

Movement of tritiated water injected into blanket peat

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SUMMARY

In 1966, tritiated water was injected at five sites at depths between 25 and 100 cm into blanket bog at Moor House National Nature Reserve. The distribution of tritium activity on a logarithmically spaced grid around these sites was sampled in 1990, 24 years after placement. The proportions of tritium accounted for ranged from 80 % for the injection at 100 cm deep, to 20 % for the injection at 25 cm deep. Both 80 and 20 should be considered as $\pm 10\%$. Results imply that diffusion close to the injection may have played a part in movement of tritium; evapotranspiration is not inconsistent with the losses inversely proportional to depth of placement; but the main process of movement is probably bulk (mass) flow of water through the peat.

KEY WORDS: diffusion, evapotranspiration, mass water flow, Moor House National Nature Reserve, peat pore water

INTRODUCTION

By the 1960s concern had developed about where to dispose of, or store, radioactive waste. It was thought that burial in peat might be a suitable method for low-activity waste. In 1966 the late D.B. Smith (DBS) of the UK Atomic Energy Research Establishment (AERE), Harwell, put tritiated water into blanket peat on the Moor House National Nature Reserve (NNR) at several depths. His plan was to sample around the five points of placement ('injection sites') at yearly intervals for five years. The first samples were taken after one year around one site, but after that DBS moved to other work and the fenced area of the experiment was left to Nature.

There are few reports of similar work. Knight *et al.* (1972) sprinkled tritiated water on the surface of peat, but did not place it into the peat. Boggie & Knight (1980) sprinkled tritiated water on the surface of peat in a Sitka spruce forest, and also at the interface of peat and underlying mineral soil. Substantial movements vertically (20–30 cm) and downslope were measured after 40–60 days. Rainfall was not recorded but the long term average, in the authors' words, was "1500 mm distributed evenly over the year", consistent with about 150 mm during the experiment. The hydraulic conductivity of these peats (approximately $10^{-5} \text{ cm s}^{-1}$, 10^{-7} m s^{-1}) was high compared with that at the DBS site at Moor House (so low that water movement could not be detected over a week; see later).

By 1990 it had become clear that releasing substantial amounts of radioactive substances into the unconstrained natural environment was unlikely to be permitted again, in the UK at least, so it seemed

worthwhile to see what could be rescued 24 years after the DBS experiment was begun. By that time 74 % of the tritium had decayed physically (26 % left), and by now (2015) barely 6 % would be left. The objectives of the work reported here were:

- (1) to record the pattern of tritium activity around the injection sites;
- (2) to make a balance sheet for tritium at the site; and
- (3) to reveal the rôle of water movement.

METHODS

The experiment area

The experiment was in an area of blanket bog, Sike Hill on the Moor House National Nature Reserve (National Grid Reference NY 766 330; latitude 54.691425, longitude -2.364962). A survey of 62 points with theodolite and 'distomat' (infra-red distance measurer) showed (Figures 1 and 2) that the site is roughly level towards the S (south), and slopes down towards the N (north). The bog surface of the five tritiated water injection sites is at almost the same altitude ($\pm 15 \text{ cm}$) in the E–W direction, and is at a point in the S–N direction where the profile steepens into an approximately uniform downward slope of -10° . (Throughout this article, maps and plans have south, 'S', at the top and north, 'N', at the bottom, as if the area is being seen from the bottom of the slope - the opposite of the usual convention).

For the period 1961–1970 the mean temperature, defined as the daily (maximum + minimum)/2, at Moor House, about 1 km NW of the experiment site,



Figure 1. The experiment area, seen from the 'level' ground to the south of the slope, which falls away out of sight at 10° beyond the brow on which the injection sites were placed. The bamboo cane 'forest' to the right of the people (SV, BRG) marks sampling places around tritiated water injection site D. Sites B, C, D, and E are marked. The conspicuous plants are *Calluna vulgaris*, and some *Eriophorum vaginatum*.

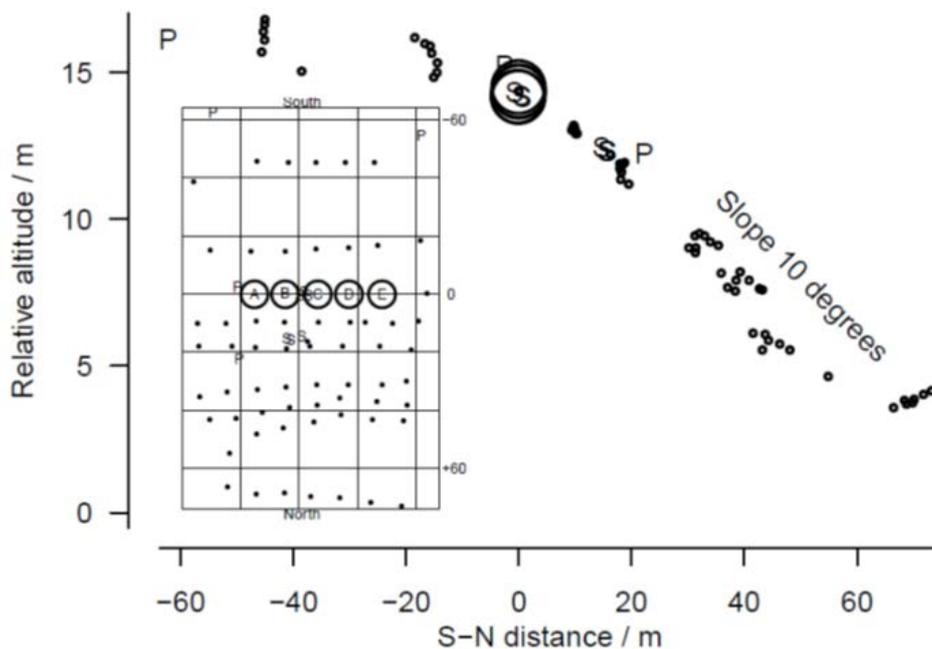


Figure 2. Topography of the experiment area on the Moor House National Nature Reserve. Origin of the E–W scale is arbitrary. S–N scale is centred on the line of injection sites. Distances to the South, across the 'level' ground at the top of the hill, are negative. Main graph: vertical section S–N of the experiment area, showing the 10° slope. (N.B. horizontal axis is S–N distance; axes have same units but scales differ.) The overlaid large circles in the centre are the injection sites. 'P' were remaining fence posts (in 1990); 'S' seepage tubes. Altitude is relative to an arbitrary local datum. Inset: horizontal projection (map), viewed from the foot of the slope, looking South. Grid is 20 m side. Tiny circles are places surveyed for the main graph (S–N profile). Large circles are injection sites 10 m apart. Site identity 'A' to 'E' inside the circle.

was 4.8 °C. The mean monthly temperature ranged from 0 to 12 °C. Mean precipitation was 198 cm yr⁻¹, fairly evenly distributed through the seasons. Potential evaporation was 35 cm yr⁻¹ (Smith 1973).

Estimates 'by eye' of plant cover by four independent assessors (range, %) were: *Calluna vulgaris* (40–60), *Eriophorum vaginatum* (10–15), scattered *Rubus chamaemorus*, *Sphagnum rubellum* plus *Sphagnum fallax* (60–70), and other bryophytes (5–10). The 'other bryophytes' included *Polytrichum commune*, *Hypnum jutlandicum*, *Aulacomnium palustre* and *Plagiothecium undulatum*.

The peat, 0.5–1.5 m deep, was highly humified (von Post H7+) with scarcely any visible macroscopic structure except the occasional fragment of wood (cf. *Calluna*) and shoot bases of *Eriophorum*. Below the peat was a notably tenacious sticky grey clay (Figure 3). Below that was a layer of white or light brown loose sandstone with pieces ranging in size from coarse sand, through less than 1 cm (recoverable in a Hiller peat borer chamber), to boulders 50–100 cm across (established by probing, and exposed in a single excavation 140 m away from the experiment site). This underlying heterogeneous sandstone is often called 'sandstone wash' and forms a blockfield similar to that exposed by erosion on Knock Fell, about 6 km from Moor House. The clay is probably colluvial derived from drift (Johnson & Dunham 1963, Johnson letter to RSC, April 1991).

Design of the experiment

Five injection sites (A to E) of tritiated water were spaced about 10 m apart from E to W along a contour. The experiment area was bounded by a galvanised wire fence 60 m E–W (across) by 20 m S–N. This fence, its warning notices, and most of the posts had been removed by the time I sampled. The original DBS plan was to sample one injection site after one

year and to decide, in the light of results, when and where to take further samples. In the event the area around point E (Figure 2) was sampled after the first year in a 1 m (square) grid of points out to 2 m on either side (E–W) of the injection site, and 2 m to the S and 3 m downslope to the N - 29 points in all - then at 5, 8 and 11 m downslope at 1 m or 2 m intervals out to 4 m on either side - a further 19 points.

Because we did not know how much this sampling of site E by DBS had disturbed the site, we omitted it in our sampling, using only sites A to D.

Root distribution in peat

Three cores, 20 cm diameter and 50–55 cm deep, were collected into PVC tubes using equipment described by Clymo (1988). The cores were taken to the laboratory, ejected and sliced across, 1.0 cm at a time. All visible roots were removed and their total length measured.

Hydraulic conductivity of peat

Six 7-cm diameter PVC seepage tubes were pushed into holes cored in peat to 50 or 100 cm depth. The tubes were covered with loose (not gas-tight) nylon bags to keep out precipitation. To all tubes water was added to place the water level at the same depth as in the surrounding peat. Then, to one tube at each depth water was added to raise the water level by 10 cm; to another water was removed to lower the water level by 10 cm, and a third was left unchanged. From measurements of the rate of discharge and recharge hydraulic conductivity may be calculated.

Placement of the tritiated water

On 14 October 1966, at each of the five injection sites, a glass ampoule containing 1510 MBq (40.8 mCi) of tritiated water had been placed at the bottom end of a 2.5 cm diameter thin walled brass



Figure 3. Typical core from the experiment region. Dark brown peat to the right (uppermost), tenacious grey clay to the left (lowermost). This was the third 50-cm core (1.0 to 1.5 m) in a vertical sequence.

tube with a sealed bottom end. The bottom 3 cm of the brass tube was perforated. A water-tight plunger was pushed down to the top of the perforations, and the assembly pushed into the peat to the required depth, leaving the top of the brass tube level with the peat surface. The water-tight plunger was then pushed down, crushing the glass ampoule, and then withdrawn again to the top of the perforations. The plunger was left in position. The tritiated water was thus free to move out into the peat (plausibly mainly by diffusion) from the 3 cm perforated section.

The depths below the peat surface (cm) of injection and underlying rock from E to W were: site A 100, 100; B 75, 105; C 50, 107; D 25, 80 (and E 75, not measured).

The injection sites were re-located on 10 June 1990, 24 years after the injections were made, using a metal detector.

Sampling pattern

The DBS sampling after one year, and four exploratory samples I made in 1988 showed that activity decreased rapidly with distance from the injection site, and less so to the S than downslope to the N. Sampling at logarithmic (geometric) distances seemed sensible. The sampling pattern is shown in Figures 4 and 5. Note that distances in the main Figure 4 are on log scales, with points at equal log intervals (1.0, 1.8, 3.2, 5.6) in each decade. The inset in Figure 4 shows the pattern as linear distances. The convention used is that distances from the injection site towards the S, on the flat plain at the top of the slope, are shown as negative; those towards the N, downslope, as positive.

This pattern defined eight shells at increasing distances from the injection site. Each shell comprised eight trapezoidal sub-areas (Figure 4).

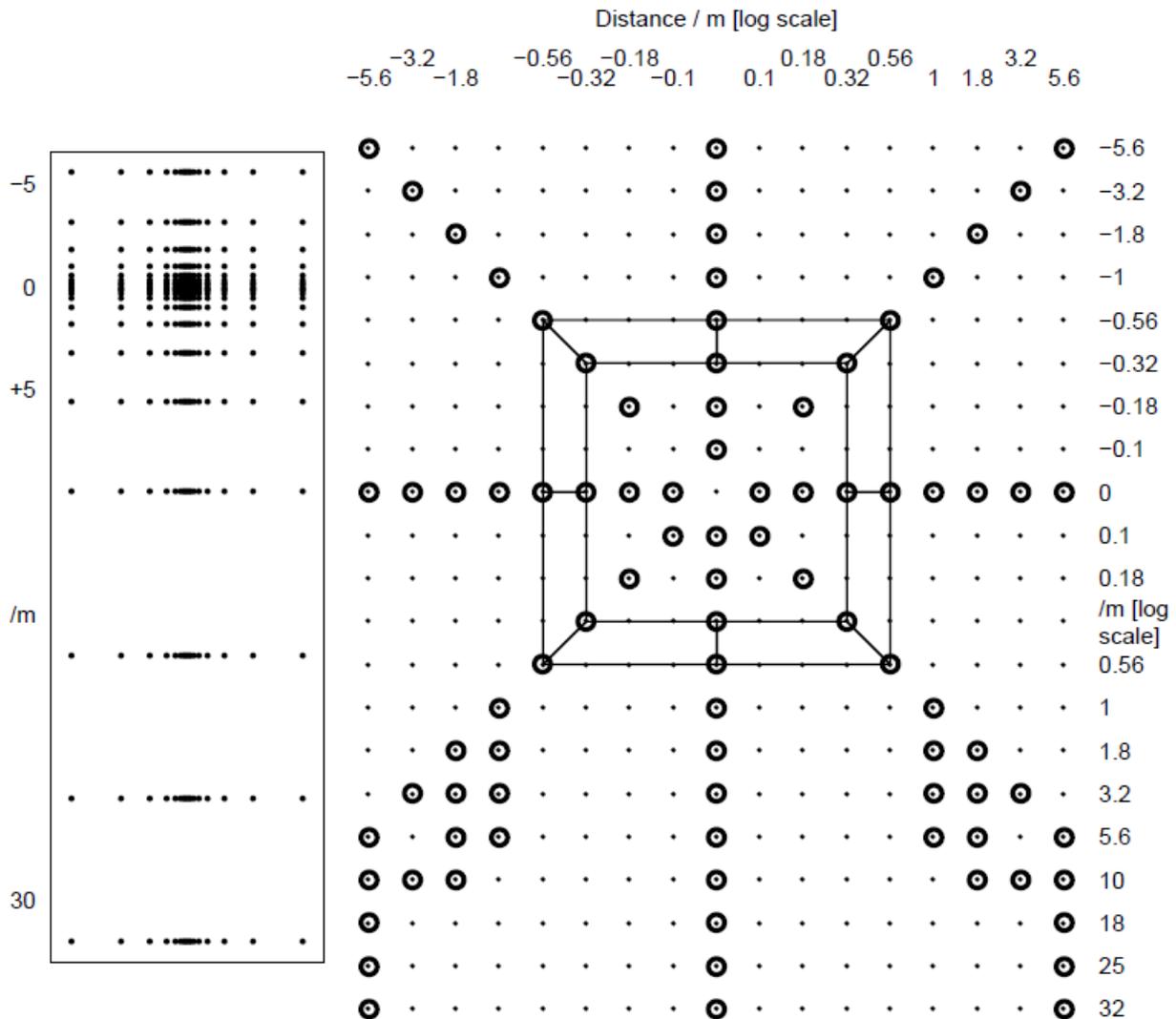


Figure 4. Sampling grid, aspect ratio 1:1. Left: potential grid, true scale. Right: 88 actual sampling positions, log scale (to show detail). The 4th of 8 shells around the injection site is outlined. It comprises 8 trapezoidal segments. There are 4 extra pairs of rectangles at the bottom of the hill.

Further downslope were four more, but rectangular (degraded trapezia) shells with only two rectangular sub-areas each. The coordinates of the centre of each trapezium in Figure 4 are at its centre of gravity (surprisingly awkward to calculate).

Sample points around an injection site are shown in Figure 5, each marked with a bamboo before



Figure 5. Bamboo cane 'forest' marking the places to be sampled around an injection site. People: MG, BRG, SV. Samples were taken from positions distant from the injection site before those nearer the injection site (to minimise contamination).

sampling. To minimise the risk of contamination, sample points distant from the injection site were sampled before those nearer to it.

Additional samples

After the main samples had been taken, samples of *Calluna vulgaris*, *Eriophorum vaginatum* and *Sphagnum rubellum* were collected at 100 cm from injection sites B, C, and D.

From places at least 500 m away from the experiment area, 24 samples of peat were also collected at depths of 20–30 cm.

Sample collection at the experiment area

Most samples of peat, clay, or both peat and clay were collected in the field as half-cylinders 25 cm long from a Russian pattern D-corer (Belokopytov & Beresnovich 1955) with a chamber 50 cm long/deep by 5 cm wide/across. A few samples were cut into sections 5 cm long/deep to allow more detailed analysis. Samples were put into polyethylene bags and sealed. Within six days after collection they were put into store at 2 °C until analysed 2–30 weeks later. (30 weeks because the counting of low activities took a long time.) Samples from within 100 cm of the injection site (expected to be of high activity) were kept separate from the others to reduce the risk of contamination.

Radioactivity assays in the laboratory

An apparatus was built to distil water from peat, clay and plant samples in batches of 24 units at a time. For a single unit, a weighed sample of about 20 g fresh weight was put into a straight-sided glass tube (all glass parts of the apparatus were borosilicate) of diameter 3 cm and length 18 cm. A silicone rubber bung sealed the tube. Through the bung ran a 140 cm long silicone rubber tube (Figure 6, left). This tube, with 23 others parallel to it, ran through a 10 cm



Figure 6. Multiple air-cooled condenser used to collect water (including tritium) after heating peat/clay in an oil bath at 130 °C in tubes attached by the silicone rubber bungs to the left. In use the condenser sloped downwards (left to right) to the collecting test tubes, shielded by the plastic caps at the right.

diameter rubber bung in one end of a 10 cm diameter, 110 cm long, glass tube, to the other end and out through a similar large bung. The whole was mounted at 30° to the vertical, and air was pumped through from an inlet at the lower end and out through an outlet tube at the upper end, the whole acting as an air-cooled condenser. The 24 tubes containing the peat were immersed to within 2 cm of their tops in an oil bath kept at 130 °C. Cloths were wrapped around the 24 tubes where they emerged from the oil bath and as far as the upper end of the condenser, thus keeping the temperature in the 24 tubes there above 100 °C. Condensed water in each of the silicone rubber tubes dripped into its own test tube through a short glass tube at the outlet, passed through a loose protective cap (Figure 6). After about 100 minutes distilling the bungs were removed from the sample tubes and any liquid water still in the silicone tubes allowed to drain to the collector tubes. A batch of blanks (distilled water) was then distilled for 100 minutes, and then the 24 tubes were flushed with air for the rest of the day until the next batch of samples was ready. This design minimised the number of junctions, and proved effective and simple in use. A total of 1527 samples were distilled, which, allowing for weekends and instrument failures, needed over 200 days of counting.

For each collecting tube separately, the water and the now dry sample were each weighed. Either 10 g (ml) of the collected water or, if less than 10 ml had collected, a weighed amount of double distilled (lab) water to make the total up to 10 ml, were mixed with 10 ml of PicoAqua (a pseudocumene based cocktail) in a low-activity counting vial. Samples were counted on a Packard Tricarb liquid scintillation counter for 200 minutes or $\sqrt{n}/n = 0.005$, where n is the number of counts, whichever was the shorter time.

Every batch contained two background samples at positions 2 and 27, with double distilled water in place of distillate, and two tritium standards from different sources (Packard and Amersham International) at positions 1 and 28. These standards agreed to within 1 %.

The sample liquids to be counted were no more than faintly coloured. The mean quench index parameter was 380 (efficiency 37 %) with only a small range (± 25) so a linear correction for efficiency was sufficient. (The low efficiency is typical for tritium.) Counting error was got from the sum of squares of the two enclosing background samples. (Sample – Background) was scaled by the mean standard for the batch.

Computer programs to deal with these and later calculations were written in C and R.

To allow for physical decay, all radioactivities were standardised to 01 June 1990.

RESULTS

DBS reported after 21 months: "...high concentrations [of tritium] still existed within a metre of the injection site . . . , but there was then a rapid reduction . . . further downslope with a maximum movement of 7 metres. The mean movement was approximately 1 metre downslope in 21 months.

[An] estimate of the amount of tritium located [around injection site E] was about 30% . . . The vertical spread [of the injection at 75 cm depth] was over the total depth of the peat . . . and into the underlying clay."

How far do our results match this DBS summary? First, six low activity results are shown in Figure 7. The concentration of tritium in distilled water is similar to the 2 Bq dm⁻³ ten-year (1998–2008) average for rain in Eskdale in the English Lake District; a place with unusually great rainfall (Mitchell 2009). The activity in plants is mostly low, but the number of samples is small. Low activity does not necessarily mean that little tritium is passing through: the concentration in a pipe tells little about the rate of transfer through it. The activity in 'distant' peat samples - at least 500 m from the experiment area - is about four times that in long-term wide-area rainwater measurements. In the absence of measurements of tritium concentrations in rainwater at Moor House one can only speculate about causes.

These results suggest two modifications that I applied to the rest of the results. First, for samples near the injection site, where activities are high, I subtracted twice the mean of distilled water values from all other distillate activities. This subtraction makes only a tiny proportional change. But about 10 % of low activity samples well away from the injection site were negative. This is a statistical effect. So I calculated the absolute mean of these 'impossible' values and argue that there are probably a roughly equal number of samples with no activity within a similar distance on the positive side of zero. I therefore subtracted twice the absolute mean of all negative values from each low activity sample.

Profiles of activity in distillates at 5 cm depth intervals are shown in Figure 8. The thicker lines are for clay. The average water proportion by mass in all peat and all clay samples is 0.88 and 0.58, but the concentration in clay parts of the profiles seems to fit well with those for peat. For site B, close to the injection (left graph), the peak of activity is at the same depth as the injection (75 cm). A bit further downslope the peak is rather lower down. Site A, injected at 100 cm deep, lacks samples from that depth, but the right graph shows that the activity at site A > site B > site C, paralleling the injection depths. The same pattern is seen in the left graph,

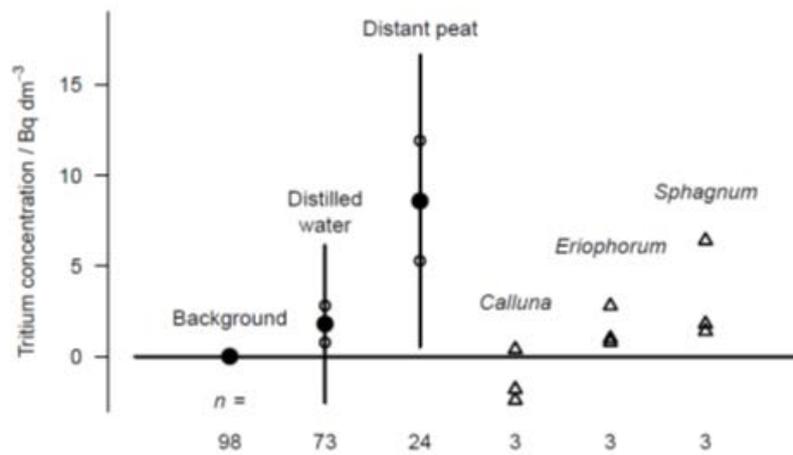


Figure 7. Concentration of tritium in water in various low-activity samples. Filled circle is mean; ‘whiskers’ show ± 1 SD; small unfilled circles show 95 % confidence limits. (For ‘Background’ the limits are inside the symbol.) ‘Distant peat’ was collected from various sites, all at least 500 m from the experiment. There were only three samples of each of the most abundant plants, collected 100 cm downslope from injection sites. Note that the tritium concentrations are as Bq dm^{-3} , but in later Figures are Bq cm^{-3} .

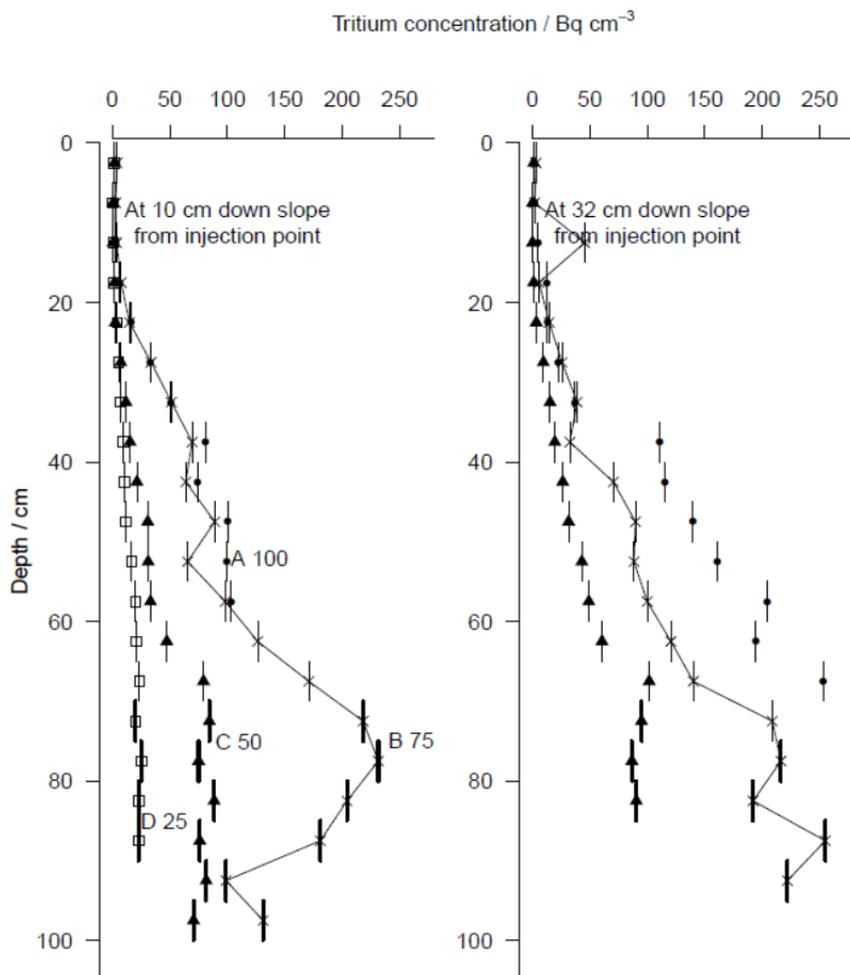


Figure 8. Profiles of concentration of tritium in pore water in 5-cm deep/long samples in cores 10 cm downslope (left) and 32 cm downslope (right) from the injection site. Results for injection sites identified by ‘A’ to ‘D’ with injection depth (cm). [In right graph, no site ‘D’.] Note, here and in later graphs, the strokes in the symbol (1 to 4) parallel the sites ‘A’ to ‘D’. Vertical bars show extent of sample - they are not error bars. Thin bars are peat, thick bars are clay. In both graphs the site ‘B’ samples are linked by lines.

where the peak in A is indeterminate, but $B > C > D$. In both graphs the activity in clay, below the injection depth, is greatest. It may be that initially greater activities in the lower peat have later been reduced by removal processes (mass flow?) but these processes have had less effect in the clay. It seems clear that the tritiated water has moved within and between peat and clay with similar ease.

The distribution of distillate activity along a S–N transect is shown in Figure 9. The tritium concentrations here are means for the whole volume of a core of peat/clay, not for individual samples of water as is the case in Figure 8. High concentrations

of tritium have appeared both to the S and downslope to the N. In both directions there is a decline beyond about 100 cm from the injection site. The same differences among injection sites, related to depth of injection, is clear.

An E–W transect through the injection sites (across the area rather than up and down it) is shown in Figure 10. Again, the graph plots the mean concentration in a whole core, and the effect of depth of injection is clear.

Transects are helpful, but what we really need is an estimate of how much of the original injection has been distributed over the whole area. For injection

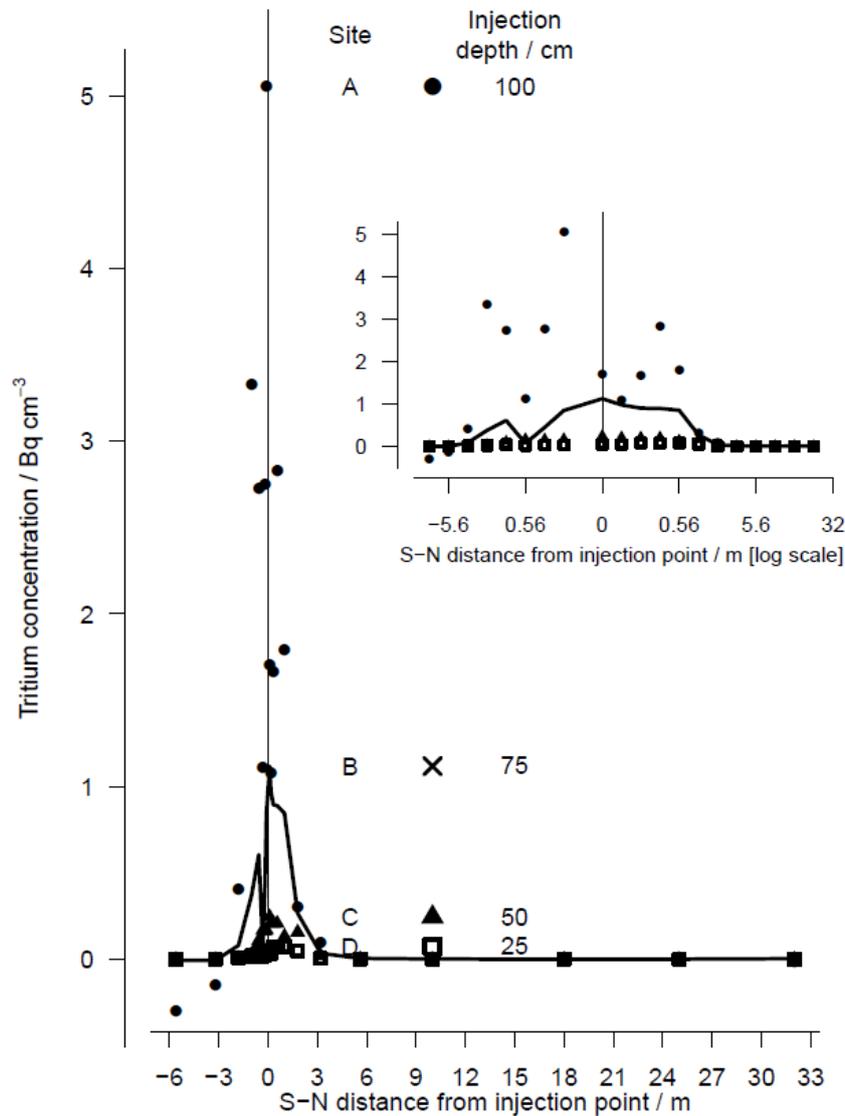


Figure 9. Mean concentration of tritium in pore water in whole core (peat and clay, if present) along a transect through the injection sites from S to N. Negative distances are along the ‘level’ towards the south; positive distances down the slope towards the north. The large symbols (repeating the small ones but shifted to the right) identify the sites and the depth of the tritiated water injection 24 years before sampling. Results for site ‘B’ are joined by lines. Symbols as in Figure 8. Inset: the same data and symbols plotted on a log-scaled distance axis, to show detail near the injection site.

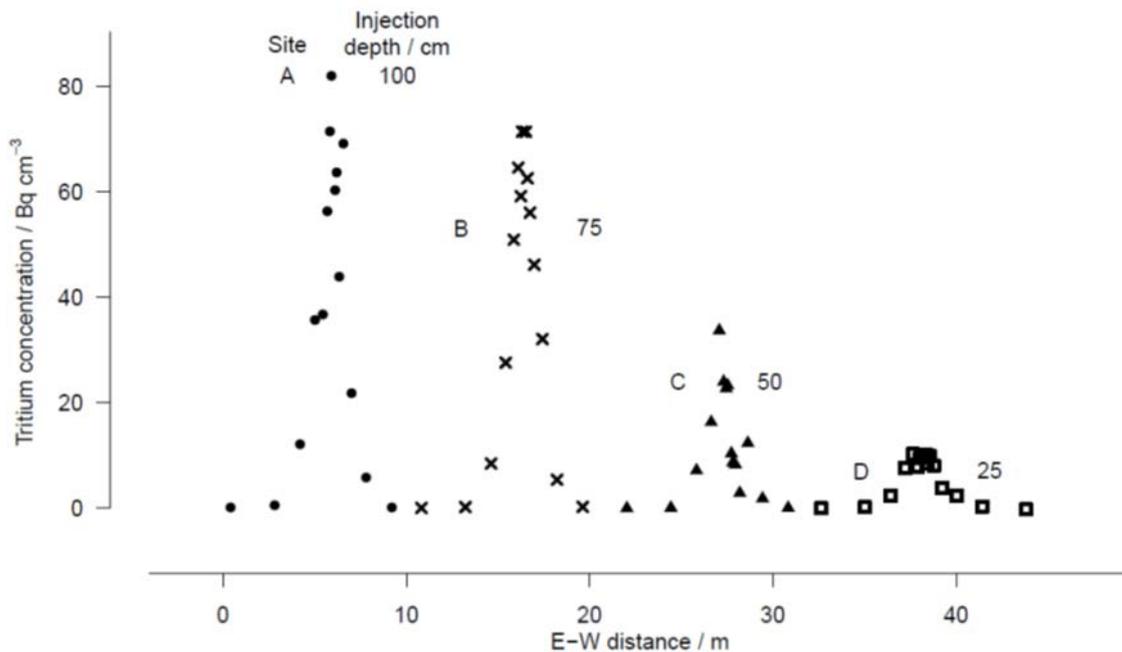


Figure 10. Mean concentration of tritium in pore water in whole core (peat and clay, if present) on a transect across the row of injection sites from E to W. Labels identify sites and the depth of the tritiated water injection 24 years before sampling. Symbols as in Figure 8.

site A this is shown in Figure 11; other sites showed a similar pattern. The totals close to the injection site are small because, though the activities are high, the areas are small. The highest totals are 2–3 m downslope, with a corresponding but smaller peak to the S of the injection site. This difference (from Figure 9) between S and N of the injection site is a result of averaging four values at the corners, and of including the E–W spread rather than a transect. The difference between S (flat) and downslope to the N is greater at injection site D than at A.

The total tritium activity, though in segments, is shown in Figure 11. From them one can calculate the proportion of the original injection (corrected for physical decay) that could still be accounted for after 24 years (Table 1). This ranges from 81 % at injection site A, to 21 % at D. These values should be viewed with caution - perhaps as 80 % to 20 %, both $\pm 10\%$ - because for the shells distant from the injection site the areas are very large while the activities are very small. A single rogue activity in a single section has a disproportionate effect.

The profile of root density is shown in Figure 12. Most of the roots are in the surface 15 cm, with a few down to 35 cm.

Water level in the seepage tubes in peat (and clay) changed so little (< 1 mm) over the week of fieldwork that I cannot infer anything quantitative about hydraulic conductivity, k , except that it is very small - perhaps smaller than that measured (later) from

water level changes at Ellergower Moss in SW Scotland, where a ‘hydraulic lever’ allowed very slow changes in water level in seepage tubes to be measured, and where k ranged from $5e-6$ to $0.7e-6$ $cm\ s^{-1}$, $5e-8$ to $0.7e-8$ $m\ s^{-1}$, with depth from 100 to 500 cm (Clymo 2004).

DISCUSSION

Some 80 % of the tritium placed at site A can still be found, but barely 20 % at site D. There is a clear relation between placement depth and activity still recoverable (Table 1). Tritium had moved, probably mainly by diffusion, into the underlying clay as Boggie & Knight (1980) also found. Rocks of many sizes prevented sampling to greater depth in the clay, and the size of this ‘loss’ cannot therefore be quantified.

Now, consider the five environmental processes (Figure 13) by which the tritium may have disappeared (ignoring physical decay, which has been accounted for by standardising all activities to the same date).

(1) Evaporation and evapotranspiration

The tritium concentration in plant materials is low, but that might be because the flow through the plants is rapid. One might expect losses from this cause to be greatest for sites with tritium injected in the top 20 cm

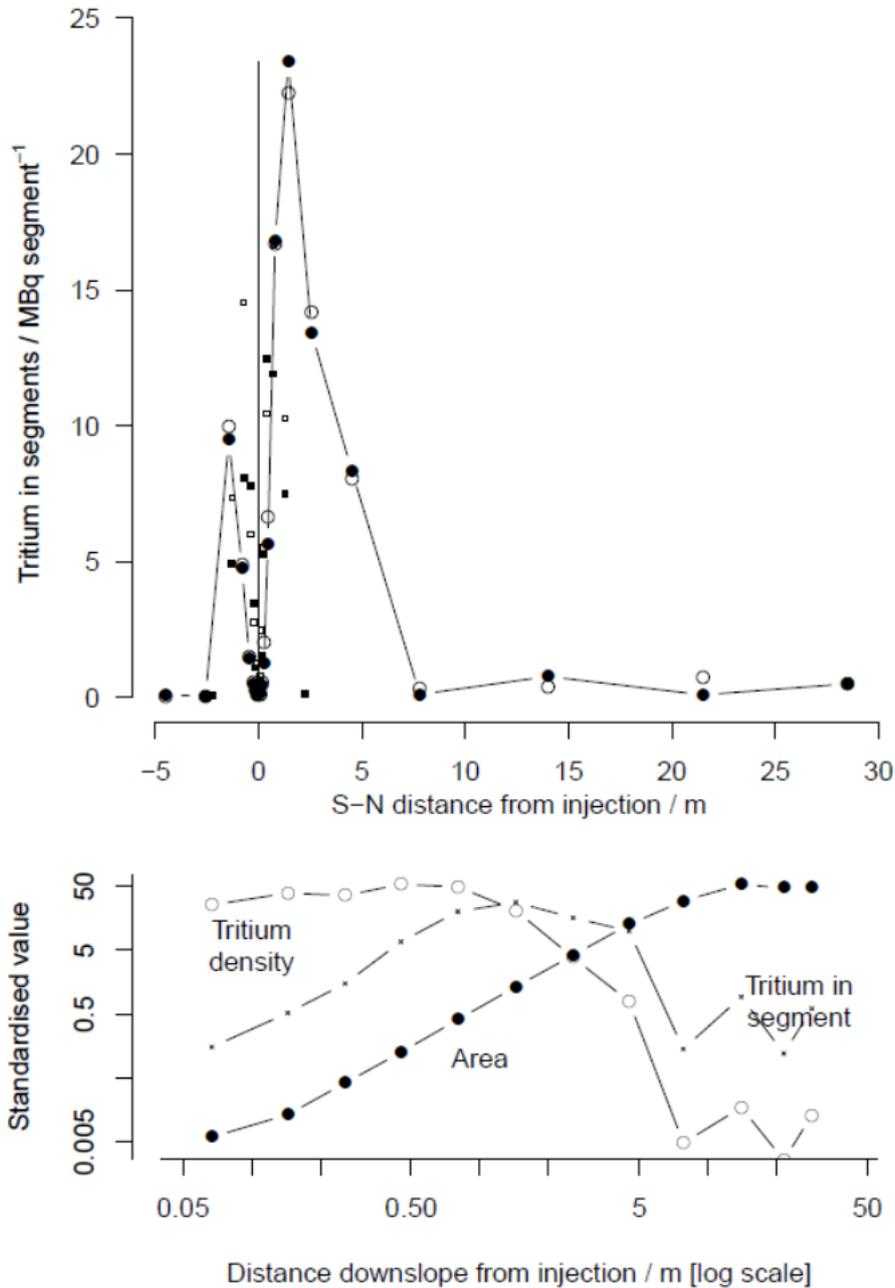


Figure 11. Upper: for injection site A. Total tritium from S to N in trapezoidal segments of shells around the injection site. The total for each segment is the mean activity for its four defining corners multiplied by the segment area. Circles are for segments with axis E–W; (smaller) squares for S–N oriented segments. The further from the injection site, the larger the trapezium. Filled symbols are for trapezia to the E of the injection site, and are also connected by lines; open symbols to the W of the injection site. S–N distances are to the centre of gravity of the trapezium.

Lower: for the two western (W) trapezia oriented along the contour (represented by open circles in the upper graph), and for the downslope direction (to the N) only, plotted on double log scales. Unfilled circles ‘Tritium density’ (concentration, as in Figure 10), filled circles ‘Area’ of trapezoidal segment, small crosses ‘Tritium in segment’ (product of the other two lines). The values have been standardised to allow comparison of shapes. Note how, at the right (a long way from the injection site), a tiny difference in ‘Tritium density’ has a large effect on ‘Tritium in segment’, because the ‘Area’ of the trapezium is so large.

Table 1. Proportion of injected tritium accounted for after 24 years at the four injection sites.

Injection site	Injection depth / cm	Recovered / %
(East end)		
A	100	81
B	75	63
C	50	46
D	25	21
(West end)		

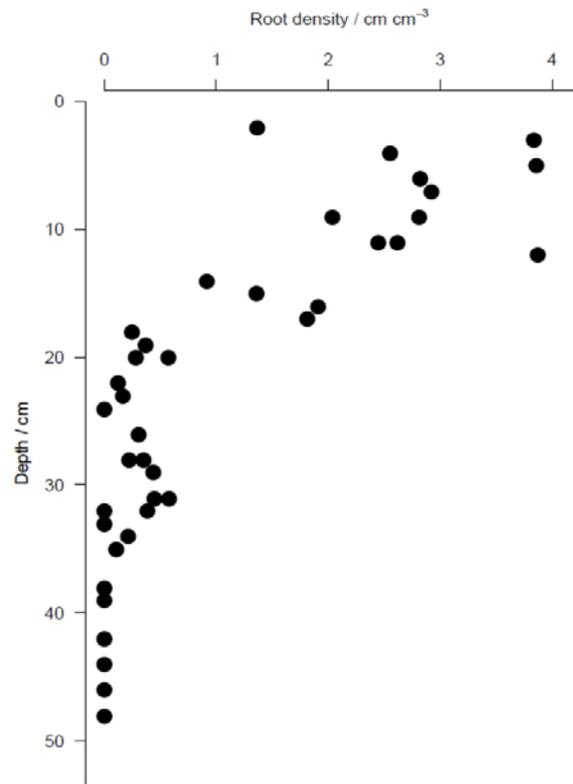


Figure 12. Profile of root density.

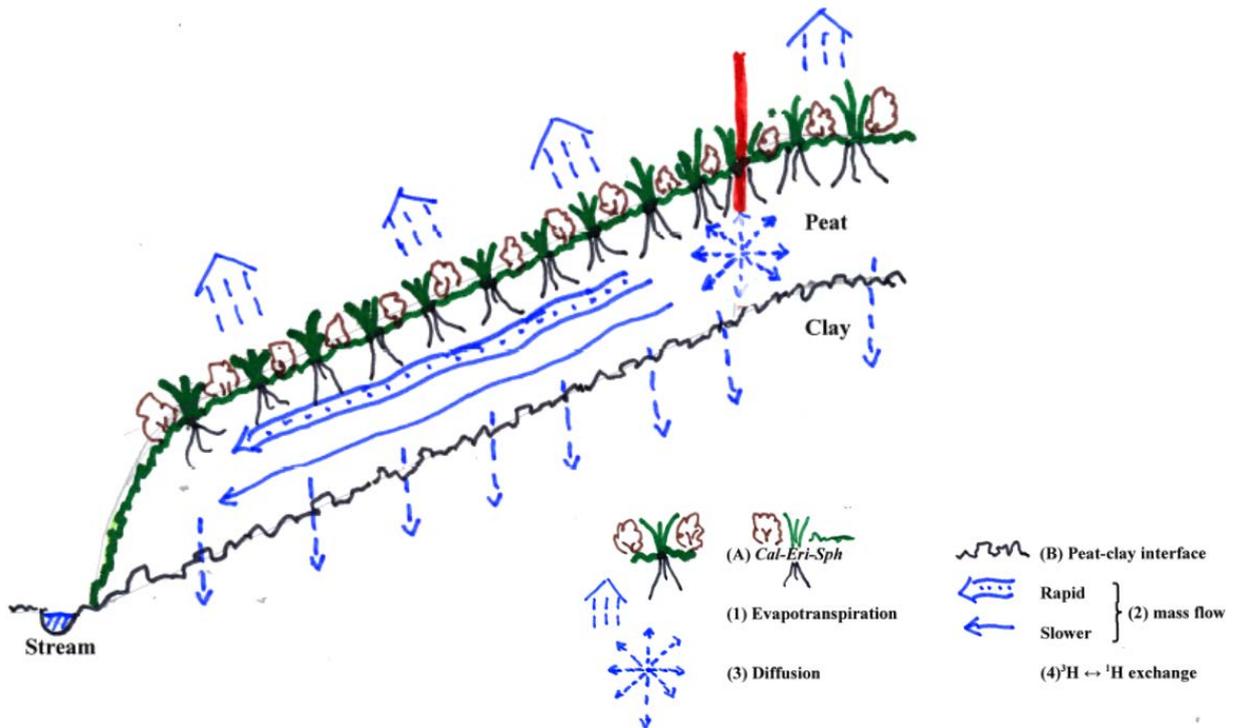


Figure 13. Cartoon of structures (A, B) and processes (1 to 4) of tritium movement. (A) *Cal-Eri-Sph* = *Calluna vulgaris*, *Eriophorum vaginatum*, *Sphagnum* spp. surface vegetation. (B) Interface between peat and sandstone fragments of many sizes embedded in tenacious clay. (1) Evapotranspiration of tritium-containing water transported through the roots and leaves of rooted plants, and around the leaves and stems of *Sphagnum*; (2) mass (bulk) mainly lateral flow of tritium-containing water, more rapidly nearer the surface; (3) diffusion, shown near the injection site and into the clay, but actually operating everywhere; (4) $^3\text{H} \leftrightarrow ^1\text{H}$ exchange, not shown specifically but operating everywhere.

in which root density is greatest, or near that depth. That means site D, and indeed the loss is greatest from that site. But there is another process, bulk (mass) flow, that would cause greater losses the shallower the injection, because seepage is greater there (see later). For evapotranspiration as the dominant process, one would also expect losses to the S to be the same as downslope to the N, but this is not so (Figure 11). Of course one cannot conclude that there is no important loss in evapotranspiration, only that it is not the dominant process.

(2) Bulk (mass) flow

Bulk (mass) flow is driven by physical pressure differences. The attempt to measure hydraulic conductivity (k) failed because the water level in the seepage tubes at 50 and 100 cm depth moved too little to be measured accurately (no more than 1 mm in a week). This is even smaller than the values measured with a 'hydraulic lever' at Ellergower Moss in SW Scotland (Clymo 2004): $k = 5e-6 \text{ cm s}^{-1}$ at 100 cm depth, declining logarithmically to less than $1e-6$ at 500 cm ($5e-8$ to $1e-8 \text{ m s}^{-1}$). These are among the lowest values recorded anywhere (Lewis *et al.* 2012, who misquote the Ellergower values by a factor of

100). It is clear that k at the experiment site is smaller than the $1e-5 \text{ cm s}^{-1}$ and $1e-7 \text{ m s}^{-1}$ at the sites used by Knight *et al.* (1972) and Boggie & Knight (1980).

On semi-log axes (Figure 14) measurements made at other places, one of them at Moor House about 1.5 km from the tritium experiment, also show a general logarithmic decline in the top 100 cm of peatlands. The differing positions of the lines reflect differing methods, differing peat types, and differing definitions of 'surface'. Those to the right were referenced to the surface of a *Sphagnum* carpet; those to the left to the surface of consolidated peat. For the present purpose what matters is that $\log(k)$ is roughly linear with depth in all cases: hydraulic conductivity decreases markedly with depth in the bog. Water flows easily through the *Sphagnum* at the surface and with increasing difficulty the further down into the peat and clay. That tritium losses are smaller the greater the injection depth (Table 1) is consistent with this. The larger amounts of tritium downslope (N) than to the S are also consistent with bulk (mass) flow downslope.

Under-peat pipes, ephemeral and persistent, of cross-section 1 to 100 cm^2 , are common at Moor House (Holden & Burt 2002, Holden 2005). Three

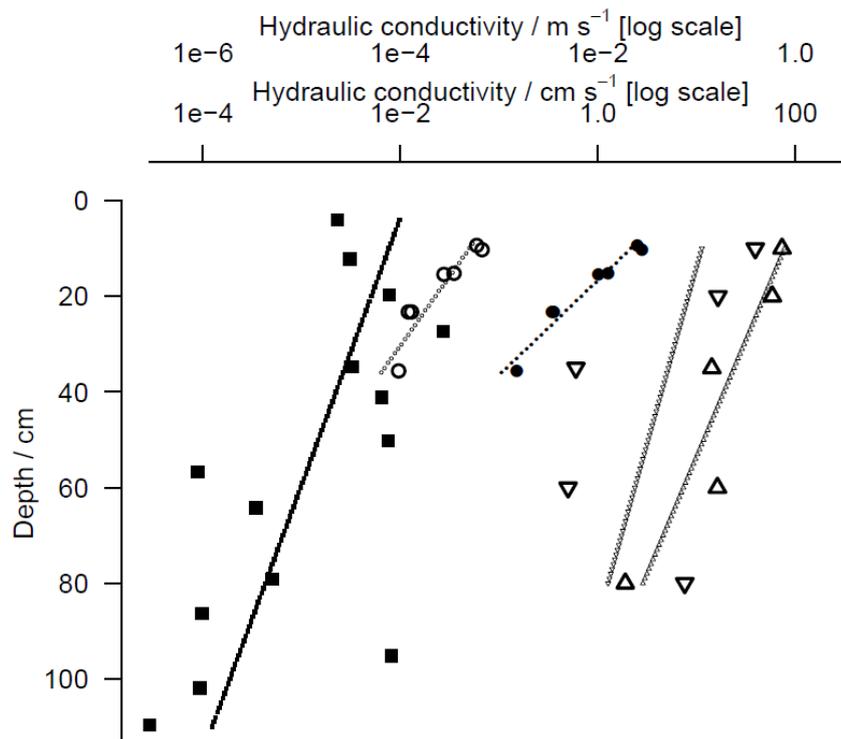


Figure 14. Relationship between hydraulic conductivity (k) and depth (d). Functional fitting to $\log(k) = b * d + a$. From the left. *Squares* (one set of data): Beckwith *et al.* (2003), laboratory measurements of peat from Thorne Moors, Yorkshire, top 20 cm removed. *Circles* (two sets): Bragg (1982), field measurements at Dun Moss. *Triangles* (two sets): Holden & Burt (2003), field measurements at Moor House, about 1.5 km from the experiment area of the current report, but in a less humified peat. Filled symbols: horizontal component of conductivity; unfilled symbols both components.

people sought evidence of pipes in the experiment area after rain, but neither saw nor heard any. The hydraulic conductivity in the experiment area is much less than elsewhere at Moor House (Holden & Burt 2003). If there are pipes, they will have provided an easy path for loss of tritium from the experiment, particularly at depths where movement is otherwise slow.

(3) Diffusion

In contrast to bulk (mass) flow, diffusion is driven by random molecular movements summarised in concentration differences. These are largest close to the injection site (Figure 9). Diffusion may be the dominant process in the zone only a few centimetres from the injection site. Clymo & Bryant (2008) showed that over millennia diffusion can be an effective transport process in peat. Over a mere 24 years, however (Clymo & Williams 2012), it could not cause the big differences among sites A to D.

(4) Exchange with ^1H in solids

It is possible for ^3H to exchange with ^1H in solids, and thus disappear from water. This process would operate everywhere. I lacked the equipment needed to measure this but, because only 20 % of the original injection is unaccounted for in site A, it is probably a very small component of the unaccounted-for losses.

(5) Biochemical incorporation into microbes and plant solids

This probably does happen but, as with (4), I have no evidence of the quantities thus immobilised except that the same applies as in (4).

Practical application?

It is unlikely that disposal of low-level nuclear waste in peat would be considered nowadays. But if it were, one might suggest that the waste be buried at least one metre below the surface in an unsloping peatland with highly humified peat, and expect that after 25 years about 80 % of the original would still be less than 5 m from the burial place. One would rely on physical decay to dispose of the radioactivity: for ^3H after 100 years barely 3 % would remain.

This work in context

Tritium movement was widely used in hydrological studies of rocky aquifers (e.g. Fritz *et al.* 1991), particularly after the 1963 peak in the testing of atomic and hydrogen bombs - a result of the moratorium on such tests. By now, 4.4 half-lives of ^3H later, detection of this 'bomb-peak' has become difficult. Similar work on peat is rarer, and most uses 'naturally occurring' widely distributed ^3H to assess residence times and flow lines (e.g. Forsgren 1966,

Gorham & Hofstetter 1971, Mažeika *et al.* 2009, Sirin *et al.* 1997). The present work seems to be the only example of the addition of substantial point sources of ^3H .

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