

THE HYDROLOGY OF THE SLAPTON CATCHMENTS

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ABSTRACT

Despite adequate rainfall throughout the year, runoff is strongly seasonal in the catchments draining into Slapton Ley. This is, in part, caused by high evaporation losses in the summer months but also because the deep permeable soils function like a shallow aquifer. Streamflow falls to a low level in the summer months; high flows resume in the winter once the large soil moisture deficit has been recharged. Despite the dominance of subsurface flow, there has been a significant increase in the incidence of surface runoff in recent years. The implications of this mixture of hydrological pathways for the quality of water draining into the Ley are briefly discussed. Slapton Ley itself is a shallow lake basin with a very low retention time in the winter. Outflow from the lake takes place mainly through the Torcross culvert but, in summer, when the water level is low, seepage through the shingle ridge is the only significant loss. Deposition of sediment during storm events is probably important at all times of the year and especially in the Higher Ley. In terms of eutrophication, the nutrient load of summer baseflow may be most important.

INTRODUCTION

The focus of Slapton Ley National Nature Reserve is its 116 ha wetland which contains the largest natural body of freshwater in south west England. The lake basin may be conveniently divided into two. The Higher Ley (39 ha) is now mainly reed swamp and willow carr, having been the sink for sediment input from its catchment over the last century and more significantly since 1945 (Heathwaite & O'Sullivan, 1991; Jenns, 1994; O'Sullivan, 1994; Johnes & Wilson, 1996). The Lower Ley (77 ha) is open water fringed with reed; being shallow (maximum depth 2.8 m), the rate of sedimentation is of concern here also, though rates of infill are only about one third of those in the Higher Ley. This is partly because the Higher Ley acts as a trap for sediment from the major part of the lake catchment (see below) and partly because the rate of sediment input is lower from the more gently sloping catchments feeding directly to the Lower Ley. In the 1960s, it became apparent that the Ley was becoming increasingly eutrophic. In order to gauge water, sediment and nutrient inputs into the lake, measurements began on the main catchment area in late 1969. Continuous monitoring of discharge and a weekly water-sampling programme have been maintained by the Slapton Ley Field Centre ever since. This long-term study has been supplemented by a number of research projects which have sought to identify the salient hydrological processes operating in the catchment and to relate these to the delivery of sediment and solutes to the stream system (and thence into the lake). The purpose of this paper is to review the hydrological studies; other papers in this part of *Field Studies* cover the research on sediment and solute transport.

The catchment of Slapton Ley occupies 46 km² (Fig. 1) and is characterised by extensive plateaux of low gradient (below 5°) with steep valley-side slopes below (up to 24°). The catchment comprises four main basins of which the Gara (gauged area, 23.62 km²) and the Start (gauged area, 10.79 km²) are most important. Given its proximity to the Field Centre, much attention has been accorded to the Slapton Wood catchment, despite its small size (gauged area, 0.93 km²). The fourth of these basins, the Stokeley Barton stream (gauged area, 1.53 km²) drains the southern part of the catchment; water budget calculations and hydrograph analysis suggest that its hydrology may differ somewhat from the rest of the catchment. In addition to the gauged area, there is a total of 5.61 km² of ungauged area below the four gauging stations, and a further 3.08 km² of minor drainage basins which flow directly into the Ley. Thus the gauged area of 36.81 km² comprises 81% of the total catchment area (van Vlymen, 1979).

As Fig. 1 shows, the lake basin is oriented north-south, with the Gara entering from the north, the other streams from the west, and the main outflow exiting over a weir at the extreme south. Details of the weir outflow and of seepage through the shingle ridge are described in van Vlymen (1979) and will be briefly discussed in a later section of this paper, and at greater length in Johnes & Wilson (1996). The Lower Ley itself has a mean depth of 1.55 m. Its volume at weir datum is 1,190,000 m³; van Vlymen (1979) notes a maximum recorded volume of 2,090,000 m³ (11th February 1974) and a minimum of 540,000 m³ (10th September 1976). Because of the relatively large size of the catchment in relation to the small lake volume, hydraulic retention averages only 18 days, equal to a flushing of 20 times per year; winter flooding may result in the loss of a third of the lake's volume in only 24 hours. The implications of this high rate of turnover are discussed later. Given its shallowness, the Higher Ley has limited storage capacity but nevertheless causes some attenuation of flood hydrographs entering from the Gara; however, very little is known about the precise hydrology of the Higher Ley.

PATTERNS OF STREAMFLOW

In the following paragraphs, a selection of commonly-used methods of analysing streamflow are presented; in general, as the timescale of analysis increases, the use of aggregate discharge figures becomes more convenient.

Annual hydrograph

The use of mean daily discharge figures provides a useful summary of flow variations during the year. Fig. 2 shows the daily mean flow for the Slapton Wood catchment for the 1978 water year (beginning 1st October 1977). The variation in discharge is surprisingly extreme, with flows well above the mean in winter, but well below in summer. High flows are generated once soil moisture has been recharged during the autumn; each major rainfall event then produces a clear flood hydrograph lasting several days, details of which are discussed below. In summer, once the shallow soils have dried out, discharge remains very low and flood hydrographs are short-lived, hardly noticeable using daily means. As will be seen later, runoff generation in the Slapton catchments is dominated by subsurface flow processes; the protracted flood hydrographs seen in winter are in fact very similar to those observed in shallow aquifers such as the Jurassic limestones of the Cotswold Hills (Haycock & Burt, 1993).

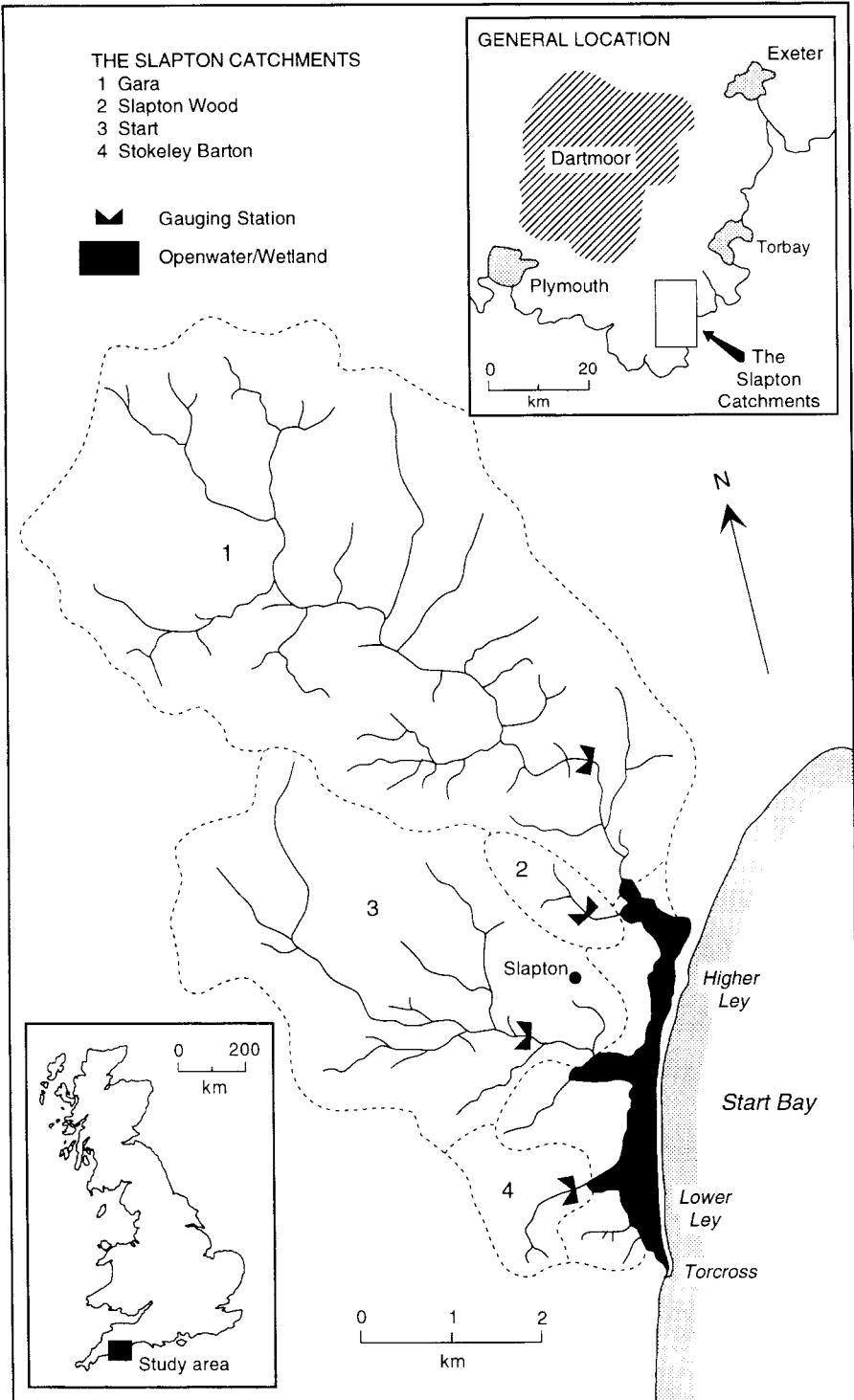


FIG. 1
The catchments draining into Slapton Ley

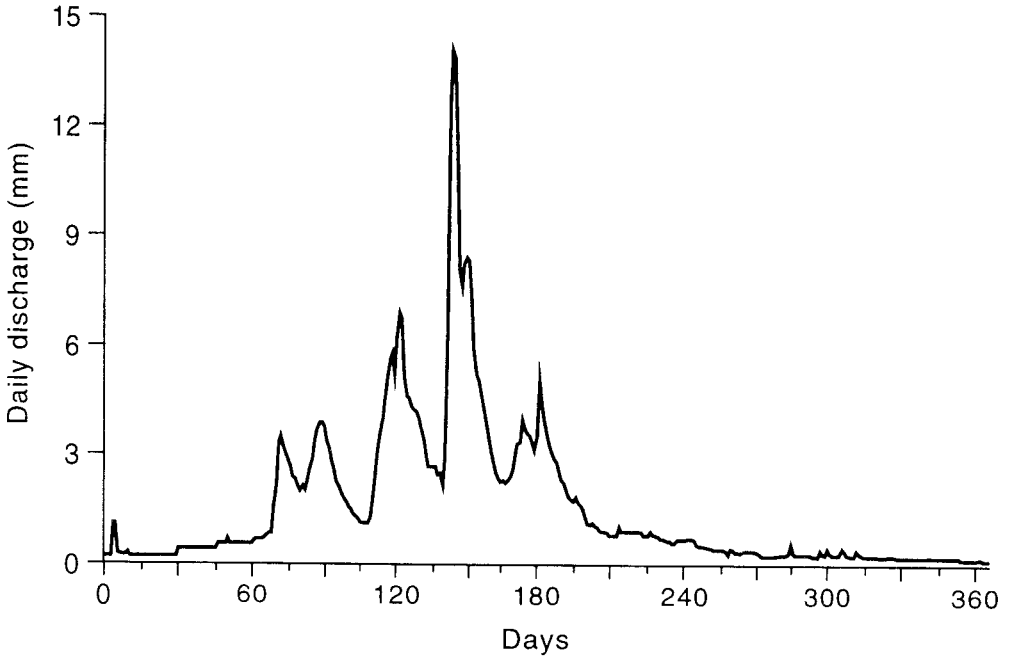


FIG. 2.
Daily mean flow for the Slapton Wood stream. 1978 water year.

However, unlike a deep aquifer, there is little water storage in the Slapton soils; this means that streamflow is not sustained through the summer and consequently falls to a very low level (though the streams remain perennial).

Runoff regime

The regime of a river may be defined as its seasonal variation and is usually portrayed by a curve based on mean monthly flow. Fig. 3 shows the runoff regime for the Slapton Wood catchment, averaged over several years. The regime confirms the extreme nature of flow in the Slapton catchments. Though a catchment dominated by subsurface flow, it is evident that flows are very low in summer once the soil has dried out. In stark contrast, once soils wet up in the autumn, discharges from December to March are well above the mean especially in January and February. It should be noted that mean monthly flows in a river fed by a deep aquifer vary only between 0.5 and 1.5 of the annual mean flow (Burt, 1992). Thus, on the evidence of Figs 2 and 3, it is concluded that the Slapton catchments are less flashy than streams fed largely by surface runoff but less dampened than those dominated by deep groundwater flow. A further example of the seasonality of runoff response in the Slapton catchments is given in Burt *et al.* (1996; Table 1), showing the dependence of nitrate leaching on stream discharge.

TABLE 1. Comparison of mean annual runoff from the Slapton catchments (van Vlymen, 1979).

	Gara	Start	Slapton Wood	Stokeley Barton	Minor Drainage
Runoff (mm)	781	535	463	294	421
% drainage area of total	58.8	28.1	2.7	3.7	6.7
% runoff of total	69.5	22.7	1.9	1.6	4.3

Flow frequency and duration

Flow duration curves are prepared by ranking the discharge values, starting with the lowest, and calculating the percentile of each value in the series. The cumulative frequency, expressed as a percentage of the total, is then the basis of the flow duration curve, which shows the percentage of time during which any selected discharge is equalled or exceeded. Fig. 4 shows an analysis of the daily mean discharges for the 1978 water year, plotted on probability paper, with a dimensionless flow axis (daily mean flow divided by mean daily flow). The flow duration curve confirms the intermediate nature of the flow regime for the Slapton Wood catchment; a steeper flow duration curve would indicate a flashy flow regime with little baseflow and large storm hydrographs; a shallow curve would indicate sustained groundwater flow with relatively little stormflow.

It is, of course, necessary to discuss the extent to which flow patterns in the Slapton Wood catchment are representative of the Slapton Ley catchment as a whole. Comparison of runoff volumes and hydrograph shapes suggests that the Slapton Wood catchment mirrors well the hydrology of the Gara and Start basins. However, the larger size of these two basins means inevitably that their flood hydrographs are less peaked and more rounded in shape. It is usual for specific discharge (absolute flow rates corrected for basin area) to be lower from larger basins. This has not been studied in detail for the Slapton catchments but there is some suggestion of this effect in hydrographs presented by Heathwaite *et al.* (1990). It is known that the Stokeley Barton catchment produces less runoff and hydrographs of different shape to the other basins. It is thought that this is caused by the distinctive soils found in that catchment, although leakage of the weir pond might account in part for the lower runoff.

Water balance

The water balance over a selected time period can be calculated as follows:

$$P - Q - G - \Delta S - E = 0$$

where P is precipitation, Q is stream discharge, G is groundwater discharge, E is evaporation and ΔS is change in storage. Given the impermeable nature of the Devonian slates and shales, it can be safely assumed that the Slapton catchments are watertight and that there is no deep seepage of groundwater into or out of the area. The exception to this may be the Stokeley Barton stream where runoff seems anomalously low; Troake & Walling (1975) assumed that there were deep seepage losses but van Vlymen (1979) suggested that surface runoff along the main road was responsible for the low runoff figures observed at the gauging station.

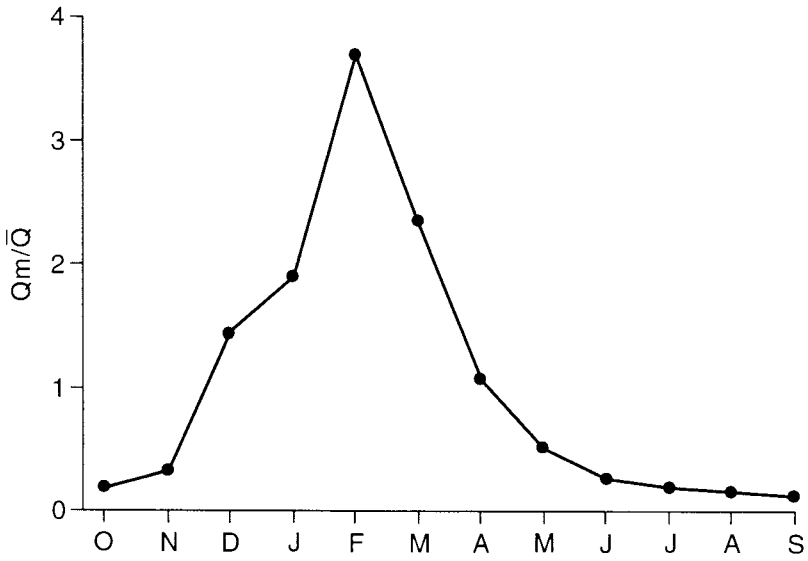


FIG. 3
The runoff regime for the Slapton Wood stream.

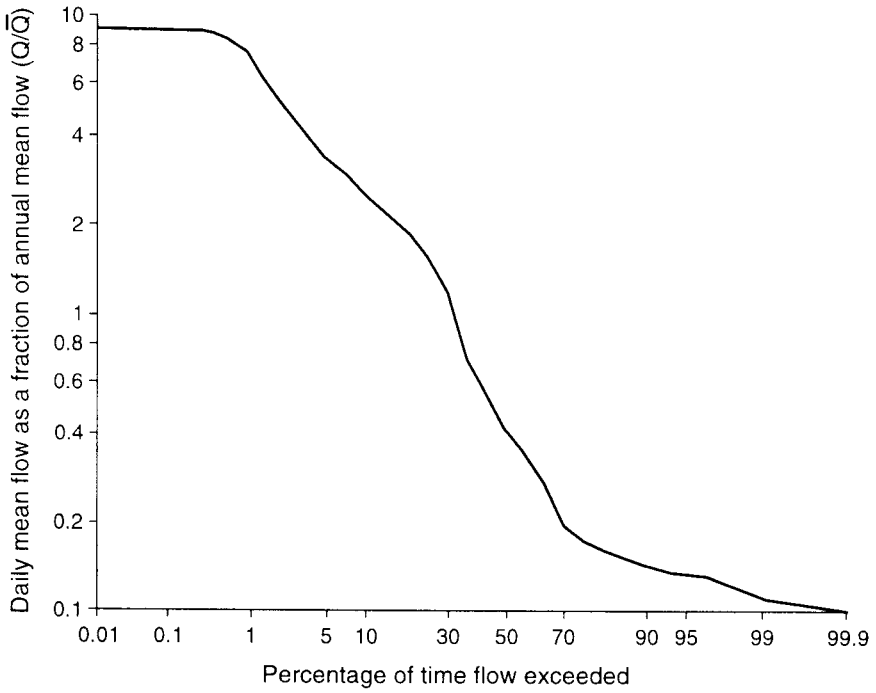


FIG. 4.
Flow duration curve for the Slapton Wood stream, 1978 water year.

Fig. 5 shows the monthly water balance for the Slapton Wood stream for the water years 1975–7, which includes the most extreme period of drought observed so far in the Slapton catchment. Potential evaporation was calculated using the Penman method and these data were then used to calculate actual evaporation losses using the ‘root constant’ concept (See Shaw, 1993, chapter 11). Two elements of climate control the annual runoff regime: high evaporation in summer and the peak in rainfall from October to February. The 1974–5 water year is fairly typical in this regard, with high winter discharges closely following the peaks in rainfall, and a steady flow recession thereafter through the summer. From February 1975 to August 1976 inclusive, however, only two months recorded above-average rainfall at Slapton, the total in this period being over 500 mm less than average. This rainfall deficit, together with high evaporation during the hot summers of 1975 and 1976, provided one of the most severe droughts recorded in Britain. Although soils returned to field capacity in the autumn of 1975, there was insufficient excess winter rainfall increase runoff. In both hot summers, soil moisture deficits were too high to sustain evaporation at the potential rate. By contrast, the period from September 1976 to February 1977 was one of the wettest on record: soil moisture was quickly recharged and winter runoff reached record levels. Assuming an arbitrary storage of 500 mm at the end of September 1974, catchment storage had fallen to 368 mm by October 1975 and to 277 mm at the end of August 1976, but had recovered to 577 mm by the end of February 1977. It should be noted that the budgeting does not provide an exact water ‘balance’ for the Slapton Wood catchment, even when using a longer data set, and suggests that the Field Centre raingauge may underestimate catchment inputs by about 7% (Burt *et al.*, 1988).

Blackie (pers. comm.) provided the following water balance for the Slapton Wood catchment for the 1990 water year:

Precipitation	1015 mm
Runoff	540 mm
Actual evaporation	475 mm
Potential evaporation	767 mm

Blackie showed that the Field Centre raingauge underestimates rainfall for the Slapton Wood catchment by 12%. Van Vlymen (1979) argues that rainfall for the Slapton catchment as a whole is under estimated by 15–20%. Table 1 shows runoff for each drainage basin within the Slapton Ley catchment, including adjustments for ungauged areas. An increase in rainfall and a decrease in evaporation towards the higher, northern part of the basin account for this variation; the low output from the Stokeley Barton stream has already been commented upon. Van Vlymen (1979) shows that the mean daily discharge for the entire catchment area is $82,000 \text{ m}^3 \text{ day}^{-1}$, equivalent to 1.75 mm runoff depth, an annual runoff of 639 mm. For a mean annual rainfall at the Field Centre of 1034 mm (1961–90 figures), this yields a rainfall:runoff ratio (‘runoff percent’) of 62%; assuming catchment rainfall to be 15% greater than the Centre total, the runoff percent becomes 54%. For the Slapton Wood catchment, the ratio of rainfall to runoff is 47% (Burt, 1993).

STORM RUNOFF GENERATION

The nature of soil and bedrock determine the pathways by which hillslope runoff will reach a stream channel. At Slapton, the main bulk of the shale bedrock is totally

impermeable, but the soil and regolith are naturally very permeable, allowing large volumes of subsurface stormflow to be produced quickly after rainfall. Troake & Walling (1973) showed that only 1% of the annual runoff of the Slapton Wood stream is stormflow (though their analysis ignored secondary, delayed hydrographs which are now known to be important components of winter runoff—see below). The terminology used here concerning storm runoff mechanisms follows that given in Burt (1992).

The hydraulic conductivity of Slapton soils

The most extensive survey of soil hydraulic conductivity in the Slapton catchments has been undertaken by Ragab & Cooper (1993a, b). They used a Guelph permeameter to determine saturated hydraulic conductivity and related parameters in the field. Three land uses were investigated: arable land (including temporary grassland), permanent grassland and woodland. Given the log-normal distribution of hydraulic conductivity values, geometric means are presented in Table 2. High values of saturated hydraulic conductivity in the grassland and woodland were attributed to preferential flow along the faces of slate stones and root channels, as indicated by dye tracing (*cf.* Coles & Trudgill, 1985). Lower values in the arable soils seem to reflect compaction following tillage. High values at depth under permanent grassland were also observed by Burt & Butcher (1985a); they stressed the importance of this highly permeable layer in facilitating the rapid subsurface stormflow response seen for the Slapton Wood stream. This effect was also reported for the other Slapton catchments in Heathwaite *et al.* (1989).

TABLE 2. Saturated hydraulic conductivity values (mm hr^{-1}) for soils in the Slapton Wood catchment (after Ragab & Cooper, 1993a).

	15 cm	30cm	45 cm	60 cm
Arable	12.0 (n=19)	11.3 (n=15)	9.9 (n=17)	8.6 (n=22)
Grassland	34.4 (n=6)	19.3 (n=6)	88.7 (n=12)	44.4 (n=7)
Woodland	14.4 (31)	no data	27.2 (n=30)	37.0 (n=30)

Infiltration

The infiltration capacity of the silty clay loams of the Slapton region is naturally high, but such soils are easily compacted and infiltration can fall to a level where infiltration-excess overland flow can occur in heavy rain if soils are mismanaged. Even light use of the soil reduces the infiltration capacity below that of woodland or freshly ploughed soil. Table 3 shows infiltration capacities for a variety of land uses measured using either a rainfall simulator (Bowyer-Bower & Burt, 1989) or a ring infiltrometer (Burt, 1978). Two points are worth making in relation to the hydraulic conductivity values presented above. Firstly, surface measurements show that infiltration can fall to a very low level if (wet) soils become compacted by overgrazing or the use of heavy machinery. Secondly, high infiltration capacities may occur where tillage or shrinkage cracks have opened up the soil surface. Permeameter measurements at 15 cm depth may well miss such macropore flow pathways. Coles & Trudgill (1985) showed that the soils at Slapton are weakly structured and that infiltration may by-pass the soil matrix and flow down macropores under certain conditions. They identified important thresholds controlling

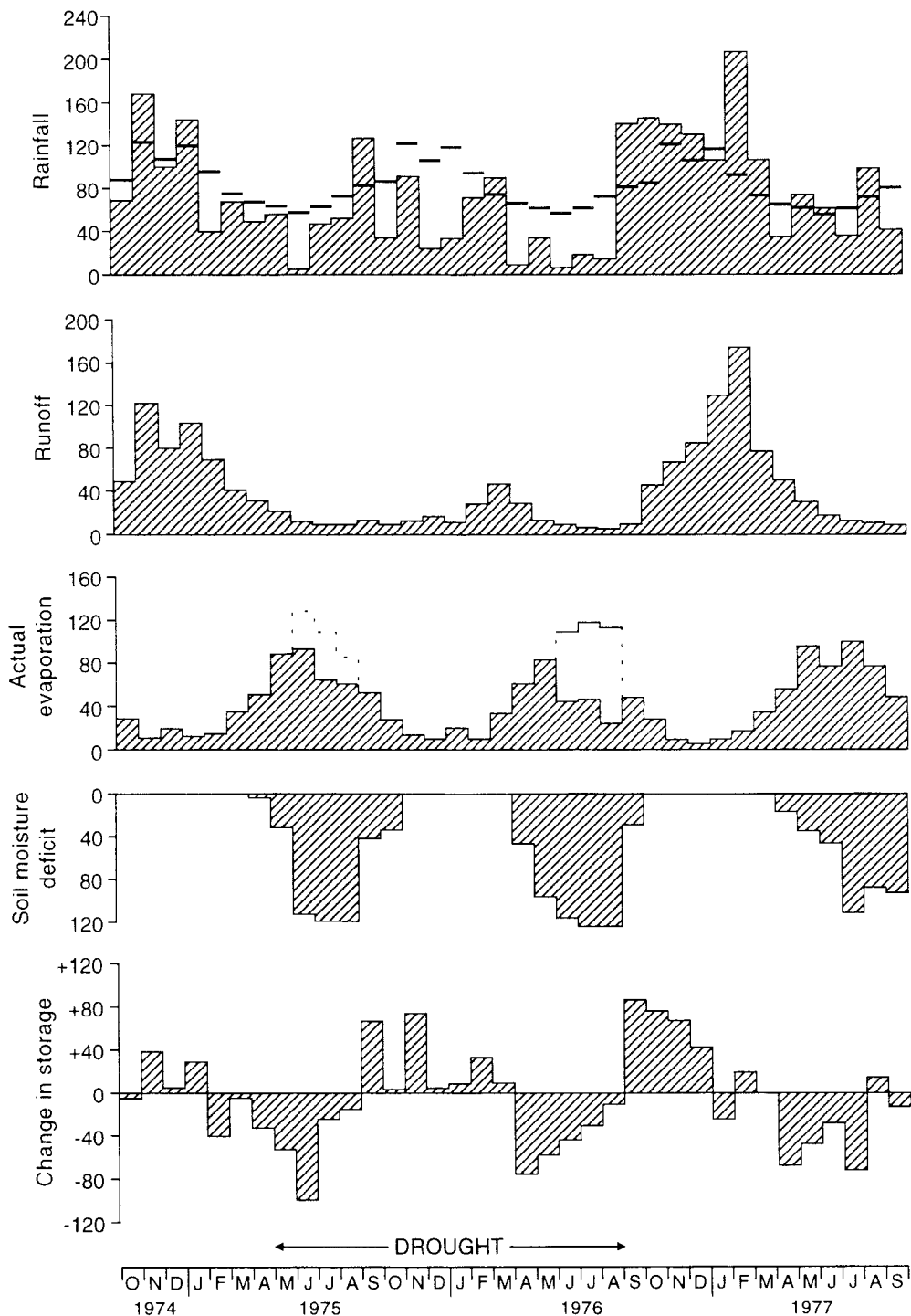


FIG. 5.
Monthly water balance for the Slapton Wood stream, 1974-1977.

macropore flow. For rainfall intensities below the hydraulic conductivity of the peds (about 2.5 mm hr^{-1}), no macropore flow will occur, except when the soil is at field capacity. A further threshold exists in relation to antecedent soil moisture; if the soil is too dry then any flow in the macropores is rapidly absorbed into the peds.

TABLE 3. *The effect of land use on surface runoff from hillslope plots.*

Land use	Rainfall intensity (mm hr^{-1})	Infiltration capacity (mm hr^{-1})	Bulk density (g cm^{-3})
Temporary grass	12.5	12.33	0.96
Barley	12.5	11.04	1.08
Rolled, bare ground	12.5	4.00	0.93
Lightly-grazed permanent pasture	12.5	5.85	1.12
Heavily-grazed permanent pasture	12.5	0.10	1.18
Permanent pasture *		9 (range 3–36)	
Freshly ploughed soil *		50	
Woodland soil *		180	

Data from Heathwaite *et al.* (1990), Burt *et al.* (1983) and Burt & Butcher (1985a).
Results obtained using a rainfall simulator except where indicated *.

Spatial and temporal controls of storm runoff generation

The combination of steep slopes, permeable soil over impermeable bedrock, and high rainfall, encourages the production of large volumes of subsurface runoff. This dominance has already been noted: Fig. 5 shows how stream discharge increases markedly in winter months and Figs 2, 3 and 4 all confirm the seasonal importance of subsurface flow. Troake & Walling (1973) estimated that *quickflow* (i.e. that fraction of precipitation which rapidly reaches the stream channel and is usually associated with high discharge) only accounts for 1% of the annual runoff total. Butcher (1984) has shown that much of the *baseflow* occurs in winter in the form of delayed flood hydrographs which peak several days after the quickflow response. An example of a delayed hydrograph is shown in Fig. 6; such discharge events occur on average about eight times every winter. Only in small catchments where conditions are particularly favourable for subsurface runoff generation are such 'double' peak hydrographs recorded. In summer, when soil moisture deficits are high, only single peak hydrographs occur, indicating that no significant amount of subsurface flow occurs at such times (Burt & Butcher, 1985b). Burt & Butcher (1985a) showed that the large dry valleys which connect the interfluvial plateaux to the stream system are especially important locations for the generation of subsurface stormflow. Smaller events may be generated by subsurface flow from the valley-side slopes alone, but the largest delayed hydrographs are associated with extensive saturation of the plateaux. Lateral flow from these areas will, under conditions of high soil saturation, move rapidly down through the dry valley network to augment the saturated zone adjacent to the main stream. Robinson (unpublished), working at the base of the Carness hollow (the dry valley adjacent to Eastergrounds, where Burt & Butcher conducted their studies) found that the water table remained well below the ground surface, even during very wet periods (February 1990). However, later observations

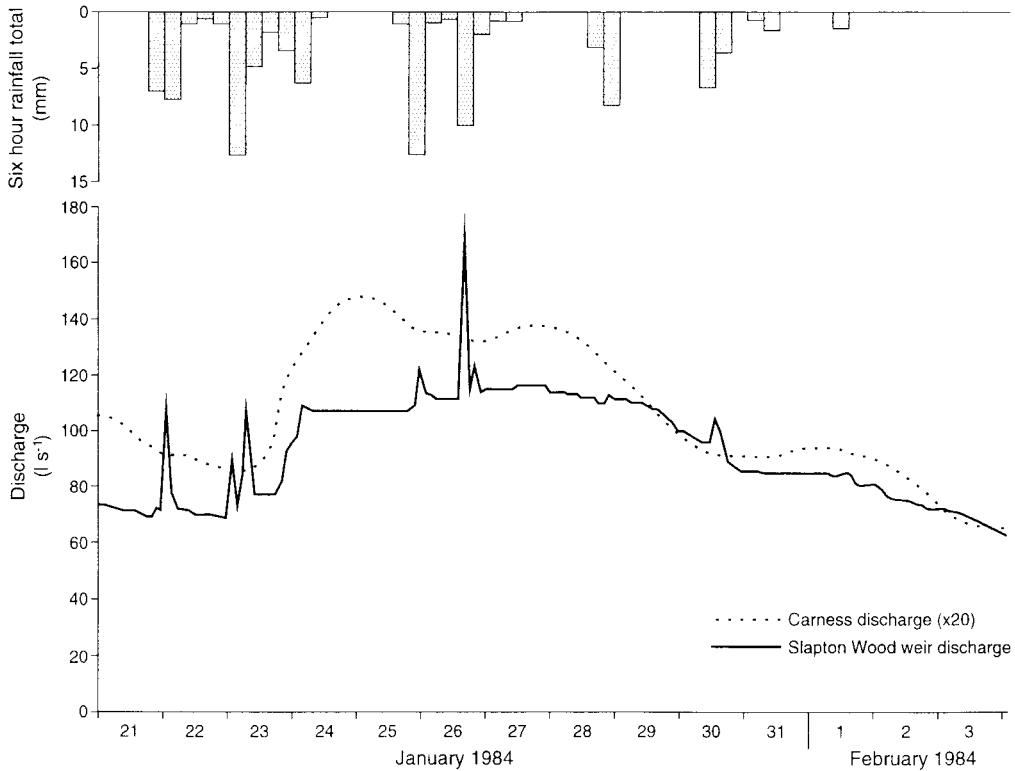


FIG. 6.
A typical double-peak hydrograph for a winter flood event

(December 1994) at the same site showed that, following blockage of a tile drain, the water table was now much higher and the soil was fully saturated at the bottom of the hollow, with a spring issuing from the hillslope and an extensive zone of surface saturation between the spring and the stream. The implication is that, in the absence of land drainage, the water table will be at or close to the ground surface in such locations during wet, winter periods.

These areas of surface saturation are important in that they generate *saturation-excess overland flow*. This is a mixture of *direct runoff* (rain falling on to the saturated area which, being unable to infiltrate, ponds on the ground surface and eventually runs off downslope) and *return flow* (subsurface flow returning to the soil surface). The large dry valleys are important locations for the occurrence of saturation-excess overland flow since subsurface drainage from large upslope catchment areas converges into a restricted zone (Burt & Butcher, 1985a). As expected, the saturated areas are most extensive in the wettest winters when, in addition to those areas already mentioned, there are extensive zones of surface saturation alongside the stream channel. The precise significance of saturation-excess overland flow in the Slapton catchments is not known; probably subsurface stormflow remains dominant under most conditions, with saturation-excess overland flow becoming more important during the largest winter flood events when the

catchment is already very wet. Such variable source areas and their associated patterns of surface and subsurface flow generation are particularly important in the context of nutrient export from the catchment. This is examined in detail in Burt, Heathwaite & Johnes (1996).

Burt *et al.* (1983) reported the occurrence of *infiltration-excess overland flow* at the Eastergrounds field site (Slapton Wood catchment). At the time of their observations (early 1980s), this type of runoff was considered rare in the Slapton catchment, and thought to be confined, apart from impermeable roads and tracks, to overgrazed fields. More recently, infiltration-excess overland flow has been more commonly observed, most notably on arable fields which have been rolled to produce a fine tilth (Heathwaite *et al.*, 1990; Heathwaite & Burt, 1992). As data on Table 3 show, infiltration capacities on such fields may fall to very low levels so that, even in light (but prolonged) rain, water may pond and eventually run off over the soil surface. Heathwaite & Burt (1992) report severe erosion on fields just south of the Slapton catchment in the winter of 1989/90; this erosion seemed to occur when hourly rainfall totals exceeded 4 mm hr^{-1} . Rainfall intensities at Slapton exceeded 4 mm hr^{-1} four times on 13th December 1989 (6.5, 7.0, 5.0, 11.0) and again on 20th December (8.0, 4.5, 4.5, 6.0); eye-witness reports of the erosion at South Allington connected the erosion and off-site flooding with these two storms. The wettest day on record at Slapton is 16th July 1987, when 88 mm fell in 5 hours; the maximum intensity was probably close to 50 mm hr^{-1} . Full crop cover at that time of year seems to have precluded widespread infiltration-excess runoff; only localised instances were observed, and there was severe erosion in only one field close to Slapton, where a winter fodder crop had been recently drilled. During the 1990s, there has been plenty of evidence of overland flow, in the form of rills and gullies, within the Slapton catchments. Even so, during the wet winters of 1993/94 and 1994/95, there was less evidence of runoff and erosion than expected, either because farmers are now rolling tilled soils less vigorously or because of the impact of set-aside measures in taking some fields out of arable production. However, severe erosion of a potato field was observed at Carness during the 1995–1996 winter.

To summarise, storm runoff production in the Slapton catchments is dominated volumetrically by subsurface stormflow. Peak quickflow discharge is usually a mixture of surface (infiltration-excess runoff, mainly from roads and tracks) and subsurface flow. Saturation-excess overland flow is probably only a major contributor to stormflow during large winter flood events when antecedent soil moisture conditions are favourable. This combination of storm runoff sources has important implications for water quality during flood events (See Burt, Heathwaite & Johnes, 1996).

LAKE WATER BALANCE

The only comprehensive study of the water balance of Slapton Ley itself has been by van Vlymen (1979). He concluded that the water balance of the lake was markedly 'flow dominated' with a relatively small storage capacity: the highly unstable water level reflects a rapid response to increased inflow. Slapton Ley is a small, shallow lake fed by a comparatively large catchment; because of this its hydraulic retention is low, averaging only 18 days during the period of van Vlymen's study (1973–77), equivalent to a flushing rate of 20 times per year. At peak winter inflow, up to one third of the lake's volume may be displaced in twenty four hours, almost all of it into the culvert constructed at Torcross in the mid-nineteenth century. In summer, when the water level is low and

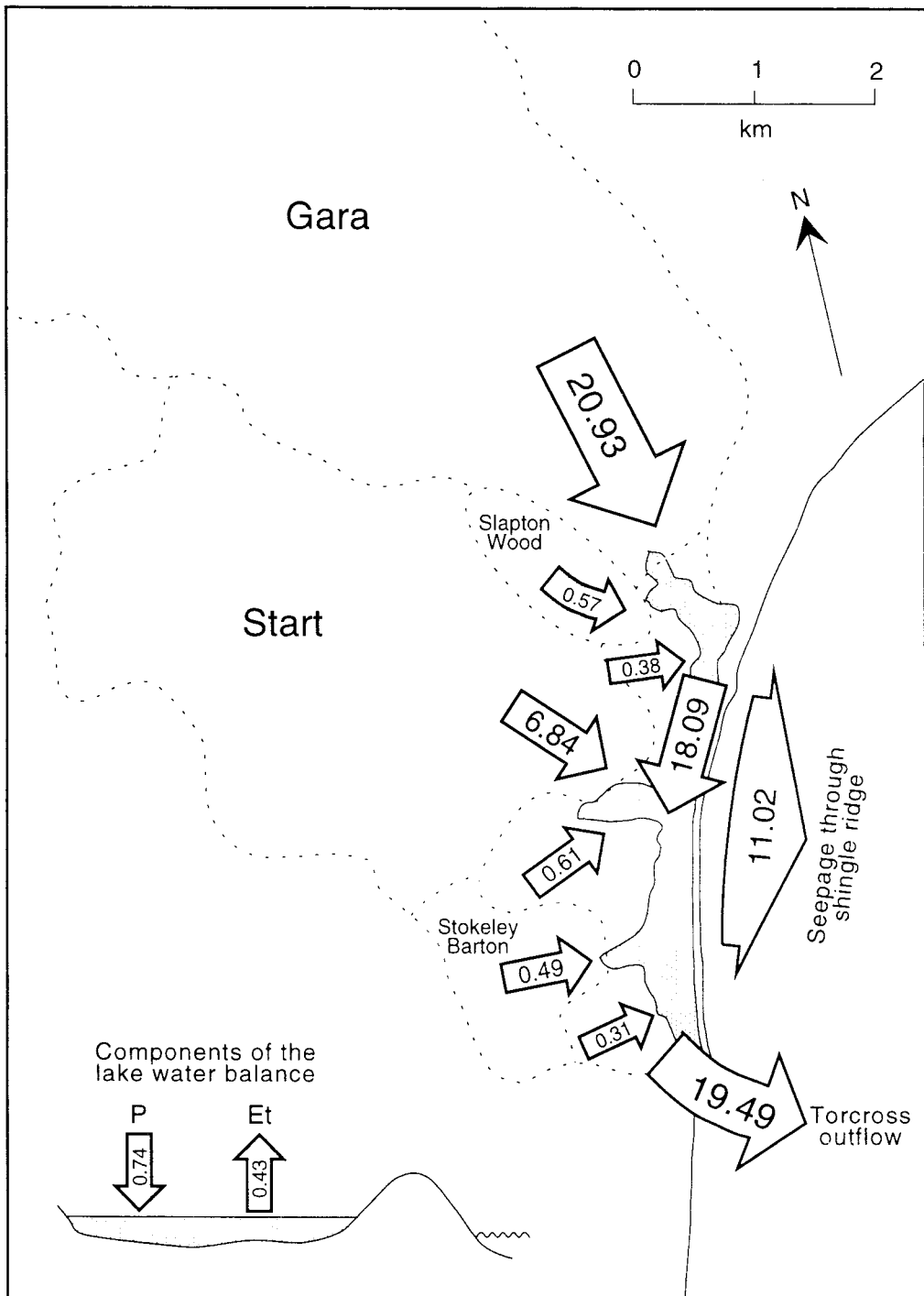


FIG. 7.

Mean annual water balance for the Slapton Ley lake basin, 1973-77 (redrawn from van Vlymen, 1979). Values are in millions of cubic metres per year.

there is no outflow over the Torcross weir, water remains in the lake for a long time and is renewed perhaps only once in the whole season. Seepage through the shingle ridge is very important at this time; apart from small evaporation losses, this is the only output from the lake during the summer. Van Vlymen concludes that seepage is the natural drain for the lake and that the culvert exists only to prevent the lake basin becoming over full. His best estimate of the annual water balance of Slapton Ley is shown in Fig. 7. Outflow at the Torcross weir is about 63% of the total output from the lake, with seepage through the shingle accounting for most of the remainder. Further details are given in Johnes & Wilson (1996).

IMPLICATIONS

Other papers in this part of *Field Studies* will discuss details of sediment and solute dynamics within the Slapton catchment. It is, however, worth making a few brief points here about the links between runoff production and sediment and solute delivery systems. The incidence of surface runoff and erosion seems to be increasing. Whilst not all the eroded material makes its way to the lake, a good deal being deposited on floodplains (Foster *et al.*, 1996), there is good evidence that sedimentation rates in the lake basin, especially in the Higher Ley, are increasing too (Heathwaite & O'Sullivan, 1991; Jenns, 1994). Despite the rapid flushing of water through the Ley during the winter, nevertheless there seems to be plenty of opportunity for deposition to occur. The rapid sedimentation of the Higher Ley has important implications for its role as a wetland system, notably in terms of changing vegetation cover as terrestrialisation takes place (Cannell, 1992), the ability of the Higher Ley wetland to act as some sort of buffer system is also limited as storage capacity is lost (see Heathwaite *et al.*, 1989). The input of sediment into the lake basin is not just problematic in terms of lost capacity; sediment bound nutrients and pesticides may seriously affect the lake's aquatic ecosystem.

Despite the increased incidence of surface runoff, the hydrology of the Slapton catchment remains dominated by subsurface flow. Though the bedrock is solute poor, the warm temperatures and lush vegetation have probably meant that waters draining into Slapton Ley have always been relatively rich in nutrients. There has, however, been much concern about eutrophication of the lake over recent decades. Given that the Lower Ley has a flushing rate of only 3 days at peak flow, it might be argued that most of the solute load is displaced, thus having little effect on eutrophication. It is in summer, when the flushing rate is very small, that inputs of solutes from the influent streams are most significant; moreover, nutrient cycling within the lake and the release of nutrients from lake sediments also assume importance at this time. There is now good understanding of sediment and solute delivery systems operating within the Slapton catchment (see Foster *et al.* and Burt, Heathwaite & Johnes, 1996) and of the longer-term pattern of sedimentation within the Ley itself (Johnes & Wilson, 1996). Curiously, there has, as yet, been little study of nutrient dynamics within the lake itself; this is an important goal for future research at Slapton Ley.

REFERENCES

- BOWYER-BOWER, T. A. S. and BURT, T. P., (1989). Rainfall simulators for investigating soil response to rainfall. *Soil Technology*, 2, 1-16.
- BURT, T. P., (1978). Three Simple and Low-Cost Instruments for the Measurement of Soil Moisture Properties. *Huddersfield Polytechnic, Department of Geography, Occasional Publications*, 6, 22pp.

- BURT, T. P., (1992). The hydrology of headwater catchments. In CALOW, P. and PETTS, G. E. (eds), *The Rivers Handbook*, Volume 1, 3–28.
- BURT, T. P., (1993). Climate and hydrology. In BURT, T. P. (ed), *A Field Guide to the Geomorphology of the Slapton Region. Occasional Publications of the Field Studies Council*, 27.
- BURT, T. P., ARKELL, B. P., TRUDGILL, S. T. and WALLING, D. E., (1988). Stream nitrate levels in a small catchment in south west England over a period of 15 years (1970–1985). *Hydrological Processes*, 2, 267–284.
- BURT, T. P. and BUTCHER, D. P., (1985a). The role of topography in controlling soil moisture distributions. *Journal of Soil Science*, 36, 469–486.
- BURT, T. P. and BUTCHER, D. P., (1985b). On the generation of delayed peaks in stream discharge. *Journal of Hydrology*, 78, 361–378.
- BURT, T. P., BUTCHER, D. P., COLES, N. and THOMAS, A. D., (1983). The Natural History of Slapton Ley Nature Reserve XV: Hydrological processes in the Slapton Wood catchment. *Field Studies*, 5, 731–752.
- BURT, T. P., HEATHWAITE, A. L. and JOHNES, P. J., (1996). Stream water quality and nutrient export in the Slapton catchments. *Field Studies*, 8, 613–627.
- BUTCHER, D. P. (1984). *Field verification of topographic indices for use in hillslope runoff models*. Unpublished PhD thesis, Huddersfield Polytechnic.
- CANNELL, S., (1992). *Slapton Higher Ley—its history, ecology and conservation*. unpublished report.
- COLES, N. and TRUDGILL, S. T., (1985). The movement of nitrate fertiliser from the soil surface to drainage waters in by preferential flow in weakly structured soils, Slapton, South Devon. *Agriculture, Ecosystems and Environment*, 13, 241–59.
- FOSTER, I. D. L., OWENS, P. N. and WALLING, D. E., (1996). Sediment yields and sediment delivery in the catchments of Slapton Lower Ley, South Devon, UK. *Field Studies*, 8, 629–661.
- HAYCOCK, N. E. and BURT, T. P., (1993). Role of floodplain sediments in reducing the nitrate concentration of surface runoff: a case study in the Cotswolds, UK. *Hydrological Processes*, 7, 287–295.
- HEATHWAITE, A. L. and BURT, T. P., (1992). The evidence for past and present erosion in the Slapton catchment. In BELL, M. and BOARDMAN, J. (eds), *Soil Erosion, Past and Present: Archaeological and Geographical Perspectives*, Oxbow Monograph 22, 89–100.
- HEATHWAITE, A. L., BURT, T. P. and TRUDGILL, S. T., (1989). Runoff, sediment and solute delivery in agricultural drainage basins—a scale dependent approach. *International Association for Hydrological Science*, 182, 175–191.
- HEATHWAITE, A. L., BURT, T. P. and TRUDGILL, S. T., (1990). Land-use controls on sediment production in a lowland catchment, south west England. In BOARDMAN, J., FOSTER, I. D. L. and DEARING, J. A., (eds), *Soil Erosion on Agricultural Land*, Wiley, 69–86.
- HEATHWAITE, A. L. and O'SULLIVAN, P. E., (1991). Sequential inorganic chemical analysis of a core from Slapton Ley, Devon, UK. *Hydrobiologia*, 214, 125–135.
- JENNS, N. J. (1994). *Sedimentation in Slapton Higher Ley*. Unpublished B.A. dissertation, School of Geography, Oxford University.
- JOHNES, P. J. and WILSON, H. M., (1996). The limnology of Slapton Ley. *Field Studies*, 8, 585–612.
- O'SULLIVAN, P. E., (1994). The Natural History of Slapton Ley National Nature Reserve, XXI: The palaeolimnology of the uppermost sediments of the Lower Ley, with interpretations based on ²¹⁰Pb dating and the historical record. *Field Studies*, 8, 403–449.
- RAGAB, R. and COOPER, J. D., (1993a). Variability of unsaturated zone water transport parameters: implications for hydrological modelling. 1. In situ measurements. *Journal of Hydrology*, 148, 109–131.
- RAGAB, R. and COOPER, J. D., (1993b). Variability of unsaturated zone water transport parameters: implications for hydrological modelling. 2. Predicted vs. in situ measurements and evaluation of methods. *Journal of Hydrology*, 148, 133–147.
- SHAW, E. M. (1993). *Hydrology in Practice*. Third edition. Van Nostrand Reinhold, London.
- TROAKE, R. P. and WALLING, D. E., (1973). The Natural History of Slapton Ley Nature Reserve VII. The hydrology of the Slapton Wood stream: a preliminary report. *Field Studies*, 3, 719–740.
- VAN VLYMEN, C. D., (1979). The Natural History of Slapton Ley Nature Reserve XIII. The water balance of Slapton Ley. *Field Studies*, 5, 59–84.