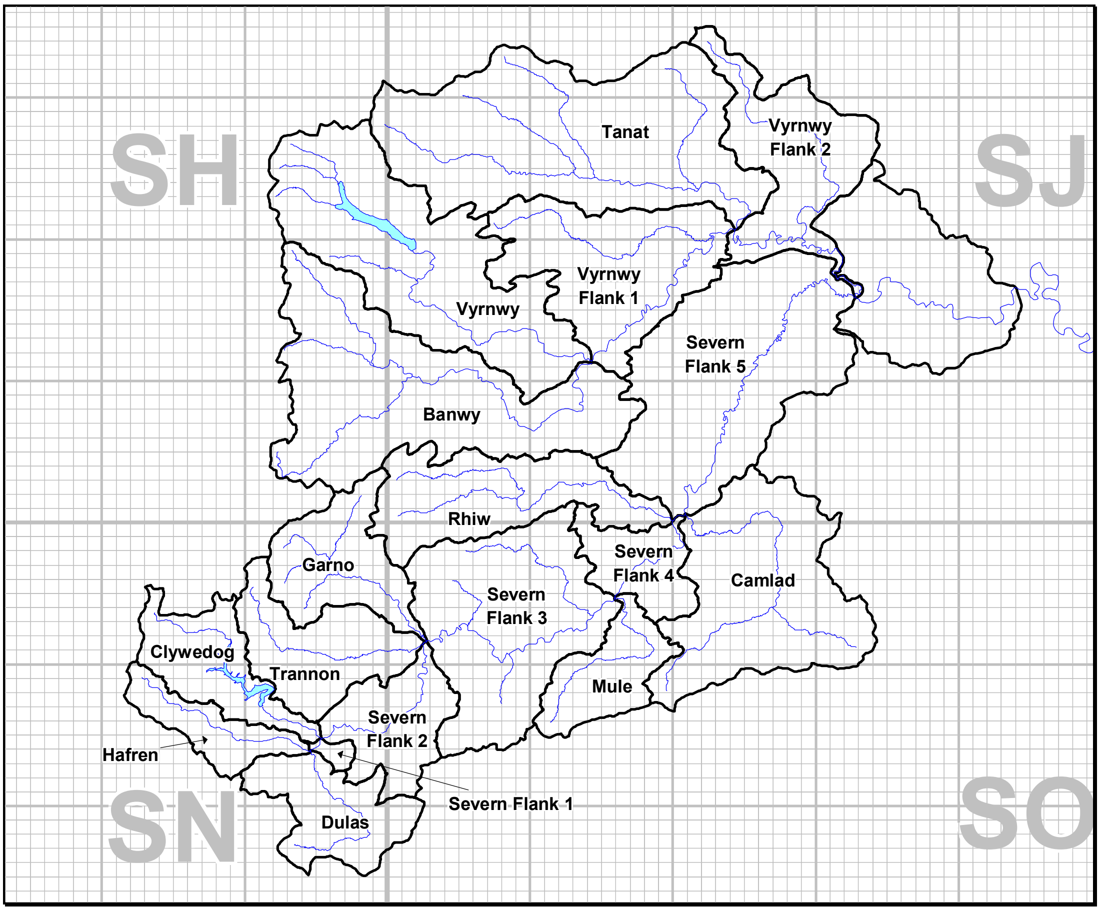

__Figure 3.1__ The Severn headwater catchment, showing its division into subcatchments for the purposes of this report

The most significant hydrological feature of the upper Severn valley is a series of headwater subcatchments flowing broadly eastwards from the Cambrian Mountains divide (from south to north, the Hafren, Clywedog, Trannon, Garno, Rhiw, Banwy, Vyrnwy & Tanat). These subcatchments receive the highest annual rainfall (up to 2500 mm on Plynlimon compared with 750 mm around Shrewsbury) and also contain the largest proportion of moorland and upland forest. Two large storage reservoirs, the Vyrnwy providing water supply to Liverpool and the Clywedog regulating the summer flow of the Severn, take advantage of the high rainfall. Three streams, the Dulas, Mule and Camlad, flow northwestwards towards the Severn: the remainder of the catchment drains the valley flanks towards the main stems of the Severn and the Vyrnwy.

The main River Severn, to the Perry confluence, has a length of about 112 km. Although the 93 km reach upstream of Montford, forming the “Vale of Powys”, is a meandering alluvial river with a broad floodplain and a channel gradient of about 1:1000, the upland section of the river is steep and has the character of a mountain stream, falling by 457 m in its first 19 km. Within the catchment, there are 277 km of streams classified as Main River (i.e. subject to maintenance and channel improvement by the Environment Agency), and a much greater length of smaller streams. The largest rivers in the catchment are gauged by the Agency, using a variety of methods imposed by the technical problems of upland hydrometry. Because of the importance of the upper Severn catchment as a gathering ground for water supply, and the effort invested in the instrumentation of the Vyrnwy and the Institute of Hydrology’s experimental catchments at the sources of the Severn and Wye, the rainfall measurement and river gauging network within the catchment is intensive and has a long run of records.

3.1.1 Landform

The Severn headwater catchment ranges from the uplands of the spine of the Cambrian Mountains in the west to the broad open floodplain of the Severn-Vyrnwy confluence in the northeast. The influence of geology is most obvious in the southwest-northeast “grain” of the land surface: prominent river valleys, including the vales of the Severn and the lower Vyrnwy, and many smaller features such as linear ridges and ranges of hills, follow the grain of the landscape. The main Welsh watershed and minor watersheds between the Severn tributaries are rounded in shape, and most tributary valleys comprise rolling uplands, steep midslopes and flat valley floors. Glacial landforms and drift deposits are widespread across the catchment.

The distribution of altitude in the upland areas of mid-Wales has been attributed to three stages of peneplain development, a “high plateau” between 520 and 610 mOD, typified by the area along the western interfluve, through which the mountain peaks rise as isolated blocks, a “middle peneplain” (365 to 490 mOD) represented by the moors in the west of the Severn catchment, and a “low peneplain” (245 to 305 mOD) that is exemplified by hills in the centre and east of the catchment. The largest area of high land is the complex of upland pasture and moorland extending from Plynlimon to the Berwyns, and the most prominent continuous steep slope is that overlooking the Severn valley from the southeast, between Llanidloes and Montgomery (Plate 3.1). The pattern of steep slopes in the middle altitude range, gently sloping moorland and level floodplains has had important consequences for land use in the past, and will be a significant factor in any future land use change.

Plate 3.1 *Hills on the southern catchment boundary, above Llandinam*

The uplands of the west are divided into two main high plateaux, around Plynlimon in the south (Pen Pumlumon Arwystli 741 mOD) and the Berwyns (Moel Sych 827 mOD) in the north. The slightly lower land between the two high plateaux is broken through by the valley of the Garno, the pass carrying the A470 trunk road and the Cambrian coast railway line reaching a summit altitude of about 210 mOD. Dissection of the upland plateaux by river valleys has been another significant factor defining land use: isolated hills, of which there are many in the tributary valleys in the north of the catchment, retained some moorland and rough grazing until recently, but have now largely been improved, so that remaining blocks of moorland tend to be confined to larger expanses of high-altitude land in the north and west.

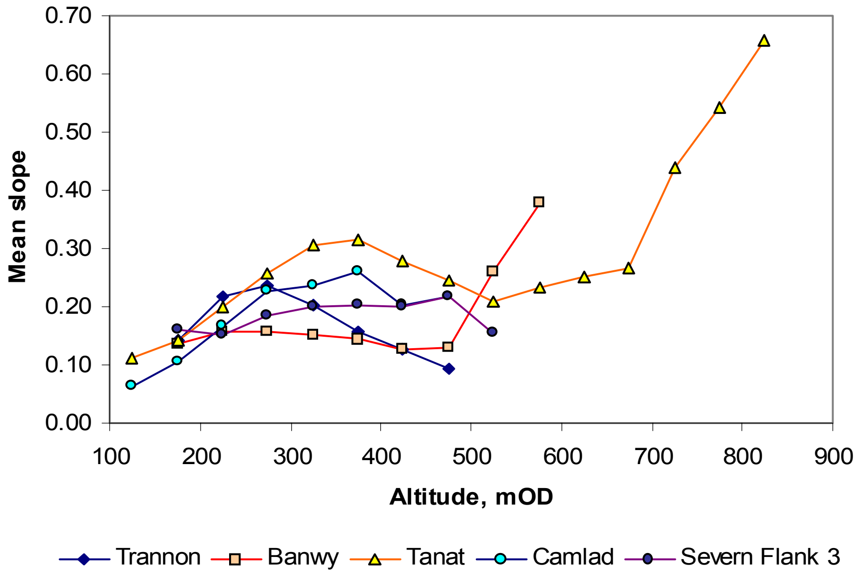

Figure 3.2 *Mean slopes estimated from OS contours. The Banwy and Tanat subcatchments rise towards the Berwyn peaks, becoming steeper in their upper reaches, but most of the sub catchments become flatter at high altitude*

Ground surface gradients, as well as climate, have helped to define the agricultural use of the catchment flanks. Mean slopes estimated for 50 m contour bands in a sample of the subcatchments show the prevalence of gradients between 0.15 and 0.30 (15 and 30%) in the middle altitude range (Figure 3.2). Such steep slopes have always presented difficulties for cultivation, and north-facing slopes in this range receive very little light or warmth in winter. It is not surprising therefore that deciduous woodland is most commonly found in the 200-350 mOD altitude range (see Figure 2.9).

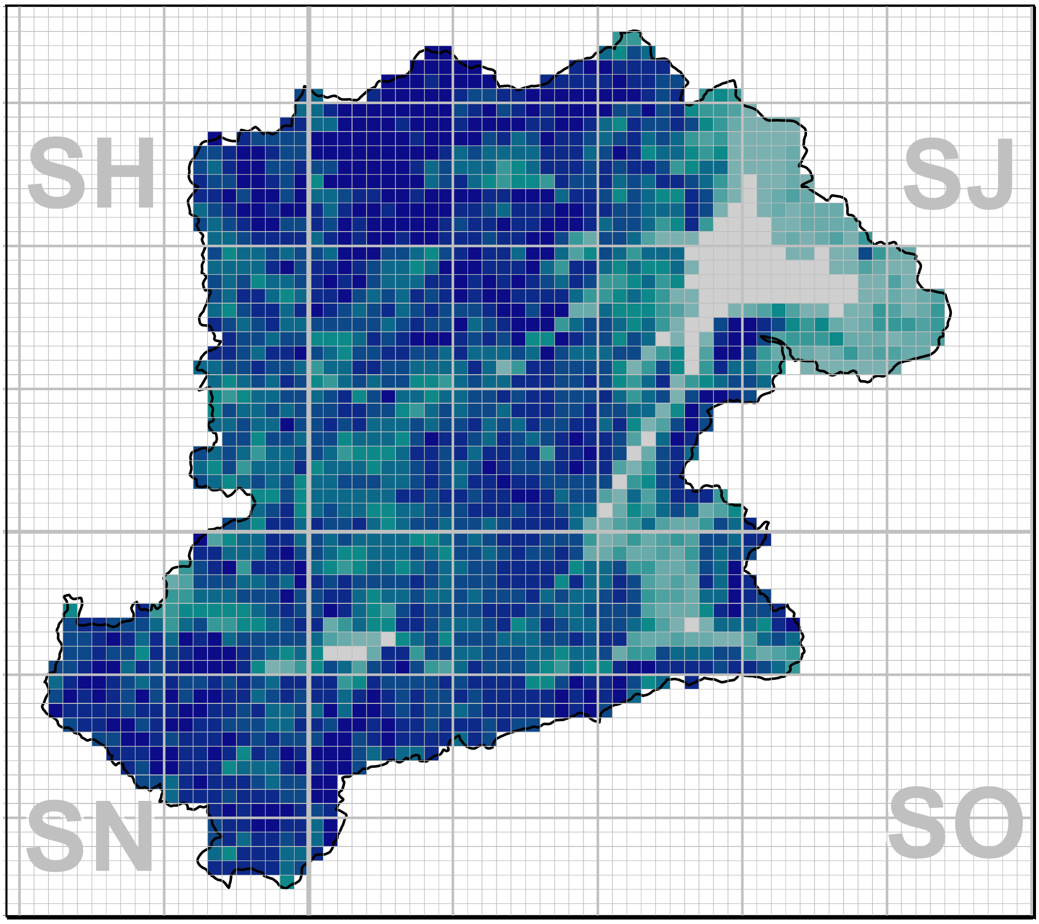

Figure 3.3 *Mean slope on 1 km square grid. Lowest gradients (pale shades) are around the Severn-Vyrnwy confluence and the Trannon and Camlad floodplains. The map also indicates the expanse of relatively flat upland along the western interfluve between Plynlimon and the Berwyns. Data source: Countryside Information System.*

Figure 3.3 shows the mean surface slope abstracted from Ordnance Survey data for the Countryside Information System (CIS)[6], on a 1 km square basis. Although the spatial interval of the final map is rather coarse for detailed interpretation, it does show the relatively low gradients in the floodplains of the Severn, Vyrnwy, Trannon, Camlad and Tanat, and on the uplands in the centre of the catchment and on the western margin. In contrast, there are areas

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[6] Countryside Information System, Windows-based spatial database developed by NERC Institute of Terrestrial Ecology on behalf of Dept, of the Environment, Version 6.01 (2001).

with very steep slopes along the northern and southern boundaries of the catchment. The darkest shade on the map represents gradients of between 15% and 77%, and the lightest shade from zero to 1%.

Figure 3.4 was produced from Ordnance Survey contours at 50 m intervals, and is presented at a larger scale in the Appendix. The 50 m contour bands have also been used on a subcatchment basis to evaluate the distribution of major habitat types and land uses, and in the development of the hydrological model that is used later in this report to examine the consequences of land use change.

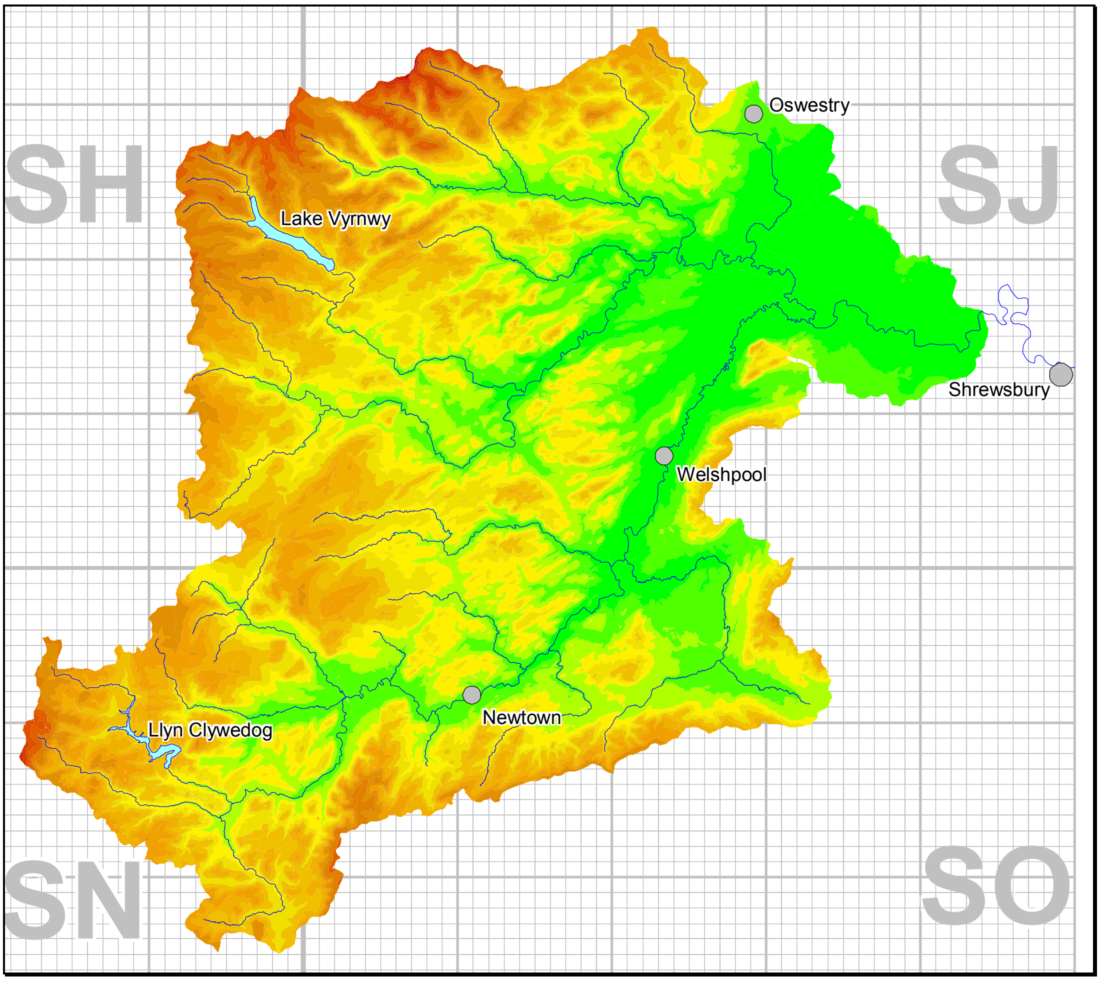

Figure 3.4 *Topographic map of the Severn headwater catchment (contours at 50 m intervals). Based upon the OS 1:50000 scale map with the permission of Ordnance Survey on behalf of the Controller of HMSO. © Crown copyright. All rights reserved. Licence No. AL 100029640.*

3.1.2 Geology and soils

The acidification of Welsh waters by atmospheric sulphur and nitrogen oxide pollution acquired considerable importance when it became clear that there were interactions between rainfall, forestry and soil chemistry in the uplands, but the hard-rock geology of the catchment also has relevance to hydrology, mainly in its influence on topography and as the source for soil parent materials. Although the majority of deposits derived from the mudstones of mid-Wales are relatively impermeable, and liable to generate rapid runoff, the impact of glacial and periglacial processes is arguably more important than the nature of the bedrock. Spatial variation in soils and superficial deposits is mainly defined by climate and topography, and the few striking exceptions to the mudstone rule, the Llanymynech limestone and isolated bodies of igneous rocks, do not appear to have had much influence on soils or on the hydrological behaviour of rivers in the catchment.

The western upland part of the catchment is dominated by the Ordovician and Silurian grits and mudstones that form the backbone of an ancient mountain chain stretching parallel to the Cardigan Bay coast of Wales, and including the peaks of Plynlimon and the Berwyns. These old rocks, deposited in a continental shelf and slope environment between 510 and 405 million years ago, are intricately folded and faulted, and relatively impermeable. They do not constitute a major groundwater unit, though fracturing close to the surface creates conditions for the storage and flow of groundwater supplying many private wells and springs, in addition to sustaining low flows in rivers, and perhaps more importantly helping to buffer against acidification.

Volcanic activity in the Ordovician period left bodies of resistant igneous rocks which now form isolated hills along the eastern catchment boundary, for example the dolerite laccoliths of Corndon and Breidden and the andesite conglomerate Moel y Golfa and Middletown Hill northeast of Welshpool (Sinker et al., 1985), and there are layers of tuff interbedded with the sandstones and mudstones. To the north the Permian Bridgnorth and Triassic Sherwood Sandstones, a thick sequence of poorly cemented red sandstones containing marls and conglomerates, constitute an aquifer of local importance. There is a small area of Carboniferous limestone, grit and Coal Measures at Llanymynech in the lower part of the Vyrnwy subcatchment. Glacial and post-glacial deposits overlie the Carboniferous and Permian rocks, and the main valleys are floored with alluvium and river terrace gravels (NRA, 1994; Trueman et al., 1995). Most steep high-altitude slopes have soils developed directly from weathered bedrock, but parts of the uplands retain a thin cover of soliflucted head on less exposed slopes, and many valleys have deep till deposits, which often form terraces overlooking the floodplain (Watson, 1970).

The soils of mid-Wales, coming for the most part from weathered mudstone and boulder clay, tend to be stony silt loams, except on the floodplains, where sorting by water has removed most of the coarser material. In the high rainfall areas to the west, leaching of the surface soil horizons has given rise to podsolisation. Vertical translocation of clay particles and iron has decreased the permeability of the soil over the period since Neolithic settlers began the clearance of the native forests. The 1:250000 soils map, published by the Soil Survey of England and Wales, shows stagnopodsols, in which a surface organic horizon has built up as a result of impeded drainage, occupying the western uplands, with deposits of deep but eroded blanket peat along the watershed in the headwaters of the Hafren, Trannon, Banwy, Vyrnwy and Tanat.

At lower altitude in the foothill region, where till deposits have provided the parent material, the soils are mainly surface water gleys, which also have impeded drainage. The better agricultural soils of the catchment, the brown earths, are deep loamy soils mainly distributed along the valleys of the Severn and the lower Vyrnwy. Groundwater gleys dominate in alluvial areas with the poorest natural drainage, on the floodplains of the Trannon, Camlad and Tanat, and in an extensive area around the Severn-Vyrnwy confluence: these are slowly permeable alluvial soils affected by a high water table.

Map 3.1, at the end of the report, shows the distribution of the various soil types throughout the catchment, expressed as percentage area within each of the 19 subcatchments. Table 3.1 shows the percentage cover of each major soil type, and Figures 3.5 and 3.6 show the broad distribution of brown earths and podsols over the catchment, based on the land classification developed for the Countryside Survey 2000 and forming the foundation of the CIS.

Table 3.1 *Soil types in the Severn headwater catchment. Data from Countryside Information System (CIS).*

Soil type	Percentage cover
Peat	6.8
Podsols	25.9
Surface water gleys	31.6
Brown earths/alluvial brown earths	29.0
Groundwater gleys	2.4
Other (mostly raw soils)	4.3

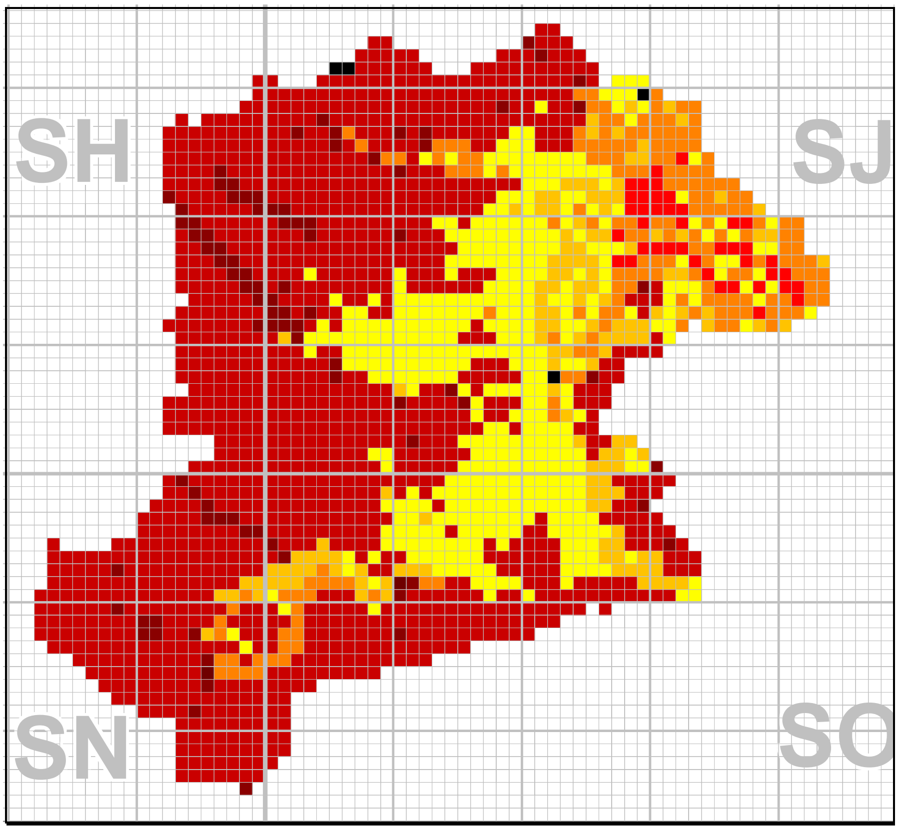

Figure 3.5 *Percentage cover of brown earths, ranging from zero (black) to >45% (yellow) Data from Countryside Information System (CIS): the percentage cover is estimated by sampling each of the 40 land classes of the Countryside Survey 2000.*

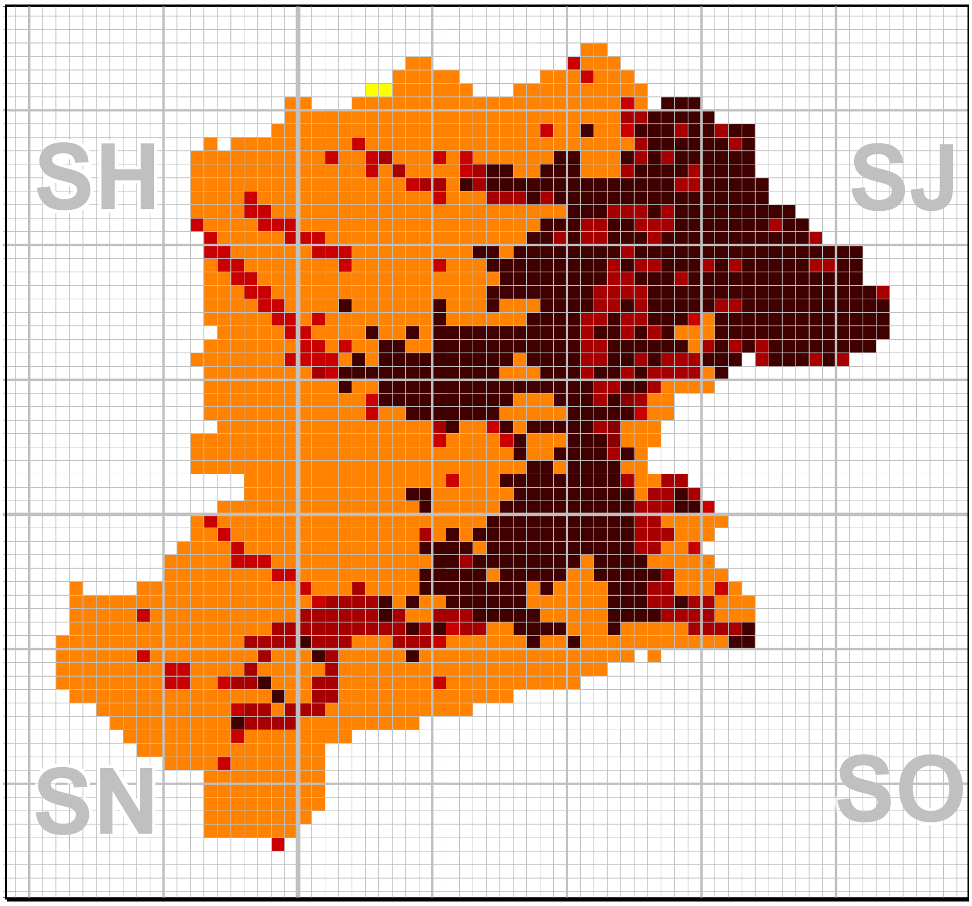

Figure 3.6 *Percentage cover of podsol soils, ranging from zero (black) to >45% (yellow) Data from CIS: the percentage cover is estimated by sampling each of the 40 land classes of the Countryside Survey 2000.*

The distribution of soil types, especially the podsols and blanket peat, is closely related to climate, and Figures 3.7 and 3.8 show the range of rainfall and temperature across the catchment. Annual rainfall near the summit of Plynlimon is about 2500 mm, high-altitude gauges in the Vyrnwy catchment record annual totals of around 2200 mm, but the average rainfall at Shrewsbury is about 630 mm. The distribution of temperature, here calculated as accumulated degree-days over the first six months of the year, is similar. The level of detail shown by the temperature map is somewhat misleading, as meteorological stations returning temperature data are far fewer than raingauges, and altitude has been used to estimate temperatures. The combination of low temperature and high rainfall along the western edge of the catchment provides ideal conditions for the growth of blanket peat.

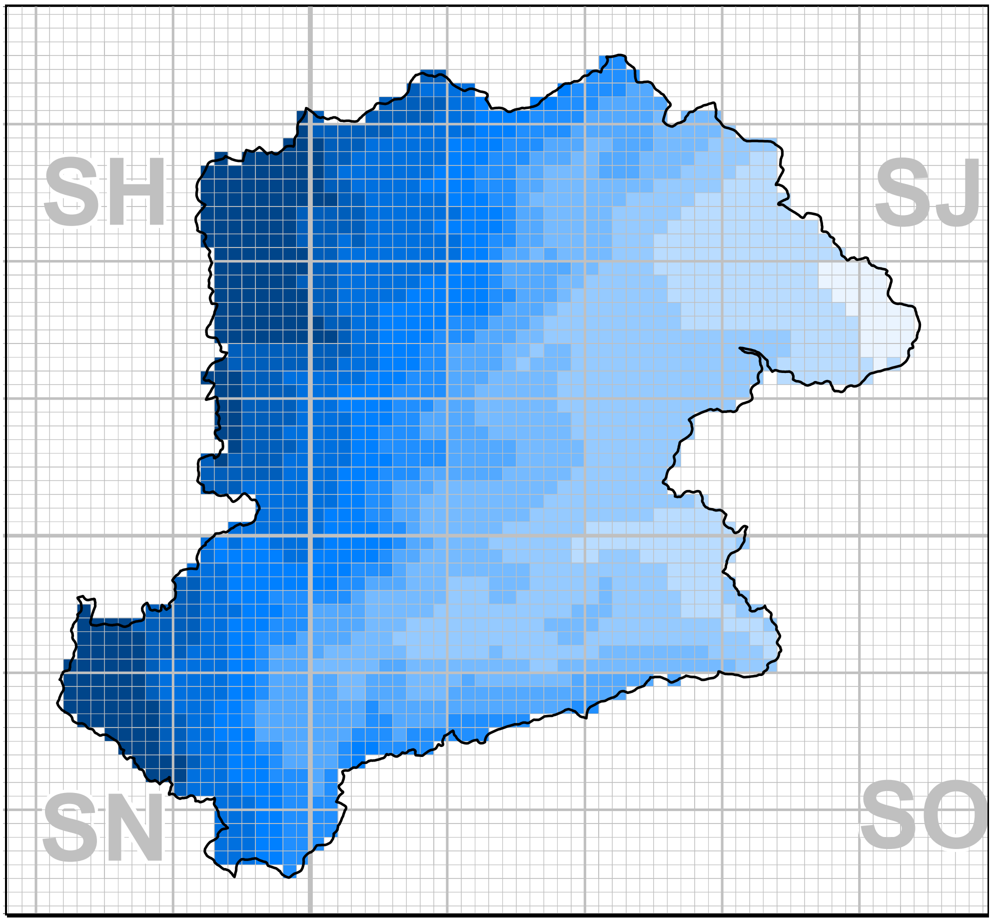

Figure 3.7 *Standard Average Annual Rainfall (SAAR) 1941-70. Data provided on 1 km square grid by the Centre for Ecology and Hydrology, Wallingford, and mapped using CIS. Contours at 100 mm intervals from 700 to 1200 mm, 200 mm intervals to 1800 mm, lightest tone indicates rainfall <700mm, darkest tone >1800 mm.*

Blanket peat develops where there is an appropriate combination of annual rainfall, altitude and slope. As a simple rule of thumb, peat is to be found above 400-450 mOD where the average annual rainfall exceeds 1000 mm. There is also an interaction between rainfall and slope: where rainfall exceeds 2000 mm peat is common on slopes up to 20° (Bower, 1961). These conditions are met over the western uplands of the Severn headwater catchment, though as altitude increases, so does erosion by wind and water, and the blanket peat of the upper Severn is intensely dissected. Bower associated erosion at high altitudes in the Pennines with increased exposure to rain, wind and frost, and with the greater age and depth of the peat. Deeper peat, growing on the flatter hilltops, tends to be wetter and less compacted than the peat of the slopes, and is easily eroded by water moving on the surface (Conway and Millar, 1960). Blanket mires eventually develop pool-and-hummock microtopography, which can act as a focus for flowing water, and lead to intricate erosion patterns and the desiccation of peat islands lying between the channels. Eroded peat is more likely to generate flood runoff than intact patterned blanket mire.

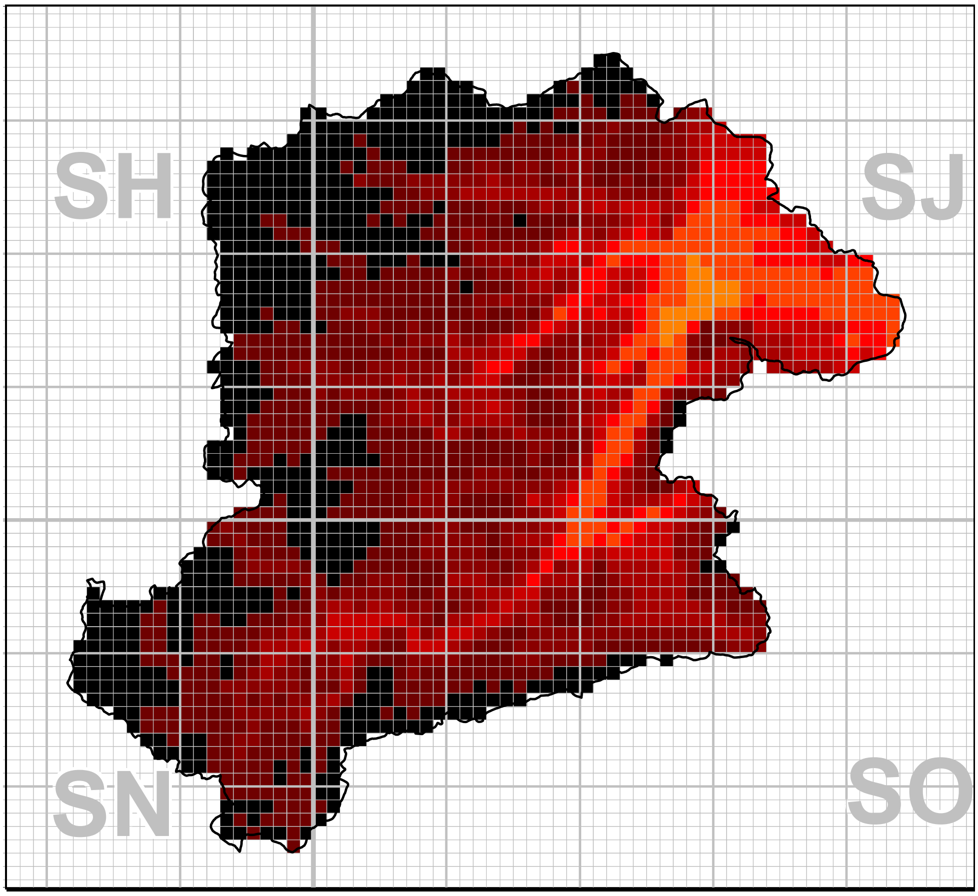

Figure 3.8 Accumulated temperature, January-June, ranging from 694 degree-days (equivalent to an average temperature of 3.8°C for the first half of the year) near the summit of Moel Sych in the north, to 1426 degree-days near the Severn-Vyrnwy confluence (average of 7.9°C). Data interpolated by FRCA from 5 km grid, processed using CIS.

The linkages between peat erosion and human activities on the hills are not obvious: Bower (1961), writing about the Pennines, says:

> "While most peat moors … have probably been affected by man's activities at some time, and the burning, draining and grazing often associated with those activities affect the vegetation in ways which could encourage erosion, it is much more difficult to prove that they have caused it".

Although peat erosion is encouraged by closeness to the drainage network, there is little evidence that artificial drainage has led to expansion of eroded areas. Burning, on the other hand, can have a drastic effect on vegetation and on the compaction of the surface peat (Conway and Millar, 1960), and grazing appears to add to the impacts of burning. Bower draws attention to the absence of *Sphagnum* from large areas of the southern Pennines, possibly a consequence of air pollution, and certainly a factor tending to reduce the capacity of the ground to retain and delay runoff.

3.1.3 Climate

The spatial variation of climate is important to this project mainly through the variation of rainfall with altitude and location within the catchment, and through its influence on the options open for land use. Relationships between rainfall and altitude, and temperature and altitude, have been mentioned in the previous section. The increase in rainfall towards the western edge of the catchment implies a much higher potential for runoff per unit area from the headwater catchments along the Welsh watershed, while it also limits the soil moisture deficit and creates the conditions for a higher percentage runoff for a given rainfall input.

Both soil moisture and temperature have an impact on the length of the growing season, and hence on the expectation of success in agricultural improvement schemes. Though the relationship is unlikely to be simple, climate is one factor determining past and future development of the moorland fringe, where improvement is feasible but financial returns may be open to question. Improvement schemes that are not followed through, for example by regular maintenance of drainage works, lime and fertiliser application and reseeding at intervals, are destined to revert. Conversely measures aimed at securing the return to a more natural habitat on the moorland fringe are more likely to be accepted if the net agricultural benefits of intensive use of this land are perceived to be minimal.

To assess the spatial variation of rainfall across the catchment, and especially to allocate rainfall from specific events to each of the subcatchments, it is necessary to call on the results from the regional network of raingauges, read on a daily or monthly basis, and automatic gauges reading on an hourly timescale. Data from current gauges have been provided by the Environment Agency, and these have been used to derive storm hyetographs for a selection of suitable events in the last three years, based on the records from a small number of hourly raingauges. A more representative spatial picture can be obtained from the long term averages of the larger number of daily and monthly gauges, some of which have now ceased operation. The records from these gauges have been compiled by the Meteorological Office into a long-term average rainfall, which is published for thirty-year periods as the Standard Average Annual Rainfall (SAAR). SAAR 1941-70 figures, normally available as contour (isohyet) maps at 1:250000 scale, have been obtained on licence from the Centre for Ecology and Hydrology on a 1 km square grid, and these data have been used to prepare a spatial distribution for the computation of subcatchment averages (see Figure 3.7).

The Severn headwater catchment has been divided into 19 subcatchments for modelling and analysis purposes (see Figure 3.1). The 1 km SAAR data were used as input to a surface generation and contouring routine, part of the MapMaker v2.4 GIS/mapping package, so that a spatial average SAAR could be derived for each subcatchment. The resulting contour plot was imported into the MapInfo v6.5 GIS package used for the maps in this report, and is presented as Map 3.2. The distinction between the headwater subcatchments along the western watershed and the more low-lying subcatchments in the east is clear from Map 3.2, but is brought out even more by the catchment average rainfalls listed in Table 3.2.

Table 3.2 Catchment average altitude and rainfall (SAAR 1941-70) for the 19 subcatchments

Subcatchment	Mean altitude mOD	Areal mean rainfall, mm/a	Minimum rainfall, mm/a	Maximum rainfall, mm/a
Western headwater subcatchments -				
Hafren	377.8	1912.2	1369.7	2411.7
Clywedog	369.2	1770.2	1272.9	2265.7
Dulas	336.8	1346.7	1089.0	1747.0
Trannon	276.7	1295.6	982.0	1637.4
Garno	302.9	1339.5	989.5	1600.6
Rhiw	269.6	1109.6	832.4	1502.1
Banwy	294.8	1468.2	934.7	2172.1
Vyrnwy	339.8	1632.5	981.1	2396.1
Tanat	319.0	1277.1	789.2	1821.6
Central and eastern subcatchments -				
Severn Flank 1	255.9	1213.9	1095.1	1337.4
Severn Flank 2	264.8	1057.9	975.1	1235.5
Severn Flank 3	229.9	970.8	847.4	1226.7
Mule	268.9	990.4	852.6	1171.8
Severn Flank 4	168.6	863.9	786.4	917.6
Camlad	196.5	854.7	780.5	1104.7
Severn Flank 5	138.5	844.6	750.6	968.7
Vyrnwy Flank 1	183.7	1070.7	825.4	1507.9
Vyrnwy Flank 2	144.3	848.5	731.4	1141.5
Severn Flank 6	84.0	724.9	677.3	809.5
Whole Severn headwater catchment		1166.9	677.3	2411.7

While the distribution of annual rainfall is a useful device to demonstrate the importance of the western headwater catchments in generating runoff on the annual scale, it does not have a direct bearing on the problem of flood generation. The UK Flood Studies Report (Anon, 1975) used a measure of rainfall that has more relevance to the magnitude and frequency of flood-producing events. The analysis in the FSR was based on the two-day total rainfall with a probability of being exceeded once in five years. The spatial variation of this measure, denoted by 2DM5, has been mapped for the whole of the UK. The two-day total is adopted because heavy rainfall frequently occurs at night, and a single storm event might easily be divided between two one-day totals, leading to an erroneous assessment of its magnitude. Figure 3.9 shows the distribution of 2DM5 across the Severn catchment: it varies between 48 mm near Shrewsbury and 154 mm at the summit of Plynlimon. The distribution is broadly similar to that of annual rainfall (Figure 3.7): 2DM5 in the catchment is generally between 6 and 7% of SAAR.

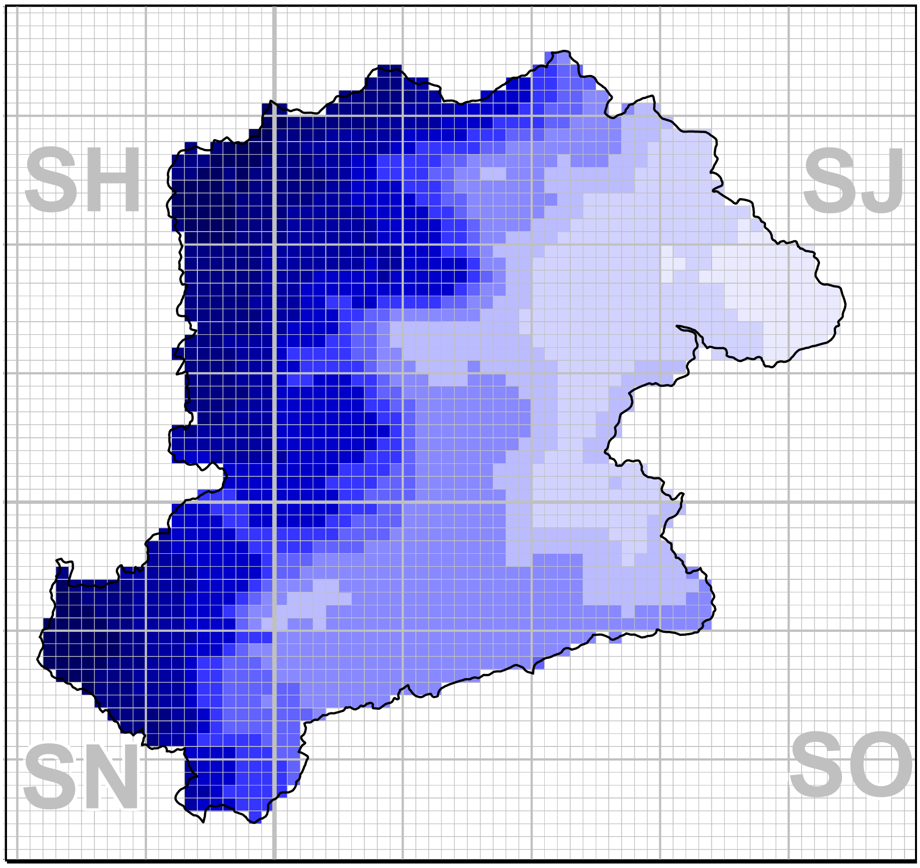

Figure 3.9 *Two-day rainfall with a probability of being exceeded once in five years (2DM5). Data provided on 1 km square grid by the Centre for Ecology and Hydrology, Wallingford, and mapped using CIS. Contours: 5 mm intervals from 45 to 80 mm, 20 mm intervals from 80 to 120 mm. Lightest tone indicates 2DM5 <50 mm, darkest tone >120 mm.*

The 1 km 2DM5 figures were contoured in the same way as the SAAR figures (Map 3.3), and the MapMaker package was used to derive catchment areal averages of 2DM5 for each of the 19 subcatchments. The results are presented in Table 3.3. Again the western headwater subcatchments, especially the Hafren, Clywedog, Vyrnwy and Banwy, show much larger inputs of water from the five-year event, all the central and eastern subcatchments falling below the average for the Severn.

Table 3.3 *Catchment areal mean 2DM5 for the 19 subcatchments*

Subcatchment	Mean altitude mOD	Areal mean 2DM5 rainfall, mm
Western headwater subcatchments -		
Hafren	377.8	111.4
Clywedog	369.2	108.9
Dulas	336.8	75.9
Trannon	276.7	74.3
Garno	302.9	73.8
Rhiw	269.6	69.6
Banwy	294.8	82.0
Vyrnwy	339.8	91.3
Tanat	319.0	78.2
Central and eastern subcatchments -		
Severn Flank 1	255.9	69.3
Severn Flank 2	264.8	69.6
Severn Flank 3	229.9	62.2
Mule	268.9	58.8
Severn Flank 4	168.6	60.3
Camlad	196.5	57.2
Severn Flank 5	138.5	54.2
Vyrnwy Flank 1	183.7	65.6
Vyrnwy Flank 2	144.3	54.9
Severn Flank 6	84.0	49.3
Whole Severn headwater catchment		70.4

Fluctuations in the UK climate are impossible to describe in terms of statistics like SAAR and 2DM5, that are defined in terms of stationary distributions, and it is now becoming clear that cyclic variations on all timescales, in addition to any long-term trend that might arise from global warming, add considerable uncertainty to predictions based on the statistics of stationary phenomena. There have been several attempts to extract firm conclusions about the impact of land use change on hydrology of the upper Severn, and all have found that it is difficult to isolate man-induced effects from climate variability as the cause of hydrological change (Higgs, 1987; Howe et al., 1967; Hudson and Gilman, 1993; Kirby et al., 1991). Within the scope of this report it is not possible to carry out a re-examination of the data collected over decades, spanning a period of intense agricultural and forestry activity in the catchment, but this is a suitable point at which to note at least one recent major change in the hydrology of the Severn basin that cannot be attributed to land use, but may prove to have a land use dimension in the longer term.

The 1960s saw a sequence of extreme floods in the Upper Severn catchment, and, the subsequent low frequency and magnitude of flood events has been attributed variously to lower frequency of large rainfall events, possible beneficial effects of agricultural drainage and the effects of the Clywedog Reservoir. Popular opinion is that the timing of individual flood events has changed to create a more “flashy” regime, and this too has been attributed to agricultural, or more commonly, forestry drainage. Hudson (1998) points out that the major flood events in Britain are often brought about by snowmelt associated with heavy rainfall, and events of this type have become less frequent in recent years. Melt rates can be very high as a result of the transfer of sensible and latent heat to the snowpack, and though their total water equivalents may not be extreme, snowmelt floodwaters are passed rapidly to the stream network by frozen ground and channels with little restricting vegetation. Furthermore, a deep snowpack across the Severn catchment could contribute a basin-wide event, with large inputs from the lower parts of the catchment where inputs of energy, and hence melt rates, would be larger.

3.2 Subcatchments

It has become clear from the preceding sections that the Severn headwater catchment has a considerable range of variation in altitude and rainfall. The variance in subcatchment areal mean rainfall shown in Table 3.2 is not accounted for by altitude alone: there is also an east-west gradient in rainfall across the rain shadow of the Welsh watershed. Land use and natural habitats change with altitude, soils and location within the catchment. Furthermore, the catchment is too large to be regarded as a single hydrological unit whose response to land use change could be simulated using a “lumped” model.

In recognition of the spatial variations within the upper Severn basin, and of the mechanics of flood propagation through the channel network, it was decided to partition the catchment into a manageable number of subcatchments, each of which could then be simulated by one of the linked components in the hydrological model. The existing river gauging network was dictated by site factors and by the needs of water resource and flood management, and subcatchments, some of them “nested”, defined by the gauging stations are not appropriate for the purposes of this report. For this reason, the 19 subcatchments introduced above (see Figure 3.1) were defined from river confluences, with the broad intention of dividing the Severn catchment into roughly equal parts.

3.2.1 Delineation

As a starting point, the headwater catchments of all the major rivers along the western and eastern edge of the catchment were delineated: this left irregularly shaped corridors along the

Severn and Vyrnwy, which were divided into several “flank” catchments with a reach of the main river and only relatively small streams entering from the sides. Contours and stream channels marked on the 1:25000 OS maps were used in the construction of catchment boundaries. In most cases the boundaries were unambiguously defined. Though it would be possible to decide problem areas with a site visit, it is believed that the resulting change in catchment area would be trivial. The external outline of the Severn headwater catchment, defined by the boundaries of 15 of the subcatchments, is in reasonably close agreement with the outline used by the Environment Agency (NRA, 1994).

3.2.2 Landform, land use and natural habitats

With the exception of the lowest of the “flank” catchments, it is possible to detect within each of the subcatchments the three broad divisions of the uplands based on agricultural use:

i) valley farmland – established improved pasture and arable land, with widespread field drainage.

ii) the moorland margin – subject to repeated cycles of improvement, the most recent of which was an expansion of pasture improvement encouraged by grant aid and the availability of machinery. Underlying climatic reasons, the short growing season and leaching of bases and nutrients from the soil, control the amount and timescale of the benefits to be gained from improvement.

iii) the moorland core – now mostly enclosed by wire fences, but still lacking shelter and difficult to improve, because of access and peaty soils. Partial drainage by gripping has been attempted. Generally there are poor returns from rough grazing.

Future changes in land use and hydrology to be simulated by the hydrological model are most likely to take the form of localised, gradual or proportional change from present conditions. A twenty percent reversion of the improved grassland in a certain contour band is within the bounds of possibility: the wholesale planting of deciduous forest over a complete catchment is not. A simplified land use and habitat map of each subcatchment, and an analysis of the relationship between land use and altitude, were essential for the design of the model.

The majority of the upper Severn catchment lies within Wales, and is covered by the Welsh Phase I habitat survey maps held by the Countryside Council for Wales (CCW) in digital form. The map data were provided by CCW as a 300 MB MapInfo table covering the whole of Wales. A small number of habitat types, those with the largest areal cover across Wales, were selected: these were acid grassland (B.1.1 & B.1.2), marshy grassland (B.5), improved grassland (B.4), bracken (C.1.1) and dry dwarf shrub heath (D.1.1). Land that was being cultivated at the time of the survey was also mapped, and this category (J.1.1) was selected, as an indication of either arable use (in the lower catchment, especially around the Severn-Vyrnwy confluence) or active grassland improvement on higher land. Areas mapped as neutral grassland and mire were found to cover only a very small part of the catchment, and were disregarded.

It was found that the survey had omitted large areas of moorland along the western watershed, so an alternative source had to be sought for information on the moorland core. The National

Assembly's Moorland Map of Wales was provided in MapInfo format, and the Moorland Map for England was obtained from DEFRA. In most cases the missing areas on the Phase I map proved to be moorland under the definition used by the Welsh Moorland Map: where there was overlap the Phase I habitat was accepted.

Owing to early uncertainty over the availability of habitat coverage for this project, forest was mapped directly from the OS 1:50000 maps (various dates 1984-2000) in two categories, coniferous woodland and deciduous/mixed woodland.

Phase I coverage was much more limited in Shropshire: only scattered patches of unimproved grassland and other semi-natural habitats appear to have been mapped. Paper maps at 1:25000 scale were examined at the Shropshire Wildlife Trust's office in Shrewsbury, but owing to the very different level of coverage no use was made of the Phase I map on the English side of the border. This deficiency applies mainly to areas in the lowest part of the catchment.

Combined Phase I habitat, moorland and forest maps were prepared for each of the 19 subcatchments, and the mapped units were further subdivided into 50 m altitude bands. Figure 3.10 shows the distribution of the principal habitats within the Dulas subcatchment, and Figure 3.11 shows the percentage cover within each altitude band. Similar maps and diagrams for all 19 subcatchments are presented in the Appendix.

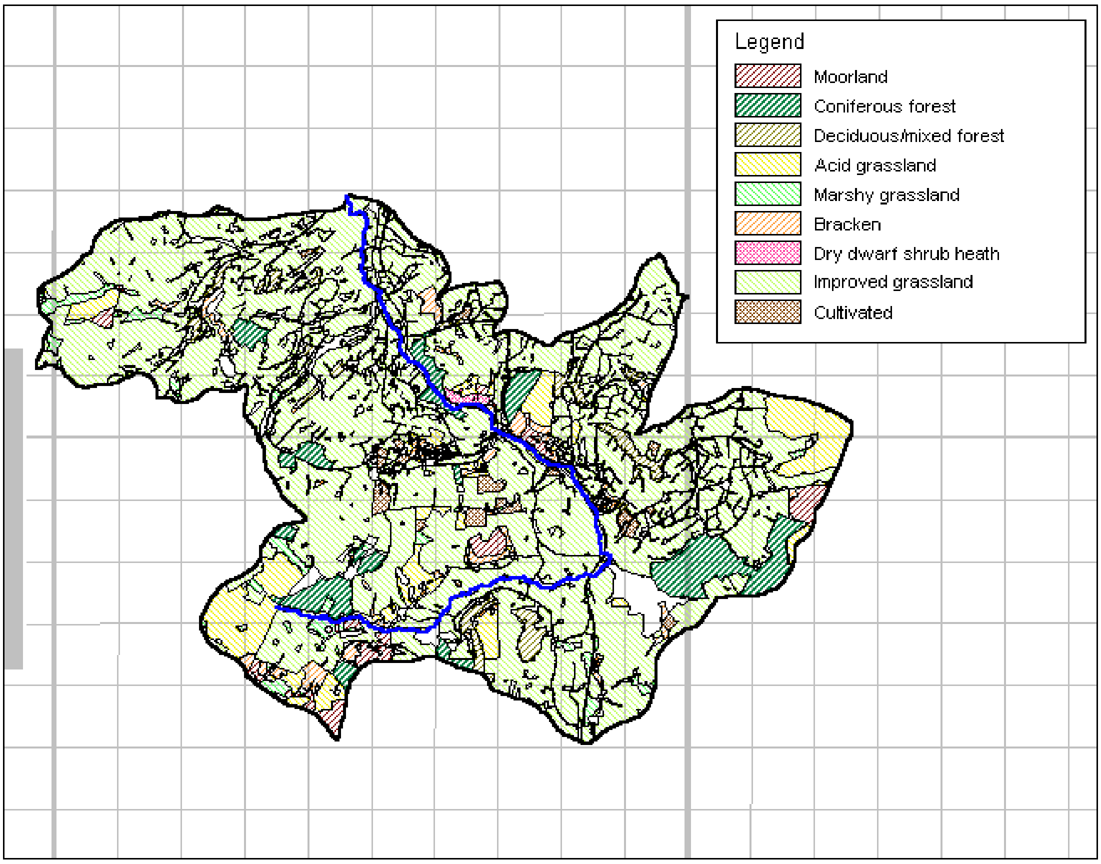

Figure 3.10 *Habitats in the Dulas subcatchment. Grid squares are 1 km.*

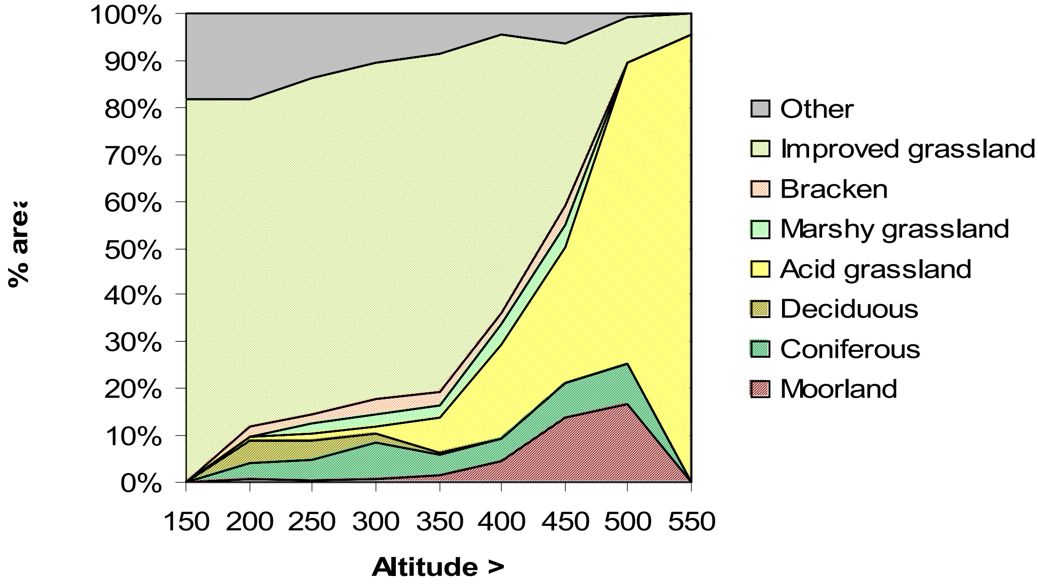

Figure 3.11 *Distribution of habitat types by altitude for the Dulas subcatchment. Note the location of deciduous woodland, typically in the lower middle part of the catchment, and the complementary relationship between improved grassland and moorland/acid grassland, which is also repeated for other catchments.*

3.2.3 The hydrometric network

The Environment Agency's river gauging network in the Severn catchment consists of six river gauging stations, recording hourly on dataloggers (Figure 3.12). Of the gauging stations in Table 3.4, three are on tributary streams (Dulas, Vyrnwy and Tanat), and three on the main Severn stem (at Dolwen, Abermule and Montford). The Vyrnwy station at Llanymynech (Plate 3.2) is downstream of the Tanat station at Llanyblodwel, and measures the total discharge from the Tanat, Vyrnwy and Banwy.

The Agency also reads or processes data from 48 raingauges, comprising 12 hourly automatic gauges, 24 daily-read storage gauges and 12 monthly-read gauges in less accessible locations (Figure 3.13). Monthly raingauges are used for resource management purposes, and do not have an application in flood studies beyond the assessment of antecedent conditions on a seasonal basis. Daily gauges can be used for areal mapping of isolated rainfall events, but in the uplands their application for this purpose is limited, as rain-days are frequent and it is difficult to separate event rainfalls. Nevertheless the daily gauges provide a useful check on the totals of some of the more intense storms recorded by the automatic gauges. In this project most use has been made of 11 of the 12 hourly raingauges: one of the gauges, Cynynion, having been installed in October 2000 (Table 3.5).

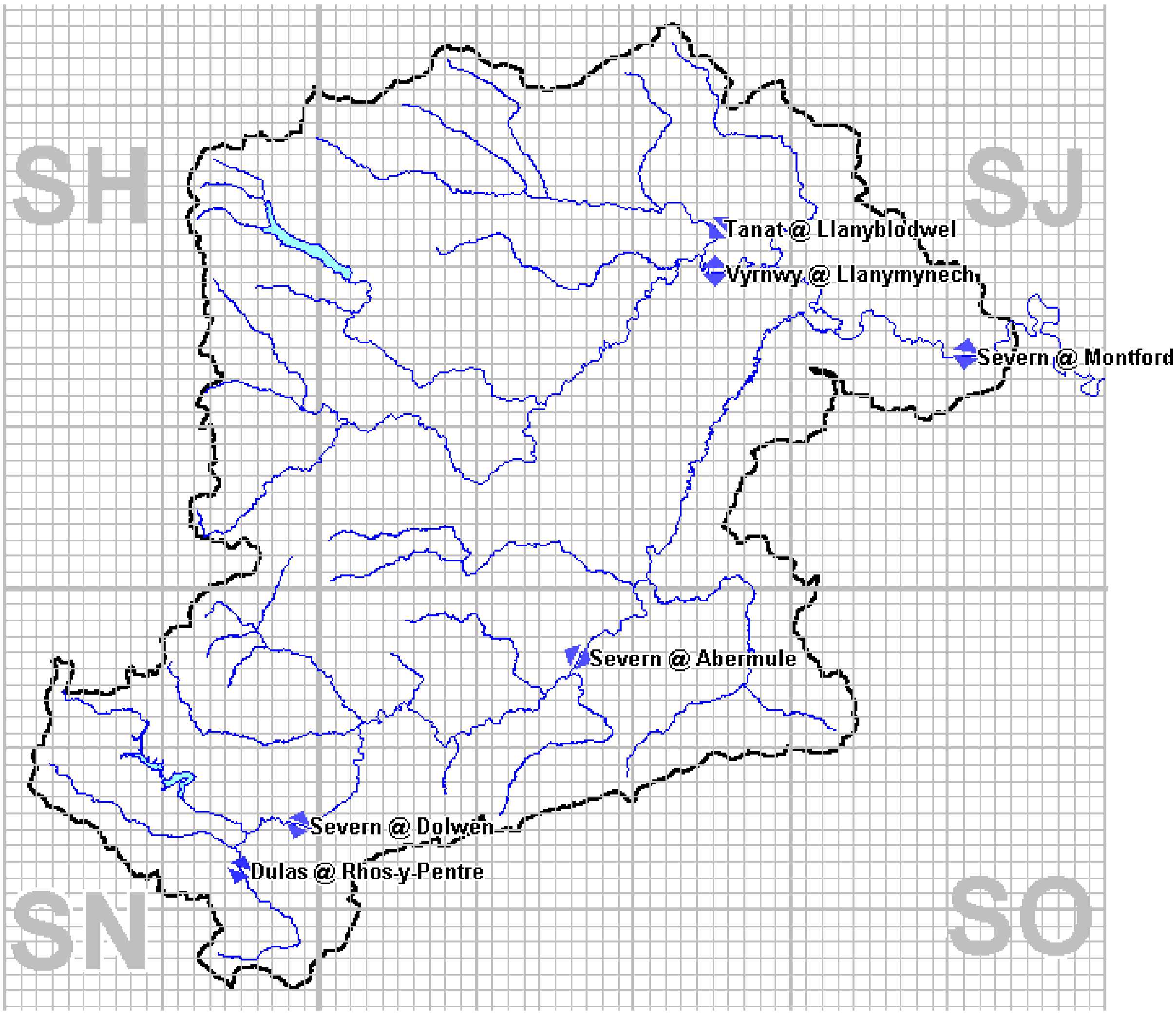

Figure 3.12 *Environment Agency gauging stations in the upper Severn catchment*

Table 3.4 *River gauging stations in the Severn headwater catchment (all data except Dolwen are from Hydrometric Register and Statistics[7])*

Station	OS grid reference	Catchment area upstream km^2	Type of station	Installed
Dulas @ Rhos-y-Pentref	SN 950824	52.7	Trapezoidal flume	1969
Severn @ Dolwen	SN 987853	171.2	Compound weir	2000
Severn @ Abermule	SO 164958	580.0	Velocity-area	1962
Tanat @ Llanyblodwel	SJ 252225	229.0	Flat-V weir replaced velocity-area station in 1992	1973
Vyrnwy @ Llanymynech	SJ 252195	778.0	Velocity-area	1970
Severn @ Montford	SJ 412144	2025	Velocity-area	1953

Plate 3.2 *Gauging station, River Vyrnwy at Llanymynech. The instrument building, housing a water level logger, can be reached by a catwalk at times of overbank flow. The station is calibrated using a current meter suspended from a cableway.*

[7] Hydrometric Register and Statistics 1991-1995, Institute of Hydrology / British Geological Survey (1998).

Plate 3.3 *Gauging station at Llanyblodwel, a flat-V weir with a precise rating of discharge versus depth*

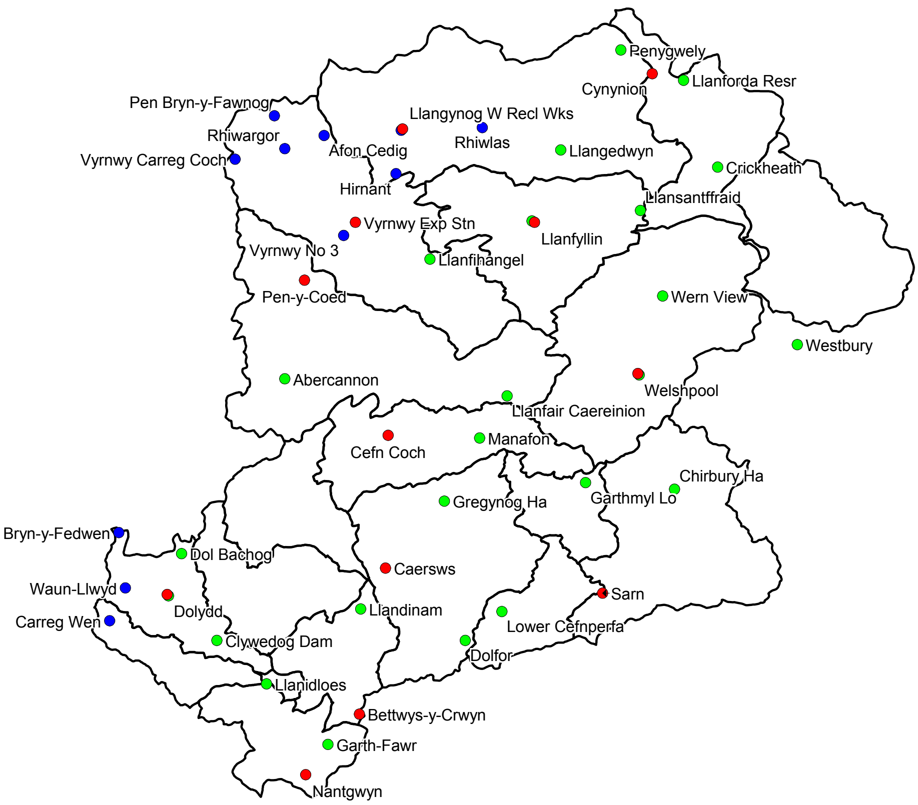

Figure 3.13 *The Environment Agency raingauge network. Where there are two gauges at a site, hourly automatic gauges (red) have been printed over daily (green) or monthly (blue) storage gauges.*

Table 3.5 *Hourly automatic raingauges in the upper Severn catchment*

Location	OS grid reference	Subcatchment
Pen-y-Coed	SH 978144	Banwy
Vyrnwy Exp Stn	SJ 017188	Vyrnwy
Dolydd	SN 873905	Clywedog
Welshpool	SJ 233073	Severn Flank 5
Llanfyllin	SJ 154188	Vyrnwy Flank 1
Cynynion	SJ 244301	Vyrnwy Flank 2
Cefn Coch	SJ 042026	Rhiw
Bettwys-y-Crwyn	SO 020814	Severn Flank 2
Nantgwyn	SN 979768	Dulas
Llangynog	SJ 053259	Tanat
Sarn	SO 206906	Camlad
Caersws	SO 040925	Severn Flank 3

3.2.4 Hydrological features of individual catchments

The presence of two large reservoirs in two of the highest subcatchments, the Clywedog on the slopes of Pen Pumlumon Arwystli (Plate 3.4) and the Vyrnwy overlooked by the Berwyns, and the floodwater storage offered by floodplain reaches of the Severn and Vyrnwy, offer a degree of attenuation of floods generated in the high-rainfall uplands.

The Clywedog subcatchment contains a large regulating reservoir, which is operated to provide around 8.5 Mm^3 of available storage at the end of each summer (Knapp, 1986). The primary function of the reservoir, and the main reason for its construction in 1967, is to provide a guaranteed minimum flow in the River Severn at the main water supply abstraction point at Bewdley, but the reservoir also has flood control and hydropower generation functions (Jones, 1997). Operating rules allow for low levels at the end of summer, to allow the reservoir to accept winter flood flows, with a maximum water level in April, when the flood hazard is usually low. The reservoir exerts a considerable control over flood runoff from the catchment upstream of the dam, and the Clywedog Dam has been popularly credited with significant reductions in the damage caused by flooding as far downstream as Shrewsbury. The precise role of the dam in the perceived change in flooding regime has been debated, and flood events of the last two years may help to dispel the public's complacency.

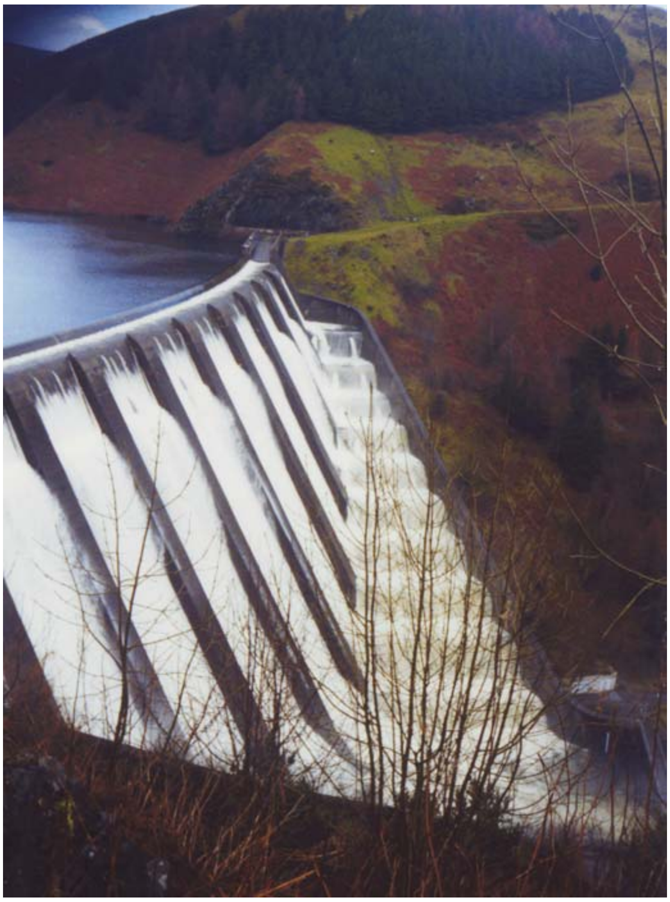

Plate 3.4 *Clywedog Dam spilling in February 2002.*

The Vyrnwy Dam was completed in the 1880s: the reservoir was intended to provide water for public supply through an aqueduct to Liverpool, but following the commissioning of additional supplies from the Dee it has recently been made available for river regulation of the Severn like the newer Llyn Clywedog (Jones, 1997).

Both the reservoirs exercise a flood control function, though the effects of the Clywedog, with a catchment area (upstream of the dam) of only 48.9 km^2, will soon dissipate with distance downstream. Spilling of the dam in winter is unusual, but the flows immediately downstream of the dam are obviously a complex function of operation rules, downstream problems with floodwaters and antecedent weather conditions. The catchment area upstream of the Vyrnwy Dam is 74.6 km^2, but the presence of the reservoir was insufficient to prevent flood alerts on the Vyrnwy and Upper Severn in October 1998 and again in February this year.

Flow statistics for several river gauging stations are presented in Table 3.6. Despite the presence of the Vyrnwy and Clywedog Dams, both subcatchments are capable of generating very high flows, and the magnitudes of flood peak flows in the Vyrnwy and the more flashy upper parts of the Severn are similar to those recorded at Montford, where the catchment is much larger, but slower to respond.

Table 3.6 Some flow statistics in the River Severn and major tributaries

River & gauging station	Catchment area	Dry weather flow[8]	Mean flow	Peak flow (pre-1995)
	km^2		m^3s^{-1}	
Dulas @ Rhos-y-Pentref	52.7	0.064	1.41	38.5 (2 Jan 84)
Severn @ Abermule	580	1.46	14.31	419.1 (13 Dec 64)
Tanat @ Llanyblodwel	229	0.57	6.45	118.2 (6 Aug 73)
Vyrnwy @ Llanymynech	778	2.11	21.04	406.7 (6 Aug 73)
Severn @ Montford	2025	5.16	42.37	467.2 (5 Dec 60)

Travel times of flood peaks between gauging stations have been computed for the Severn: the average time for a peak to move downstream from Caersws to Newtown, a distance of 13.2 km along the river channel, is 3½ hours, from Newtown to Abermule it takes only one hour to travel 8.1 km, but the distance along the river from Abermule to Montford is 66.7 km, and flood peaks reach Montford on average 25½ hours after they pass Abermule, providing a useful interval in which to issue warnings to Shrewsbury (Higgs, 1987). The meandering reach between Welshpool and Montford is also prone to overbank flows, and there is now a proposal to use the floodplain at the Severn-Vyrnwy confluence as a managed flood storage area, to further delay and diffuse the flood peaks from Wales. Flood wave velocities for the middle Vyrnwy are similar to those for the Severn floodplain reach from Abermule to Montford: average travel times of flood peaks from Pontrobert, to Meifod (7.06 km) and from Meifod to Llanymynech (20.81 km) are 2¼ hours and 7¼ hours respectively.

3.3 Land use past, present and future

3.3.1 Historic development

Land use in the uplands of Britain, with their unpredictable and sometimes hostile climate, generally unproductive soils and lack of infrastructure and social amenities, has presented a challenge for centuries. The need for better productivity in upland agriculture, to retain the rural population at reasonable income levels and prevent the further loss of social facilities, has long been recognised. Improvement of productivity was traditionally achieved by providing sheltered grazing in the valleys and moving stock on to the better pasture for part of their life cycle, using the hills only for rough grazing in summer. The quality of rough pasture could be improved by more use of lime and manure, and by the draining of waterlogged ground. These improvements could only realistically be carried out in the wake of enclosure, so upland agricultural land can now conveniently be divided into established valley farmland (mostly below 300 mOD), the moorland margin where most improvement has taken place (300-450 mOD), and the moorland and mountain core of largely unenclosed, exposed and

[8] Mean annual minimum 7-day discharge

unimproved land. The general upper limit for improvement of rough grazing is around 560 mOD (Higgs, 1987).

The momentum of agricultural improvement has ebbed and flowed with the fortunes of agriculture as a whole, and some land on the moorland fringe (*ffridd* land) has seen repeated attempts at enclosure and more intensive use, interspersed with periods of recession and reversion (Andrews, 1940). Within the moorland fringe in four Welsh upland parishes, Ball et al. (1981) found that 30% of the land had reverted at some time from agriculture to moorland.

Because of problems of climate and access, there was always a stark contrast between the hill and valley land. In the 18th century about one-third of the upper Severn valley, perhaps the part accessible for lime carted from Llanymynech, was under tillage for oats, rye and barley, while by 1795, 250000 acres of land in Montgomeryshire remained unenclosed, mostly in the southwestern parishes of Carno, Trefeglwys, Llanidloes, Llandinam and Kerry. Agricultural recession in the 19th century affected hill land more than the cultivated lowlands, which benefited from the better availability of lime following the opening of the canal through Llanymynech to Garthmyl and Newtown (Andrews, 1940). In the 1860s the total number of sheep in Montgomeryshire was 200,000 (Trueman et al., 1995), but this had increased to 600,000 by 1938, possibly matching the decline in arable cultivation in the hills.

In 1940, at the time of the Land Utilisation Survey, Andrews wrote that the hills of the central part of the catchment "have sunny southern slopes invaluable for late summer ripening of grain" while the upper reaches had a "bleak aspect of rugged rock outcrops and precipitous treeless slopes useless for agriculture and even indifferent as sheepwalks". Only the margins of the moorland were utilised, even sheep grazing being restricted to within easy distance of farmsteads, and steep slopes around Llanidloes and Trefeglwys had reverted to bracken and gorse over a 50 year period as stock had been removed. In 1935, 24% of the land below 700 ft (213 m) in the Plynlimon area was bracken and gorse, while between 700 ft and 1500 ft (213-457 m) only 21% of the land was "cultivated" (in this context presumably intended to mean enclosed), the rest being rough pasture (Stapledon, 1935).

3.3.2 Recent expansion of pastoral agriculture

Over the last 60 years, grant aid has led to an increase in land drainage in the cause of agricultural productivity, while more recently there have been marked improvements in vehicular access to upland pastures and a renewed programme of ploughing and re-seeding. Even moorlands have been subject to partial drainage through the practice of gripping. As a consequence of improvement and conversion to coniferous forest the moorland core has shrunk to a fraction of its former extent, and isolated pockets of moorland, on the lower hill summits, have disappeared altogether. The number of sheep in Montgomeryshire had risen to almost 1.5 million by 1988, with a breeding ewe complement of 500,000 (Trueman et al., 1995). Between 1934 and 1988, the area of rough grazing had fallen from 36% of the vice-county to 23%, and a study of an area around the Berwyns concluded that heather-dominated habitat had declined by 44% between 1946 and 1984 (Walker and Elias, 1989, quoted by Trueman et al. 1995).

Records abstracted on a parish basis from MAFF's June returns between 1959 and 1982 show an interesting pattern of declining arable cultivation, increased permanent grassland and decreased rough grazing (Higgs, 1987). Higgs selected several parishes as examples of the variation of the trend across the upper Severn catchment. Llandinam, in the southeast of the catchment mirrored the catchment as a whole, with a 10% decrease in rough grazing and a 5% decrease in arable. Llandrinio, near the Severn-Vyrnwy confluence, had increased its arable area by 5% at the expense of permanent grassland, with no change in rough grazing. Trefeglwys, an upland parish in the Trannon subcatchment, had halved both its arable and rough grazing acreages to create more improved pasture. At Llangynog in the Tanat valley, possibly because the land was too steep for pasture improvement, rough grazing had been lost to forestry.

Between 1978 and 1984, 146000 hectares of rough grazing were improved in England, Wales and Scotland (Barr et al., 1986). Of this total, the majority (79 %) had previously been rough grassland, while a smaller proportion (10%) had been classified as moorland. In Wales rough grazing improved between 1978 and 1984 amounted to 0.7 % of the total land area. Pasture improvement had been accompanied by a programme of track construction, some of it to provide improved access to the upland pastures, and the greatest length of tracks (40 m km^{-2}) had been built in Wales and southwest England. Underdrainage in England and Wales expanded from virtually zero in 1940 to a maximum rate of about 100,000 ha/a in the 1970s (Figure 3.13), and has since declined to about half that level, though detailed records are no longer kept (Robinson, 1990). During the 1970s, an area of 8500 ha (6%) of Montgomeryshire was drained (Green 1979, quoted by Higgs, 1987).

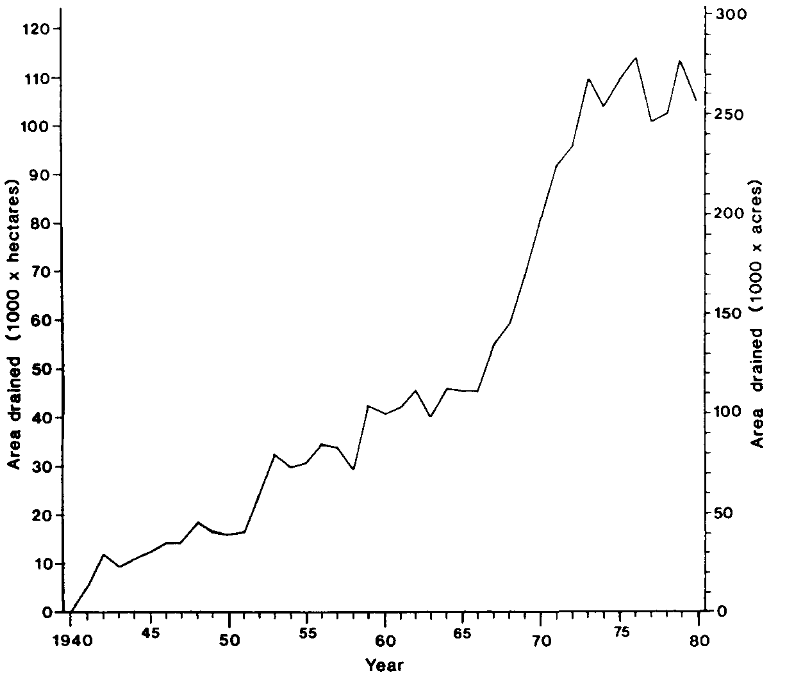

Figure 3.13 *Rates of underdrainage in England and Wales from 1940 to 1980 (from Robinson, 1990)*

3.3.3 Forestry

In 1924 the area of forest in Montgomeryshire was 13411 ha, 6.6 % of the total area (May and Wells, 1942 cited by Higgs 1987). By 1985, following a major afforestation programme, especially in the upper parts of the catchment, forestry covered 9.5 % of the vice-county. Planting of the area around the Lake Vyrnwy began immediately after the completion of the dam, and by 1912 there was 364 ha, but most of the present forest area in the Vyrnwy dates from 1920-1936. The first planting in the Hafren Forest was in 1937/8. The depression of agriculture after World War II increased the availability of hill land for afforestation, and the annual rate of conifer planting in the upper Severn catchment reached a peak in 1950, with the acquisition of hillslopes and moorland up to 700 mOD. After a temporary pause, planting was resumed in the 1960s, particularly in the Hafren Forest. Most afforestation up to the late 1960s had been by the Forestry Commission, but tax concessions in the 1980s increased the rate of private planting, particularly in the headwaters of the Tanat, Banwy, Cain (a tributary of the Vyrnwy) and Trannon.

Felling of the first generation conifer plantations has been going on for some years, and large areas of the forest in the upper part of the Hafren catchment have been felled and replanted. New planting follows revised guidelines related to aesthetics, the creation of more diverse habitats along rivers, and the protection of water quality, but it is unclear what effects these more environmentally aware policies may have on the generation of flood flows, as the watercourses of the main drainage system, if not the furrows, have survived the first rotation virtually intact.

3.3.4 Future of the upland economy

The present crisis in hill and upland farming, brought about by livestock diseases striking at an economy almost totally reliant on meat production, may lead to yet another retreat from the moorland margin, i.e. to reduced stocking densities, deterioration in field drainage and the reversion of improved and rough pasture. Viability of farming in the uplands is and has always been precarious, and changes may involve the amalgamation of farms and the reduction of the land area in use (Anon, 1978; Eadie, 1984). Even a modest increase in the farmer's perception of his workload, especially in administrative matters such as new disease control measures (e.g. individual tagging of sheep and stricter licensing of stock movements), may be sufficient to reduce his enthusiasm for improving his business. In view of recent trends towards increased mechanisation and off-road vehicle use, it is difficult to see how manpower per livestock unit could be reduced from present levels.

Depression in the farming sector could cause a more general retreat from the uplands, a declining local population, the loss of the rural infrastructure and a decrease in the proportion of the population finding local employment. Economic support for hill farms, an important part of the EC and UK government strategy aimed at preventing this, cannot be sustained indefinitely with agricultural production as the sole objective. Management of the uplands with more diverse objectives, integrating farming with the maintenance of landscape and conservation values, will require diversion of manpower and resources, and a shift in grant aid away from livestock production towards the maintenance of the environment through agri-environment schemes may be one solution.

Forecasts of a decline in agriculture in the uplands have been around for some time. A distinction is sometimes made between hill farms, in which the emphasis is on sheep farming and a heavy dependence on rough grazing, and upland farms, where both sheep and cattle are reared. Intensification can still maintain incomes on upland farms, which have more sustainable improved pastures and the ability to produce a hay crop, but the more remote hill farms are under threat (Heal, 1984), and the age distribution of hill farmers has often been taken as an indicator of future problems. A study of upland land use commissioned by the Countryside Commission (Anon, 1978) predicted that the areas showing a reduction in agricultural use would be those with

i) a high proportion of poor land (<48% in Agricultural Land Classification grades 1-4)

ii) predominance of sheep farms (>40% of livestock units in sheep)

iii) predominance of farms supporting less than one full-time worker (>30 part-time farms per 100)

The hill farms of mid-Wales fall squarely into all of these categories.

3.3.5 Possible patterns of land use on the hills

One of the most outstanding features of the upland climate is the dependence of important climate variables on altitude. Rainfall increases with altitude, largely because the hills force moisture-laden air to rise. On the rain shadow side of the hills, e.g. the eastern flank of the Plynlimon massif of mid-Wales, the change in rainfall with altitude is even more pronounced, and within the upper Severn valley the annual rainfall drops from 2500 mm on the summit of the Cambrian Mountains ridge to below 700 mm in the lower lands around Shrewsbury. High rainfall has significant effects on the viability of farming systems, through high leaching rates for soil nutrients and high soil moisture levels leading to waterlogging, poor root performance and low soil temperatures early in the growing season.

Air and soil temperatures fall with increasing altitude, by 0.55-0.7° C per 100 m in mid-Wales, and there is a corresponding decrease in the length of the growing season, simply defined as the length of time for which the temperature exceeds 6° C. In Wales the growing season decreases by about 20 days for each 100 m increase in altitude: at 500 mOD it is less than six months, and it is impossible to sustain livestock farming without access to lower land for wintering. The climatic template, which has defined traditional land use patterns, can be brushed aside in the short term through a sufficient input of financial support, but the rural community needs a secure income as well as injections of capital, and a system that relies on high inputs of fuel and fertilisers is not sustainable in the long term. In many cases modern controls, e.g. the 30-month rule for cattle, the lack of demand for ponies and older or smaller sheep, and the expectations of farmers and their families for a 21st century lifestyle, prevent a return to traditional patterns.

Possible future changes in land use have hydrological implications:

- extension of coniferous afforestation – the impetus for large-scale planting has abated at present, largely owing to environmental concerns from effects on water resources to acidification. Severe exposure on the higher plateaux may limit the extent of any new planting. The costs of harvesting on steep, rocky or peaty land are becoming clearer as the present phase of felling proceeds. Improved practices may reduce the environmental impacts of new and second-rotation planting on runoff, by interrupting the drainage network before it reaches the river channel. Interception losses increase with the area of forest and ungrazed forest-marginal vegetation, leading to increased soil moisture deficits and infiltration, and hence to reduced flood runoff from the upper catchment.

- reversion of moorland margins – drainage schemes have a limited lifetime, and eventually the hydrological system will revert to surface runoff, moderated by natural mulching of soils and the re-establishment of a humus layer. Taller vegetation (heather, bracken, tussocky moorgrass etc.) increases losses by interception. The moorland margins, including steeper slopes and riparian zones, are appropriate for the re-establishment of deciduous woodland, in turn leading to interception losses and deeper bioturbation of soils. As with coniferous forest, the soil moisture deficit could assume a more significant role in limiting rapid runoff.

- reduction in grazing of moorlands – dwarf shrub re-establishment, mainly on upland peat, increases interception. Mulching creates storage and reduces the velocity of runoff. Blanket peat erosion (dissection and desiccation of peat islands, the exposure of the regolith, and a high channel density transmitting runoff to the stream network) will remain a long-term problem, though most grips will deteriorate in time, and gully-control methods may help with recolonisation of channels. Control of burning will be a high priority, if more permeable soil surface conditions are to be maintained.

4 Flood hydrology of the Severn headwaters

There have been several past attempts to determine whether land use changes in the Upper Severn have had an identifiable, unambiguous effect on flood hydrology. Unfortunately the period of maximal afforestation and agricultural improvement was also a period of change in other factors, notably the construction of the Clywedog Dam. Pronounced fluctuations in the rainfall regime, in particular the sequence of serious floods in the 1960s before the completion of the Clywedog Dam and flood protection works at Caersws and Newtown, followed by the relatively dry 1970s and 1980s, may have given the superficial impression that concern about flooding was misplaced. The signal arising from land use is obscured by the impact of these other major factors and by "noise" arising from channel changes, for instance the numerous smaller river management schemes, and possibly the arrival in the main channel of the bedload sediment produced by afforestation drainage practices.

An alternative approach is to develop a model of the system that can be used to explore the consequences of either localised or widespread land use changes within the catchment, taking into account the spatial dimension, especially the relationships between flood flows generated in the headwaters or in lower reaches of the catchment. Use of such a model might explain the failure to detect impacts in the hydrometric data, by providing upper limits to the influence of given perturbations of the system, i.e. the percentage change to be expected in peak discharges downstream as a result of changes in the headwaters or on the catchment flanks.

This chapter covers the collation of the hydrometric data and theory necessary for the development of a simplified hydrological model of the upper Severn catchment, the results of reported studies examining changes in the flood response of the catchment in the light of concurrent land use change, and the scenarios of potential land use change in the subcatchments that can be examined using the model.

4.1 Flood response

4.1.1 Selected recent flood events

The hydrological model should be able to simulate both winter and summer flood events, and though the accuracy of the simulation itself is not critical, it should be able to predict the magnitude of changes as a percentage of the peak flow. Rather than deal with hypothetical events of a given return period, it was decided to use a few sample events taken from the recent record. Three events were used in the calibration of the model, each resulting from rainfall spread widely across the catchment:

i) a storm averaging 52 mm in January 1999, heavier in the north and west of the catchment

ii) a more uniformly distributed storm of about 104 mm in September 1999, falling on dry soils

iii) a smaller event in February 2001, averaging 48 mm across the catchment, but concentrated in the high-altitude southwestern parts of the catchment.

Subcatchment rainfalls for each event were estimated from the 2DM5 rainfall totals of Table 3.3:

$$P_i = 2DM5_i \times \frac{PG_j}{2DM5G_j}$$

where P_i is the subcatchment areal rainfall estimate for subcatchment *i*

$2DM5_i$ is the subcatchment areal 2DM5 from Table 3.3

PG_j is the measured rainfall at hourly raingauge G_j within or closest to the subcatchment (see Figure 3.13)

and $2DM5G_j$ is the estimate of 2DM5 for the raingauge location

The subcatchment areal rainfalls for each event are presented in Table 4.1, and the raingauge totals are in Figures 4.1 to 4.3. Discharges measured at five gauging stations for the earlier events, and six for the third event, are shown in Figures 4.4 to 4.6.

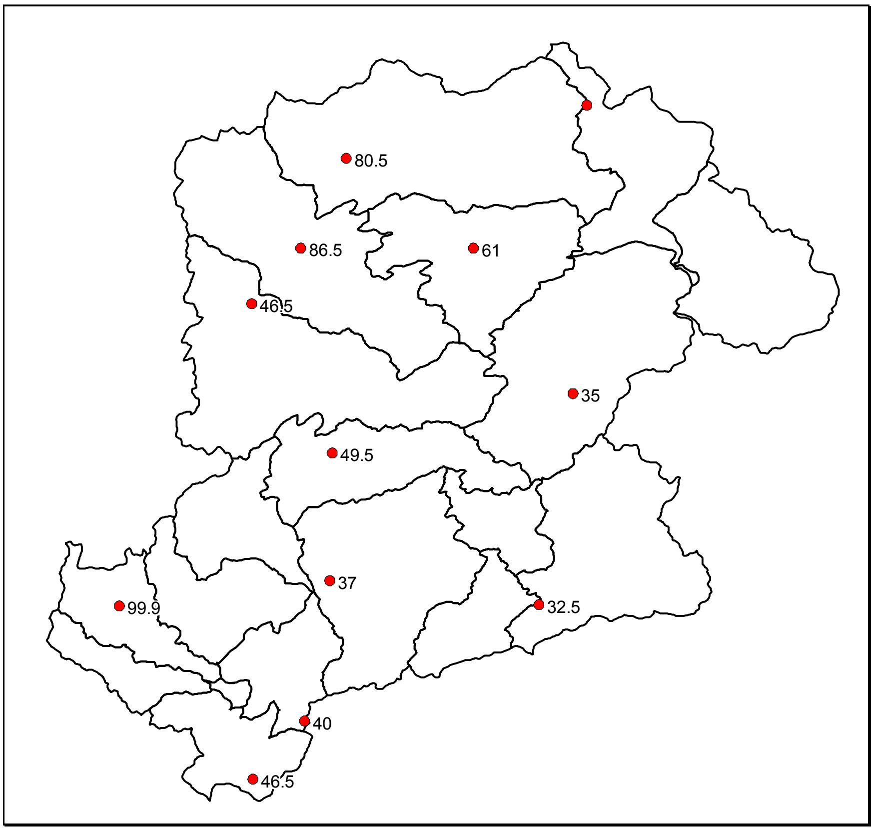

Figure 4.1 *Rainfall event of 15 January 1999. Rainfall totals (mm) from hourly gauges.*

Table 4.1 *Subcatchment rainfall totals for the three rainfall events (mm), estimated from the distribution of 2DM5 within each subcatchment*

Subcatchment	Areal mean 2DM5 rainfall, mm	15 Jan 1999	18 Sept 1999	10 Feb 2001
Western headwater catchments -				
Hafren	111.4	98.2	56.3	184.2
Clywedog	108.9	96.0	55.0	180.1
Dulas	75.9	48.3	107.7	40.8
Trannon	74.3	65.5	37.6	122.9
Garno	73.8	46.3	124.7	30.1
Rhiw	69.6	45.9	91.4	36.9
Banwy	82.0	40.4	144.6	80.0
Vyrnwy	91.3	89.5	83.9	72.4
Tanat	78.2	71.8	85.0	39.8
Central and eastern subcatchments -				
Severn Flank 1	69.3	44.1	98.4	37.3
Severn Flank 2	69.6	41.8	147.9	31.9
Severn Flank 3	62.2	39.0	105.1	25.4
Mule	58.8	32.4	153.8	20.1
Severn Flank 4	60.3	39.5	122.3	21.2
Camlad	57.2	31.6	149.6	19.5
Severn Flank 5	54.2	35.5	109.9	19.1
Vyrnwy Flank 1	65.6	57.0	85.0	31.1
Vyrnwy Flank 2	54.9	47.7	71.1	26.1
Severn Flank 6	49.3	32.3	100.0	17.4
Whole Severn headwater catchment	70.7	52.4	103.6	47.9

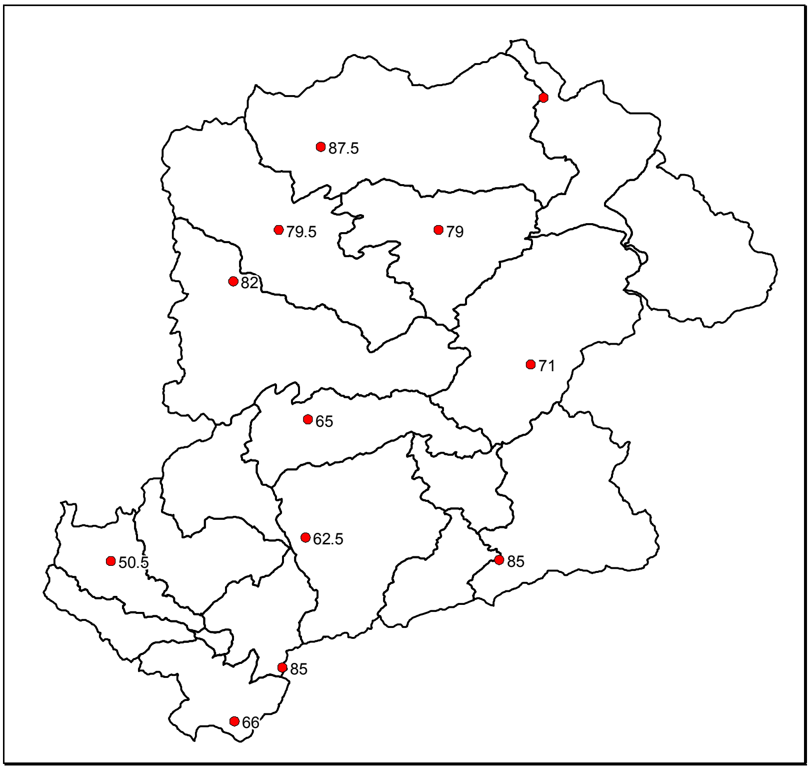

Figure 4.2 *Rainfall event of 18 September 1999. Rainfall totals (mm) from hourly gauges.*

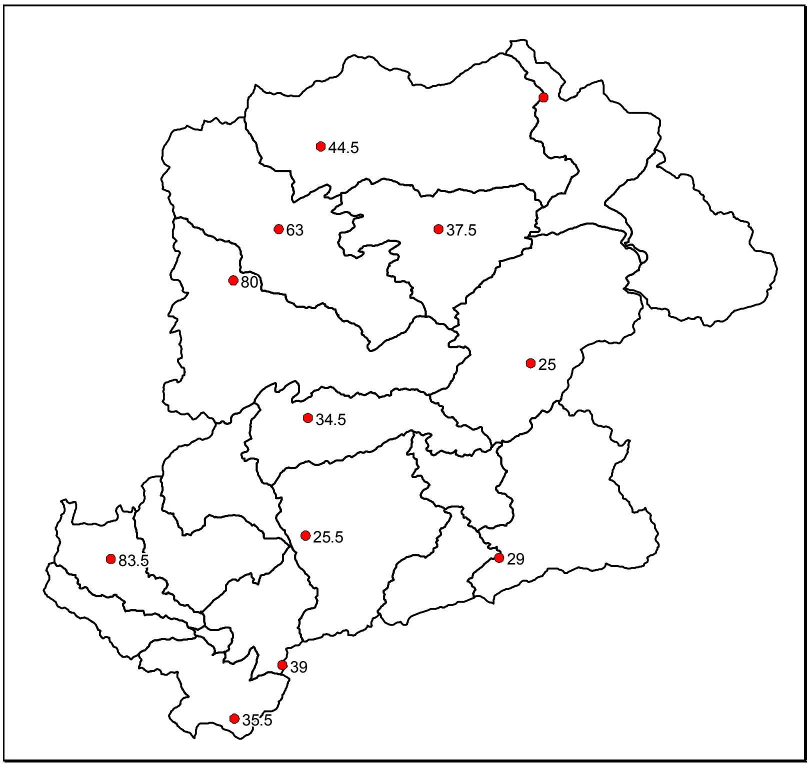

Figure 4.3 *Rainfall event of 10 February 2001. Rainfall totals (mm) from hourly gauges.*

15 Jan 99

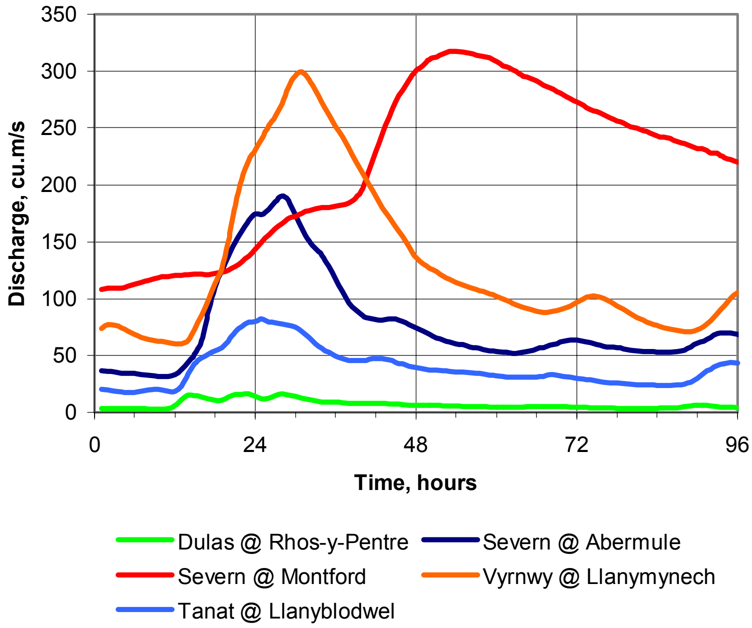

Figure 4.4 *Flood event following rainfall on 15-16 January 1999. There were three distinct spikes of rainfall, including one very intense fall recorded by the Dolydd raingauge in the Clywedog subcatchment, but the complex form of the event shows only in the record from the Dulas at Rhos-y-Pentre.*

18 Sept 99

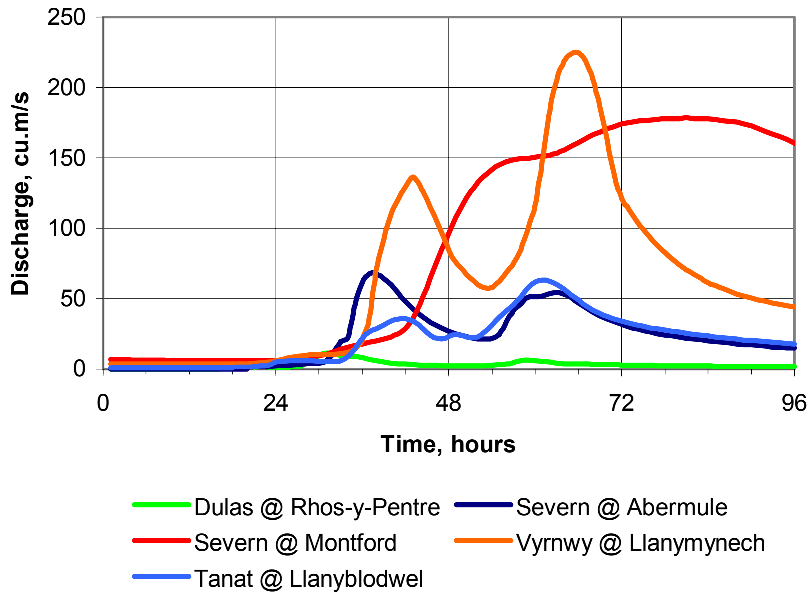

Figure 4.5 *Flood event following rainfall on 18-19 September 1999. Two spikes of rainfall yielded a compound hydrograph, which was almost smoothed out into a single peak at Montford.*

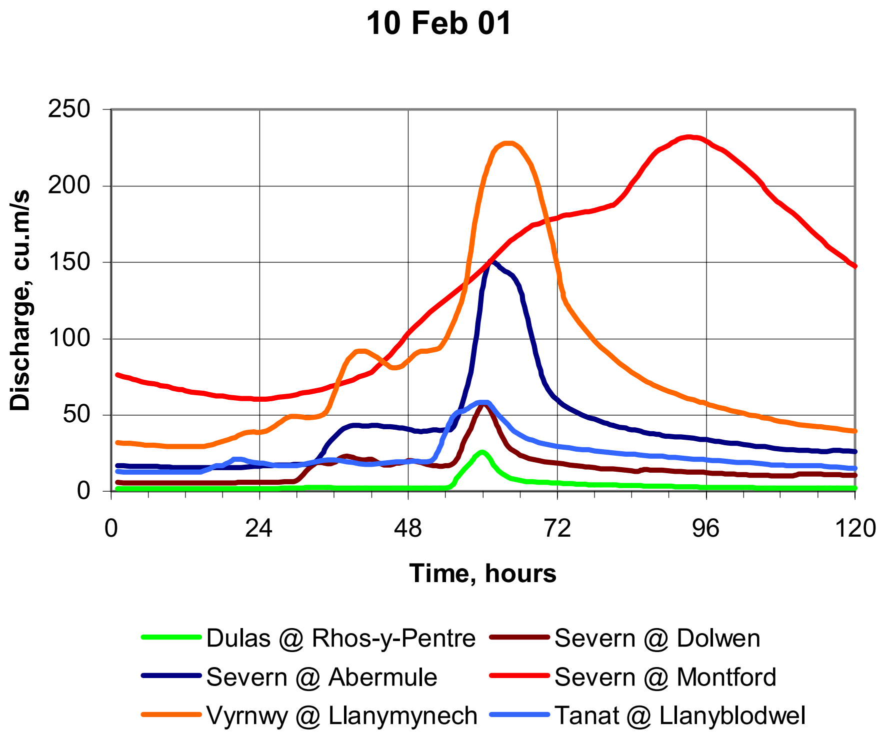

Figure 4.6 *Flood event following rainfall on 10, 11 & 12 February 2001.*

Discharge hydrographs for the three events show a consistent temporal pattern, once allowance has been made for the pronounced double-peaked form of the September 1999 rainstorm. Table 4.2 shows the time of each of the hydrograph peaks relative to the approximate centroid of the rainfall event, measured at Nantgwyn for the upper part of the catchment, and Welshpool for the lower part of the catchment.

The flood wave speed is a complicated function of the depth of flow in the channel: while it would be expected that in general higher flows within the channel would have higher velocities, the occurrence of overbank flow and storage of floodwaters on the floodplain would delay the passage of the flood wave. According to the Hydrometric Register and Statistics (1991-1995), flows are out of bank at Montford once the Severn discharge exceeds 220 m^3s^{-1}, and at Llanymynech when the flow of the Vyrnwy exceeds 160 m^3s^{-1}, indicating that overbank discharge may have occurred at other locations along the floodplain for the highest flows represented on Figures 4.4 to 4.6. This may explain the apparently longer time of passage for the January 1999 event, though it does not explain how the smaller event on 10 February 2001 could produce similar floodwave velocities.

Three flood events taken from a three-year period are likely to lie in the range of small to moderate-sized events, with return periods ranging say from 1 to 5 years. The Floods Studies Report provided tabular methods of calculating the magnitude of rainfalls of given return period, based on the maps of 2DM5. For the range of 2DM5 found in the upper Severn catchment, for instance, a two-day rainfall total of $0.63 \times 2DM5$ would be expected to occur twice in a given year, while a two-day total of $1.12 \times 2DM5$ would be expected to occur once in ten years. Taking the areal average rainfall for each event over the whole of the upper Severn catchment, and comparing it with the estimated 2DM5 rainfall for the same catchment, the three events have approximate return periods of 1.1 years and 0.8 years for the two winter events, but a surprising 57 years for the September event. However, extreme rainfalls in the summer months do not always give rise to exceptionally high river discharges, unless, like the August 1973 event described in Section 2.2.2, they fall on soils already wetted by prior rainfall. The September event was unusual for the time of year, but its maximum flow was exceeded at least six times during 1999. In Table 4.3, the peak flows for each station and each event are compared with the mean annual flood, as presented in the Hydrometric Register and Statistics (1991-1995).

Table 4.2 *Time of hydrograph peak after approximate centroid of rainfall event (hours). A "shelf" on the Montford peak is taken as the first peak of the 18 Sept 99 flood.*

Station	Rainfall event			
	15 Jan 99	18 Sept 99 (1st peak)	18 Sep 99 (2nd peak)	10 Feb 01
Dulas @ Rhos-y-Pentre	7	7	7	10
Severn @ Dolwen	-	-	-	10
Severn @ Abermule	12	13	11	11
Severn @ Montford	41	33	29	41
Tanat @ Llanyblodwel	7	16	9	8
Vyrnwy @ Llanymynech	13	17	14	12

Table 4.3 *Comparison of peak discharges with mean annual flood for each station (m^3s^{-1})*

Station	Mean annual flood[9]	Flood event		
		15 Jan 99	18 Sep 99 (Larger peak)	10 Feb 01
Dulas @ Rhos-y-Pentre	22.1	16.2	11.3	25.7
Severn @ Dolwen	-	-	-	57.6
Severn @ Abermule	232.8	190.1	68.0	150.0
Severn @ Montford	302.7	317.1	178.7	231.8
Tanat @ Llanyblodwel	77.9	82.0	63.4	58.7
Vyrnwy @ Llanymynech	292.2	299.2	224.4	227.7

[9] from "Hydrometric register and statistics 1991-95", published by Inst. Hydrol. & Brit. Geol. Surv. (1998).

4.1.2 The form of the flood hydrograph

The flood hydrograph is not only defined by the relationship between rainfall and runoff, as it is modified by soil and vegetation properties, but also by the properties of the stream channel network, both within headwater catchments and down the major river channels. Runoff generated on the catchment flanks, on reaching the stream channel, causes a rapid increase in water depth, velocity and total discharge, but the resulting flood wave has to pass down the channel, overcoming the resistances offered by the roughness of the bed, large-scale elements such as boulders and other obstructions, and the form of the channel itself, for example narrow passages or meandering channels with frequent current swings. The resistance of the channel, and the opportunities for storage of water within the channel, significantly delays the arrival of the flood wave at points downstream.

The familiar bell-shaped hydrograph produced by a simple rainfall event in a small catchment (see Figure 2.2) is a consequence of both the runoff response of the slopes and the attenuation and smoothing caused by channel processes. The lag between the maximum rainfall input and the hydrograph peak is strongly dependent on the length of channels, and this is the primary cause of the slower response of larger catchments. Flow paths down the hillslopes to the stream channels are similar for small and large catchments, but the length of stream channels increases with catchment area, and moreover the larger catchments tend to develop low-gradient floodplain reaches, where more within-channel and overbank storage is available.

There have been many attempts to find mathematical or statistical rules governing the relationships between catchment geometry and catchment response: generally it is found that two geometrical variables, area and mean slope, are significant determinants of response times, though these variables are correlated, and there are many ways of calculating a catchment slope, for example from analysis of mapped contours, digital terrain models or measurements of the fall of bed elevation with channel distance (Saxton and Shiau, 1990).

Examination of a series of flood hydrographs from a catchment suggests that there may be fundamental properties that are invariant despite the obvious differences between rainfall events. The unit hydrograph concept was developed as a means of quantifying and making practical use of this underlying, though sometimes elusive, integrity of response. Basically, the unit hydrograph is the response of the catchment to a standardised rainfall input: if the unit hydrograph can indeed be derived from the response of the catchment to natural rainfall events, it should be invariant, and a small number of determinations should be sufficient to define a catchment average unit hydrograph, which can then be used for predictive purposes. In practice, the technique is more complex, and the results open to debate, but unit hydrograph theory has been one of the most useful advances in hydrology, numbering among its successes the methods outlined in the Floods Studies Report, which have been the basis of flood prediction in the UK for many years (Boorman and Reed, 1981).

Catchment behaviour is markedly non-linear, in that similar rainfall events do not necessarily produce the same result, and double the rainfall, falling in the same time, will not generate double the discharge. The non-linearity mostly arises from the antecedent conditions, which lead to larger or smaller infiltration rates according to the state of the soil, from other losses such as evaporation and interception occurring at the same time as the rainfall, and from spatial variations across the catchment. There is an optimal range of catchment size that is suitable for unit hydrograph analysis: too small a catchment will require measurements at a very intensive timescale, and boundaries may be difficult to define, while too large a catchment will incorporate other non-linear processes such as routing of floodwaters down the main channels, and the spatial distribution of rainfall may prove significant.

There are many procedures for the estimation of the unit hydrograph. The common starting point is the derivation of the rapid runoff hydrograph from the measured hydrograph, by separating out the baseflow component (see Figure 2.2). Even at this stage, many methods exist for the definition of the separation line, most approaches being equally effective and equally flawed, depending as they do on assumptions about the processes of throughflow and baseflow that cannot usually be tested in the field. It is important that within any given investigation the same separation method is applied, though the actual choice of separation technique is generally considered to have little relevance to the final result. A frequently-used technique (Anon, 1975) is to extrapolate the antecedent recession to a point lying below the peak of the hydrograph, then to draw a straight line to a defined point on the recession after the peak (Figure 4.7). This point is at a time T after the cessation of rainfall, where T is four times the lag between the centroid of the rainfall and the peak of the hydrograph.

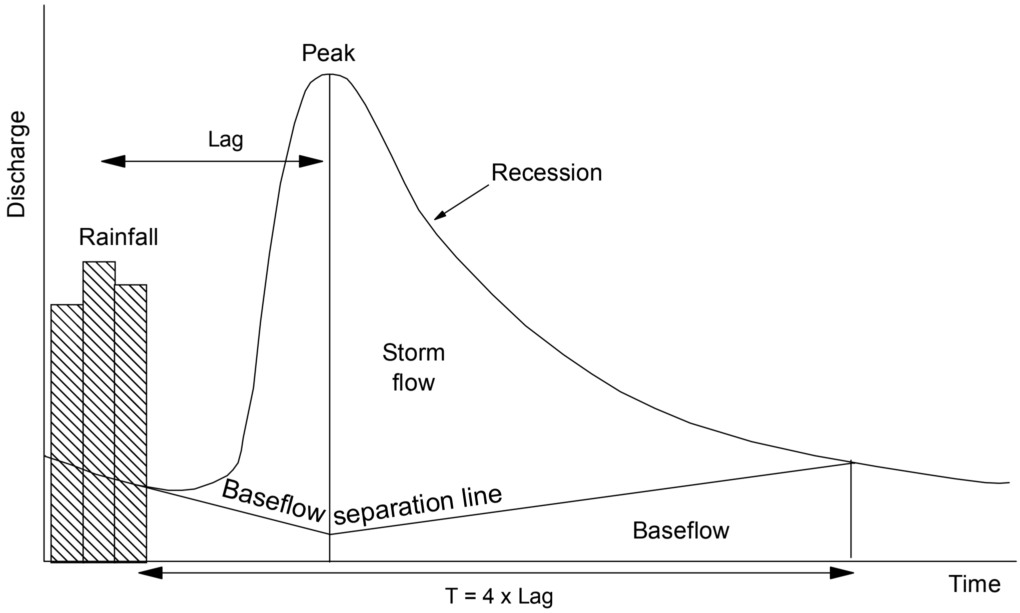

Figure 4.7 *Separation of baseflow from stormflow by the FSR method*

Infiltration and other losses are taken into account in a “loss equation” which is used to determine the effective rainfall from the actual event rainfall. A constant rate of loss from the incoming rainfall can be assumed, or more realistically a loss rate that decreases with time, to simulate the reduction in infiltration rate as the soil becomes saturated. The parameters of the loss equation are adjusted to make the total effective rainfall equal to the total storm runoff.

The unit hydrograph is used in flow prediction by dividing the effective rainfall into a sequence of pulse inputs of equal duration (say an hour), and calculating the response to this compound rainfall event as the superposition of several copies of the unit hydrograph, each one a response to a single rainfall pulse. For this purpose it is important to define a timescale for the unit hydrograph, and it is usual to standardise on a one-hour unit hydrograph representing the catchment's response to a 10 mm input of effective rainfall lasting for one hour.

In the context of this report it is necessary to discuss two further applications of unit hydrograph theory, which have been used in the construction of the Severn land use change model. At an early stage in this project, it was proposed to use unit hydrographs estimated from the hydrometric data for individual catchments, but the model required the definition of catchment responses for a number of ungauged catchments. The next stage in the process, extension of the unit hydrographs from the small number of gauged headwater catchments (the Tanat and the Vyrnwy, and "nested" subcatchments such as the Dulas, the Severn to Dolwen and the Severn to Abermule) promised to be difficult, and it was decided to drop the direct computation of subcatchment unit hydrographs in favour of a simpler indirect method, using the Flood Studies Report's methods for estimating the time to peak of a triangular unit hydrograph hybridised with a semi-analytical solution, the Nash unit hydrograph.

The FSR offers a simple method for the derivation of unit hydrographs of ungauged catchments from catchment characteristics such as stream length and slope. For the purposes of this study the time to peak parameter was estimated for all 19 subcatchments, using data abstracted from OS maps (Table 4.4). Neglecting the urban influence for these predominantly rural catchments, the FSR equation for the time to peak T_p is

$$T_p = 46.6(MSL)^{0.14}(S1085)^{-0.38}(RSMD)^{-0.4}$$

where MSL is the main stream length in the catchment

S1085 is the stream slope between points 10% up the main stream from the catchment outfall and 15% down the main stream from its source as marked on the 1:25000 OS map

and RSMD is the 1-day M5 rainfall minus the effective mean soil moisture deficit.

The linear reservoir is often used as a simple model of a hydrological system, in which the output is proportional to the quantity in storage. The response of a linear reservoir to a pulse input, e.g. a brief rainstorm, is an instantaneous rise followed by an exponential recession, but if the output is channelled into a second reservoir, the output from the second reservoir rises less steeply to its peak. Nash (1957) noted that the unit hydrograph of a real catchment usually resembled the output from a cascade of equal linear reservoirs, and he derived the two-parameter equation for this output as a general model of the unit hydrograph, one parameter n being the number of reservoirs in the cascade, the other k being a time parameter controlling the steepness of the recession. The equation was generalised to embrace the case of a non-integral number of reservoirs, and Nash presented a simple tabulation for the calculation of the parameters n and k for a given catchment. Inspection of the variation of the shape of the hydrograph as n is varied suggests that the larger the catchment, the larger the value of n. The parameter n controls the symmetry of the hydrograph: low values of n produce a very skewed curve (Figure 4.8). The parameter k merely controls the timescale of the hydrograph, without changing its shape (Figure 4.9).

In the land use change model, the hydrological response of each of the 19 subcatchments is simulated using a two-reservoir cascade (n = 2), with a k parameter inversely proportional to the time to peak computed from the FSR equation above. Thus the subcatchment response is reduced to a simple model for the loss rate, and a single parameter relating the subcatchment unit hydrograph time to peak to the estimate derived from the FSR equation.

Table 4.4 *Time to peak of FSR unit hydrographs for the 19 subcatchments*

Subcatchment	Area	Main stream length	S1085	RSMD	Time to peak
	km^2	km	m km^{-1}	mm	hours
Western headwater subcatchments					
Hafren	36.583	16.252	18.541	78.3	3.97
Clywedog	58.66	22.479	12.456	76.4	4.88
Dulas	62.058	15.932	11.716	52.1	5.55
Trannon	72.988	20.001	19.332	50.9	4.78
Garno	68.721	18.803	4.538	50.5	8.24
Rhiw	99.213	27.579	7.929	47.4	7.21
Banwy	213.224	38.932	6.267	56.6	7.71
Vyrnwy	190.569	36.658	5.674	63.4	7.58
Tanat	244.251	34.909	3.858	53.8	9.32
Central and eastern subcatchments					
Severn Flank 1	4.616	2.803	56.130	47.2	2.49
Severn Flank 2	57.948	14.423	10.354	47.4	5.95
Severn Flank 3	157.227	19.192	10.560	41.9	6.46
Mule	48.966	18.544	6.543	39.4	7.90
Severn Flank 4	42.272	11.875	5.502	40.5	7.84
Camlad	155.255	30.937	4.655	38.3	9.78
Severn Flank 5	196.503	24.989	3.682	36.0	10.62
Vyrnwy Flank 1	126.785	24.946	6.574	44.5	7.83
Vyrnwy Flank 2	99.201	36.561	5.400	36.6	9.63
Severn Flank 6	120.244	18.631	1.961	32.4	13.51

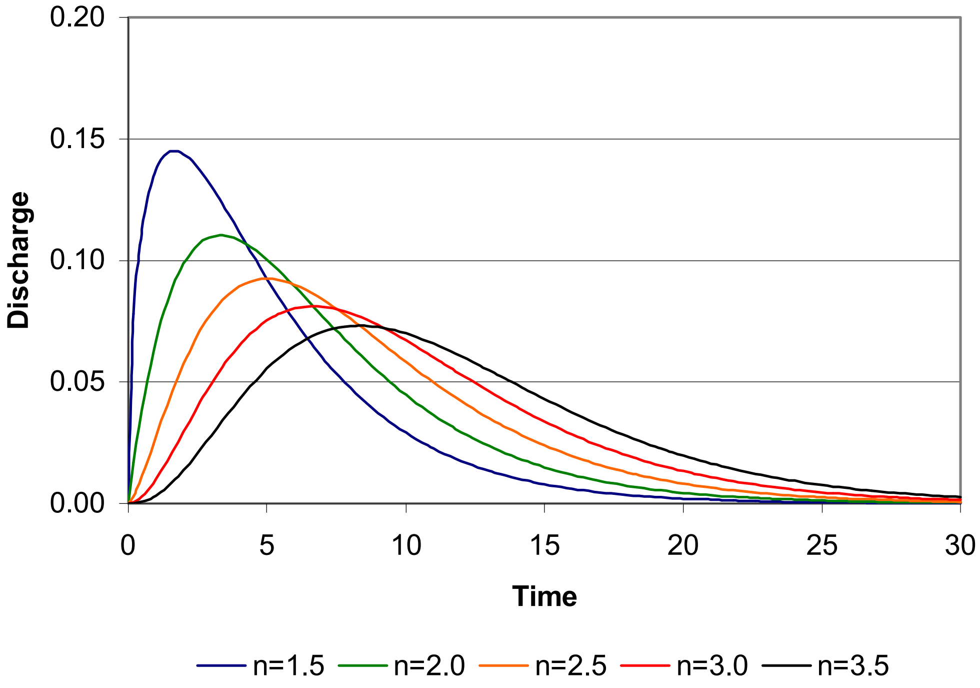

Figure 4.8 *Nash unit hydrographs: variation with parameter n*

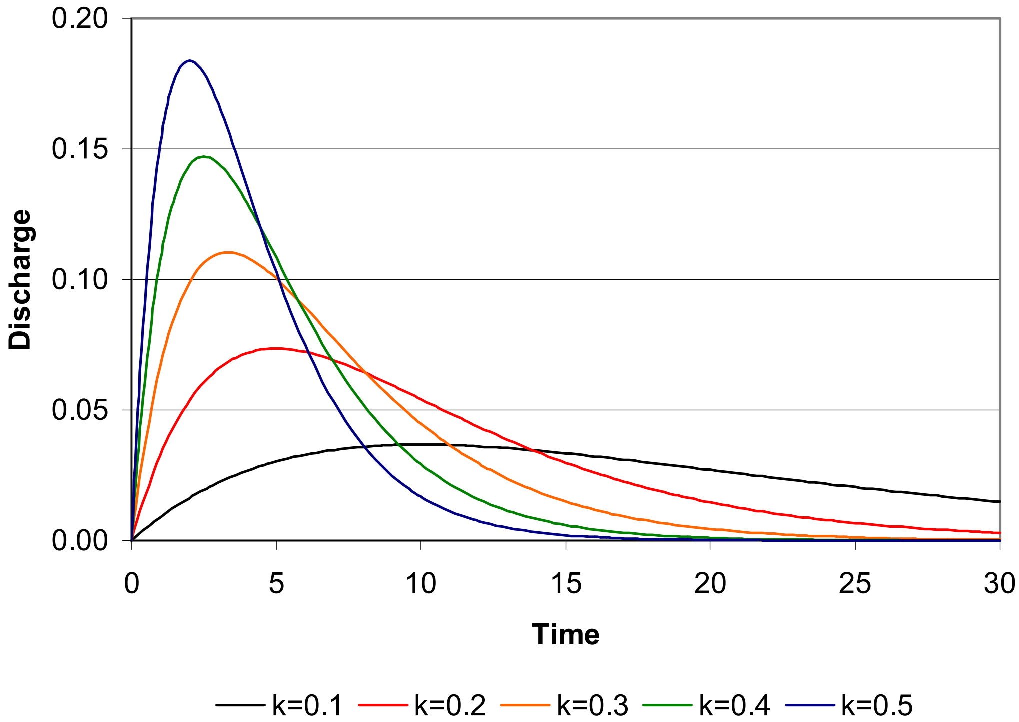

Figure 4.9 *Nash unit hydrographs: variation with parameter k*

4.1.3 The flood wave in the channel

A more rapid response to rainfall on the plot scale, or even in small catchments, does not necessarily lead to increased flood peaks in rivers, as the effect of water flows joining the main river from the various tributaries depends upon location within the larger catchment. A faster response from the headwaters might add to flood peaks generated downstream, increasing the flood flow. Conversely, faster runoff from a downstream area might pass before the major flood peak, so that the peak would be reduced. In large catchments, the direction of movement of an individual rainstorm is important. A storm moving downstream generates flood runoff that adds to the hydrograph already moving down the channel, building up an enhanced flood peak: conversely the runoff produced by a storm moving upstream has time to pass down the channel before the later additions, and the overall hydrograph is more spread out (Knapp, 1986). The complexities of river floods, integrating the inputs from a varied network of tributary streams and subcatchments, are such that it may be difficult or impossible to identify the causes of changes in the river flow regime on the catchment scale (Burt, 1992).

Without seriously increasing the complexity of the land use change model, it is difficult to incorporate a good model of flood movement down the main channels. The most general feature of such "flood routing" models is the incorporation of both translation, movement of the flood wave without change of shape, and attenuation, the change in shape resulting from the relationship of depth with storage of water in the channel. In the land use change model developed for this project, the effects of the main channels have been simulated by a system of delays and storages related to the channel gradients and the known average times of passage of flood peaks. Additional parameters have been introduced to allow the model to be calibrated against the three sample events. It is believed that this system, while not the equal of a physically-based hydraulic model, offers a framework within which the importance of the spatial context of any proposed land use change can be explored.

4.2 The detection of past changes

If land use change does cause a significant change in the flood response of a large catchment, then the effects should be visible in the hydrometric data from the catchment, which provide for the most part an accurate measurement of the timing and quantity of rainfall inputs and discharge hydrographs at discrete points within the catchment. In the Severn headwaters there have been widespread changes in land use as a result of afforestation and agricultural improvement, especially in the decades following World War II, and trends and cycles in the flood response have been clearly demonstrated by various studies. For a number of reasons, attempts to correlate observed changes in the hydrology of the Severn with documented land use changes have proved inconclusive.

The largest well-documented floods in the upper Severn catchment were in the late 1940s and early 1960s, and the public outcry after extensive flooding in 1960, 1964 and 1965 led to substantial investment in flood protection schemes for Caersws, Newtown and Meifod. The lack of severe floods for nearly three decades has encouraged encroachment of development on to floodplain areas, conversion of floodplain pasture in formerly flood-prone areas in the lower catchment to arable cultivation, and perhaps an over-reliance on the flood attenuation effect of the Clywedog Dam. A report commissioned by the Severn-Trent Water Authority in 1982 to examine increased flooding in the Caersws area concluded that by the early 1980s there had been a change in the hydrograph pattern, with a shorter time to peak: the late 1970s and early 1980s had returned to the flooding frequencies of the early to mid-1960s after a relative lull in the period 1968 to 1977 (quoted by Higgs, 1987). As similar trends were observed on the Afon Dulas, the changes were considered to have little to do with a reduction in the upstream flood storage volume caused by flood protection embankments at Caersws, channel improvement works on the Cerist and Trannon. More diffuse catchment factors such as agricultural drainage, improvement of rough pasture and afforestation were advanced as major possible causes of a change in the hydrograph. The report concluded that "the most dominant cause of the quickened hydrograph response at Caersws in recent years is the increase in the rate of surface runoff in the upland part of the catchment caused by tile drainage and improvements in agriculture", but in view of the lack of statistics to support this assertion, the authors added that "it would be difficult if not impossible to evaluate the effects of this land use change on catchment runoff".

A major problem in attributing changes in flood frequency and magnitude to one cause or another lies in the natural fluctuations in rainfall. It was noted by Howe et alia (1967) that the 25-year flood level at the Welsh Bridge in Shrewsbury had risen from 5.1 m (above local datum) in the period 1911-1940 to 5.94 m in the period 1940-1964, Analysis of a longer period showed three intervals of relatively stable flood statistics, high levels in 1840-1880, low levels in 1880-1940 and higher levels from 1940 onwards. Though it was tempting to attribute the more recent high levels to land use factors, for instance the early 1960s corresponded with the expected maximum effect of pre-planting drainage of the Hafren Forest (Howe et al., 1966), there had also been a greater incidence of daily heavy rainfall events. There were similarities between the rainfall statistics and the flood statistics that supported the compromise conclusion reached by Howe et alia (1967)(1967): "the triggering mechanism for the increase in flooding is thought to be the increased incidence of intense storm events, but it is suggested that the concomitant land use changes … have aggravated the problem".

Higgs (1987) quoted a series of studies of long-term rainfall variations within the catchment, mostly concerned with a small selection of gauges chosen for their long records or because they were in some sense typical of upland or lowland altitude ranges. An internal Severn-Trent Water Authority report by Goodhew, based on an analysis of records from five raingauges, three upland and two lowland, showed in 1980 that there had been a scarcity of very heavy winter rainfall events since 1968, and a decrease in moderate winter events. However there had been a slight increase in the frequency of very heavy summer events, and an increase of minor winter floods in the lower Vyrnwy in the late 1970s. The overall conclusion was that the intense events responsible for floods had decreased significantly since 1968, though there was "no reason to suppose that this reduction is anything more than an example of the variability of British weather". Also published in 1980, an investigation of long-term records of three raingauges (Banc Cynon Isaf 1905-80, Fron Llwyd 1910-1980 and Tynant 1910-80) showed evidence of the variability in the frequencies of heavy winter rainfall events, with no strong trend over the whole time period but a steep decreasing trend in the frequency of heavy one-day and two-day events since 1968 (Jones, 1980).

Frequencies of heavy rainfalls were investigated in the range of publications by Lawler (1979; 1980; 1981; 1985). Lawler's analysis showed that the trend noted by Howe et alia (1967) had been reversed from 1975 onwards at the Bryn Vyrnwy raingauge, i.e. there had been a decline in the frequency of heavy daily rainfalls in excess of 63.5 mm. The increased noted by Howe et alia up to 1964 had not been sustained for the period 1964-80, at least in events exceeding 63.5 mm. However the increase in smaller falls (50-57 mm) had carried on into the 1970s. The pattern of decreasing heavy winter rainfall events and an increase in summer convective events was confirmed by further analysis by Higgs (1987), who drew attention to the dominance of anticyclonic conditions in the 1970s, compared with cyclonic dominance in the mid-1960s.

Separating the effects of the natural fluctuation in rainfall pattern from those of land use change has proved to be very difficult. So far modelling of the system, which can eliminate the climatic factor by comparing catchment responses to individual events, has been largely restricted to unit hydrograph studies. The inherent instability in some unit hydrograph techniques, coupled with changes in the instruments and locations of the hydrometric network has meant that the variance of unit hydrograph parameters within a given time interval can be significant when compared to the variance between time intervals, so that it is difficult to distinguish trends. It is difficult to see how the impact of afforestation can be separated from that of agricultural development, in a period when both have changed concurrently. Higgs (1987) found that high flows at Caersws were associated with low 5-year totals of forestry planting and a decline in the area of rough grazing, suggesting that afforestation is of less importance than grassland improvement with its associated underdrainage. However, for large and small catchments alike, the frequency of heavy rainfall, presumed to be independent of land use, is generally found to be the most important variable defining flood frequency.

5 Modelling changes in land use and flood response

The hydrological model that forms the final part of this project is intended to give a means of exploring land use change in upland subcatchments, as a factor affecting flood flows downstream. As such it does not have to be a precise model of flood flows, but it must incorporate the main factors likely to be changed by land use practices. In a large catchment, where the timing of floods is defined by the passage of the flood wave down the river channels, major differences are likely to arise from the supply of water for generating runoff, though of course the hydrological impact of a land use change will always be in approximate proportion to the area of land surface affected. Changes in the timing of runoff on the plot scale or subcatchment scale will also affect peak flows downstream, though for larger catchments this factor will become less significant, as the proportion of time spent by water in the main river channels becomes greater.

A change in the interception of rainfall by vegetation, a major impact of afforestation, is important in defining both the fraction of rainfall reaching the ground. Between flood events, interception of minor rainfall events increases the magnitude of the soil moisture deficit, which in turn affects the infiltration rate. The soil moisture deficit itself is also increased by effective drainage of the soil, and for the purposes of this study both interception and drainage factors have been assumed to affect the infiltration rate via the soil moisture regime. Similarly mulching of the soil surface by leaves and the activity of soil animals, a probable consequence of pasture reversion, would be expected to counteract the effects of grazing and trampling, and to decrease the proportion of rapid runoff. Clearly soil moisture is a seasonally varying factor, and land use may have little effect on the runoff from winter storms, when the soil moisture deficit even in well-drained land is made up by the high rainfall of the uplands, but dry soil could have a major impact on the infrequent but severe summer storms, and on the earliest storm events of each winter.

Later in the winter the impact of the soil moisture deficit is reduced. The majority of rainstorms giving rise to floods in the upper Severn occur between November and March, and more than 20% of the flood events at Caersws, Llanymynech and Montford take place in December (Higgs, 1987). Furthermore the most severe events, for instance those of 1946, 1948, 1960, 1964 and 1965, were floods generated on saturated catchments, with low soil moisture deficits, maximum surface detention and storage of water, a low infiltration capacity and rivers running at or near bankfull at the onset of the rainfall event (Howe et al., 1967).

The land use change model itself is inherently simple, but its complexity has been increased by the need to divide the catchment up into subunits for comparison with flow records from the gauging stations, and for the exploration of possible land use changes on the subcatchment or altitude band scale. Parameters have been kept to the bare minimum, by assuming that the major soil types abstracted from the soil map can be used to estimate soil hydrological characteristics, especially the percentage runoff, and that the passage of the flood wave down the major stream channels is simply related to the channel length and location within the Severn catchment. The model would benefit from a period of testing and refinement, but its performance on simple land use change scenarios has been encouraging.

Flow and rainfall records were obtained for three years, 1999-2001, so that a representative sample of flood events could be used to calibrate and test the hydrological model (see Section 4.1.1). The model successfully simulates two major features of the catchment response, the relative magnitudes of flood peaks at the various gauging stations (a function of catchment area, percentage runoff and rainfall distribution) and the relative times of peak discharge (defined by channel characteristics and incorporated into model using simple delays and storage elements). The difference between the peaked response of the Vyrnwy at Llanymynech and the more rounded hydrograph of the Severn at Montford is reproduced well by the model, as is the tendency of the Montford hydrograph to consist of two overlapping peaks produced by flows from the Severn and Vyrnwy. The peak discharge at Llanymynech, in the real world and the model, is often greater than that at Montford, despite the much larger catchment size.

5.1 Structure of the model

The objective of modelling in this project is not to develop yet another flood prediction model for the Severn, but to provide a model that can demonstrate the impacts of general or local land use change within the catchment on flood flows at Montford. Model parameters are given a spatial context, through the division of the upper Severn catchment into subcatchments and altitude bands, and the model is capable of making predictions of changes in flood discharges as a consequence of specific land use changes (e.g. a percentage of a given altitude band within the Garno subcatchment turned over to deciduous forest or reverted to moorland). The aim is to furnish preliminary answers to three questions:

i) do likely land use changes within the catchment have a significant effect on flood peak discharges, after spatial effects and channel characteristics have been taken into account?

ii) which of the possible land use changes has the greatest hydrological effect?

iii) how extensive does land use change have to be for land management to become a practical means of controlling flood flows?

The model is semi-distributed, i.e. its principal elements the subcatchments have a spatial context defined by the geometry of their real-life counterparts, but it lacks the spatial resolution and the physical basis of fully distributed models. The benefits of adopting this level of simplicity are apparent in savings of time in development and programming, and in the time taken for each run of the model.

5.1.1 The subcatchments

Each of the 19 subcatchments is treated as a cascade of two equal linear reservoirs, to represent the temporary storage of runoff water (see Section 4.1.2). At any moment, the instantaneous outflow from each reservoir is proportional to the volume of water contained within it (Figure 5.1). The two reservoirs in series produce an output that is smoothed and delayed: the output in response to a pulse input of 10 mm over an interval of one hour is similar in form to observed unit hydrographs from real catchments (Nash, 1957). The choice of two reservoirs rather than any other number, or even a conceptual non-integral number of reservoirs as in Nash's paper, is somewhat arbitrary, and standard fitting techniques could be employed to improve on this and other details of the model. However, for the smaller catchments such as the Dulas, the time interval between successive flow measurements is rather short for precise determination of the parameters of the unit hydrograph.

The relationship between flow and storage for each reservoir

$$Q = kS$$

where S is the volume of water stored

and Q is the discharge from the reservoir

includes a parameter k with units of (1/time). For the purposes of the model, the parameter k is set equal to

$$\frac{b}{T_p}$$

where T_p is the time-to-peak of the one-hour unit hydrograph computed from catchment characteristics by the FSR method, and b is a dimensionless coefficient that is assumed constant for all the subcatchments. This formula for k takes into account the variation of the unit hydrograph time-to-peak with subcatchment characteristics such as main stream length and gradient. Values of T_p range from 2.49 hours for the very small Severn Flank 1 subcatchment to 13.51 hours for the large, flat Severn Flank 6 subcatchment. Eleven subcatchments have values of T_p between 6 and 10 hours (see Table 4.4).

A proportion of the rainfall reaching the ground runs off directly and rapidly, resulting in the generation of flood flows. This proportion is usually expressed as a percentage, and is determined by three main factors:

i) the antecedent conditions, in the form of the soil moisture deficit or the accumulated rainfall over several days prior to the storm

ii) the intensity of rainfall. Heavy rainfall can exceed the capacity of the soil to absorb it.

iii) the soil type.

Some estimation procedures for flood flows, such as those set out in the Flood Studies Report, calculate the percentage runoff as a Standard Percentage Runoff (SPR), defined by soil type, modified by additional terms taking account of the total storm rainfall and the soil moisture deficit. For example the FSR formula for the percentage runoff is

$$\text{SPR} + 0.22\ (\text{API5} - \text{SMD}) + 0.1\ (\text{P} - 10)$$

where API5 is the Antecedent Precipitation Index computed as the weighted average of precipitation over the five days preceding the storm

SMD is the soil moisture deficit and P is the total precipitation for the storm.

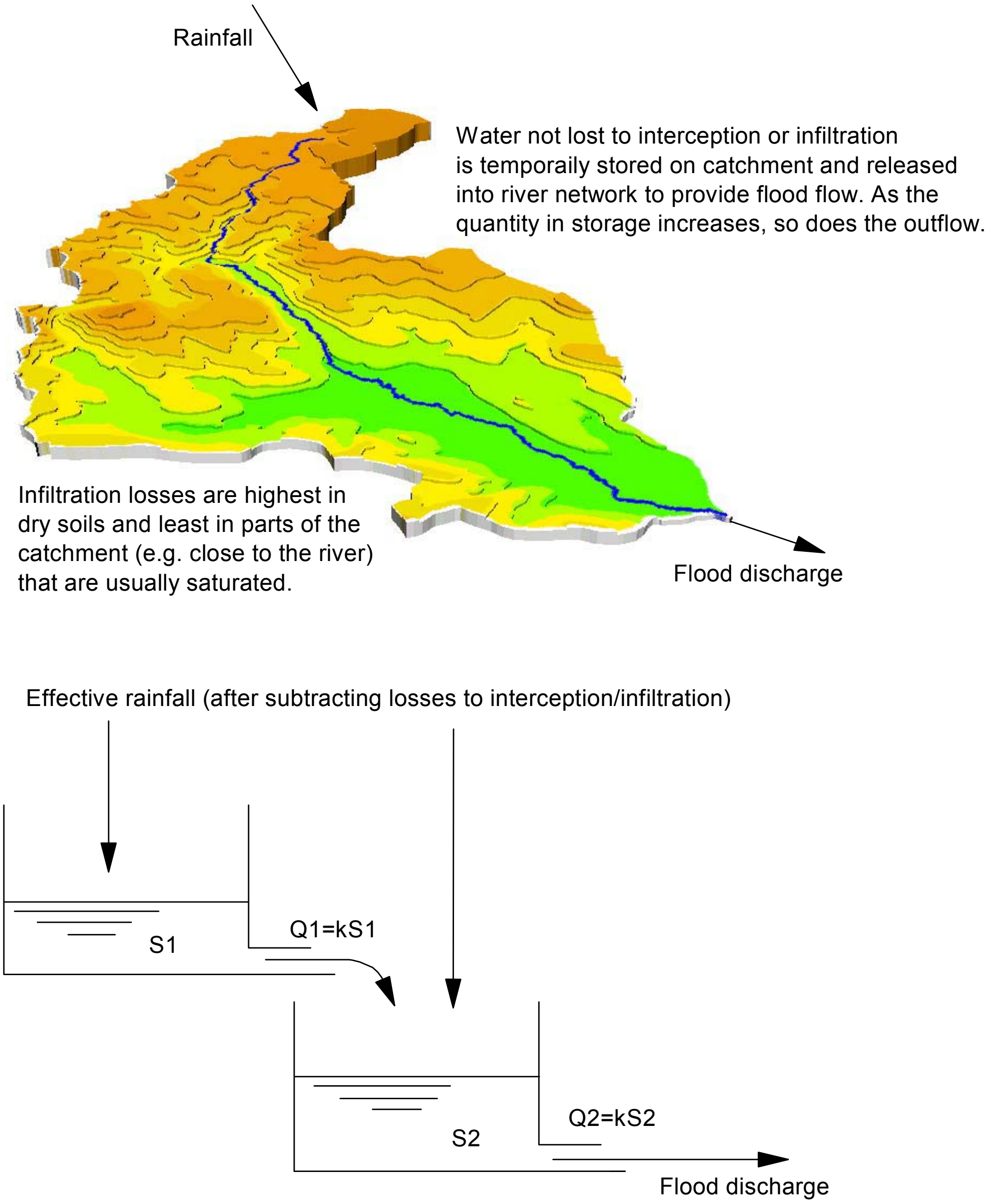

Figure 5.1 *A simple catchment model reproduces the most significant processes going on in the real catchment. All catchment models incorporate storage of water on the surface or in the soil, and all model formulations include some form of relationship between storage and flow.*

In the FSR itself the SPR was calculated according to the Winter Rainfall Acceptance Potential (WRAP), a five-point scale ranging from 1 for deep and permeable soils to 5 for shallow, less permeable slopes, especially those on steeper slopes. Essentially, each WRAP class was assigned its own Standard Percentage Runoff (SPR), and the catchment average SPR could be computed from the maps that accompanied the FSR. A later, more detailed study replaced the WRAP system with a method for calculating the catchment SPR from a map of soil types (Boorman et al., 1995). The data on the 1:250000 series of soils maps was assembled into a database, the HOST (Hydrology Of Soil Types) classification: by analysis of the hydrological responses of some 200 catchments, every mapped soil series was assigned a value of SPR.

The approach adopted here, which combines the antecedent conditions and the SPR in a slightly different way, is to calculate an exponentially decreasing loss rate to account for infiltration into relatively dry soils

$$Loss = f_0 \exp(-c\ t) \quad \text{when rainfall rate} > 0$$

where the coefficient c is regarded as constant across the upper Severn catchment.

In winter conditions in upland Wales the soil moisture deficit is effectively zero, and it can be assumed that f_0 and the subsequent loss rates are zero. The formula above applies mainly to summer storms when there may be an appreciable soil moisture deficit to satisfy before a constant low rate of infiltration is achieved. The loss rate is subtracted from the hourly rainfall to give net rainfall P_{net} (P_{net} being taken as zero if $Loss > Rainfall$), then the rapid runoff is calculated from

$$\sum_i A_i\ SPR_i \times P_{net}$$

where A_i is the area of a contour band of the subcatchment

and SPR_i is the weighted average Standard Percentage Runoff calculated for that contour band, the weighting being based on the area of each major soil type present.

For each subcatchment this “effective rainfall” is distributed equally between the two linear reservoirs. The output from the second reservoir is the flood flow from the subcatchment.

5.1.2 The river network

Each of the headwater subcatchments discharges into the main river network, i.e. into the Severn or the Vyrnwy, at its downstream point. It is assumed that the discharge point for each of the eight “flank” subcatchments is at the downstream end of the subcatchment, whereas in fact it is clear that discharge into the main stem of the river occurs along its entire length, and at discrete points of discharge from smaller rivers such as the Bechan and Morda. The response of the whole catchment is made up of the accumulated subcatchment responses, but the flood wave is modified by its passage down the main channels, and some sinuous reaches take a considerable time to traverse.

Both delays and storage elements are incorporated into the model, in an attempt to simulate not only the delay in the passage of the flood wave but also some longitudinal diffusion (attenuation) due to the storage of water in the river channel. For each of three reaches of the River Severn, two reaches of the Vyrnwy and the lower reach of the Tanat, storage in the channel alone was insufficient to produce the observed behaviour, and a combination of delay and storage has been assigned that will match the times of passage of observed flood peaks, the same parameters being used for all three flood events used in the development of the model.

Predicted flows in the model for points closest to the gauging stations have been adjusted for catchment area to produce predictions that can be compared directly with observed flows at the six gauging stations.

The complete structure of the model is shown diagrammatically in Figure 5.2. Each of the rectangular boxes with a double outline represents a submodel for an individual subcatchment, incorporating code for the calculation of infiltration loss, net rainfall, effective rainfall and discharge (see Section 5.1.1).

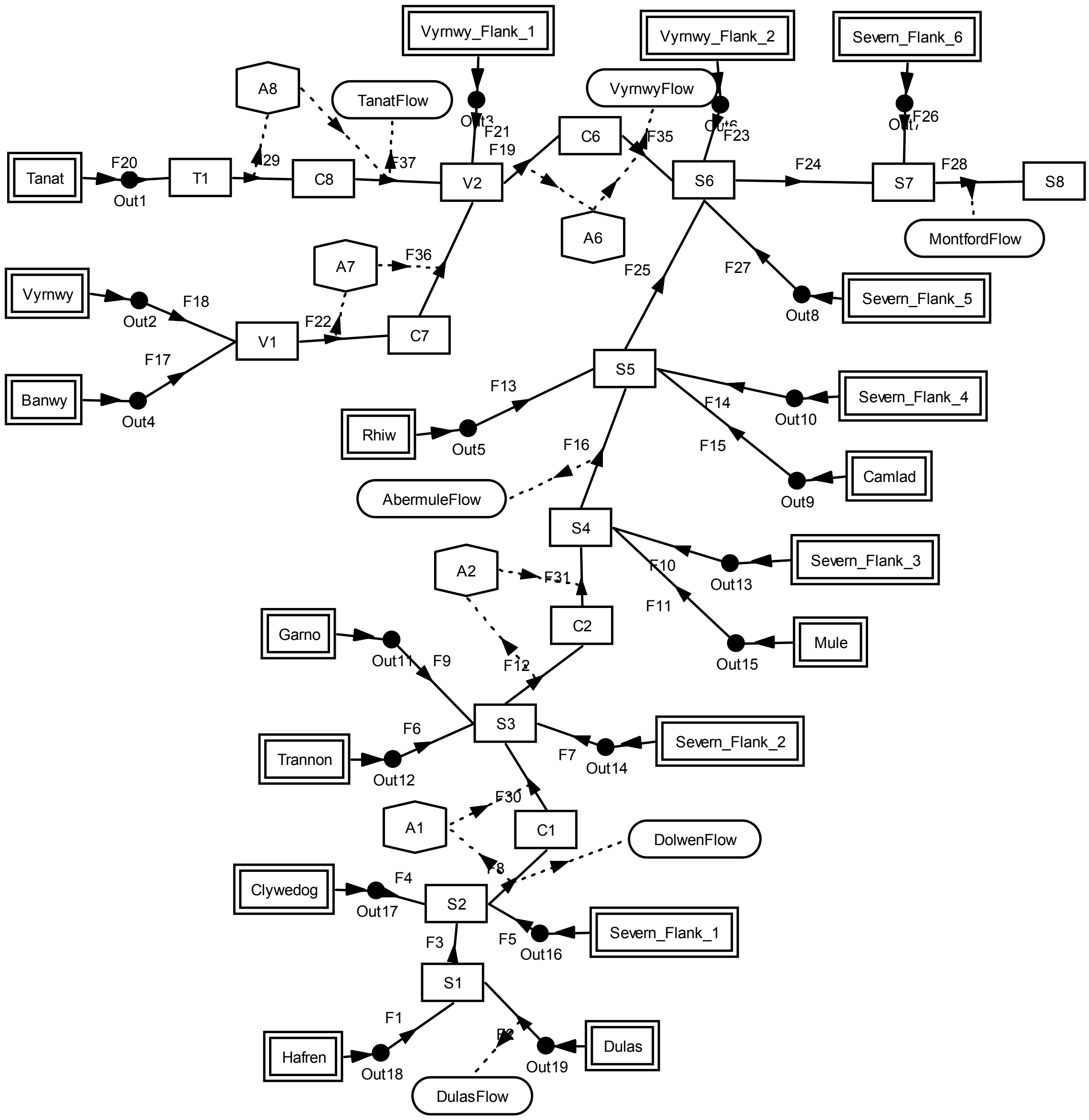

Figure 5.2 *Schematic of compartmental model of Severn Valley, used to predict effects of land use change within subcatchments on peak discharges in Severn and tributaries*

5.2 Operational use

The model has been developed using a proprietary modelling package, ModelMaker (Version 4)[10], which allows the specification of compartments and flows, and the assembly of complex, dynamically-linked systems. ModelMaker can be used to explore the sensitivity of predictions to parameter values, and to optimize parameters to give the best fit to observations. It is well suited to the type of model described above, though the adjustment of large numbers of parameters, for example to simulate a land use change distributed over an extensive part of the catchment, can be tedious.

The three sample flood event hydrographs have been reduced to rapid runoff hydrographs by the application of the simple baseflow separation technique outlined in Section 4.1.2. Baseflow separation for the Montford station was made rather more difficult by the tendency of hydrographs for the large catchment to merge together, so that the recession of the previous event is not necessarily composed entirely of baseflow from groundwater and subsurface flow, but contains some delayed runoff and bank drainage from the previous event. The rapid runoff hydrographs for Montford are approximated by subtracting a constant baseflow figure obtained at the start of the rising limb of the hydrograph.

Each rapid runoff hydrograph starts from zero, and the recession limb declines to zero, though for the purposes of this study it was not necessary to work with the full-length hydrograph, especially those such as Llanymynech and Montford, which represent large catchments with long response times. The model was run with four- or five-day data sequences, each starting on the day of the rainfall input and lasting until after the passage of the hydrograph peak at Montford.

5.2.1 Setting the model parameters

Each of the subcatchment submodels has two parameters for each 50 m contour band (e.g. a total of 22 for the Tanat subcatchment which has eleven contour bands from 50-100 mOD to >550 mOD) and one parameter defined by the FSR time to peak (see Section 5.1.1). The parameters for each contour band are total area in km^2 (denoted for instance by A350 for the area of the 350-400 mOD contour band) and average Standard Percentage Runoff, expressed for convenience as a decimal fraction (denoted for instance by SPR350 for the SPR associated with the 350-400 mOD contour band). The average SPR for each contour band is calculated according to the formula in Section 5.1.1, using a division of the subcatchments into major soil types, and further subdivision into contour bands. The data used in the derivation of the full contour band area and SPR parameter set is presented in the Appendix to this report. The area of each contour band, although characterized as a parameter in the model, is of course invariant, but the SPR parameter for each contour band can be altered to reflect a change in the land use of a given contour band in a given subcatchment.

The time to peak parameter, which defines the timing of the response of each linear reservoir to a given input of effective rainfall, is initially set equal to the FSR predicted time to peak, but it can be varied for each subcatchment to demonstrate the impact of changes in the timing

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[10] Developed by Cherwell Scientific Ltd, marketed by ModelKinetix. Web-site:- www.modelkinetix.com

of the subcatchment unit hydrograph, for instance as the result of an extensive afforestation programme. Splitting the time to peak parameter into contour bands was considered to introduce rather too much complication into the model at this stage, when the precise implications of land use changes on unit hydrograph timing are quite poorly understood, and when the model does not incorporate spatial separation within the subcatchments. The model as it stands could not simulate the impact of spatially distributed forest planting such as that within the Llanbrynmair experimental catchment (Robinson, 1990).

The parameters of the loss equation, f_0 and c (see Section 5.1.1) are regarded as universal throughout the model, and are not defined separately for each subcatchment. Similarly the parameter b, which relates the reservoir characteristic k to the FSR time to peak T_p, is defined universally.

Finally, the model includes a group of eleven parameters that define the speed of passage of the floodwave, and its attenuation, as it moves downstream in the Tanay, Vyrnwy and Severn channels. Storage/discharge relationships for six reaches of the Severn, two of the Vyrnwy and one of the Tanat are defined by formulae of the type

$$Discharge = k_2 \frac{ks_i}{T_i} Storage_i \text{ for } i = 1 \ldots 6$$

Five delays, ranging from 1.66 to 3.13 hours, complete the parameter set.

5.2.2 Initial runs – present land use

The model was run for the initial set of parameter values, and predicted hydrographs were compared with the rapid runoff derived from the observed values, for each of the six gauging stations. For the first and second of the three sample events, there were no observed data for the Dolwen gauging station, which was commissioned in June 2000. Minor changes were made to the universal parameters f_0 c b and the flood routing parameters k_2 etc. to improve the fit. Automatic optimization of parameters proved effective in establishing an acceptable value for c, b and k_2. It was found that the initial loss rate parameter f_0 could be set to zero for the first winter event (15 January 1999), but values of 5 mm/hr and 1.5 mm/hr respectively and a c value of 0.1 mm/hr^2 were required for the 18 September 1999 event, which started with relatively dry soils, and the 10 February 2001 event, which followed a few days with only light rain showers. Further changes to these parameters should not be necessary, as land use change scenarios can be explored using only the *SPR* and T_p parameters. Figures 5.3 to 5.5 show the results of the simulation of present conditions.

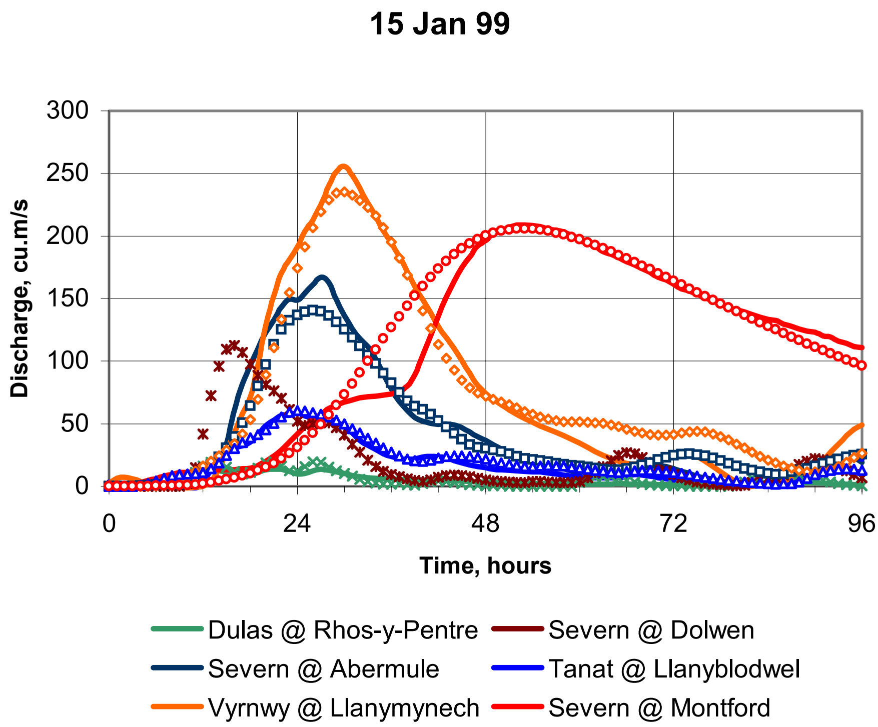

Figure 5.3 *Predicted rapid runoff hydrographs of 15 January 1999 flood event, compared with rapid runoff derived from observed discharges at gauging stations.*

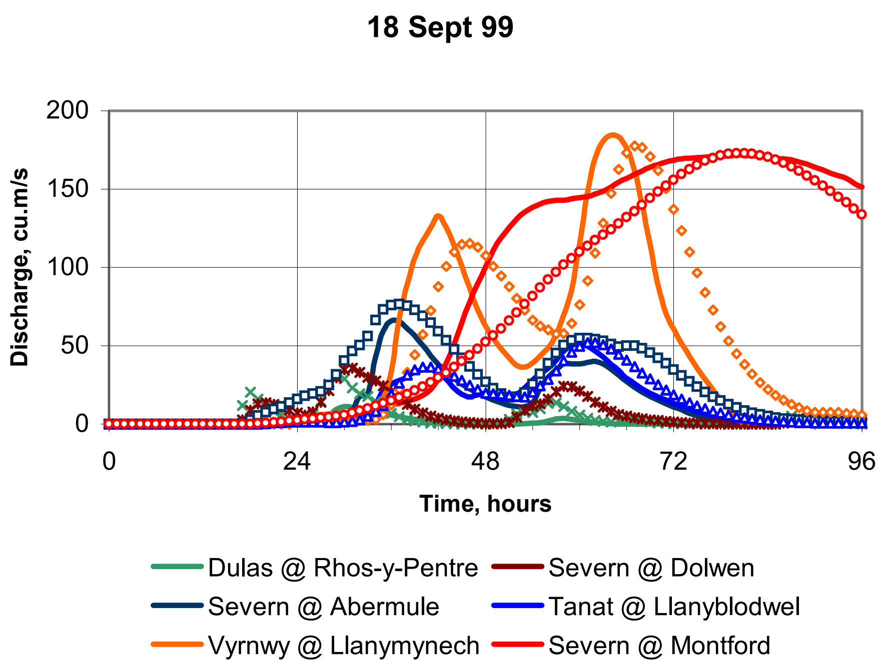

Figure 5.4 *Predicted rapid runoff hydrographs of 18 September 1999 flood event, compared with rapid runoff derived from observed discharges at gauging stations.*

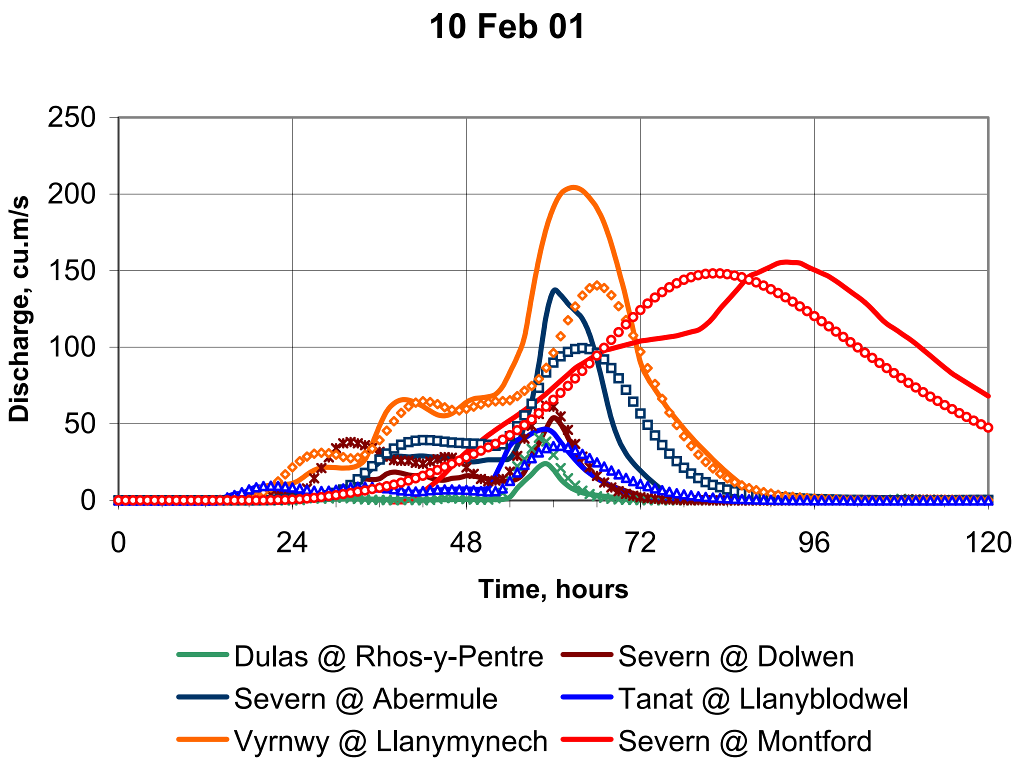

Figure 5.5 *Predicted rapid runoff hydrographs of 10 February 2001 flood event, compared with rapid runoff derived from observed discharges at gauging stations.*

The simulations of peak discharges for the 1999 events are reasonable, and can be used with confidence as a basis for comparative studies of land use change, but the predictions for the Tanat and Vyrnwy for the February 2001 event are about 30% low. The discrepancy is probably due to an underestimate of the rainfall in the high-altitude northwest of these subcatchments. The raingauge network in the headwaters of the Vyrnwy and Tanat consists only of monthly-read gauges which were not visited in February 2001 because of foot and moth disease.

It should be noted that the model simulates the rapid runoff hydrograph: for a direct comparison with observed flows it is necessary to add the baseflow component.

5.2.3 Changing land use in specific areas of the catchment

By changing the *SPR* and T_p parameters, it is possible to simulate the flood hydrograph for a wide range of catchment land use changes. However, the scientific basis for adopting particular parameter values is not well established, as has been seen in earlier chapters of this report. It is proposed to use the model to examine percentage changes in the peak discharges at appropriate points in the river network, in response to changes in the *SPR* and T_p parameters that can be shown to have some scientific justification, recognizing the difficulty of estimating the precise effect of any given land use change on these parameters.

It has been shown above (see end of Chapter 2) that the net effect of upland drainage is probably to speed up the passage of runoff waters to the catchment outlet, and the role of drainage in creating increased storage of water in the soil may have been over-rated for peat soils at all but the smallest plot scale. Heavy grazing leads to bare soil, trampling and the loss of the mulch layer. Conversely it might be expected that reversion of improved grassland to rough grazing, especially when grazing densities are low and the opportunity exists for the buildup of a mulch or litter layer, would delay the passage of runoff and create opportunities for storage in the litter layer, while also increasing infiltration rates by removing the compacted surface layer resulting from trampling and poaching. There is little quantitative data on which to base changes in model parameters, and we can only proceed on the basis of assumptions, which are of course open to question.

For the reversion of upland improved grassland to rough grazing, it has been assumed that there is a change in the Standard Percentage Runoff equivalent to one Winter Rain Acceptance Potential grade, i.e. an SPR of about 90% of its present value.

Another major land use possibility is an increase in the cover of deciduous forest, particularly in the mid-altitude range, where steep slopes are not ideally suited to cultivation. Deciduous trees intercept a slightly smaller proportion of rainfall than conifers, but soil moisture deficits are certain to be greater under trees than pasture, and the steady buildup of the litter layer over a period of decades, and the encouragement offered to soil decomposers, will lead to increased infiltration.

For conversion to deciduous forest, it has been assumed that the combination of increased infiltration rates and increased losses due to interception will be equivalent to two Winter Rain Acceptance Potential grades, i.e. an SPR of about 80% of its present value.

Several authors have suggested that changes in hydrograph timing will result from land use changes on the subcatchment scale, and the results of plot scale studies have often been expressed in terms of changed time to peak of the unit hydrograph. The unit hydrograph of even a small subcatchment is a compound of effects of the slope processes associated with the generation and transport of water down catchment slopes to the stream, and channel processes carrying runoff to the catchment outlet. Land use changes do not generally bring about changes in the channel, except where gradients are very low and channel improvement is a necessary part of the development. The change in the time of passage of water from the point of rainfall impact to the catchment outlet is therefore limited to a proportion of the time taken for water to traverse the hillslope to the stream. In small catchments with a very short streamlength this may be a large proportion of the catchment time to peak, but as the catchment size increases the significance of channel processes increases.

To test the relative significance of percentage runoff and changes in the timing of the unit hydrograph, it is assumed that a typical land use change may decrease or increase the average time of passage of water to the stream by a constant amount, say one hour.

Because of the structure of the model, changes in time to peak can only be implemented on a subcatchment scale.

Six model runs were carried out to test the significance of land use changes to the peak discharge, for the selected medium-sized flood events. The land use changes tested were

i) the reversion of high land to rough grazing and moorland, which has been assumed to increase infiltration rates by 10%, by reducing the compaction due to grazing, and by encouraging the formation of a mulch layer. The result of this change over land above 350 mOD in the subcatchments of the Banwy, Tanat and Vyrnwy (a total of 230.42 km^2) was to decrease peak flows in the Vyrnwy by an average of 4 %, and in the Severn at Montford by 2 %.

ii) when the same change was applied to land above 350 mOD (a total area of 106.00 km^2) in subcatchments centred on Caersws (the Trannon, Garno, Rhiw, Mule and parts of the main Severn) the impact was a decrease of 2 % in peak flows of the Severn at Abermule, and a decrease of only 0.5 % in peak flows at Montford.

iii) conversion of large areas of grazing to deciduous woodland in a specific altitude band. The altitude band presently occupied by the main area of deciduous woodland, and therefore considered appropriate for conversion, is 250 to 350 mOD. In the Banwy, Vyrnwy and Tanat subcatchments there are 157.71 km^2 of land in this range, not already forested. Conversion to woodland, assumed in this case to increase infiltration by 20 %, brought about an 8 % decrease in peak discharge of the Vyrnwy, and a 4 % fall in peak flow rates at Montford.

iv) the same land use change applied to the subcatchments centred on Caersws (with a total of 131.32 km^2 of land in the altitude band) caused an average decrease of 5 % in the peak flows of the Severn at Abermule, and a decrease of 2 % in the peak flows of the Severn at Montford.

v) an unspecified land use change causing a one hour decrease in the time to peak of subcatchments near the upper end of the Severn catchment, i.e. the Dulas, Hafren, Clywedog and Trannon headwater catchments and the associated flanking catchments of the Severn (a total catchment area of 292.85 km^2).

vi) An unspecified land use change causing a one hour decrease in the time to peak of subcatchments near the lower end of the Severn catchment, the Tanat, Banwy and Vyrnwy subcatchments (a total catchment area of 774.83 km^2).

The results of the simulation showed that the model was robust enough to produce similar estimates of the percentage change in peak discharges for the three sample events, and to predict changes in keeping with the location of the land use change within the catchment. Table 5.1 shows the results for selected gauging stations for the six land use change scenarios.

Table 5.1 *Results of model runs for six land use change scenarios, for the three sample events, expressed as percentage changes in peak discharge*

Scenario	Gauging station	Event			Mean
		15 Jan 99	18 Sep 99	10 Feb 01	
(i)	Llanyblodwel	-4.77	-4.77	-4.77	-4.77
	Llanymynech	-4.23	-4.28	-4.11	-4.21
	Montford	-2.33	-2.17	-2.11	-2.20
(ii)	Abermule	-1.45	-1.86	-1.93	-1.75
	Montford	-0.51	-0.53	-0.55	-0.53
(iii)	Llanyblodwel	-10.09	-10.09	-10.09	-10.09
	Llanymynech	-7.89	-7.89	-7.87	-7.88
	Montford	-4.43	-4.10	-4.07	-4.20
(iv)	Dolydd	-0.11	-0.61	-0.51	-0.41
	Abermule	-4.21	-6.13	-5.80	-5.38
	Montford	-1.68	-1.90	-1.84	-1.81
(v)	Dulas	+6.32	+10.94	+8.11	+8.46
	Dolydd	+5.70	+5.18	+5.31	+5.40
	Abermule	+0.93	+1.76	+2.76	+1.82
	Montford	+0.16	+0.04	+0.04	+0.13
(vi)	Llanyblodwel	+2.97	+3.38	+3.87	+3.41
	Llanymynech	+2.06	+3.21	+2.04	+2.44
	Montford	+0.11	+0.49	+0.15	+0.25

For land use changes involving a reduction in the SPR, the results show that the percentage change in peak discharge is less for changes taking place in the upstream part of the Severn catchment. It has been noted that the hydrograph of the Severn at Montford for the three sample events consists of a plateau, presumably associated with the arrival of Severn water, followed by a peak that corresponds with the arrival of Vyrnwy water. This may explain why the hydrology of the catchments feeding the Vyrnwy have more effect on the maximum flow at Montford than do the catchments flowing into the Severn. Investigations based on a larger number of events would be useful to clarify this important point. In scenarios (iii) and (iv) the area of land affected is very similar, but the impact on the peak flow at Montford is almost doubled for deciduous afforestation in the Vyrnwy group of subcatchments.

Scenarios (v) and (vi) demonstrate that the impact of a change in the timing of the subcatchment hydrograph dissipates rapidly with distance downstream. In this case the percentage change in the peak discharge at Montford is approximately proportional to the area affected by the land use change, and there is certainly no amplification of the impact by closeness to the catchment outflow. It is certainly worth noting the small percentage change in Montford peak flow for what is quite a large change in the hydrology of a substantial proportion of the catchment. In planning for flood control, it appears that there is more to be gained by decreasing the SPR, i.e. diverting more rainfall into slower pathways, especially subsurface flows, and reducing water yield by encouraging interception losses, than there is by merely slowing down the passage of water through surface or near-surface pathways.

6 Conclusions and recommendations

Intuitively, it seems that flood waters originating over a wide area of a large catchment should be susceptible to the influence of land use within the catchment, through the effects of changes in soil properties, antecedent conditions and vegetation. The various land uses also have their requirements for drainage and other infrastructure such as roads and tracks, all of which can affect the quantity and timing of the arrival of flood waters at the main river channels. Many river channels have been modified to perform better as recipients of flood waters, though unfortunately the modification has often been limited to improvement in the capacity of the channel to move water downstream, where it may once again become a problem.

Various investigations have been undertaken to confirm or disprove hypotheses relating to widespread activities like land drainage and afforestation, often in the wake of damaging floods that cannot be totally attributed to climatic factors. For practical reasons, manipulation experiments, where the results of a well-documented land use change are monitored and compared against an unchanged control area, have been few and generally of very small scale. Scale is perhaps the most significant factor limiting the application of results from experiments and field observations of land use effects: it could be argued that the extension of results from the plot scale to the catchment scale has never been satisfactorily achieved, because of the expense of instrumenting a sufficient number of plots on the one hand, and on the other hand the impossibility of identifying inputs to the river with runoff generated on a specific part of the catchment area.

One issue has been resolved beyond doubt by catchment research: the contribution of urbanisation, with its impermeable surfaces and increased density of effective drainage channels. Impacts of flood generation from urban areas are now being addressed by the redesign of drainage systems with more use of storage and infiltration. Other questions, such as agricultural drainage, the effects of soil management and grazing, remain essentially unresolved despite decades of experimentation. Disappointingly, for the purposes of this project, numerical data on the impacts of various land management options at the catchment scale are very scarce.

Two of the most extensive investigations of catchment data in the UK, the Flood Studies Report and the Flood Estimation Handbook, have not obtained unambiguous confirmation of land use effects other than urbanisation (Kirby et al., 1991, p59), and it is not surprising that investigations limited to one catchment such as the upper Severn have been unable to isolate the effects of land use from those of climate. What may be a trend towards more extreme weather will not help to resolve this question, though it may provide more flood hydrographs to analyse.

It is expected that land use effects might be more noticeable for smaller floods, especially those occurring during the summer, a time of maximum variability of one of the factors that does have an indisputable land use dimension, the development of the soil moisture deficit. Afforestation, which increases soil moisture deficits through interception of rain and snow by the canopy, should give clear indications, were it not for the fact that conifer planting in the uplands is invariably accompanied by intensive ditch and furrow drainage. Investigations of forest hydrology have indicated that a reduction of the total runoff because of interception is compensated by a decreased time delay between rainfall and flow in the stream network. In the early stages after initial planting, it is likely that the increased drainage density has a serious effect on downstream peak flows, but within a large catchment the proportion of newly-planted forest is always relatively small. An extension of deciduous woodland, on slopes where prior drainage is not necessary, and the development of taller vegetation as a result of decreased grazing, for instance the spread of bracken and gorse, is expected to decrease runoff, but there is little or no experimental evidence to support theoretical studies. For the larger events, in particular the extreme floods resulting from the impact of heavy rainfall on saturated ground, it is doubtful that land use *per se* would be a significant control on the generation of runoff, though the way in which drainage channels and floodplains are used to handle the resulting flood waters can turn a hazard into an inconvenience.

This study has attempted to explore the ways in which land use in the upper Severn catchment may affect flood response for small to medium-size events, in particular to create a model structure in which the spatial dimension of this large catchment is taken into account, and comparisons can be made between changes or manipulations in the various subcatchments of which the upper Severn basin is composed. Land use maps have been used to predict those areas where changes such as reduced grazing, reversion to moorland or scrub, or planting of forest on presently grazed hillslopes, might realistically be expected to occur.

It is recognised that the western headwater subcatchments attract the bulk of the rainfall, and contribute most to the buildup of the flood peak at Montford, but it is also clear from an examination of any set of event hydrographs from the gauging stations in the catchment that the storages and delays in the river channels have a modifying effect, and that the location of the putative land use change within the upper Severn catchment may be important.

Simulations of various possible land use changes within the upper Severn catchment have been carried out to investigate the significance of the resulting changes in peak discharge, for a selection of medium-sized flood events. The results are expressed as percentage change in peak discharge: as the events examined approximated to the mean annual flood, a 5% decrease in the peak is roughly equivalent to reducing the flood from 1 in 1 year to 1 in 0.75 year, while a 10% decrease in peak discharge is roughly equivalent to reducing the flood from 1 in 1 year to 1 in 0.45 year. The land use changes tested have been

i) the reversion of high land, presently grazed as improved pasture (on the moorland fringe) or as rough grazing with a high enough stocking density to suppress heather and other dwarf shrubs, to lightly grazed rough pasture and moorland. This has been assumed to increase infiltration rates by 10%, by reducing the compaction due to grazing, and by encouraging the formation of a mulch layer. The result of this change over land above 350 mOD in the subcatchments of the Banwy, Tanat and Vyrnwy (a total of 230.42 km2) was to decrease peak flows in the Vyrnwy by an average of 4 %, and in the Severn at Montford by 2 %. When the same change was applied to land above 350 mOD (a total area of 106.00 km2) in subcatchments centred on Caersws (the Trannon, Garno, Rhiw, Mule and parts of the main Severn) the impact was a decrease of 2 % in peak flows of the Severn at Abermule, and a decrease of only 0.5 % in peak flows at Montford.

ii) conversion of large areas of grazing to deciduous woodland in a specific altitude band. The altitude band presently occupied by the main area of deciduous woodland, and therefore considered appropriate for conversion, is 250 to 350 mOD. In the Banwy, Vyrnwy and Tanat subcatchments there are 157.71 km2 of land in this range, not already forested. Conversion to woodland, assumed in this case to increase infiltration by 20 %, brought about an 8 % decrease in peak discharge of the Vyrnwy, and a 4 % fall in peak flow rates at Montford. The same land use change applied to the subcatchments centred on Caersws (with a total of 131.32 km2 of land in the altitude band) caused an average decrease of 5 % in the peak flows of the Severn at Abermule, and a decrease of 2 % in the peak flows of the Severn at Montford.

iii) Because many land use change studies at the plot scale have identified modification of the time to peak of the runoff hydrograph, two simulations have been run in which time to peak was altered for a group of subcatchments making up a significant fraction of the Severn catchment. For a one-hour reduction in time to peak at the upstream end of the catchment, affecting a total area of 292.85 km2, the peak discharges at Montford were increased by only 0.13%, and a similar change in a much larger area of 774.83 km2 around the Vyrnwy produced only a 0.25% increase in the peak flow at Montford.

It is recognised that land use change has impacts on other hydrological parameters in addition to infiltration rates, and that the dependence of infiltration rate on soil moisture deficit will enhance the significance of changes leading to drier soils. A process leading to taller vegetation will increase interception losses and, provided it is not accompanied by ditch drainage, as in the case of conifer forest, will lead to reduced flood runoff. Such a succession to drier soils will naturally have more impact in the summer, as the soil moisture deficit in high rainfall areas falls effectively to zero each winter regardless of the vegetation cover. The model used in this project to simulate land use impacts on flood hydrology probably takes too little account of soil moisture deficit effects, and so underestimates the reduction in summer flood flows due for example to the planting of deciduous forest.

The overall conclusions to be drawn from the study are:

- Land use impacts are the result of complex interactions

Vegetation, soil properties, the structure of channel networks and the time of passage of flood waves in the rivers all play a part. The inevitable intervention of climate in any investigation of the hydrological record adds to the difficulty of detecting the changes that may be related to land use.

- More intensive development of the land does not always lead to undesirable effects on the flood regime

There are benefits from land drainage on the plot scale, in the form of increased infiltration capacity of the drier soil in a drained plot, though these can be negated by accompanying changes such as increased grazing density, improvements to arterial drainage networks and protective works for the sake of properties and land within the floodplain, which all tend to increase flood peaks.

- The hydrological consequences of land use changes relate mainly to soil water

The infiltration rate, which controls the quantity of water available to generate rapid flood runoff, is sensitive to changes in both the permeability of the soil and its moisture status. Soil hydraulic properties and moisture regime can be influenced by the choice of vegetation cover and by tillage practices. The intensity of grazing can affect the hydraulic properties of the uppermost layer of soil.

- Available data do not allow adequate quantification of impacts for predictive purposes

Modelling of land use impacts is open to question on many counts. Only a fully distributed model can take proper account of the spatial dimension of causes and effects: the calibration of such a model may require a more intensive hydrometric database than currently exists for the Severn, and a programme of fieldwork for the collection of information on soil properties and processes.

- Likely land use changes on higher ground, e.g. extension of deciduous woodland on slopes, reversion of improved grassland and reduction in grazing of moorland, will significantly affect flood peaks, but only if land use over a large area is changed

The impact of changes in the less intensively-used areas will be moderated by the larger proportion of the catchment that is likely to remain under agricultural use on the present pattern. Effects would be in broad proportion to the area covered: only changes over areas of 200 km^2 or so will produce detectable effects.

- The magnitude of land use impacts on flows at Montford depends on location within the catchment

Floodwaters generated on high ground in the Banwy, Tanat and Vyrnwy catchments may reach Montford with less attenuation than those passing through the greater length of channel from catchment areas nearer the Severn source. Data examined in this investigation suggest that for widespread rainfall events the main peak of the hydrograph at Montford may be generated by the later arrival of a more sharply defined peak from the Vyrnwy. Thus the flood control value of land use changes may be higher in the northern part of the Severn catchment than in the southern part. To resolve this issue would require a more intensive study of the composition of the Montford hydrograph, taking in a much larger selection of flood events.

There is no simple way to deduce the impact of modifications to the flood response of a subcatchment, or just a part of a subcatchment, on the total output from the basin. The model produced in the course of this project offers a conceptually simple approach which, in application to real catchment structure, soils and topography, soon developed into a complex framework of subcatchments, contour bands, storage elements and delays. However, there are few parameters in the strict sense, most of the numerical values built into the model being defined topographically or through established techniques to relate hydrological behaviour to soil type.

It is envisaged that the model will be used to investigate the downstream influence of localised changes, for instance a land use change in a specific altitude band of a subcatchment, on the peak discharge at Montford for a flood of a given magnitude. Though more calibration or validation may be desirable, in view of the sparsity of manipulable parameters it is suggested that further refinement will not necessarily improve the model's ability to carry out its function of predicting *changes* in flood hydrology rather than absolute peak discharges.

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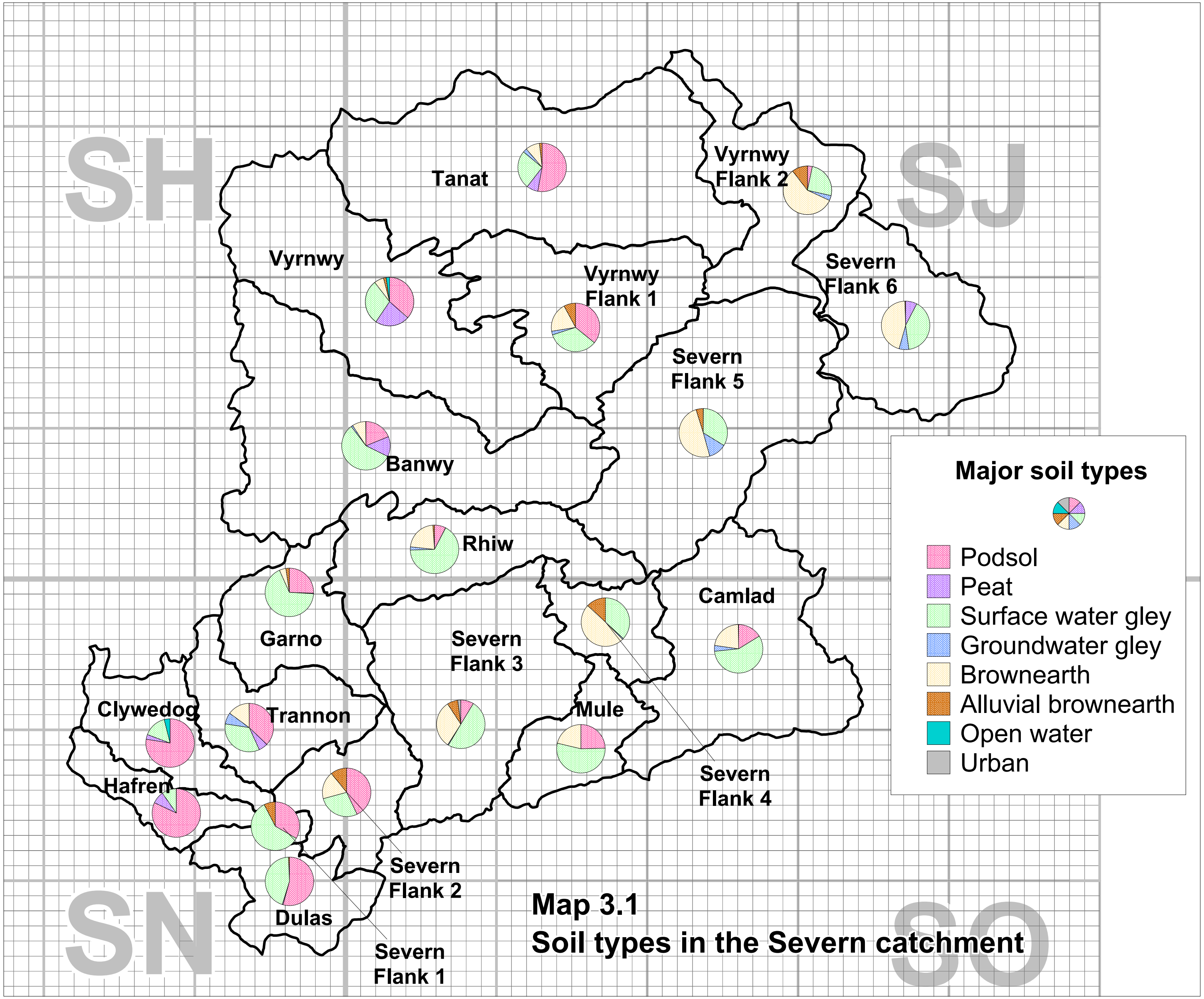

Map 3.1
Soil types in the Severn catchment

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