

# FLOW PATH DIMENSIONALITY AND HYDROLOGICAL MODELLING

NICK CHAPPELL

*Centre for Research on Environmental Systems, Institute of Environment and Biological Sciences, University of Lancaster, Lancaster LA1 4YQ, UK*

AND

LES TERNAN

*Department of Geographical Sciences, Polytechnic South West, Plymouth PL4 8AA, UK*

## ABSTRACT

Increasingly, research is indicating that subsurface flow paths govern ion transport within river catchments. Distributed prediction of these solute flow paths in typically heterogeneous catchments must inevitably be highly uncertain without some identification of a spatial structure relating small-scale measurements of soil properties to flow predictions distributed over large catchments. To date, the evidence for profile and catenal structure within soil hydrological properties and resultant solute flow paths is not fully embraced by the hydrological community. As a consequence soil parameters are often poorly distributed within catchment-scale distributed models. This paper seeks, first, to generalize the disparate sources of evidence of parameter and flow path structure within the profile-ward and catena-ward dimensions. Second, to outline how much of this structure has been incorporated into previous hydrological simulations using distributed models, and third, to examine the physical basis of attempts to simplify parameter and flow path dimensions using pedological classifications. The available evidence suggests that a considerable number of world soils show profile-ward structure within their hydrological properties and resultant flow paths. Changes in profile-ward patterns along catenal sequences remain uncertain. The Plynlimon region of mid-Wales has been the focus for many detailed studies of solute flow paths, catchment-scale model simulations, soil property characterizations and soil classification. Comparison of these studies suggests that most model simulations and hydromorphic classifications of soil taxa fail to distinguish adequately between soil horizons and soil types with markedly different property distributions. Preliminary analysis, however, suggests that by using a catena based criterion to classify the hydromorphic characteristics of soils, soil elements with distinct patterns of properties and flow paths can be identified. This might suggest that the accuracy of distributed predictions of ion movements within river catchments could be greatly improved by the derivation of profile-specific patterns in soil properties. These profile-specific effective parameters need to be derived from measurements over a range of scales, including individual layers, profiles and complete catenas.

KEY WORDS Distributed models Catenas Flow paths Soil properties Catchment scale

## INTRODUCTION

Considerable research effort is currently directed towards predicting hydrological responses distributed over large catchments. The ability to make flow predictions about every hillslope within a catchment is essential to pinpoint areas sensitive to possible disturbances, or to predict the fate of localized pollutant sources. Within selectively logged rain forest catchments, for example, sediment production is related to hydrological pathways within localized stream-head (Clinnick, 1985) and near-stream areas (Salleh *et al.*, 1983). Hydrochemical research within podzolized catchments has indicated that changes in soil-water pathways during storm periods markedly affects ion concentrations within rivers (Hornung *et al.*, 1986; Lawrence *et al.*, 1986). Other studies have noted that the pathway of water through distinct slope zones such as toe-slopes, mid-slopes and crest-slopes develop very different water chemistries (Dixon, 1986; Hill, 1990).

Streamflow can be generated by water flowing along many different pathways within river catchments. Freeze (1972), Dunne (1978) and Anderson and Burt (1990) argue that saturation overland flow is the most

important mechanism for streamflow generation during storm periods. This saturation overland flow is produced in saturated riparian zones by a combination of precipitation failing to infiltrate and the exfiltration of subsurface flow. Two key observations suggest that this view greatly underestimates the role of subsurface flow.

The first of these is the dissimilarity of precipitation and stream water chemistries. Numerous studies conducted in catchments in North America, Australasia and Europe note dissimilarities between the temporal variation of stable isotope concentrations within precipitation and those within stream waters (e.g. Martinec, 1975; Kennedy *et al.*, 1986; Pearce *et al.*, 1986). At Plynlimon in mid-Wales, similar dissimilarities between the precipitation and stream waters have been observed with chloride concentrations (Neal *et al.*, 1988). This would imply that streamflow, even during storm periods, is generated principally by the displacement of pre-event subsurface waters rather than by precipitation failing to infiltrate saturated areas.

The second observation is a lack of visible signs of overland flow in riparian zones. Hydrological studies in catchments ranging from Plynlimon in mid-Wales (Robinson and Newson, 1986; Fiebig, 1988; Chappell, 1990; Jones, 1990) and Coweeta in the Appalachian mountains of the USA (Hoover and Hursh, 1943; Dowd, unpublished data), to various catchments in the humid tropics (Walsh, 1980; Walsh, personal communication; Dubreuil, 1985) note that overland flow is absent from riparian zones during many storms. Hence, subsurface flow does not always exfiltrate to form saturation overland flow before reaching the stream channel.

The current emphasis on the hydrological behaviour of saturated soils in near-stream zones could be seen to divert research efforts away from perhaps a correct consideration of subsurface flows within the greater part of the catchment. Before the popularity of the variable source area theory that places great emphasis on the role of near-stream zones, Hursh and Hoover (e.g. Hoover and Hursh, 1943; Hursh, 1944) maintained that subsurface flows upslope of the near-stream zones exert a marked influence on the movement of storm waters to stream channels. Further, the direct input of subsurface flow into stream channels was seen as an important water pathway during storms. In catchments where subsurface water is the principal source of storm period streamflow, then distributed hydrological models should be able to predict subsurface flow pathways.

To distribute predictions of subsurface flow within catchments we need to first be able to represent our flow equations (physical theory) over scales possibly ranging from a 0.1 m deep soil horizon to a 10 km<sup>2</sup> catchment. Second, we need to be able to represent the magnitude and spatial distribution of the soil physical properties affecting subsurface water flow with the same detail as we hope to make our distributed predictions. There is an increasing body of evidence suggesting that stationary soil properties or soil parameters are a dominant control on the pathways of water through catchments. Despite this, there is no widely accepted rationale by which to examine their distribution at the catchment-scale and consequently to guide their collection for the parametrization or validation of distributed modelling.

### SOIL PARAMETER ESTIMATION

Distributed calculations of water flow within catchment soils require the estimation of three soil parameters: (1) the intrinsic permeability,  $k$ , which is a function of the saturated hydraulic conductivity,  $K_s$  (i.e.  $k = (K_s \mu) / (\rho g)$ , where  $\mu$  is the dynamic viscosity of water,  $\rho$  is the water density and  $g$  is the gravitational acceleration); (ii) the state dependent hydraulic conductivity,  $K_{(\theta)}$  or  $K_{(\phi)}$ ; and (iii) the specific moisture capacity ( $\partial\theta/\partial\phi$ ; where  $\theta$  is the soil moisture content and  $\phi$  is the capillary potential). Many modelling studies state that their simulations are most sensitive to the magnitude of  $K_s$  (e.g. Freeze, 1972; Loague and Freeze, 1985; Rogers *et al.*, 1985). Currently, many numerical simulations incorporate catchment distributions of  $K_s$  by adjusting  $K_s$  distributions to fit the lumped streamflow response, which is derived from small numbers of measured values. For example, the application of Troendle (1979) of the variable source area model (VSA1) to a 0.38 km<sup>2</sup> catchment in the Fernow Experimental Forest, VA, USA was based on six measurements of  $K_s$ . Similarly, the application of the Système Hydrologique Européen model (SHE) to the Institute of Hydrology's Wye catchment in mid-Wales was attempted by calibrating 17 values of  $K_s$  (Bathurst, 1986). These data were measured with small soil cores (Knapp, 1970; Table 10.4). Assuming a

mean soil depth of only 2 m (Bathurst, 1986), these samples represent only  $1/2 \times 10^{11}$  of the soil volume of the Wye catchment. Furthermore, these 17 samples were extracted from only one soil horizon of only one of the eight to ten soil subgroups found within the Wye catchment. This yields two obvious problems: (i) immense statistical uncertainty associated with representing the population  $K_s$  values with such a small number of samples, which themselves appear to be unrepresentative; and (ii) a failure to characterize the spatial structure or correlated variability within the  $K_s$  field (Gelhar *et al.*, 1985; Hoeksema and Kitandas, 1985).

These two problems lead to:

- (i) *Multiple optima.* Effective  $K_s$  values for large soil blocks are often derived by fitting their lumped behaviour observed in the streamflow response. Unfortunately, any number of different distributions of  $K_s$  can give the same streamflow response (Anderson and Rogers, 1987; Beven, 1989; Beven and Jakeman, 1990)
- (ii) *Dimensionality reductions.* Integrating each  $K_s$  measurement over a larger soil volume may remove the effects of any unmeasured layering or slopeward changes in the soil properties upon the water flow
- (iii) *Additivity failure.* Flow equations for partially saturated porous media are parametrically non-linear. Effective parameters for large soil volumes are therefore not necessarily represented by the mean of the frequency distribution of the small-scale measurements (Gelhar *et al.*, 1985). For example, reductions of  $K_s$  in the direction of a flow path will give a lower effective  $K_s$  value for a soil block compared with the mean for the distribution of sample values (Bear *et al.*, 1968; Chappell, 1990).

Increasing the number of samples allows parameter distributions and spatial structure to be identified. To attempt to characterize the spatial variability of a 1–10 km<sup>2</sup> catchment using measurements integrated over only 0.1–1 m<sup>3</sup> requires the collection of vast numbers of samples given no *a priori* knowledge of the property distributions (Nielsen *et al.*, 1973; Newson, 1978; Troendle, 1985). Given limited *a priori* understanding of the approximate correlation lengths of any deterministic structure within catchment soil properties, more realistic sampling objectives could be achieved. The impact of uncorrelated variability on the flow paths and effective parameters at the deterministic scale would, however, still need to be assessed.

Catchment soils often show large variations in their  $K_s$  values between specific soil horizons ranging between  $10^{-4}$  and  $10^2$  cm/hr<sup>1</sup>, for example, across the Plynlimon catchments (Table I). Further, many distributed catchment models assume that the soil parameters are distributed purely randomly. Assuming

Table I. Measurements of saturated hydraulic conductivity (cm/hr<sup>1</sup>) recorded for specific horizons and soil types of the Plynlimon massif

Soil type	$K_s$ (cm/hr <sup>1</sup> )	Number*	Layer	Reference
Histosol	$1.98 \times 10^2$	NK	Surface	Edwards (1976)
	3.60 to 36	NK	Surface	Jones (1990)
	$3.00 \times 10^{-3}$	NK	0.25 m	Edwards (1976)
	$2.70 \times 10^{-4}$	NK	0.5 m	Edwards (1976)
Gleyic podzol	3.38	26	O/A	Jones (1981)
	$2.19 \times 10^2$		Ea	Jones (1981)
Placic podzol	$3.00 \times 10^{-1}$ to 33.5	17	O/A	Knapp (1970)
	$2.00 \times 10^{-1}$	1	Eag	Chappell (1990)
	5.70	1	B	Chappell (1990)
	$5.00 \times 10^{-1}$ to 5.40	NK	B	Morgan (1977)
Ferric podzol	1.50	1	BCg	Chappell (1990)
	$8.00 \times 10^2$	3	O/A	Chappell (1990)
	33.0 to $2.21 \times 10^2$	3	Ea	Chappell (1990)
	$8.00 \times 10^{-2}$ to $3.20 \times 10^{-1}$	5	Bs	Chappell (1990)
	22.0 to 35	3	BC	Chappell (1990)
Humic gleysol	$< 8.00 \times 10^{-3}$	NK	1 m	Calder (1976)
	$1.50 \times 10^{-2}$ to 1.04	3	1 m	Chappell (1990)
	$8.00 \times 10^{-4}$ to $2.00 \times 10^{-1}$	9	1.2 m	Allen (1981)

\* NK = not known.

that all the variability is uncorrelated within such heterogeneous catchments would mean that predictions of water flow at any resolution or scale less than that of the lumped catchment response would be similarly uncertain and in effect uninterpretable. Fortunately, the likelihood of internal state properties showing a deterministic structure at the meso-scale between the  $10^{-1} \text{ m}^3$  measurements and  $10^7 \text{ m}^3$  catchments seems reasonable given the vast difference in scales. This meso-scale structure will have its own dimensionality, which will be echoed in the dimensionality of the subsurface flow paths.

### FLOW PATH DIMENSIONALITY

The possible dimensions over which the meso-scale structure could affect the representation of flow paths within catchment soils may be divided into: (i) Euclidean dimensions ( $x$ ,  $y$  and  $z$  dimensions); (ii) stationarity (time dimension); and (iii) spatial discretization of flow calculations.

The Euclidean dimensions are the three spatial dimensions  $x$ ,  $y$  and  $z$ , i.e. the slopeward, streamward and profileward directions. Stationarity is the permanence of the spatial structures and flow path patterns within the landscape. The spatial discretization is the way in which the landscape is divided into elements over which to average soil parameters and choose the number of spatial dimensions (one, two, or three) over which to solve the flow equation.

Evidence for the existence of patterns in the soil parameters and their effect on the flow paths are examined in the profile ( $z$ ) dimension and the catenal ( $x$ ,  $y$ ) dimensions. The stationarity of such patterns is addressed. The extent to which such profile and catenal structures have been included within previous simulations of catchment-scale subsurface flow will then be examined.

#### Profile structure

Most soils and regoliths show layering in their intrinsic permeability (Bear *et al.*, 1968; Gelhar *et al.*, 1985; Yeh *et al.*, 1985). This layering is often coincident with the classification of soil horizons (Chappell, 1990). A few soil profiles such as cambisols and regosols have relatively little layering within their upper soil profile (ca. 0–50 cm; Figure 1).

Many other soils such as ferric/placic podzols, gleysols, acrisols and ferralsols have marked discontinuities in their vertical  $K_s$ . For example, vertical variations in  $K_s$  and  $k$  of five orders of magnitude (Figure 2 and Table II) were recorded in a profile of a ferric podzol by Chappell (1990) and in a humic gleysol by Hartley (1987).

Within acrisols, ferrasols, luvisols, planosols and podzols, for example,  $K_s$  discontinuities of between one and two orders of magnitude are often noted between their A and indurated B horizons (Table III). If the pattern of the  $K_s$  values within profiles of the same soil type was broadly similar in terms of the order of magnitude of the discontinuity in  $K_s$  values between each soil horizon, then idealized  $K_s$  patterns could be used to distribute flow predictions in similar soils, thereby reducing the extent of field data required to be collected.

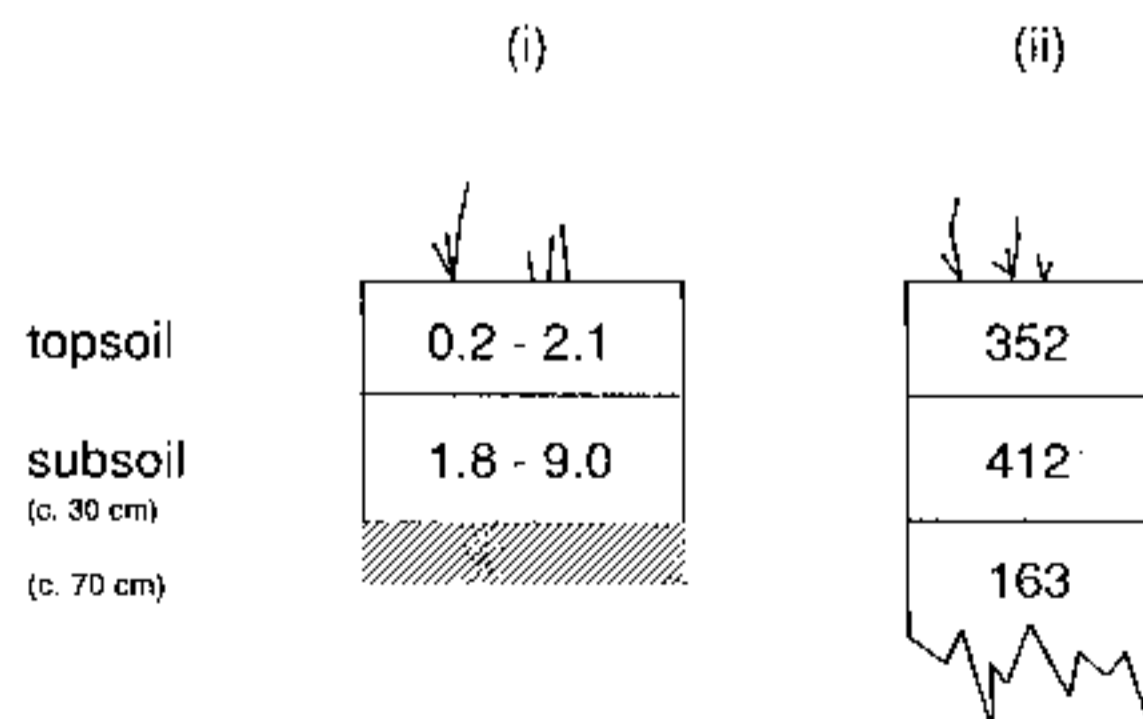


Figure 1. Saturated hydraulic conductivity ( $\text{cm/hr}^1$ ) of soil horizons within (i) a calcic cambisol (SSEW: brown calcareous earth, after Crabtree and Trudgill, 1985), and (ii) a regosol (after Harr, 1977)

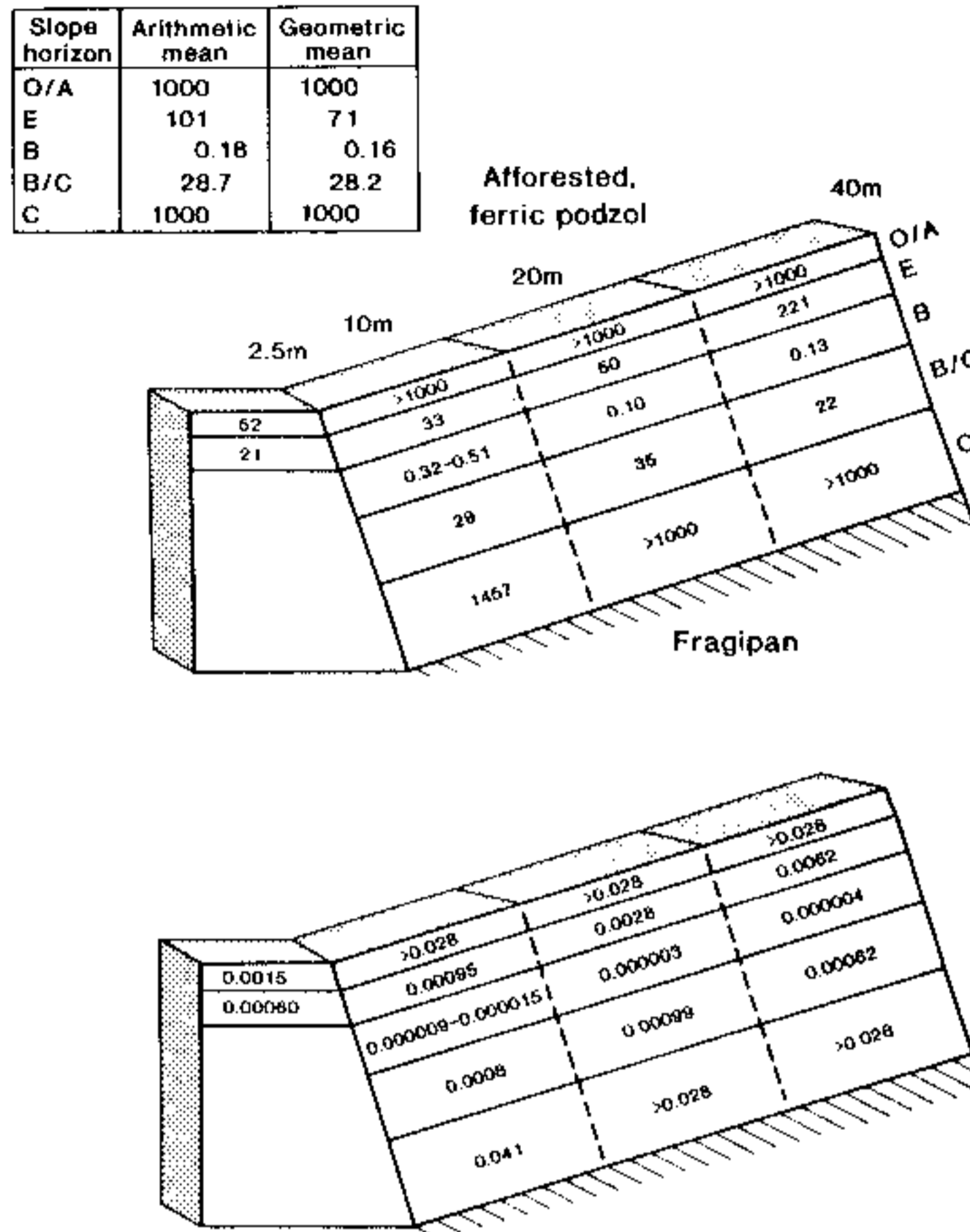


Figure 2. Horizon-specific saturated hydraulic conductivities (cm/hr<sup>1</sup> at 20°C) and intrinsic permeabilities (cm<sup>2</sup>) in a hillslope of ferric podzol soil (after Chappell, 1990)

As most of the soil volume within a catchment is only partially saturated with water we need to understand how vertical patterns in the state dependent hydraulic conductivity,  $K_{(\theta)}$  change as the soil moisture content reduces. It is not known if the patterns observed for saturated soils persist as the soils dry, or if completely different patterns emerge. Furthermore, should the patterns change, it is essential to determine over what timescale, on a seasonal or storm basis, the variation occurs.

Few  $K_{(\theta)}$  patterns or fields are available for hillslope profiles. Chappell (1990) monitored flow within a 20° slope of a ferric podzol in the Tir Gwyn catchments at Plynlimon, mid-Wales. Profile discontinuities

Table II. Horizon-specific saturated hydraulic conductivities (cm/hr<sup>1</sup>) of a humic gleysol (after Hartley, 1987)

Depth (cm)	Saturated hydraulic conductivity (cm/hr)	
	Mean	Range (n = 56)
0-10	9.1	1.31 - 30.7
10-20	21.8	8.98 - 57.0
20-50	0.11	0.21 - 3.02
50-100	0.002	0.0007- 0.21

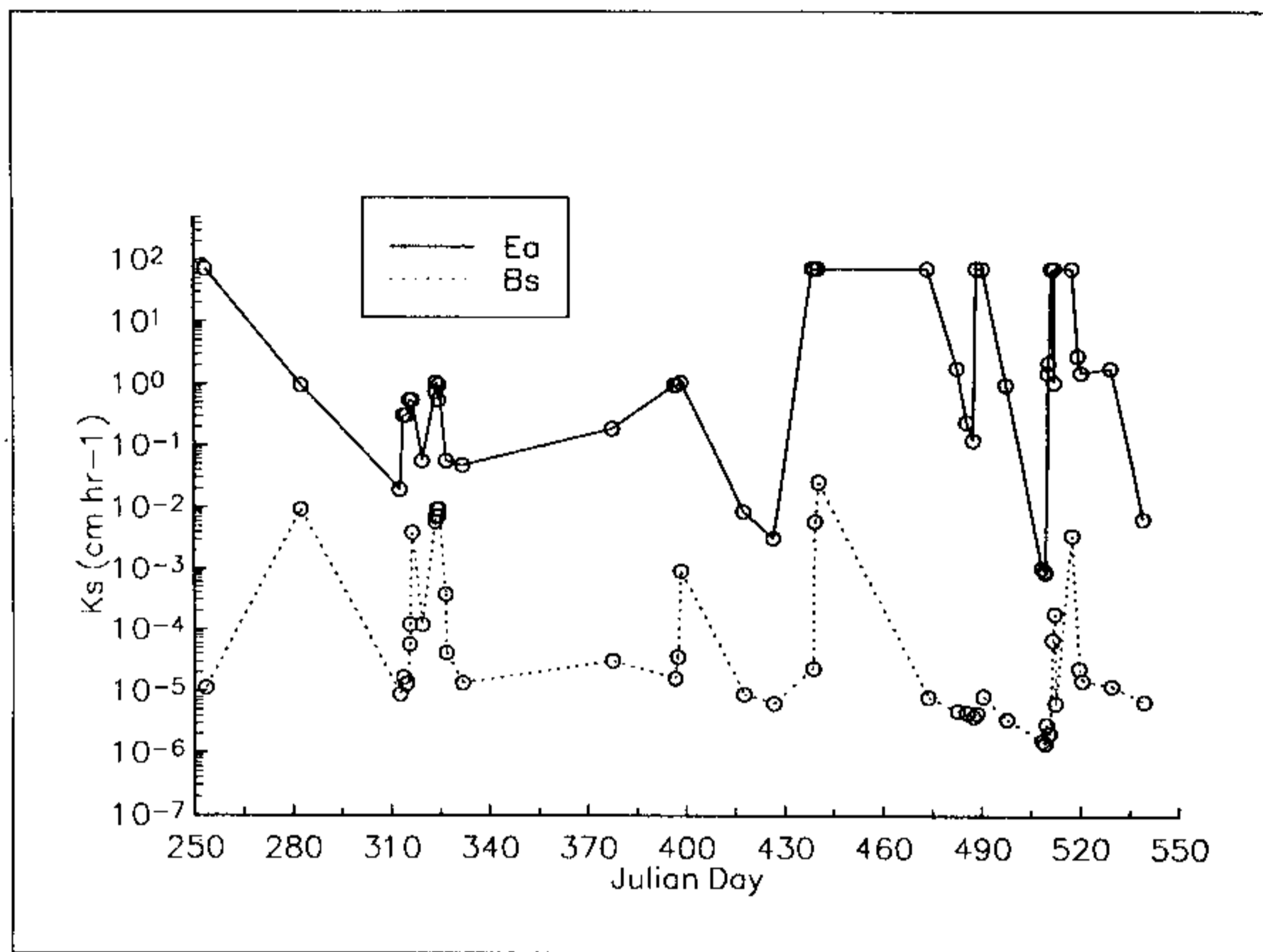


Figure 3. State-dependent hydraulic conductivities of the Ea and Bs horizons at the 5 m slope position, within the instrumented forest hillslope, Tir Gwyn, mid-Wales

observed in the hydraulic conductivity at saturation (Figure 2) were similarly observed over a range of field moisture contents. Between 8 September 1987 and 22 June 1988 the Ea horizon consistently maintained approximately three orders of magnitude more conductivity than the underlying Bs horizon (Figure 3). As a result, flow paths were diverted laterally, maintaining the continuity described by the tangent refraction law (Chappell *et al.*, 1990). During the winter storm periods, about 75% of the flow from the podzolic midslope was generated from lateral flow above the indurated Bs horizon. Gaskin (1987) monitored hillslope flows using tensiometry and field permeametry within a 43° slope in Watershed 1 of the Coweeta experimental catchments, North Carolina, USA. The orthic Acrisol soils that form the slope are characterized by their argillic Bt horizon. Gaskin (1987) reported large lateral flows within the A and AB soil horizons, which increased from 71% of infiltration during winter storms to 87% during summer storms.

Numerical modelling of hillslope-scale flow regions (i.e. 10<sup>1</sup>–10<sup>3</sup> m<sup>2</sup>) has similarly indicated the dominant effect of profile structure on flow paths over a range of soil moisture conditions. Freeze (1971) simulated subsurface flow within a hypothetical 37 × 7 m hillslope. The slope consisted of sand with a single layer of clay at a depth of 3 m. A perched water-table and concomitant lateral flow were generated above the clay layer in response to the clay layer having a lower  $K_{(0)}$  value than the surrounding sandy soil. The clay had a  $K_s$  value one order of magnitude less than that of the sand. Zaslavsky and Sinai (1981) modelled flow in a 20 m long hillslope catena of yermosolic soil using soil properties measured by Sinai and Zaslavsky (1976). During rainfall events of low and high intensity (0.1 and 40 mm/hr<sup>1</sup>, respectively), lateral flow was seen to dominate over vertical flow within the top 4–5 m of soil at the steep mid-slope positions. They attributed this to the effect on the  $K_{(0)}$  value of the order of magnitude decrease in  $K_s$  for every 5.5 cm depth increment.

Table III. Order of magnitude of the discontinuities in  $K_s$  values between the A and B horizons of acrisolic, ferralsolic, luvisolic, planosolic and podzolic profiles

Discontinuity*	Soil type (FAO)†	No. of samples	Region	Reference
1.36-1.51	Acrisol	NK‡	SE Australia	Talsma and Hallam (1980)
1.95-2.08	Humic acrisol	6	NE Australia	Bonell <i>et al.</i> (1983)
0.71	Orthic acrisol	14	NC, USA	Gaskin (1987)
0.83	Acrisol	4	Sabah, Malaysia	Chappell (unpublished data)
0.49-0.98	Orthic acrisol	NK	NC, USA	Betson and Marius (1969)
1.65-2.83	Ferralsol	>62	SE Australia	Talsma and Hallam (1980)
0.88-2.62	Rhodic ferralsol	16	NE Australia	Bonell <i>et al.</i> (1983)
1.19	Ferralsol	12	Grenada	Ternan <i>et al.</i> (1987)
1.45-2.38	Ferralic cambisol	4	NE Australia	Bonell <i>et al.</i> (1983)
1.59	Luvisol	99	SE Australia	Talsma and Hallam (1980)
2.06	Planosol	NK	SE Australia	Talsma and Hallam (1980)
2.01-3.23	Ferric podzol	6	UK	Chappell (1990)
0.90	Podzol	2	UK	Stagg (1974)

\*  $(\log_{10}K_sA - \log_{10}K_sB)$ , where  $K_s > 1$  mm/day.

† FAO-Unesco (1974).

‡ NK = not known.

Perhaps more significant is the transiency of flow paths within soils showing very little layering in their intrinsic permeability ( $k$ ), but considerable layering within their  $K_{(\theta)}$  values with the concomitant lateral deflection of flow. Harr (1977) monitored flow paths in a homogeneous regosol in the H. J. Andrews Experimental Forest, Oregon, USA. During one winter storm, he observed flow vectors changing direction from 40 to 60° from the vertical at 10 cm in the profile, 25 to 50° at 70 cm and 15 to 80° at 130 cm. McCord and Stephens (1987) added a bromide tracer to a 23° hillslope of homogeneous luvisol in the Sevilleta National Wildlife Refuge, New Mexico, USA. They similarly noticed marked lateral flow attributable to discontinuities in the vertical distribution of  $K_{(\theta)}$ . Kool *et al.* (1990) measured the  $K_s$  value and moisture content ( $\theta$ ) at 387 locations in a plot 12 × 12 m and 5.8 m deep. The soil was yermosolic. Although no layering was apparent within the  $K_s$  field, a marked anisotropy was apparent in the moisture distribution observed in the field and predicted by the numerical simulations.

There is some evidence that even patterns of intrinsic permeability and  $K_s$  values are non-stationary in particular soils. Drying and subsequent cracking of surface soil horizons during the summer months of temperate climates has been shown to increase the surface  $K_s$  values of dystric cambisols (SSEW: brown earths) by 1/20 of an order of magnitude (Arnett, 1976), disturbed ferric podzols by one order of magnitude (Chappell, 1990) and swelling clay soils by four orders of magnitude (Bouma, 1980). Other less significant effects on the stationarity of  $K_s$  patterns include the effect of temperature on the viscosity of soil water. Over water temperatures ranging from 5 to 20 °C the  $K_s$  value will increase by 150%. Further, Waine *et al.* (1985) have shown that the  $K_s$  value of some peat soils can increase by 80% as the hydraulic gradient increases from one to 17. This phenomena is described as non-zero storativity.

#### Catenal structure

Soil forming processes vary in the  $x$  dimension with changing slope angle and position, and in the  $y$  dimension as climate changes with altitude (Wilding *et al.*, 1983). It would therefore be expected that soil properties would similarly vary with topography and altitude. This association between the landscape and soils is defined as the hillslope catena (Milne, 1936). Geological catenas also can be formed in response to the effect of geological changes on soil development (Milne, 1936).

Natural hillslope catenas in upland areas of Britain often show humic gleysol crest-slope and toe-slope soils. The poor incorporation of organic matter and chemical reduction of the mineral soil that leads to a peaty gleyed profile result in part from the high moisture status in the soil. Within these areas the

humification of the peat and chemical reduction of the mineral soil leads to a reduction in the  $K_s$  value (Rudolf, 1967; Burt *et al.*, 1990). Water flow through such profiles is preferred or localized in either the surface horizons or in pipe systems generated by the high seepage forces resulting from the reduced  $K_s$  value of the soil matrix (Jones, 1990). Shallow pipe systems within an instrumented grassland hillslope at Plynlimon (Chappell, 1990) appeared to be very sensitive to changes in such seepage forces. During major storm periods (i.e. greater than 40–50 mm of precipitation in two days), large subsurface fluxes from the podzolic mid-slopes appeared to force open completely new pipes within the toe-slope peats. Pipes were observed to issue water above the soil surface. These new preferential pathways increase the effective  $K_s$  value of the toe-slope soils, consequently regulating the differences between the slowly conductive peat matrix in the toe-slopes and the conductive topsoils of the mid-slopes. In slope elements where such pipes are an important subsurface flow pathway, consideration may have to be given to the resultant partially turbulent flow regime. This is rarely incorporated in subsurface flow models.

Effective parameter values representing idealized parameter distributions within particular slope elements are rarely derived. From the limited evidence available it appears that some catenas show marked changes in their profile characteristics with changing topographic position and altitude, whereas others express very little. It might be expected that soil catenas containing soil profiles that have developed marked vertical discontinuities (e.g. well developed acrisols, gleysols and podzols), also show pronounced discontinuities in their slopeward and streamward directions. The processes leading to marked vertical discontinuities such as chemical reduction and plasma translocation are similarly observed in the slopeward direction (Huggett, 1976; Dixon, 1986).

Examples of hillslope catenas showing slopeward or streamward variations in  $K_s$  patterns or related patterns include Murgatroyd (1980, pp. 143–150), who monitored the depth of perched water-tables within topsoils along a hillslope catena in the Narrator catchment, Devon, UK. He reported that perched water-tables within the topsoils of the upslope placic podzols were deep and persistent, whereas those within the dystric cambisols in the lower slopes were shallow and ephemeral. Williams *et al.* (1984) monitored hillslope flow within the same catchment using throughflow troughs. They noted that flow within the upslope placic podzols was dominated by lateral flow above an ironpan (Bf horizon), whereas significant lateral flow within the downslope dystric cambisols was not generated until percolation reached a depth of 60–90 cm (i.e. the fragipan layer). Within an experimental basin in central Japan, Tsukamoto and Ohta (1988) measured  $K_s$  values and capillary potential within a 30° slope of layered loams and gravels. They noted marked discontinuities in the  $K_s$  values in both the profile and slopeward directions (Table IV) that generated similar discontinuities in the total potential field. Vertical flow dominated to depths in excess of 3 m within the shoulder-slope soils, whereas flow was diverted laterally at depths as shallow as 0.3 m within the mid-slope soils. Rogowski *et al.* (1974) measured the distribution of  $K_s$  values in soils across the 0.7 km<sup>2</sup> Mahantango Creek catchment, Pennsylvania, USA. The catchment has riparian/toe-slopes with luvisols, mid-slopes with orthic acrisols and crest-slopes with dystric cambisols. Within the luvisols, vertical changes in  $K_s$  values of between one-half and one order of magnitude are observed, whereas the orthic acrisols and dystric cambisols

Table IV. Saturated hydraulic conductivity (cm/hr<sup>1</sup>) distribution in a hillslope catena of layered loams and gravels (adapted from Tsukamoto and Ohta, 1988)

Layer (cm)	$n^*$		
	Shoulder	Mid-slope	Foot-slope
0–30	2	2	2
30–50	0	–2	1
70	0–1	–3	–2

\* Order of magnitude of the saturated hydraulic conductivity, i.e.  $1 \times 10^n$  cm/hr<sup>1</sup>.

are internally homogeneous. Further, the orthic Acrisols and Dystric Cambisols have similar  $K_s$  values, which are up to 1.5 orders of magnitude larger than those of the riparian Luvisols, particularly with respect to the substratum (i.e. deeper than 76 cm).

Very few modelling studies have examined the effect of deterministic, catena-ward variations in  $K_s$  and  $K_{(\theta)}$  on subsurface flow. Hillel and Hornberger (1979) modelled flow within a 250 m long hillslope using two hypothetical soils with a one order of magnitude difference in their  $K_s$  value (i.e. 9 and 0.72 cm/hr<sup>1</sup>). Their model restricted flow calculations to vertical flow within the unsaturated zone and lateral flow within the saturated zone. Catenal sequences with (i) the conductive soil occupying a 42 m wide toe-slope, (ii) the less conductive soil in the toe-slope and (iii) half the hillslope with conductive and half less conductive soil, generated hillslope outflows which differed by only 8%. In contrast, those simulations with completely homogeneous soil properties differed by 83%. This might imply that the effective  $K_{(\theta)}$  value of particular slope elements is constant along catenal sequences.

Further research to derive these effective  $K_s$  and  $K_{(\theta)}$  values for individual segments is required. Evidence for a profile structure would, however, seem well founded. Identification of deterministic  $K_s$  distributions within the profiles of particular soil types could form the basis for the calculation of effective  $K_s$  values for slope elements. For example, a simple anisotropy tensor could be used to represent the lateral and vertical components of flow within each element of the catena (Yeh *et al.*, 1985). Given the previously outlined examples of profiles with changing  $K_{(\theta)}$  fields, the form of this tensor may have to change with changing moisture status. Unfortunately, not even the identifiable profile structure is incorporated within most catchment-scale numerical simulations.

#### *Spatial discretization and euclidean dimensionality in current distributed models*

Hydrological models that present spatially distributed predictions of subsurface water flow within catchments logically require that the soil parameters are averaged to the same or a greater resolution as the flow prediction. Computing time and capacity restrict the spatial discretization of a flow simulation and therefore set the minimum soil volume to which spatial distributions of soil properties can be represented. Eight examples of catchment-scale hydrological models purporting to be 'distributed' are presented in Table V.

Two aspects of these simulations give rise to some concern. First, the most spatially distributed predictions of water flow are generated by model simulations using only one  $K_s$  value per catchment (i.e. O'Loughlin,

Table V. Nature of the distribution within current 'distributed' models

Catchment	Size (km <sup>2</sup> )	Nature of the distribution		Model	Reference
		Internal state parameters	Predicted flow paths		
Wye Wales, UK	10.55	Lumped	Lumped	DDCM	White and Jayawardena (1975)
W5 Fernow VA, USA	0.38	2	Lumped	VSA1	Troendle (1979)
Whitchall GA, USA	0.24	5	Lumped	VSA2	Bernier (1982)
Tanllwyth Wales, UK	0.89	Lumped	Lumped	IHDM3	Rogers <i>et al.</i> (1985)
Wye Wales, UK	10.55	8	1.02-3.98 km <sup>2</sup>	SHE	Bathurst (1986)
Packapunyal Australia	0.05	Lumped	ca. 50 m <sup>2</sup>	WETZONE	O'Loughlin (1986)
Saeternbekken subcatchment	0.001	Lumped	4 m <sup>2</sup>	--	Erichsen and Myrabo (1990)
Wye Wales, UK	10.55	Lumped	2500 m <sup>2</sup>	TOPMODEL	Quinn <i>et al.</i> (1990)

1986; Erichsen and Myrabo, 1990; Quinn *et al.*, 1990). Spatially distributed predictions of subsurface flow produced by these models are therefore likely to be highly uncertain in catchments within heterogeneous and spatially correlated soils.

Second, those numerical studies using distributed soil parameters (i.e. Troendle, 1979; Bernier, 1982) have not presented similarly distributed predictions of the water flow, only the lumped response at the catchment outflow. The presentation of distributed predictions of flow allows the accuracy of the distributed modelling to be verified against state variables such as capillary potential, soil moisture content or tracer concentration. If the accuracy of distributed predictions of flow is not tested then distributed models are not *a priori* better than lumped catchment models. Generalized  $K_s$  variations along catenas are parametrized in the SHE model; however, predictions are not similarly distributed. The SHE model distributes predictions only at the 1.02–3.98 km<sup>2</sup> scale of the three gauged subcatchments of the Wye catchment (Bathurst, 1986). Further, although SHE allows for layering within its parametrization, the algorithm limits flow to only one dimension in the largely unsaturated upper soil profile.

The need to improve the spatial distribution of soil parameters within distributed catchment models is appreciated by many modelling hydrologists (e.g. Troendle, 1985; O'Loughlin, 1986; Quinn *et al.*, 1990). If deterministic soil taxonomies could be related to particular patterns of soil properties, then such classifications could form the basis for parametrizing distributed models.

### HYDROMORPHIC CLASSIFICATION OF SOILS

Soils have been classified into spatial elements with similar physical properties since 1883 (Dokuchaev, 1883). The international Food and Agricultural Organization (FAO) soil taxonomic system classifies all soils into 26 main groups (e.g. podzols, gleysols) based on diagnostic features of specific soil horizons (FAO-Unesco, 1974). Twenty-four adjectives are used to classify the soils further (e.g. ferric podzol, eutric gleysol). The standard soil taxonomy for England and Wales, classifies soils according to 10 major groups, 43 soil groups and 109 subgroups. The subgroups are further subdivided into soil series (Avery, 1980). Regional groupings of soil series forming on the same regional geologies are classified as soil associations. Regional groupings that also include geomorphological and vegetation criterion are called land systems. Topographically and altitudinally linked soils form hillslope catenas (Milne, 1936). All these classification systems implicitly include hydrological or hydromorphic characteristics, but none are solely hydrologically derived. The only widely used hydrological classifications of soils are those systems derived from Musgrave (1955) and Farquharson *et al.* (1978).

The Musgrave system classifies either soil series or soil associations into four classes based on their potential for generating 'run-off', where run-off implies overland flow (Table VI). The concept of the 'minimum infiltration rate' was defined to separate each class quasi-physically (Edmonds *et al.*, 1970). This system was subsequently incorporated into the US Soil Conservation Service's classification of catchment soils for determining stormflow generation (SCS, 1964). Edmonds *et al.* (1970) and Painter (1971) applied this modified system to determine the stormflow and drainage characteristics of the soils of England and

Table VI. Musgrave hydromorphic taxonomy of soils (adapted from Musgrave, 1955; SCS, 1964)

Class	Infiltration and transmission	Texture and structure	Run-off
A	High	Deep sands or gravels	Low
B	Moderate	Intermediate texture	
C	Slow	Fine texture or indurated horizon	
D	Very slow	Clay or high water-table or near-surface induration	High

Wales. Chaing (1970) and Chaing and Petersen (1970) further modified the system by specifying drainage characteristics with reference to location on idealized hillslope catenas.

Farquharson *et al.* (1978) attempted to improve the hydromorphic classification of soils by developing a system that explicitly incorporated approximate water-table depth ('drainage class'), depth to an 'impermeable' horizon,  $K_s$  value above the 'impermeable' horizon and slope angle (Figure 4). A taxonomy consisting of five classes was developed from quantitative information from the River Dee above Erbistock, and from two subcatchments of the River Soar (Farquharson *et al.*, 1978). Soil information was distributed to the level of the soil association. They termed their index the winter rain acceptance potential (WRAP). A very low WRAP (class 5) corresponds to a very high run-off potential. The WRAP index was subsequently used in the UK flood studies report (NERC, 1975) in the prediction of river peak flows.

The most recent hydromorphic soil taxonomy applied to the soils of England and Wales is the hydrology of soil types (HOST) system. Boorman and Hollis (1990) revised the Farquharson *et al.* (1978) system by incorporating hydrogeological properties deeper within the profile. The number of classes used to classify the hydromorphology of soils and near-surface hydrogeology was increased to 29.

In summary, all of the approaches use infiltration or permeability and water-table characteristics to compare the ability of the different soils or porous media to 'store' or 'lag' incoming precipitation from immediately entering a river. This makes their use in the parametrization of distributed hydrological models rather difficult. First, none of the systems generate response indices distributed over individual soil profiles. This, consequently, prevents any vertically distributed predictions of subsurface flow paths from being made. Secondly, and more importantly, most of the indices or parametrizations are a function of the water-table depth. The water-table is the most sensitive characteristic (Thomasson, 1978). Given that distributed models predict 'internal state' variables, including water-table location, it should not be included within a parameter.

Drainage class	Depth (cm)	0 -2° slope			2 -8° slope			>8° slope		
		Hydraulic conductivity above an impermeable layer (R = rapid; M = medium; S =slow)								
		R	M	S	R	M	S	R	M	S
1	>80	WRAP 1								
	40 -80	WRAP 1						WRAP 2		
2	>80	WRAP 1			WRAP 2			WRAP 3		WRAP 4
	40 - 80	WRAP 1		WRAP 2				WRAP 3		
	<40	WRAP 1		WRAP 2					WRAP 3	
3	>80	WRAP 1		WRAP 2						
	40 -80	WRAP 1		WRAP 2						
	<40	WRAP 2								



1 2 3 4 5

WRAP

Figure 4. Farquharson *et al.* (1978) hydromorphic taxonomy of soils (adapted from Thomasson, 1978)

Furthermore, the indices are insensitive to the  $K_s$  distribution. For example, soils classified as having a WRAP index of anything but unity can be within any of the  $K_s$  classes of Farquharson *et al.* (1978). Similarly, soils with a WRAP index of 3, 4, or 5 may or may not have an impeding horizon within 80 cm of the soil surface.

What is needed is a system that is based solely on idealized parameter fields in the  $x$ ,  $y$  and  $z$  directions. Given the lack of data for  $K_{(z)}$  values, patterns in the  $K_s$  field and perhaps effective  $K_s$  values for 'type soils' could initially form the basis of the classification. These type soils ought to use the classes of an internationally recognized soil taxonomy, such as the FAO system. The number of type soils used should be minimized without obfuscating any hydrological similarities that have a marked effect on flow paths. Classification to the level of the soil subgroup (e.g., ferric podzol) seems to be required to separate the soils with markedly different hydromorphic characteristics in the Plynlimon area of mid-Wales (Chappell, 1990).

Complete coverage of the soils of England and Wales extends only to the definition of the regional soil association. Each soil association includes many different soil groups. These soil groups and their related hydromorphic characteristics could, however, be distributed across particular catchments by relating the soil association classification to an idealized hillslope catena. Several distributed models have been applied to the hydrological simulation of catchments on the Plynlimon massif (Table V). This region will be used as an example for the derivation of an idealized hillslope catena. Furthermore the  $K_s$  patterns and soil processes leading to such patterns will be described for this catena. The presence of  $K_s$  patterns within an example catena that are both deterministic and physically based will hopefully underline the need for distributed models to be parameterized with heterogeneous distributions of soil parameters.

#### HYDROMORPHIC CLASSIFICATION OF THE PLYNLIMON CATENA

The Soil Survey of England and Wales (SSEW) have classified the Plynlimon massif (an area of approximately 50 km<sup>2</sup>) as the Hafren (654a) and Crowdy (1013ab) associations. The 'type' soil subgroup for the Hafren association is a ferric podzol-placic podzol intergrade (SSEW: ferric stagnopodzol) and for the Crowdy association is a histosol (SSEW: raw amorphous peat).

The typical catena for acidic upland soils in cool temperate climates (Figure 5) has histosols (SSEW: raw peats) on the crest-slopes and toe-slopes, grading into humic gleysols (SSEW: stagnohumic gleys) towards (i) the crest-slope shoulders and (ii) the foot-slopes between the mid-slopes and toe-slopes. The steep mid-slopes have ferric podzols or even rankers on very steep slopes. At the crest-slope shoulders and foot-slopes the

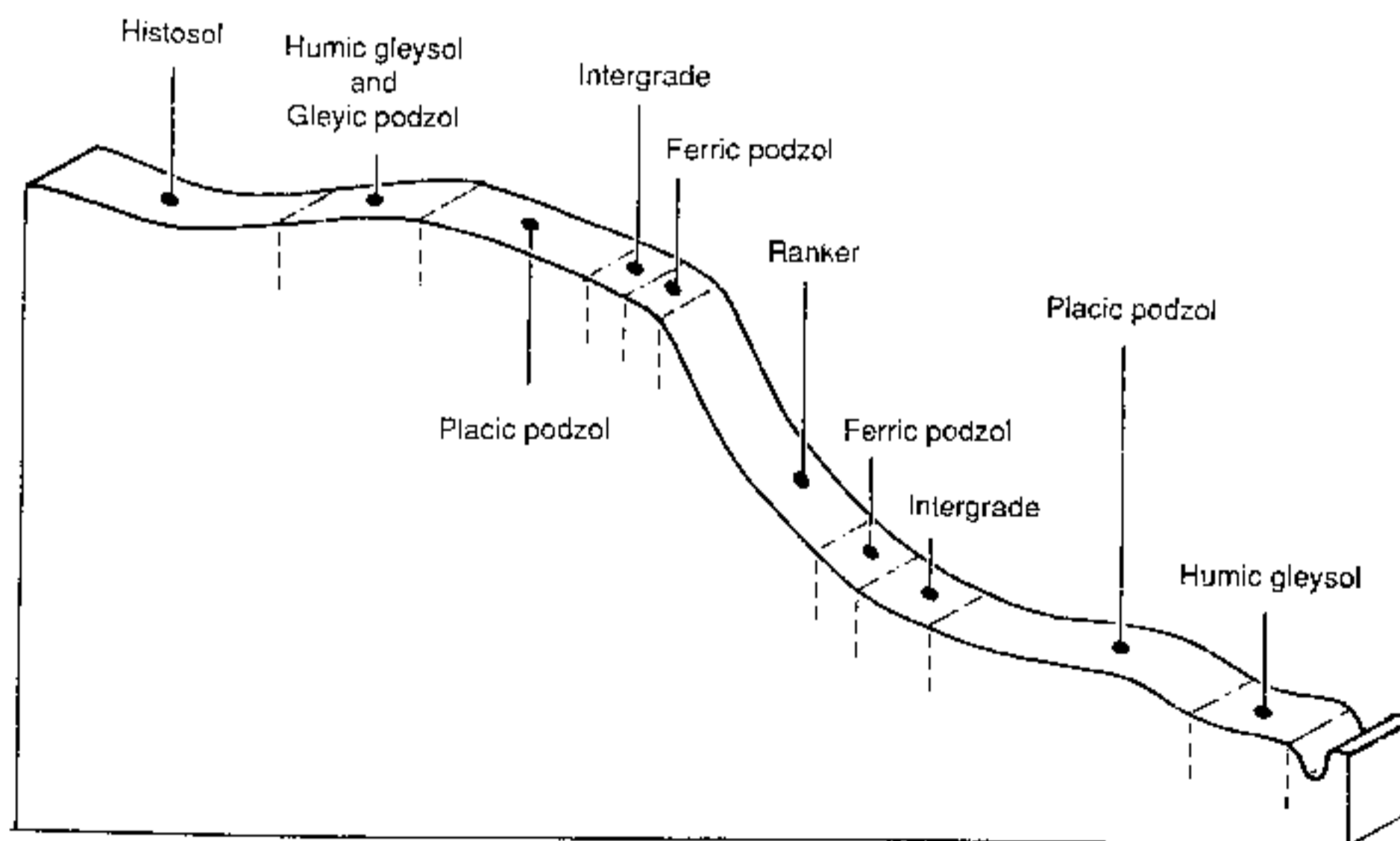


Figure 5. An idealized hillslope catena for acidic upland soils

ferric podzols grade into placic podzols (SSEW: ironpan stagnopodzols) (Crampton, 1967; Bridges, 1970; Rudeforth *et al.*, 1984). The SSEW distinguishes an intergrade between those two soils -- the ferric stagnopodzol. Saturated hydraulic conductivity measurements are related to these type soils found within particular slope elements of the Plynlimon massif (Table I). These data are idealized and presented in Figure 6. The correlation lengths for this catena based deterministic variability range between  $10^1$  and  $10^2$  m<sup>2</sup>.

#### *Patterns of $K_s$ values*

Within the ferric podzol, soil plasma and aluminium/iron (Al/Fe) oxides are deposited over a 5–10 cm depth of the Bs horizon and form an indurated, slowly permeable horizon (Figure 6). The surficial organic horizon (L, H, O/A horizons) remains relatively freely drained, thereby reducing humification, increasing the eluviation of organics and hence maintaining high conductivities (Burt *et al.*, 1990). Permeability is maintained within the Ea horizon, largely because of the extensive structural cracking (Crampton, 1963; Adams and Raza, 1978; Chappell, 1990). Differentiation between the organic, Ea and Bs horizons is marked.

Further down towards the foot-slopes or up towards the crest-slope shoulders, the Al/Fe oxides released from the Ea horizon are precipitated into an indurated ironpan (Figure 6). The Ea horizon above the pan becomes gleyed (Eag) and organic horizons further humify to form a peat. The permeability of both the Eag and peaty horizons are reduced by two to three orders of magnitude (Rudeforth, 1967; Adams, 1974). This typically leads to the development of shallow soil pipes within the peaty O/A horizons (Jones, 1981; pp. 77–86). Without the deposition of Al/Fe oxides over the Bs horizon, the horizon remains permeable compared with the Bs horizon of the ferric podzol (Adams and Raza, 1974). This is the fully developed placic podzol (SSEW: ironpan stagnopodzol).

The mid-slope soils at Plynlimon are typically developed on several metres of soliflucted regolith (Watson, 1967). At a depth of 60–70 cm below the ground surface a slowly permeable fragipan is found (Fitzpatrick, 1956; Chappell, 1990). Fragipans have developed at the base of Pleistocene freeze–thaw activity in many upland areas of the UK (Fitzpatrick, 1956; Ternan and Williams, 1979). Results of tensiometry and throughflow trough measurements have indicated that fragipans developed in steep slopes can divert a

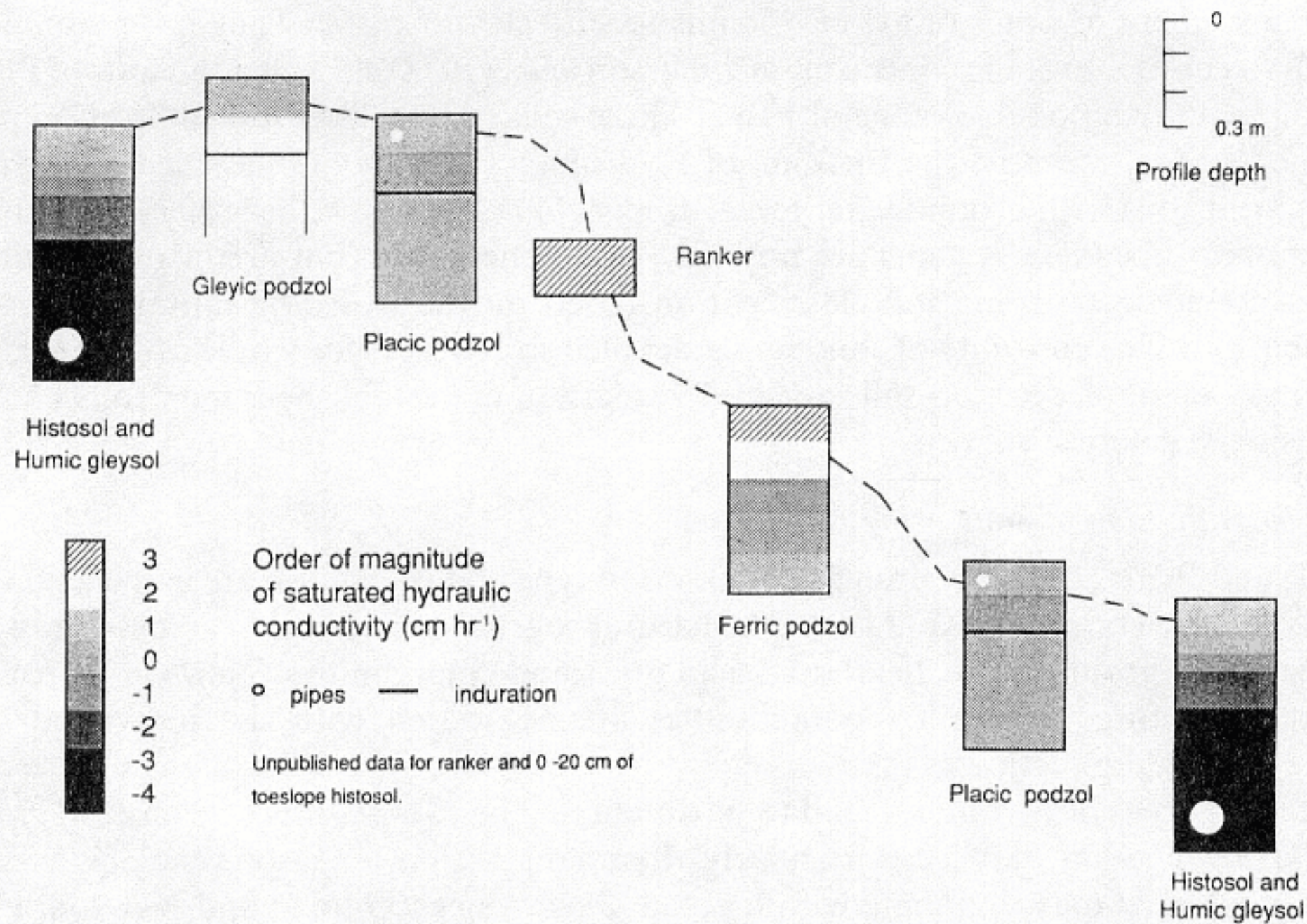


Figure 6. The idealized  $K_s$  distribution in the  $x$  and  $z$  dimensions of the Plynilimon catena (adapted from Table I; Crampton, 1967; Rudeforth, 1967; Knapp, 1970; Chappell, 1990). Units are in orders of magnitude of  $\text{cm/hr}^1$

considerable proportion of subsoil percolation laterally (Chappell, 1990; Williams *et al.*, 1984). Stratification below the fragipan is also observable within the regolith at Plynlimon.

Further onto the crest-slope or toe-slope the depth of the peat increases and the subsoil becomes gleyed forming a gleyic podzol (SSEW: gley-podzol) and then a humic gleysol (SSEW: stagnohumic gley). As the depth of the peat increases to more than 40 cm of the upper 80 cm of the soil profile, the soil is then classified as a histosol or peat (Rudeforth *et al.*, 1984). Networks of large subsoil pipes have developed within these poorly permeable soils (Gilman and Newson, 1980), conducting 50% of all hillslope flow on some hillslopes (Jones, 1990). Flow at the discontinuity between the peat and gley within the humic gleysols at Plynlimon is likely to be a further important flow pathway. Boggie and Knight (1980) noticed that a large percentage of a tritium tracer moved laterally at this depth within a humic gleysol at Kershop Forest, Cumbria, UK.

Along the margins of the major tributaries draining the Plynlimon massif riparian gravel and alluvial complexes are found (Newson, 1976). These soils are often markedly layered, generating stratified flows (Fiebig, 1988).

The Plynlimon catena has developed on Ordovician and Silurian formations, which are dominated by mudstone and shale geologies (Newson, 1976). The catchment average  $K_s$  value (if such a value can be determined) for the soils developed on these geologies is likely to be different to that for soils developed on coarser or finer geologies showing the same catenal soil sequences. This would, however, not mean that profile-ward and catena-ward patterns in  $K_s$  values are necessarily different in soils developed on different geologies. Qualitative and quantitative evidence (e.g. Glentworth and Dion, 1949; Crampton, 1967; Bridges, 1970; Williams *et al.*, 1984) suggests that the soil and  $K_s$  patterns found across the hillslopes within the Plynlimon region are similarly observed within other geological regions of the UK. Even without extrapolation to other regions, the variations in the  $K_s$  patterns between soil profiles at different slope locations at Plynlimon are marked and amenable to physical interpretation. Assuming that such distributions do not affect subsurface flow paths through their effect on the  $K_{(\theta)}$  values at best seems unproved.

Reference to  $K_s$  patterns observed in the Plynlimon region also suggests that the previous application of the Musgrave (1955) and Farquharson *et al.* (1978) hydromorphic systems to the region are unrealistic given the size of area over which they have been applied. Using the Musgrave system, Painter (1971) classified the whole of the Plynlimon massif as C1, out of a possible range A1 to D2. Soils given this classification have ... 'slow infiltration rates when thoroughly wetted. They either have a layer that impedes the downward movement of water or are clay loams to silty clay loams'... They have minimum infiltration rates of 0.28–0.40 cm/hr<sup>1</sup>. In some contrast, Farquharson *et al.* (1978) classified the soils of Plynlimon with a WRAP index of 5, out of a possible range of 1 to 5. These soils have a 'very low infiltration potential' and a 'very high run-off'. Most recently, the Institute of Hydrology (1991; p.44) classified all Plynlimon soils as HOST class 14, peat soils with groundwater levels deeper than 2 m below the surface (Boorman and Hollis, 1990). It is apparent that these systems are not only over-generalized, but are also inconsistent with each other. The need for hydromorphic soil classification based on the hydrologically related soil catena and horizon is emphasized. The enormity of conducting detailed soil surveys for whole catchments is appreciated. If deterministic associations between soil type and vegetation are established, then soils could be classified more rapidly using vegetation surveys.

#### *Hydromorphic classification of soils using vegetation*

Jeffries (1917) and Pyatt (1967) have suggested that soil type and vegetation are associated by their mutual responses to the soil moisture status and flow. The natural vegetation succession across the Plynlimon massif consists of three major groups: mire, heath and acid grassland communities (Newson, 1976). There is some suggestion that these three vegetation communities are associated with the individual soil subgroups identified in the preceding sections.

The very wet, mire areas of Plynlimon tend to be dominated by *Eriophorum* spp. (cotton grass) and *Juncus* spp. (rush). The *Eriophorum* may be particularly dominant within areas of very acidic, stagnant water (Jeffries, 1917) and *Juncus* may dominate within piped 'flush zones' (Gilman and Newson, 1980). Histosols and humic gleysols are formed within these areas. Wet placic podzols often support heath communities of *Molinia* spp. (purple moor grass) with some *Vaccinium* spp. (bilberry) and *Calluna vulgaris* (heather);

Newson, 1976). The *Vaccinium* spp. are often found in the channelized depressions produced by deep pipes (Jones, 1981). Natural acid grassland communities are dominated by *Festuca/Nardis* or *Nardis/Festuca* spp. (matgrass/fescue) and are developed on the slightly drier placic podzol-ferric podzol intergrade (SSEW: ferric stagnopodzol) and true ferric podzol soils. Very dry, dystic cambisols and rankers may have *Pteridium* spp. (bracken), in addition to the acid grassland species (Pyatt, 1967).

To further speed the identification of soils using vegetation, aerial photography or digital imagery collected from airborne platforms could be used. More data on the association between soil type and hydromorphic properties must be assimilated from previous studies and soil survey databases and from newly collected data before such soil-vegetation associations prove useful in model parametrizations.

### NEW DIRECTIONS FOR MEASUREMENT OF SOIL PARAMETERS

An increase in the use of large-scale distributed models combined with an identification of deterministic spatial structures within soil parameters suggests that measurements should be tailored towards producing parametrizations suitable for modelling over large scales. Given the present uncertainty of the effect of even very detailed, layer specific pathways on water flow within a single soil profile (Kool *et al.*, 1990; Pearce *et al.*, 1986), these measurements need to be performed over scales ranging from individual layers to complete catenal sequences.

#### *Layer measurements*

Within the near-surface groundwater zone (or soil profile), soils are mostly unsaturated. During storm periods, soils become 'near-saturated' (i.e. less than  $-100 \text{ cm H}_2\text{O}$  capillary potential, greater than 80% saturated). Unfortunately, flow calculations at these moisture levels are at their most uncertain. This is because of (i) the sensitivity of  $K_{(\phi)}$  to small changes of moisture and (ii) the inaccuracies in the estimation or measurement of  $K_{(\phi)}$  within 'near-saturated' soils. More emphasis needs to be given to improving the accuracy of the  $K_{(\phi)}$  or  $K_{(\theta)}$  parameter.

Indirect estimation of  $K_{(\phi)}$  using moisture release data can easily introduce large errors in the  $K_{(\theta)}$  value through small errors in core weight and volume calculations, in part resulting from sampling disturbance (e.g. Rogers and Carter, 1987). Uncertainty also surrounds the universality of the quasi-physical relationship between the moisture release ( $\delta\theta/\delta\phi$ ) and  $K_{(\phi)}$  (e.g. Demond and Roberts, 1987). Direct measurements of  $K_{(\phi)}$  using large soil cores, such as steady-state permeametry or *in situ* tension permeametry (Chappell and Ternan, unpublished data) are therefore suggested. The tangent continuity method (TCM: Chappell, 1990; Chappell *et al.*, 1990) could then be used to either verify the resultant  $K_{(\phi)}$  distributions or estimate the  $K_{(\phi)}$  curve for horizons above or below a layer with measured  $K_{(\phi)}$  values. This is achieved within a transform of the tangent refraction law, by combining the measured  $K_{(\phi)}$  values with capillary potential ( $\phi$ ) values measured through the soil profile. Two to three measurements of  $\phi$  are required to represent the equipotential lines within each soil layer.

#### *Profile measurements*

Soil parameters representative of distributions within soil profiles might be derived from the layer-specific measurements. It would be valuable, however, to have profile parameters derived directly from profile scale experiments which are free from the constraints associated within the use of cores. Cores both constrain flow to one dimension and induce edge effects during core sampling. Further, the effect of the uncorrelated variability in each layer's measurements on the parameter patterns at the next larger integral scale (i.e. a soil profile at a specific catenal position) could be examined.

The  $K_{(\phi)}$  values of homogeneous soil profiles at very low slope angles can be calculated using the instantaneous profile method. Alternatively,  $K_{(\phi)}$  functions for a soil profile (homogeneous or layered) can be derived by optimizing numerical predictions of observed moisture migration within controlled plot experiments (e.g. Kool *et al.*, 1990). Inversion of the numerical predictions of the migration of the chemical tracer can similarly be used to predict  $K_{(\phi)}$  functions for soil profiles (e.g. McCord and Stephens, 1987). Many more of these profile-scale measurements are needed.

*Full catena measurements*

Many catchment-scale numerical simulations derive effective  $K_{(\phi)}$  values for complete slope catenas. This is achieved by back calculation of the lumped subsurface response observed in the stream response. Effective  $K_s$  values for the Plynlimon catena have been derived from several catchment-scale modelling studies (Table VII). Mean catchment values which can be used to fit streamflow responses range over more than two orders of magnitude. This implies that there are inaccuracies in either the specification of boundary conditions (perhaps depth of porous media) or the model structure itself.

Such inverse techniques for the estimation of soil parameters are, however, useful in conjunction with the parameter estimates derived at smaller scales. For the Plynlimon soils, similarity in the  $K_s$  values between catchment areas (e.g. Beven, 1985) suggests that the contribution of water flow from different soil layers is similar within different catchment areas.

## CONCLUSIONS

In the collation of evidence of profile and catenal structures pertaining to particular soil types, it was surprising how few hillslope and catchment hydrological studies present  $K_{(\theta)}$  fields or even  $K_s$  fields. Without this information, or at least very detailed capillary potential fields or patterns of tracer concentrations, it is difficult to see how the results from such studies can be unambiguously related to hillslopes within other catchments.

From the limited information available, marked profile structures appear to be present within several soil types and appear to have a marked effect on the direction and magnitude of subsurface flow pathways. The interaction of flows between individual profiles along catenal sequences remains uncertain.

These two observations indicate that there is a need for further field experimentation. Given the example of the deterministic association between  $K_s$  patterns and soil types developed along the catena at Plynlimon, such experimentation should centre on the determination of idealized  $K_{(\theta)}$  patterns for representative soil types at idealized catenal positions. Given the theoretical and practical (measurement) problems associated with deriving these hillslope-scale parameters, measurements taken over a range of scales from individual layers to complete catenas need to be compared.

Identification of idealized  $K_{(\theta)}$  patterns would allow, first, model dimensionality to be reduced according to sound empirical evidence. For example, flow within homogeneous cambisols could be represented by only one dimension, whereas two dimensions would be needed to be used for ferric podzols. Second, it would allow flow to be predicted for subcatchment elements which could be verified against measured large-scale parameters. These distributed predictions of flow could then be used to predict solute flows at the same resolution.

## ACKNOWLEDGEMENTS

Many of the ideas leading to this paper were developed during an Natural Environment Research Council studentship GT4/AAPS/86/41. Drs A. Williams and J. F. Dowd are thanked for their practical and

Table VII. Effective  $K_s$  values for the Plynlimon catena, fitted from catchment-scale numerical modelling

Effective $K_s$ (cm/hr <sup>1</sup> )	Catchment	Model	Reference
3.6	Wye	DDCM	White and Jayawardena (1975)
0.18-1.08	Tanllwyth	IHDM3	Rogers <i>et al.</i> (1985)
2.52-3.6	Wye subcatchments	IHDM	Beven (1985)
2.88	Hore, Hafren, Lower Severn	IHDM	Beven (1985)
1.44	Tanllwyth	IHDM	Beven (1985)
6.2	Wye	SHE	Bathurst (1986)
3-30	Wye	TOPMODEL	Beven (1986)
1-5	Wye	TOPMODEL	Quinn <i>et al.</i> (1990)

theoretical contributions during this period. Comments by Dr R. Walsh and Dr A. Binley are also appreciated.

## REFERENCES

- Adams, W. A. 1974. 'Pedogenesis of soils derived from Lower Palaeozoic sediments in mid-Wales', *Welsh Soils Discussion Group, Annual Report*, **15**, 10-17.
- Adams, W. A. and Raza, M. A. 1978. 'The significance of truncation in the evolution of slope soils in mid-Wales', *J. Soil Sci.*, **29**, 243-257.
- Allen, D. J. 1981. 'A report on permeability investigations at the Institute of Hydrology lysimeter, Plynlimon, Wales', *Rep. No. WD/ST/81/16*, Institute of Geological Sciences, London.
- Anderson, M. G. and Burt, T. P. 1990. 'Subsurface runoff' in Anderson, M. G. and Burt, T. P. (Eds), *Process Studies in Hillslope Hydrology*, Wiley, Chichester. pp. 365-400.
- Anderson, M. G. and Rogers, C. C. M. 1987. 'Catchment scale distributed hydrological models: a discussion of research directions', *Progr. Phys. Geogr.*, **11**, 29-51.
- Arnett, R. R. 1976. 'Some pedological features affecting the permeability of hillslope soils in Caydale, Yorkshire', *Earth Surf. Process.*, **1**, 3-16.
- Avery, B. W. 1980. 'Soil classification for England and Wales (Higher Categories)', *Soil Survey Tech. Monogr. No. 14*. Soil Survey, Harpenden.
- Bathurst, J. C. 1986. 'Physically-based distributed modelling of an upland catchment using the Systeme Hydrologique Europeen', *J. Hydrol.*, **87**, 79-102.
- Bear, J., Zaslavsky, D., and Irmay, S. 1968. *Physical Principles of Water Percolation and Seepage*, Unesco, Paris.
- Bernier, P. Y. 1982. 'VSA2: a revised source area simulator for small forested basin', *Unpublished PhD Thesis*, University of Georgia, Athens, GA.
- Betson, R. P. and Marius, J. B. 1969. 'Source of storm runoff', *Wat. Resour. Res.*, **5**, 574-582.
- Beven, K. 1985. 'Distributed models' in Anderson, M. G. and Burt, T. P. (Eds), *Hydrological Forecasting*, Wiley, Chichester. pp. 405-435.
- Beven, K. 1986. 'Hillslope runoff processes and flood frequency characteristics' in Abrahams, A. D. (Ed.), *Hillslope Processes*, Allen and Unwin, Boston. pp. 187-202.
- Beven, K. 1989. 'Changing ideas in hydrology — the case of physically-based models', *J. Hydrol.*, **105**, 157-172.
- Beven, K. and Jakeman, 1990. 'Complexity and uncertainty in predictive models' in D. G. De Coursey (Ed.), *Proceedings of the International Symposium on Water Quality Modeling of Agricultural Non-Point Sources. Utah State University, Logan, UT, 19-23 June 1988, ARS-81*, United States Department of Agriculture.
- Boggie, R. and Knight, A. M. 1980. 'Tracing water movement using tritium in a peaty gley soil under Sitka spruce', *Forestry*, **53**, 179-185.
- Bonell, M., Gilmour, D. A., and Cassells, D. S. 1983. 'A preliminary survey of the hydraulic properties of rainforest soils in tropical north-east Queensland and the implications for the runoff processes' in J. De Ploey (Ed.), *Rainfall Simulation, Runoff, and Soil Erosion, Catena Suppl. No. 4*, pp. 3-24.
- Boorman, D. B. and Hollis, J. M. 1990. 'Hydrology of soil types: a hydrologically-based classification of the soils of England and Wales', *Second National Hydrology Symposium, Sheffield, UK, 4-6 September 1989*. Institute of Hydrology, Wallingford.
- Bouma, J. 1980. 'Field measurement of soil hydraulic properties characterizing water movement through swelling clay soils', *J. Hydrol.*, **45**, 149-158.
- Bridges, E. M. 1970. *World Soils*, Cambridge University Press, Cambridge.
- Burt, T. P., Heathwaite, A. L., and Labadz, J. C. 1990. 'Runoff production in peat-covered catchments' in Anderson, M. G. and Burt, T. P. (Eds), *Process Studies in Hillslope Hydrology*, Wiley, Chichester. pp. 463-500.
- Calder, I. R. 1976. 'The measurement of water losses from a forested area using a "natural" lysimeter', *J. Hydrol.*, **30**, 311-325.
- Chaing, S. L. 1970. 'A runoff potential rating table for soils', *J. Hydrol.*, **13**, 54-62.
- Chaing, S. L. and Petersen, G. W. 1970. 'Soil catena concept for hydrologic interpretations', *J. Soil Water Conserv.*, **25**, 225-227.
- Chappell, N. A. 1990. 'The characterization and modelling of soil-water-pathways in a coniferous hillslope in mid-Wales'. *Unpublished PhD Thesis*, Polytechnic South West, Plymouth.
- Chappell, N. A., Ternan, J. L., Williams, A. G., and Reynolds, B. 1990. 'Preliminary analysis of water and solute movement beneath a coniferous hillslope in mid-Wales, U.K.', *J. Hydrol.*, **116**, 201-215.
- Clinnick, P. F. 1985. 'Buffer strip management in forest operations: a review', *Austral. Forest.*, **48**, 34-45.
- Crabtree, R. W. and Trudgill, S. T. 1985. 'Hillslope hydrochemistry and stream response on wooded permeable bedrock: the role of stemflow', *J. Hydrol.*, **80**, 161-178.
- Crampton, C. B. 1963. 'The development and morphology of ironpodzols in mid and south Wales', *J. Soil Sci.*, **14**, 282-302.
- Crampton, C. B. 1967. 'The evolution of soils on the hills of south Wales and factors affecting their distribution, and their past, present and potential use' in Jenkins, D. (Ed.), *Upland Soils, Welsh Soils Discussion Group Rep. No. 8*. pp. 52-69.
- Dagan, G., Russo, D., and Bresler, E. 1990. 'Effect of spatial variability upon subsurface transport of solutes from nonpoint sources' in D. G. De Coursey (Ed.), *Proceedings of the International Symposium on Water Quality Modeling of Agricultural Non-Point Sources, Utah State University, Logan, UT, 19-23 June 1988, ARS-81*, United States Department of Agriculture.
- Demond, A. H. and Roberts, P. V. 1987. 'An examination of relative permeability relations for two-phase flow in porous media', *Wat. Resour. Bull.*, **23**, 617-628.
- Dixon, J. C. 1986. 'Solute movement on hillslopes in the alpine environment of the Colorado Front Range' in Abrahams, A. D. (Ed.), *Hillslope Processes*, Allen and Unwin, Boston. pp. 139-159.
- Dubreuil, P. L. 1985. 'Review of field observations of runoff generation in the tropics', *J. Hydrol.*, **80**, 237-264.
- Dokuchaev, V. V. 1883. *Russian chernozem*. St Petersburg.

- Dunne, T. 1978. 'Field studies of hillslope flow processes' in Kirkby, M. J. (Ed.), *Hillslope Hydrology*, Wiley, Chichester. pp. 227-293.
- Edmonds, D. T., Painter, R. B., and Ashley, G. D. 1970. 'A semi-quantitative hydrological classification of soils in north-east England', *J. Soil Sci.*, **21**, 256-264.
- Edwards, A. R. 1976. 'The peat hagg as a source of runoff — Plynlimon, mid-Wales', *Unpublished BSc Dissertation*, University of Bristol, Bristol.
- Erichsen, B. and Myrabo, S. 1990. 'Studies of the relationship between soil moisture and topography in a small catchment' in *Computational Methods in Subsurface Hydrology*. (Ed.), G. Gambolati *et al.* Proc. of the Eighth International Conference on Computational Methods in Water Resources, Venice, 1990. CML Publications and Springer-Verlag, Southampton and Berlin.
- FAO Unesco 1974. *Soil Map of the World, 1:5,000,000*, Vol 1, Unesco, Paris.
- Farquharson, F. A. K., Mackney, D., Newson, M. D., and Thomasson, A. J. 1978. 'Estimation of run-off potential of river catchments from soil surveys', *Spec. Surv. No. 11*, Soil Survey, Harpenden.
- Fiebig, D. M. 1988. 'A study of riparian zone and stream water chemistries, and organic matter immobilisation at the stream-bed interface', *Unpublished PhD Thesis*, University College of North Wales, Bangor.
- Fitzpatrick, E. A. 1956. 'An indurated soil horizon formed by permafrost', *J. Soil Sci.*, **7**, 248-254.
- Freeze, R. A. 1971. 'Three-dimensional, transient, saturated-unsaturated flow in a groundwater basin', *Wat. Resour. Res.*, **7**, 347-366.
- Freeze, R. A. 1972. 'Role of subsurface flow in generating surface runoff 2. Upstream source areas', *Wat. Resour. Res.*, **8**, 1272-1283.
- Gaskin, J. W. 1987. 'Water and solute movement in the soil of a pinus strobus plantation during storm events', *Unpublished MSc Thesis*, University of Georgia, Athens, GA.
- Gelhar, L. W., Mantoglou, A., Welty, C., and Rehfeldt, K. R. 1985. 'A review of field-scale physical solute transport process in saturated and unsaturated porous media', *EPRI EA-4190, Project 2485-5*, EPRI, Palo Alto, CA.
- Gilman, K. and Newson, M. D. 1980. *Soil Pipes and Pipeflow: A Hydrological Study in Upland Wales*, British Geomorphological Research Group Res. Monogr. 1, Geobooks, Norwich, p. 110.
- Glentworth, R. and Dion, H. G. 1949. The association of hydrologic sequence in certain soils of the podzolic zone of north-east Scotland. *J. Soil Sci.*, **1**, 35-49.
- Harr, R. D. 1977. 'Water flux in soil and subsoil on a steep forested slope', *J. Hydrol.*, **33**, 37-58.
- Hartley, R. 1987. 'An investigation into the effects of pipeline installation upon soil permeability and related soil properties', *Unpublished BSc (Hons) Dissertation*, Polytechnic South West, Plymouth.
- Hill, A. R. 1990. Groundwater cation concentrations in the riparian zone of a forested headwater stream. *Hydrol. Process.*, **4**, 121-130.
- Hillel, D. and Hornberger, G. M. 1979. 'Physical model of the hydrology of sloping heterogeneous fields', *Soil Sci. Soc. Am. J.*, **43**, 434-439.
- Hoeksema, R. J. and Kitandis, P. K. 1985. 'Analysis of the spatial structure of properties of selected aquifers', *Wat. Resour. Res.*, **21**, 563-572.
- Hoover, M. D. and Hursh, C. R. 1943. 'Influence of topography and soil depth on runoff from forest land', *Trans. Am. Geophys. Union*, **24**, 693-698.
- Hornung, M., Adamson, J. K., Reynolds, B., and Stevens, P. A. 1986. 'Influence of mineral weathering and catchment hydrology on drainage water chemistry in three upland sites in England and Wales', *J. Geol. Soc. London*, **143**, 627-634.
- Huggett, R. J. 1976. 'Lateral translocation of soil plasma through a small valley basin in the Northaw Great Wood, Hertfordshire', *Earth Surf. Process.*, **1**, 99-109.
- Hursh, C. R. 1944. 'Appendix B — Report of sub-committee on subsurface flow', *Trans. Am. Geophys. Union*, **5**, 743-746.
- Institute of Hydrology 1991. *Report of The Institute of Hydrology 1989/90*, Natural Environment Research Council, Swindon. p.58.
- Jeffries, H. 1917. 'On the vegetation of four Durham coal-measure fells. III. On water-supply as an ecological factor', *J. Ecol.*, **5**, 129-154.
- Jones, J. A. A. 1981. *The Nature of Soil Piping: A Review of Research*, British Geomorphological Research Group, Res. Monogr. 3, Geobooks, Norwich.
- Jones, J. A. A. 1990. 'Piping effects in humid lands' in Huggins, C. G. and Coates, D. R. (Eds), *Groundwater Geomorphology: The Role of Subsurface Water in Earth-Surface Processes and Landforms*, Geol. Soc. Am. Spec. Pap. No. 252.
- Kennedy, J. C., Kendall, C., Zellweger, G. W., Wyermanta, and Aranzino, R. J. 1986. 'Determination of the components of stormflow using water chemistry and environmental isotopes, Mattole River Basin, California', *J. Hydrol.*, **84**, 107-140.
- Knapp, B. J. 1970. 'Patterns of water movement on a steep upland hillside, Plynlimon, central Wales', *Unpublished PhD Thesis*, University of Reading, Reading.
- Kool, J. B., Huyakorn, P. S., and Wierenga, P. J. 1990. 'Model calibration and simulation of flow in a heterogeneous soil' in K. Kovar (Ed.), *ModelCARE 90: Calibration and Reliability in Groundwater Modelling, Proceedings. The Hague, The Netherlands, September 1990. IAHS Publ. No. 195* pp. 321-330.
- Lawrence, G. B., Fuller, R. D., and Driscoll, C. T. 1986. 'Aqueous aluminum chemistry in the streams of two upper elevation watersheds in the White Mountains of New Hampshire', *Biogeochemistry*, **2**, 115-135.
- Loague, K. M. and Freeze, R. A. 1985. 'A comparison of rainfall-runoff modelling techniques on small upland catchments', *Wat. Resour. Res.*, **21**, 229-248.
- Martinez, J. 1975. 'Subsurface flow from snowmelt traced by tritium', *Wat. Resour. Res.*, **11**, 496-498.
- McCord, J. T. and Stephens, D. B. 1987. 'Lateral moisture flow beneath a sandy hillslope without an apparent impeding layer', *Hydrol. Process.*, **1**, 225-238.
- Milne, G. 1936. 'A soil reconnaissance through parts of Tanganyika Territory', *J. Ecol.*, **30**, 192-265.
- Morgan, A. L. 1977. 'An investigation of the location, geometry, and hydraulics of ephemeral soil pipes on Plynlimon, mid-Wales', *Unpublished BSc Dissertation*, University of Manchester, Manchester.
- Murgatroyd, A. L. 1980. 'Fluvial transport in the Narrator Brook, Devon, a summary of sources, dynamics and controls', *Unpublished PhD Thesis*, Polytechnic South West, Plymouth.
- Musgrave, G. W. 1955. 'How much of the rain enters the soil?'. *Water, The Yearbook of Agriculture*. United States Department of Agriculture. pp. 151-159.
- NERC (Natural Environment Research Council) 1975. *Flood Studies Report*, Natural Environment Research Council, Swindon.

- Neal, C., Christophersen, N., Neale, R., Smith, C. J., Whitehead, P. G., and Reynolds, B. 1988. 'Chloride in precipitation and streamwater for the upland catchment of River Severn, mid-Wales; some consequences for hydrochemical models', *Hydrol. Process.*, **2**, 155-165.
- Newson, M. D. 1976. 'The physiography, deposits and vegetation of the Plynlimon catchments', *Institute of Hydrology Rep. No. 30*, Natural Environment Research Council, Swindon.
- Newson, M. D. 1978. 'Hydrological introduction' in Farquharson, F. A. K., Mackney, D., Newson, M. D., and Thomasson, A. J. (Eds), *Estimation of Run-off Potential of River Catchments from Soil Surveys, Spec. Surv. No. 11*, Soil Survey, Harpenden. pp. 1-5.
- Nielsen, D. R., Biggar, J. W., and Erh, K. T. 1973. 'Spatial variability of field-measured soil water properties', *Hilgardia*, **42**, 215-259.
- O'Loughlin, E. M. 1986. 'Prediction of surface saturation zones in natural catchments by topographic analysis', *Wat. Resour. Res.*, **22**, 794-804.
- Painter, R. B. 1971. 'A hydrological classification of the soils of England and Wales', *Proc. Civ. Engin.*, **48**, Technical Note 29, pp. 93-95.
- Pearce, A. J., Stewart, M. N., and Sklash, M. G. 1986. 'Storm runoff generation in humid headwater catchments 1. Where does the water come from?', *Wat. Resour. Res.*, **22**, 1263-1272.
- Pyatt, D. G. 1967. 'Soil survey for forestry purposes in upland Wales' in Jenkins, D. (Ed.), *Upland Soils, Welsh Soils Discussion Group Rep. No. 8*. pp. 110-119.
- Quinn, P., Beven, K., Morris, D., and Moore, R. 1990. 'The use of digital terrain data in modelling the response of hillslopes and headwaters', *Second National Hydrology Symposium, 4-6 September 1989, University of Sheffield, UK*. Institute of Hydrology, Wallingford, 1.37-1.42.
- Robinson, M. and Newson, M. D. 1986. 'Comparison of forest and moorland hydrology in an upland area with peat soils', *Int. Peat J.*, **1**, 49-68.
- Rogers, J. S. and Carter, C. E. 1987. 'Soil core sampling for hydraulic conductivity and bulk density', *Soil Sci. Soc. Am. J.*, **51**, 1393-1394.
- Rogers, C. C. M., Beven, K. J., Morris, E. M., and Anderson, M. G. 1985. 'Sensitivity analysis, calibration and predictive uncertainty of the Institute of Hydrology distributed model', *J. Hydrol.*, **81**, 179-191.
- Rogowski, A. S., Engman, F. T., and Jacoby, E. L. 1974. 'Transient response of a layered, sloping soil to natural rainfall in the presence of a shallow water table: experimental results', *ARNS-NE-30*, Agricultural Research Station, United States Department of Agriculture.
- Rudolf, G. C. 1967. 'Upland soils from Lower Palaeozoic sedimentary rocks in mid-Wales' in Jenkins, D. (Ed.), *Upland Soils, Welsh Soils Discussion Group Rep. No. 8*. pp. 42-51.
- Rudolf, G. C. 1984. *Soils and their Use in Wales, Bull. 11*, Soil Survey of England and Wales.
- SCS (Soil Conservation Service) 1964. *National Engineering Handbook: Section 4. Hydrology*, Soil Conservation Service, United States Department of Agriculture.
- Salleh Mohd. Nor, Abdul Rahim Hj. Nik, and Mushrifah Idris. 1983. 'The effect of logging on sediment yield in two forested catchment areas' in Kamis Awang, Lai Food See, Lee Su See, and Abdul Rahman Md. Derus (Eds), *Proceedings of the Regional Workshop on Hydrological Impacts of Forestry Practices and Reafforestation*, Faculty of Forestry, University Pertanian Malaysia, Serdang. pp. 61-69.
- Sinai, G. and Zaslavsky, D. 1976. 'Rainfall in the soil and near its surface, observations, models and solutions', *Publ. No. 264*, Faculty of Agricultural Engineering, Technion, Haifa, Israel.
- Stagg, M. J. 1974. 'Storm runoff in a small catchment in the Mendip Hills', *Unpublished MSc Dissertation*, University of Bristol, Bristol.
- Talsma, T. and Hallam, P. M. 1980. 'Hydraulic conductivity measurement of forest conductivity', *Austral. J. Soil Res.*, **30**, 139-148.
- Ternan, J. L. and Williams, A. G. 1979. 'Hydrological pathways and granite weathery of Dartmoor' in Pitty, A. F. (Ed.), *Geographical Approaches to Fluvial Processes*, Geobooks, Norwich, pp. 5-30.
- Ternan, J. L., Williams, A. G., and Solman, 1987. 'A preliminary assessment of soil hydraulic properties, and their implications for agroforestry management in Grenada, W. Indies', *Forest Hydrology and Watershed Management, IAHS Publ. No. 167*, pp. 409-422.
- Thomasson, A. J. 1978. 'Soil properties and winter rain acceptance potential' in Farquharson, F. A. K., Mackney, D., Newson, M. D., and Thomasson, A. J. (Eds), *Estimation of Run-off Potential of River Catchments from Soil Surveys, Spec. Surv. No. 11*, Soil Survey, Harpenden.
- Troendle, C. A. 1979. 'A variable source area model for stormflow prediction on first order forested watersheds', *Unpublished PhD Thesis*, University of Georgia, Athens, GA.
- Troendle, C. A. 1985. 'Variable source area models' in Anderson, M. G. and Burt, T. P. (Eds), *Hydrological Forecasting*, Wiley, Chichester. p. 115.
- Tsukamoto, Y. and Ohta, T. 1988. 'Runoff process on a steep forested slope', *J. Hydrol.*, **102**, 165-178.
- Waine, J., Brown, J. M. B., and Ingram, H. A. P. 1985. 'Non-Darcian transmission of water in certain humified peats', *J. Hydrol.*, **82**, 327-339.
- Walsh, R. P. D. 1980. 'Runoff processes and models in the humid tropics', *Zeitsch. Geomorphol.*, **36**, 176-202.
- Watson, E. 1967. 'The geomorphological factor in upland soil formation' in Jenkins, D. (Ed.), *Upland Soils, Welsh Soils Discussion Group Rep. 8*. pp. 11-18.
- White, J. K. and Jayawardena, A. W. 1975. 'A distributed and deterministic catchment model using finite elements', *Int. Rep.*, Department of Civil Engineering, King's College, London. p. 21.
- Wilding, L. P., Smeck, N. E., and Hall, G. F. 1983. *Pedogenesis and Soil Taxonomy 1. Concepts and Interactions*, Elsevier, Amsterdam.
- Williams, A. G., Ternan, J. L., and Kent, M. 1984. 'Hydrochemical characteristics of a Dartmoor hillslope' in Burt, T. P. and Walling, D. E. (Eds), *Catchment Experiments in Fluvial Geomorphology*, Geobooks, Norwich. pp. 374-398.
- Yeh, T.-C. and Harvey, D. J. 1990. 'Effective unsaturated hydraulic conductivity of layered sands', *Wat. Resour. Res.*, **26**, 1271-1279.
- Yeh, T.-C., Gelhar, L. W., and Gutjahr, A. L. 1985. 'Stochastic analysis of unsaturated flow in heterogeneous soils 3. Observations and applications', *Wat. Resour. Res.*, **21**, 465-471.
- Zaslavsky, D. and Sinai, G. 1981. 'Surface hydrology: V In-surface transient flow', *J. Hydraul. Div.*, **107**(1), 65-93.