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# ASSESSMENT OF THE HYDROLOGICAL SIGNIFICANCE OF A DISUSED RAILWAY ACROSS FENNS & WHIXALL MOSSES, CLWYD/SHROPSHIRE BORDER

**Report to Countryside Council For Wales**

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## Background

Fenns, Whixall and Bettisfield Mosses, together with Wem and Cadney Mosses, form a large, complex peatland site that has a long history of peat-cutting. Following the recent cessation of large-scale peat winning on the central area of Fenns and Whixall Mosses, a programme of restoration of the site, including raising and controlling water levels, is under way. Along the north-western boundary of the roughly oval site there is an embanked railway, now disused, which was constructed over the peat, apparently isolating from the main mire expanse the strip of peat between the track and the glacial sands and gravels underlying Bettisfield and Bronington to the west (Figure 1).

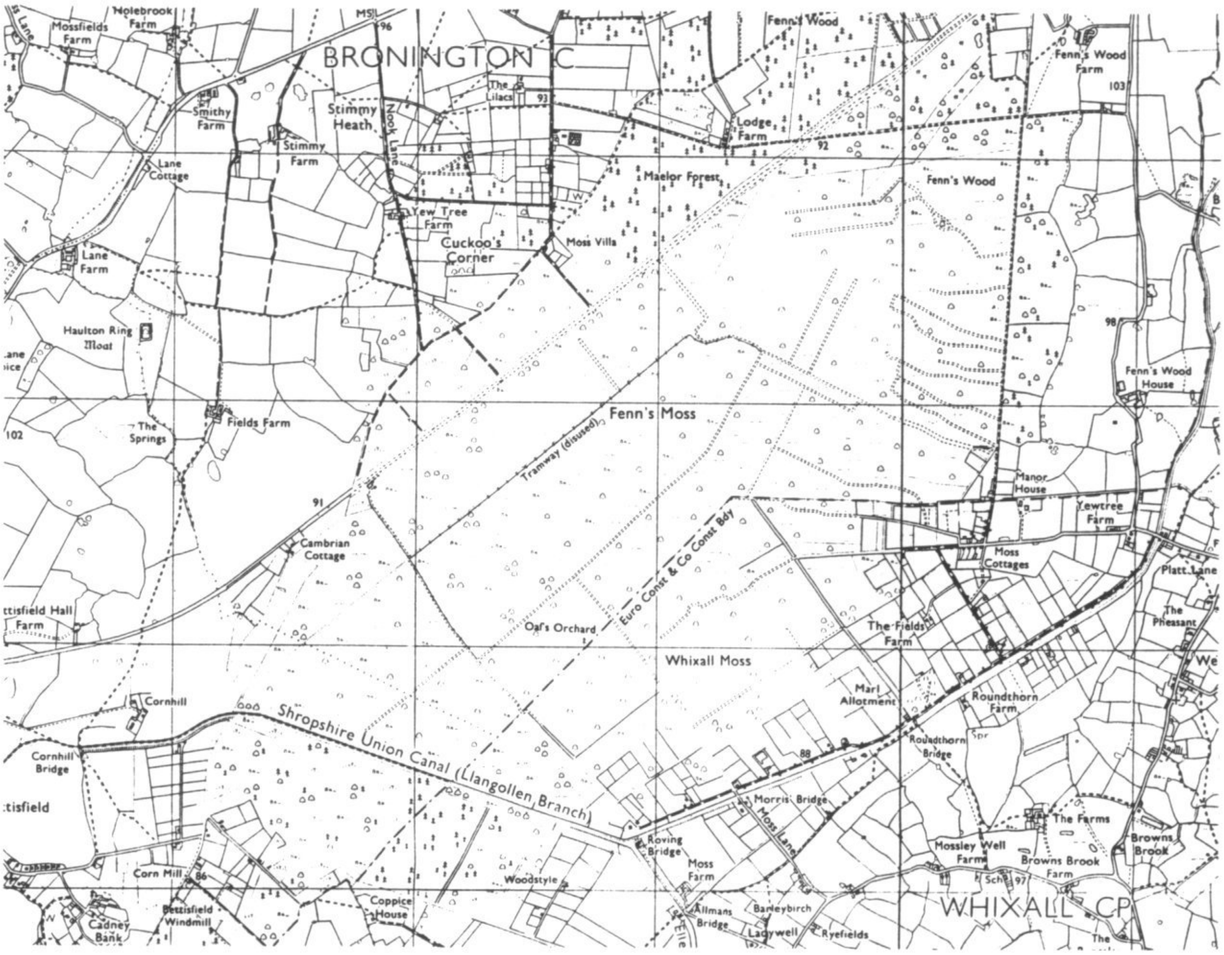

*Figure 1  Fenns & Whixall Moss (SJ 490370).*

Landowners to the north-west of the railway track have raised objections to the new water level regime on the mire, on the grounds that the present drainage status of their land will be compromised, while others have proposed their own drainage improvements, and have objected to the proposed extension of Site of Special Scientific Interest (SSSI) designation, basing arguments on the assumption that the railway isolates their land hydrologically from the central expanse of the site.

Groundwater consultant Steve Bennett prepared a report for English Nature, in which he addressed the general topic of compaction of peat under applied loadings, e.g. the construction of a railway embankment, and assessed the importance of peat depth in relation to each landholding in turn. The Institute of Hydrology (IH) was invited by the Countryside

Council for Wales (CCW) to offer a second opinion on the hydrological performance of the railway embankment, using broadly the same information base as was used by Bennett, but also taking account of new information, particularly postgraduate work by Birmingham University.

## The Bennett report

Although Bennett had access to large numbers of determinations of peat depth in the vicinity of the railway track, he acknowledged that there was little available information on the construction of the embankment or on the hydraulic properties of the peat, which could be expected to vary over a wide range. Furthermore, the engineering and scientific literature indicates that the construction of embanked roadways across peat is often accomplished by trial and error techniques, as the field properties of peat are not easily assessed by laboratory tests.

Bennett's general conclusion in respect of hydraulic continuity across the line of the track was that, though there must have been some reduction in permeability (hydraulic conductivity) of the peat consequent on compression, the efforts of the railway engineers to "float" the line by spreading its weight across a wide area would have been at least partially successful, so that there remained a significant, in places considerable, depth of peat beneath the trackbed, and this peat would still be capable of transmitting water.

Taking each landholding in turn, and considering the depth of peat indicated by various probing surveys, Bennett concluded that along the length of the mire there was hydraulic continuity between the two sides of the track. It follows that the track cannot be considered as an effective boundary to the peatland SSSI. Moreover the depth of peat below the base of drains within the individual landholdings would prevent hydrological isolation across boundary drains.

## Available data on the peat at Fenns & Whixall Mosses

Lowland raised mires commonly develop from beginnings as fens or lakes, and it is probable that the Fenns and Whixall Mosses originated in this way in a depression in the surface of the till (Pringle 1994), deriving some of their water supply from seepage out of the glacial sands and gravels. An origin in a groundwater-fed fen rather than a lake is supported by the apparent absence of indications of a basin in the results of peat depth surveys. As fen peat accumulated, the upper peat, especially that near the centre of the mire, became isolated from the chemical influence of the groundwater and the mire community changed to one of acid bog dominated by the base-intolerant but extremely effective peat-forming *Sphagnum* mosses. Continuing peat growth resulted in the classical outward radial flow of water and eventually, perhaps after the coalescence of two or more smaller raised mires, in a domed shape. Cutting of the peat, firstly by hand along the more accessible peripheries of the mire, and later by machine cutting of the central dome, has removed the central mire expanse and left a much flatter landform with older, more compacted peat exposed. Drainage associated with peat winning has also added to the compaction of uncut peat, by oxidation and increasing overburden pressures due to reduced buoyancy of the upper, dewatered peat layers.

Peat depth is a critical factor in the assessment of hydraulic continuity: although the underlying sands (in some places) may have a moderately high permeability, it is commonly found that peat deposits are isolated partially or completely from the mineral substrate by a layer of finely-divided lacustrine sediments or outwash deposits, frequently of a clayey or clayey-silty texture. In view of the possibility that flows above and below this impeding layer (if it is present) are independent, it is proposed that hydrological continuity should be assessed only in terms of the thickness and properties of the peat, though Bennett noted that the mattress and probably the embankment itself were constructed of reasonably permeable materials.

There have been several surveys of peat depth over the Moss, and relevant data, i.e. points within 150 m of the centreline of the railway track, were abstracted from the following surveys made available by CCW:

1. The 1989 morphometric survey (Richard Lindsay). This extensive survey covered the major part of the SSSI but omitted the area to the north of the railway. 24 of the survey points were used in this report.
2. The 1990 Fenns Moss depth survey (Soil Survey and Shropshire Highways Dept) which covered the strip of land to the north of the railway. 26 points used in this report.
3. The undated boundary survey (Soil Survey & Land Research Centre) which was instituted to delineate the edges of the mire. Seven points used in this report.
4. The 1992 survey of Mr Lloyd's land (Clwyd County Council & Joan Daniels). 19 points used in this report.
5. The 1994 peat depth investigation of land owned by Major Trefor-Barnston, Lodge Farm and Maelor Forest (Paul Day & Joan Daniels). 60 points used in this report.

When these surveys are combined, they give a total of 136 points (40 north and 96 south of the track), covering a distance of 3.08 km along the track, and representing a 150 m strip on each side of the track (Table A1-1 & Figure A1-1). Figure A1-1 shows that peat depths on both sides of the track are consistent: in particular the two areas of deep peat are well represented in data from north and south of the track.

Surface elevations along the track, and in peat areas adjacent to the track, were taken from the topographic maps prepared on behalf of English Nature. A local co-ordinate system was created by selecting a "zero point" SJ 4834 3710 on the track and measuring distances along the track and perpendicular to the track (referred to as "north" and "south" for brevity). Spot heights on the track (Table A1-2) were indexed by their along-track distance, ranging from -466.3 (the most south-westerly point) to 2618.0 m (between the lakes of landholding 192). For the more numerous spot heights outside the track area, a less labour-intensive method had to be adopted. On either side of a line along the centre of the track, a row of 100 m squares was marked on the map, making 31 two-hectare dyads denoted A centred on SJ 4798 3683) to EE (centred on SJ 5036 3865), and map spot heights representing the peat surface, i.e. outside the embanked area, were averaged within each 100 m square to give an estimated mean ground elevation for each square (Table A1-3 & Figure A1-2). The distance of the centre of each dyad along the track is listed in Table A1-3.

There is very little data on the thickness of the trackbed. Three boreholes were drilled on behalf of the sand and gravel resources survey (Institute of Geological Sciences 1982). Though they lie along the line of the railway, two of the boreholes are offset towards the southern edge of the track. If it is assumed that compaction of the peat layer depends on the weight of the embankment material, these elevations may provide an over-estimate of the elevation of the upper surface of the consolidated peat beneath the centre of the track. The three boreholes indicate a depth of made ground of 1.3 to 1.7 m, and a peat depth of 1.7 to 2.3 m (Table 1). Absolute levels may be suspect, though this will not affect the estimates of strata thicknesses.

*Table 1 Selected information from the sand and gravel resources survey*

| Station no. | Horizon | Grid reference | Elevation mOD |
|---|---|---|---|
| SJ 43 NE 24 | | SJ 4785 3672 (125m SW of dyad A) | |
| | Surface level | | 92.0 |
| | Upper surface of peat | | 90.3 |
| | Lower surface of peat | | 88.2 |
| SJ 43 NE 20 | | SJ 4744 3768 (dyad J) | |
| | Surface level | | 92.0 |
| | Upper surface of peat | | 90.5 |
| | Lower surface of peat | | 88.2 |
| SJ 43 NE 21 | | SJ 4872 3739 (dyad V) | |
| | Surface level | | 92.0 |
| | Upper surface of peat | | 90.7 |
| | Lower surface of peat | | 89.0 |

Data on the hydraulic properties of peat at Fenns and Whixall, especially permeability, were provided by Mills (1994) from a large number of field and laboratory tests. Rising head piezometer tests were undertaken in the field at nine stations (a total of 24 usable results) distributed across the mire, and falling head tests were carried out in the laboratory, using samples from 23 stations (a total of 50 results). Relationships between permeability and depth varied from station to station, and Mills' plausible conclusion was that peat cutting could have had the effect of removing surface layers (the acrotelm) with the highest permeabilities. Alternatively increased surface loading due to machinery or trees could have compacted the peat of the acrotelm. Although it is believed that peat permeability is usually higher in the horizontal direction than in the vertical, anisotropy of permeability generally does not show up incontrovertibly in Mills' results, as there is some doubt about the comparability of field rising-head and laboratory falling-head tests, but this could also be a effect of the removal of the acrotelm.

The other properties of direct interest in this context are those connected with the consolidation process, i.e. the compaction of peat or other soft deposits as a result of surface loading. Mills carried out a series of laboratory tests on six samples taken from a station towards the western end of the machine-cut area, and obtained values for the main parameters of the consolidation process.

## An interpretation of possible changes in the peat beneath the railway

The construction of the railway in the 1860s followed the normal practice of the times: the peat was first drained by a series of hand-dug ditches, then a permeable and fibrous mattress was laid, followed by sand and finally ballast. It was the intention that the track should run on an embankment three to five feet high, and to prevent excessive compaction of the peat, which was recorded as up to 18 feet deep (probably an over-estimate for the peat in the vicinity of the track), the load of the embankment was spread by a mattress of the local materials heather and brushwood faggots, supported where necessary (i.e. on deeper peat) by stakes, poles and longitudinal baulks.

The purpose of the mattress was not to "float" the railway on the saturated peat, in the sense that the buoyancy of the fibrous material would compensate partly for the weight of the track (the organic materials would soon become waterlogged) but to spread the loading across a wide area. By keeping lateral effective stresses low, horizontal movement of the saturated peat, out of the way of the descending trackbed, could be prevented, and the subsequent decline in track level was due only to *in situ* consolidation of the peat profile.

The addition of a considerable weight of sand and ballast on top of the mattress creates an increase in effective pressure that consolidates the underlying peat. Consolidation is a process with two more or less well-defined stages: in the first stage (*primary consolidation*) the compaction of the peat matrix is restricted by the need to expel moisture, and in the second, much more prolonged, stage (*secondary consolidation*) compaction is due to the plastic deformation of the solid matrix. The low permeability of peat impedes the movement of the pore water, delaying the arrival of the point at which the load is supported entirely by the solid matrix. Once this point is achieved, after a period of several weeks or months for typical peat depths, the slower process of plastic deformation takes over. Provided the applied load is sufficient to cause secondary consolidation, the rate at which it occurs is independent of pressure. Indeed, under the low overburden pressures created by the unsaturated zone of the acrotelm, secondary consolidation acting over the lifetime of a mire helps to reduce the permeability of deep peat and to establish the catotelm as a distinct hydrological unit.

The most comprehensive general account of peat consolidation is given by Hobbs (1986). Using the results obtained by Mills (1994) in laboratory tests, and the theoretical developments brought together by Hobbs, it has been possible to give an estimate of consolidation that may have taken place beneath the trackbed at Fenns and Whixall Moss, and hence to estimate the consequent reduction in permeability and transmissivity of the peat deposit.

### *Theory of consolidation*

Primary consolidation is dependent on the applied pressure, and the oedometer measurements described by Mills (1994) demonstrate the variation in the strain (the degree of compression) shown by a thin peat sample under a range of applied loads. The experimental results can be used to determine several peat properties relating to primary consolidation. The most important properties defining the consolidation process are the compression index $C^*_c$ and the coefficient of secondary compression $C_{\alpha\varepsilon}$, which determine the rate and extent of the two stages of consolidation (Hobbs' notation is used here).

If the relative strain $\varepsilon$ (the reduction in sample thickness divided by its initial thickness) is plotted against the logarithm of total stress $p$, the slope of the line is

$$C_c^\bullet = \frac{\varepsilon}{\Delta \log p} \qquad (1) \qquad \text{Hobbs (1986) equation 23}$$

The progress of primary consolidation depends on the past history of the soil. For a *normally consolidated* material, i.e. where the present effective overburden pressure $p_0$ is the maximum pressure to which the soil has been subject in the past, the eventual strain is given by

$$\varepsilon = C_c^\bullet \log \frac{p_0 + \Delta p}{p_0} \qquad (2) \qquad \text{Das (1990)}$$

For an *overconsolidated* medium (e.g. peat from a cutover mire), there is a preconsolidation (or critical) pressure $p_c$ which exercises some control over subsequent compression. If the sum of the overburden pressure $p_0$ and the applied pressure $\Delta p$ is less than $p_c$ the eventual strain is

$$\varepsilon = C_s^\bullet \log \frac{p_0 + \Delta p}{p_0} \qquad (3)$$

where the coefficient $C^\bullet_s$, the swell index, may be obtained by performing repeated oedometer tests. The swell index generally lies between 10% and 20% of the compression index, and for the purposes of this report it has been taken as 15% of $C^\bullet_c$.

For larger values of the total pressure, i.e. for $p_0 + \Delta p > p_c$

$$\varepsilon = C_s^\bullet \log \frac{p_c}{p_0} + C_c^\bullet \log \frac{p_0 + \Delta p}{p_c} \qquad (4)$$

For a thin peat sample, the oedometer test induces secondary as well as primary compression, and it is possible to estimate $C_{sec}$ from timed readings, but there is insufficient information to compute $C_{sec}$ from Mills' tests, and so a typical value of 0.025, taken from Hobbs (1986), has been used in the calculations.

The secondary consolidation occurring between times $t_1$ and $t_2$ is

$$\varepsilon = C_{sec} \log(t_2/t_1) \qquad (5)$$

The primary consolidation has reached 90% of its final value after a time $t_{90}$, which is calculated for the field peat layer from the $t_{90}$ obtained in the oedometer test by

$$t_{90}(field) = t_{90}(test)\frac{H^2}{d^2} \qquad (6)$$

where $H$ is the thickness of the peat layer and $d$ is the thickness of the laboratory specimen. The field value of $t_{90}$, which is of the order of three months, is a convenient time to set as the start of secondary compression, i.e. $t_1$. The construction of the railway dates from 1861, so a time of 134 years has been taken as $t_2$.

It remains to calculate three effective stresses: $p_0$ the overburden pressure, $p_c$ the preconsolidation pressure and $\Delta p$ the loading due to the embankment.

The overburden pressure on a compressible layer is a result of the weight of overlying material, for instance the topsoil. In a mire, where most of the deposit is neutrally buoyant, overburden pressures are low, being due to the weight of the upper peat above the water table. For the purposes of this report, it has been assumed that the water table is about 0.4 m below the ground surface and so the overburden pressure

$$p_0 = g(h_g - h_w)\gamma_w = 9.81 \times 0.4 \times 1000/1000 = 3.92 \text{ kPa}$$

where $h_g$ is the ground elevation

$h_w$ is the elevation of the water table

and $\gamma_w$ is the unit weight of water (1000 kg/m$^3$).

There are standard methods (e.g. the Casagrande method, described by Das 1990) for obtaining the preconsolidation pressure from oedometer tests, but it is difficult to apply these to Mills' data, as there are too few data points. Instead, a simplified and rather approximate method, based on Casagrande, has been applied (Figure 2). On a log-log plot of relative strain against effective stress, the line formed by the last two points is produced backwards to meet a horizontal (constant relative strain) line through the point at which the radius of curvature of the graph appears to be least. The preconsolidation pressure $p_c$ is the pressure coordinate of the intersection.

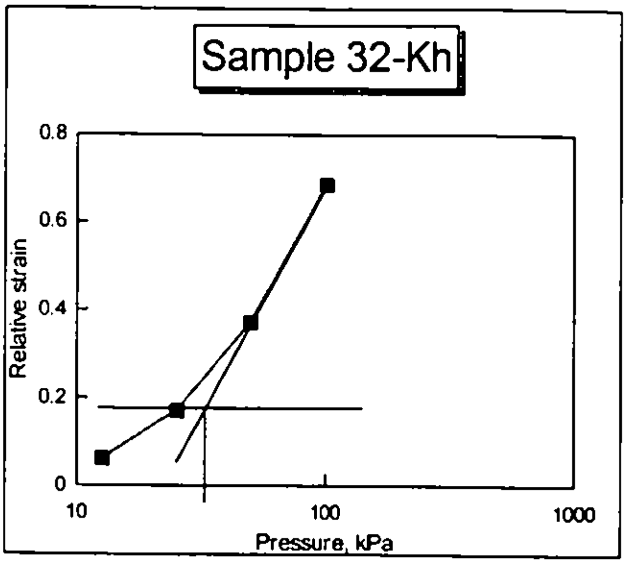

*Figure 2 Illustration of simplified method for estimating preconsolidation pressure from oedometer test results. A value of $p_c$ of 32.1 kPa is indicated for this sample.*

The calculation of the loading from the embankment is a more complex procedure, involving the summation of effective pressures due to embankment material above and below the water table. It is assumed that, owing to capillary action, a zone of thickness 1.1 m above the water table in the embankment material (taken as fine sand) is saturated though under soil moisture tension, and that saturation then falls off until the sand is dry at 1.65 m above the water table (Figure 3).

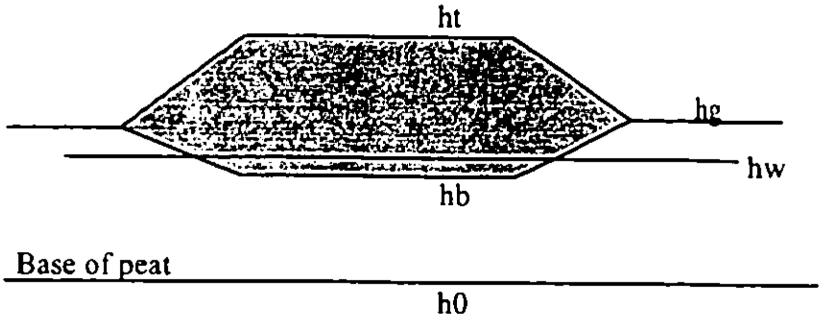

***Figure 3*** *Definition sketch for consolidation due to embankment. It is assumed that the peat beneath the embankment has been compressed in situ from an initial thickness of* $(h_g - h_0)$ *to a present thickness of* $(h_b - h_0)$*.* $h_w$ *is the elevation of the water table.*

The objective of the consolidation calculations is to estimate the reduction in thickness of the peat layer due to the weight of the embankment. Of the variables indicated in Figure 3, $h_t$, $h_o$ and $h_g$ are known for each of the 31 100 m dyads along the track. $h_w$ has been taken to be 0.4 m below ground level, and only $h_b$ remains completely unknown. It is however possible to estimate $h_b$ using an iterative process based on simple consolidation theory.

For a given thickness of embankment material $(h_t - h_b)$ it is possible to estimate the compaction that would have taken place in a peat layer of thickness $(h_g - h_0)$. The change in peat thickness, expressed in terms of the relative strain ε, is a function of the preconsolidation pressure, the overburden pressure, the loading and the compaction parameters $C^*_c$ and $C_{sec}$. The applied load depends mostly on the thickness of the embankment material, so the relative strain is also a complicated function of the elevation of the base of the trackbed $h_b$. The final thickness of the peat layer is:

$$h_b - h_0 = (h_g - h_0) \times \varepsilon(h_t - h_b) \qquad (7)$$

This implicit equation for $h_b$ can only be solved iteratively, but it appears to be stable and can be solved easily by manual iteration, trial and error or by using an equation solving system such as Lotus 123's Backsolver routine.

Once the consolidation undergone by the peat, expressed as a relative strain

$$\varepsilon = 1 - \frac{h_b - h_0}{h_g - h_0} \qquad (8)$$

is known, the change in void ratio (the ratio of void volume to solid volume) can be calculated in terms of the initial void ratio $e_0$ and the relative strain ε:

$$\frac{e}{e_0} = 1 - \frac{1 + e_0}{e_0}\varepsilon \qquad (9)$$

and it is possible to use an empirical relationship between permeability and void ratio

$$\kappa = \kappa_0(e/e_0)^{11} \qquad (10) \quad \text{Hobbs (1986) equation 8}$$

to calculate the permeability after consolidation. As there has also been a decrease in the thickness of the peat layer, the water-transmitting capacity of the peat layer is better expressed in terms of the transmissivity $T$, which is the integral of permeability over depth, or more simply

$$T = \kappa(h_b - h_0) \qquad (11)$$

### *Calculations*

Ground surface elevations and peat depths for each 100 m square along the north and south of the track were computed from the map and from the results of the peat surveys (Table 2).

***Table 2** Ground surface levels and peat depths along track*

| Dyad | Ground surface ($h_g$) | | Peat depth | | Track ($h_t$) |
|---|---|---|---|---|---|
| | North | South | North | South | |
| A | 89.6 | 90.1 | 2.62 | -- | 90.43 |
| B | 90.3 | 90.5 | 3.29 | -- | 90.96 |
| C | 90.6 | 91.3 | 2.30 | -- | 91.17 |
| D | 90.2 | 91.1 | 1.78 | 3.15 | 91.30 |
| E | 90.0 | 89.6 | 2.51 | 3.12 | 90.89 |
| F | 89.7 | 89.4 | 2.47 | 2.91 | 90.73 |
| G | 89.9 | 88.8 | 2.28 | 3.00 | 90.41 |
| H | 89.8 | 90.2 | 2.84 | 2.79 | 90.65 |
| I | 90.2 | 90.0 | 1.76 | 2.73 | 91.13 |
| J | 90.5 | 90.1 | 1.76 | 2.37 | 91.55 |
| K | 90.6 | 90.4 | 2.04 | 1.88 | 91.55 |
| L | 90.8 | 90.8 | 2.60 | 2.06 | 91.58 |
| M | 91.1 | 90.8 | 3.20 | 2.73 | 91.60 |
| N | 91.1 | 90.8 | 2.19 | 3.71 | 91.60 |
| O | 91.3 | 91.4 | 2.80 | 5.16 | 91.65 |
| P | 91.1 | 92.1 | 4.55 | 2.24 | 92.09 |
| Q | -- | 92.0 | 2.96 | 3.13 | 92.46 |
| R | -- | 91.9 | 0.40 | 0.60 | 92.53 |
| S | -- | 92.2 | 0.31 | 1.15 | 92.60 |
| T | 91.7 | 92.2 | 1.10 | 0.65 | 92.60 |
| U | 91.8 | 92.3 | 0.60 | 0.94 | 92.67 |
| V | 91.6 | 91.9 | 1.00 | 0.80 | 92.54 |
| W | 91.7 | 92.2 | 1.30 | 1.36 | 92.17 |
| X | 90.8 | 91.8 | 4.00 | 2.77 | 91.69 |
| Y | 90.6 | 91.8 | 1.35 | 4.00 | 91.39 |
| Z | 91.1 | 90.7 | 2.20 | 3.23 | 91.25 |
| AA | 91.5 | 91.9 | 0.21 | 0.56 | 91.95 |
| BB | 92.1 | 91.4 | 0.33 | 0.74 | 92.39 |
| CC | 91.6 | 91.0 | 1.00 | 0.92 | 92.17 |
| DD | 90.2 | 90.0 | 0.45 | 1.10 | 91.95 |
| EE | 89.9 | 90.4 | 0.80 | -- | 91.90 |

From the figures in Table 3, mean values of ground level and peat depth were calculated, and hence for each dyad a mean elevation of the base of the peat ($h_0$) was computed (Figure A1-2). In Figure A1-1, the two lines represent the interpolated values of peat depth north and south of the track for each dyad. These lines demonstrate that the thickness of the deeper peat tends to increase towards the central part of the mire.

Mills' (1994) oedometer results were re-calculated to provide estimates of $C^*_c$ and $p_c$ (Table 4).

***Table 4*** *Compression index and preconsolidation pressures from Mills' results*

| Sample | Depth in profile | Compression index<br>$C^*_c$ | Preconsolidation pressure, kPa<br>$p_c$ |
|---|---|---|---|
| 32-Kh | 0.0 - 0.2 m | 0.83 | 32.08 |
| 32-Kv | 0.0 - 0.2 m | 1.04 | 31.07 |
| 32-2-Kh | 0.2 - 0.4 m | 0.35 | 14.47 |
| 32-2-Kv | 0.2 - 0.4 m | 0.52 | 9.93 |
| 32-3-Kh | 0.55 - 0.75 m | 0.51 | 16.40 |
| 32-3-Kv | 0.55 - 0.75 m | 0.45 | 14.65 |

For the purposes of this report, an average compression index computed from the results of samples 32-2-Kh, 32-2-Kv, 32-3-Kh and 32-3-Kv was used:

$$C^*_c = 0.454$$

and an average preconsolidation pressure computed from the results of samples 32-2-Kh, 32-3-Kh and 32-3-Kv was used (it was not possible to derive a reliable result from sample 32-2-Kv):

$$p_c = 15.17 \text{ kPa}$$

In the calculation of the loading due to the embankment, the dry unit weight of sand was assumed to be 1762 kg/m$^3$. Table 5 and Figure A1-2 show values of $h_b$ computed for each dyad. These values of $h_b$ satisfy the implicit equation (7).

*Table 5 Computed trackbed base elevations*

| Dyad | Track | Ground level (average of north & south) | Base of peat (average of north & south) | Computed base of trackbed |
|---|---|---|---|---|
| | $h_t$ | $h_g$ | $h_0$ | $h_b$ |
| A | 90.43 | 89.88 | 87.26 | 89.43 |
| B | 90.96 | 90.41 | 87.12 | 89.80 |
| C | 91.17 | 90.93 | 88.63 | 90.74 |
| D | 91.30 | 90.62 | 88.15 | 90.14 |
| E | 90.89 | 89.80 | 86.99 | 89.05 |
| F | 90.73 | 89.54 | 86.85 | 88.81 |
| G | 90.41 | 89.38 | 86.74 | 88.70 |
| H | 90.65 | 89.99 | 87.17 | 89.43 |
| I | 91.13 | 90.13 | 87.88 | 89.57 |
| J | 91.55 | 90.30 | 88.24 | 89.75 |
| K | 91.55 | 90.51 | 88.55 | 90.02 |
| L | 91.58 | 90.78 | 88.45 | 90.25 |
| M | 91.60 | 90.97 | 88.01 | 90.40 |
| N | 91.60 | 90.93 | 87.98 | 90.34 |
| O | 91.65 | 91.31 | 87.33 | 90.73 |
| P | 92.09 | 91.60 | 88.21 | 91.01 |
| Q | 92.46 | 91.95 | 88.91 | 91.43 |
| R | 92.53 | 91.90 | 91.40 | 91.84 |
| S | 92.60 | 92.20 | 91.47 | 92.14 |
| T | 92.60 | 91.93 | 91.06 | 91.81 |
| U | 92.67 | 92.03 | 91.26 | 91.93 |
| V | 92.54 | 91.70 | 90.80 | 91.53 |
| W | 92.17 | 91.94 | 90.61 | 91.84 |
| X | 91.69 | 91.26 | 87.87 | 90.72 |
| Y | 91.39 | 91.19 | 88.52 | 90.98 |
| Z | 91.25 | 90.91 | 88.20 | 90.66 |
| AA | 91.95 | 91.68 | 91.29 | 91.65 |
| BB | 92.39 | 91.74 | 91.21 | 91.68 |
| CC | 92.17 | 91.31 | 90.35 | 91.12 |
| DD | 91.95 | 90.08 | 89.30 | 89.85 |
| EE | 91.90 | 90.15 | 89.75 | 90.04 |

The estimated trackbed base levels appear to be plausible: it is interesting to compare the results for dyads A, J and V with the borehole data of Table 1. In the boreholes the depths of made ground were recorded as 1.7, 1.5 and 1.3 m respectively: the above analysis has produced estimates of the thickness of embankment material of 1.0, 1.8 and 1.0 m. The peat has been compressed by up to 29% of its thickness, most of this change having taken place along the section of track opposite Moss Villa (dyads E to N) and at the very eastern end of the track (dyads DD and EE). The mean computed trackbed thickness is 1.1 m, reaching a maximum of 2.1 m at the eastern end of the SSSI.

Quite modest consolidation of peat results in a considerable reduction in permeability. Using Mill's estimates of initial void ratio $e_0$, the ratio of post-consolidation to "natural" permeabilities was calculated for each dyad. Multiplying this by the ratio of peat thicknesses gives the transmissivity ratio (Table 6 & Figure 4).

***Table 6*** *Ratios of post-consolidation to natural permeability and transmissivity*

| Dyad | Relative strain | Permeability ratio | Transmissivity ratio |
|---|---|---|---|
| A | 0.173 | 0.0504 | 0.0417 |
| B | 0.185 | 0.0394 | 0.0321 |
| C | 0.084 | 0.2592 | 0.2375 |
| D | 0.194 | 0.0329 | 0.0265 |
| E | 0.266 | 0.0065 | 0.0048 |
| F | 0.270 | 0.0060 | 0.0044 |
| G | 0.259 | 0.0078 | 0.0058 |
| H | 0.198 | 0.0304 | 0.0244 |
| I | 0.247 | 0.0103 | 0.0077 |
| J | 0.268 | 0.0062 | 0.0046 |
| K | 0.251 | 0.0093 | 0.0070 |
| L | 0.228 | 0.0159 | 0.0123 |
| M | 0.192 | 0.0339 | 0.0274 |
| N | 0.200 | 0.0288 | 0.0231 |
| O | 0.146 | 0.0840 | 0.0717 |
| P | 0.174 | 0.0493 | 0.0407 |
| Q | 0.171 | 0.0523 | 0.0434 |
| R | 0.120 | 0.1369 | 0.1205 |
| S | 0.082 | 0.2665 | 0.2446 |
| T | 0.141 | 0.0930 | 0.0799 |
| U | 0.130 | 0.1143 | 0.0995 |
| V | 0.189 | 0.0363 | 0.0294 |
| W | 0.073 | 0.3099 | 0.2872 |
| X | 0.159 | 0.0658 | 0.0554 |
| Y | 0.079 | 0.2838 | 0.2615 |
| Z | 0.093 | 0.2212 | 0.2006 |
| AA | 0.065 | 0.3566 | 0.3334 |
| BB | 0.117 | 0.1433 | 0.1265 |
| CC | 0.198 | 0.0301 | 0.0242 |
| DD | 0.290 | 0.0036 | 0.0026 |
| EE | 0.275 | 0.0053 | 0.0039 |

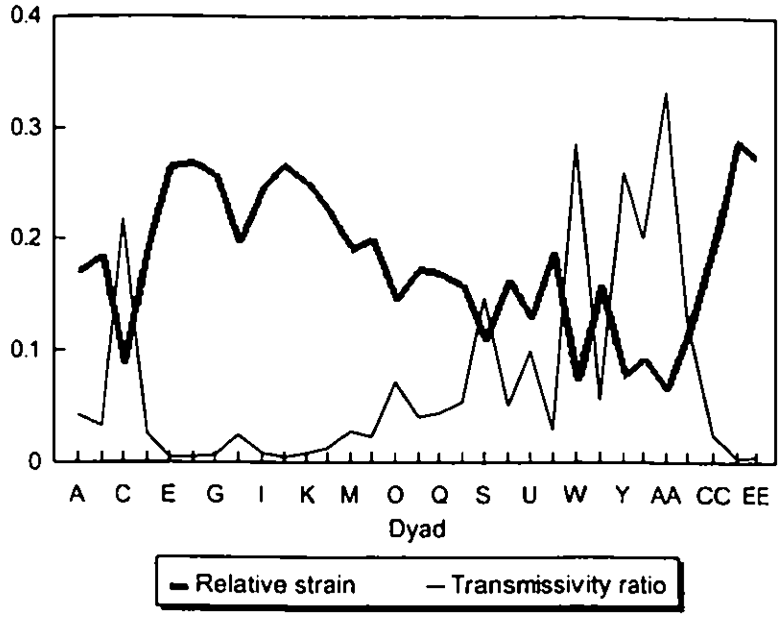

***Figure 4** Changes in peat compaction and transmissivity along the track. Greater consolidation of deeper peat has resulted in a greater lowering of transmissivity. Shallow peats towards the eastern end of the site retain a transmissivity of about a third of its initial (pre-railway) value.*

The consolidation associated with the railway has resulted in a reduction of the transmissivity by a factor of between 3 and 400, with an average of about 30. Although this is a significant reduction, it does not render the peat matrix impermeable, and there is a wide area between dyads M and Z (750 and 2050 m along the railway on Figures A1-1 & A1-2) where peat is relatively deep and the transmissivity reduction factor is less than about 35. Figure 5 shows the relationship between the thickness of embankment material and the reduction in transmissivity, according to the results presented in Table 6.

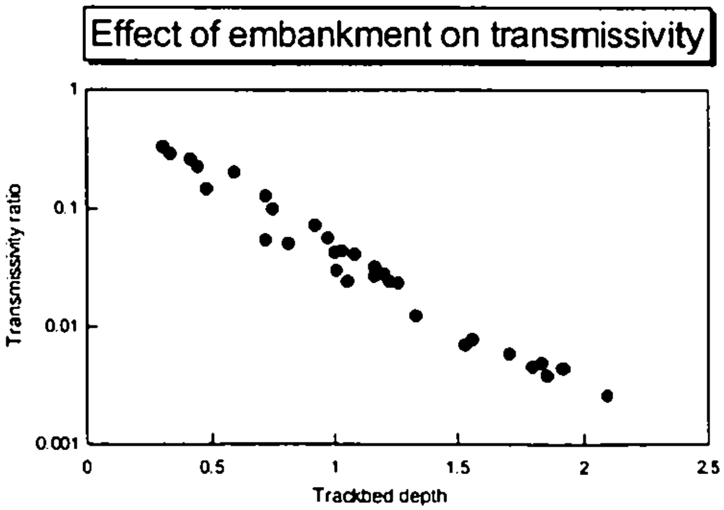

***Figure 5** Comparison of the transmissivity ratio with the thickness of the embankment material, as computed using consolidation theory, shows a simple logarithmic relationship*

## Conclusions

This study confirms that the peat at Fenns and Whixall Mosses forms a single hydrological unit, and peripheral areas cannot be regarded as isolated by the railway track. The railway embankment, though its weight has compressed the peat and caused serious reductions in permeability and transmissivity, does not form an impermeable seal between parcels of land to north and south.

The reduction in permeability and transmissivity have been estimated by considering the amount of consolidation to be expected from the loading of the embankment material, and using available data from Fenns and Whixall and elsewhere to calculate the thickness of embankment material. Calculated values are within an acceptable tolerance of measured values, and the expectation that the railway engineers would have used a thicker trackbed to cross deeper peat layers (or that the embankment may have been raised where necessary in subsequent years) is borne out by the calculations. The peat layer beneath the embankment has been reduced in thickness by up to 29%, and because of the unique structure and composition of peat this causes a disproportionate decrease in the ability of the peat to transmit water, as indicated by the two hydraulic parameters permeability and transmissivity. Transmissivity, a measure of the water-transmitting capacity of the whole saturated peat profile, has on average been reduced by a factor of 30.

There remains about 1.4 km of track, along the southern boundary of landholdings 167 and 183, sitting on relatively deep peat whose transmissivity, though reduced by compression, is still significant. On shallower peat, mostly towards the eastern end of the site, the consolidation has been proportionately less, as less embankment material has been used, and in this case there has been less relative change in the hydraulic properties. The railway track cannot be taken as a hydraulic boundary to the site.

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Table A1-1 Combined peat survey results

North of track

| Along track m | N of track m | Peat depth m |
|---|---|---|
| -501.2 | 19.7 | 2.97 |
| -408.8 | 27.0 | 2.62 |
| -344.1 | 34.1 | 3.29 |
| -260.6 | 44.5 | 2.74 |
| -235.9 | 89.9 | 2.30 |
| -157.6 | 37.5 | 2.62 |
| -63.0 | 44.4 | 1.78 |
| -28.6 | 102.5 | 2.51 |
| 21.2 | 39.2 | 3.34 |
| 111.6 | 40.5 | 2.47 |
| 157.7 | 95.9 | 2.28 |
| 196.8 | 59.7 | 2.95 |
| 305.1 | 33.4 | 2.84 |
| 305.1 | 33.4 | 2.46 |
| 476.8 | 19.2 | 1.76 |
| 502.1 | 91.7 | 2.16 |
| 571.5 | 26.0 | 2.04 |
| 594.5 | 89.0 | 1.23 |
| 656.6 | 35.2 | 2.60 |
| 703.6 | 95.0 | 2.60 |
| 711.1 | 32.5 | 3.85 |
| 729.8 | 20.7 | 3.57 |
| 745.1 | 93.4 | 2.80 |
| 748.4 | 53.1 | 3.05 |
| 754.6 | 33.3 | 3.20 |
| 790.6 | 95.1 | 2.75 |
| 813.2 | 32.5 | 3.20 |
| 819.6 | 32.6 | 3.01 |
| 835.0 | 34.7 | 2.80 |
| 843.0 | 81.4 | 2.00 |
| 847.8 | 35.0 | 2.80 |
| 864.9 | 88.6 | 2.19 |
| 868.8 | 37.8 | 2.47 |
| 880.4 | 79.2 | 3.30 |
| 892.0 | 35.1 | 2.95 |
| 894.5 | 64.7 | 3.49 |
| 915.6 | 34.7 | 1.22 |
| 923.3 | 25.0 | 3.17 |
| 925.5 | 88.8 | 2.81 |
| 948.8 | 32.0 | 3.90 |
| 976.4 | 33.5 | 2.80 |
| 1032.9 | 69.6 | 4.60 |
| 1052.2 | 96.4 | 4.55 |
| 1094.9 | 48.6 | 3.20 |
| 1152.0 | 80.4 | 2.96 |
| 1159.7 | 22.9 | 5.00 |
| 1214.9 | 90.2 | 0.51 |
| 1238.9 | 1.4 | 0.85 |
| 1244.3 | 29.9 | 2.00 |
| 1301.3 | 3.9 | 0.40 |
| 1308.7 | 44.9 | 0.95 |
| 1362.2 | 98.4 | 0.31 |
| 1365.2 | 38.1 | 0.95 |
| 1365.3 | 5.3 | 1.35 |
| 1429.7 | 41.7 | 1.10 |
| 1442.5 | 25.6 | 0.80 |
| 1513.3 | 45.7 | 1.10 |
| 1524.7 | 62.2 | 1.00 |
| 1544.6 | 9.2 | 0.60 |
| 1552.1 | 60.1 | 0.60 |
| 1568.6 | 75.1 | 0.70 |
| 1680.6 | 10.9 | 1.00 |
| 1690.1 | 41.4 | 1.00 |
| 1690.9 | 62.2 | 1.00 |
| 1728.0 | 8.6 | 1.45 |
| 1734.5 | 68.5 | 2.10 |
| 1734.9 | 101.5 | 1.50 |
| 1735.5 | 43.1 | 0.80 |
| 1814.6 | 16.6 | 1.30 |
| 1822.4 | 49.7 | 2.00 |
| 1909.6 | 15.6 | 4.00 |
| 1970.7 | 82.2 | 1.35 |
| 1972.9 | 22.6 | 3.15 |
| 2003.3 | 45.9 | 3.10 |
| 2019.1 | 61.6 | 1.50 |
| 2087.2 | 5.7 | 2.20 |
| 2091.2 | 93.3 | 0.60 |
| 2096.6 | 95.4 | 0.56 |
| 2107.3 | 25.5 | 0.70 |
| 2111.6 | 52.5 | 0.60 |
| 2112.0 | 92.5 | 0.45 |
| 2118.1 | 3.4 | 0.75 |
| 2161.1 | 66.2 | 0.21 |
| 2166.2 | 28.3 | 0.30 |
| 2279.5 | 39.8 | 0.33 |
| 2388.2 | 86.4 | 1.00 |
| 2494.3 | 76.9 | 0.45 |
| 2510.1 | 64.8 | 0.90 |
| 2532.1 | 60.6 | 1.35 |
| 2532.4 | 26.4 | 2.00 |
| 2533.1 | 15.8 | 1.50 |
| 2548.1 | 15.6 | 0.50 |
| 2564.3 | 59.9 | 0.80 |
| 2571.2 | 93.6 | 0.60 |
| 2571.3 | 55.8 | 0.75 |
| 2579.3 | 76.1 | 1.10 |

South of track

| Along line | N of line | Peat depth |
|---|---|---|
| -240.5 | -48.3 | 1.97 |
| -138.5 | -46.1 | 3.30 |
| -135.2 | -150.0 | 3.53 |
| -46.4 | -48.1 | 3.10 |
| -39.1 | -150.0 | 2.86 |
| 56.4 | -37.9 | 2.91 |
| 59.8 | -146.8 | 2.42 |
| 156.4 | -37.7 | 3.04 |
| 156.6 | -44.7 | 2.80 |
| 157.8 | -145.7 | 2.56 |
| 262.5 | -40.3 | 2.82 |
| 265.7 | -139.3 | 3.38 |
| 329.4 | -35.2 | 2.81 |
| 468.9 | -142.8 | 2.30 |
| 470.5 | -34.7 | 1.79 |
| 635.5 | -96.5 | 1.97 |
| 725.5 | -125.7 | 2.53 |
| 821.4 | -122.7 | 3.30 |
| 980.3 | -51.6 | 5.60 |
| 1021.2 | -79.3 | 1.94 |
| 1105.5 | -121.6 | 2.82 |
| 1139.1 | -44.5 | 1.29 |
| 1161.0 | -3.3 | 5.00 |
| 1164.9 | -32.7 | 5.00 |
| 1214.0 | -103.2 | 2.88 |
| 1241.8 | -28.1 | 0.55 |
| 1306.2 | -22.5 | 0.95 |
| 1372.3 | -20.1 | 1.25 |
| 1374.4 | -114.1 | 2.12 |
| 1434.4 | -9.7 | 0.60 |
| 1542.1 | -15.4 | 0.95 |
| 1679.5 | -13.5 | 0.80 |
| 1728.5 | -17.0 | 1.30 |
| 1796.8 | -31.5 | 1.50 |
| 1901.7 | -16.1 | 4.00 |
| 2030.6 | -13.9 | 4.00 |
| 2106.3 | -41.7 | 1.00 |
| 2113.9 | -18.6 | 0.50 |
| 2480.3 | -21.9 | 1.15 |
| 2536.5 | -20.9 | 0.60 |

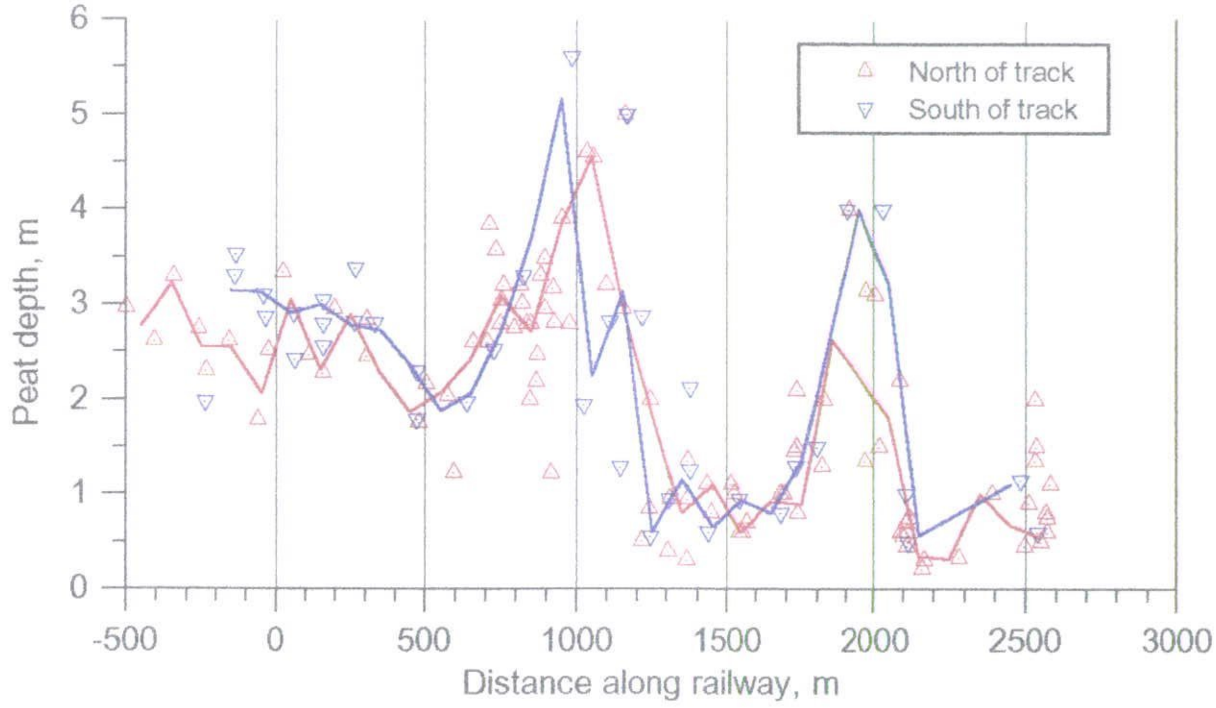
## Table A1-2 Track spot heights

| Along track<br>m | Elevation<br>m |
|---|---|
| -466.3 | 90.4 |
| -417.5 | 90.5 |
| -378.0 | 90.8 |
| -342.0 | 91.0 |
| -285.5 | 91.1 |
| -237.5 | 91.4 |
| -177.5 | 91.4 |
| -119.8 | 91.2 |
| -55.0 | 90.9 |
| -11.8 | 90.8 |
| 20.5 | 90.8 |
| 65.8 | 90.7 |
| 153.5 | 90.4 |
| 205.0 | 90.4 |
| 278.3 | 90.8 |
| 388.0 | 91.3 |
| 463.5 | 91.6 |
| 516.0 | 91.6 |
| 588.3 | 91.5 |
| 663.3 | 91.6 |
| 742.5 | 91.6 |
| 827.0 | 91.6 |
| 916.3 | 91.6 |
| 990.0 | 91.7 |
| 1066.0 | 92.2 |
| 1162.0 | 92.5 |
| 1232.0 | 92.5 |
| 1302.0 | 92.6 |
| 1382.0 | 92.6 |
| 1455.0 | 92.6 |
| 1522.0 | 92.7 |
| 1612.0 | 92.6 |
| 1680.0 | 92.5 |
| 1728.0 | 92.2 |
| 1798.0 | 92.1 |
| 1875.0 | 91.5 |
| 1938.0 | 91.5 |
| 2006.0 | 90.9 |
| 2093.0 | 91.6 |
| 2207.0 | 92.3 |
| 2245.0 | 92.4 |
| 2290.0 | 92.3 |
| 2337.0 | 92.2 |
| 2386.0 | 92.1 |
| 2470.0 | 91.9 |
| 2515.0 | 91.9 |
| 2573.0 | 91.9 |
| 2618.0 | 91.9 |

## Table A1-3 Elevation of ground level away from track

| Dyad | Along-track distance m | Average elevation, m North | Average elevation, m South |
|---|---|---|---|
| A | -450 | 89.6 | 90.1 |
| B | -350 | 90.3 | 90.5 |
| C | -250 | 90.6 | 91.3 |
| D | -150 | 90.2 | 91.1 |
| E | -50 | 90.0 | 89.6 |
| F | 50 | 89.7 | 89.4 |
| G | 150 | 89.9 | 88.8 |
| H | 250 | 89.8 | 90.2 |
| I | 350 | 90.2 | 90.0 |
| J | 450 | 90.5 | 90.1 |
| K | 550 | 90.6 | 90.4 |
| L | 650 | 90.8 | 90.8 |
| M | 750 | 91.1 | 90.8 |
| N | 850 | 91.1 | 90.8 |
| O | 950 | 91.3 | 91.4 |
| P | 1050 | 91.1 | 92.1 |
| Q | 1150 |  | 92.0 |
| R | 1250 |  | 91.9 |
| S | 1350 |  | 92.2 |
| T | 1450 | 91.7 | 92.2 |
| U | 1550 | 91.8 | 92.3 |
| V | 1650 | 91.6 | 91.9 |
| W | 1750 | 91.7 | 92.2 |
| X | 1850 | 90.8 | 91.8 |
| Y | 1950 | 90.6 | 91.8 |
| Z | 2050 | 91.1 | 90.7 |
| AA | 2150 | 91.5 | 91.9 |
| BB | 2250 | 92.1 | 91.4 |
| CC | 2350 | 91.6 | 91.0 |
| DD | 2450 | 90.2 | 90.0 |
| EE | 2550 | 89.9 | 90.4 |

## Figure A1-1 Peat depth survey results



## Figure A1-2 Section along railway track

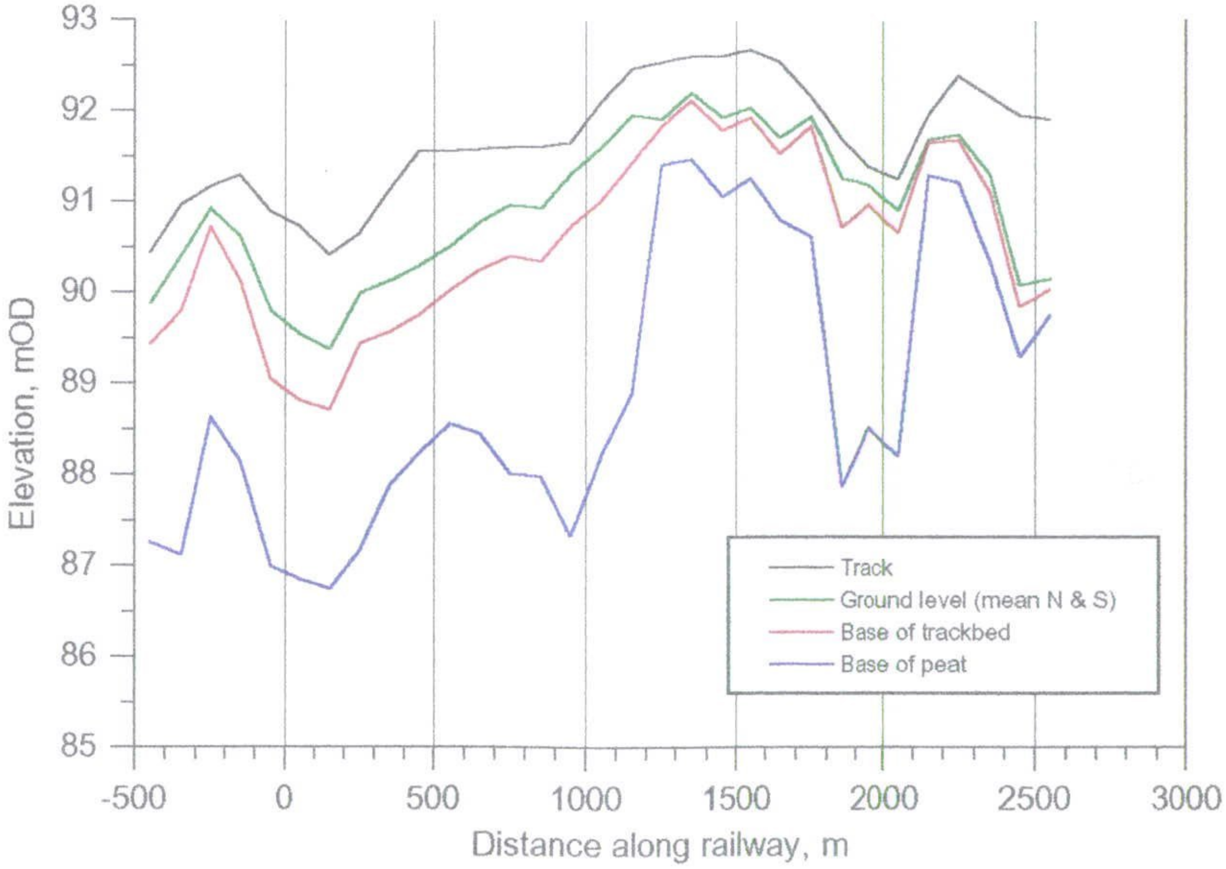


Figure A1-1 Peat depth survey results

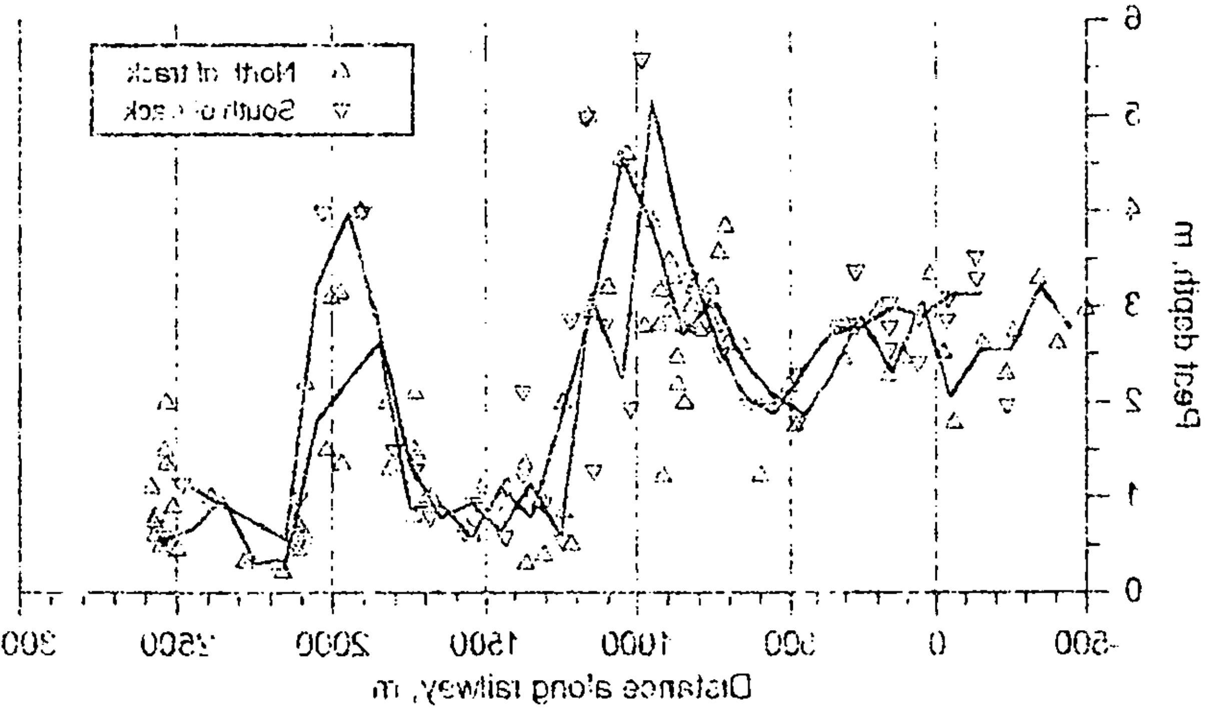
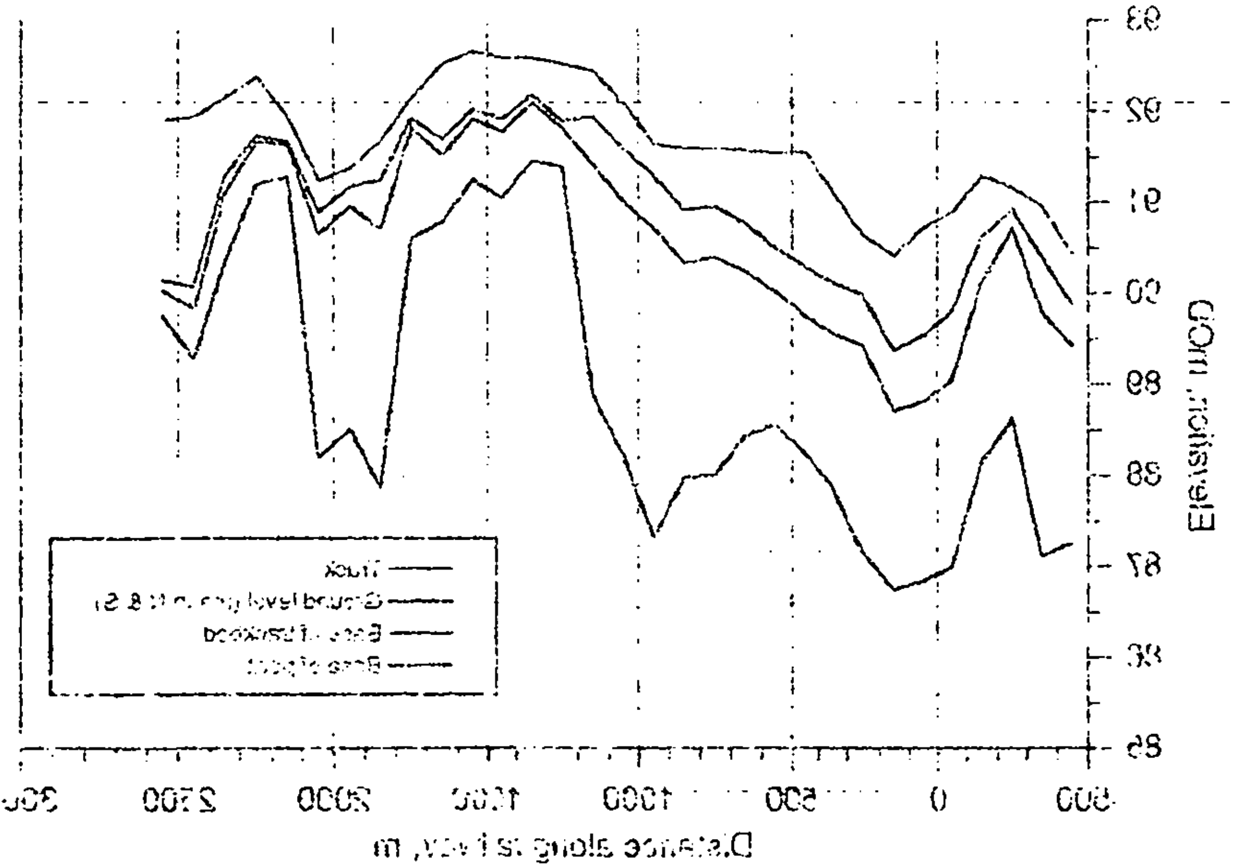


Figure A1-2 Section along railway track



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