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THE NATURAL HISTORY OF SLAPTON LEY NATURE RESERVE XIII: THE WATER BALANCE OF SLAPTON LEY

C. D. VAN VLYMEN

Slapton Ley Field Centre, Slapton, Kingsbridge, Devon

ABSTRACT

The monthly water balance of a shallow, coastal lake is described for the period April 1973 to March 1977. The hydrology of Slapton Ley is clearly "flow-dominated" and its highly unstable water level reflects not only a rapid response to increases of rainfall in the catchment but also the presence of a man-made outflow designed to operate within specific limits. Seepage is an important component of the water balance and for more than half the year is the only significant output from the system. Hydraulic retention averages 18 days, equivalent to a flushing rate of 20 year^{-1} and winter flooding may result in the loss of a third of the lake's volume in 24 hours. A comparison with other lakes implies that the ratio of catchment area to lake volume is an important morphometric determinant of throughflow.

INTRODUCTION

SLAPTON LEY NATURE RESERVE (Grid Reference: SX825439) has attracted considerable research interest since the morphological description of the area by Mercer (1966). Its documentation has been greatly enhanced both by its conservation status of national importance and by its use as an outdoor laboratory for teaching field studies. Much of this attention has been oriented towards short-term biological studies but a programme of continuous surveillance of various aspects of stream hydrology was initiated in 1970. This latter work was focused on fluvial processes within individual drainage basins (Troake & Walling, 1973) and the contribution of agricultural fertilisers to nitrate loading (Troake & Walling, 1975; Troake, Troake & Walling, 1976).

The central point of the reserve is its 116 hectare wetland which contains the largest natural body of freshwater in the South West Region. Instrumentation of the catchment and its principal tributaries was completed in March 1973, and this facilitated a detailed analysis of the water balance. This paper presents the results of monthly budgets for the period between April 1973 and March 1977, which was notable for the exceptional variability of rainfall highlighted by the prolonged drought of 1975/76.

Slapton Ley is of comparative recent origin following its impoundment as a coastal lagoon, similar in setting to the Chesil Beach complex in Dorset. Radiocarbon-dating has suggested that it is no more than a thousand years old (Morey, 1976). The lake is divided into two unequal basins, the Higher and Lower Leys, linked by an openwater channel and separated from the sea by a raised shingle beach 3.5 km long. The contemporary and evolutionary morphology of this barrier has been fully discussed by Mercer (1966), Hails (1975) and Morey (1976). Seepage readily occurs through the shingle and has been observed as leakage from the seaward face of the barrier at low water springs (Mercer, 1966). Examination of water table levels in boreholes sunk to a depth of 7.6 m (−2.1 m OD) below the crest of the barrier confirms that the hydraulic gradient is from lake to sea and that this flow pressure is probably maintained throughout the tidal cycle, even at its seasonal extremes (C. R.

Morey, *personal communication*). As about 35% of the lake's shore line is in contact with the shingle barrier it may be anticipated that seepage will be a significant component of the water balance, and its quantification requires special consideration.

A study of hydrological events within a lake and its catchment will inevitably include a description of basin structure and morphology, and reference should be made to Mercer (1966) and Morey (1976). Hutchinson (1957) discussed the value of a morphometric approach in comparing different lakes and outlined the computation of essential parameters. Consideration of a lake's surface area, mean depth and shore line configuration will help to define the limits of its storage capacity. Their measurement is based on a bathymetric map. The quantity of water entering a lake will depend on a number of factors operating within the catchment, and may show considerable seasonal variation. Orographic factors of basin relief and slope, drainage density and the permeability of rock and sediment materials regulate the rate of run-off which will be further modified by vegetation and climate (Gregory & Walling, 1971). In many instances, lakes are little more than depressions within the landscape through which the channelling of water is temporarily impeded. The delay between input and output of a unit mass of water will depend on the lake's storage capacity relative to the total input volume. This relationship reflects the flow through the lake and is conceived as a 'replacement quotient' (Brook & Woodward, 1956) which is calculated as the time taken for the lake basin to be filled by all inflow sources. The seasonal rate of water renewal is essentially controlled by the intensity and incidence of rainfall but in the long-term the catchment area and storage capacity of the lake basin will be fundamental factors defining the magnitude of the relationship. Consequently, it may be possible to estimate an approximate replacement quotient for any given lake by referring to its known morphometric features.

It is the intention of this paper to review the monthly water balance in terms of the relative contribution of individual components and to portray annual criteria as a schematic flow model. Emphasis is placed on the importance of seepage and an approach to its quantification is assessed. The effect of basin morphometry on water renewal in Slapton Ley is discussed in comparison with other lakes. It is hoped that the content will not only be treated as background information to other research studies but that it may also further understanding of catchment hydrology.

DESCRIPTION OF THE LAKE AND ITS CATCHMENT

The catchment of Slapton Ley occupies 46 km^2 and is largely composed of flat-top ridges dissected by steep valleys often covered by dense woodland. It may be superficially divided into four main basins (Fig. 1): Gara, Slapton Wood, Start and Stokeley Barton. The principal tributary is the River Gara which drains 59% of the total catchment; of the remainder, 4% is drained by spring-fed streams lying outside the instrumented basins, and, together with a further 3% associated with direct run-off, has been designated as minor drainage in Table 1. Each inflow feeds either marsh or reedswamp before emptying into the lake and often the channelling of water becomes multiple or indistinct, particularly during winter flooding. For gauging purposes the entry point has been located by reference to a permanent feature such as a bridge across a causeway (e.g. the River Gara at Goldswell Bridge; Start Stream at Ireland Bridge).

The Higher and Lower Leys, which together make up the wetland system of

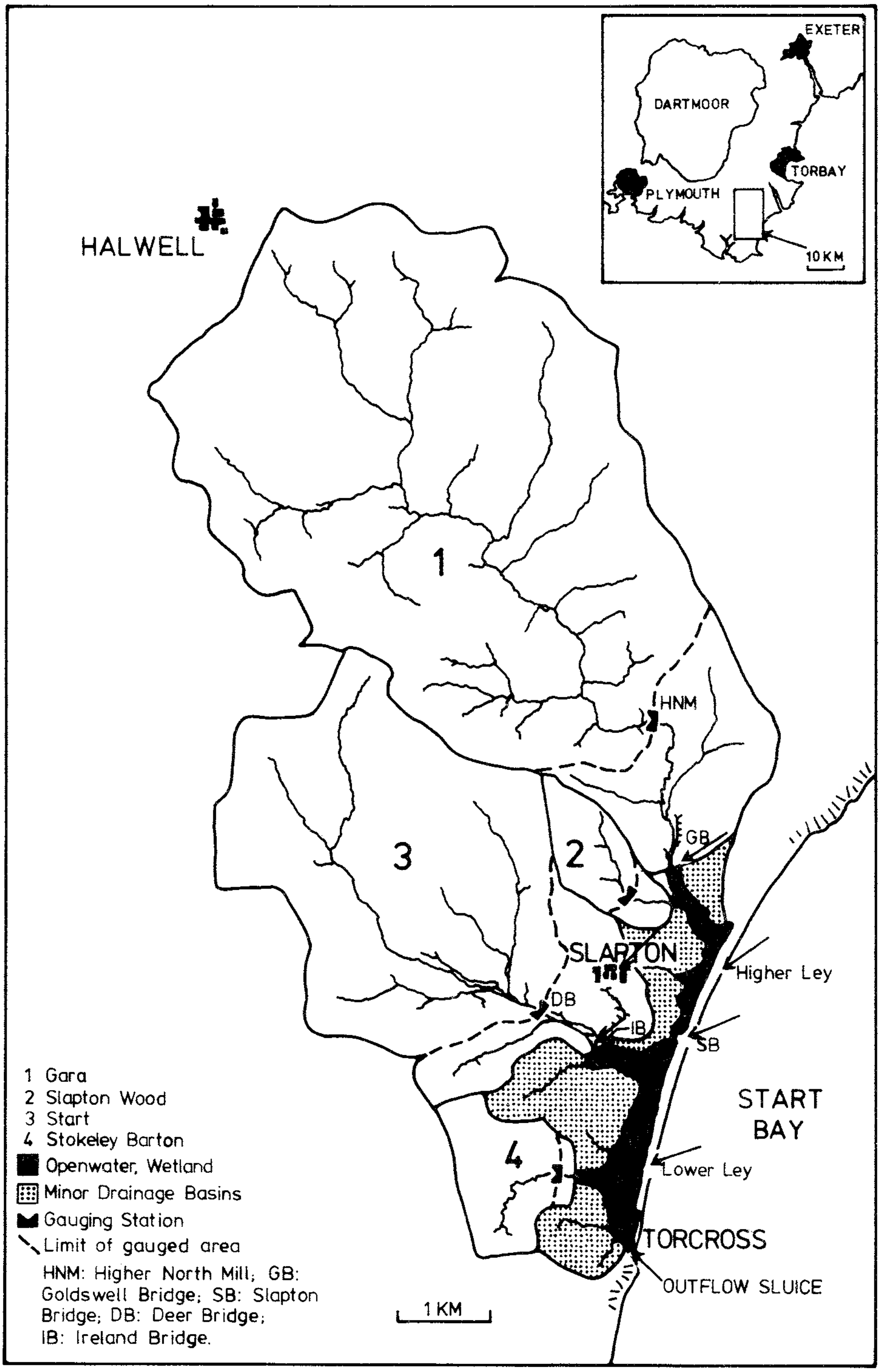

Fig. 1.
The catchment of Slapton Ley. The map has been divided into the drainage basins described in Table 1. The inset shows the position of the area in South Devon.

Table 1. *The Major Drainage Basins of Slapton Ley*

Lake basin	Drainage basin	Distance of gauge above entry to lake km	Gauged Area		Ungauged area km^2	Total km^2	Minor drainage basins km^2	Total km^2
			km^2	%				
Higher Ley	Gara	2.12	23.62	88	3.18	26.80	1.00	29.02
	Slapton Wood	0.45	0.93	76	0.29	1.22		
Lower Ley	Start	1.04	10.79	84	2.00	12.79	2.08	16.54
	Stokeley Barton	0.24	1.53	92	0.14	1.67		
Total			36.87		5.61	42.48	3.08	45.56
(%)				(81)	(12)	(93)	(7)	(100)

Slapton Ley, exhibit remarkably different patterns of vegetation cover. In the former case, *Phragmites*-dominated reedswamp and willow-alder carr have encroached over the whole basin, limiting the open water to small pools and a discontinuous channel. In the Lower Ley, however, the development of reedswamp has been restricted to the lake margins and 84% of its 0.77 km^2 area is open water. Including adjacent marshes, the entire wetland occupies an area of 1.16 km^2. The lake basins are oriented on a north-south axis with the River Gara entering from the north, the other streams from the west and with the outflow at the extreme southern tip (Fig. 1). The outflow consists of a horizontal weir, culvert and sluice gate system which remains inoperative for most of the year, due to blockage by shingle, and is only opened as a consequence of unacceptable flooding.

On the basis of echo-sounding data by R. P. Troake in 1972 and rod-sounding data by both C. R. Morey in 1973 and the author in 1976, sufficient information has been collated for the provision of a bathymetric map of the Lower Ley (Fig. 2). Aspects of its morphometry are described in Table 2 and compared with other notable lakes in Table 6. The survey results are based on a datum corresponding to the level of the outflow weir which is 2.71 m above mean sea level (Fig. 3). The lake is uniformly shallow with a mean open water depth of 1.8 m and a survey maximum of 2.8 m which is equivalent to 0.1 m below mean sea level. Water deeper than 2.0 m has been channelled into well-defined trenches along the western shore by substantial wash-over fans of shingle. At survey datum (= weir datum) the Lower

Table 2. *Morphometry of Slapton Ley (Lower Basin)*

Mean depth	1.55 m
Maximum depth	2.80 m
Surface area	0.77 km^2
Volume (at weir datum)	1.19×10^6 m^3
Maximum volume (11/02/74)	2.09×10^6 m^3
Minimum volume (10/09/76)	0.54×10^6 m^3
Length	2.32 km
Mean breadth	0.33 km
Length of shoreline	6.67 km

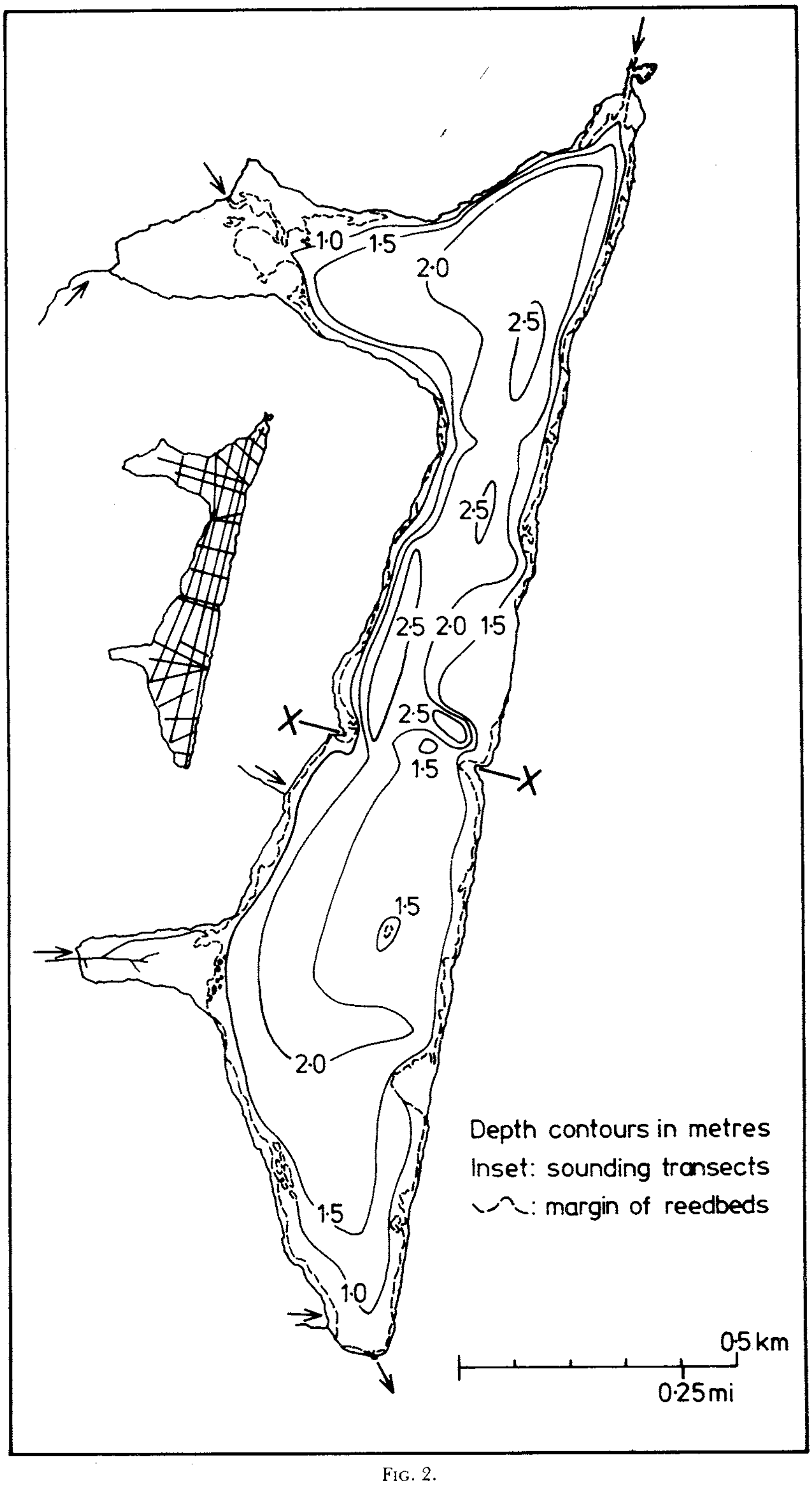

Fig. 2.

Bathymetry of the Lower Basin of Slapton Ley. The X—X intersection locates the cross-sectional profile of Fig. 3. The inset shows the sounding transects.

Ley has a total volume of 1.19×10^6 m^3 but this may be almost doubled by flooding, particularly when the sluice is blocked.

Little is known of the bathymetry of the Higher Ley because of its inaccessibility. The presence of large swards of *Phragmites* suggests that these areas are extremely shallow since the reed will only tolerate water less than about 1.5 m deep (Haslam, 1970). Depths of less than 0.5 m have been recorded in the openwater pools but in the main channels, stretches of more than 3.0 m may be found.

The retention of water by a lake basin depends not only on the balance between climatic and hydrological factors but also on the permeability of the basin itself. Morey (1976) has examined the stratigraphy of the lake sediments and his findings have been incorporated into Fig. 3 which shows a cross-section of the Lower Ley at a point midway along its length (indicated by X—X in Fig. 2). The lake floor is formed of submerged peats which may be intermixed with successive wash-over fans of shingle and the whole system backs against an old slate cliff. The presence of underlying clay resists any further downward movement of water and probably aids lateral seepage through the barrier. This situation is not necessarily reflected by conditions in the Higher Ley where shingle has been thrown across the entire floor of the basin, and has so far prevented coring of the sediments beneath. Consequently, any suggestion of a seepage zone along the eastern shore should be interpreted with discretion because there may be additional losses through the lake bottom.

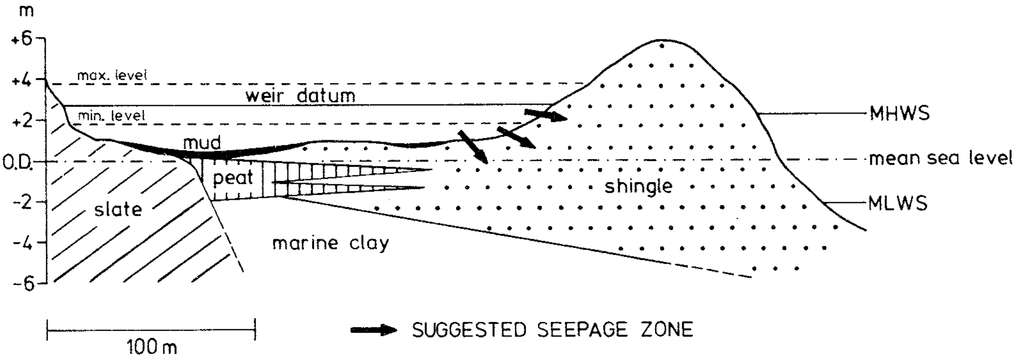

FIG. 3.

Cross-section of the Lower Ley and shingle barrier through X—X in Fig. 2 to show the relationship between lake and sea levels and the importance of sediment structure in delineating the suggested seepage zone (data after Morey, 1976).

INSTRUMENTATION AND METHODOLOGY

Each of the four main drainage basins has a permanent gauging station located at some distance above the stream's entry into the lake (Fig. 1 and Table 1). Run-off has been estimated according to an established rating relationship between discharge (Q) and stream height (H). Discharge has been measured by two different approaches depending on the size and velocity of the stream. In all cases, water level has been continuously measured by Monroe and Ott recorders and the data transcribed at intervals of thirty minutes. The equivalent discharge volumes have been summed to give a daily total (in m^3 day^{-1}). This represents the gauged inflow.

In the River Gara and Start Stream, discharge has been measured by the technique of current meter rating. The cross-sectional profile of the stream channel is determined by first measuring the depth of water at 0.2 m intervals and then calculating the enclosed areas (in m^2). Stream velocity (in $msec^{-1}$) is measured in each profile sub-section at 0.6 of the depth below the surface using a calibrated current meter, such as the Braystoke (Valeport Developments, Dartmouth). The suitability of this instrument has been fully evaluated by Herschy (1976). The minimum speed of response of the standard impeller is 0.03 $msec^{-1}$ and requires a minimum water depth of about 13 cm. Using a miniature version (No. M-SER-7666) this may be reduced to 5 cm. Discharge (in m^3sec^{-1}) is calculated by summing the series of profile area x velocity products obtained across the stream. Repeated estimates of discharge over a wide range of stream heights will form the basis of the rating, usually plotted in log transformation. Since a particular rating is only accurate for a given profile, it is necessary to formulate new ratings whenever the stream changes its bottom configuration or erodes away its banks. This has been required every 3 to 6 months.

The two smaller basins of Slapton Wood and Stokeley Barton have been instrumented by 120° V-notch weirs of a type described by Gregory and Walling (1971). Discharge is estimated according to a specific formula which relates the height of water above the apex of the notch to a coefficient of velocity determined by the angle of the V. The 120° weir was chosen in preference to the more widely used 90° type because of its greater capacity to contain high flows (Troake & Walling, 1973).

Eighty-one per cent of the catchment has been gauged by the procedures mentioned above (Table 1). The areas below each instrumented basin have been accounted for by a simple proportional correction, based on a linear run-off equivalent, to provide an estimate of stream run-off to the lake. The contribution from the minor drainage basins indicated in Fig. 1 has not been measured directly. In the case of spring-fed streams, monthly run-off has been estimated from totals derived for the nearest gauged basin. In the remaining basins there is no channelled drainage and it has been assumed that direct run-off to the lake shore is equal to the difference between rainfall and evaporation, with the proviso that the former is in excess and that there is no soil moisture deficit. The summation of monthly discharge totals from all run-off sources is homologous with the total inflow to the Ley wetland.

The method of current meter rating has also been applied for measurements of water movement between the Higher and Lower Leys at Slapton Bridge and the outflow discharge at Torcross. In the latter case, the channel profile is a permanent rectangular weir and only one rating is required for all hydrological conditions (Fig. 4). For discharges below about 200 $lsec^{-1}$, corresponding to a flow height of about 5 cm above weir datum, measurements have been made at the sluice gates on the seaward side of the culvert, where a narrowing of the channel increased the depth of water sufficiently to permit the use of the Braystoke meter. Estimates of outflow loss have been based on daily readings of lake level (relative to weir datum) at fixed stages located in the channel at Slapton Bridge and 10 m from the weir at Torcross.

From a consideration of the lake's bathymetry, the volume of the Lower Ley may be calculated for any given lake level and, therefore, a difference between consecutive days will be a measure of the change in storage. Changes in the Higher Ley have been assessed proportionally by assuming that the two basins exhibit

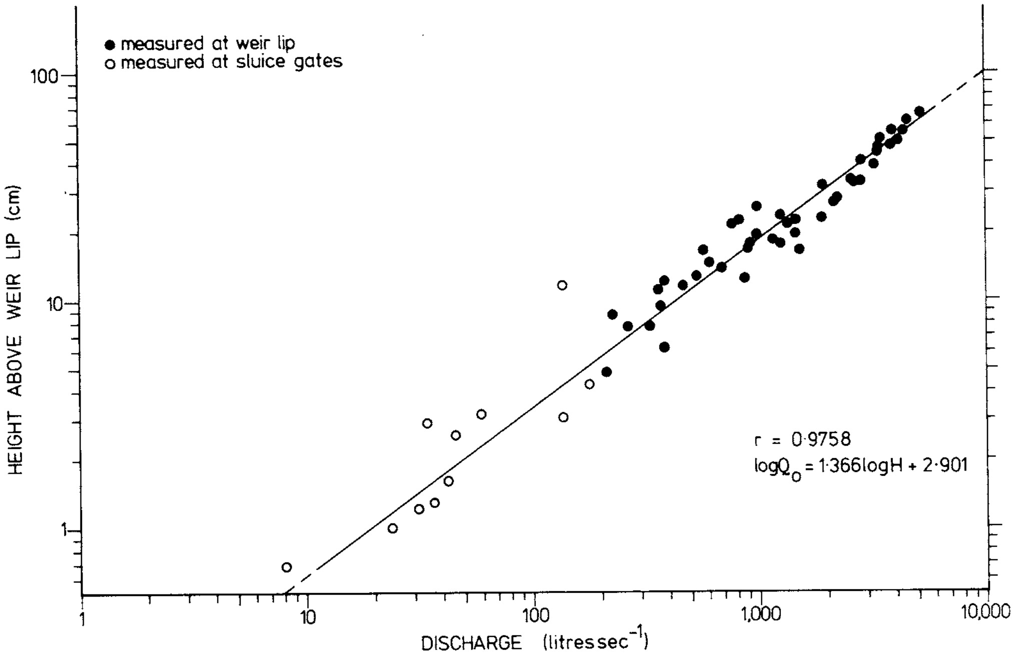

Fig. 4.

Logarithmic rating of water discharge (Q_0) over the outflow weir in relation to lake level (H).

similar fluctuations of water level and do not significantly differ in shore aspect, which will be important in its inferred relationship with surface area.

Rainfall within the catchment has been recorded at a number of stations but principally at the Field Centre, where readings have been taken daily using a standard Meteorological Office Mark II raingauge of 12.7 cm diameter. No attempt has been made to integrate the variation between stations because of the sparsity of records during the period of this study and reliance has been placed on the Centre data.

There is no satisfactory method for directly measuring evaporation losses which is applicable to different types of environment. A number of techniques have been proposed for its estimation, including the use of lysimeters and evaporimeter pans, formulae based on meteorological factors (e.g. Penman, 1963) and catchment budgeting (Barry, 1969). An American Class A evaporimeter pan of 1.22 m diameter and 0.25 m depth, standing about 5 cm above a grass surface within the meteorological compound at the Field Centre has provided daily readings which have been summed to give monthly losses. Criticism of the usefulness of such an instrument is extensive and its accuracy depends on the maintenance of a specific depth of water free of debris and organic growths. There are additional, almost uncontrollable errors resulting from freezing, excessive warming of the pan and occasional slop in high winds. Evaporation losses from a lake are dependent on a number of factors, apart from climatic effects, which include lake surface area, degree of exposure and density of vegetation; all of which create saturation gradients between water and air. A small lake may have a relatively high rate of evaporation because the continuous movement of dry air from the surrounding land prevents saturation of the air above the water surface. An evaporimeter pan in a terrestrial environment behaves in much the same way and will yield values which over-estimate actual losses from a large open water surface. Correction coefficients have been reported as lying between 0.69 and 0.74 (Gregory & Walling, 1973). Lapworth (1965) has compared actual evaporation losses from a watertight reservoir with indirect methods and found an annual reservoir to pan ratio of 0.7 with little seasonal bias. The pan readings have therefore been corrected by a factor of 0.7 for each month and the data used as the evaporation component for the whole lake without any further adjustment for vegetation effects.

THE DETERMINATION OF A WATER BALANCE

The water balance of a lake may be expressed by an equation which indicates that the rate of change of volume of the lake is equal to the rate of inflow from all sources, less the rate of water loss (Hutchinson, 1957). For Slapton Ley, this relationship may be simply written as:

$$\begin{array}{c}\text{Change}\\\text{in Lake}\\\text{Storage}\end{array} = \begin{array}{c}\text{Total}\\\text{Inflow}\end{array} + \begin{array}{c}\text{Rainfall}\\\text{On Lake}\end{array} - \begin{array}{c}\text{Evaporation}\\\text{Loss}\end{array} - \begin{array}{c}\text{Outflow}\\\text{Removal}\end{array} - \begin{array}{c}\text{Seepage}\\\text{Loss}\end{array} \qquad (1)$$

Procedures for the computation of each component have already been described, with the exception of seepage. Its direct quantification would rely on a series of localised measurements of short duration which could not be easily extrapolated to monthly values for the whole barrier without a detailed mapping of the seepage zone and an experimental analysis of its flow potential. Since the completion of the lake's water balance requires only a total loss, it is convenient to estimate seepage as the unknown term in Equation 1. Since the most likely pathway for seepage is through a 'wall' of the lake basin, it may be expected that the quantity of loss (derived from Equation 1) will be correlated with lake level, which is fundamental to the hydraulic gradient. One of the most favourable opportunities for resolving this relationship occurred in October 1976, when the daily change of lake storage was one of continual increase in the absence of any surface outflow. Under these conditions, the only significant water loss could be attributed to seepage and daily values were calculated from a simplification of Equation 1, *viz.*:

$$\begin{array}{c}\text{Seepage}\\\text{Loss}\end{array} = \begin{array}{c}\text{Total}\\\text{Inflow}\end{array} + \begin{array}{c}\text{Rainfall}\\\text{On Lake}\end{array} - \begin{array}{c}\text{Evaporation}\\\text{Loss}\end{array} - \begin{array}{c}\text{Increase in}\\\text{Storage}\end{array} \qquad (2)$$

The rate of flow within a lake will be almost undetectable, at least in the short term, if its storage capacity is large or if internal currents disturb any channelling effect. However, there are several mathematical expressions which define the flow regime in terms of a relationship between either inflow or outflow discharge volume per unit time (Q_i or Q_o, respectively) and lake storage volume (V). Equations 3 and 4 reflect the retention of water by the lake (tD), measured as a time integral, and derive theoretical estimates because they are based on 'instantaneous' quantities of Q_i or Q_o and V. Brief mention has been made of the replacement quotient, which is one of the most widely used concepts and may be defined as:

$$tD_i = \frac{V}{Q_i} \qquad (3)$$

Similarly, retention times may also be calculated from measured outflow volumes but in the case of Slapton Ley additional losses due to seepage (Q_s) should be included (Equation 4).

$$tD_{o+s} = \frac{V}{Q_o + Q_s} \tag{4}$$

Values of tD are normally reported in terms of either days, months or years. Estimates of tD_i and tD_o will be approximately equal providing that changes of lake storage are minimal, which implies that the outflow responds rapidly to increases of inflow discharge. It may be preferable to use the reciprocals of the above relationships because they are then expressed as 'rate' measurements. The equivalent quotients are dilution rate (ρ) for tD_i and removal rate (R_o or R_{o+s}) for tD_o or tD_{o+s}. Various other terms have been used synonymously with those described here: retention has been referred to as replacement and renewal time (specifically for tD_i), detention, turnover and residence time; and dilution rate may also be known by flushing rate, throughflow and flowthrough.

In this paper, emphasis has been placed on the determination of monthly water balances which have subsequently been summed for summer and winter budgets. The Water Year begins on 1st October, the time of minimum basin storage, and is divided into two six-month periods: summer, from April until September, and winter, from October until March. This paper complies with this demarcation except that for the convenience of past records, the year begins on 1st April.

THE WATER BALANCE: COMPONENT RESULTS

General Features

With the exception of changes in lake storage, each component of the monthly water balance depicted in Fig. 5 follows a well-defined seasonal pattern corresponding to the equilibrium between rainfall and evaporation. The data have been expressed as fractions of total lake storage and it is evident that the water balance is predominantly controlled by the inflows, outflow and seepage. Table 3 gives six-monthly and annual water budgets.

Table 3. *Summer and Winter Water Budgets in Slapton Ley for the years 1973-1977 (all values as 10^6 m^3)*

		Rainfall on lake	Evaporation	Total inflow	Outflow	Days sluice closed	Seepage loss	Change in lake storage
1973/4	Summer	0.43	0.42	5.72	1.05	158	4.60	+0.08
	Winter	0.63	0.13	27.39	17.94	97	10.08	–0.13
	Total	1.06	0.55	33.11	18.99	255	14.68	–0.05
1974/5	Summer	0.49	0.40	11.39	6.30	55	5.05	+0.14
	Winter	0.61	0.15	26.59	23.71	14	3.36	–0.03
	Total	1.10	0.55	37.98	30.01	69	8.41	+0.11
1975/6	Summer	0.34	0.46	5.59	3.30	95	2.35	–0.18
	Winter	0.36	0.14	9.73	3.51	137	6.15	+0.28
	Total	0.70	0.60	15.32	6.81	232	8.50	+0.10
1976/7	Summer	0.23	0.50	3.00	0.94	161	2.31	–0.52
	Winter	0.87	0.11	31.09	21.20	66	10.19	+0.46
	Total	1.10	0.61	34.09	22.14	227	12.50	+0.10

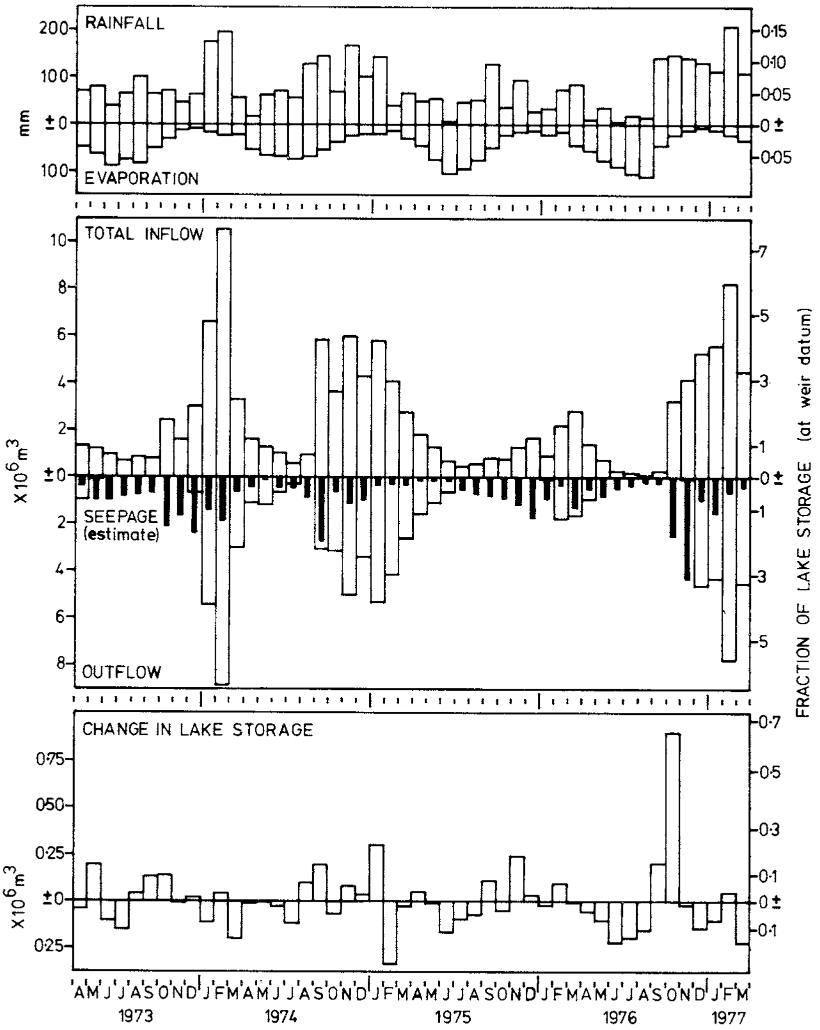

FIG. 5.
Monthly totals of water balance components in Slapton Ley.

Rainfall and Evaporation

The maritime climate of Slapton Ley during the period 1960 to 1973 has been described by Ratsey (1975). The subsequent years have included periods inconsistent with past trends and new seasonal records of rainfall have been proclaimed by the Meteorological Office. The mean annual total (April to March) for the years 1973-77 has been 964 mm, compared with 1048 mm for the period 1960-77. Mean monthly totals of rainfall recorded at the Field Centre during the last seventeen years have been presented in Fig. 6. The normal summer:winter distribution is approximately 0.4:0.6 but in 1975/6 this was reduced to 0.49:0.51 by an unusually mild winter. Its effects aggravated the summer drought of 1976/7 which was dramatically offset by the two-month wet period that followed, 60% above the average forecast, thus broadening the seasonal quota to 0.21:0.79. The general trend has been one of increasing dryness between January 1974 and August 1976,

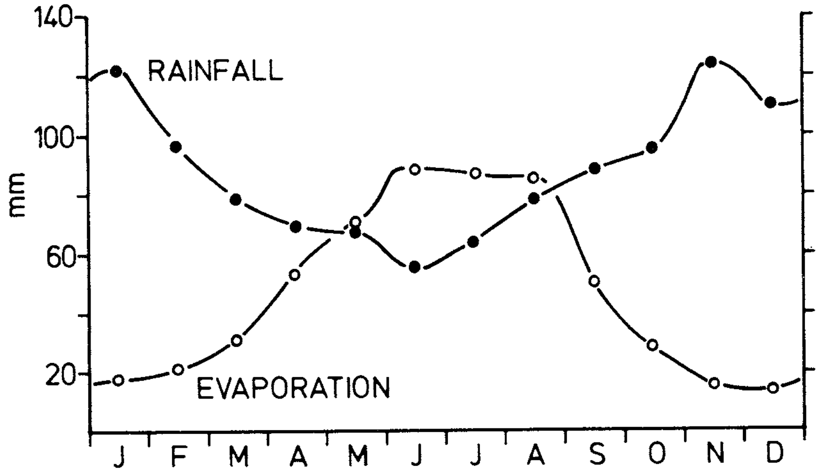

FIG. 6.
Comparison of mean monthly estimates of rainfall (1960-77) and open water evaporation (1973-77).

and this has been reflected by a lowering of the lake level to successive summer minima (Fig. 7).

Variation of rainfall within the catchment may be described by a series of convex arcs, each of greater intensity, extending in a northwest direction towards the heart of Dartmoor. The upper part of the Gara basin at Halwell (see Fig. 1), where the relief rises to over 200 m, is perpetually the wettest with a mean annual rainfall 29% above that of Slapton for the years 1965-77. A second raingauge, recently located on the edge of the Slapton Wood catchment only 2.2 km from the Centre, has produced values 16% higher. It is probable that the records presented in Figs. 5 and 7 under-estimate the average input to the catchment by between 15 and 20 per cent.

The monthly contribution of direct precipitation onto the lake's surface is rarely more than 15% of the total input and, with notable exceptions, this is insignificant compared to the additions from drainage influents. Following a dry spell, sudden increases of rainfall, as occurred in the Septembers of 1975 and 1976 (Fig. 5), may directly account for up to a third of the water entering the lake.

Losses due to evaporation have followed a uniform pattern of seasonal variation which is inversely related to rainfall (Figs. 5 & 6). Evaporation exceeds precipitation between May and August with the differences least apparent in those two months. Annual losses have increased from 535 mm in 1973/74 to 597 mm in 1976/77 and in August of the latter year evaporation rates amounted to 3.6 mm day^{-1}, equivalent to 50% of the total output for the month.

In the long-term and in most six-month periods, rainfall gains exceed evaporation losses but their effects on the behaviour of the lake appear insignificant in comparison with the quantities derived for the other components, which are one or two orders of magnitude higher (Table 3). However, this does not preclude their immediate influence in times of drought.

Catchment Run-off

The monthly discharges for each stream, together with the contributions from minor drainage and direct run-off, have been combined to provide an estimate of total inflow (Fig. 5). The daily total is within the range 0.002 × 10^6 m^{3}day^{-1} (28th

August 1976) to 0.781 × 10^6 m^3day^{-1} (10th February 1974) but the four year average has been 0.082 × 10^6 m^3day^{-1}. In contrast, the mean input from direct rainfall is only 0.003 × 10^6 m^3day^{-1}.

The relative flow proportions of each input are illustrated in Fig. 8 which is a schematic model of the annual water balance. About 70% of the total enters by way of the River Gara, whilst 23% is supplied by the Start basin. There is an apparent lack of correspondence between the proportions of run-off and drainage area for each basin (Table 4) which is further indicated by the greater run-off depth (that is, run-off divided by drainage area) for the Gara compared with the more southerly basins. Although there is a superficial agreement with the observed variation of rainfall in the catchment, this needs to be assessed in relation to land use since vegetation will influence the nett input to each basin. One aspect of the run-off pattern that requires clarification concerns the apparent anomaly of low discharge from the Stokeley Barton stream, particularly when compared with the smaller Slapton Wood basin. In consideration of this problem, Troake and Walling (1975) conceded a correction of 40% to account for unknown leakage but it has since been suggested that the basin is effectively watertight and that the loss may be attributed to a diversion of storm run-off by a nearby road running parallel to the stream (R. P. Troake, *personal communication*).

Table 4. *Comparison of mean annual Run-Off Conditions for each Drainage Basin*

	Gara	Start	Slapton Wood	Stokeley Barton	Minor drainage
% run-off of total	69.5	22.7	1.9	1.6	4.3
% drainage area of total	58.8	28.1	2.7	3.7	6.7
Equivalent run-off depth (mm)	781	535	463	294	421

The two larger streams, of the Gara and Start basins, drain into areas of marsh and reedswamp before entering the open water of the Lower Ley (Fig. 8). In summer the increased transpiration by vegetation in the wetland system, coupled with the low discharge in the streams (Table 3) may reduce flow from the Higher to Lower Ley to zero. If the lake level is sufficiently high and demands excessive, water may be drawn from the Lower Ley into the swamps as "backflow", a situation which has greatly hampered the establishment of accurate ratings at Slapton Bridge (SB) and Ireland Bridge (IB). In the drought of 1976 the Higher and Lower Leys were separated for 38 days (from 4th August until 11th September) and the Start Marsh was virtually dehydrated except for a distinct channel carrying the stream. The concomitant loss of volume, though of obvious detriment to the marsh, no doubt facilitated the continuity of flow between the gauging station at Deer Bridge and the lake entry point at Ireland Bridge where the respective discharges were measured as 3.338 $lsec^{-1}$ and 3.009 $lsec^{-1}$. It is probable that these baseflows were buffered by the many springs which emerge throughout the catchment but this has not been quantified.

Water Level Fluctuations and Lake Storage

During this study the level of water in the Lower Ley has fluctuated over a range

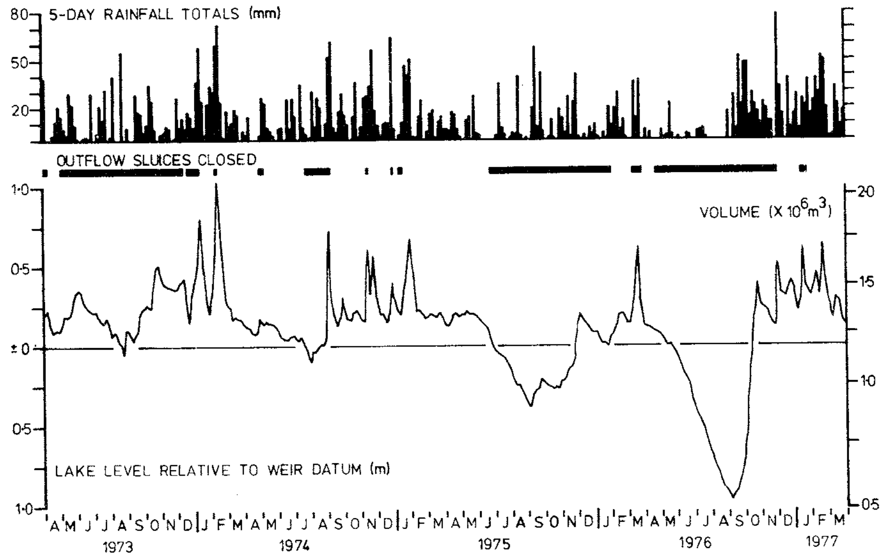

FIG. 7.

Seasonal fluctuations of water level and volume in the Lower Ley in comparison to 5-day totals of rainfall measured at Slapton Ley Field Centre. Periods when the outflow sluices were closed are indicated by horizontal bars.

of two metres with considerable short-term variability (Fig. 7). In the absence of any outflow, heavy rainfall normally produces a rapid increase in lake height of up to 0.3 m per day, as has occurred in most autumn and winter periods. On a few occasions the level has actually continued to rise following the opening of the sluices and this has been attributed to inflow flooding (e.g. early February and September 1974; December 1976) although the damming of the culvert entrance by reed detritus may be partly to blame, particularly during dieback (of the reeds) from mid-winter. At certain times the level has been observed to drop as much as 0.2 m in ten days (27th October to 6th November 1976) without being attributable to either the outflow or evaporation. There have been 6 incidents of between 15 and 140 days duration during which the level has decreased at an average rate of 2-22 times greater than the daily evaporation rate (Table 5). The level usually falls below weir

Table 5. *Daily Water Balance in the Lower Ley for specific periods, characterised by a continuous decrease of lake level in the absence of outflow removal (all values as cm-equivalents)*

			Initial lake level		Mean daily water balance				
Year	Dates	Days duration	(above weir datum)	Nett change in level	Storage loss	Surface evaporation	Direct rainfall	Total inflow	Seepage estimate
1973	3 June–18 June	15	34.9	−12.4	0.83	0.30	0	0.26	0.79
1973	24 Oct–8 Nov	15	51.6	−15.4	1.03	0.07	0	0.53	1.49
1975	27 June–11 Sept	76	0	−39.3	0.52	0.26	0.01	0.12	0.39
1975	7 Dec–23 Jan	47	19.7	−19.7	0.42	0.06	0.05	0.36	0.77
1976	23 April–10 Sept	140	8.3	−104.9	0.75	0.29	0.06	0.13	0.65
1976	27 Oct–27 Nov	31	39.4	−27.5	0.89	0.04	0.25	1.15	2.25

datum in mid-summer, but occasionally as early as May, and at its lowest extreme in 1976 it corresponded to a 69% reduction in volume compared with the previous peak, with a loss in surface area of 22%.

Water level has a direct bearing on lake storage for which the nett monthly change is an important component of the balance equation (Fig. 5). No regular trend can be ascertained due to the spontaneity of water level fluctuations and therefore each month must be assessed individually with respect to the other hydrological parameters. It is noteworthy that there is little nett change in storage from one year to the next (Table 3) and that the annual mean volume of the Lower Ley is only 6% greater than the survey volume at weir datum.

Outflow Losses and the Estimate of Seepage

Operation of the outflow is dependent primarily on lake level (Fig. 7; Table 3). It is, by construction, an overflow system, but water has flowed out for only 169 of the 278 days in a year that there has been a potential "overspill". On average about 65% of the total input passes through the sluices but in some months this has exceeded 95%. Mean daily losses from the Ley have been $0.053 \times 10^6 \, m^3 day^{-1}$ for the whole year, compared with $0.115 \times 10^6 \, m^3 day^{-1}$ for the time the sluices were open. The maximum daily discharge estimated from the field rating has equalled $0.537 \times 10^6 \, m^3 day^{-1}$ (or 6,215 $l sec^{-1}$) and this value is probably close to the capacity of the culvert, beyond which the tunnel entrance is over-reached and the lake ponded.

Monthly estimates of seepage reach a peak in the latter part of the year after lake storage has been swelled by increased inflow but before the outflow sluices have been opened (e.g. October and November 1976; Fig. 5). Minimal losses are observed during the summer at a time of reduced input and increased evaporation but not always in accordance with a blocked outflow or at the lowest lake level.

Discussion

The Water Balance

From a consideration of monthly budgets, the water balance of Slapton Ley is markedly "flow-dominated" with a relatively small storage capacity. The highly unstable water level reflects a rapid response to increased inflow but is also a consequence of the man-made outflow designed to operate within specific limits. Hydrological conditions exhibit considerable seasonal extremes but always return to an equilibrium point, usually in April when the water level is within a few centimetres of the long-term average of 0.10 m above weir datum. It would appear that rainfall and evaporation have little direct influence on the water balance, except during periods of prolonged drought, and the determination of annual budgets based solely on flow parameters would include an error of only 0.1%.

Slapton Ley is a complex freshwater wetland system divided into well-demarcated areas of marsh, reedswamp and open water by specific natural and man-made boundaries. As such, it is characterised by a relatively large number of flow points both within the lake and around its perimeter. The water balance has been reviewed in terms of the wetland aggregate and there is sufficient information to represent the hydrology of Slapton Ley as a schematic annual model (Fig. 8). Inputs and outputs are scaled to a relative channel width and the enclosed area of each "flow box" is proportional to the annual discharge. Potential backflow between the Lower Ley and both the Start Marsh and Higher Ley is indicated by broken arrows. In the Start

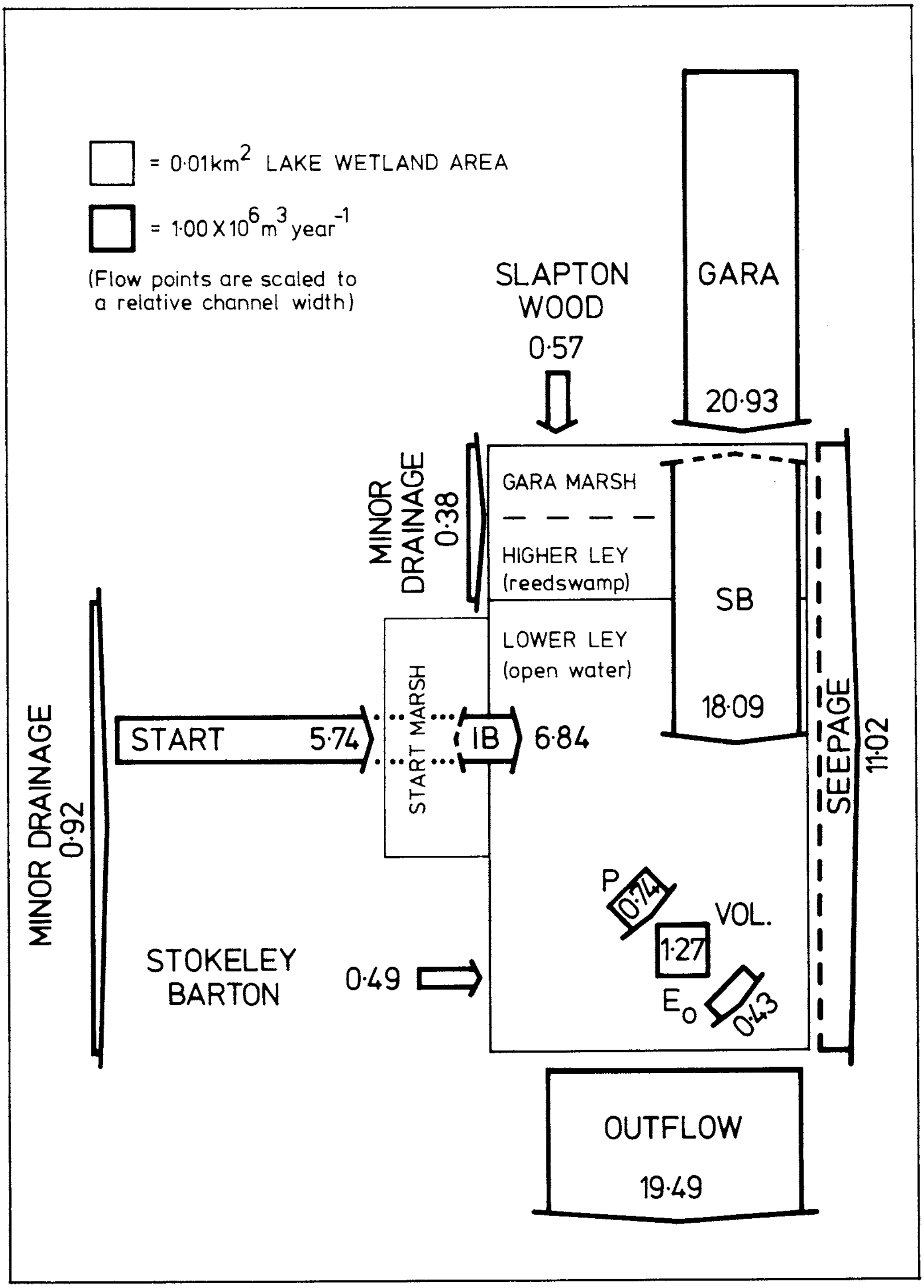

Fig. 8.
Schematic flow model of the mean annual water balance in Slapton Ley for the years 1973-1977 (see text for explanation).

Stream, the difference between the given discharges is equal to the run-off from ungauged basins draining directly to the marsh. The quantity contributed by minor drainage basins has been divided between the Higher and Lower Leys but no distinction has been made between spring-fed channels and direct run-off. The storage capacity of the Lower Ley is also indicated, together with direct gains due to rainfall (P) and losses to evaporation (E_0). Unlike most lakes which receive drainage from virtually 100% of their shore circumference, a significant length of the Ley's shore line is associated with water output. The location of inflow and outflow sites on opposite shores is an important factor in consideration of flow through the wetland, particularly between the R. Gara, Slapton Bridge (SB) and the outflow. The complexity of the system has resulted from the damming and subsequent drowning of the lower reaches of three major valleys by the landward movement of the shingle barrier to form the Ley.

The Lower Ley contains about 80% of the lake's storage volume and is the focal point for much of the research interest. However, it has been impossible to provide a direct quantification of its water balance. Apart from the seepage loss, which can only be adequately estimated from the mass water balance (Equation 1), the most significant problem encountered was the measurement of discharge to the Lower Ley at Slapton Bridge. The rating method applied elsewhere in the catchment proved unreliable because of the variability of discharges (Fig. 9a). Although the plotted data are significantly correlated ($r=0.587$, $p=99\%$), the rating does not include instances of backflow and undetectable flow. These conditions were caused by an irregular flow gradient between the Higher and Lower Leys, resulting from the ponding effects of a blocked outflow and a raised water level in the Lower Ley.

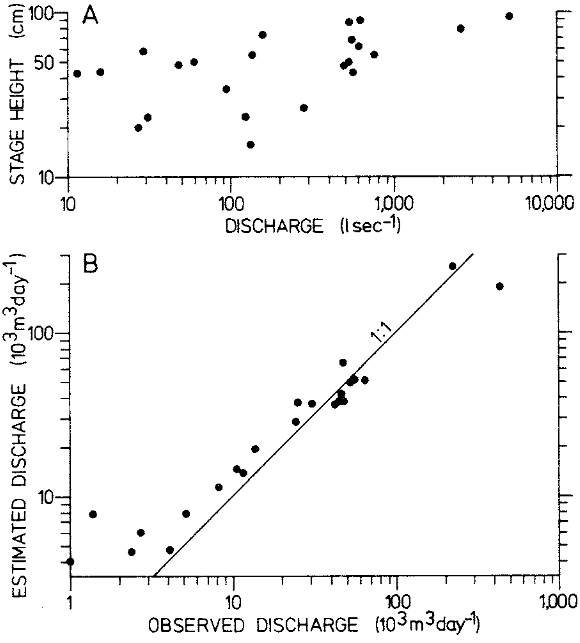

FIG. 9.

(A) Logarithmic relationship of discharge to stage height at Slapton Bridge and (B) a comparison between observed daily discharges and estimates derived from the water balance of the Higher Ley on the occasions plotted in (A).

The problem was overcome by estimating the input from a water balance for the Higher Ley, allowing for a proportional seepage loss based on the length of the shingle barrier. The validity of this approach has been checked by a regression of budget estimates on the measured discharges (Fig. 9b) and the calculated correlation of 0.965 is highly significant at $p = 99.9\%$ ($n = 24$). The results obtained have been used in the computation of throughflow rates within the Lower Ley.

Seepage

One of the most notable features of the lake's water balance is the inferred occurrence of seepage through its shingle boundary with the sea. Indirect quantification by the budget method suggests a quantity of loss which is not only far greater than could be attributed to errors on other accounts but also one which follows a regulated seasonality. A number of observations have tended to confirm the occurrence of seepage on a large scale:

(1) There has been the visible leakage from the seaward face of the barrier first mentioned by Mercer (1966). Additional evidence was obtained in February 1978 after the beach profile had been radically altered by easterly gales when it assumed an extreme concavo-convex shape from the crest downwards. Water collected in the depression and percolation was demonstrated with a dye. Levelling indicated that the surface of the water table was approximately 0.7 m above the level of the incoming tide and 4.5 m below the lake level. With a measured distance of about 130 m between the lake shore and the point of leakage, the hydraulic gradient was calculated to be 0.035, which compares very favourably with the gradient inferred from borehole data (C. R. Morey, unpublished).

(2) For more than half the year water loss can only occur by way of evaporation and seepage because the outflow is blocked. A simple treatment of the data testifies to the overriding effect of seepage in lowering the lake level (Table 5) which remains plausible even allowing for 100% error in the measured quantities of evaporation and inflow.

(3) The seasonal variability of the monthly estimates may reflect a dependence on lake level associated with a narrowing of the contact zone between water and shingle as the lake shore dries out. This has been endorsed by a regression analysis of daily events in October 1976 (Fig. 10), with a computed correlation of 0.699 ($p = 99.9\%$). From an extrapolation of the regression line, the calculated seepage loss at maximum lake level (0.99 m above weir datum) would be $0.469 \times 10^6\,\mathrm{m^3 day^{-1}}$, or 24% less than the corresponding budget estimate ($0.618 \times 10^6\,\mathrm{m^3 day^{-1}}$). The precision of the calculation would be improved by an analysis of additional data but the disagreement between the two estimates may indicate that the relationship is not linear. An alternative approach has been sought.

It may be anticipated that the flow of water through the shingle barrier will conform to principles of groundwater movement through a free aquifer composed of unconsolidated materials. Permeability is a measure of the capacity of the sediment material to transmit water under pressure and is defined by Darcy's Law which states:

$$\text{Permeability} = \frac{\text{flow velocity}}{\text{hydraulic gradient}} \tag{5}$$

The velocity may be calculated by dividing the daily seepage loss by the cross-

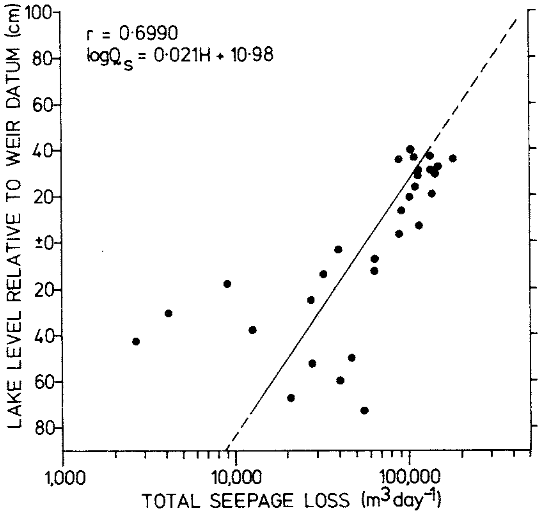

FIG. 10.
Relationship between daily estimates of seepage (Q_S) through the shingle barrier and observed lake levels (H) during October 1976.

sectional area of the barrier through which the water flows. The hydraulic gradient represents the slope between two flow heads and will vary with lake and sea levels. Assuming a contact zone of 10 m (3.9 times the mean depth at maximum lake level) and a shingle shore length of 3,573 m, the mean barrier velocity for a maximum daily loss of 0.618 × 10^6 m^3day^{-1} is 17.3 $mday^{-1}$. On the basis of the 0.035 gradient given earlier, the estimated permeability of the shingle-complex is therefore 494 $mday^{-1}$. The mean daily seepage loss over the four-year period has been 0.030 × 10^6 m^3day^{-1} and this is equal to a permeability of only 60 $mday^{-1}$ (hydraulic gradient = 0.018). The apparent discrepancy between the two values may be explained by the interplay of several factors. Changes of the hydraulic gradient between 0.008 and 0.035 (at minimum and maximum lake levels, respectively) have important effects on the flow pressure, and hence the velocity. Measurement of the gradient is based on mean sea level but different values are obtained at times of high and low water. This implies that the rate of seepage exhibits a diurnal variation in sequence with the tidal cycle. Permeability is regulated by porosity and the degree of sediment consolidation. The lower sediments of the barrier have been compacted and cemented and their permeability is considerably less than the more freely draining surface materials. The velocity of flow through the barrier increases with lake level, and the rate of seepage will be amplified at higher levels. Consequently, the correlation shown in Fig. 10 is not linear. In the absence of specific data, the expected permeability for the shingle barrier lies within the range 10-10^3 $mday^{-1}$. This is in good agreement with the reported permeabilities of 10^{-3}-10 for silt, 10-10^4 for sand and 10^2-10^6 for gravel (Gregory and Walling, 1973).

Seepage is undoubtedly of prime importance to the hydrology of Slapton Ley and at times is the only significant output from the system. There is normally a delay of between two weeks and seven months before the sluices are opened in response to increased rainfall but seepage reacts almost instantaneously and balances the input until excessive flooding necessitates the operation of the outflow. The inherent balance between seepage and outflow is made more conspicuous by a consideration of long-term budgets (Table 3) in which the dominance of one component over the other is distinctly governed by the functioning of the sluices. In view of the observed lake lowerings, it may be judged that seepage is the natural drain from the lake and that the culvert system exists solely to prevent the overfilling of the basin.

The Throughflow Factor

The location of the main inflow and outflow on the same axis, together with the general shape of the lake, likens the system to a widened river. Such a flow regime may also be implied by the longitudinal orientation of depth contours (Fig. 2). The narrowness of the basin will assist flushing efficiency (Lomax, 1971) but the channelling of water through the lake will be disturbed by the mixing effects of wind-generated currents.

Hydraulic retention in the Lower Ley (Fig. 11) has averaged 18 days during the four years studied which may be reciprocated to a flushing rate of about twenty

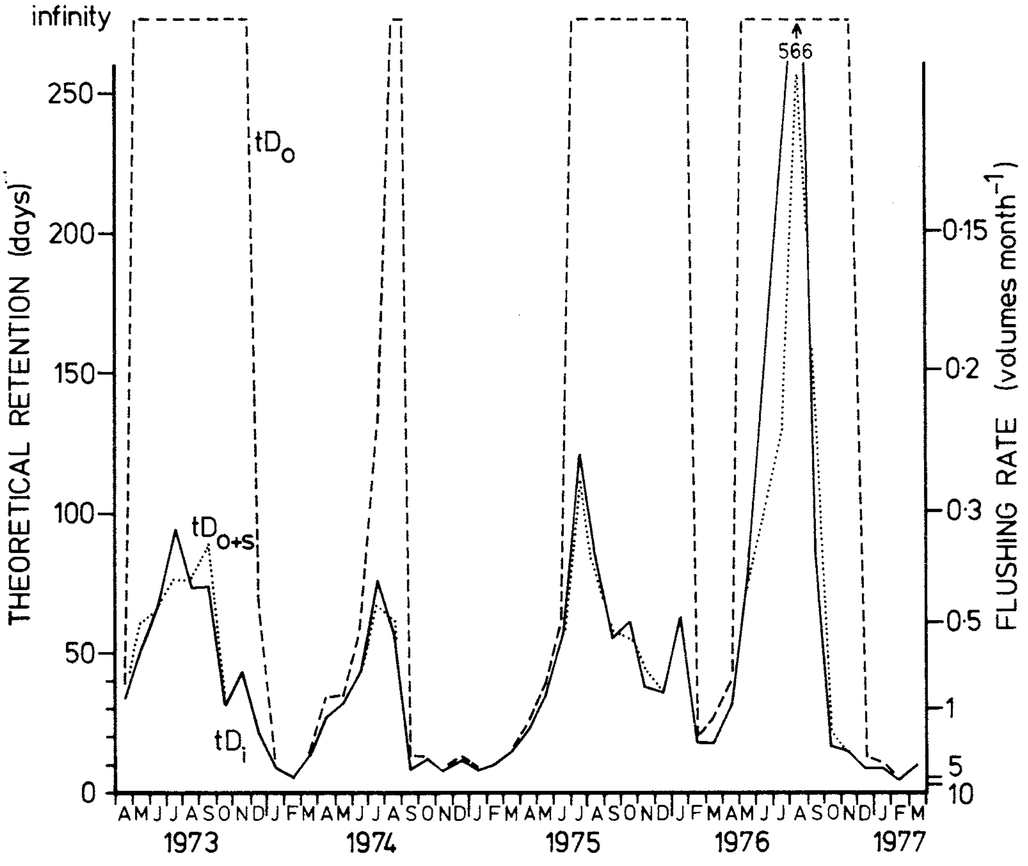

FIG. 11.

Variation of mean monthly throughflow parameters in the Lower Ley, including theoretical retention times based on inflow (tD_i), outflow (tD_O) and summed losses due to outflow and seepage (tD_{O+S}). Values for the latter two quantities are plotted only where they deviate significantly from tD_i. A scale of reciprocal flushing rate is provided for comparison.

times per year. At the peak winter flood as much as a third of the lake's volume may be displaced in 24 hours. In the summer, however, the water remains in the lake for relatively long periods and is renewed perhaps only once in the whole season. When the outflow is blocked, estimates of tD_O are theoretically infinite and the primary throughflow effect is due to inflow replacement. Although the quantity is mathematically balanced by seepage (such that $tD_i = tD_{O+S}$), the rate of percolation per unit area of the barrier is only a fraction of the simultaneous channel discharges and, therefore, will not have the same implications as the outflow when the sluices are operative.

Fig. 12 portrays a typical throughflow response to a sudden increase in rainfall. There is normally a delay of at least a day between the occurrence of a storm and peak inflow discharge, although this will vary with the amount of rainfall and according to the condition of soil moisture in the catchment. The apparent increase of lake storage is pronounced by the non-functioning of the outflow and will continue until such time that seepage exceeds the input. The opening of the sluices results in an 'instantaneous' increase in the removal rate from 0 to more than 0.3 volumes per day. Its subsequent decline is rapid, reaching a stable rate of less than 0.1 day^{-1} usually within 4 days, and has the effect of maintaining a comparatively high dilution rate due to the loss of lake volume, despite the continually decreasing inflow.

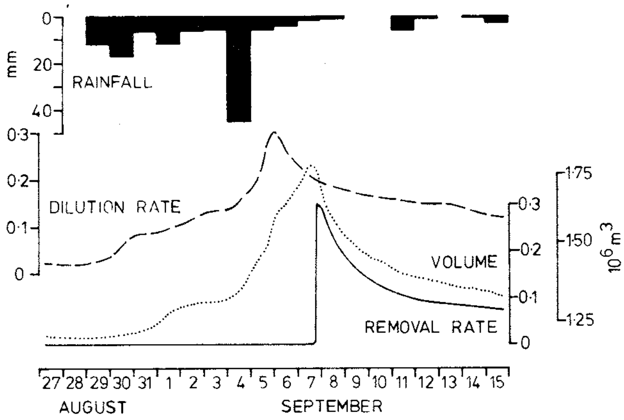

FIG. 12.

Hydrological response of the Lower Ley to sudden storm rainfall and its effect on inflow dilution, lake volume and outflow removal during the period 27th August to 15th September 1974.

A prime reason for the high degree of flushing in Slapton Ley is the large ratio of catchment area to lake volume (C.A./V = 35.9) which is considerably greater than for the majority of lakes cited in the literature. Table 6 describes the morphometry and hydrography of 34 lakes, 6 of which are in the United Kingdom, 6 in Continental Europe, 21 in North America and 1 in Africa. The list is by no means exhaustive and an equal number could not be included for lack of sufficient information. Hydraulic retention (tD) in these lakes has been plotted against their respective C.A./V ratios in Fig. 13, with a calculated correlation coefficient of —0.9295. The relationship would be made more significant by the inclusion of a rainfall term since a greater annual input will promote a correspondingly higher flushing rate. This effect is most apparent when comparing lakes 16 and 27 with 3, 7 and 11, for which the annual rainfall totals are 1,850 mm and 645-820 mm, respectively. The 13 New

Table 6. *Morphometric and Hydrographic Data for various Lakes, ranked in order of increasing mean depth*

No	Lake	Mean depth m	Catchment area km²	Lake volume 10^6 m³	$\frac{C.A.}{V}$	tD days	Reference
1	Glaningen	1.5	34.7	1.125	30.8	29.2	Ryding and Forsberg, 1977
2	Slapton Ley	1.55	45.6	1.269	35.9	17.5	This paper
3	Trummen	1.75	13.1	1.14	11.5	152	Gelin and Ripl, 1978
4	Ramsjon	1.8	12.3	0.702	17.5	73	Ryding and Forsberg, 1977
5	Ryssbysjon	1.8	99.1	4.914	9.67	47.5	Ryding and Forsberg, 1977
6	Sodra Bergundasjon	2.3	44	9.9	4.44	213	Bengtsson, 1975
7	Lake George	2.4	9,955	600	16.6	131	Viner and Smith, 1973
8	Geist Reservoir	3.6	551.9	26.208	21.1	58	US Env Prot Ag, 1976*a*
9	Loch Leven	3.9	145.4	52.4	2.78	158	Smith, 1974
10	Lake 227	4.4	0.268	0.22	1.22	785	Schindler *et al*, 1977
11	Crosemere	4.8	2.154	0.734	2.93	706	Reynolds, 1975
12	Honeoye	4.9	95.0	34.8	2.73	292	Schaffner and Oglesby, 1978
13	Shagawa	5.7	110	53	2.08	226	Larsen *et al*, 1975
14	Uttran	5.7	17.1	15.846	1.08	1,606	Ryding and Forsberg, 1977
15	Hamilton	6.3	39.6	20.475	1.93	657	US Env Prot Ag, 1976*b*
16	Esthwaite	6.4	17.1	6.444	2.65	105	Lund, 1972; Ramsbottom, 1976
17	Canadarago	6.7	165.0	50.9	3.24	219	Schaffner and Oglesby, 1978
18	Oneida	6.8	3,293.4	1,400.0	2.35	219	Schaffner and Oglesby, 1978
19	Cameron	7.1	3,157	90.17	35.0	22.4	Dillon, 1975
20	Lake James	7.3	119.6	30.514	3.92	312	US Env Prot Ag, 1976*c*
21	Lough Neagh	8.6	5,700	3,150	1.81	640	Gibson *et al*, 1971
22	Four Mile Lake	9.3	44.9	71.4	0.63	1,553	Dillon, 1975
23	Otisco	10.2	93.8	77.8	1.21	694	Schaffner and Oglesby, 1978
24	Conesus	11.5	158.2	156.8	1.01	511	Schaffner and Oglesby, 1978
25	Hemlock	13.6	96.2	105.9	0.91	730	Schaffner and Oglesby, 1978
26	Canadice	16.4	31.8	42.6	0.75	1,643	Schaffner and Oglesby, 1978
27	Windermere	21.3	230.5	314.5	0.73	274	Macan, 1970; Ramsbottom, 1976
28	Owasco	29.3	470.0	780.7	0.60	1,132	Schaffner and Oglesby, 1978
29	Keuka	30.5	404.6	1,433.7	0.28	2,300	Schaffner and Oglesby, 1978
30	Canadaigua	38.8	407.2	1,640.1	0.25	2,701	Schaffner and Oglesby, 1978
31	Skaneateles	43.5	151.4	1,562.8	0.097	6,461	Schaffner and Oglesby, 1978
32	Cayuga	54.5	1,870.5	9,379.4	0.20	3,468	Schaffner and Oglesby, 1978
33	Ontario	84	60,000	1,600,000	0.038	2,306	Robertson and Jenkins, 1978
34	Seneca	88.6	1,180.6	15,539.5	0.076	6,607	Schaffner and Oglesby, 1978

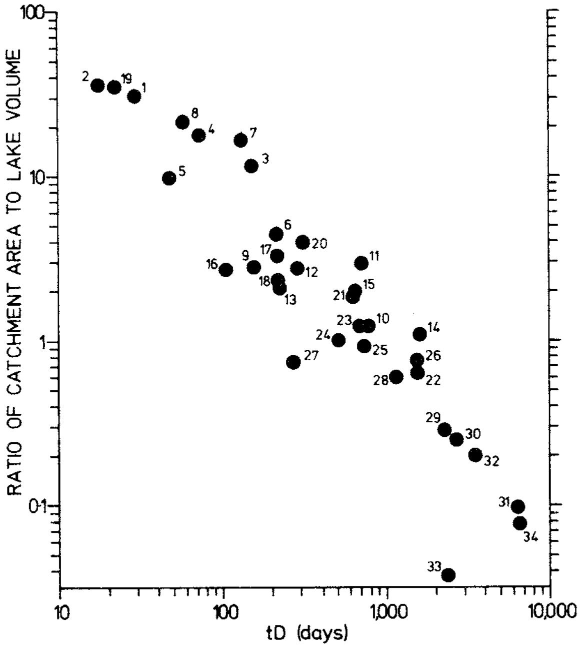

FIG. 13.
Relationship between mean hydraulic retention time (tD) and the ratio of catchment area to lake volume for the lakes, including Slapton Ley (No 2), described in Table 6.

York Finger Lakes described by Schaffner and Oglesby (1978) are confined within a narrow belt to the south of Lake Ontario, into which they ultimately drain, and their proximity must ensure a fundamental similarity of catchment topography, basin morphology and precipitation input. This is borne out by a C.A./V:tD correlation of –0.9811. In the absence of detailed water balance data, the ratio of C.A./V could be applied as a simple hydrographic index in the comparison of different lake water budgets and as an approximate measure of the probable magnitude of the rate of water renewal.

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