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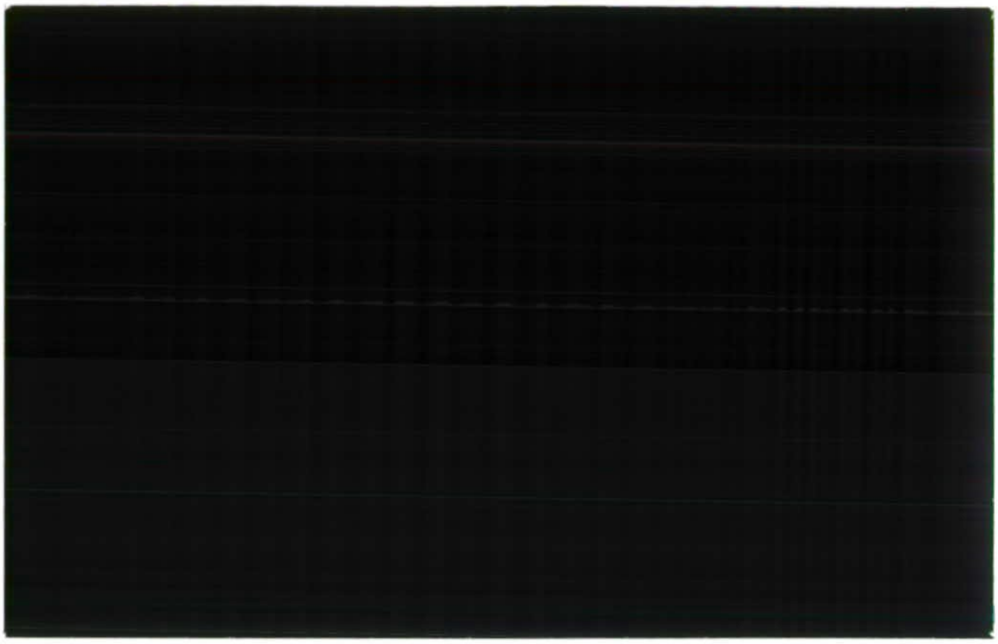

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FENNS WHIXALL & BETTISFIELD MOSSES SSSI, CLWYD/SHROPSHIRE - EVALUATION OF HYDROLOGICAL CONNECTIONS ACROSS THE BRONINGTON MANOR DRAIN

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). To the north of the railway the mire abuts against land used for agriculture and forestry, and the peat becomes thin and discontinuous. Drainage ditches, one of the most important of which is the Bronington Manor Drain, have the effect of lowering the water table and providing an outlet for surface water through a culvert beneath the railway track and into the main drainage network of the mire.

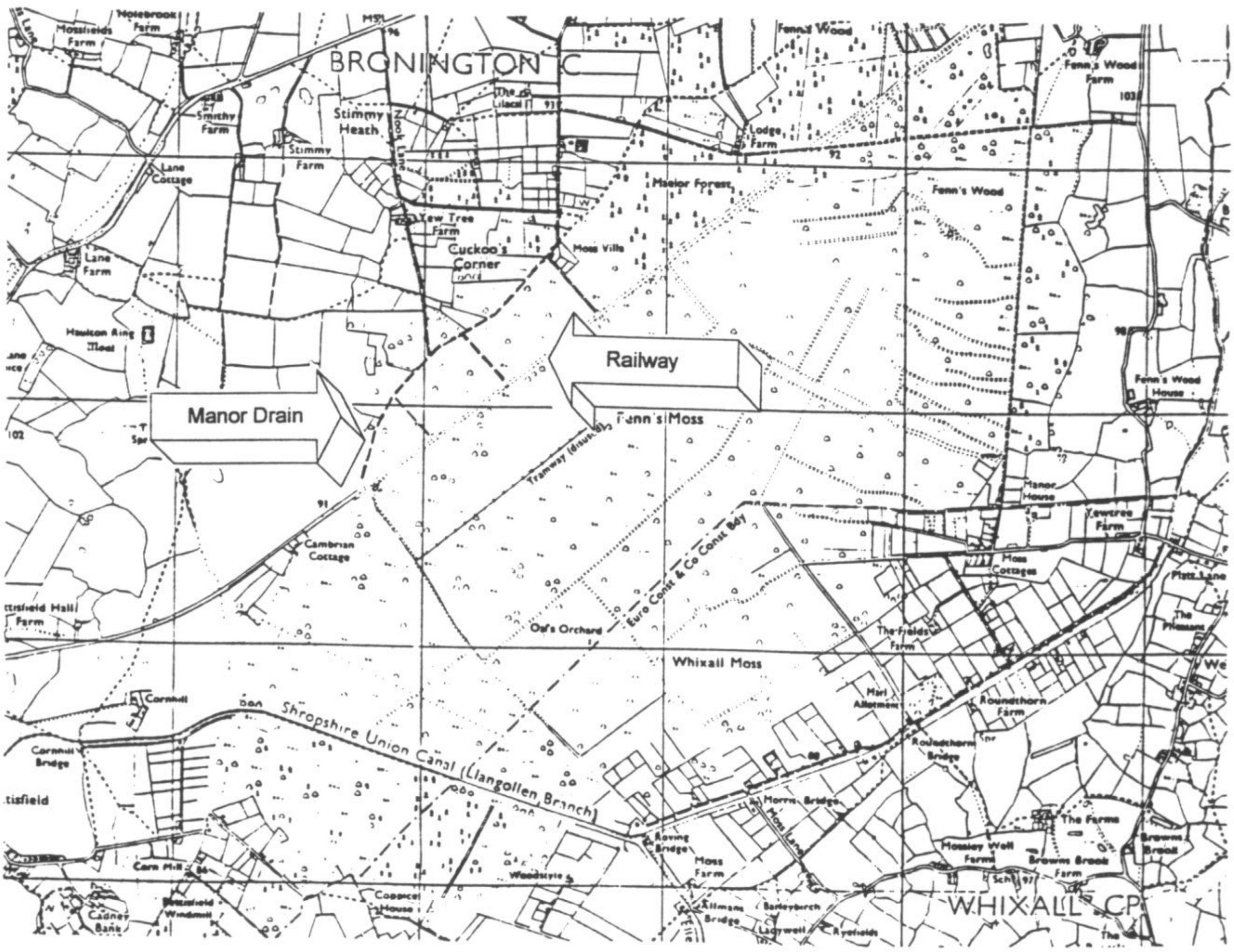

***Figure 1** Fenns & Whixall Moss (SJ 490370).*

The owners of the Maelor tree nursery have proposed improvements to the drainage of peripheral land north of the railway, under-draining an area of land used for raising conifer seedlings, and making use of the Manor Drain as an outlet. The Institute of Hydrology (IH) was commissioned by the Countryside Council for Wales (CCW) to advise on the possible effects of the drainage scheme on undrained mire land across the Drain, and on the impact of raised water levels within the mire on the effectiveness of the Maelor drainage scheme. Four questions were posed:

1) is there hydraulic continuity across the Manor Drain, especially where peat is deep and the drain does not penetrate to mineral soil?

2) is the current water level in the Manor Drain a factor in retaining a high water table and sustaining mire vegetation in the Nursery and to the southeast of the Drain?

3) will the proposed drainage improvements cause a fall in water levels in the Drain and to the southeast?

4) will any fall in the Drain water level or the water table have an impact on the mire community southeast of the Drain?

In this report it is proposed to answer these questions by detailed consideration of the hydrology and the hydraulics of groundwater flow in the vicinity of the Manor Drain under a range of conditions.

CLIMATE AND THE SEASONAL PATTERN OF WATER LEVELS

Fenns and Whixall Mosses developed into a raised bog system because the climate and landscape were able to provide the unique combination of conditions for the growth of peat-forming plants. The climatic conditions still apply - raised mire formation requires only a sufficient excess of rainfall over evaporation for groundwater flow in the peat to be radially outwards. The tolerance of raised mire systems to seasonal or longer-term variations in climatic components is rather less clear: some of the water stored in the mire can be released to make up deficits over dry seasons, but longer spells of a drier climate can inhibit peat growth, cause a degree of oxidation and accelerated humification of existing peat and give rise to firmer, more humified layers, above which bog growth continues as normal.

However, where mire systems are failing to make peat growth, this is almost inevitably related to other factors, notably drainage for agricultural use or the effects of peat extraction. Increasing localised drainage by ditching or gripping causes a lowering of the water table in the adjoining peat, followed by oxidation and wastage that reinforces the tendency to faster and more localised flow off the mire expanse. Chemical conditions change from reducing to oxidising and there are changes in the vegetation community away from peat-forming ecosystems towards those of heath and moorland. Accompanying the general drying of the peat, there is an increase in seasonal fluctuations in soil moisture and the water table. Drained peat contains less water to sustain soil moisture levels over dry spells, and the more solid peat that results from drainage cannot respond to seasonal withdrawal of water by the reversible process of *Mooratmung* ("mire-breathing") in which moisture-loving mire communities, especially mosses in hollows, are able to maintain contact with the water table by vertical (upward and downward) movement of the ground surface (Gilman 1994).

Within the peat of an intact raised mire, there are fluctuations in the water table that can be attributed unambiguously to seasonal and short-term variations in the climate. Superimposed on the seasonal march of water levels that relates to increased rainfall in the winter months and the more regular variation in evaporation rates, controlled mainly by solar radiation, there are irregular peaks and troughs resulting from spells of dry, wet or warm weather, and from summer rainfall, which is sometimes intense. In an undisturbed mire, these fluctuations are moderated by lateral flows to and from hummocks, hollows and small open water bodies, and the litter layer and the upper layers of peat have a very high capacity to retain water. Thus the amplitude of fluctuations of all frequencies is attenuated, and the plant community never suffers a long period of moisture stress. Within the zone of influence of a drainage ditch or peat excavation, the lowering of the water table eliminates the superficial reservoirs of water, and the water table is drawn down into a region where the peat is more compact and its specific yield is reduced. This means that the water table is not only further from the ground surface, but its seasonal and short-term fluctuations increase in amplitude, and the probability of periods of very low water levels, and consequent stress on the plant community, is increased considerably.

In considering the impact of drainage, it is important to take into account the extremes of climate: while changes in average soil climate may be small, the tolerance of the ecosystem to drought years may be considerably reduced. In this context, recent years have evidenced a tendency towards sequences of drought summers, and though this apparent trend may be merely an artefact of long-period cycles in climate rather than a long-term movement (such as for example incipient global warming) it would be unwise to ignore the consequences for already-stressed wetland sites. Total annual rainfall, or even the total of rainfall in the summer months, does not characterise drought summers: they can be measured only by their effects. For wetland sites, the two most important factors are the duration and seriousness of the summer water table decline, and both of these factors can be quantified by the evaluation of the Potential Soil Moisture Deficit (PSMD), which is a cumulative quantity based on a simple water budget. The PSMD is computed as a cumulative total of potential evaporation minus rainfall. Excess rainfall in winter is assumed to run off, leading to a zero deficit over the winter. At other sites with a long water table record, the PSMD has been found to be a good indicator of the movements of the water table (Gilman 1995). Figure 2 shows the evolution of the PSMD for Fenns & Whixall Moss for the years 1961 to 1996, and demonstrates clearly the significance of the drought years 1975-76, 1984, 1989-91 and 1994-96. Not only the height of each peak but also its width is important, as this is a measure of the duration of the drought. In this respect the most recent drought years, 1989-90 and 1995 stand out as particularly dangerous times for wetland communities.

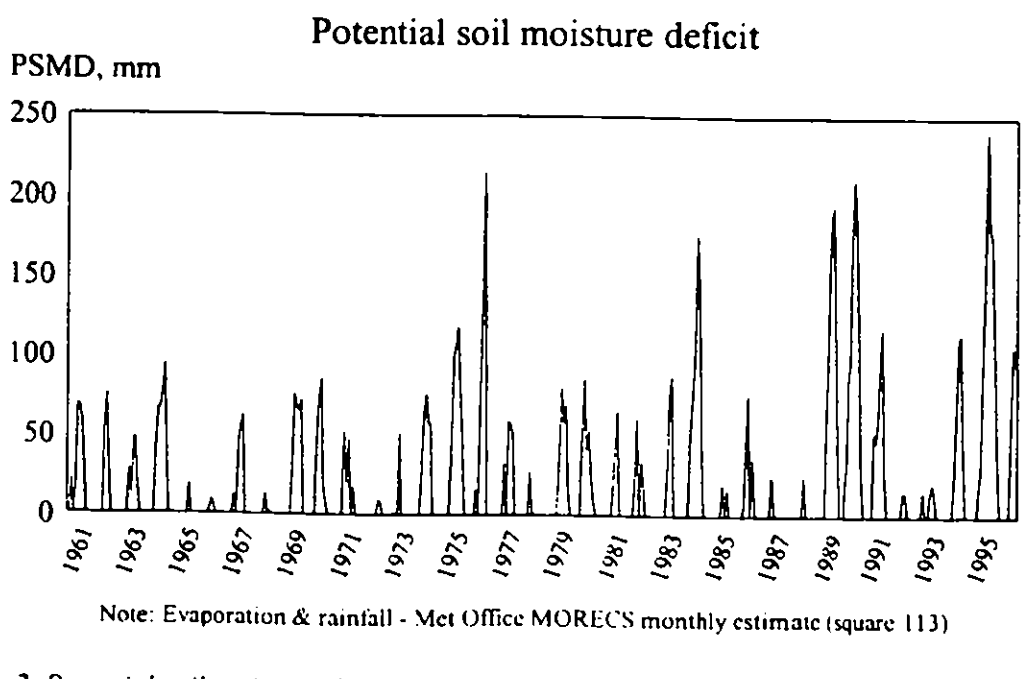

Figure 2 Potential soil moisture deficit calculated for Fenns & Whixall Moss, 1961-96.

Since early 1994, rainfall has been measured at Oaf's Orchard, near the centre of Fenns & Whixall Moss. Monthly rainfall figures from Oaf's Orchard tend to be lower than those produced by the Meteorological Office's MORECS model, which works on a 40-kilometre square basis, and thus takes account of higher ground in Clwyd and Shropshire. A comparison between PSMDs calculated from MORECS and Oaf's Orchard rainfall for 1994-96 (Figures 3 & 4) suggests that Figure 2 gives a fair picture of the overall variation of *in situ* PSMD in the longer term, particularly the significance of the various drought year peaks.

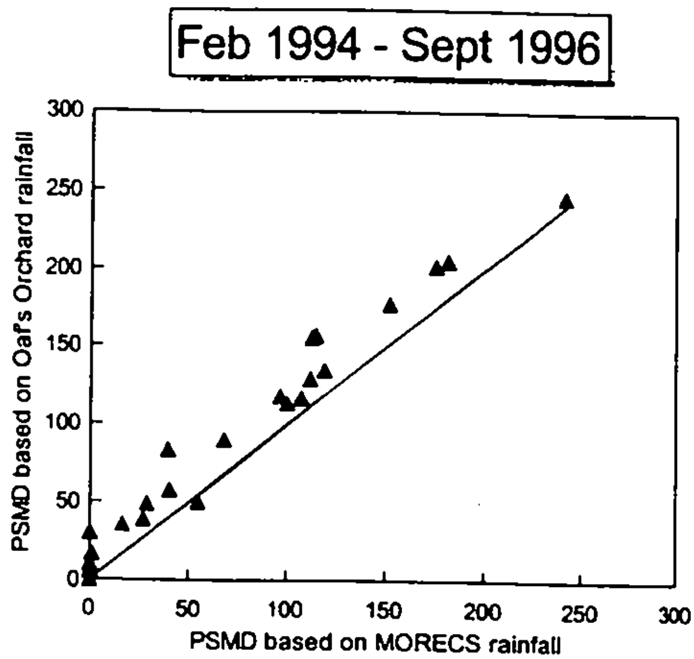

Figure 3 PSMD calculated using Oaf's Orchard rainfall tends to produce higher values, as could be expected from the generally lower rainfall values, but the relationship is a simple one and scatter is acceptable.

While it is obvious that drainage ditches have an effect on adjacent peat - indeed most of these effects are beneficial to the use of the land for grazing and cultivation - the spatial extent of deleterious effects on natural vegetation communities is less clear. Time is an important factor, as peat wastage and the development of ecosystems by succession are slow processes, but there are other important factors, notably the "biological inertia" demonstrated by some plant species that can persist for a considerable period under unfavourable conditions, and the self-healing processes that tend to restore the mire structure by blocking drainage lines and returning the drainage pattern to the more diffuse seepage that typifies the undisturbed mire. Intact raised mires consist of two peat layers with very different hydraulic characteristics (Ingram 1978). The *acrotelm*, formed from poorly humified peat and plant litter, is the shallow upper layer, no more than a few centimetres thick, and has high permeability and specific yield, while the *catotelm* is made up of a much greater depth of compacted and more humified peat with a much lower permeability. Within the zone of influence of a drainage ditch, the water table is likely to be drawn down into the compact peat of the catotelm where horizontal flow of water is difficult and slow. The zone of influence of the ditch within the catotelm would therefore be of very limited extent (Boelter 1972). However, a considerable width of acrotelm peat may be dewatered by the presence of the ditch, and in this wider strip there will almost certainly be an increase in the seasonal amplitude of water table fluctuations, accompanied by chemical and floristic changes.

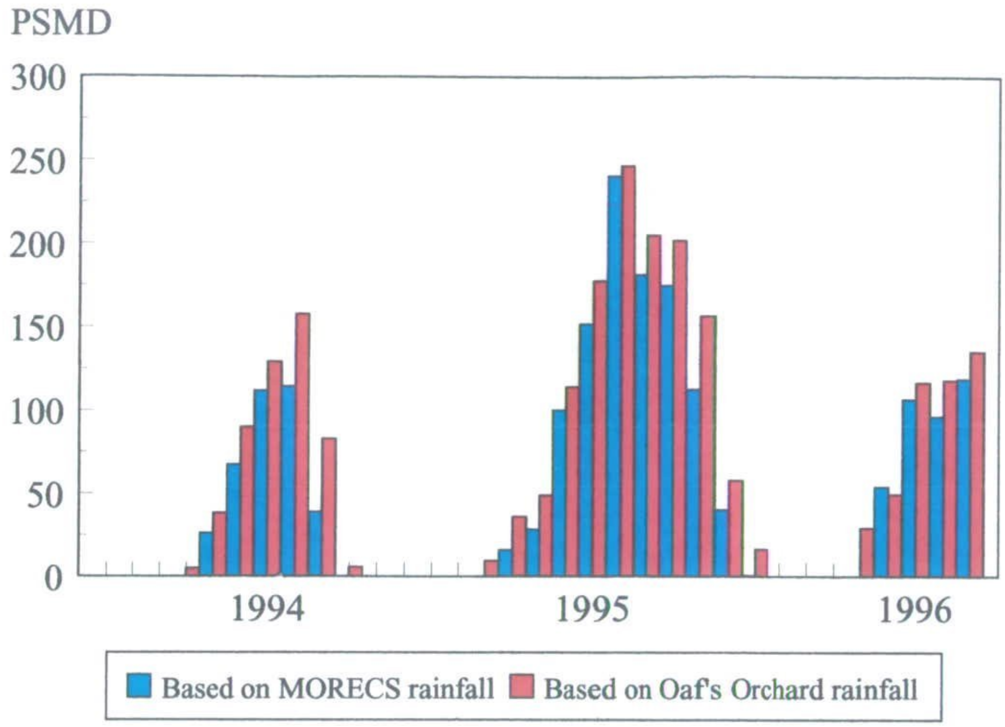

Figure 4 *Development of the PSMD over the summers of 1994-96. The lower Oaf's Orchard rainfall has the effect of deepening and prolonging the season of soil moisture deficit relative to the regional figure given by the MORECS estimates of rainfall and evaporation.*

The long-term impact of lower water levels in the Manor Drain, should these be caused directly or indirectly by changes in the drainage of the Maelor Nursery, would be wastage of the peat within a strip parallel with the Drain and possibly up to 50 m wide. The short-term impact would be less dramatic, and limited to the interception of surface water and the dewatering of pools and hollows. Any impact of dewatering would be exacerbated by sequences of "dry" years (according to the PSMD definition developed above) during which wastage and desiccation cracking would be accelerated.

PEAT AND UNDERLYING DEPOSITS

The Bronington Drain and Maelor Nursery are located very near the northern periphery of Fenns & Whixall Moss, where the peat is relatively thin and uneven in depth. As a result, drainage ditches may or may not penetrate the peat into underlying silt and sand. A survey of peat depths was carried out by field staff of English Nature and CCW in July 1996, to determine the relationships between existing ditch beds and the peat/mineral soil boundary.

The Maelor nursery occupies an area of peat that is essentially a salient of Fenns & Whixall Moss extending up a north-west to south-east trending valley. On the axis of this salient, near to the junction between the Manor Drain and the southward extension of Nook Lane, peat is up to 1.7 m deep, but elsewhere the peat thickness is much less, and drains penetrate well into the mineral substrate. This mineral substrate varies in texture between sand and clay, but most sample borings returned silty clay or sandy loam with varying organic fractions.

An important part of the peat survey was a series of 14 stations along the Manor Drain and the ditch along side Nook Lane (Figure 5). At each station depths of peat were measured close to the ditch and at a distance of about 10 m. The depth to water and to the bottom of the ditch was measured from a board laid across both banks. Table 1 presents these results, with all measurements expressed in metres relative to the base of the peat. In most cases the ditch water level was below the base of the peat, and in only one case (station 11 at the junction between the Manor Drain and Nook Lane) did the bottom of the ditch lie within the peat. For most of its length therefore, the Drain divides the peat body underlying the Nursery from that of the main Moss.

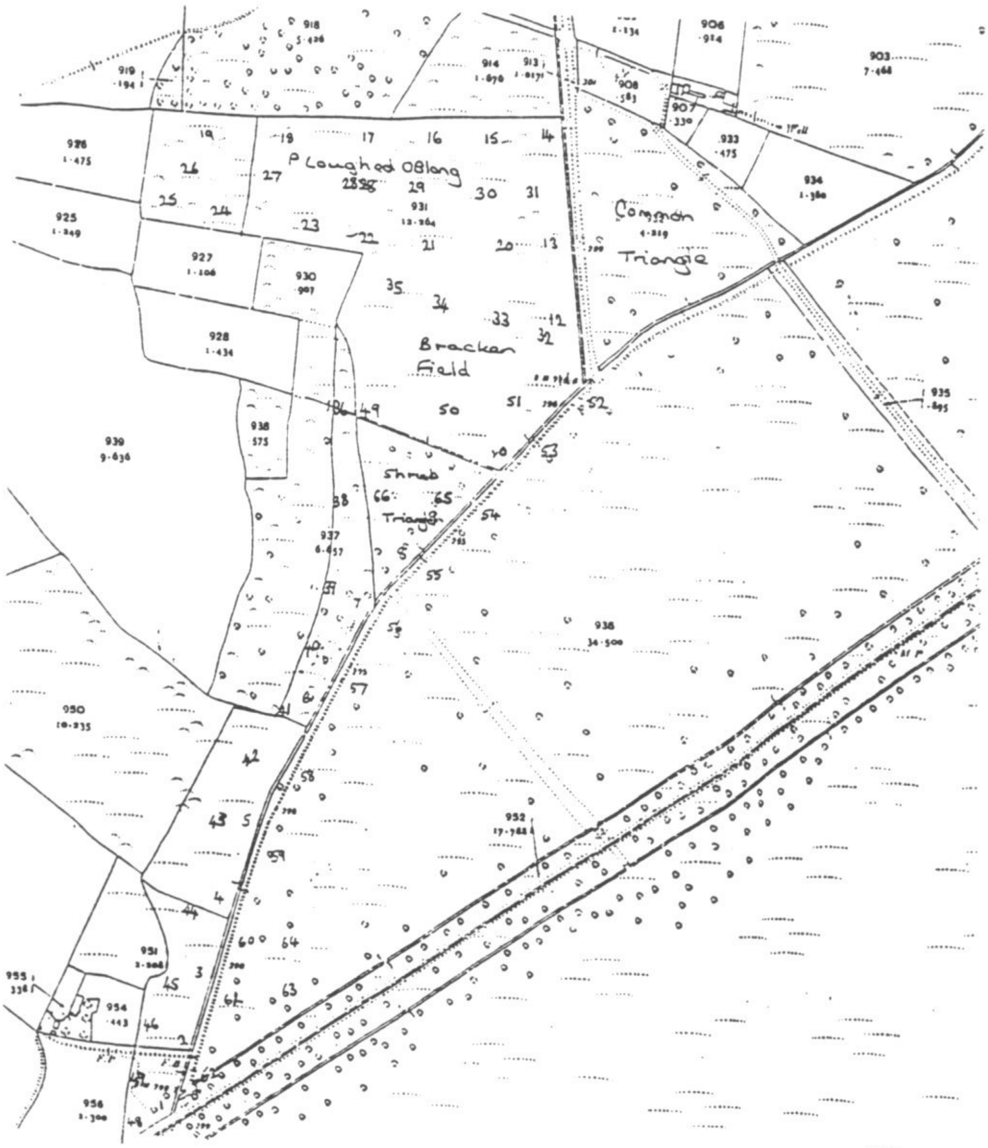

***Figure 5** Location map. The disused railway runs from bottom left to centre right, and the proposed drainage scheme comprises the parcels labelled "Ploughed Oblong", " Bracken Field" and "Shrub Triangle" and the narrow strip of land west of the "Shrub Triangle". Nook Lane is the track extending from centre top of the map to its junction with the Manor Drain, which flows from top right to bottom left of the map, passing through a culvert under the railway.*

Table 1 Results of peat depth survey along Manor Drain

Station	Ground level above peat base		Water level above peat base	Ditch bottom above peat base
	10m from ditch	0.3m from ditch		
Disused railway				
1	0.45	0.35	-0.15	-0.52
2	0.73	0.71	0.10	-0.50
3	0.19	0.50	-0.60	-1.20
4	0.50	1.02	0.40	-0.28
5	0.18	0.79	-0.23	-0.90
6	0.00	0.00	-1.00	-1.68
7	0.00	0.48	-0.05	-0.79
8	0.87	0.76	-0.34	-0.82
9	1.50	0.33	-0.22	-0.53
10	1.25	0.91	0.22	-0.23
11	1.79	1.38	0.75	0.14
Junction of Manor Drain & Nook Lane				
12	0.43	0.40	-0.49	-0.96
13	0.33	0.33	-1.02	-1.30
14	0.25	0.00	-1.80	-1.88
East-west drain				

Except at one point, the peat is not continuous across the ditch, and this has important implications for predicting the impact of drainage on one side of the ditch, and possible re-wetting of the mire on the other. The nature of the mineral substrate assumes central importance in defining the flow of water and the possible propagation of water level changes across the ditch. Table 2 shows the recorded texture of the substrate at stations near the ditch (see Figure 5 for locations). It is difficult to obtain a reliable estimate of permeability from simple texture classification, but it is reasonable to take the presence of a silt and clay fraction as defining a soil with relatively low permeability (say 0.1 m/d or less), where the presence of sand, alone or with peat, would indicate rather higher permeabilities (up to 10 m/d). This simple assumption suggests that there are two main areas where concern about water movement across the ditch through the mineral substrate might be justified: towards the southern end of the proposed drainage scheme and at its upper end opposite the "Common Triangle". There is a third area around station 11 where flow through the overlying peat might be important.

Table 2 Texture of mineral substrate

Station	Depth of peat	Substrate
62	0.70	Clayey peat
61	0.00	Silty peat loam
60	0.60	Silty peat
59	1.50	Silty peat
58	0.25	Sand
57	0.30	Sand
56	0.85	Silty peat
55	0.40	Sand
54	0.95	Sandy clay
53	1.70	Sandy clay
52	0.95	Sandy clay
32	0.70	Wet silty clay
20	0.90	Sandy peat
31	0.30	Silty peat
15	0.30	Sandy clay

THE EFFECTS OF A BOUNDARY DRAIN

It has often been asserted that a deep open drain, whose water level is controlled by conditions downstream, creates an effective hydraulic boundary that prevents changes in the hydrology of land on one side of the drain from propagating to the other. Though this is generally true where groundwater flow is horizontal and confined to a thin layer of permeable material, it is possible to envisage a scenario where a strong contrast in permeability could create conduits for groundwater that would bypass the drain. In this case the effect of raising the water table on one side of the drain could induce higher water levels on the other side without bringing about a substantial change in the drain water level. To investigate this possibility, a simple groundwater model was developed to simulate the flow of groundwater in the vicinity of a partially penetrating ditch. Using this model, and a set of very broad assumptions that approximate the conditions obtaining in the field at Fenns & Whixall Moss, it is possible to take into account various possible permeability distributions, for example a peat body sitting on a silty clay or sand substrate, and to examine the effects of changing water table levels on one side, or both sides, of the ditch.

The model, constructed using Cherwell Scientific's ModelMaker software package, consists of a rectangular array of elements, each element representing a block of soil 0.5 m deep and 5 m wide, with flows between elements determined by the equation of saturated groundwater flow (Figure 6). Recharge from the ground surface, from infiltrating rainfall, was assumed to be 0.0005 m/d (= 183 mm/a) distributed uniformly. The water level in the ditch, which for simplicity was assumed to be 5 m wide and 1.5 m deep, was fixed at h_f = 4.5 m above an arbitrarily located impermeable base 5 m below ground surface. The drawdown of the water table, for example near the ditch, was taken into account in defining near-surface flows, and the model was run as a steady-state simulation, i.e. transient behaviour was not considered. The boundary conditions, which determine the behaviour of the water table and hydraulic pressures distant from the ditch, were simplified by assuming that the water table elevation on each side of the ditch was defined by an "imaginary" ditch whose water level was maintained at h_0 (to the left of the ditch) and h_2(to the right of the ditch).

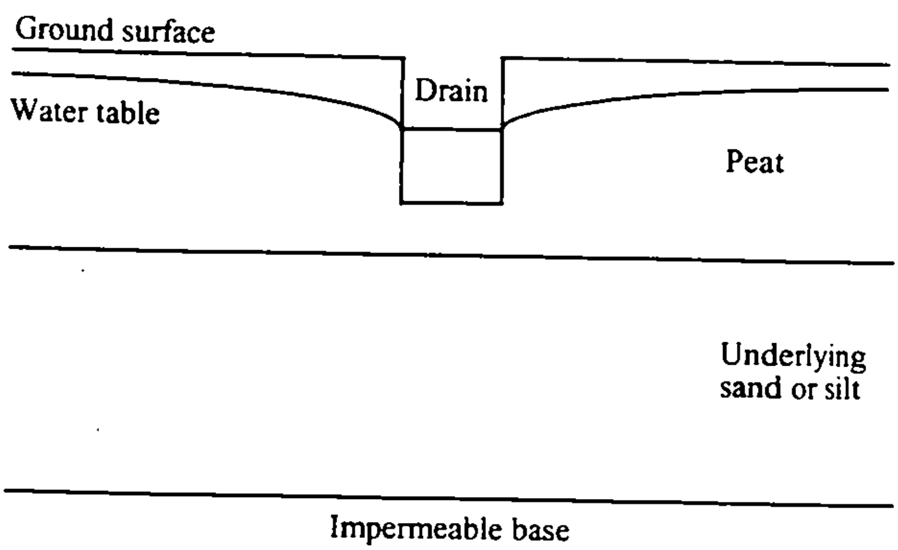

Figure 6 *Schematic diagram of groundwater model.*

A total of fifteen runs of the model were used to determine the effects of

1) soils of varying permeability (a peat layer of permeability 1 m/d underlain by either sand or silt of permeability 10 or 0.1 m/d respectively)

2) lowering the water table on the left side of the ditch to 4.5 m above the base (representing improved drainage on this side)

3) raising the water table on the right side of the ditch to 5 m (representing the intentional wetting-up of the mire).

The results are presented in Figures 7 to 11, with the convention that grey lines represent the current state ($h_0 = h_2 = 4.7$ m, $h_1 = 4.5$ m), red lines represent improved drainage ($h_0 = h_1 = 4.5$ m, $h_2 = 4.7$ m) and blue lines represent the wetting-up of the mire ($h_0 = h_1 = 4.5$ m, $h_2 = 5.0$ m).

Though the model represents approximately the range of materials present at Fenns & Whixall Moss, it has not been calibrated for application to specific sites along the Manor Drain. This further refinement would require additional fieldwork, especially the determination of hydraulic properties, more detailed stratigraphy and water level measurements, and might require the extension of the model to three dimensions.

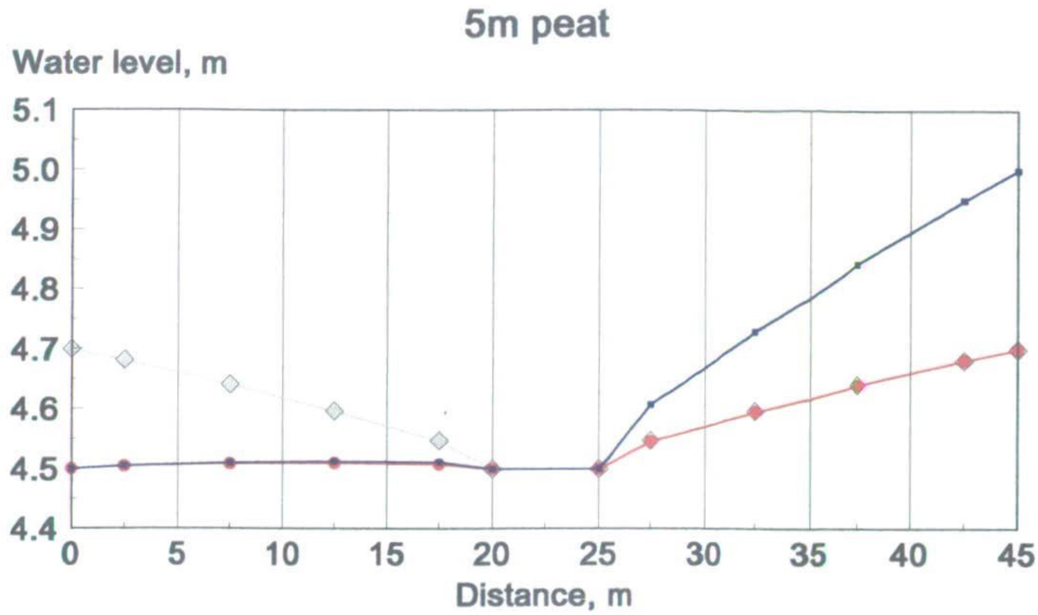

Figure 7 *A 5 m wide ditch draws down the water table in surrounding land. Here the peat is 5 m thick and the ditch is 1.5 m deep. The effects of lowering the water table on the left (red line) or raising it on the right (blue line) are not perceptible on the other side of the ditch.*

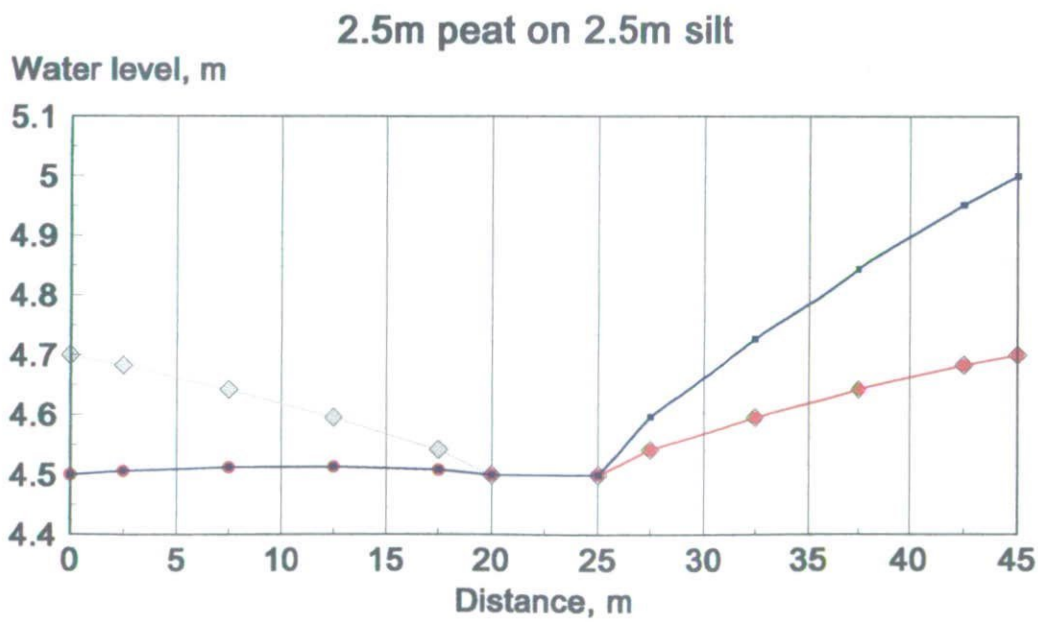

Figure 8 *A reduced thickness of peat lies on a less permeable silty substrate. Here there remains 1 m of peat below the bottom of the ditch. The ditch acts as a barrier, preventing the effects of drainage or wetting-up from propagating.*

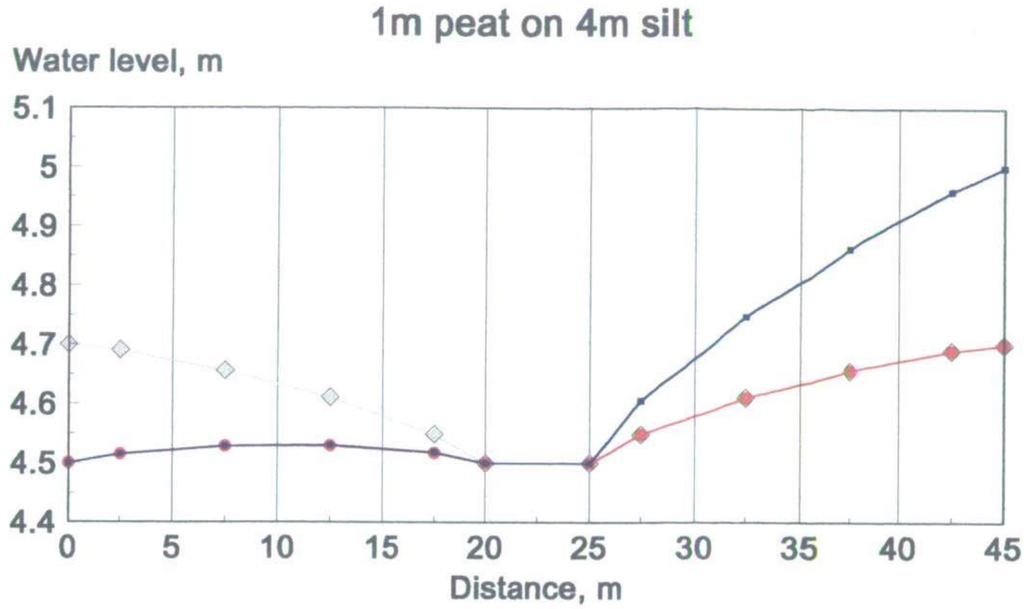

Figure 9 *1 m of peat resting on 4 m of silt produces an almost identical picture. The two peat bodies are now separated by the ditch, which penetrates 0.5 m into the silt.*

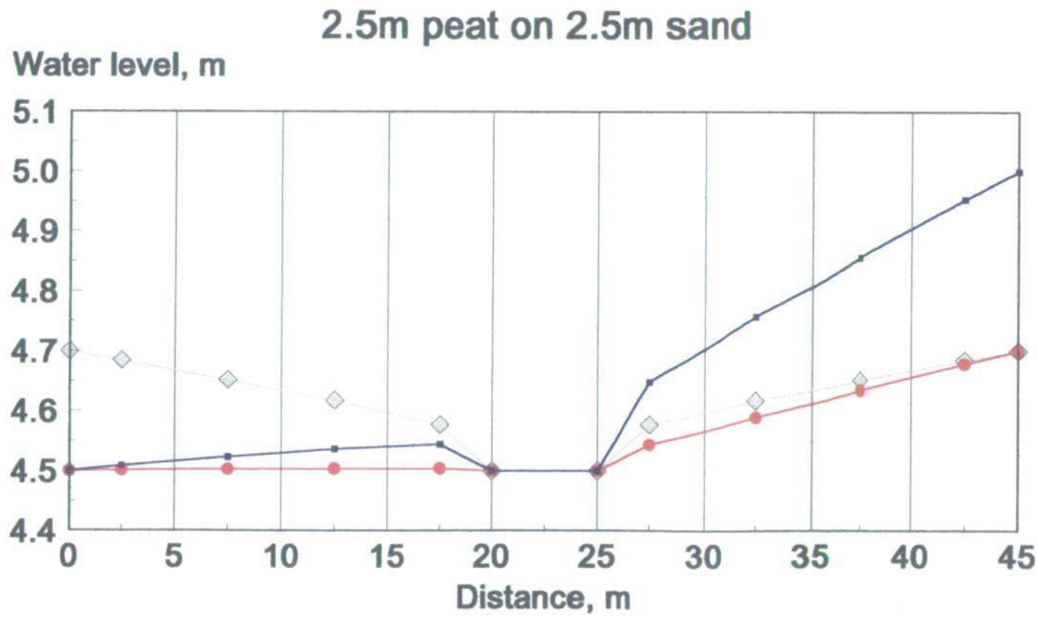

Figure 10 *A 2.5 m layer of sand underlying the peat provides a conduit for groundwater movement, leading to a generally flatter water table, steepening towards the ditch. Infiltration, which provided the curvature of the water table, is now a much less significant component of the groundwater flow, but vertical flow, caused by the geometry of the peat/sand system forms part of a flow system bypassing the ditch. Drainage to the left now causes a detectable (about 30 mm) lowering of the water table on the other side of the ditch, and there is a slightly larger "upwelling" effect (36 mm) on drained land to the left when the water table to the right is raised.*

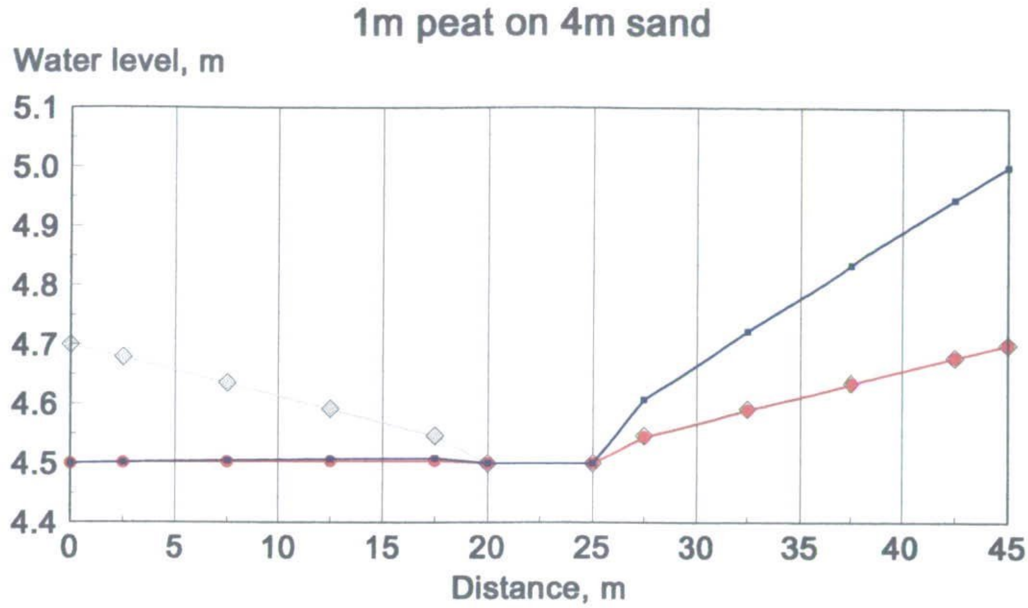

***Figure 11** A thicker sand layer, intercepted by the ditch, almost eliminates the upwelling effect, and the ditch acts as a barrier, in the same way as in deep peat. The two peat bodies are now separated by the ditch.*

The model confirms that a ditch in peat overlying a sand layer can be ineffective as a boundary, as the sand provides a conduit which is essentially independent of the ditch. The flow of groundwater in this case is horizontal (from right to left) through the sand layer, and then upwards into the peat. The very slight groundwater mound created by the combination of this upward flow and infiltration from the surface is then dissipated by divergent lateral flows towards the left-hand boundary and towards the drain. However, this applies only if there is peat or a less permeable material (e.g. silt) below the ditch base and above the sand. A ditch penetrating into the sand does act as a barrier, as does a ditch in deep peat, but it must be emphasised that the ditch acts only as a barrier to the propagation of raised (or lowered) water levels, and not necessarily as a barrier to flow, which can take place freely across the ditch as long as there is a hydraulic gradient. Where the ditch intercepts a permeable medium such as coarse sand or gravel, groundwater flow through the gravel will be cut off by the ditch.

For the drain to be effective as a boundary, two conditions are necessary:

1) there must be water in the ditch - a dry ditch lies in the unsaturated zone above the water table, and exercises no control over saturated groundwater flow. For example the lowered water table consequent on drainage on one side of a dry ditch will have the effect of lowering the water table on the other side, and this effect will not be moderated by the presence of the ditch, or by any other works, for instance the insertion of impermeable membranes, carried out above the water table. In extreme cases a ditch containing standing water could be dewatered by nearby drainage, and it may be necessary to arrange a supply of water to maintain ditch water levels.

2) the water level in the ditch must be controlled - if the ditch water level rises in response to the wetting-up of land on one side, the rise in the water table will be propagated to land across the ditch, and *vice versa*. Control of water level in the ditch involves the maintenance

of a sill (for instance the culvert invert or a stoplog, sluice or weir) that will limit flow in the ditch at low levels but allow free flow at higher levels, and the provision of a supply of water in excess (see above) to compensate for losses from the ditch.

CONCLUSIONS AND RECOMMENDATIONS

The four questions posed at the start of this report can be answered more or less simply by drawing on the results of the peat survey and the modelling work:

1) deep peat is quite localised, and hydraulic continuity through the peat below the Drain is confined to one small area near the junction of the Drain with Nook Lane. Along most of its length, the bed of the ditch is silty or sandy.

2) though a lowering of Drain water levels would not result in an instantaneous lowering of the water table in mire communities on either side, there would be dewatering of pools and hollows and a tendency towards peat wastage that could drain a gradually widening strip of land on each side of the Drain, in the long term leading to increased scrub growth and a more heathy community. The water table is only partly controlled by Drain water levels, as the supply of upslope water from excess rainfall also maintains wet conditions, so it is not easy to go on to predict the impact of a change in Drain water levels on the mire community. Within the area drained by the proposed scheme, upslope water would be intercepted by a cutoff drain, so the ultimate control on water levels would be the point at which the new drains entered the Manor Drain.

3) the current drainage proposal appears to consist of underdrainage, supported by a cutoff drain, with a main drain parallel to, and set back by between 20 and 40 m from, the existing open drain. There are no laterals or underdrains in the narrow strip between the new main drain and the Manor Drain. This strip is flatter, and would be less likely to repay drainage investment unless the Manor Drain itself were lowered. There is no indication in the proposal documents seen that the Manor Drain would be improved, and it is concluded that the drainage scheme as presented would pose little threat to the land across the Drain. Model results suggest that drainage effects propagating across the Drain would be small, and, in view of natural seasonal and short-term fluctuations in the water table, would probably not be measurable on the ground. The area most susceptible to the propagation of drainage effects across the Drain would be towards the southern end of the scheme, where the lowering of the water table within the Nursery area would be small (being limited by the fall towards the Manor Drain). Further northward, around peat survey stations 54, 53 and 52, the mineral soil contains a significant clay fraction, and the ditch would act as a barrier.

4) there is no reason to expect that drainage effects would propagate across the Drain, to an extent that would damage the conservation interest of the land to the southeast. Nor is the water level in the Drain likely to change as a result of the proposed drainage scheme. However, mire communities are subject to changes ranging from the effects of long-term drainage and other abuses to those of natural succession, and the impact of possible global climate change is now superposed. It is not unlikely that the mire community is changing, and it is almost certain that is has changed substantially in the past, as a consequence of peat extraction and the building of the railway. It is therefore virtually impossible to point to case studies that could be applied to the situation of Fenns and Whixall Moss to predict the long-term effects of additional dewatering brought about by the sort of peripheral drainage that is proposed here and elsewhere along the peripheries of the Moss. A simpler and more effective form of monitoring would be the measurement of water table levels in this area, before and after drainage works. A programme of water level measurement might be able to

detect incipient changes where a more involved and time-consuming programme of quadrat survey would not.

Though it is likely that the drainage scheme as proposed in outline would not have much effect on the land on the mire side of the ditch, there is a real possibility that the scheme would bring with it, either at installation or in operation, pressure for improvement of the Manor Drain downstream of the scheme, possibly downstream of the railway culvert. The invert of the culvert is an essential control on water levels in the Manor Drain, and is a key factor in the "barrier" function of the Drain. Substantial lowering of Drain levels would have an effect on land on both sides of the Drain, and could also pave the way for more intensive drainage to improve marginal agricultural land. There is a case to be made for the negotiation of acceptable profiles for all the ditches in the area, based on certain clearly identifiable control points like the railway culvert, so that future land use along the periphery of this important wetland site can be planned against a stable hydrological background.

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