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PROPERTY DISTRIBUTIONS AND FLOW STRUCTURE IN THE SLAPTON WOOD CATCHMENT

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ABSTRACT

Statistical and spatial patterns of saturated hydraulic conductivity and soil moisture have been observed within the Slapton Wood Catchment, Devon. These data combined with visual observations of exposures provide evidence for a more complex subsurface flow structure than has been described previously. This may have profound implications for the explanation of river hydrograph behaviour and the migration of nitrates towards the eutrophic Slapton Ley.

INTRODUCTION

The Slapton Wood Catchment, Devon (UK) has been the focus for hydrological and hydrochemical research for over 25 years (Burt & Heathwaite, 1996). Concern over the increasing nitrate losses via the Slapton Wood Stream has provided the key stimulus for a large proportion of this work. The stream's nitrate load increased at a rate of 0.15 mg l^{-1} a^{-1} between 1970 and 1990 (Heathwaite & Burt, 1991) and has been implicated in the eutrophication of Slapton Ley further downstream. The availability of long-term hydrological records for the catchment has more recently facilitated studies on the validation of catchment-scale hydrological models (Fisher & Beven, 1996; Thorne *et al.*, 1995).

In addition to nitrate (NO_3-N) flux via the stream, nitrate is also lost from the Slapton Wood Catchment in harvested crops and by denitrification to NO, N_2O and N_2. The slower the route of the nitrate toward a stream channel, the greater opportunity for denitrification or crop uptake. Therefore, where surface flow occurs on a recently fertilised near-stream areas, nitrate input to the channel will be rapid allowing little opportunity for denitrification or uptake. Identifying where areas of surface flow are likely to occur is therefore critical to the designation of intra-catchment areas likely to have the highest potential flux of NO_3-N into the local stream. This notion has led to the delineation nitrate 'buffer zones' within other catchments having streams with high nitrate loads. Within these buffer zones, tillage and the direct application of nitrate fertiliser is restricted (Burt *et al.*, 1993; Collier *et al.*, 1995).

Rapid surface flow is initiated where the saturated hydraulic conductivity (K_s) of the topsoil is less than the prevailing rainfall intensity (i.e., an infiltration-excess process), where precipitation falls on to saturated soils, or where subsurface flow exfiltrates (i.e., the saturation-excess processes). Identification of the most sensitive parts of a catchment to infiltration-excess overland flow can be estimated from a spatial distribution of topsoil K_s measurements. Areas of a catchment likely to saturate and hence produce saturation-excess overland flow are more difficult to predict being dependent on the K_s of the whole depth of the subsurface system, the subsurface contributing area and local slope angle (Kirkby, 1976). Within some experimental catchments both the pattern of K_s and pattern of moisture content can be related to specific topographic elements (Quinn *et al.,* 1991; Chappell & Ternan, 1992). If such relationships can be established for the Slapton Wood Catchment, this would allow the rigorous delineation of nitrate buffer zones, perhaps the most cost-effective method (*cf.* DOE, 1988) of reducing nitrate losses into Slapton Ley.

CATCHMENT CHARACTERISTICS

The Slapton Wood Experimental Catchment is 0.93 km^2 in area and underlain by Dartmouth Slates of the Lower Devonian formation. Field observation and British Geological Survey (1976) indicate that this bedrock has been extensively folded with a 70° dip to the south beneath the catchment. Such deformation is likely to have opened the cleavage planes between the slates (Wilson, 1982).

The catchment has an elongated shape with average hillslope lengths of 180 m to the NE of Slapton Wood Stream and 550 m on the more complex SW side of the stream. Along the main valley, slopes exceed 30° while above *ca* 120 m on the SW side of the catchment, slopes are typically less than 5°. Two zero-order drainage basins, the 0.26 km^2 'Carness Hollow' and the 0.17 km^2 'Eastergrounds Hollow' drain eastward from the 120 m high 'plateau' towards the Slapton Wood Stream. Oak (*Quercus* spp.) and sweet chestnut (*Castanea sativa*) trees of Slapton Wood cover the lower 0.12 km^2 of the catchment, while land above 100 m is largely arable. The remaining slopes along the main valley and in the hillslope hollows are mixed arable and permanent pasture. Measurements of groundwater properties were collected from this range of hillslope and land-use types found within the Slapton Wood Catchment.

GROUNDWATER PROPERTY CHARACTERISATION

Groundwater properties comprise the moisture content and potential *variables* and temporally-invariant *parameters* such as saturated hydraulic conductivity and moisture release. Sensitivity analysis indicates that the moisture variables are most responsive to the statistical and spatial distribution of the parameter of saturated hydraulic conductivity (K_s).

Saturated hydraulic conductivity

Measurements of the soil K_s were collected within the Slapton Wood Catchment using a ring permeameter, where the 'soil' comprises the A and B horizons (Brady, 1984). The ring permeametry method described by Bonell *et al.* (1983) and Ternan *et al.* (1987) involves the excavation of an 'undisturbed' core 0.30 m in diameter and 0.10 m in depth. The K_s is then derived in the field by application of a constant-head to the core's upper surface, with the lower surface at atmospheric pressure. A total of 32 soil cores have been extracted from the surface 0.10 m which typically represents the A soil horizon, and a further 13 cores from the same x-y location but at 0.10 to 0.20 m depth, which represents the upper part of the B soil horizon. These core sampling locations are shown in Fig. 1.

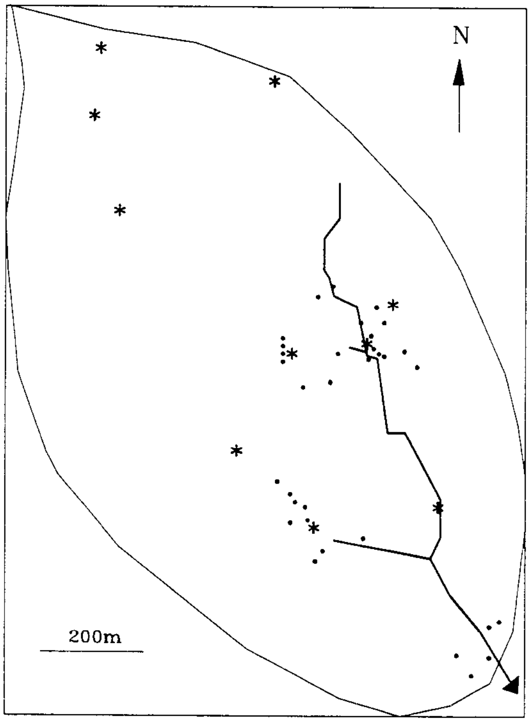


Fig. 1.
The x-y location of the sampling locations for the ring permeametry (•) and piezometry (⋆) tests in the Slapton Wood Catchment.

The spatial structure in the 32 spatially-referenced data points representing the A horizon were analysed by calculation of the semi-variance ($\hat{\gamma}(h)$) over lag distances (h) of up to 550 m where:

$$\hat{\gamma}(h) = \frac{1}{2(n-h)} \sum_{i=1}^{n-h} \{z(i) - z(i+h)\}^2$$

z is a value of saturated hydraulic conductivity and n is the sample position. The results plotted as semi-variograms allow continuous changes in K_s within hydrologically similar soil types to be distinguished from step changes between different soil types (Chappell & Ternan, 1992). Two semi-variograms were calculated for the K_s data, with one for the dominant slope direction of SW-NE which is likely to be the dominant direction for any catenary development. A second semi-variogram was calculated for the direction normal to this i.e., NW-SW.

In addition to the measurements of soil permeability, K_s was also derived from piezometer recovery (Luthin & Kirkham, 1949) and piezometer slug tests (British Standards Institution, 1981) conducted on 14 piezometers with tapping depths at between 0.05 and 18.50 m into the Dartmouth Slate. These piezometers had been installed by the Institute of Hydrology as part of a programme of experimentation for UK Nirex Ltd. (Thorne *et al.*, 1995). The dataset subsequently used within the statistical analysis is based on a combination of tests undertaken by the authors and on test data made available by J. Ewen (pers. comm. 1995). Those boreholes used for *Ks* testing and subsequent analysis are shown in Fig. 1.

Soil moisture content

The influence of an observed *Ks* pattern on catchment flow-paths can be examined through the effect on soil moisture pattern. Kirkby (1976) demonstrated how spatial patterns in soil moisture (θ) can be related to both the topographic controls of slope angle (β) and convergence, and to the soil's saturated hydraulic conductivity (*Ks*), where:

$$\theta_i \ \alpha \ ln\{a/(K_s \ tan \ \beta)\}$$

and *a* is the upslope area that would drain to location *i*, which on planar slopes becomes the distance to the catchment divide. Where marked step changes in K_s (i.e., catenary patterns) are either not present or where K_s is inversely correlated to the topographic index of $ln\{a/(tan \ \beta)\}$ then only the topographic index is required to identify spatial patterns in soil moisture. Such a situation is assumed in most simulations of TOPMODEL, including its application to the Slapton Wood Catchment (Fisher, 1995; Fisher & Beven, 1996). To examine the topographic versus K_s control on soil moisture within the Slapton Wood Catchment values of soil moisture were derived from measurements of the soil's apparent dielectric constant (*Ka*) where:

$$Ka = (ct/L)^2$$

and *ct* is 'apparent length of the wave-guide' (m) measured using a Tektronics 1502 time-domain-reflectometer (TDR) and *L* is the actual length of the wave-guide (m). These data were collected along transects 40 to 190 m in length, located normal to the elevation contours on planar slopes (i.e., neither converging nor diverging). Each measurement of the *Ka* was integrated over the upper 0.30 m of the soil, with recordings being taken every 5 or 10 m along each experimental transect. The twin-rod wave-guides used gave a sampling volume of approximately 3×10^{-4} m^3 (Baker & Lascano, 1989). Volumetric soil moisture content was derived from the *Ka* data using the empirical formula of Topp *et al.* (1980) where:

$$\theta = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} \, Ka \ 5.5 \times 10^{-4} \, Ka^2 + 4.3 \times 10^{-6} \, Ka^3$$

where θ is the volumetric soil moisture content (as a ratio) and *Ka* is the apparent dielectric constant. A total of 202 moisture measurements were derived from the transects *a* to *p* shown in Fig. 2. Transects *i* and *j* are located in Carness Hollow, transects *d, e, f, g* and *h* are located in Eastergrounds Hollow, while *a, b, c, k, l, m, n, o* and *p* are all located in the main valley. As with the hydraulic conductivity measurements, all moisture values were sampled at known x-y locations within the catchment. As the slopes within the main valley have the same general direction, the presence of a step (or catenary) change in θ should be clearly observed in a uni-directional variogram. Only those data collected from the main valley slopes (transects *a* to *c* and *k* to *p*) were therefore analysed using uni-directional variograms. The whole data set collected within the Slapton Wood Catchment was used to identify the underlying statistical distribution.

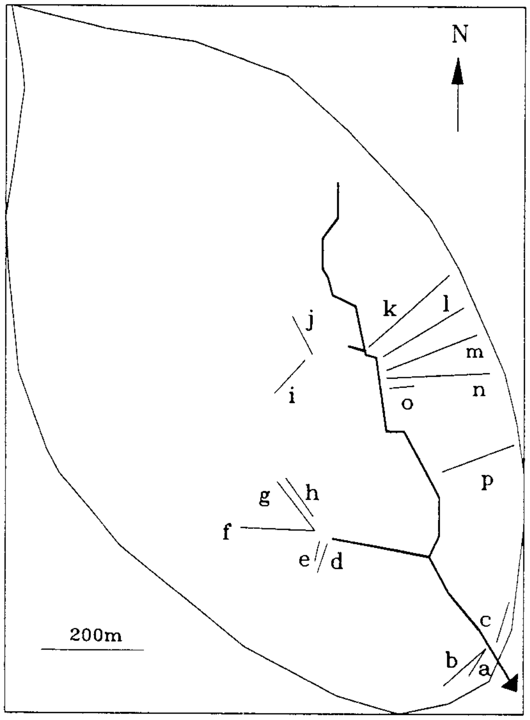


FIG. 2.
The x–y location of the experimental transects (*a* to *p*) in the Slapton Wood Catchment. Measurements of soil moisture content by time-domain-reflectometry, bulk resistivity, slope angle and distance to catchment divide were taken at either 5 m or 10 m intervals along each transect.

Topography and bulk resistivity
Measurements of slope angle and bulk resistivity were also taken at each Ka sampling location. The local slope angle was estimated with a clinometer and was used in the assessment of topographic controls on moisture pattern. Bulk resistivity measurements were taken with an Abem Terrameter with electrodes arranged in a Wenner configuration, where the bulk resistivity (ρ_a in Ωm) is:

$$\rho_a = 4\,\pi R\,a$$

where R is the resistance measured by the resistivity meter (Ω) and a is the electrode spacing (m). The electrode spacing was fixed at 0.5 m to give a sampling region centred on a depth of approximately 0.25 m. The ρ_a data were later used to examine the effects of varying soil matrix properties on soil moisture, as changing matrix properties are likely to be associated with varying K_s. Where a strong inverse relationship is observed between the spatial pattern in bulk soil resistivity and that of volumetric soil moisture content, this implies that the soil matrix is either homogeneous (with the ρ_a varying only with changing θ) or that the soil texture becomes finer (less resistive) as moisture content increases. Conversely, where a strong inverse relationship is not observed, this implies either that the flow-controlling parameters, notably K_s, are poorly correlated with the bulk resistivity or that the soil moisture control of the matrix parameters is not correlated with the other moisture control of topography.

TABLE 1. *Kolmogorov-Smirnov test statistics for the raw soil moisture data (θ) and the raw and log_{10} transformed saturated hydraulic conductivity data (Ks). A significance level of greater than 0.950 indicates a normal distribution.*

Data distribution	Significance level
θ, raw data	0.999
K_s, raw data	< 0.001
K_s, $\log_{10}$ transformed data	1.000

Visual observations

In addition to the permeametry, TDR and resistivity, over twenty soil pits have been excavated within the Slapton Wood Catchment for detailed observation of the soil stratigraphy. These logs have been complemented with stratigraphic data on the underlying solifluction head and bedrock recorded during the piezometer drilling (J. Ewan, pers. comm., 1995) and more limited exposures of the bedrock and head at NGR81914666 (UK National Grid Reference), NGR82034647, NGR821246333 and NGR82154585.

CONDUCTIVITY DISTRIBUTIONS

Statistical distribution

The data set of all ring permeametry and piezometer-based measurements indicates that the statistical distribution of saturated hydraulic conductivity in the Slapton Wood Catchment is very positively skewed (Fig. 3a). A Kolmogorov-Smirnov test (Wrinkler & Hays, 1975) indicates that the underlying distribution is log-normal (Table 1) and this is confirmed with the symmetry of the box-and-whisker plot of the $\log_{10}$ transformed data (Fig. 3b). Most data sets of saturated hydraulic conductivity indicate a log-normal distribution (e.g., Nielsen *et al.*, 1973; Bonell *et al.*, 1983), though less skewed data sets have been observed (e.g., Elsenbeer *et al.*, 1992). The mean of such a distribution is the geometric mean, and at Slapton Wood the geometric mean *Ks* of the soil and Dartmouth Slate is 14.0×10^{-6} m s^{-1}. The geometric mean K_s for the soil A and B horizons alone is 23.1×10^{-6} m s^{-1} which is broadly comparable with the mean soil *Ks* of 6×10^{-6} m s^{-1} derived using a Geulph permeameter at four plots within the Slapton Wood Catchment (Ragab & Cooper, 1993). No data are available for the *Ks* of the lenses of solifluction head observed within the catchment.

Rainfall intensities recorded at Slapton rarely exceed 4 mm hr^{-1} or 1×10^{-6} m s^{-1} (Burt & Heathwaite, 1996; Ratsey, 1975) and therefore in gently sloping terrain almost all rainfall should infiltrate the subsurface flow system. However, on steeply sloping land a small component may generate surface flow as a result of rain splash (Zaslavsky

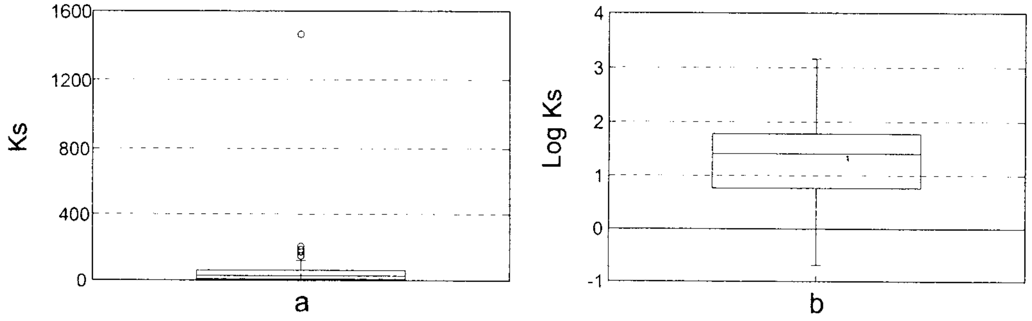


FIG. 3.
Box-and-whisker plots of the saturated hydraulic conductivity data collected within the Slapton Wood Catchment in (a) raw form ($\times 10^{-6}$ m s^{-1}) and (b) after normalisation by a $\log_{10}$ transform. The interquartile range forms the 'box', the central bar is the median, the lower 'whisker' is the lower quartile minus 1.5 times the interquartile range, the upper 'whisker' is the lower quartile plus 1.5 times the interquartile range and ¤ is an outlier.

& Sinai, 1981a). This flow component is critical to the downslope movement of particulates (Burt & Heathwaite, 1996).

The ring permeametry and piezometry data have a standard deviation (σ) of 50.1×10^{-6} m s^{-1} and a coefficient of variation (ε) of 358 percent which is larger than the range of 5 to 200 percent reported in the review paper of Durner & Flüher (1993). Given such high values it is worth examining the K_s data for deterministic spatial structure.

Spatial distribution

The soil surveys indicate that the dominant soil type in the Slapton Wood Catchment is a eutric cambisol (brown earth), although poorly developed humic, gleyic, regic and albic characteristics (FAO-UNESCO, 1974) are found in certain areas. The greatest catenary development is shown within the central portion of the main valley, where 'patches' of regosol (thin soils) have developed on the steepest slopes and 'patches' of gleysol have developed within 5 m of the Slapton Wood stream (Fig. 4). Development of gleysol within the footslopes of the catchment as a whole is very limited, with humic cambisol being characteristic of most footslope areas of the main valley and hillslope hollows. Inevitably tillage and chemical applications to the fields have affected the soils in most of the catchment. Evidence of such anthropogenic affects are seen with the accumulations of eroded fines upslope of field boundaries and adjacent to the Slapton Wood Stream at for example at NGR82064626 and NGR82304577. The dystric cambisol (Trudgill, 1983) and ferric podzol found on the mid-slopes beneath the oak woodland in the SSW corner of the catchment may represent a remnant of soil largely unaffected by long-term agricultural activity. These soils may have been more extensive prior to soil disturbance by agriculture.

Given the dominance of cambisol with only patches of other soils, marked catenary development and the associated step changes in K_s are not expected (Chappell & Ternan, 1992). A lack of step changes in K_s in the slope-ward direction is often associated with a lack of a distinct step in K_s between the A and B horizons (i.e., z-

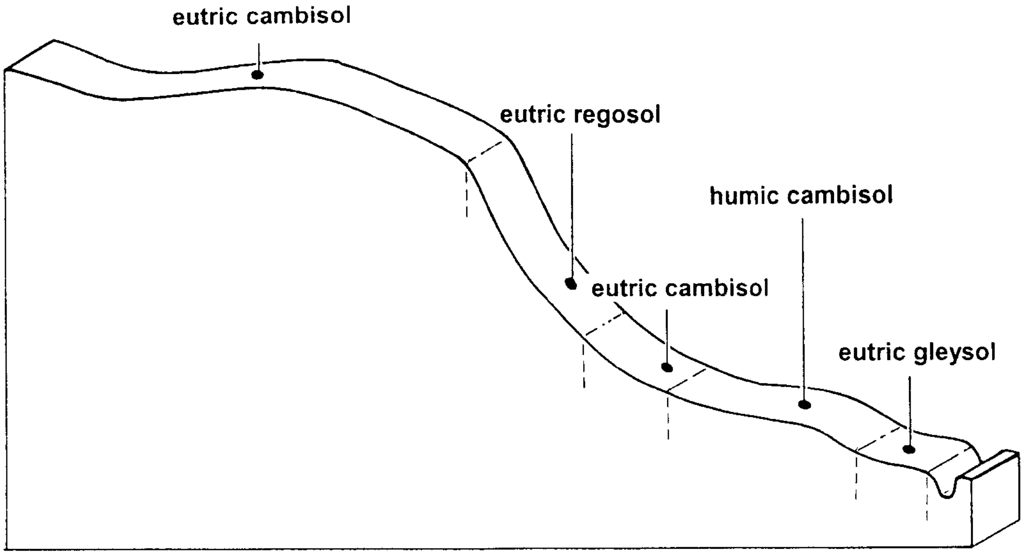


FIG. 4.
An idealised soil catena for the slope section between NGR82074632 and NGR82274639 on the NE side of the Slapton Wood Stream in the centre of the Slapton Wood Catchment.

direction; Chappell & Ternan, 1992). The K_s of the A horizon has a geometric mean of 20.1×10^{-6} m s^{-1} (σ 48.3×10^{-6} m s^{-1}) which is statistically different at the p 0.05 level from the 32.6×10^{-6} m s^{-1} geometric mean of the B horizon data (σ 382×10^{-6} m s^{-1}), but only a factor of 0.62 smaller. Such a difference does not constitute of a major step change in K_s (Chappell & Ternan, 1992). The extent of catenary development in the K_s pattern was examined using variogram analysis. The semi-variogram calculated for the direction normal to the direction of possible catenary development, i.e., NW-SE shows a simple monotonic increase in semi-variance (Fig. 5a), which indicates an increasing dissimilarity of K_s values with horizontal distance. This is the expected pattern for a spatial structure within a particular soil type. The absence of 'holes' in the variogram indicates that there are no step changes in soil K_s and hence no step changes in soil type in the direction normal to the soil catena, as expected. In some contrast, the SW-NE semi-variogram exhibits a more complex spatial structure (Fig. 5b) indicative of catenary development; however, this is not easily related to the length dimensions of different soil types along an idealised catena (e.g., Fig. 4). The complex nature of the spatial structure in this direction is further illustrated by the presence of 'nugget variance' which is a high semi-variance at very small lags. This indicates that K_s varies considerably even over very small horizontal distances.

Of equal or even greater hydrological and hydrochemical significance than the pattern of soil K_s, is the relatively high conductivity at depth within the Slapton Wood Catchment. The geometric mean conductivity for the bedrock of 3.08×10^{-6} m s^{-1} (σ 8.19×10^{-6} m s^{-1}) and the absence of a decline in K_s with depth in the Dartmouth Slate (Fig. 6) indicates that the conductivity is dependant on the presence of hydro-

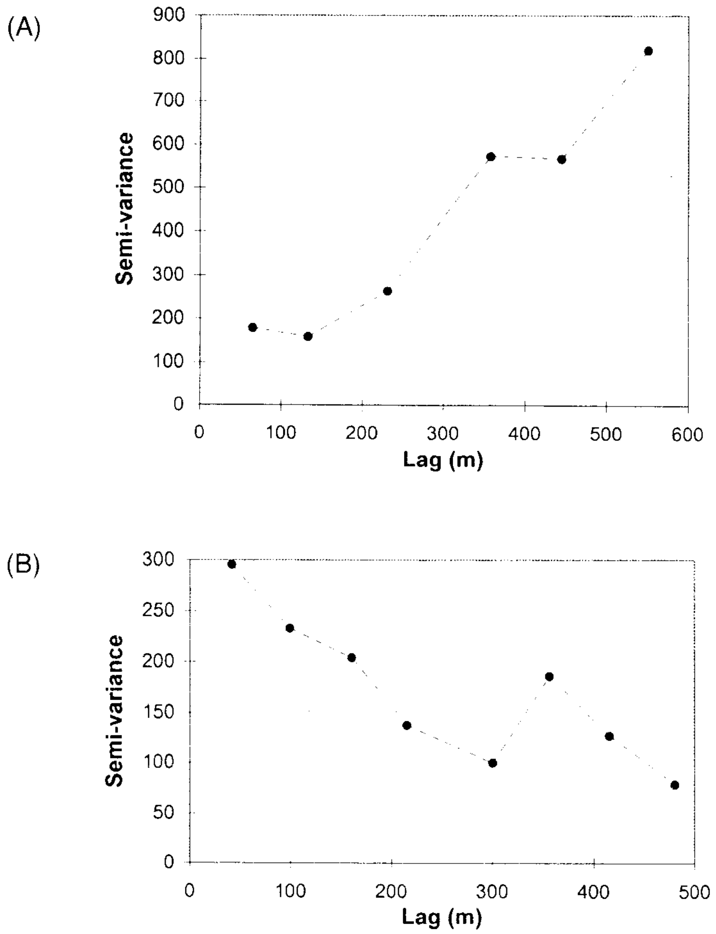


FIG. 5.
Uni-directional semi-variograms for the soil K_s, in (a) the NW-SE direction which is normal to the dominant slope and in (b) the SW-NE direction which is parallel to the dominant slope, the direction most likely to exhibit catena-related step changes in soil K_s.

logically active fractures. This hypothesis is supported by the large-scale deformation of the brittle Dartmouth Slates (British Geological Survey, 1976; Wilson, 1982), by the behaviour of the river hydrograph, by the chaotic piezometric surface and by the results of the TOPMODEL simulations (Fisher, 1995). Troake & Walling (1973), Burt *et al.*, (1983) and Burt & Heathwaite (1996b) report that the Slapton Wood Catchment generates 'double-peaked hydrographs' during the winter months, with the second peak being delayed by several days and integrating the majority of the discharge. This second peak may be related to response propagating through 'wedges' of saturated soil (Burt *et al.*, 1983) but equally may relate to flow along a much deeper pathway in the bedrock. This deep pathway would be along specific fractures, as the catchment's Q_{95} low-flow

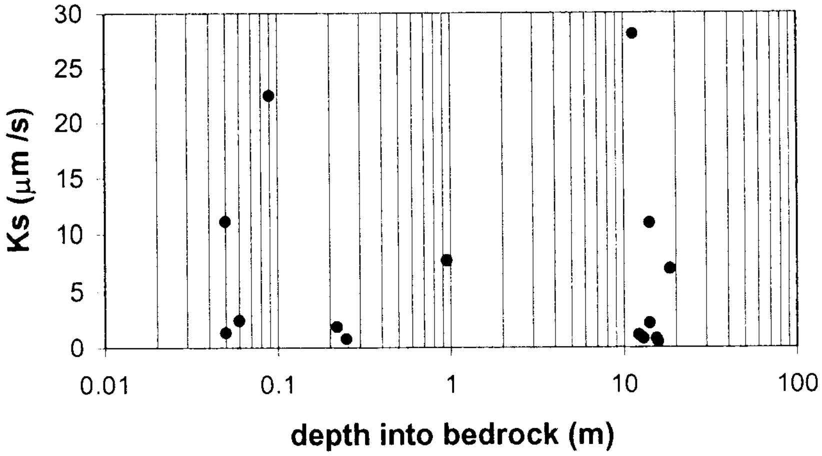
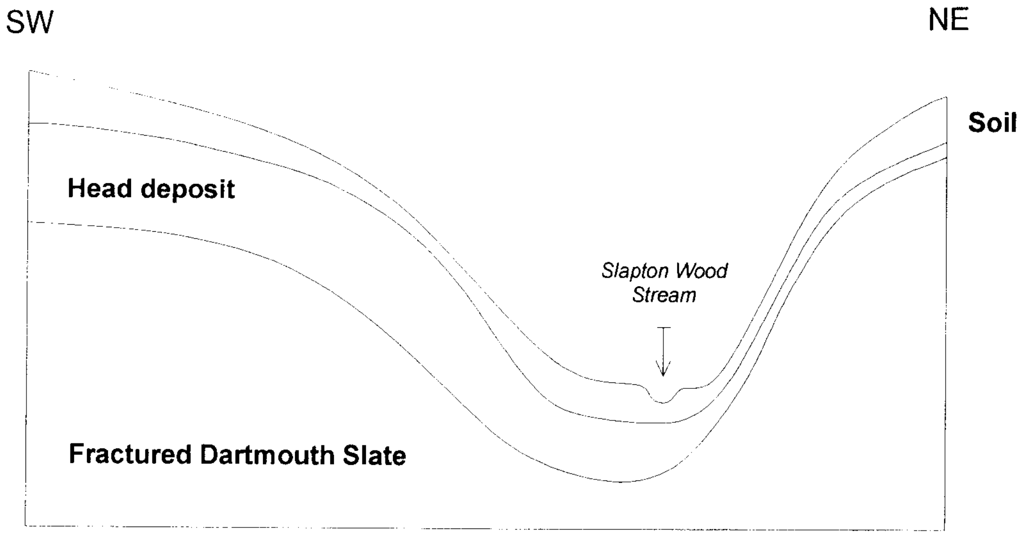


FIG. 6.
The relationship between K_s and sampling depth in the Dartmouth Slate bedrock.

statistic of 0.14 (derived from Fig. 4 in Burt & Heathwaite, 1996) is relatively small indicating that the subsurface system has a low total porosity compared to that of a major aquifer (*cf.* Institute of Hydrology, 1985). Interpolation of the piezometer water levels within the Dartmouth Slate gives a very chaotic surface at the catchment scale (Fisher, 1995) which can be again explained by the dominance of fracture flow.

The subsurface flow system at Slapton Wood is further complicated by the presence of solifluction head. These deposits extend to a depth of approximately 2.5 m beneath the 0.5 m of soil on much of the SW side of the catchment (i.e., NE facing slopes), though they are almost absent on the SW facing slopes in the NE sector. This greater development of head on NE and N facing slopes has been observed at many other sites in western Britain (e.g., Watson, 1967; Chappell *et al.*, 1990). The presence of head within the subsurface system has been shown by several studies (e.g., Williams *et al.*, 1984; Chappell *et al.*, 1990) to generate zones of saturated soil or sediment 'perched' above unsaturated rock. Percolation is impeded either because of the fine matrix or because of the presence of localised 'fragipan' layers (Fitzpatrick, 1956; Harris, 1987; Chappell *et al.*, 1990). While descriptions of the particle-size-distributions are available for the head deposits developed on the region's metamorphic rocks (Mottershead, 1971; Harris, 1987) there is a complete dearth of permeability data. There is, however, compelling evidence for the presence of perched water-tables above a slowly conductive head within the Slapton Wood Catchment. For example, in the centre of Eastergrounds Hollow in the SW sector of the catchment, soil and surface saturation can be observed adjacent to the piezometer at NGR81954599 where water-tables are typically 3 m below the ground surface within the upper layer of Dartmouth Slate. Further evidence for the slowly permeable nature of the head can be seen in Carness Hollow where augering through the solifluction head to the Dartmouth Slate (at NGR81994634) has yielded artesian flow.



Soil depths range from 0.2 m on the steep NE slopes to 0.5 m on the crest-slopes in the SW catchment sector

Depths of head deposit range from less than 0.1 m on the steep NE slopes to over 2 m on SW slopes

FIG. 7.
A schematic diagram of the proposed subsurface system in the Slapton Wood Catchment.

Evidence for the presence of perched water tables on the SW catchment sector plus more extensive fractured bedrock is gained from the application of TOPMODEL to the catchment. Such simulations have required two model parameter sets to hindcast the catchment behaviour for both the summer and winter periods (Fisher, 1995). This can be explained by the presence of two 'stores' with different time-constants and therefore may be associated with a saturated zone developed above the head in the SW of the catchment showing different temporal dynamics to those of the phreatic zone in the fractured bedrock. A schematic diagram summarising this proposed complex subsurface system is given in Fig. 7.

MOISTURE DISTRIBUTIONS

Statistical distribution

In contrast to the distribution of conductivity, volumetric soil moisture is normally distributed across the Slapton Wood Catchment. Presentation of the data in a box-and whisker diagram indicates that the distribution of moisture content shows weak positive skew (Fig. 8a), which can be normalised with a square root transform (Fig. 8b). A Kolmogorov-Smirnov test (Table 1) does, however, indicate that the raw data are sufficiently normal for parametric statistics. Most data sets of soil moisture collected in other catchments similarly indicate a normal distribution (e.g., Nielson *et al.*, 1973). The arithmetic mean moisture content for the Slapton soils (averaged over the upper 0.3 m of the 0.5 m soil profile) is 0.396 m^3 m^{-3}. Assuming a mean porosity of *ca* 0.5 m^3 m^{-3}

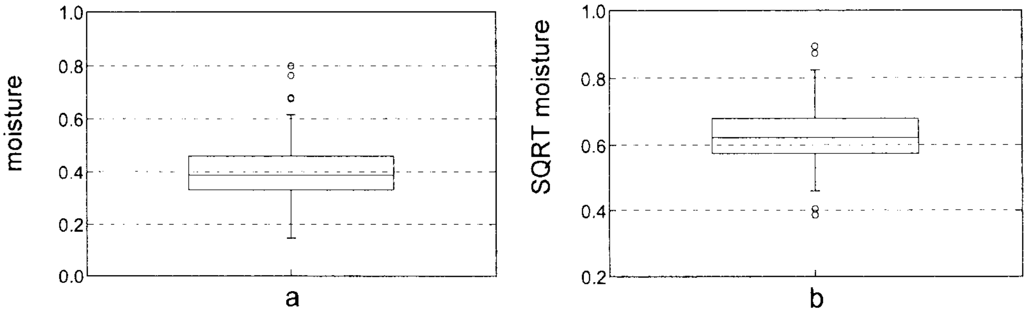


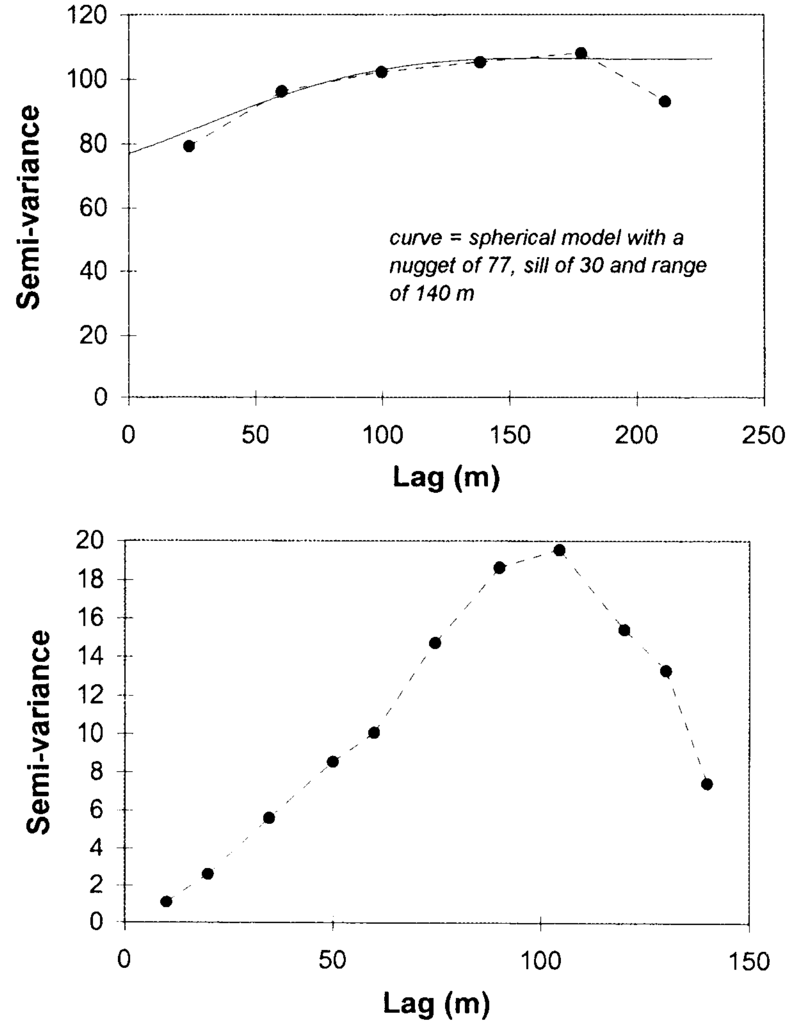
FIG. 8.
A box-and-whisker plot of the distribution of soil moisture content in the Slapton Wood Catchment in (a) raw form ($m^3\ m^{-3}$) and (b) after normalisation by a square root transform. The interquartile range forms the 'box', the central bar is the median, the lower 'whisker' is the lower quartile minus 1.5 times the interquartile range, the upper 'whisker' is the lower quartile plus 1.5 times the interquartile range, and is an outlier.

(Brady, 1984) this equates with *ca* 70 percent saturated soil, which is comparable to that monitored at other sites in western Britain (Hudson, 1988; Chappell, 1990). The coefficient of variation of 26 percent (σ 0.101 $m^3\ m^{-3}$) for the moisture data is smaller than that of the K_s data, as noted at other experimental sites (e.g., Durner & Flüher, 1993). This relatively small spatial variation is however significantly larger than the temporal variation in moisture at a point (Chappell, 1990; Schiffler, 1992) and may therefore be useful in the identification of surface and subsurface flow structure.

Spatial distribution

Using all transects on the uni-directional main valley slopes, the semi-variance in the direction normal to the slope contours (SW-NE direction) increases with distance (Fig. 9a). This indicates that there are no regionally extensive step changes in moisture that could be related to observed step changes in the topographic index or to possible step changes in soil K_s. Examination of the 15 soil moisture values collected along transect *l* alone does, however, indicate a contrasting situation. The semi-variogram for transect *l* (Fig. 9b) shows clear topographic pattern, with the wet soils at the slope base being correlated with the wet crest soils at the opposite end of the transect and poorly correlated with the dry soils on the mid-slopes. Such a soil moisture pattern is predicted by the topographic index of $ln\{a/(tan\ \beta)\}$ where soil K_s is either homogenous, or inversely correlated to the index.

At transect *l*, the correlation (r^2) of 0.65 between the moisture and index (Fig. 10) is high compared to those correlations for most other experimental transects within the catchment measured by this study (Table 2) and by Butcher (1985) in Eastergrounds Hollow. The clear topographic control on soil moisture in transect *l* could be explained by the soil K_s in the immediate vicinity of that transect being inversely correlated with the topographic index where the mid-slopes have a higher K_s in comparison to that of the foot and crest slopes. While K_s data to confirm this hypothesis are limited, the highest K_s value recorded anywhere in the catchment (1,464 × 10^{-6} m s^{-1} at 0.10 to



curve = spherical model with a nugget of 77, sill of 30 and range of 140 m

FIG. 9.
Uni-directional semi-variograms for the soil moisture content in the SW-NE direction parallel to the dominant slope (or normal to the contours) (a) for all transects in the main valley (transects *a* to *c* and *k* to *p*) and (b) for transect *l* (Fig. 2) alone.

0.20 m depth) was sampled on the regic mid-slope relatively close to transect *l* and the lowest recorded value (0.203×10^{-6} m s^{-1}) was sampled at 0 to 0.10 m in the gleysol near to the foot of transect *l*.

An alternative hypothesis to explain the atypical correlation between θ and *ln*{*a*/(*tan* β)} along transect *l* is a less fractured bedrock in the area of transect *l* compared to that beneath the other experimental transects. Where lateral flow in the soil is not significant with all percolation moving vertically into the underlying fractured bedrock, then soil moisture is not expected to be correlated with surface topography (Quinn *et al.*, 1991).

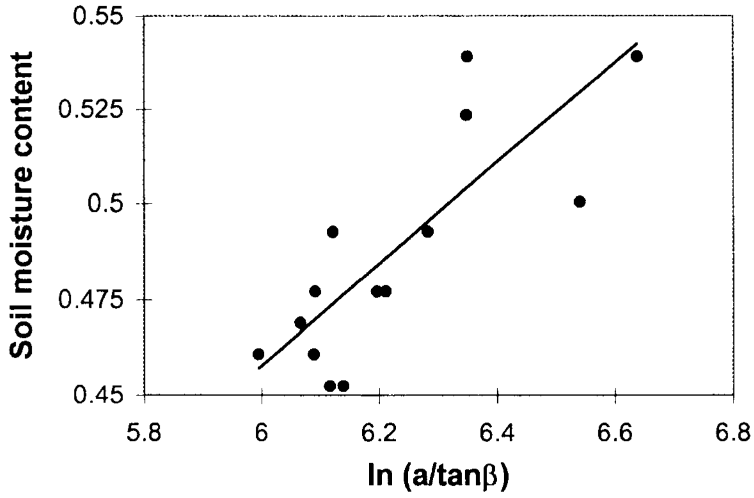


FIG. 10.
The correlation between the soil moisture content (m^3 m^{-3}) and the topographic index of *ln*{*a*/(*tan β*) for data collected along transect *l* (Fig. 2).

Thus, transect *l* may overly a relatively massive bedrock which generates significant throughflow within the soil. This process would be aided by the downslope orientation of the slate fragments in the regic B horizon, and by the steepness of the slope at this locality (*cf.* Zaslavsky & Sinai, 1981b). Examination of the soil resistivity data does however, support the former of the two hypotheses. In the vicinity of transect *l* the correlation between the soil's bulk resistivity and its volumetric moisture content is 0.55, while at all other transects the r^2 is less than 0.30. This finding could be explained with the wetter soils being associated with finer, less resistive and less permeable soils. Accepting this explanation would imply that soils covering most of the catchment exhibit complex catena-ward patterns. This is consistent with the results of the semi-variogram for K_s in the catena-ward direction (Fig. 5b).

CONCLUSIONS

Analysis of the distributions of saturated hydraulic conductivity and soil moisture appears to indicate that the subsurface flow system at Slapton is significantly more complex than described previously. There are perhaps three distinct elements to this complexity. First, there are step changes in soil K_s occurring over varying length scales in the direction of the soil catena. Such structure is absent within most of the soil moisture data, implying that the complex pattern in soil, head and rock K_s obfuscate moisture patterns caused by topographic controls of slope angle or convergence. Second, perched water-tables are observed in the SW side of the catchment, implying the presence of slowly conductive solifluction head. Lastly, significant fracture flow may be present in the Dartmouth Slate even at depths in excess of 15 m.

This new model of the subsurface system may better explain the multiphasic hydrograph response of the Slapton Wood Stream, with the delayed storm peaks resulting from response propagation through saturated soil and the fractured slate and the marked seasonality in hydrograph form (Fisher, 1995) resulting from the differential behaviour of phreatic zones above the head and in the slate. There are also implications for the delineation and use of nitrate buffer zones within the catchment. First, the complex structure of the soil K_s distribution in the slope-ward or catena-ward direction means that the generation of surface flow in riparian soils is likely to be very patchy along the length of the stream. This makes it difficult to delineate a fixed-width nitrate buffer-zone adjacent to the streams. Second, the presence of highly conductive fractures deep within Dartmouth Slate that dip at 70° towards the catchment outlet, may mean that high nitrate inputs to a particular field close to the catchment divide will not follow the pathway indicated by the surface topography, but will flow to depth and enter the stream much further down the catchment. This becomes important if one wishes to protect only those channel reaches affected by a point source of nitrate entering the groundwater on either mid- or crest-slopes.

TABLE 2. *The correlation between the soil moisture content and the topographic index of* $\ln\{a/(\tan\beta)$ *for data collected along the experimental transects in the Slapton Wood Catchment. An* r^2 *of 1.00 indicates a perfect correlation.*

Transect	r^2	Transect	r^2	Transect	r^2
a	0.04	*g*	0.21	*m*	0.02
b	0.13	*h*	0.53	*n*	0.20
c	0.01	*i*	0.11	*o*	0.16
d	0.01	*j*	0.13	*p*	0.03
e	0.16	*k*	0.01		
f	0.41*	*l*	0.65		

* statistic in error due to significant slope convergence along transect, but assumed to be planar in the calculation of $\ln\{a/(\tan\beta)$.

Further measurements, notably K_s tests in the solifluction head, and a deep geophysical survey of the structure of the fractured bedrock are required to substantiate the proposed model of the subsurface system at Slapton.

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