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Hydraulic conductivity of peat at Ellergower Moss, Scotland

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Abstract:

Falling head (and a few rising head) measurements were made of hydraulic conductivity k in a profile of a 7 m deep, small raised bog in southwest Scotland. The seven piezometer pipes were 39 mm diameter, and most of the measurements were made with attached tubes of 2·5 mm diameter, so that only 2–3 mm of water crossed the peat interface during a run. There were no consistent effects of pre-flushing, direction of flow (falling, rising), or measuring-tube size. Variability of 10–20% in k did not obscure an exponential decrease with depth from 5×10^{-6} cm s^{-1} at 100 cm to $0{\cdot}7 \times 10^{-6}$ cm s^{-1} at 500 cm. This decrease was uncorrelated with dry bulk density or peat stiffness, and only loosely so with a measure of humification. Calculated mean bulk velocity of pore water may be as low as 1 mm $year^{-1}$. Pressure in the silty sand below the peat was 180 mbar less than expected, suggesting a thin highly impermeable layer ('pan'?) at the peat base. The substratum may have hydrological connection with an adjacent lake. The hydraulic properties of this raised bog contrast strongly with those of a raised bog in Minnesota, and do not fit the assumptions made for Ingram's simple groundwater mound model of raised bog shape. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS peat bog; Scotland; hydraulic conductivity

INTRODUCTION

Peatlands cover about 3% of the Earth's land surface (Matthews and Fung, 1987) and contain about 450 Gt of carbon (Gorham, 1991)—similar to the amount there is in the atmosphere (Clymo *et al.*, 1998). The peat is formed from the remains of the plants, only partially decayed, that grew, and grow, on the surface. Peat depths of 5–10 m accumulated over 5000–10 000 years are not uncommon, though the average depth is probably 2–3 m (Gorham, 1991). Some peatlands are enormous: an area about 1800×800 km^2 in the West Siberian Plain forms a single peatland complex (Walter, 1977). The very existence of these massive deposits depends on their hydrology. The majority of peatlands are in the boreal zone and many have a perched water table, which Ingram (1982) proposed depends dynamically for its maintenance on precipitation exceeding the sum of evaporation and of seepage into underlying and marginal mineral strata.

The top 5–70 cm of a typical rainwater-dependent peatland has high hydraulic conductivity k ($[LT^{-1}]$, typical units cm s^{-1}), is at least periodically oxic, and is the site of plant growth, death, and relatively rapid aerobic, mainly fungal, decay. As a result of decay the dead plant structures collapse, reducing the space between them, and thus greatly decreasing k. Precipitation that has flowed easily downwards to this point is now impeded and forced to flow sideways. In droughts the water table may sink a few decimetres into the peat, but it recovers rapidly on the first rains. Because k increases rapidly upwards (Bragg, 1982) the upward movement of the water table is self-limiting. This surface layer down to the depth to which the water table falls in a dry summer, and within which the water table oscillates, is the acrotelm (Ingram, 1978).

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The rate of diffusion of most common gases in water is 10 000 times slower than it is in air. Bacteria in the first few centimetres below the water table use up oxygen faster than it can diffuse down from the air, so the peat becomes permanently anoxic. This layer, extending from perhaps 50 cm depth to the peat base (perhaps 10 m below), is the catotelm. Anaerobic decay processes result in decay rates two to four orders of magnitude lower than in the acrotelm, and to the consequent accumulation of peat. Clymo and Pearce (1995) give further details.

Some of the most spectacular peatlands are the domed raised bogs with a relatively steep margin (the rand) and a gently domed cupola. Ingram (1982) suggested that this shape was enforced by the perched water table. He assumed, among other things, that the peat was homogeneous and isotropic, with a single value of k, and that it formed on a plane impermeable base (assumptions that made possible an analytical solution). Imagine a circular palisade, 1 km across, on a flat impermeable rock and filled to a depth of, say, 10 m with sand. Rain falls continuously over the whole area, and is able to leave the enclosure through innumerable drains around the perimeter at the base of the palisade. What shape will the water table assume in the steady state? Ingram (1982) showed that the cross-section should be hemi-elliptical, and its thickness determined by U/k, where U is the rate of 'lateral discharge [through the catotelm] towards the [marginal] lagg stream'. Two small raised bogs fitted this solution reasonably closely (Ingram, 1982, 1987), but field measurements of substratum k are rare (Siegel (1983) inferred some) and measurements of profiles of k in peat differ by orders of magnitude (Chason and Siegel, 1986; Kneale, 1987; Korpijaakko *et al.*, 2000) in value and uniformity.

The work to be described here was begun for two reasons. First, in a small rainwater-dependent bog in Scotland the age of the gases CH_4 and CO_2 was a thousand years or more younger than the peat at the same depth (Clymo and Bryant, in preparation). Diffusion and mass flow of gas in pore water are both plausible qualitative explanations, but making a model to test these quantitatively requires knowledge of the bulk velocity and direction of pore water flow in the whole peat profile, and thus of the profile of k.

Second, was to discover whether or not Ingram's (1982, 1987) groundwater mound model for peatland gross shape, which assumes a homogeneous isotropic peat on an impermeable base, could be justified for the same small peatland. This, too, needs at least one profile of k.

This article, therefore, describes measurements of k using mostly the falling head in piezometer pipes placed to various depths, with the deepest at over 700 cm (which is more than twice the deepest recorded in peat bogs so far). Supporting measurements were made of pore water pressure, of dry bulk density, of 'humification', and of peat stiffness to help interpret the k measurements.

THE SITE

Ellergower Moss (latitude 55°05′N, longitude 4°23′W; National Grid reference: NX4880) is a small raised bog 31 km west of New Galloway in southwest Scotland. It is roughly elliptical, with major axis 800 m and minor axis 500 m long, and is also hemi-elliptical in section (Ingram, 1987), being just over 700 cm thick at the measurement site at the highest point near the centre. The annual precipitation of about 3000 mm is mostly as rain. The mean air temperature is 8·1 °C, the amplitude of the fitted annual sine wave is 4·8 °C, the mean wind speed is 4·5 m s^{-1}, and the mean daytime incident radiation is 160 W m^{-2}. (Meteorological data are averages of measurements at 1 h intervals for the period October 1991 to October 1993; Clymo and Hargreaves, unpublished data). Most of the bog centre is *Sphagnum*-covered, with the dwarf shrubs *Calluna vulgaris* and *Erica tetralix* on hummocks up to 50 cm tall, sedges *Eriophorum vaginatum* and *Trichophorum cespitosum* on lawns, and *Rhynchospora alba* in hollows. Hummocks, lawns and hollows occupy about 67%, 23% and 10% of the central area respectively (Clymo and Pearce, 1995). The observations reported here were made in what is, at present, a lawn.

The bog has developed over 9000 years in the third of a series of contiguous basins running from southwest to northeast. The first two are occupied by Loch Dee. In the first basin are several sub-basins over 10 m deep. The second basin is nowhere more than 2 m deep and is floored by coarse sand derived from the local granite.

The third basin in which the bog has developed is underlain by sand and silt. The sand (based on mineralogical analysis under crossed Nicol prisms and on X-ray probe analysis on a scanning electron microscope) is similar in composition to, though more angular than, the sand on the shore of the lake. The sand in this basin may be in hydrological contact with that under the lake. A topographic survey (Ingram, 1987) shows that the sand on which the peat developed was nearly flat, with hollows that were no more than 20 cm deep and which filled with sedge peat formed from *Carex, Equisetum, Phragmites*, and hypnoid mosses. Similar vegetation may be seen today in lows behind the lake shore.

The peat, above a thin layer of sedge peat, is dominated by *Sphagnum* at all depths. It has become well humified at all depths below 50 cm and shows little stratigraphic differentiation.

METHODS

Hydraulic conductivity

This article concerns k in the catotelm only, but depths are relative to the top of the acrotelm, which was about 20 cm thick at the chosen site.

Hydraulic conductivity was calculated from time-course observations of the falling (or, in a few cases, rising) head of water connected to rigid PVC piezometer pipes sunk in the peat. Falling and rising head are the most straightforwardly descriptive of several terms used for such measurements; the terminology is discussed by Butler (1998). In this article, piezometer 'pipes' are distinguished from 'tubes' of flexible PVC connected to the pipes at the surface (Figure 1). The pipes had internal diameter 39 mm. A 30 cm long auger fitted inside the pipe with about 1 mm play. Attached peat borer extension rods brought the auger shank clear of the top of the PVC pipe, and a collar was fastened to the rods to hold the tip of the auger level with the bottom of the PVC pipe. Thus, the auger stopped the ingress of peat. The pipe and auger were raised to the vertical, and a rope attached to the collar was used to pull the pipe and auger down into the peat. When the bottom end of the pipe reached 20 cm above its intended final position the collar was removed and the auger was used to cut 20 cm of peat ahead of the pipe (Figure 1). The pipe was then pushed down the last 20 cm, leaving the top flush with the vegetation surface and no cavity below the pipe. The auger and trapped peat were removed, and peatland water poured from a bucket into the pipe to fill it to the surface. There was no cavity for three reasons. First, a zero-length cavity is the most easily created accurately in peat; second, the shape factor is least affected by other variables; and third, there is a smaller chance of the interface distorting.

Six such PVC pipes were cut to 100, 200, 300, 400, 500 and 600 cm in length. These all ended in peat. The base of the peat was at 720 cm, and a seventh pipe was driven down into the underlying silty sand at 745 cm, augering the bottom 25 cm. Pipes to 400 cm were made from a single length. Longer ones were made in the field: a 400 cm length, with the auger inside as usual, was pushed down to near its full depth. The required extra piece of pipe was then joined with a standard double socket and PVC cement, and the composite pipe drawn down as before. The socket, being of larger diameter than the tubes it joins, probably causes leakage around the tube above it. But either the whole length of pipe (100 to 400 cm cases) or at least the lowest 400 cm (500 to 745 cm cases) were of uniform diameter and formed as tight a seal as is possible.

Into the top of each pipe was pushed a #37 rubber bung with two flexible PVC tubes through it (Figure 1). Both tubes were thick walled, with internal diameter 2·5 mm. One tube projected about 50 cm on both sides of the bung and could be joined with thick-walled tubing to one of several measuring tubes of internal diameter 2·5, 12, 22, or 39 mm, the last two being glass. For falling head measurements these measuring tubes were attached to the emergent part of a 3 m length of rigid PVC electrical conduit pushed vertically into the peat to leave 125 cm showing. A scale was stuck to the conduit parallel to the measuring tube. The second tube through the rubber bung was cut flush with the bottom end of the bung and projected about 10 cm above the bung. It was joined to a short piece of silicone tube that could be closed by a screw clip (PVC is too stiff in cold weather). A water reservoir was attached by 6 mm tubing to the free end of this silicone tube. With the clip open, the reservoir was raised to the top of the scale so that water drove out contained air and filled the

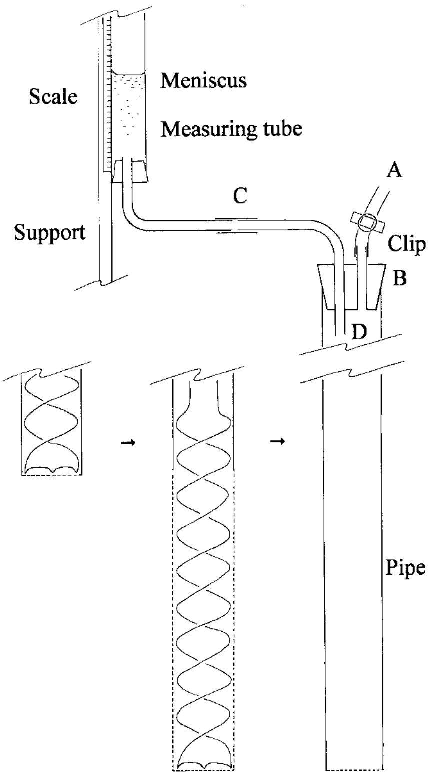

Figure 1. Apparatus for falling and rising head measurements in peat. The process of placing the piezometer pipe is shown at the bottom. The pipe with the auger held in place by an adjustable collar (not shown) is pushed down to within 20 cm of its final position. The collar is removed and the auger used to cut a hole for the last 20 cm. The pipe is then pushed down around the auger, to its final position, and the auger, with flutes now peat filled, removed. Dashed lines show cut peat interfaces. Water enters the pipe across the cut peat at the end of the pipe: the 'cavity' has zero depth. The measurement system is at the top. A reservoir is attached at A and the clip is opened. When the reservoir is raised, water displaces any air through the thick-walled tube B and out of the measuring tube. Water rises in the transparent measuring tube to the same height as in the reservoir. When the clip is closed, the meniscus in the measuring tube begins to fall and its progress against the scale is recorded. Measuring tubes of different sizes can be attached at the joint B. Different size tubes can be attached at D for rising head measurements, water being sucked out of A to start a run. In this case, it is necessary to use a pressure sensor (not shown) inserted through the rubber bung B for measurements of head. The same sensor can also be used for falling head measurements

measuring tube. This process took no more than 10 s, and less than 5 s if there was no air to displace. (The 22 and 39 mm measuring tubes were filled even more quickly by pouring in water from a beaker.) This rapid setting, compared with the time to reach $h/H_0 = 0{\cdot}5$, of the starting conditions may be of some importance (Rycroft *et al.*, 1975b). The clip was then closed and the position of the meniscus in the thick-walled tube was followed over time. When the same thick-walled PVC tube was used for measuring, then the relative cross-sectional area of the piezometer pipe in the peat and the flexible thick-walled scale tube was 240 : 1. This 'hydraulic multiplier', as we may call it, was suggested by Kirkham (1946) and may be defined as $M = (R/r)^2$, where R and r are the radius of the piezometer pipe and measuring tube respectively. This has at least two advantages. First, the depth of the layer of water that flows across the peat interface during a run is given by $D_w = H_0/M$. In the Ellergower work for $M = 240$ and $H_0 = 500$ mm, then $D_w \approx 2$ mm. Flow velocities are, therefore, much smaller, though still three to four orders of magnitude greater than in natural conditions. Second, a run that would take 10 days if made on a measuring tube of the same diameter as the piezometer pipe took only 60 min with the multiplier. But it can be argued that such a small volume of water may be sampling only the peat immediately adjacent to the end of the pipe, and that may be disturbed. This was the reason for making comparative measurements with different sizes of measuring tube.

A nest of seven piezometer pipes was placed at 1·5 m intervals along the arc of a circle of radius 3 m at a site near the peatland centre. The order of pipes was 1, 4, 7+, 3, 6, 2, 5 m, thus maximizing the distance between the base of adjacent pipes. The minimum separation of piezometer pipe basal ends was 340 cm. The observer sat at the centre of the circle and read the water levels with a telescope, thus minimizing disturbance. For a few runs a prototype pressure-measuring device was used, which allowed rising head as well as falling head measurements to be made. The detector was a Honeywell 26PCAFA6D device with a silicon diaphragm at one end of a 5 m cable, powered (from the other end) by an LT1021 stabilized 10·00 V supply, with its output amplified by an AD AMP04FP instrument amplifier to give an output from 0 to 500 mV for a pressure differential from −50 to +50 cm head of water.

The majority of runs reached 90% or more of completion. Individual runs with 2·5 mm measuring tubes had response times (the time for h/H_0 to reach 1/e = 0·37 from the asymptotic value) from 5 to 400 min, but much longer with bigger tubes.

A hydraulic level (Bragg, 1982) was used to link the scales to the local water-table level as (arbitrary) datum. All observations were standardized (reduced) to this datum.

The zero time was taken as that of the first reading, at the top of the scale, and that reading became H_0, where h is the standardized height. A simple negative exponential response curve was an acceptably accurate description of the time course of h. The asymptote a, toward which it was tending, was known in the cases where a run overnight was within 1% of completion; but, often the run was ended 10% (or more) from completion and the asymptote was known only approximately. The data were fitted to

$$\frac{h - a}{H_0 - a} = \exp(-\beta t)$$

allowing a a range of 5 cm to give estimates of a and of β (min^{-1}), the decay rate coefficient. The optimization technique is described later. Hydraulic conductivity k was calculated following the Kirkham (1946) and Youngs (1968) definition of $h/H_0 = \exp(-kst/\pi R^2)$ equated with $h/H_0 = \exp(-\beta t/M)$ to give $k = \pi R\beta/MY_f$, where R is the radius of the piezometer pipe, $s = Y_f R$ (with Y_f being Youngs' cavity factor), and M is the hydraulic multiplier given by $(R/r)^2$, with r being the measuring-tube radius.

Pressure measurements

A silicon diaphragm 0–1 bar pressure sensor (Druck PDCR 820-0800-05) was mounted in a cylindrical shield of the same diameter as a standard peat borer extension rod (25·4 mm). The shield was attached to a 140 cm hollow rod of the same diameter with, at its top, a handclasp connection to a standard peat borer extension rod. A flexible 'Tygon' tube to the surface travelled up inside the hollow rod before emerging at the side and continuing for 10 m to an electronics box on the peat surface. The tube carried electrical connections and allowed air pressure at the free end of the tube to be available to one side of the diaphragm. The other side connected to a water-filled, but only half-inflated, balloon made from the tip of a disposable plastic glove. This created a defined interface with the surrounding peat pore water. The electronics provided a temperature-compensated output of 100 mV bar^{-1}. This probe presented to the peat as a 150 cm long smooth cylinder, interrupted at that point by the emergence of the flexible tube and by the locking collar of the extension rod. The voltage reading was negative exponential with time, with a response time of 5 s in water at the surface, and from 2 min at 50 cm deep to 6 min at 600 cm deep.

Dry bulk density

Samples were taken with a 1·8 m long 'box corer' (Digerfeldt, 1966) consisting of a vertical three-sided channel, approximately 10 × 10 cm square, that made the initial cut and a fourth side that slid down and curved round to complete the enclosure of a square core. The cross-sectional area was 103·7 cm^2. Blocks 20 cm tall were massed ('weighed'), dried at 85 °C, and massed again.

Humification

There are many methods for measuring 'humification', ranging from the rather subjective 1–10 scale based on colour and turbididty of water squeezed by hand from the peat in the field and on consistency of the peat residue (Von Post and Granlund, 1926) to operational laboratory methods that measure the transmission or absorbance of light by, or luminescence (Caseldine *et al*., 2000) from, the brown-coloured compounds in an extract of alkali, pyrophosphate, or other reagent. This work used a simplified version of the recipe devised by Blackford and Chambers (1993), in which volume measurements were substituted by masses. They explored variations in extraction time, temperature, and wavelength of measurement. A sample of peat was dried under vacuum at 20 °C and ground. A suspension was made in a conical flask of 0·20 g of dry peat in 50 g of 8% w/v NaOH, and a glass marble put on the top of the flask to minimize vapour loss. The mixture was simmered on a sand tray on a hotplate for 60 min. The suspension was made up to 250 g and filtered through Whatman Qualitative #1 paper, the filtrate being clear of even traces of opalescence. Absorbance of the filtrate in a 1 cm cell was measured in a colorimeter against reagent blanks (with filter paper in place of peat) with a filter centred on 550 nm. Proportional corrections were made for the small deviations of sample mass from 0·2 g and of final mass from 250 g. Samples were treated in random order. Absorbance was preferred to Blackford and Chambers' use of transmission because absorbance is generally proportional to concentration, whereas transmission is not.

Torque

A five-sided vertical blade was mounted symmetrically on the end of a peat borer extension rod. The blade shape was a rectangle, 20 cm across by 4 cm deep, extended downward across its full width in a 6 cm deep triangle. At the peat borer handle at the top, an electronic ('spring') balance was attached at 30 cm from the centre. An assistant held a loose collar around the central rod and opposed the sideways force created when the observer applied torque to the balance to rotate the blade. A small correction was applied for the torque needed to turn the bare rod.

Precision

Variability of measured values is expressed as standard deviation (SD) or, where the median measure of centrality has been used, as 'G-ile'. This is the quantile range 0·16–0·84: the proportioniles that would give the same values as mean ±1 SD if the distribution were Gaussian ('normal'). Details are given in Pearce and Clymo (2001).

Optimization

The simplex method of Nelder and Mead (1965) was used to optimize asymptote and rate parameters in the negative exponential (falling/rising head) model. The criterion to be minimized was the dimensionless sum of $[(\text{observed} - \text{modelled})/\text{modelled}]^2$. Estimates of the precision of parameters were made on repeated optimization of sets of simulated data (Press *et al*., 1989) assuming 15% random Gaussian errors added to the measured values of differences between adjacent levels.

RESULTS

Figure 2 shows the 2001 set of standardized data made with 2·5 mm measuring tubes plotted on log–linear scales, with the optimized lines whose slope is β. All but one of the data sets form a shallow 'S' shape about the modelled straight lines, as did the results reported by Brown and Ingram (1988), but these systematic differences do not obscure those between piezometer pipes ending at different depths. The variability of the slopes of nominal replicates in Figure 2a is about 10–20%, a value confirmed by the replicates in Figure 3a.

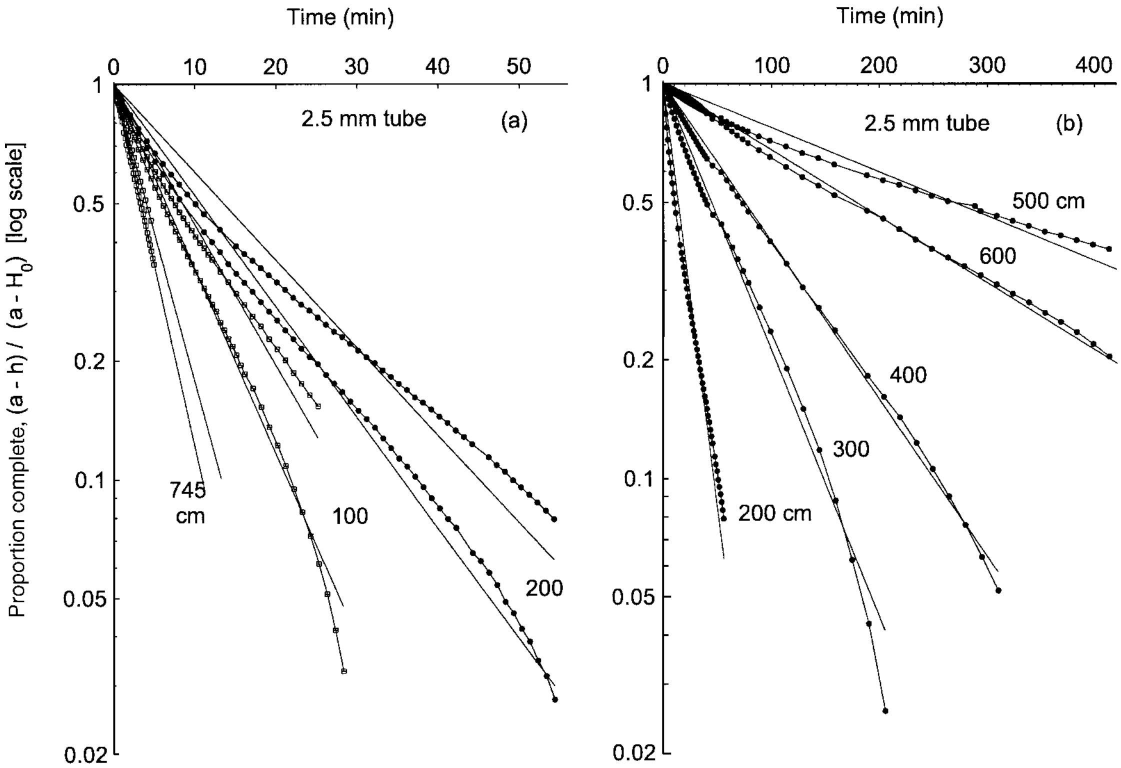

Figure 2. Falling head measurements made with 2·5 mm diameter tubes on 39 mm piezometer pipes (see text) fitted to $(h - a)/(H_0 - a) = -\beta t$, where h is the head, H_0 is the head at time t_0, a is the asymptote being approached, and $\beta[\mathrm{T}^{-1}]$ is the slope on the log–linear plot. Numerical annotations are the depth (cm) in the peat to which the measurements refer. The time scale in (b) spans about eight times as long as that in (a). The faster of the two 200 cm curves in (a) is repeated in (b) to help comparisons

It may be important to 'develop' wells in mineral soil and rock strata by bailing out and allowing interstitial water to flow in, thus flushing out fine debris (Butler, 1998). This was not done before the 2001 measurements, but it was done before the 2002 measurements in the same piezometer pipes. The results in Figure 3b show 10–20% variation, similar to that in Figures 2a and 3a, but no consistent differences between pretreatments.

The results in Figure 3a and in Figure 4a, made with different diameter measuring tubes, show the (by now expected) variation at the same depth, but no clear sign that measuring tube diameter in the range 2·5–39 mm has an effect on the measured value of k.

Some authors (e.g. Yamamoto, 1970; Dai and Sparling, 1973; Ingram *et al.*, 1974) have found differences between rising head and falling head measurements in peat, but the results in Figure 4b, made with 2·5 mm diameter measuring tubes, show no substantial difference.

Figure 5a summarizes all 57 runs, 44 of them with 2·5 mm diameter measuring tubes. This shows k declining with depth at first, then increasing at 600 cm and becoming highest of all in the silty sand at 745 cm.

The pressure profile is shown in Figure 5b. The peat solids have an intrinsic density of about 1·6 g cm^{-3} (Clymo, 1970; Clymo, unpublished data) but they occupy barely 5% of the volume, and thus (right straight line) have only a small effect on expected pressure. Measured pressure is close to expectation for the top 300 cm or so. It then falls slightly below expectation to 600 cm depth, slightly above to 700 cm, and then unambiguously well below, by about 180 mbar, in the underlying silty sand. This surprising result was confirmed by the discovery that the water level in the deepest piezometer tube had sunk well below the top in

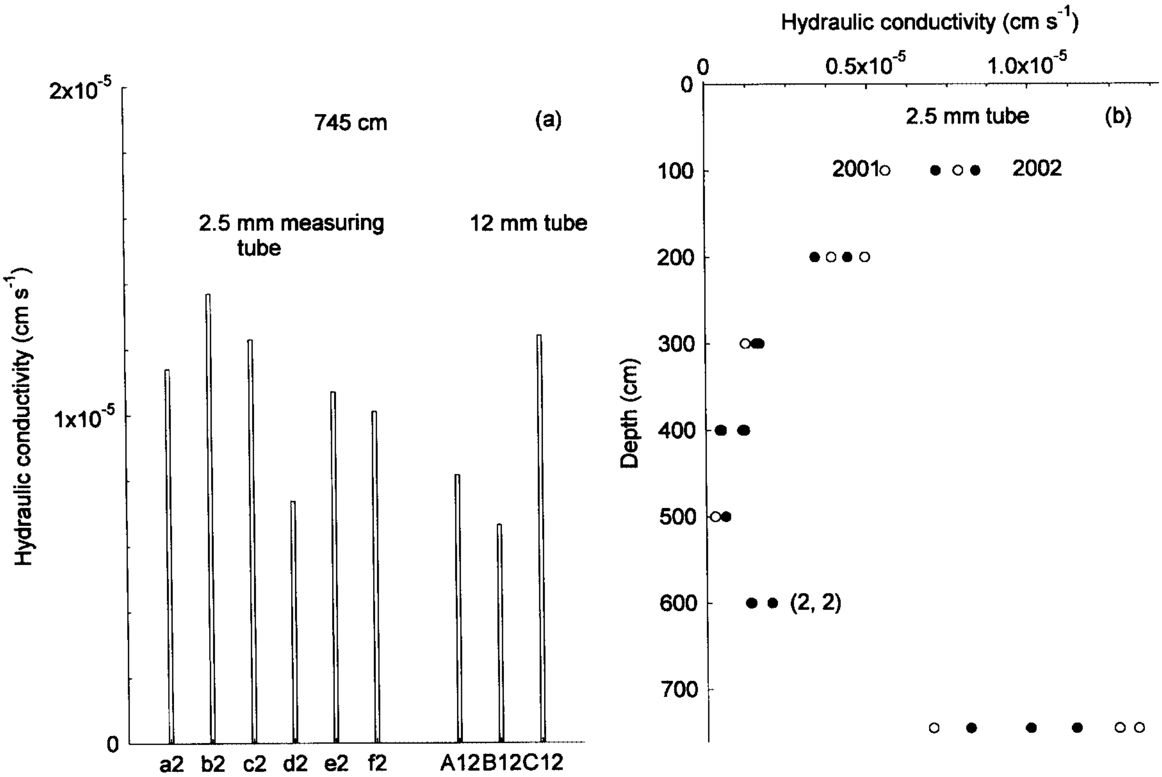

Figure 3. (a) A sequence of measurements of hydraulic conductivity made in the same 745 cm deep 39 mm piezometer pipe with a 2·5 mm measuring tube (cases a2–f2) and a 12 mm tube (A12–C12). (b) Hydraulic conductivity measured with a 2·5 mm tube at various depths of 39 mm piezometer pipes in August 2001 (open symbols) and 10 months later in June 2002 (filled symbols)

2001, and on return to the site in 2002 it was 180 cm below the top of the pipe, in keeping with the optimized asymptote and the directly measured pressure.

Figure 6 shows three sorts of ancillary profile. Dry bulk density is steady at 0·06 g cm^{-3} to about 550 cm depth, then increases gradually to about 0·9 g cm^{-3}. (In the top 30 cm not shown it is less than 0·06 g cm^{-3}.) ‘Humification’ (measured as absorbance in the yellow at 550 nm) increases fairly sharply down to about 80 cm, then more gradually to 700 cm, then declines markedly in the thin sedge peat at the base. Torque, the force needed to turn a blade in the peat, is steady down to 550 cm, then increases fairly sharply to 700 cm.

DISCUSSION

Reliability of hydraulic conductivity values

Individual runs plotted on log–linear scales were slightly S-shaped. This is a consistent effect already reported by Brown and Ingram (1988) and may be one of the consequences of elastic changes in storativity (Hemond and Goldman, 1985; Baird and Gaffney, 1994). Though interesting, it is a second-order effect compared with the differences between piezometers at different depths.

There have been several sets of recommendations for the conduct of rising and falling head measurements (specifically of slug tests) in wells (Butler *et al.*, 1994, 1996; Butler and Healey, 1998; Butler, 1998). These arise from: experience with well diameters and heads that are both an order of magnitude greater than those used at Ellergower; tests that were often half complete in only 0·2 to 0·5 min; water volumes four to

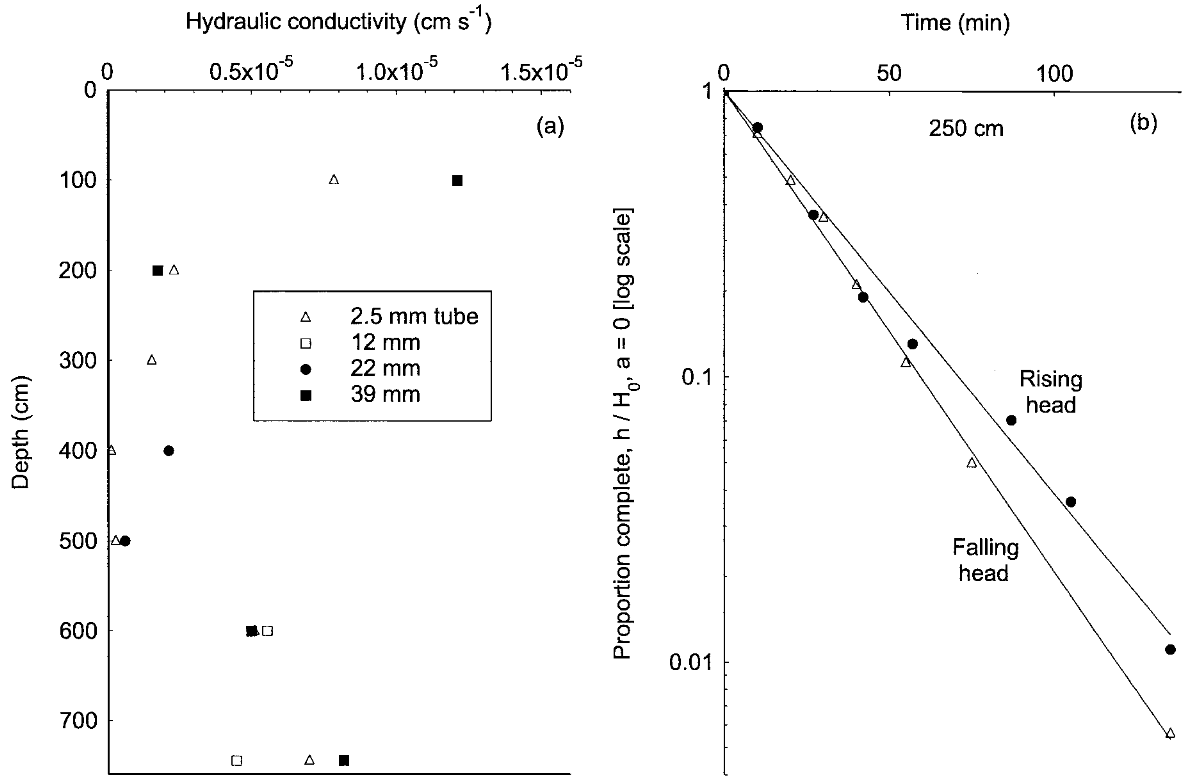

Figure 4. (a) Hydraulic conductivity measured at various depths in piezometer pipes of 39 mm diameter with tubes of four different diameters. (b) Falling head and rising head measured with a 2·5 mm diameter tube in a 250 cm deep piezometer pipe and with an electronic pressure sensor. Though the water moved in opposite directions in the two runs, the plots both slope down towards equilibrium

six orders of magnitude greater than those described in this article; quite complex structures screening the bottom of the well; special sealants; and values of k two to three orders of magnitude greater than those measured at Ellergower Moss. These large wells in mineral strata are also likely to penetrate complex and relatively thin layers with differing hydraulic conductivities. At Ellergower Moss: the times to half-height with the narrowest measuring tubes ranged from 3 to 300 min; H_0 was no more than 120 cm, and usually about 50 cm; there was water movement D_w of only 2 mm during many of the runs with the narrowest measuring tubes; and in at least the top 6 m of peat there were no obvious stratigraphic horizons. In short, the recommendations were devised for conditions differing greatly from those in which the measurements at Ellergower were made.

More compelling is that the Ellergower measurements with narrow measuring tubes and D_w only a few millimetres show no consistent effects of pretreatment (flushing out) or direction of water movement (rising versus falling head) when D_w is small. The reports that rising-head recovery in peats is sometimes notably slower than falling-head recovery (Yamamoto, 1970; Dai and Sparling, 1973; Ingram *et al.*, 1974) are based on piezometer pipes of eight or more times the area of those used at Ellergower, and on measuring tubes the same diameter as the pipe. These effects may be another consequence of elastic storativity in the peat (Hemond and Goldman, 1985). The relatively small pipes and narrow tubes used in the Ellergower work, with consequent small values of D_w, may have minimized this problem.

The variability of nominal replicates of k is 10–20% of mean values. This is larger than desirable, but it does not obscure the differences in values at differing depths shown in Figure 5a. Some of this variability may result from starting a new run before storage has equilibrated completely.

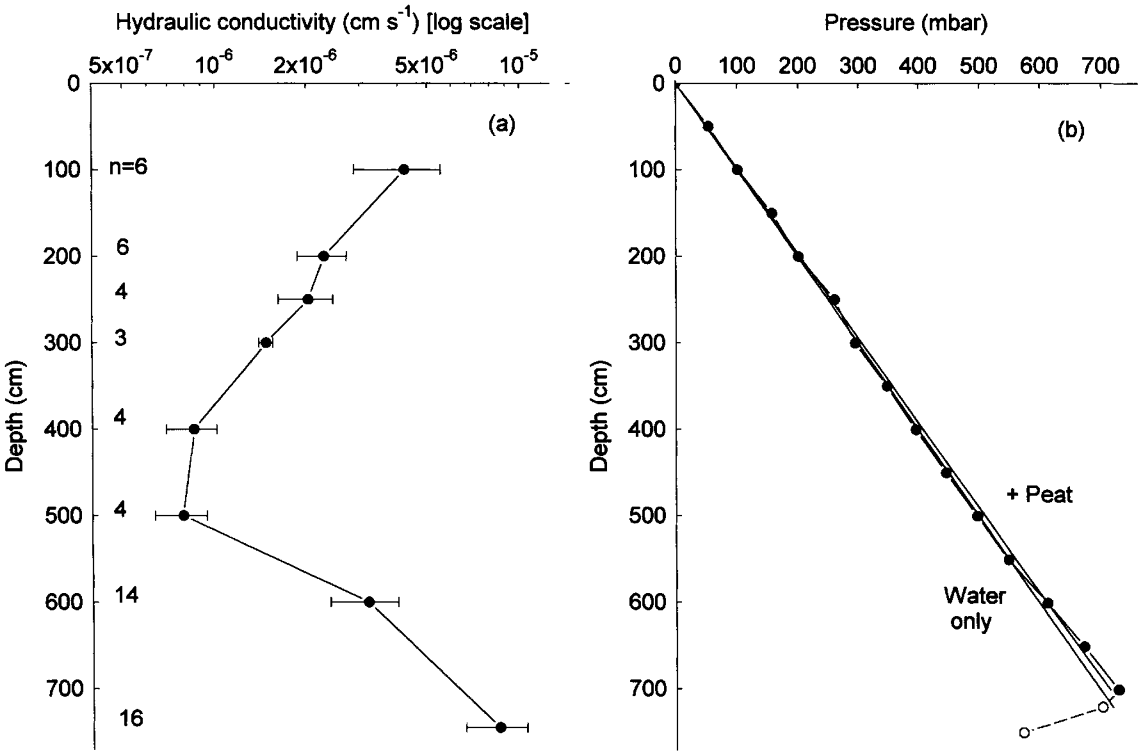

Figure 5. (a) Hydraulic conductivity mean (four or fewer) or median (>4) with ±1 SD bars for means or ±G-ile (see text) for medians for all 57 runs. (b) Profile of measured pressure (circles) with lines calculated for the same depth of water and of water plus peat. Note the 'hook' in the pressure measured at the bottom

It has been argued (Butler, 1998) that results obtained with narrow measuring tubes and measurements made with small volumes of water moving may be liable to distortion by locally disturbed conditions at the peat interface. The analysis by Premchitt and Brand (1981), however, shows how pressure in the piezometer is most affected by what goes on close to the peat interface and progressively less the further away from the interface. The process is *proportional* and is independent of D_W. This is consistent with the Ellergower measurements with narrow tubes: values of k were not obviously biased when compared with those made with wider measuring tubes.

Shape factors have been re-evaluated several times since the work of Youngs (1968), but Brand and Premchitt (1980), for example, show that there is no consensus. Their factors are about twice those of Youngs for the Ellergower conditions. But the piezometer pipes were all of the same diameter, so this would simply halve all the values of k reported here.

There was no cavity below the Ellergower piezometer pipes, so the values of k potentially reflect conductance in all directions, rather than the horizontal bias when the cavity is deep. Of course, the measured k will be affected (Baird *et al.*, 1997) by the actual directional distributions of k. Chason and Siegel (1986) found that horizontal k, measured in the laboratory, tended to be rather greater than vertical k. But their peat was composed of '*Sphagnum* interbedded with numerous layers of wood, rootlets, and sedge', reflecting the *Picea mariana* on the surface and resulting in values of k two to three orders of magnitude greater than those measured at Ellergower, where the peat appears to be unusually homogeneous and well-humified; certainly, it lacks any distinct horizontal or vertical structures that might act as macropores that could make bulk conductivities larger.

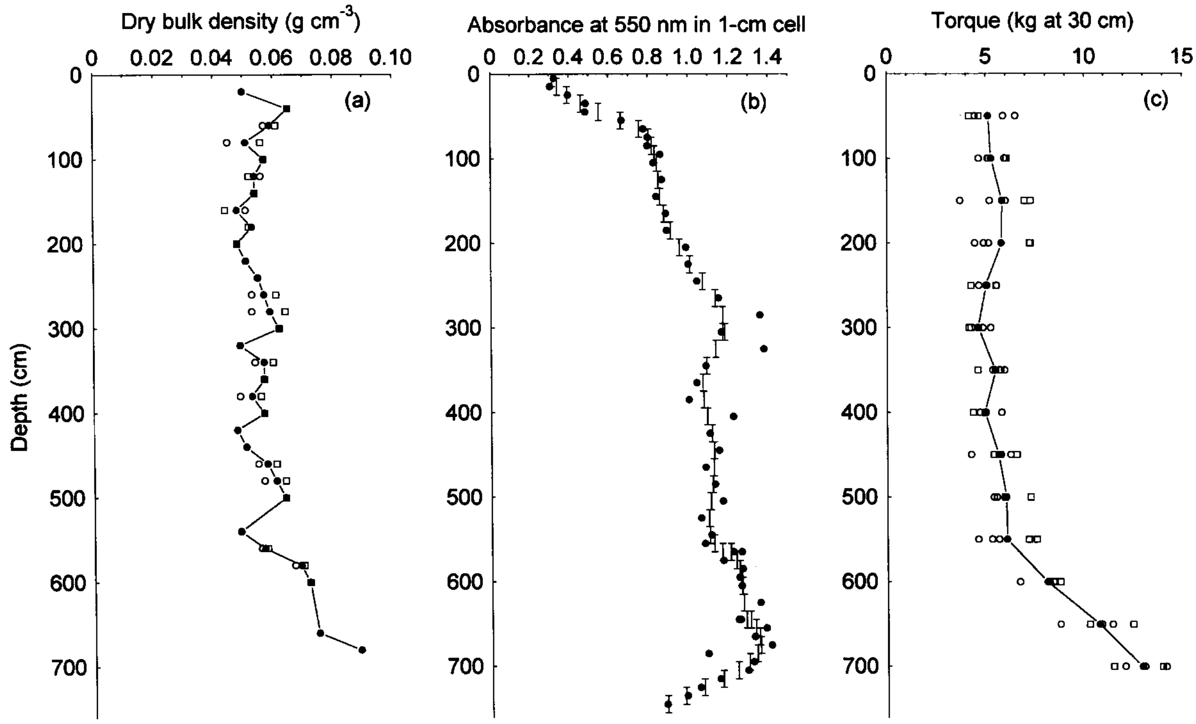

Figure 6. (a) Dry bulk density profiles for replicate cores (unfilled symbols) taken, with a box corer, about 20 m from the piezometer pipes at Ellergower Moss, Scotland, and mean values (filled symbols). (b) 'Humification' profiles assessed by absorbance in a 1-cm cell at 550 nm of an 8% w/v NaOH extract (Blackford and Chambers, 1993); filled circles are measured values; bars are smoothed using the 4253EH/* strategy of Velleman and Hoaglin (1981). (c) Profiles of torque (force applied at a radius of 30 cm) needed to rotate a blade of area 140 cm^2. Five measurements (three in August 2001, open circles; two in June 2002, open squares) and the mean are shown at each depth

The values of hydraulic conductivity

The values of k at Ellergower Moss are at the lower end of the ranges for all peatlands summarized, amongst others, by Rycroft *et al.* (1975a), Ingram (1983), Chason and Siegel (1986), and Waddington and Roulet (1997), but they are consistent with reports for the restricted categories of blanket bog and other highly humified peats in maritime climates similar to that at Ellergower.

Most of these values refer to no more than the top 250 cm. Only Korpijaakko *et al.* (2000: two values at 280 cm), Chason and Siegel (1986: profile down to 290 cm), and Kneale (1987: profile down to 300 cm) have measured below 250 cm deep in bog peat. The Ellergower measurements more than double these depths, and extend through the whole peat mass and into the underlying mineral material.

Variation with depth

Figure 5a shows that k decreases exponentially about eight fold between 100 and 500 cm depth. This is similar to the findings of Sturges (1968), and Päivänen (1973), but contrasts in pattern and magnitude with the Lost River Peatland in Minnesota, where Chason and Siegel (1986) found k was at least 200 times greater than at Ellergower, and varied little at 20 cm intervals down to 290 cm. (Their k values were near the top of the reported ranges.) It also contrasts with the 800 cm deep Mongan raised bog in Eire, where Kneale (1987) found that k varied by one to four orders of magnitude at 50 cm intervals down to 300 cm in an Irish peatland. The median k was 8×10^{-5} cm s^{-1} (at least ten times that at Ellergower), but Kneale (1987) describes how 'the bulk density [below 300 cm] decreased to that of a liquid', indicating that the peat was very fluid. Given this large variation it is not surprising that there was little sign of a relationship with depth. One is forced to conclude that different peatlands have very different hydraulic properties and that generalization is not possible at present.

Over the range 100–500 cm, as Figure 6a shows, the dry bulk density varies little, and that erratically. Absorbance at 550 nm (a measure of humification) in Figure 6b does increase, rather erratically, by about 50%. This is, again, the opposite of Chason and Siegel's (1986) Minnesota raised bog, in which k changed little with depth but the absorption (absorbance?) at 350 nm of a pyrophosphate extract *decreased* with depth. Reynolds *et al.* (1992), Baird (1995) and Baird and Gaffney (1995), amongst others, suggest that k may be substantially reduced by the accumulation of gas bubbles (by-products of continued very slow decay) in the peat. This is certainly plausible for the region just below the water table, but measurements from 50 cm downwards in peat at Ellergower (Clymo, in preparation) show only very small ($<2\%$) concentrations of gas bubbles.

That the k value at 600 cm at Ellergower is greater than that at 500 cm, and about the same as at 100 cm, is surprising. The peat at this depth is predominantly *Sphagnum*, as it is everywhere above. Sedge peat begins only at about 680 cm. At 600 cm, as Figure 6 shows, the peat is slightly denser, a bit more humified, and is becoming mechanically stiffer. In experiments on Minnesota peats by Ours *et al.* (1997), flushing with $CaCl_2$ increased k by several-fold. Peat has high cation exchange ability—typically 1·3 mmol g^{-1} (Clymo, 1983)—and as the concentration of higher valence cations in the exchanger increases so the exchanger shrinks, thus increasing k. The total concentrations of calcium, iron and aluminium in the peat at Ellergower all increase five- to tenfold between 500 and 600 cm deep, and the concentration of Ca^{2+} in the pore water does the same (Clymo, unpublished data). Whether or not this explains, even partly, the greater value of k at 600 cm must await further work. Poiseulle's law states that the volume rate of flow in a tube is proportional to the fourth power of the radius. One cannot apply this directly, but to double k in a simple tube would require only a 19% increase in diameter.

The pressure profile

The discovery, shown in Figure 5b, that pressure in the mineral ground below the peat was about 180 mbar less than that at an equivalent depth in the peat mass, was a surprise but is confirmed by the depth to which the water level had fallen in the 745 cm pipe in the 10 months since it was put in place. In August 2001 there was a similar sharp gradient at the base of the peat, though its magnitude was not measured accurately. What can be causing this?

The mineral layer here was at least 50 cm thick, but the auger hit an obstruction (perhaps rock) at this depth in three places a few metres apart. Similar mineral material was found during a survey in at least a dozen intersections of a 50 m grid, but the full extent and shape of this layer is unknown. It is possible that it is continuous with the similar layer that underlies the shallower basin of Loch Dee that abuts the peatland about 300 m away. A survey shows that the high water level in the Loch is at about 650 cm below the peat surface at the measurement site. The water level in the Loch is managed and falls as much as 50 cm at times (Ingram, 1987).

The most plausible explanation of the observed 180 mbar fall in pressure below that expected is that there is an almost impermeable layer somewhere in the range 700–730 cm, so that the water bodies above and below it are behaving virtually independently. One may speculate that a compacted humic or iron pan may have formed, and this may indeed be what allowed peat accumulation to begin about 9000 years ago. More detailed observations at this depth are necessary.

The bulk velocity of pore water movement

This work began from the need to know the profile of bulk velocity of pore water in the Ellergower peat. This is crucial in a model to explain the observation (Clymo and Bryant, in preparation) that gases in the peat are about a 1000 years younger than the peat at the same depth, because (younger) carbon may be carried downward in pore water before being metabolized One can now make tentative calculations of the mean bulk velocity of pore water. The peatland is approximately hemi-elliptical (Ingram, 1987). For illustration, take a point 5% from the centre of an ellipse whose principal radii in the x and h directions are 350 m and 7 m respectively. The mean hydraulic gradient dh/dx there is about 0·001. For $k = 2 \times 10^{-6}$ cm s^{-1}, then, the bulk velocity might be $0{\cdot}001 \times 2 \times 10^{-6} \times 31\,557\,600$ (s year^{-1}) $\times$ 10 (mm cm^{-1}) $= 0{\cdot}6$ mm year^{-1} $=$ 60 cm ka^{-1}. In the Minnesota peat described by Chason and Siegel (1986), however, with k about 1×10^{-3} cm s^{-1}, the bulk velocity might be 320 mm year^{-1}, i.e. 500 times greater.

Consequences for peatland models

It is clear that the assumption that k is the same throughout a peat mass is not true of Ellergower Moss, though it may be so in some peatlands. Yet the surface of Ellergower Moss conforms, ±50 cm, to a hemi-ellipse in three dimensions (Ingram, 1987; Clymo, unpublished data), as the simple groundwater mound model described by Ingram (1982) predicts, even though that model assumes that k is the same everywhere in the peat mass and that the base is impermeable. Armstrong (1995) shows how to calculate the shape of the groundwater mound when k decreases exponentially, though he too assumes the peat is underlain by an impermeable base. He does show, however, that with exponential decline in k the water table shape is similar to the hemi-ellipse but with less abrupt shoulders. For the regular but C-shaped profile of k at Ellergower there is no analytical solution and simulation will be essential.

Ingram (1987) gives a shape-based value for U/k of $1{\cdot}0 \times 10^{-3}$ at Ellergower, where U is the rate of 'lateral discharge [through the catotelm] towards the [marginal] lagg stream' (Ingram, 1982). This is almost identical to the value for Dun Moss (a similar-sized raised bog in southeast Scotland). At Dun Moss, based on detailed hydrological measurements from May 1972 to April 1973, Ingram (1982) estimated U to be $5{\cdot}9 \times 10^{-7}$ cm s^{-1}, from which k is about $5{\cdot}9 \times 10^{-4}$ cm s^{-1}. This is two orders of magnitude greater than even the most permeable peat at Ellergower, indicating that either there is a major error in the calculation of U or a big difference between Ingram's model and reality at Ellergower, or both. A simulation will have to model flow through the acrotelm as well as through the catotelm if it is to cope with all the water falling on the peatland.

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