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Report to River and Coastal Engineering Group, Ministry of Agriculture, Fisheries and Food

WATER REGIME OF RIVER MEADOW HABITATS

by

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Executive summary

1. The results are presented of an investigation of the water regime in two meadows adjacent to the River Thames in Oxfordshire, at Yarnton and Howbery. The focus is quantification of water fluxes through the groundwater/soil/plant system.

2. Areal actual evaporation measurements were conducted using a Hydra (an eddy correlation system) at Yarnton in 1991, and at Howbery in 1992. These formed the first such full-scale field measurements in the UK. Soil water content and soil water potential were also monitored. Botanical survey showed that the Yarnton sward contained more species characteristic of damp soil conditions than at Howbery.

3. At Yarnton, at times when the soil profile was not draining, an upward potential gradient persisted in the unsaturated zone, demonstrating that upward flow from the groundwater could occur. At Howbery, where the water table is deeper, this situation only developed at one site on the floodplain transect, and not until late May. At other times a downward potential gradient (draining) was present in the lower part of the unsaturated zone of the Howbery soil profiles.

4. When soil conditions permitted, the Howbery soil physics data were used to obtain point measurements of actual evaporation. The agreement between these and the Hydra measurement of actual evaporation rates was very good; this is the first time such a comparison has been achieved on a seasonal timescale.

5. Rates of influx of water to the unsaturated zone from the groundwater were estimated using the Hydra data with the measurements of rainfall and soil water content change in a straightforward water balance. During spring 1991 at Yarnton there was little net removal of water from the soil profile, the plant water requirement being met largely by rainfall and groundwater use; they contributed 47% and 36% of the actual evaporation loss respectively. In the wet summer of 1992 at the one Howbery site where an influx occurred (the shallowest groundwater site), the influx was equivalent to less than 4% of the actual evaporation loss.

6. The actual evaporation measurements at both meadows showed that the potential evaporation estimate by the conventional Penman technique using site automatic weather station data was too high in the spring even though soil water was non-limiting. This unexpected result has wider implications than this study had time to explore. A temperature dependent model was used, with partial success, to predict spring time actual evaporation rates from the potential evaporation estimate.

Contents

1 Introduction

The need to assess the probable environmental impact of modifications to local groundwater levels associated with drainage and/or flood protection measures, and to implement appropriate management practices, is a recurring problem for the river engineer, hence the sponsorship of this research by the Ministry of Agriculture, Fisheries and Food (Flood Defence Division). The potential effect of such schemes is often upon wetland areas of the flood plain which may be of important nature conservation interest. It is recognised that understanding of the basic hydrologic processes associated with the wide variety of wetland types is inadequate and a hindrance to effective management (Winter and Llamas, 1993). Furthermore, there is a lack of quantitative information concerning the tolerance of wetland communities to change in groundwater conditions (Spoor *et al.* 1990).

The study of plant water use in wetlands is central to understanding these habitats from two perspectives:

- determining the water requirements of given species and communities, and
- quantifying groundwater discharge through plant uptake.

Measuring plant water use in wetland situations is difficult. Where there is no standing water, continuous monitoring of bulk evaporation rates is possible with the Hydra, an instrument developed at the Institute of Hydrology. The Hydra employs the eddy correlation method to provide direct measurements of evaporation (Shuttleworth *et al.*, 1988). This project was the first in which the Hydra had been used for evaporation measurement over lowland meadows for periods of several months.

This report brings together the results of soil physics and Hydra measurements of the water regime in two meadows adjacent to the river Thames near Oxford. The focus is the quantification of water fluxes through the groundwater/soil/plant system. Point measurements of evaporation determined using a soil physics approach have been compared with the areal Hydra measurements where the two could be determined independantly of one another. The Hydra evaporation measurements have been used in soil water balances to derive rates of water influx to the unsaturated zone from the groundwater. A temperature dependant model has been used to derive actual evaporation rates from potential evaporation rates in spring when soil water is non-limiting.

In 1991 field work was conducted at Yarnton Mead, an ancient hay meadow located 6 km to the north west of Oxford city. The Mead has been designated by English Nature, with the adjacent Pixey Mead, as a Site of Special Scientific Interest because of its flora, fauna and long documented management history of a hay cut and aftermath grazing. Monitoring there in spring 1991 was the final phase of a programme described in the Yarnton Mead Case Study Report (Gardner, 1991).

In 1992 the monitoring equipment was moved to a drier meadow known as Howbery, located adjacent to the Institute of Hydrology grounds at Wallingford. Howbery meadow has been used as permanent pasture, and occasionally for a hay cut, since shortly after World War II during which it was cultivated. During the 1992 study it was grazed by cattle through the spring and then a hay cut was taken in August. Four soil water measurement sites were established which permitted assessment of spatial variability of plant water use and of the manner in which the Hydra areal measurements represented this.

2 Measurement sites

2.1 SEDIMENTS AND SOILS

The Thames today flows across a broad valley infilled with Pleistocene fluvial sands and gravels upon which finer deposits from the hill sides and river alluvium have been deposited. At Yarnton the gravels are 3 to 6 m thick and overlie the Oxford clay. They are covered by recent clayey alluvium, of 0.5 to 2 m or greater depth, which forms the present flood plain surface. The meadow often floods in winter. In summer the water table falls to between 0.7 m and more than 1 m below the flood plain surface. Pelo-vertic-alluvial gley soils have developed in the alluvium at the western end of the Mead; two series are present distinguished by the depth of alluvium above the gravel. Where the alluvium boundary is greater than 0.8 m depth, the soils are classified as Fladbury series; where the alluvium depth is shallower the soils are Carswell series (Gardner, 1991). Two soil water monitoring sites were installed to represent the soil types: site 253 in the deeper alluvium, and site 553 where the alluvium was shallow.

The Howbery meadow (Fig. 1) extends eastward from the Thames across the present flood plain surface and a terrace approximately 1.5 m higher. A layer about 4.5 m thick of calcareous gravels and sands with lenses of finer sediment, overlies the Upper Greensand. Over most of the meadow these gravels are covered by 0.7 to 1.5 m of clay loam textured material but in places remnants of alluvium occur below this deposit. Alongside the river there is a zone about 100 m wide where the soils are developed directly in clay loam textured alluvium, 1 to 1.6 m deep. The water table here is directly influenced by the river level which is controlled. The water table depth fluctuates about 1.4 m below ground level, rising in winter so that occasionally this part of the meadow floods. The water table is deeper below the terrace surface, fluctuating between 1.5 and 2.5 m below ground level.

The soils across the Howbery meadow are lighter in texture than those at Yarnton, and drain freely to the deeper water table. They have been mapped as typic-argillic brown earths of the Sutton 2 association (Soil Survey of England and Wales, 1983). Four soil water measurement sites were installed along an east-west transect across the meadow to the river. One site (1) was located on the terrace, one (4) on the flood plain close to the river and two on the gentle slope between the terrace and the flood plain (2 and 3, Fig. 1).

2.2 VEGETATION

Botanical surveys of the areas around the monitoring equipment at both meadows have been conducted by Dr. A.W.McDonald, who also classified the vegetation. Details are given in the Annex.

The vegetation of the meadows reflects their contrasting management and soils. At Yarnton the species-rich and rather heterogeneous sward of grasses and herbs with occasional Carex species (sedges) comes into the *Alopecurus pratensis-Sanguisorba officinalis* flood-meadow grassland community of the National Vegetation Classification, NVC (Rodwell, 1993). There is a difference in species abundance in the vegetation immediately around the two soil water monitoring sites, 23 m^{-2} at site 253 (deep alluvium) compared with 29 m^{-2} at site 553 (shallow alluvium) but most species recorded at 253 also occur at 553. At both sites the water values of the species, as defined by Ellenberg (1988) range from 3 (dry site indicator) to 8 (between damp, 7, and wet site indicator, 9) but more species with water values of 3 and 4 occur at 553 while three damp site indicator species were recorded at greater frequencies at 253.

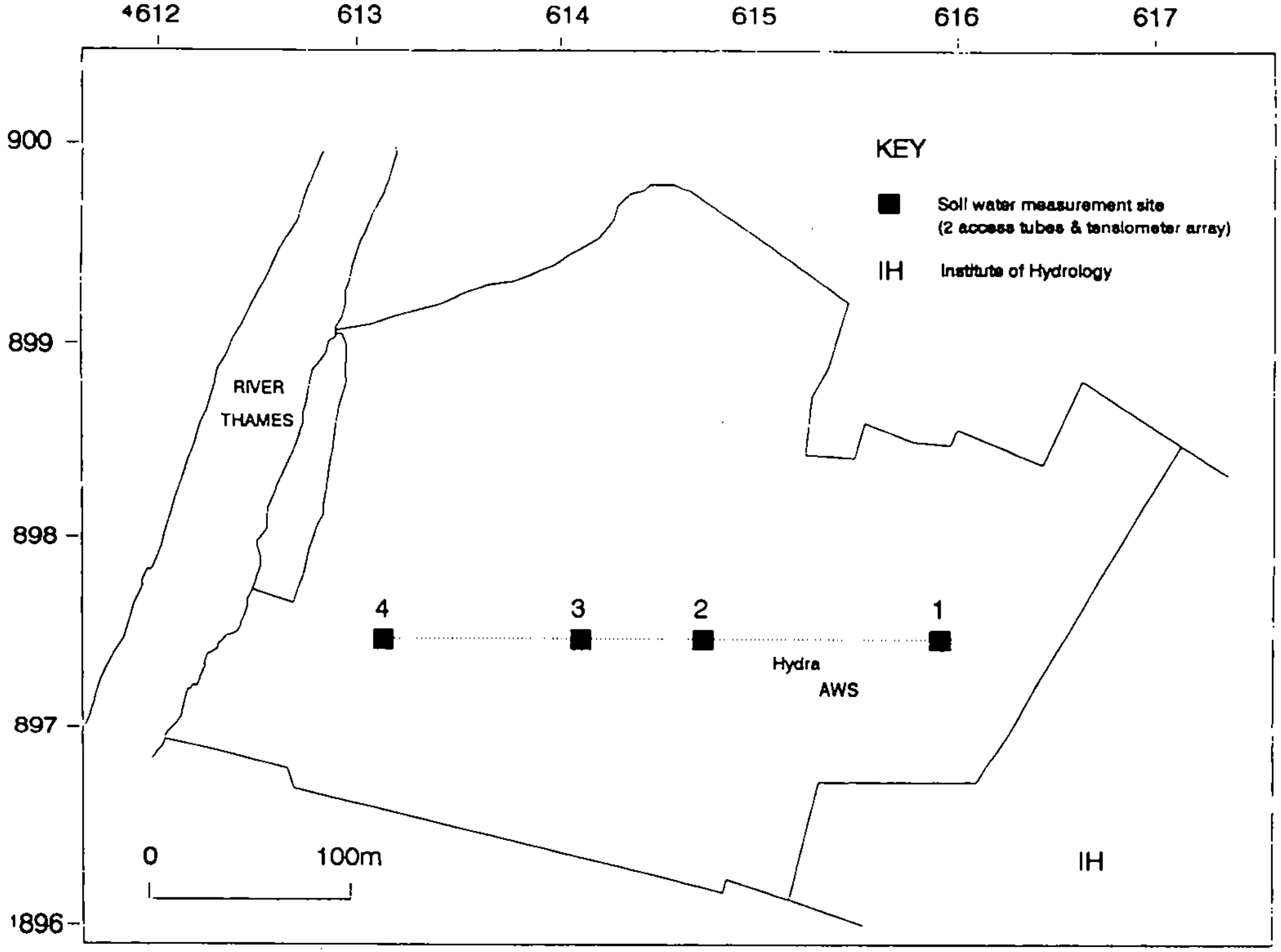

Figure 1 *Location of the field measurement sites.*

Eighty-two different species in total were recorded at Yarnton compared with 32 at Howbery. The average species abundance at the four Howbery soil water monitoring sites was only 15 m^{-2} and all, including the site adjacent to the river, were similar. The water values of the species recorded ranged from 3 to 7 but species with values less than 7 accounted for 90% of those for which water values were available, compared with 79% for the area around the Yarnton sites, and 65% for the western end of the Mead as a whole. The vegetation was classified as an *Alopecurus pratensis* variant of the *Lolium perenne-Cynosaurus cristatus* grassland community of the NVC.

In 1992, the development of the crop canopy and extent of its transpiring surfaces was recorded by taking field samples of the foliage to determine the leaf area index (LAI). 0.25 x 0.25 m quadrats were used to collect 25 samples at intervals along the transect between sites 1 and 4, as described in Gardner (1991). Results are detailed later in Table 4.

3 Measurement methods

3.1 ACTUAL EVAPORATION

Hydras were used to measure bulk actual evaporation from the meadow vegetation from 28 March to 4 June 1991 at Yarnton, and 11 March to 31 August 1992 at Howbery. A Hydra is an eddy-correlation system which provides measurements of actual evaporation from the area upwind of the instrument. The instrument's response is dominated by the evaporation from vegetation closer to it but extends to 200 m or more upwind according to the height and character of the vegetation (Gash, 1986). The direction of the prevailing wind at both meadows is from the south west.

There are three components to the Hydra measurement: transpiration, evaporation of intercepted water and dew from the vegetation, and evaporation of water directly from the soil surface. In conditions of continuous vegetation cover, as at the field sites studied, there is little evaporation directly from the soil surface and it may be ignored. Therefore, during dry weather the Hydra measurement from these sites represents transpiration. The Hydra cannot operate when the sensors, in particular the infra-red hygrometer, are wet, i.e. during or immediately after rainfall, and therefore the interception component of the evaporation measurement is restricted to evaporation of water that persists on the canopy after the sensors have dried. The instrument provides hourly totals of evaporation which for the purpose of this investigation were accumulated to daily values. Where short gaps in the hourly data arose because the sensors were wet it is reasonable to interpolate the hourly data to obtain a daily total for actual evaporation. Depending on the degree of wetting of the canopy before and after the "gap", the interpolated hourly evaporation rate will be closer to the rate of water loss from the wet canopy, or to the transpiration rate. Evaporation during dewy mornings was assumed to be zero because the negative evaporation flux as the dew condenses counterbalances the enhanced flux as it evaporates and so does not affect the daily cumulative total. When the dew was persistent, or there was more than a trace of rainfall, the day's data were excluded from the analysis of the transpiration response of the vegetation. However, to enable water balances to be calculated, it was necessary to interpolate the available daily data to provide a dataset of daily values (see Section 4.2).

3.2 METEOROLOGICAL

An automatic weather station (AWS) recorded rainfall, temperature, humidity, wind speed and direction, and radiation (Strangeways, 1972) over those periods when the actual evaporation monitoring equipment, the Hydras, were operational in each meadow. The weather stations were located adjacent to the Hydras in each case. These data were used to calculate daily Penman potential evaporation. A tipping bucket rain gauge at Yarnton, and a gauge at the Institute of Hydrology, adjacent to Howbery meadow, provided rainfall data at other times.

Permission to install ground level rain gauges in the meadows could not be granted. The gauges used were set conventionally on the ground surface. The mean undercatch of similar gauges at the Institute of Hydrology is 6.4%, varying with windspeed. The undercatch of the meadow gauges was expected to be of the same order.

3.3 SOIL WATER

Figure 1 shows the layout of the equipment installed in the two meadows at Yarnton and Howbery, and Table 1 gives details of the equipment at each of the soil water monitoring sites. Arrays of manually read mercury manometer tensiometers were used to monitor soil water potential (Mullins, 1990). The tensiometer measurements indicate the potential gradients within the profiles which govern water movement through the soils. Determining the direction of water movement in the profile is essential to permit distinction of water content changes due to plant uptake from those due to drainage.

Soil water content was measured by neutron probe (Bell, 1987), two access tubes being installed at each monitoring site. Groundwater level was recorded along the transect of dip wells at Yarnton, and determined from the tensiometer data at Howbery.

Table 1 *Details of soil water measurements*

		Soil water potential Tensiometers		**Soil water content Neutron probe**	
	Tube/array	**Depth interval m**	**Max depth m**	**Depth interval m**	**Max depth m**
Yarnton					
253	1	0.1	1,0	0.1	1.1
	2	0.1	0.9	0.1	1.5
553	1	0.1 to 1 m then 0.2	1.2	0.1	1.4
	2			0.1	1.2
Howbery					
1		0.1 to 0.4 m then 0.2	2.6	0.1 to 1 m then to 0.2	2.9
	2		2.0	•	2.9
2	1	•	2.0	•	2.9
	2				2.0
3	1	•	1.6	•	3.0
	2			•	2.9
4	1	•	1.4	•	2.5
	2			•	1.9

4 Water balance calculations

Water balances for the sites were calculated using two methods. The Zero Flux Plane method (Cooper *et al.* 1991) was used when possible, i.e. when a zero flux plane (ZFP) was present, to provide point estimates of evaporation independent of the Hydra measurement. At other times, the Hydra measurements of actual evaporation were included in the water balance.

4.1 ZERO FLUX PLANE METHOD

A ZFP is a horizontal plane in the soil profile across which there is no water movement (Wellings and Bell, 1987). Above the ZFP the potential gradient is upward inducing water movement towards the soil surface. Below the ZFP the direction of the potential gradient is downward and so any water flux will be towards the base of the profile. The ZFP method requires rainfall and soil water content data, and the depth of the ZFP must be known. All water content changes below the ZFP are assigned to drainage fluxes, and changes above the ZFP are used in a straight forward water balance with the rainfall to derive evaporation fluxes. At times when no ZFP is present, it is assumed that soil water is non-limiting and so potential evaporation rates apply.

4.2 HYDRA METHOD

This required rainfall, Hydra and soil water content data. All the available Hydra data were used, i.e. data collected on days when the instrument only operated part of the time were included, the data having been adjusted to provide a daily total as described in Section 3.1. To obtain data for days when the Hydra was inoperative, first the daily actual to potential evaporation ratios were interpolated to give daily values over the period concerned. Then these values were used to calculate actual evaporation estimates from the daily potential evaporation data obtained from the AWS.

The calculation procedure is described in Gardner (1991). It provides a drainage estimate which represents vertical fluxes between the saturated part of the shallow aquifer, and the unsaturated zone above. The extent of the saturated part of the aquifer, and conversely of the unsaturated zone, change with time as the water table fluctuates and the calculation method allows for this. The drainage flux is therefore a measure of recharge to, and discharge from, the saturated part of the aquifer, by vertical movement through the unsaturated zone. As the principal interest here is in the extent to which the groundwater supplies water for plant use, i.e. when negative drainage is calculated in the water balance, the negative drainage has been made a positive value and termed influx in the following discussion. An alternative term would be groundwater discharge.

5 Results and discussion

5.1 HOWBERY, SPRING AND SUMMER 1992

The weather at Howbery during the measurement period (March to August 1992, Table 2) was cooler and wetter than during the monitoring at Yarnton in previous years which coincided with exceptionally dry weather (Gardner, 1991). Potential evaporation rates were consequently lower. For example, the mean daily potential evaporation estimate at Howbery, from April to August 1992 was 2.8 mm compared with 3.7 mm at Yarnton in 1989.

5.1.1 Soil Water Movement

The water regime of the Howbery sites contrasts with that at Yarnton due to the deeper water table and presence for much of the summer of a Zero Flux Plane (ZFP) in the unsaturated profile. Figure 2 shows the development of the ZFP at site 4 between 16 April when the whole profile was draining, and 27 April when the ZFP had fallen to 44 cm depth. Plant abstraction from the surface horizons resulted in progressively lower potentials towards the soil surface while drainage continued to the water table below. Over the same period the water table was also falling resulting in more negative potentials below the ZFP encouraging further drainage. Earlier in April, after rainfall, wetting fronts moved through the profile reaching and cancelling the ZFP which re-established in subsequent dry periods.

Table 2 *Monthly rainfall and potential evaporation at Howbery, spring 1992*

Month	Rainfall mm	PE mm
March (from 9th)	36.5	32.5
April	49	58.6
May	63.5	106.2
June	28	103.5
July	75.5	83.3
August	100.5	79.1

This pattern of ZFP development was observed at each of the measurement sites and as the spring progressed the ZFPs gained depth (Fig. 3). The ZFP persisted throughout the summer at sites 1, 2 and 3, but not at 4, nearest to the river.

Figure 2 illustrates the potential profile at site 4 three weeks later (21 May) than described above, by which time the ZFP had reached 86 cm depth. Plant uptake of water during the following 6 days caused the ZFP to fall further, intersecting the zone above the water table where potentials were in equilibrium with the water table position (the capillary fringe). The ZFP was thus cancelled. Thereafter the upward potential gradient above the water table indicated the possibility of water movement into the unsaturated zone and hence plant use of groundwater. The rate of water movement depends on the unsaturated hydraulic conductivity of the profile and the gradient of the soil water potentials. The amounts of water involved were quantified in the water balance calculations described in Section 5.1.4 below.

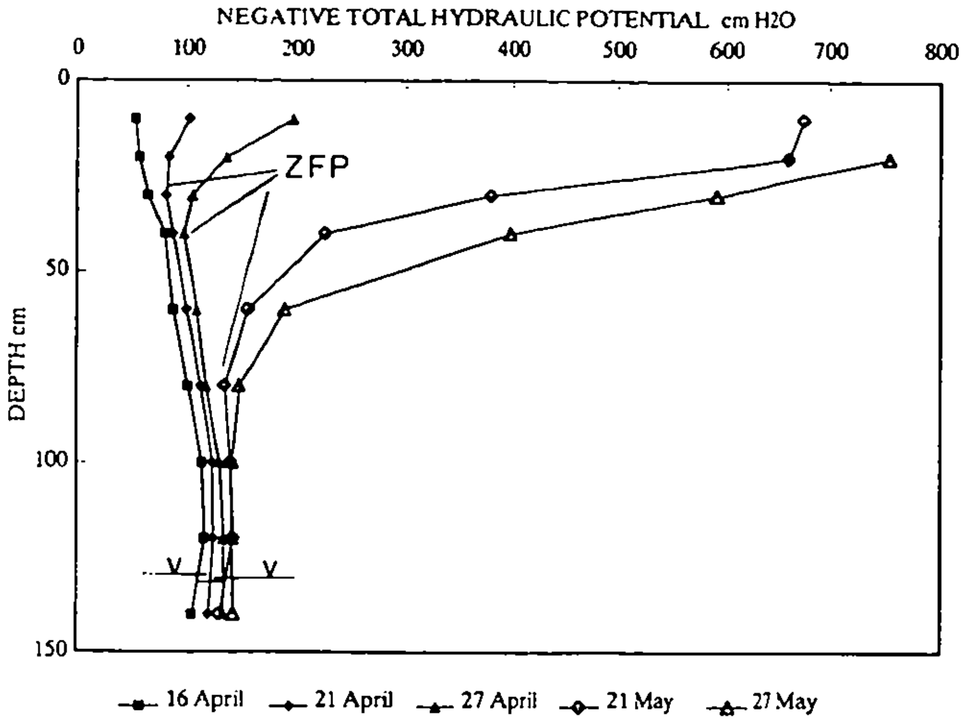

Figure 2 *Profiles of total hydraulic potential at site 4 (Howbery) showing the development of the ZFP in late April, and the intersecting of the ZFP with the equipotential zone above the water table in late May.*

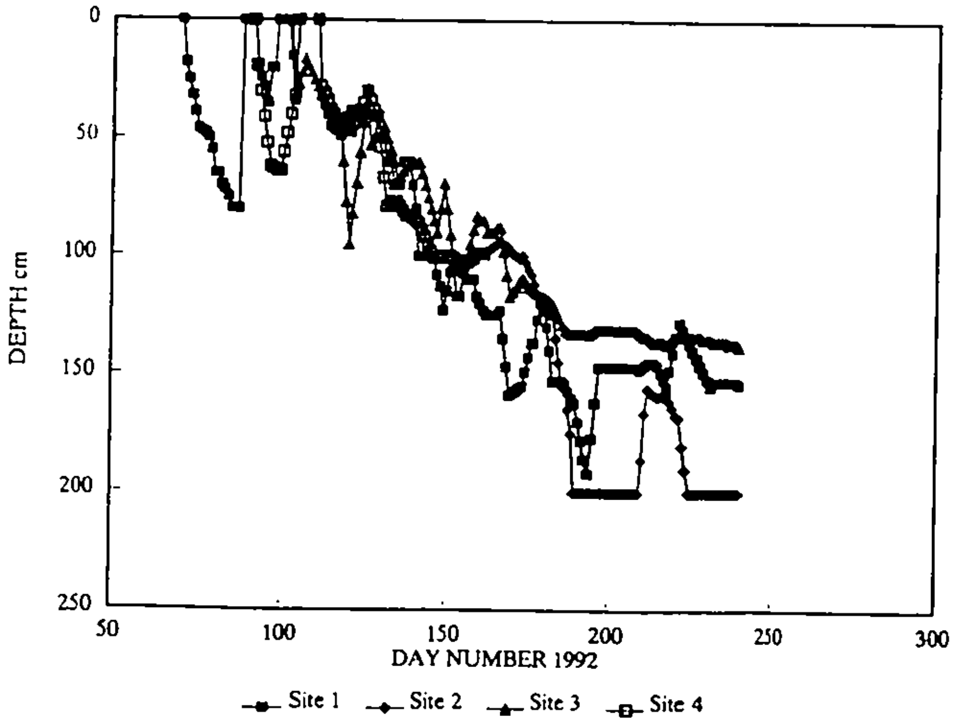

Figure 3 *Movements of the ZFP within the profile at the measurement sites.*

The upward gradient above the water table persisted at site 4 for the remainder of the measurement period. Wetting fronts due to rainfall, and shallow ZFPs occurred temporarily above the water table but were cancelled due to plant uptake. The development of the water potential profile at site 4 is characteristic of shallow water table locations (Gardner *et al.*, 1991). In a drier season it is possible that the ZFP may move deep enough to intersect the capillary fringe above the water table at the other Howbery sites.

5.1.2 Actual Evaporation Measurements

The Hydra actual evaporation measurements at Howbery in summer 1992 are shown in Fig. 4a and plotted as a ratio of the potential evaporation in Fig. 4b. Before considering the Hydra data in detail, they will be compared with the point measurements of actual evaporation from the soil water measurement sites determined using the ZFP method. In Fig. 5 the mean of the evaporation measurements determined for the pair of access tubes at each of sites 1 and 3 are plotted cumulatively with the Hydra data for the period 9 April to 27 August 1992. The data derived for site 2 are included in Fig.6 which represents the period 27 May to 27 August when site 2 was operational.

The differences in evaporation estimates between access tubes at individual sites were small (Table 3). The greatest difference was 26 mm at site 2; this developed over 92 days. The data post 27 May at site 4 cannot be considered for these purposes but prior to that, the evaporation determined for the site was similar to that at sites 1 and 3. Evaporation rates at site 3 were slightly higher than elsewhere and rates at site 1 tended to be lower (Figs. 5 and 6). However, the differences between sites are similar to those between access tubes at individual sites. They are insufficiently large to warrant distinguishing between the sites on the basis of spatial variability. Accordingly all the data have been grouped for comparison with the Hydra results without weighting factors to allow for distance from it.

Table 3 *Actual evaporation measurements at Howbery (Values in parentheses are results obtained if adjustment made for raingauge undercatch)*

Period	Sites	Total mm	Mean mm	s.d. mm	Hydra mm	% Hydra*
9 April to	1	305.1	323.3	14.7	337.7	4.3
27 August		319.5	(341.6)			(1.2)
	3	329.0				
		339.6				
9 April to	1	112.9	114.9	7.8	106.3	8.0
27 May		110.9	(118.9)			(11.9)
	3	123.5				
		125.4				
	4	106.2				
		110.2				
27 May to	1	208.6	213.4	16.2	231.4	7.8
27 August		192.2	(227.7)			(1.6)
	2	241.9				
		215.4				
	3	208.4				
		214.0				

* Difference between measurements (Hydra-soil mean) expressed as % of Hydra total

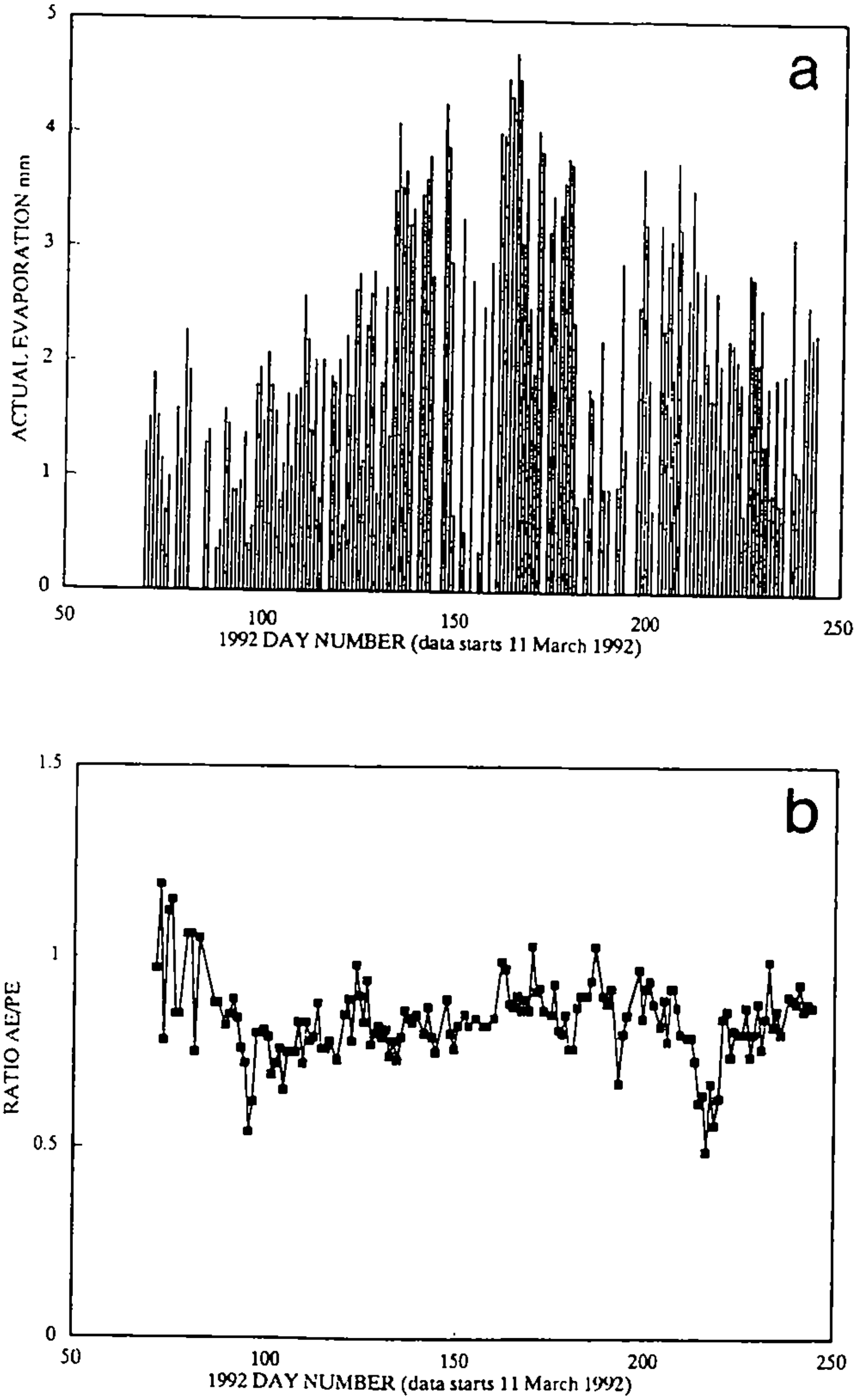

Figure 4 a. *Hydra measurements of evaporation at Howbery;*
b. *Hydra measurements as a ratio of Penman potential evaporation.*

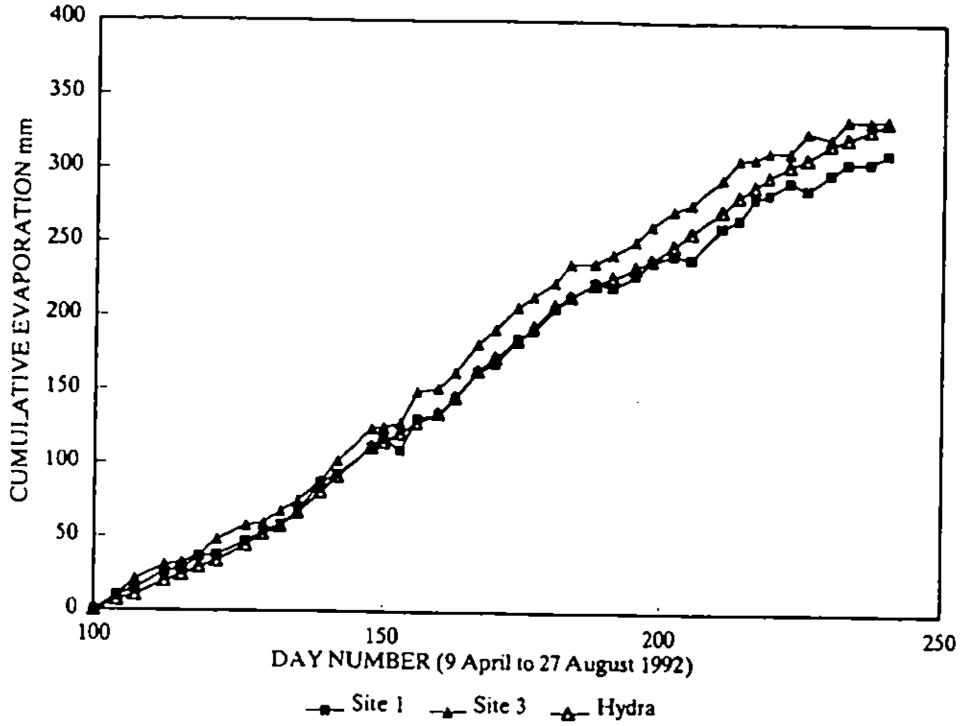

Figure 5 *Evaporation determined by the ZFP method for sites 1 and 3, and using the Hydra.*

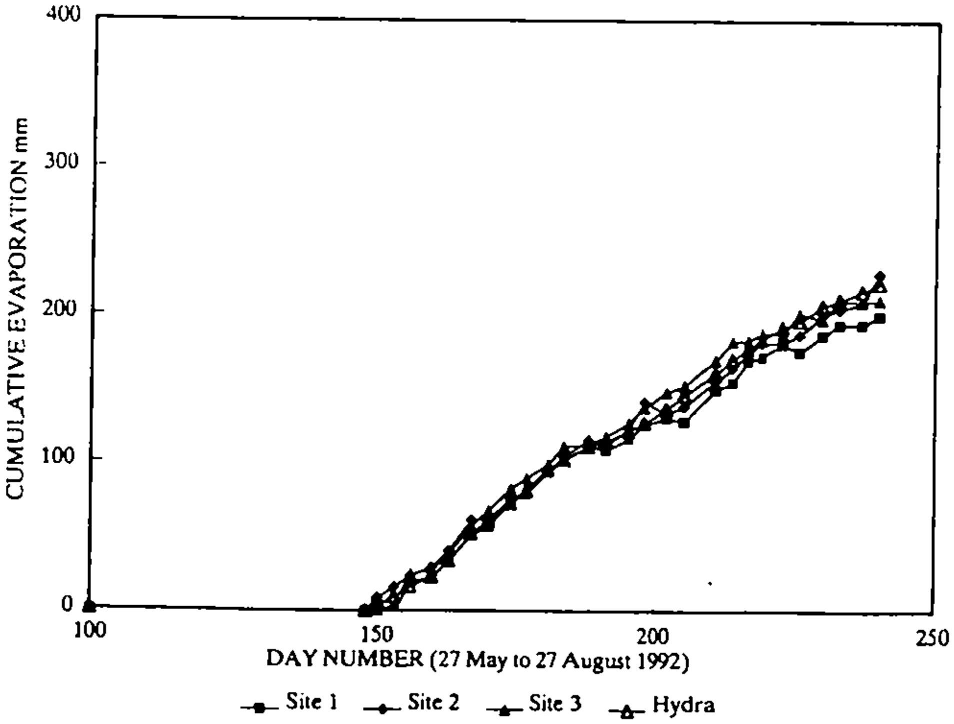

Figure 6 *Evaporation determined by the ZFP method for sites 1, 2 and 3, and using the Hydra.*

Depending on the time period considered, the Hydra results differ by plus or minus 8% from the soil physics determination of evaporation (Table 3), but fall within the range of the soil physics results. If the probable rainfall undercatch is allowed for in the ZFP evaporation estimation, by using a factor of 0.64 to increase the rainfall amounts, regardless of windspeed (Section 3.2), the similarity between the Hydra and soil physics results improves further (Table 3). Both methods of determining actual evaporation are subject to error, in the case of the Hydra these have been detailed above. In the case of the ZFP method, these include the errors associated with the neutron probe and tensiometer techniques, and the need to assume potential evaporation rates on the few occasions when no ZFP was present. Given these, and the small element of spatial variability in the soil data, the agreement between the two sets of results is very good. These findings confirm confidence in both methods for monitoring actual evaporation.

It was expected that the Hydra evaporation measurement could be lower than those from the ZFP method because of the need to interpolate the hourly data to cover periods when the sensors are wet. The ZFP method includes evaporation of intercepted water in the calculated evaporation. There is a lack of information in the literature concerning interception losses from grassland and it is not possible to judge how much water was intercepted by the vegetation at these sites; amounts will have varied from one event to the next. Campbell and Murray (1990) indicated that interception losses from grassland can be as high as 20% of the incident rainfall.

The similarity between the evaporation results from both methods suggest that the daily Hydra measurement includes evaporation of much of the intercepted water, and that the interpolation procedure used for those periods when the Hydra was not operating allows for the evaporation of intercepted water. This finding indicates that earlier concerns that water balances calculated using Hydra data may slightly overestimate groundwater recharge, due to under measurement of evaporation by the Hydra on rain days, (Gardner, 1991) were unwarranted.

5.1.3 Hydra results

Actual evaporation from a sward is driven by the atmospheric evaporative demand, i.e. the potential evaporation, but is limited by the growth activity of the crop, the degree of crop cover (measured here as leaf area index, LAI) and water availability to the crop. Under conditions of full crop cover, i.e. a LAI of about 3 or greater (Ritchie and Johnson, 1990), favourable weather conditions and with plentiful soil water, the actual evaporation rate is expected to equal the potential rate.

During the first 2½ weeks of the measurements (11 to 28 March), the actual to potential evaporation ratio (Fig. 4b) fluctuated considerably for no clear reason. Thereafter the ratio was much more consistent showing a fall to 0.5 in the first week of April, thereafter rising gradually to mid-June. Over the same period the LAI of the crop increased from 1.0 to 2.7 (Table 4). There was very little rain in the second half of June and the ratio showed a slight decline from about 0.9 to 0.75, but quickly recovered with the rainfall at the beginning of July. The ratio then fluctuated until mid July when during an almost dry three week period it steadily declined to 0.5. The hay cut was made on August 2. However, although the LAI of the crop post harvest was only 0.6 (Table 4), rainfall on and after August 8 caused an almost immediate recovery in the evaporation ratio to 0.8. This result contrasts with the evidence from Yarnton where in dry weather, the crop took some time to recover after the 1989 and 1990 hay cuts (Gardner,1991).

Table 4 Results of Leaf Area Index (LAI) measurements

Date		Number samples	LAI green material
9 April		25	1.00
19 May	Cattle removed from meadow		
2 June		25	2.69
7 July		25	3.67
3 August	Meadow mown		
14 August		10	0.60

The main trend in the data of a gradual increase in the actual to potential evaporation ratio until mid-June, through a fairly wet spring and early summer, suggest that lack of soil water only restricted evaporation rates temporarily and that other factors were influential. The assumption that soil water was not persistently limiting is supported by the fact that between April 1 and the end of June, when the evaporative demand (i.e. potential evaporation - rainfall) was 91 mm, the soil water content reduction in the top metre at each of the sites ranged from 66 to 90 mm, indicating that the soil could have supplied most of the vegetation's water requirements.

5.1.4 Water Balance at Site 4

The water balance results from the Howbery sites used above demonstrated the similarity of the water regime at the sites. The Hydra measurements were used to calculate a water balance for site 4 from 27 May (Fig. 7) when the water potential profiles demonstrated the possibility of influx of water to the unsaturated zone from the saturated zone. Over the three month period the net influx calculated for each tube was only 9.6 and 4.3 mm, 4% and 2% of the actual evaporation measured over the same period. Net drainage of 4.7 and 10 mm respectively is calculated if adjustment is made to allow for the possible rainfall undercatch. As Fig. 7 shows, over short periods the groundwater contribution was more significant but never of the order observed at the Yarnton sites (Gardner, 1991, and below). Comparison between the two meadows is difficult because of the different summer weather conditions experienced. The results indicate that due to the frequent rainfalls there was sufficient water in the unsaturated zone to supply the vegetation's water requirements. It is not possible to conclude whether the hydraulic conductivity of the unsaturated zone was great enough to permit an influx of water.

5.2 YARNTON, SPRING 1991

The spring of 1991 at Yarnton was wetter than in the two previous years which were exceptionally dry (Gardner, 1991). The water table only fell from 0.52 to 0.8 m b.g.l. during the Hydra monitoring period (26 March to 4 June), compared with 0.66 to 1.02 m over the corresponding period in 1990. Heavy rainfall at the end of April resulted in the water table rising to 0.36 m below ground level on April 30.

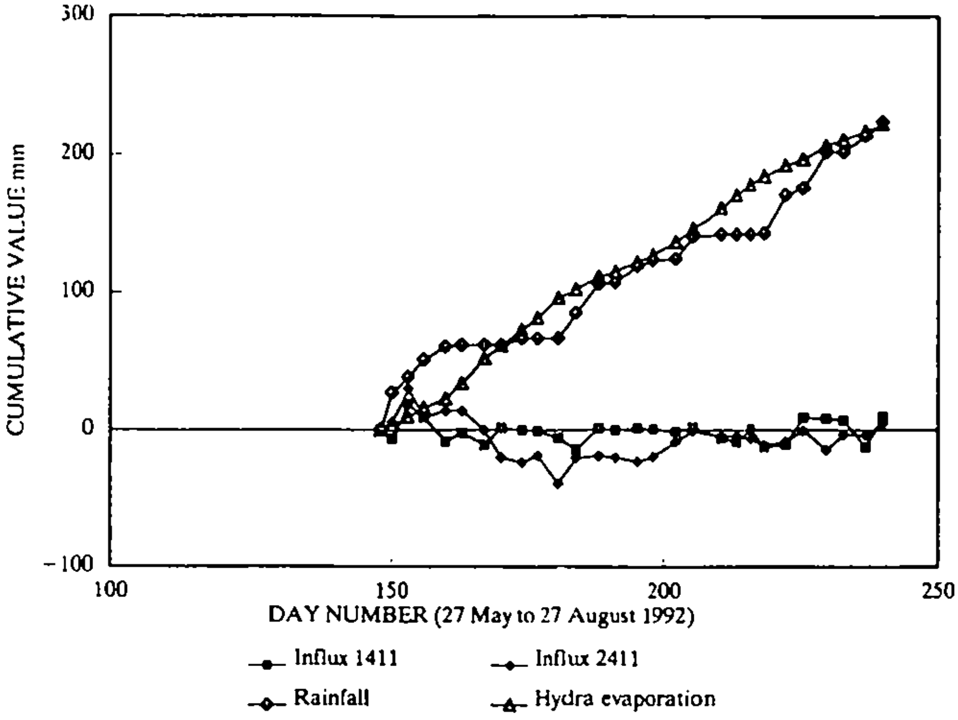

Figure 7 *Water balance estimates of groundwater influx for the pair of access tubes at site 4.*

5.2.1 Soil water movement

The soil water regime at the Yarnton sites has been described in detail for the period 1987 to 1990, in Gardner (1991). The behaviour of the profiles during spring 1991 conformed to the pattern observed in 1988 when the water table remained within 0.8 m of the ground surface throughout the spring and summer. At both the shallow and the deeper alluvium site, the presence of the water table dominates the movement of water in the unsaturated zone above it. In summer, when the soil profiles are not draining, plant abstraction causes an upward gradient of soil water potential to develop in the unsaturated zone producing upward movement of water from the water table. At neither site was the presence of a ZFP observed.

5.2.2 Actual evaporation

As in spring 1990 and as described above for Howbery, in spring 1991 at Yarnton, actual evaporation rates were less than the Penman potential rate (Fig. 8). The 1990 results from Yarnton suggested that LAI could be one important factor controlling evaporation rates in spring, and probably through the winter too, due to the relation between increasing leaf area, and the increasing ratio of actual to potential evaporation during the spring (Gardner, 1991). In 1991 there was not such a clear increase in the ratio although the vegetation developed from a very short sward to a hay crop as in 1990. However, there was a temperature contrast between the two years during spring, April 1990 being rather cooler than the next year but followed by a warmer May.

Wright and Harding (1993) evaluated temperature dependant models for deriving actual evaporation from potential rates in an upland situation where it was assumed that soil water was non-limiting through the spring and summer. The data from this study were used to assess whether the same approach would be applicable in a lowland situation in spring, when soil water is non-limiting. The models are readily applied because the only inputs are daily potential evaporation and air temperature.

Plant growth is related to air temperature. In the UK it is commonly assumed that the growing season commences in spring when temperatures exceed 5 or 6°C (Broad and Haugh, 1993) although grass and other crops can continue to produce leaves at temperatures near to freezing (Peacock, 1975). Hall (1987) suggested that transpiration behaves similarly to plant growth and is insignificant at temperatures below 5°C. Accordingly Wright and Harding assumed in their simplest model that transpiration was zero at temperatures below 5°C, increased linearly to the potential rate between 5 and 10°C, and equalled the potential rate at temperatures greater than 10°C.

$E = K(T)\ E_p$
where: E is daily evaporation
E_p is Penman potential evaporation
T is temperature (°C)
and: $K(T) = 0$ for $T < AA$
$= (T-AA)/(BB - AA)$ for $AA<T<BB$
$K(T) = 1$ for $T>BB$
AA and BB are lower and upper temperature thresholds respectively

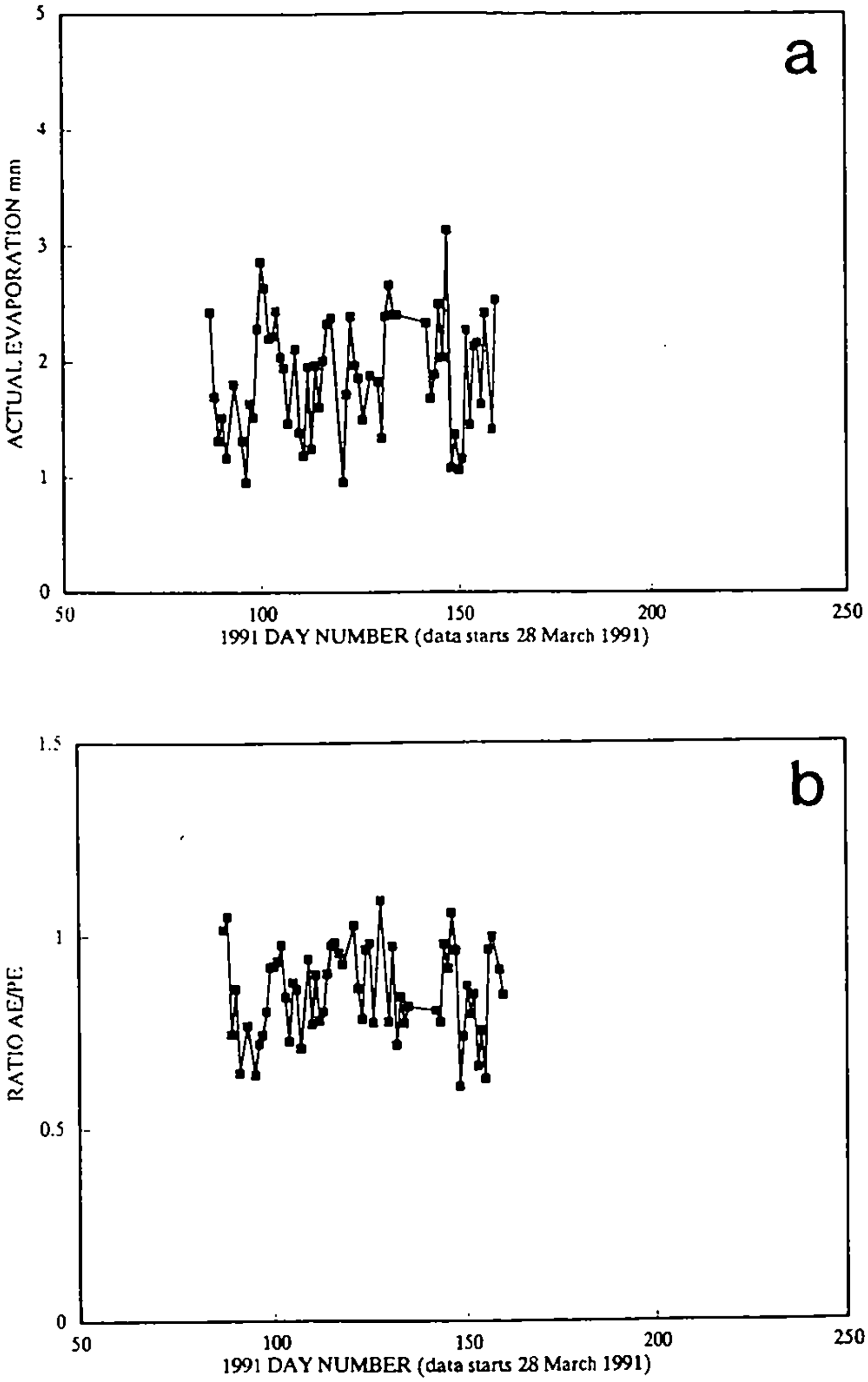

Figure 8 *a. Hydra measurements of evaporation at Yarnton;*
b. Hydra measurements plotted as a ratio of Penman potential evaporation.

They also tested the same model with the temperature parameters optimised and achieved a better model fit. Use of near surface air temperature rather than air temperature improved the simulation further. As Wright and Harding note, the temperature function in the models allows for the effect of the increasing leaf area of the crop as the spring progresses, for air temperatures usually rise through the season. It is not, therefore, clear whether the mechanism reducing the evaporation rate is via low leaf area, a direct temperature effect on transpiration or a combination of the two.

Surface temperature data were not available here, but the AWS air temperature measurement was used in the same models with the AWS potential evaporation measurement. The results were compared with the daily Hydra measurements for those days that no or minimal adjustment of the Hydra data were necessary, for the period up to 15 May. Two criteria were used to assess the model fit, the sum of squares of the daily model error and the difference between the measured and modelled cumulative evaporation expressed as a percentage of the measured total.

A poor simulation was obtained when the fixed 5 and 10°C temperature thresholds were used. This was principally because the Hydra recorded some transpiration on days when mean temperatures were below 5°C. A reasonable fit was achieved with all the data using the optimised temperature values of -8 and +11°C determined by Wright and Harding (Table 5).

Table 5 *Sums of squares of daily error and percentage error of cumulative total (observed -predicted) for model simulations*

Site/Year	**Wright/Harding** **AA= - 8, BB= 11**		**Optimised with Yarnton 1990** **AA= - 8, BB= 15**		**PE as % AE same period**
	SS	%	SS	%	%
Yarnton 1990	10.1	+14.2	6.5*	-0.01*	+27.3
Yarnton 1991	5.5	-2.1	18.5	-18.4	+17.4
Howbery 1992	10.5	+14.4	7.2	-1.1	+23.4

* model parameters optimised to fit dataset

However by optimising the temperature parameters a very good fit to the 1990 Yarnton data was obtained (Fig. 9); the optimized temperatures were -8°C and +15°C. The same model with the values obtained using the 1990 data was then applied to the 1991 Yarnton data, and the 1992 Howbery data (Fig. 10). The simulation was very satisfactory for the Howbery data but not for Yarnton 1991. The poorer performance can be attributed to the model reducing the evaporation rate too much in early May when low air temperatures occurred (between 6 and 10°C). Use of surface temperature may have produced more satisfactory results in these circumstances. However, the problem may reflect the absence of a leaf area factor in the model. The findings suggest that caution is required in using Wright and Harding's approach to obtain springtime actual evaporation measurements from Penman potential values for lowland wet grassland.

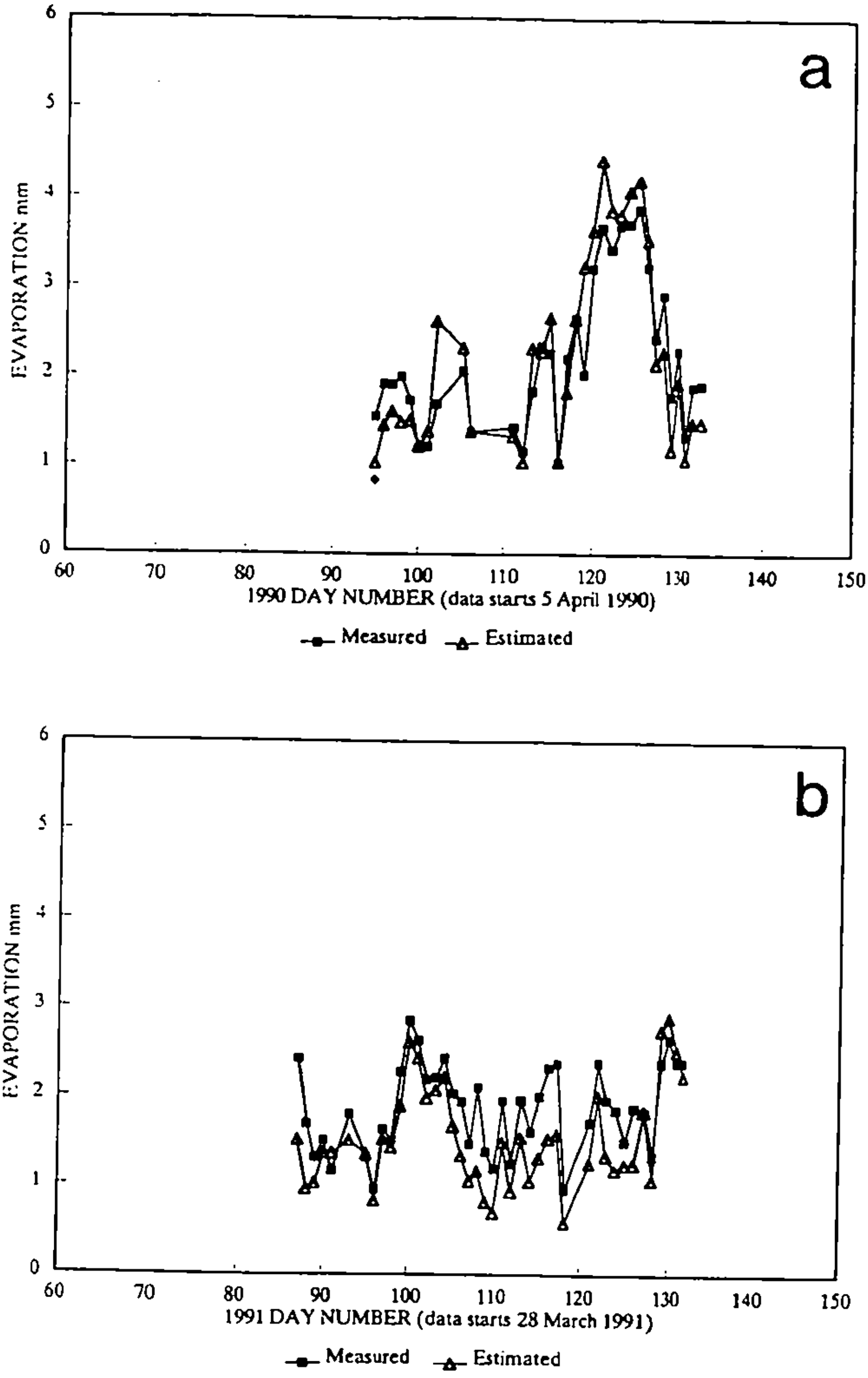

Figure 9 *a. Measured and estimated evaporation at Yarnton, spring 1990.*
b. Measured and estimated evaporation at Yarnton, spring 1991

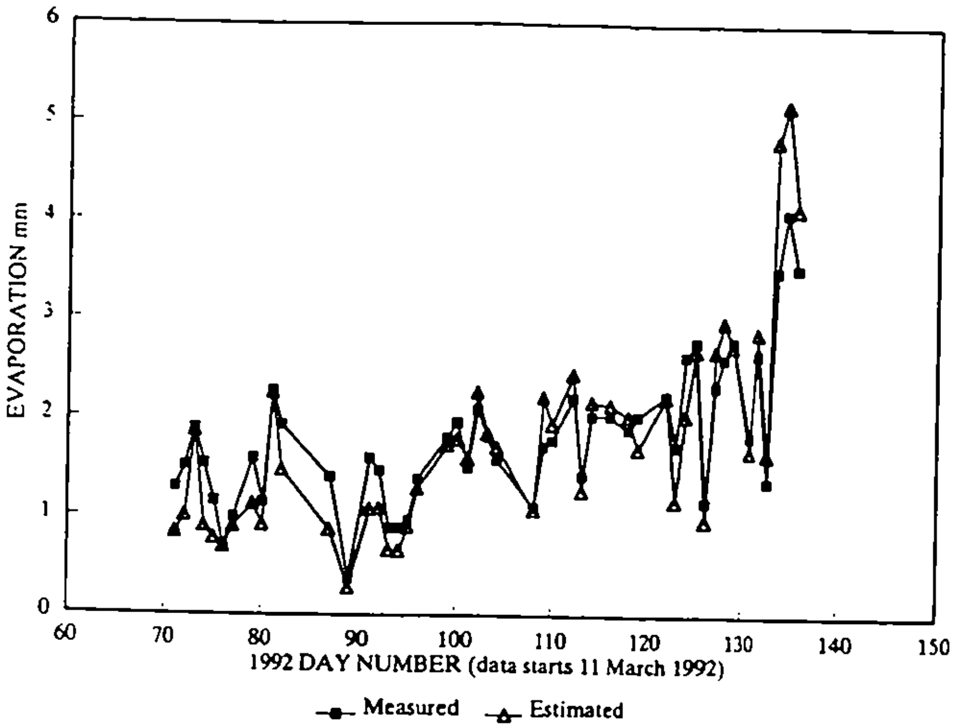

Figure 10 *Measured and estimated evaporation at Howbery, spring 1992.*

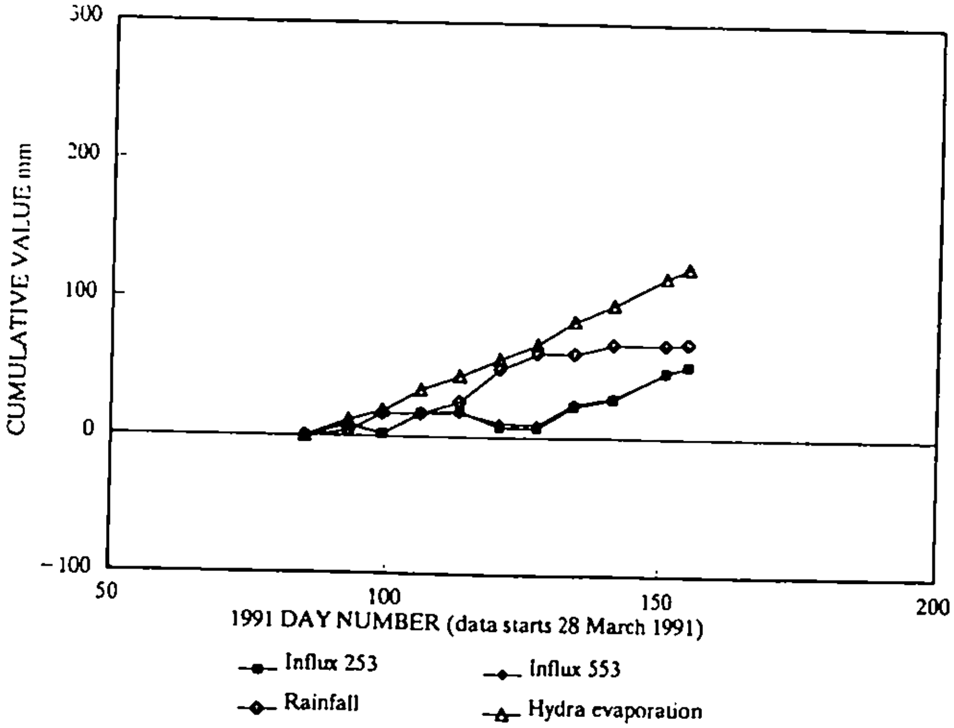

Figure 11 *Water balance estimates of evaporation for the deep and shallow alluvium sites at Yarnton (253 and 553 respectively) in spring 1991.*

5.2.3 Water Balances

The influx from the groundwater during the 1991 measurement period at Yarnton was almost identical at both the shallow and deep alluvium sites (Fig. 11). Most of the actual evaporation (144.6 mm) can be accounted for by the rainfall (68.5 mm) and influx (52 mm) inputs, and so the net removal of water from the unsaturated zone of the soil was very small. Plant abstraction will have removed water from the soil profile in the first instance but this was subsequently replaced by rainfall and upward movement from the groundwater.

Because the water table depth did not exceed 0.8 m, and the soils were temporarily almost re-saturated on 30 April, the effect on the water balance of drainage of the gravels below the shallow alluvium site, so clear in 1990, was not apparent.

6 Conclusions

The comparison of the Hydra measurement of evaporation from a meadow sward, with measurements by the ZFP method, has demonstrated the effectiveness of the Hydra for monitoring evaporation rates in the United Kingdom. The results demonstrate that the procedures used to interpolate the data to include periods when the instrument cannot operate due to rainfall do not cause serious error. The two methods are complementary, the ZFP approach permitting assessment of spatial variability.

This finding adds confidence to the estimates of plant use of groundwater derived using Hydra measurements and reported herein and for previous years at Yarnton (Gardner, 1991). The field work at Yarnton in 1991 demonstrated that when the groundwater remains shallow (< 0.8 m below ground level) in spring, most plant water use may be satisfied by rainfall and discharge from the groundwater. Under such conditions the difference between the shallow and deeper alluvium soils is insignificant. The measurements from the Howbery site have demonstrated that, although the groundwater level is relatively shallow there (within 3 m of the surface), in a wet summer there is negligible discharge from it through the unsaturated zone. This is so even where the water table remains within 1.4 m of the surface.

The Hydra evaporation measurements at both sites showed repeatedly that the Penman estimate of potential evaporation was too high between March and mid-May, or later. In each case the over-estimation could not be attributed to lack of soil water. The low LAI of the vegetation at the end of the winter, due to autumn grazing, is one factor in this, for the capacity of the crop to transpire will increase as crop growth proceeds. Another factor may be temperature. Use of a temperature dependant model to estimate spring evaporation rates from Penman estimates of potential evaporation was successful in two years, but less so where low temperatures persisted for several days late in the season.

The monitoring of early spring evaporation rates lower than the potential rate at different sites in different seasons suggests that this occurs more widely in lowland meadow situations. However caution should be exersized in extrapolating this finding to fertilised pasture where greater water use may accompany the improved growth rates.

To assess the environmental impact of any river channel management scheme an understanding of the hydrological processes involved is essential. Models incorporating this information and which indicate how greater change the natural habitat of the floodplain will tolerate, are required. This project has provided a detailed analysis of the water regime of 2 flood plain meadows directly quantifying actual evaporation rates and groundwater use by the natural vegetation. It has demonstrated that the usual assumption that Penman potential evaporation rates are applicable in such areas, when the water supply is non-limiting, are inappropriate. The data collected are suitable for the evaluation of existing soil water models, and/or the development of alternatives, to simulate the water regime of flood plain meadows.

Acknowledgements

The support of Mr E Townsend with regard to the use of Howbery field and the Yarnton Meadsmen, Mr P Shurmer and Mr D Carter, has been essential to this project

The Hydra and AWS operation and data processing was undertaken by David McNeil and Floss Standley. Other practical assistance has been provided by Sam Boyle, Mike Stroud and Helen Follett. The interest of other colleagues at the Institute of Hydrology has been appreciated, including the comments of J David Cooper and Mark Robinson on this report.

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Annex

Botanical Surveys

The botanical surveys and vegetation classification were conducted by Dr. A.W.McDonald of Oxford University in June and July 1992 just before the hay cut at each meadow. Higher plant species were recorded in 1 m^2 quadrats using the DAFOR method to assess species abundance. The height of the leafy-vegetation and that of the inflorescences were noted together with the percentage of bare ground per quadrat.

Four quadrats were located as close as possible to the monitoring equipment at each soil water measurement site in the two meadows. In addition, at Yarnton Mead, quadrats were recorded at 50 m intervals along the well transect (PX23 to PX27) which runs SSE from site 553 (Gardner, 1991).

The results of the surveys are shown in Tables A1 and A2, which also indicate Ellenberg's (1988) life-forms and water values. The following features were noted in the course of the surveys.

Yarnton

1. There was a considerable variation in the number of species per quadrat across the Mead, from 15 to 35. The lack of bare ground in many of the quadrats was due to the presence of bryophytes.

2. The most common species were Holcus lanatus, Festuca rubra, Dactylis glomerata and Sanguisorba officinalis. Of the total number of species recorded, 13 were noted only once and none occurred in every quadrat.

3. Species such as Bromus sterilis, Anthriscus sylvestris, Cirsium arvense and Urtica dioica occur only at PX19 reflecting its position at the edge of the meadow where the vegetation is likely to escape the mower in most years. Phragmites australis, Bromus racemosus, Epilobium hirsutum and Symphytum officinale reflect the presence of the ditch bounding the Mead.

4. There is a difference in species abundance between the soil water monitoring sites; most growing at 253 (PX20) also grow at 553 (PX21) but additional species are present at 553. The presence of Carex acutiformis, Carex hirta and Senecio aquatus at PX23 may indicate wetter soil conditions here, as do the Cardamine pratense, Equisetum palustre, Juncus articulatus, Stellaria palustris and Thalictrum flavum at quadrat 16 between PX24 and PX25.

5. Although the data are limited it is possible to classify the communities within the NVC as follows:

   Q1 and Q2 *Arrhenatherum elatius* tall oat coarse grassland, *Urtica dioica* sub-community often found where there is no cutting or grazing of the vegetation.

Q3 to Q23 *Alopecurus pratensis-Sanguisorba* officinalis flood-meadow community, a species rich and somewhat varied sward of grasses and herbaceous cotyledons in which there are usually no dominants. *Carex acutiformis* is occasional (and maybe abundant) and other sedges e.g. *C.panicea* and *C.hirta* are less frequent and never dominant.

Howbery

1. Of the 32 species recorded 15 are grasses. The most abundant species are *Lolium perenne*, *Dactylis glomerata*, *Phleum pratense*, *Holcus lanatus*, *Festuca rubra*, *Agrostis stolonifera* and *Arrhenatherum elatius* with *Hordeum secalinum*, *Poa trivialis*, *Geraneum dissectum* and *Poa pratensis* also scoring 75% or more. *Trifolium repens* is the second most abundant broad-leaved species.

2. In the NVC the *Lolium perenne-Cynosurus cristatus* pasture has an *Alopecurus pratensis* variant which is regularly mown and has a grass dominated sward in which the rarity of *Cynosurus cristatus* indicates younger, re-sown grassland, and coarser grasses such as *Dactylis glomerata* and *Holcus lanatus*, older swards. The sown community may be enhanced by therophytes, often annual weeds such as *Geraneum dissectum*, and by species of the *Centaureo-Cynosuretum* such as *Pimpinella saxifraga* and *Silaum silaus*. The Howbery grassland is therefore classified as an *Alopecuris pratensis* variant of the *Lolio-Cynosuretum critati* pasture.

Table A1 *Botanical survey at Yarnton Mead, species abundance in $1m^2$ quadrats; a: abundant, d: dominant, f: frequent, o:occasional, r: rare*

Species no	Water value	Life form	No of occurrences	Quadrat number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
					PX	PX	PX	PX	PX	PX	PX	PX	PX	PX	PX	PX	PX		PX		PX			PX			PX
				Grid reference	19	19	20	20	20	20	20	21	21	21	21	22	23		24		25			26			27
				Bare ground %	25	20	-	-	4	-	-	-	-	-	-	-	-	-	-	6	2	-	-	-	-	-	-
				Vegetation height cm	120	100	20-100	20-100	25-100	20-75	20-75	20-100	20-100	20-75	20-75	20-100	30-75	30-75	25-75	35-110	50-90	40-100	25-90	30 90	35-80	20-100	30-100
				Total no species	15	19	19	27	21	25	34	27	32	32	26	35	32	26	30	30	23	28	33	29	26	27	17
1	5	H	15	Arrhenatherum elatius	a	a	f	f	f	a	r					f			o			a	f	a	f	f	o
2		T	2	Bromus sterilis	o	o																					
3	5	H	20	Dactylis glomerata	o	a	f	a	a	o	f	o	f	o	f	o			f		f	o	f	f	f	f	f
4	5	GH	21	Holcus lanatus	o	a	o	o	f	o		r	r	r		f	a	a	f	a	f	a	f	f	f	f	f
5	6	H	9	Hordeum secalinum	o	r				o							o	o		o		o			f		a
6	10	GH	4	Phragmites australis	o	r															r						r
7	7	HC	4	Poa trivialis	a	o											r								o		
8	5	H	1	Anthriscus sylvestris	o																						
9	x	G	2	Cirsium arvense	r	o																					
10	x	TH	5	Galium aparine	f	r		r	r																r		
11		T	2	Geranium molle	r	r																					
12	5	H	2	Heracleum sphondyl	o																						r
13	6	H	2	Urtica dioica	a	r																					
14	5	H	6	Vicia cracca	r	r	o		o	r								r									
15		G	2	Calliategia sepium	r	r																					
16	8	T	2	Bromus racemosus		f																				r	
17	5	H	18	Lolium perenne		o		o	f	o		o	r	r		r	f	o		o	o	o	r	a	o	f	f
18	5	H	14	Phleum pratense		f		r	o	o	a			o	r		r	o		o	f	o	o			o	
19	8	H	1	Epilobium hirsutum		o																					
20	7	H	4	Ranunculus repens		o											f	a		r							
21	8	H	1	Symphytum officinalle		r																					
22	6	H	13	Agrostis capillaris			f	o	o	o	o	f	o		f		f		f	o			o	o			
23	x	T	14	Anthoxanthum odoratum			f	o	o		r			r		o		f	o	f	f	f		f	f	o	
24	5	H	16	Cynosurus cristatus			o					o	o	o	o		f	o	f	o	o	f	o	f	o	o	f
25	7	H	13	Deschampsia cespitosa			o	f	a		o	o	r	o	o	o		o				o	o		o		
26	6	H	16	Festuca pratensis			r	o		f	f	f	f	f	f	o		o		o	o	o	a	o	o		
27	x	H	21	Festuca rubra			a	a	a	a	a	f	f	f	f	a	f	f	f	f	f	f	f	f	f	f	f
28	x	H	19	Trisetum flavescens			f	f	o	f	f	f	o	o	o	o		o	f		f	f	f	f	f	f	f
29	5	C	11	Cerastium fontanum			r	r								o	o		o	r		r	o	f	o	o	
30	4	H	13	Primula veris			o	o	r	o	o	r	o	r		o			o				o	r		o	
31	x	H	17	Ranunculus acris			o	o		r		r	r		r	r	f	o	f		o	r	o	o	o	f	f
32	3	GH	18	Ranunculus bulbosus			f	f	f	f	f	r	o	o	o	o	r		f	o		r	o	o	o	o	
33	x	H	10	Rumex acetosa			r	r		o	r	o	o			o				f			r		o		
34	7	H	20	Sanguisorba officinalis			d	a	f	a	f	f	f	o	a	a	f		a	a	a	f	f	a	f	f	r
35	7	H	15	Succisa pratensis			o	a	o	f	f	f	f	o	f	f			f		r		o		o	o	
36	x	H	14	Trifolium pratense			o	r			o	f	o	o	o	o	o	o	f				f	o			f
37	6	H	17	Agrostis stolonifera				o	a	f	f	f	f	r	f	f	f	f		o	o	f	f	f		f	
38	x	H	12	Briza media				r	o	r	f	f	o	f	o	f			f				r	r			
39	7	GH	14	Carex panicea				o		f	o	f	a	f	f	o	o		o	o		r	o	o			

40	6	H	10	Lathyrus pratensis				r	r					r	r	o	r	o					o		r		r
41	4	H	2	Lotus corniculatus				r																		o	
42	4	H	2	Luzula campestris				r																r			
43	4	T	5	Trifolium campestre				r			r	r	r							f							
44	8	H	4	Filipendula ulmaria					r		r						f			r							
45	x	H	11	Plantago lanceolata					r				r	r		r	o	f	o			o	o	o			o
46	x	T	7	Bromus hordeaceus						r	f					f	o							o	f	o	
47	x	H	3	Danthonia decumbens						r	o			r													
48	8	G	4	Carex nigra						o		o	r					r									
49	x	H	12	Prunella vulgaris						r	o	r		r		o	f		f		o	r	o	o		o	
50		T	5	Vicia sativa						r	r		r						r	r							
51	3	H	1	Bromus erectus							o																
52	6	G	7	Carex flacca							o		o	f	f	f			o							o	
53	5	H	13	Centaurea nigra							r	o		o	o	f	a	f	o		f	f		f	o	o	
54	4	H	11	Leucanthemum vulgaris							o	o	o	o	f	f	r	o			r		f			o	
55	5	H	4	Polygala vulgaris							r	f				r			r								
56	x	HC	5	Potentilla erecta							o	r	o	o	o												
57	x	T	10	Rhinanthus minor							o			r		r	f	o		f		o	r	o		o	
58	x	GH	4	Serratula tinctoria							r		r	r	o												
59	7	H	12	Silaum silaus							r		r	r	o	o	o	r	o	o	o	o			r		
60	x	GH	3	Trifolium repens							o						f										f
61	4	H	3	Galium verum								a											f			o	
62	6	H	4	Alopecurus pratensis									r		r	r						r					
63	4	GH	1	Carex caryophyllea									r														
64	6	H	2	Ajuga reptans									o	r													
65	8	H	8	Lotus uliginosus									o	o	r	o			o		r		r			o	
66	x	T	5	Linum catharticum										r	r	f	o		f								
67	4	H	6	Leontodon hispidus												r			f	o	f		o	o			
68	7	G	2	Ophioglossum vulgatum												r			r								
69	9	GA	1	Carex acutiformis													o										
70	6	G	2	Carex hirta													o									o	
71	5	H	7	Leontodon autumnalis													f	r	o	o	f	o		o			
72	8	H	1	Senecio aquaticus													o										
73	5	H	7	Taraxacum officinale													r	f		r	r	r		o	r		
74	6	G	1	Lysimachia nummularia														r									
75	5	T	1	Trifolium dubium														r									
76		T	7	Bromus commutatus															r	r	r	o	f		f	f	
77	7	H	2	Cardamine pratensis																r	r		f				
78	6	G	1	Equisetum palustre																r							
79	8	H	4	Juncus articulatus																r		r	o	o			
80	8	H	1	Stellaria palustris																r							
81	8	H	1	Thalictrum flavum																r							
82	4	G	1	Allium vineale																			r				

Water values: 1: extreme dryness; 2 between 1 and 3; 3: dry site indicator; 4: between 3 and 4; 5: moist site indicator; 6: between 5 and 7; 7: damp site indicator; 8: between 7 and 9: wet site indicator; 10: occasional flood; 11: rooting under water; 12: submerged plant.

Life-form: A: hydrophyte; C: herbaceous chamaephyte (buds 25-50 cm above ground; G: geophyte (bulbs and rhizomes); H: hemicryptophyte (perennating buds at ground level); T: therophyte (annuals); Z: woody chamaephyte

Table A2 *Botanical survey at Howbery, species abundance in 1 m^2 quadrats. Key as for Table A1*

Species no.	Water value	Life form	No. of occurrences	IoH Reference	1				2				3				4			
				Quadrat no.	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
				Bareground %	5	·	3	·	·	·	·	·	·	·	·	·	·	·	·	·
				Vegetation height cm		30/75				20/100				30/100				25/80		
				Total no. species	16	15	16	19	16	16	16	15	14	12	15	17	15	13	13	15
1	5	H	16	Lolium perenne	f	f	r	o	f	f	o	f	f	o	f	o	o	f	a	f
2	5	H	16	Dactylis glomerata	f	f	f	f	f	f	f	a	f	f	f	f	f	a	a	f
3	5	H	16	Phleum pratense	f	a	f	a	o	o	o	o	a	a	f	f	o	f	a	f
4	5	GH	16	Holcus lanatus	o	o	o	o	o	f	o	a	o	r	r	r	f	r	r	o
5	7	HC	13	Poa trivialis	o	o	f	o	o		f	f	f		o	o	o		r	r
6	6	H	15	Hordeum secalinum	f	f	f	r		o	a	o	o	o	a	f	a	a	a	a
7	x	H	16	Festuca rubra	r	r	o	r	a	f	a	f	f	a	f	a	f	f	o	a
8	6	H	16	Agrostis stolonifera	r	o	f	o	o	o	o	o	r	f	f	o	o	f	o	o
9	5	H	16	Arrhenatherum elatius	o	f	a	f	f	f	a	f	f	o	o	o	o	r	r	o
10	6	H	7	Alopecurus pratensis	o	o	r						o	r	o	o				
11	6	H	12	Poa pratensis	r	o	r			o		r	f	f	o	o	f	r	r	o
12	3	GH	8	Ranunculus bulbosus	r		f	o	r	r			r			r		r		r
13	x	H	2	Trifolium pratense	r											r				
14	5	C	3	Cerastium fontanum	f			r			o									
15	5	T	14	Geranium dissectum	o	r	r	o	o	o	o		o	o	f	o	r		r	r
16	x	H	8	Ranunculus acris	r		o		r	r	r	r						f		r
17	5	H	1	Taraxacum officinale		o														
18	x	GH	10	Trifolium repens		f	o	a		o			o		r	r	r	a	r	
19	x	H	8	Trisetum flavescens		o		o	o	o					o		o	r	r	
20	7	H	1	Deschampsia cespitosa			o	o												
21	5	H	4	Cirsium vulgare				r								r	r			r
22			2	Crepis vesicaria				r				r								
23	4	TH	3	Medicago lupulina				r			f	o								
24	6	H	1	Lathyrus pratensis				r												
25	4	H	1	Achillea millefolium					f											
26	x	T	2	Anthoxanthum odoratum					o			o								
27	x	G	6	Cirsium arvense					r	f	a	f					r			r
28	4	T	1	Trifolium campestre					r											
29	x	H	2	Rumex acetosa						r	o									
30	x	H	1	Plantago lanceolata							r									
31	5	H	2	Cynosurus cristatus										f	f					
32	5	H	1	Anthriscus sylvestris												r				

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