THE WATER USE RATES OF REEDBED AND WET WOODLAND HABITATS

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SUMMARY

To create hydrologically sustainable wetlands, knowledge of the water use requirements of target habitats must be known. Extensive literature reviews highlighted a dearth of water-use data associated with large reedbeds and wet woodland habitats and in response to this field experiments were established.

Field experiments to measure the water use rates of large reedbeds [ET(Reed)] were completed at three sites within the UK. Reference Crop Evapotranspiration [ETo] was calculated and mean monthly crop coefficients [Kc(Reed)] were developed. Kc(Reed) was less than 1 during the growing season (March to September), ranging between 0.22 in March and reaching a peak of 0.98 in June. The developed coefficients compare favourably with published data from other large reedbed systems and support the premise that the water use of large reedbeds is lower than that from small / fringe reedbeds.

A methodology for determining water use rates from wet woodland habitats (UK NVC Code: W6) is presented, in addition to provisional ET(W6) rates for two sites in the UK. Reference Crop Evapotranspiration [ETo] data was used to develop Kc(W6) values which ranged between 0.89 (LV Lysimeter 1) and 1.64 (CH Lysimeter 2) for the period March to September. The data are comparable with relevant published data and show that the water use rates of wet woodland are higher than most other wetland habitats. Initial observations suggest that water use is related to the habitat's establishment phase and the age and size of the canopy tree species.

A theoretical case study presents crop coefficients associated with wetland habitats and provides an example water budget for the creation of a wetland comprising a mosaic of wetland habitats. The case study shows the critical role that the water use of wetland habitats plays within a water budget.

KEYWORDS

Lysimeters, Evapotranspiration, Crop Coefficients, Water Budget, Wetland Creation

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NOTATION

β	Bowen ratio
γ	Psychrometric constant (= 0.66 for temperature in °C and vapour pressure in mb)
ρ_a	Bulk density of air (kg m^{-3})
ρ_b	Bulk density of a sample of soil (kg m^{-3})
ρ_l	Bulk density of a liquid (kg m^{-3})
ρ_v	True humidity fluctuation
Λ	Latent heat of vapourisation of water
λE	Energy available for evaporation (MJ m-^{2} s^{-1})
λET	Energy available for evapotranspiration (MJ m-^{2} s^{-1})
λET_m	Measured energy available for evapotranspiration (calculated from Mark 2 “Hydra” equipment)
λET_R	Raw energy available for evapotranspiration (raw data from Mark 2 “Hydra” equipment)
λETo	Energy available for reference crop evapotranspiration (MJ m^{-2} d^{-1})
θm	Gravimetric soil moisture content
θv	Volumetric soil moisture content (%)
A	Area (m^2)
a_w	An empirical wind function coefficient
BAP	Biodiversity Action Plan
B_o	Calibration parameter (typically 0.3)
b_w	An empirical wind function coefficient
CD	Crop Density (stems m^{-2})
CH	Crop Height (m)

NOTATION continued

c_p	Specific heat capacity of dry air (MJ k^{-1} $^oC^{-1}$)
c_s	Specific heat capacity of sap (J g^{-1} K^{-1})
D	Depth of water table (m)
DO	Dissolved oxygen
E Pan	Evaporation from an evaporation pan (mm day^{-1})
e_a	Actual vapour pressure (kPa)
E_a	Bulk aerodynamic expression
Eo	Evaporation from open water (mm day^{-1})
e_s	Saturation vapour pressure (kPa)
Es	Evaporation from bare soil (mm day^{-1})
ET	Evapotranspiration (mm day^{-1})
ET(Habitat)	Evapotranspiration from a given habitat (mm day^{-1})
ET(Reed)	Evapotranspiration from a reedbed (mm day^{-1})
ET(W6)	Evapotranspiration from a W6 wet woodland (mm day^{-1})
Eta	Actual evapotranspiration (mm day^{-1})
ETo LMS Grass	Reference crop evapotranspiration developed from local meteorological station data (mm day^{-1})
ETo MORECS Grass	Reference crop evapotranspiration developed from the appropriate MORECS 2 grid square data (mm day^{-1})
ETo Pan	Reference crop evapotranspiration developed from evaporation pan data (mm day^{-1})
ETo SAMS Grass	Reference crop evapotranspiration developed from a site-based automatic meteorological station (mm day^{-1})
G	Soil heat flux density (MJ m^{-2} d^{-1})
G_{in}	Ground water flows into a wetland

NOTATION continued

G_{out}	Ground water flows out of a wetland
HAP	Habitat Action Plan
Hf	Sensible heat flux
I	Interception, the evaporation rate from the leaves of vegetation (mm day^{-1})
Kc(Habitat)	Crop coefficient associated with a given habitat
Kp	Pan coefficient
M	Mass of an object or sample (grams)
m.a.g.l.	Metres Above Ground Level
m.b.b.l.	Metres Below Bed Level
m.b.g.l.	Metres Below Ground Level
NVC	National Vegetation Classification
P	Precipitation (mm)
PET	Potential evapotranspiration (mm day^{-1})
P_{net}	Net precipitation (mm)
Q	Calibration parameter (typically 0.008)
Q_f	Amount of heat dissipated by sap as it flows through the heated region of a tree trunk
Q_{in}	Surface flows into a wetland
Q_{out}	Surface flows out of a wetland
r	Mean mixing ratio
r_a	Bulk aerodynamic resistance (s m^{-1})
R_n	Net radiation (MJ m^{-2} d^{-1})
r_s	Bulk surface resistance (s m^{-1})

NOTATION continued

S	Heat storage term
s	Sap flow rate ($g\ s^{-1}$)
S4	Reedbed habitat
SC	Standing Crop ($m\ stem^{-1}\ m^{-2}$)
SE	Standard Error
SMD	Soil moisture deficit
SRC	Short Rotation Coppice
SY	Specific yield
T	Mean daily temperature at 2 m height (^oC)
T_a	Temperature of air (^oC)
T_k	Temperature of air (in degrees Kelvin)
Tr	Transpiration rate from vegetation ($mm\ day^{-1}$)
T_s	Stabilised temperature for detector and filter in infrared hygrometer
u	Wind speed ($m\ s^{-1}$)
V	Volume of a sample (m^3)
W1	*Salix cinerea – Galium palustre* woodland habitat
W2	*Salix cinerea – Betula pubescens – Phragmites australis* woodland habitat
W3	*Salix pentandra – Carex rostrata* woodland habitat
W4c	*Betula pubescens – Molinia caerulea* woodland: Sphagnum sub-community habitat
W5	*Alnus glutinosa – Carex paniculata* woodland habitat
W6	*Alnus glutinosa – Urtica dioica* woodland habitat

NOTATION continued

W7	*Alnus glutinosa – Fraxinus excelsior – Lysimachia nemorum* woodland habitat
Δ	Slope of saturation vapour pressure curve at temperature T_a (kPa $^oC^{-1}$)
Δe	Vertical difference in vapour pressure
Δs	Change in storage of water in the soil
ΔT	Vertical difference in temperature
ΔTs	Temperature increase of sap (Kelvin)
ΔV(Habitat)	Change in the volume of water storage within a habitat

CHAPTER 1. INTRODUCTION

In the UK, the National Biodiversity Action Plan (BAP) provides targets for the restoration and / or creation of a range of wetland habitats in response to a loss of wetland biodiversity and changes in attitudes to wetland conservation over the past decade. These two factors have lead to: the creation and rehabilitation of many wetland habitats; attempts to halt and reverse the decline of those remaining in existence; and, the implementation of projects to prevent the loss of the associated wetland species. Much of this work has been focused in areas of the UK and central Europe where annual rainfall is low, and water supplies are limited.

Two wetland BAP habitats with specific Habitat Action Plans (HAPs) are reedbeds and wet woodlands (UKBG, 1995 and UKBG, 1998 respectively). The restoration and creation targets as outlined in the relevant HAPs for these two habitats are given in Table 1.1.

ACTION	AREA (ha)	TIMESCALE
Reedbeds		
Create habitat on land of low nature conservation. The creation of new reedbed should be in blocks of at least 20 ha with priority for creation in areas near to existing habitat, and linking to this wherever possible.	1,200	Completed by 2010
Wet Woodland		
Initiate restoration of native wet woodland	3,200	Half by 2010 All by 2015
Initiate colonisation and/or planting of wet woodland on unwooded or ex-plantation sites	6,750	Half by 2010 All by 2015

Table 1.1: UK BAP Reedbed and Wet Woodland Restoration / Creation Targets
(after UKBG, 1995 and UKBG, 1998)

The targets for habitat creation outlined in Table 1.1 will be met by creating new wetlands throughout the UK and to ensure that these wetlands are hydrologically sustainable, a water budget must be completed as part of the design process. To successfully carry out detailed water budgets, information with respect to the water use (measured as evapotranspiration [ET]) of target wetland habitats must be available. Indeed with respect to wet woodlands, the EC Environment Committee have called upon the government *'to determine how its forestry policy may be realised without detriment to the water supply'* (Stationery Office, 1997).

Literature reviews undertaken by Fermor (1997) and as part of this project highlighted a dearth of information associated with the water use rates of large reedbeds and wet woodland habitats. Water management is the single most important factor in managing a reedbed for wildlife (Ward, 1992) and therefore investigation of the impact of reedbed size on water use was deemed necessary. Fermor (1997) developed a methodology for the determination of ET(Reed) from small reedbeds based on the technique of lysimetry, and in this study, Fermor's methodology was extended and applied to large reedbeds. ET(Reed) was measured from three research sites situated throughout the UK.

NVC habitat W6 (see Rodwell, 1991) was chosen as a target wet woodland habitat for use in this study. A methodology for the determination of wet woodland water use rates [ET(W6)] using lysimetry was developed and initial ET(W6) values were calculated from two research sites within the Midlands region of the UK.

Various forms of Reference Crop Evapotranspiration [ETo] were used to develop monthly crop coefficients for large reedbeds [Kc(Reed)] and W6 wet woodlands [Kc(W6)].

In summary, this thesis provides:

(1) a set of monthly Kc(Reed) values suitable for use in the creation of large reedbed systems throughout the UK and continental Europe;

(2) a method for the determination of water use rates from wet woodland habitat using the technique of lysimetry; and,

(3) a set of provisional monthly Kc(W6) values suitable for use in the creation of W6 wet woodland habitats throughout the UK and continental Europe.

1.1 ORIGINS OF THE PROJECT

During his research Fermor (1997) produced monthly ET(Reed) values from three wetland sites, all of which were classed as having small or fringe reedbeds. Collaborative work with Cranfield University (Fermor et al, 2001) included results from a study within a larger reedbed and appeared to show that large reedbeds have lower water requirements than fringe reedbeds. The reedbed HAP provides targets for large reedbed creation (Table 1.1) and therefore further experimental work was required to verify the water use requirements of these habitats.

Whilst undertaking various wetland design projects in the late 1990's, Fermor (2000) revealed a paucity of information with respect to water use rates of wet woodland habitats. Indeed the Environment Agency (1998) acknowledged the lack of information with respect to the evaporative properties of different combinations of tree species and soil type. Extensive literature reviews confirmed this and in response a method for the determination of ET rates from wet woodlands was developed and tested. Initial ET(W6) and Kc(W6) values were calculated from collected data.

1.2 AIMS AND OBJECTIVES

Although the aim of the project has not altered during its course, the focus of some of the objectives has. Initially the project focused on the establishment of research sites suitable for study of the water use rates of reedbed habitats. Simultaneously, investigation of the need for research into the water use rates of wet woodland and wet grassland habitats was carried out. Initial research showed that the water requirements of wet grassland habitats were well understood. The Wet Grassland Guide (Benstead et al, 1997) provided detailed information regarding the habitat and various projects undertaken at Cranfield University supplied data for specified grasslands (e.g. Souch et al, 2000; Gilbert, 2001). However, literature reviews highlighted the lack of information about wet woodland habitats in general, with very little understanding with respect to their hydrology. Thus it was agreed that once the reedbed research sites were established, attention would be focused on the development of an appropriate technique for measuring water use in wet woodland habitats.

1.2.1 AIM

The overall aim of the project was to refine water budget design methodology for wetland habitats to enable the maintenance of the biodiversity of target species in created wetland systems.

1.2.2 OBJECTIVES

The aim of the project would be achieved through a number of objectives:

(1) the installation of lysimeters in a series of large reedbeds, and the subsequent monitoring of phenological characteristics, hydrometeorological and water quality parameters;

(2) the determination of design water use parameters for the monitored reedbeds;

(3) the development and application of field methods for determining water use rates from other wetland habitats, primarily wet woodland;

(4) investigation of the relationship between phenological parameters and water use rates for the habitats studied;

(5) the development of a procedure for enabling the calculation of water budgets for wetlands containing a variety of habitats;

(6) research into the water use rates of other wetland habitats which are likely to be found as part of a wetland mosaic (wet grassland, sedge beds and marsh); and,

(7) presentation of a sample water budget for sites with a mosaic of wetland habitats.

1.3 THESIS STRUCTURE

Chapter Two provides a brief introduction to water budgets and their use within this project and investigates the theory behind the determination of ET rates and Kc values from empirical field-data.

Chapter Three presents an introduction to reedbed habitats: their distribution, associated wildlife, hydrological requirements and details of their restoration and creation. In addition an extensive review of the different methodologies available for the determination of water use rates and published results are presented. Chapter Four includes the same information associated with wet woodland habitats.

A description of each of the reedbed study sites and the experimental design and monitoring regimes associated with the methodology is provided in Chapter Five. Chapter Six provides the same information with respect to wet woodland habitats.

The results of the water use experiments within the reedbed and wet woodland habitats are presented in Chapters Seven and Eight respectively.

A summary of the published water use rates for a number of additional target lowland wetland habitats is presented in Chapter Nine. This information is used to provide an water budget case study for a wetland creation site containing a mosaic of wetland habitats.

Chapter Ten presents an evaluation of the project and details further research requirements whilst Chapter Eleven contains the conclusions of the study.

CHAPTER 2. ENABLING THE DETERMINATION OF WATER BUDGETS

2.1 INTRODUCTION

Wetlands are a major feature of the landscape in almost all parts of the world, and are among the most important ecosystems on earth. The Ramsar Convention, 1971 defined wetlands as:

> *'areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres'.*

Wetlands also incorporate the riparian habitats adjacent to water bodies and waterways, along with the islands, berms and other in-stream features within these waterways (Bardsley, 2001a).

Wetlands are unique because of their role as ecotones between terrestrial and aquatic systems. Mitch and Gosselink (2000) describe them as being the 'kidneys of the landscape' because they function as the downstream receivers of water and waste from both natural and anthropogenic sources. Wetlands act to stabilise water supplies through ameliorating floods and drought; they can cleanse polluted water; protect shorelines; and recharge ground aquifers (Mitch and Gosselink, 2000).

Spiers (no date) undertook a review of international / continental wetland resources and concluded that the current world wetland area was approximately 560 million ha. He suggested that since 1900, 50% of the total area of inland and mangrove wetlands that existed has been lost.

Stevenson and Fraizer (no date) completed a review of wetland inventory information in Western Europe and estimated the total wetland areas within the UK presented in Table 2.1.

WETLAND TYPE	**BEST ESTIMATE OF AREA (ha)**
Marine / Coastal	854,498
Inland	518,713
Artificial	2,303
TOTAL	**1,375,514**

Table 2.1: Best Estimates of Total Wetland Area in the UK
(after Stevenson and Fraizer, no date)

Of the total UK wetland area presented in Table 2.1, 420,145 ha is located within 114 sites included in the Ramsar List of Wetlands of International Importance (Stevenson and Fraizer, no date). The total wetland area would historically have been much larger as UK loss rates of 23% of estuaries and 50% of saltmarshes since Roman times (Davidson et al 1991; cited by Stevenson and Fraizer, no date), and 40% of wet grasslands (RSPB, 1993) have been reported.

To ameliorate for habitat loss and degradation, the UK National Biodiversity Action Plan created targets for the appropriate management, restoration and creation of a range of wetland and terrestrial habitats. To meet the creation targets, new wetlands will have to be created throughout the UK in areas with suitable hydrology, geology, sediments, topography, ecology and meteorology, all of which must be considered in the design of the new wetland.

To analyse the hydrological requirements of a target wetland habitat, wetland designers use water budgets to provide data with respect to the hydrological inputs and outputs from an area. This chapter provides an introduction to water budgets, details of their use in the design of wetland systems and their application to this project.

2.2 WETLAND WATER BUDGETS

The creation of a wetland fundamentally relies on the presence of water in sufficient quality and quantity, therefore knowledge of water requirements and availability are essential to ensure that target habitats are tenable (Bardsley et al, 2001). The key to understanding the hydrology of a wetland lies in the water budget (Gilvear and Bradley, 2000). Gilman (1994a) presented a standard water budget equation for wetlands (Equation 2.1) whereas Mitch and Gosselink (2000) provided a diagrammatic representation (Figure 2.1), which shows the effect of interception [I] on the volumes of precipitation [P] reaching the wetland [P_{net}].

$$\begin{array}{lclcl} \textbf{Sum of inputs} & = & \textbf{Sum of outputs} & + & \textbf{Change in storage} \\ P_{net} + Q_{in} + G_{in} & = & ETa + Q_{out} + G_{out} & + & \Delta s \end{array} \tag{2.1}$$

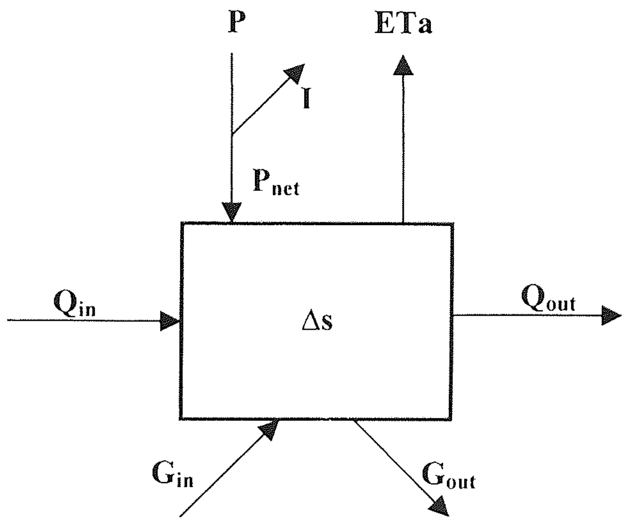

Fig. 2.1: Generalised Water Budget for a Wetland
(after Mitch and Gosselink, 2000)

where:

P_{net} is the net precipitation i.e. that portion of the precipitation that reaches the ground;

Q_{in} and Q_{out} are surface flows into and out of the wetland area;

G_{in} and G_{out} are groundwater flows into and out of the wetland area;

ETa is the actual evapotranspiration; and,

Δs is the change in storage of water.

To successfully develop a wetland water balance for a given site, accurate measurements of those parameters outlined in Equation 2.1 must be provided. Precipitation rates can be recorded using on-site rain gauges or data purchased from the Met Office (in the UK). Surface inflow and outflows can include hydrological inputs from streams or flooding events and in the UK data from existing hydrometric stations can often provide relevant information. Although it is difficult to measure groundwater changes within wetland areas, they are usually researched using dipwells and geological and sedimentological data. Gilman (1994b) highlighted ET losses from wetland habitats as being the most important and complex parameter within the wetland water budget and concluded that they were often the most difficult to measure. In agreement with this statement, Bardsley et al (2001) suggested that due to its complexity, the determination of ET is generally left to those carrying out hydrological research.

To allow the calculation of ET from a given wetland habitat, it is therefore necessary to employ a methodology that allows a wetland designer to develop site-specific ET rates using standard data. One such technique involves the use of standard Reference Crop Evapotranspiration [ETo] data and crop coefficients [Kc(Habitat)] to develop ET(Habitat) values (Equation 2.2).

$$\mathbf{ET(Habitat) = ETo \,.\, Kc(Habitat)} \tag{2.2}$$

This methodology was developed by the Food and Agriculture Organisation (Doorenbos and Pruitt, 1977 updated in Allen et al, 1998) to provide an international technique for calculating ET rates from different agricultural crops.

Section 2.3 provides information with respect to some of the different techniques for determining ETo rates for a specific site.

2.3 DETERMINATION OF ETo

ETo values are a standard measurement of evaporation or evapotranspiration from a given surface at a given location. ETo data can be determined using a number of different reference surfaces. Penman (1948) devised a formula (Equation 2.3) from a combination of mass transfer and energy balance (Allen et al, 1998) to allow the estimation of evaporation from an open water surface from standard climatological records of sunshine, temperature, humidity and wind speed. The formula takes into account two main elements of evaporation (Ward, 1975).

(1) A measure of the drying power of the air. This increases with a large saturation deficit (indicating that the air is dry) and with high wind-speeds. The input from this element was derived from the turbulent transfer approach.

(2) An estimation of the net radiation available for evaporation and heating the earth's surface. Penman assumed that the heat flux into and out of the soil was small enough to be neglected and simply divided the net radiation between heating the air and evaporation. The input from this element was derived from the energy balance approach.

$$\lambda E = \frac{\Delta(R_n - G) + \gamma E_a}{(\Delta + \gamma)} \tag{2.3}$$

where:

λE is the energy available for evaporation in MJ m^{-2} d^{-1};

Δ is the slope of the saturation vapour pressure curve at temperature T_a in kPa $^{o}C^{-1}$;

T_a is the temperature of air in ^{o}C;

$R_n - G$ is the net radiation minus water heat flux density in MJ m^{-2} d^{-1};

γ is the psychrometric constant in kPa $^{o}C^{-1}$ (0.66 for temperatures in ^{o}C and vapour pressure in kPa); and,

E_a is a bulk aerodynamic expression containing an empirical wind function.

E_a is determined using Equation 2.4.

$$E_a = 6.43(a_w + b_w u_z)(e_s - e_a) \tag{2.4}$$

where:

E_a is a bulk aerodynamic expression containing an empirical wind function;

a_w and b_w are both empirical wind function coefficients;

u_z is the wind speed at the z height in m s^{-1};

e_s and e_a are the saturation and actual vapour pressures in kPa; and,

e_s-e_a is the vapour pressure deficit of the air in kPa.

Penman (1963) proposed $a_w = 0.5$ and $b_w = 0.54$ for open water for z = 2 m and for e_s computed using daily mean temperature. Since this time, various other values for the empirical coefficients a_w and b_w have been proposed (ASCE, 1996).

ASCE (1996) concluded that an important point to consider in the use of combination equations is that the use of weather data collected over a typical weather station on land cannot be expected to give as good an accuracy as computations using data collected over the water surface. The wind speed at height z over aerodynamically smooth water will be significantly higher than wind speed at height z over a typical weather station site. In addition, temperature and humidity may also be quite different.

Since Penman's first equations, techniques for calculating ETo from other surfaces have been developed and currently one of the most widely used reference crop surfaces is grass. Monteith (1965 and 1981) modified Penman's equations and introduced a surface resistance parameter into the formula and replaced the linear wind function term with an aerodynamic resistance parameter. The resulting formula (Equation 2.5) is known as the Penman-Monteith combination method.

$$\lambda ET = \frac{\Delta(R_n - G) + \rho_a c_p \dfrac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \dfrac{r_s}{r_a}\right)} \tag{2.5}$$

where:

λET is the energy available for evapotranspiration in MJ m^{-2} d^{-1};

$R_n - G$ is the net radiation minus soil heat flux density in MJ m^{-2} d^{-1};

e_s and e_a are the saturation and actual vapour pressures in kPa;

e_s-e_a is the vapour pressure deficit of the air in kPa;

ρ_a is the air density in kg m^{-3};

c_p is the specific heat of dry air in MJ kg^{-1} $^{o}C^{-1}$;

Δ is the slope of the saturation vapour pressure curve at temperature T_a in kPa $^{o}C^{-1}$;

T_a is the temperature of air in ^{o}C;

γ is the psychrometric constant in kPa $^{o}C^{-1}$; and,

r_s and r_a are the (bulk) surface and aerodynamic resistances in s m^{-1}.

In 1990, a panel of experts from the Food and Agriculture Organisations of the United Nations (FAO) recommended the adoption of the Penman-Monteith combination method as a new standard for calculating ETo (Allen et al, 1998). By defining the reference crop as

> *'the rate of evapotranspiration from a hypothetic crop with an assumed height of 12 cm, a fixed canopy resistance of 70 s m^{-1}, and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, completely shading the ground and not short of water'.*

and deriving empirical estimations of various parameters of the equation, they developed the FAO Penman-Monteith formula (Equation 2.7). They recommend that this be the sole standard method for estimating ETo as the method has a strong likelihood of correctly predicting ETo in a wide range of locations and climates and has provision for applications in data-short situations. The formula is given as ETo in mm day^{-1} as the energy units for radiation are converted to equivalent water depths (mm) using Equation 2.6.

$$\textbf{Radiation (mm day}^{-1}\textbf{)} = \frac{\textbf{Radiation (MJ m}^{-2}\textbf{ d}^{-1}\textbf{)}}{\textbf{2.45}} = \textbf{Radiation.0.408 (MJ m}^{-2}\textbf{ d}^{-1}\textbf{)} \qquad \textbf{(2.6)}$$

$$\lambda ETo = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

(2.7)

where:

λETo is the energy available for reference crop evapotranspiration in MJ m^{-2} d^{-1};

$R_n - G$ is the net radiation minus soil heat flux density in MJ m^{-2} d^{-1};

e_s and e_a are the saturation and actual vapour pressures in kPa;

e_s-e_a is the vapour pressure deficit of the air in kPa;

T is the mean daily temperature at 2 m height in ^{o}C;

u_2 is the wind speed at 2 m height;

Δ is the slope of the saturation vapour pressure curve at temperature T_a in kPa $^{o}C^{-1}$;

T_a is the temperature of air in ^{o}C;

γ is the psychrometric constant in kPa $^{o}C^{-1}$.

Equation 2.7 presents the current accepted technique for determining ETo using grass as a reference crop from easily sourced climatological data. ASCE (1996) stated that there are disadvantages in using grass as a reference crop. They suggest that as grass is short and aerodynamically quite smooth, the ET losses are considerably lower than from other types of vegetation with rougher canopies, particularly in hot, dry and windy conditions. As an alternative, alfalfa is proposed as a reference crop, although this also has its disadvantages. Despite this, grass is widespread in its use as a reference crop and is therefore employed in this project. In the UK, the Met Office use grass as the standard reference crop and therefore its use in this project makes the resulting data more applicable to UK wetland designers.

There are a number of techniques used to calculate ETo from a site, extensive discussions of the techniques available are provided by ASCE (1996) and Fermor (1997). Information with respect to the techniques used during this project is presented in Sections 2.3.1 to 2.3.4.

2.3.1 PAN EVAPORATION METHOD

The use of evaporation pans is one of the simplest techniques for determining ETo as they provide a measurement of the integrated effects of radiation, wind, temperature and humidity on evaporation from a standard open water surface (Doorenbos and Pruitt, 1977). By installing an evaporation pan, the evaporation from the pan [E Pan] can be determined.

E Pan is usually measured using a US Class A Evaporation Pan or a Colorado Sunken Pan. During each monitoring visit the volume of water required to reset the pan to a specified point is measured, enabling the calculation of E Pan in mm day^{-1}. From this, ETo Pan is developed using Equation 2.8.

$$\mathbf{ETo\ Pan = E\ Pan\ .\ Kp} \qquad \mathbf{(2.8)}$$

where:
ETo Pan is the Reference Crop Evapotranspiration in mm day^{-1};
E Pan is the measured pan evaporation in mm day^{-1}; and,
Kp is the pan coefficient.

The pan coefficient [Kp] is a value which takes into account the local climate and pan environment and thus allows the evaporation pan to be used as a tool throughout the world. Internationally applicable values for Kp are provided by Doorenbos and Pruitt (1977), with 0.8 being appropriate for the study sites used in this project.

2.3.2 SITE AUTOMATIC METEOROLOGICAL STATION

Given a suitable location, an automatic weather station can be installed on a site to provide site-specific meteorological data. This data can be used to develop ETo values based on the FAO Penman-Montieth equation.

The following outputs are required for the calculation of ETo using the FAO Penman-Monteith equation: daily maximum air temperature; daily minimum air temperature;

daily rainfall totals; daily sunshine hours; mean daily wind speed; and, vapour pressure at 09GMT. This raw data can then be entered into a computer programme such as CROPWAT (Smith, 1992) or AWSET (Cranfield University, 1999), which will automatically generate site-specific ETo Grass data in mm day^{-1}.

2.3.3 MET OFFICE RAINFALL AND EVAPORATION CALCULATION SYSTEM (MORECS 2.0)

MORECS 2.0 is a methodology produced by the UK Met Office designed to provide estimates of weekly and monthly ETo and soil moisture deficit (SMD) averages for each of 190 grid squares (40 km x 40 km) that cover Great Britain using daily synoptic weather data as inputs (Fermor, 1997). The MORECS 2.0 grid is shown in Figure 2.2. The methodology is based on an empirical modification of the Penman-Monteith formula, is applicable to the UK only, and is presented in Equation 2.9 (Hough et al, 1996).

$$\lambda ET = \frac{\Delta(R_n - G) + \rho_a c_p (e_s - e_a)\left(\frac{1 + br_a}{\rho_a c_p}\right)/r_a}{\Delta + \gamma\left(\frac{1 + r_s}{r_a}\right)\left(\frac{1 + br_a}{\rho_a c_p}\right)} \qquad \textbf{(2.9)}$$

where:

λET is the energy available for evapotranspiration MJ m^{-2} s^{-1};

Δ is the rate of change of saturated vapour pressure with temperature in kPa ^{o}C^{-1};

$R_n - G$ is the net radiation minus soil heat flux density in MJ m^{-2} d^{-1};

ρ_a is the air density in kg m^{-3};

c_p is the specific heat of dry air in MJ kg^{-1} ^{o}C^{-1};

e_s and e_a are the saturation and actual vapour pressures in mb;

e_s-e_a is the vapour pressure deficit of the air in kPa;

γ is the psychometric constant;

r_s and r_a are the (bulk) surface and aerodynamic resistance in s m^{-1}.

The MORECS 2.0 ETo data used in this project was based on a 'Grass' surface. 'Grass' is assumed to have the attributes detailed in Table 2.2.

PARAMETER	ASSUMPTION
Albedo - used to determine R_n	0.25
Leaf Area Index (LAI) - used to determine r_s	2.0 (Jan, Feb), 3.0 (Mar), 4.0 (Apr), 5.0 (May, Jun, Jul, Aug), 4.0 (Sep), 3.0 (Oct), 2.5 (Nov), 2.0 (Dec)
Surface Resistance (r_s) - day-time values (s m^{-1})	80 (Jan, Feb), 60 (Mar), 50 (Apr), 40 (May), 60 (Jun, Jul), 70 (Aug, Sep, Oct), 80 (Nov, Dec)
Crop Height (m)	0.15 m
Available Water Capacity (AWC)	Constant

Table 2.2: Assumptions Applied to MORECS Calculations Using a 'Grass' Surface
(after Hough, 1996)

A network of stations supplies synoptic data which is averaged to provide daily readings (were appropriate). The data from each station is then normalised and eventually interpolated to provide values for each 40 x 40 km square. Hough et al (1996) stated that the errors involved in the use of these interpolation methods are unlikely to be large for temperature and humidity and conclude that acceptable estimates of wind speed are also usually obtained. However, the authors stated that there are greater difficulties with sunshine estimates and concluded that the square values for sunshine will be overestimated for squares with large amounts of high ground. In addition, there are problems providing accurate rainfall data as this parameter shows large special variation especially in summer. They conclude that the long-term sunshine estimates are likely to be satisfactory but admit that in the shorter-term rainfall estimates can be misleading.

The MORECS 2.0 system can provide a range of data to the user in a variety of formats ranging from 30-year averages to weekly data. MORECS 2.0 30-year average data is often used in the development of water budgets associated with the design of new wetland systems (Fermor, 2000).

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2.3.4 LOCAL METEOROLOGICAL DATA (MORECS 2.0)

Throughout the UK a network of meteorological stations record varying parameters associated with local weather conditions. Although they do not own the entire network of stations, the Met Office holds hourly synoptic records of the measured parameters from these stations.

Using the national grid reference of a site, the Met Office can determine which of the stations provide the parameters (see Section 2.3.2) required for the determination of ETo using the modified Penman-Monteith equation developed for the MORECS system. The use of local meteorological data reduces the potential problems associated with inaccurate estimates of sunshine and rainfall of using MORECS square data.

This data can then be purchased from the Met Office in its required format – either as the raw data (given hourly or daily), which would then be input into one of the computer programmes used for generating ETo (see Section 2.3.2), or alternatively, the Met Office can carry out the relevant calculations and provide daily or monthly ETo Grass data directly.

The applicability of this data to a given site is related to the proximity of the meteorological stations from which the data is collected and the similarity between the local environment in which the station is located, and the study site.

2.3.5 SUMMARY

Sections 2.3.1 to 2.3.4 provide an introduction to the different methodologies for determining ETo that have been used in this project. A summary of the equipment required and the advantages and disadvantages associated with each methodology is presented in Table 2.4. The nomenclature used to indicate which method of ETo calculation was used to develop Kc(Habitat) values are:

- Pan Evaporation Method - **Kc(Habitat) Pan**;
- Site-based Automatic Meteorological Station - **Kc(Habitat) SAMS Grass**;
- MORECS 2.0 Local Meteorological Station - **Kc(Habitat) LMS Grass**;
- MORECS 2.0 40 x 40 km Square - **Kc(Habitat) MORECS Grass**.

In the published literature, ET Penman (Penman, 1948) is widely used as reference crop evapotranspiration. To allow Kc(Habitat) values from different researchers to be comparable, it is useful to be able to convert ETo data developed using open water [Eo] or evaporation pan [E Pan] to ET Penman data. Ingram (1981; presented in Fermor, 1997) provides a relationship between ET Penman, Eo and E Pan (Table 2.3).

PERIOD	**COMPARISON**
Complete Year	ET Penman = Eo
Growing Season	ET Penman = 1.1 Eo
Complete Year	ET Penman = 0.7 E Pan
Growing Season	ET Penman = 0.8 E Pan

Table 2.3: Comparison Between ET Penman, Eo and E Pan
(Ingram, 1981 presented in Fermor, 1997)

CROP COEFFICIENT	METHOD FOR DEVELOPING ETo	EQUIPMENT NEEDED / DATA REQUIRED	ADVANTAGES	DISADVANTAGES
Kc(Habitat) Pan	Evaporation Pan	• Evaporation Pan - US Class 'A' Evaporation Pan or Colorado Sunken Pan • Rain gauge	• Simple method • Widespread (international) use • Relatively cheap equipment	• Provides very localised values • Evaporation pan must be sited properly to produce suitable data • Must be monitored regularly
Kc(Habitat) SAMS Grass	Penman-Monteith equation (using site-specific met data) CROPWAT / AWSET computer programme	• Automatic Meteorological Station with suitable parameters for calculating Penman-Montieth equation • Computer programme for analysing data	• Provides site specific values	• Equipment is expensive to purchase and maintain • Requires laptop computer for downloading data • Requires computer programme to analyse data
Kc(Habitat) LMS Grass	Penman-Montieth equation (using local met data) CROPWAT / AWSET computer programme (optional)	• Purchase data from Met Office in UK – may be either raw data or pre-calculated data • Computer programme for analysing data (optional)	• Data readily available from Met Office in UK • Does not require any fieldwork • Data can be purchased at any time during the project • Additional data analysis optional	• Data must be purchased • Data is not site specific • Requires computer programme to analyse data (optional)
Kc(Habitat) MORECS Grass	Penman-Monteith equation (using MORECS 2 data)	• Purchase data from Met Office	• Data readily available from Met Office • Does not require any fieldwork • Data can be purchased at any time during the project • No additional data analysis is required	• Data must be purchased • Data is not site specific - it covers a 40 km x 40 km area. • Kc(Habitat) MORECS Grass values only useful within the UK.

Table 2.4: Summary of Different Methods Used to Develop Kc(Habitat) Values

2.4 EVAPOTRANSPIRATION

The water use rates of wetland habitats are defined as the amount of water lost to the atmosphere via ET over a given period. The ET rate of a plant (Equation 2.10) is the sum of transpiration from the plant [Tr], the evaporation from bare soil [Es] and / or open water [Eo] and evaporation from the leaves of the vegetation (known as the interception, [I]).

$$\mathbf{ET = Tr + Eo + Es + I} \tag{2.10}$$

ET rates for a target habitat can be determined using a range of methodologies (see ASCE, 1996 for a review of available techniques, and Chapters 3 and 4 for reviews of techniques used to determine ET rates for reedbed and wet woodland habitats respectively). Most practical (ie not theoretical) methodologies will measure the actual rate of ET [ETa], rather than the potential rates [PET]. Blaney (1956; in Linsley et al, 1958) defined PET as

> '*the evapotranspiration that would occur where there was an adequate moisture supply at all times*'

The Working Group on Water Requirements of the International Commission on Irrigation and Drainage (ICID) provided an updated terminology listing (ICID, 1985, in ASCE, 1996), which stated that PET is

> '*the evaporation from a given surface when all surface-atmospheric interfaces are wet (saturated) so that there is no restriction due to either biological control or soil water content on the water vapour loss from the surface area.*'

When developing a wetland water budget, it is most valuable to know a habitat's PET, as this provides information with respect to the maximum water use of a habitat assuming no restriction on water availability. This project aims to develop crop coefficients for large reedbeds and provisional crop coefficients for wet woodland habitats that provide data associated with the potential maximum water use of the given habitat. Crop coefficients were calculated by determining ETo and ET(Habitat) values, and re-arranging Equation 2.2.

The calculation of ETo was carried out using the methodologies discussed in Section 2.3. The various methodologies used to determine ET(Reed) are discussed in Chapter 3, with the technique used in this project outlined in Chapter 5. Chapter 4 details published methodologies for determining ET rates from woodland habitats and species, with Chapter 6 providing details of the technique used in this project.

2.4.1 DEFINITIONS

This section provides brief definitions of some of the terms that are used in evapotranspiration studies and are discussed throughout this thesis.

Advection – the horizontal transport of heat energy by large-scale motions of the atmosphere. Evidenced by a horizontal gradient of temperature or humidity in the direction of the mean wind (ASCE, 1996).

Boundary Layer – a general term for the layer of air adjacent to a surface (Oke, 1987)

Clothes-line effect – horizontal heat transfer (advection) from warm and dry upwind area to a relatively cooler crop field resulting in increased ET(Habitat); particularly refers to the field border effects or to patchwork of small interspersed fields (Doorenbos and Pruitt, 1977).

Fetch – the upwind distance of a surface similar in nature to an area of interest, over which meteorological measurements are taken (ASCE, 1996).

CHAPTER 3. REEDBED INTRODUCTION AND WATER USE RATES

3.1 REEDBED INTRODUCTION AND DISTRIBUTION

Reedbeds are wetlands dominated by stands of the common reed *Phragmites australis*, wherein the water table is at or above ground level for most of the year. There are about 5000 ha of reedbed in the UK, and although this area is comprised of over 900 sites, only 20 are greater than 20 ha in size (UKBG, 1995). In the UK, the most extensive reedbeds are found in river floodplains and low-lying coastal plains. However, reedbeds occur in other situations such as along natural lake margins, within estuaries and within artificial sites, such as clay pits / gravel pits (Hawke and Jóse, 1996). The greatest concentration of UK reedbeds is located in East Anglia, with 36% of the UK's total reedbed area occurring in Norfolk and Suffolk (Gilbert et al, 1996, cited by Fermor, 1997), with other important areas including Anglesey and the south coast (Fermor, 1997).

Numerous texts are available which provide comprehensive details with respect to reedbed distribution, associated wildlife, hydrology, management and creation (e.g. Hawke and Jóse, 1996; Fermor, 1997; Bardsley, 2001b) and therefore this thesis presents only a brief overview of these topics (Sections 3.2 to 3.5). Section 3.6 presents a detailed review of different techniques to determine reedbed water use rates and the results from the studies.

3.2 REEDBED WILDLIFE

Reedbeds are amongst the most important habitats for birds in the UK (UKBG, 1995). Indeed there are a range of plants and animals specifically associated with reedbeds including: milk parsley; the reed leopard moth; bittern; bearded tit; marsh harrier; Cetti's and Savi's warblers; and harvest mouse. As reedbeds are a nationally scarce habitat (Hawke and Jóse, 1996) many of these species are also limited in their distribution. Bardsley (2001b) provides a comprehensive list of those species of conservation concern that are associated with reedbeds.

3.3 REEDBED HYDROLOGY

A summary of the published water level regimes for reedbeds is provided in Table 3.1. Haslam (1970) stated that water regimes in Phragmites populations are very variable, ranging from 2 m above the substrate to 1 m below it. She concluded that reeds grow best when they are flooded for at least several months of the year with nutrient rich water and have water levels ranging between +0.5 m to -0.2 m.

Hawke and Jóse (1996) presented a comprehensive review of reedbed water level management to meet different objectives (e.g. wildlife interest or reed harvest).

Many large reedbeds are managed and created with the aims of providing bittern feeding and breeding sites. Gilbert and Smith (2001) concluded that to provide bitterns with ideal feeding habitat, the water levels within a reedbed should fluctuate between +0.1 m and +0.25 m.

3.4 REEDBED RESTORATION AND CREATION

The Reedbed HAP recommended that reedbed creation should ideally take place in blocks of at least 20 ha. Figure 3.1 presents the restoration and creation targets outlined in the Reedbed HAP, and shows the amount achieved by the end of 1999 (after Bardsley, 2001b).

RESEARCHER	WATER LEVEL REGIME	WATER LEVELS	
		MINIMUM	MAXIMUM
Haslam (1970)	Total Range	- 1.0 m	+ 2.0 m
	Preferred Range	- 0.2 m	+ 0.5 m
Everett (1989) cited by Fermor (1997)	*Phragmites australis* thriving	N/a	0.3 to 0.5 m
Hawke and Jóse (1996) reproduced in Bardsley (2001b)	Optimum for reedbed wildlife - wet in winter and summer	N/a	Winter: + 1.0 m Summer: + 0.05 to + 0.3 m
	Optimum for reed harvest - wet in winter with summer drawdown	N/a	Winter: + 1.0 m Summer: +0.02 m
	Integration for wildlife and reed harvest - wet in summer with winter drawdown	N/a	Winter: below ground level Summer: + 0.3 to + 1.0 m
Newbold and Mountford (1998)	Total Range	- 0.1 m	+ 0.5 m
	Preferred Range	-0.2 m	0.0 m
Gilbert and Smith (2001)	Range suitable for bitterns to feed	N/a	Fluctuating between + 0.1 m and + 0.25 m

Table 3.1: Published Water Level Regimes for Reedbeds

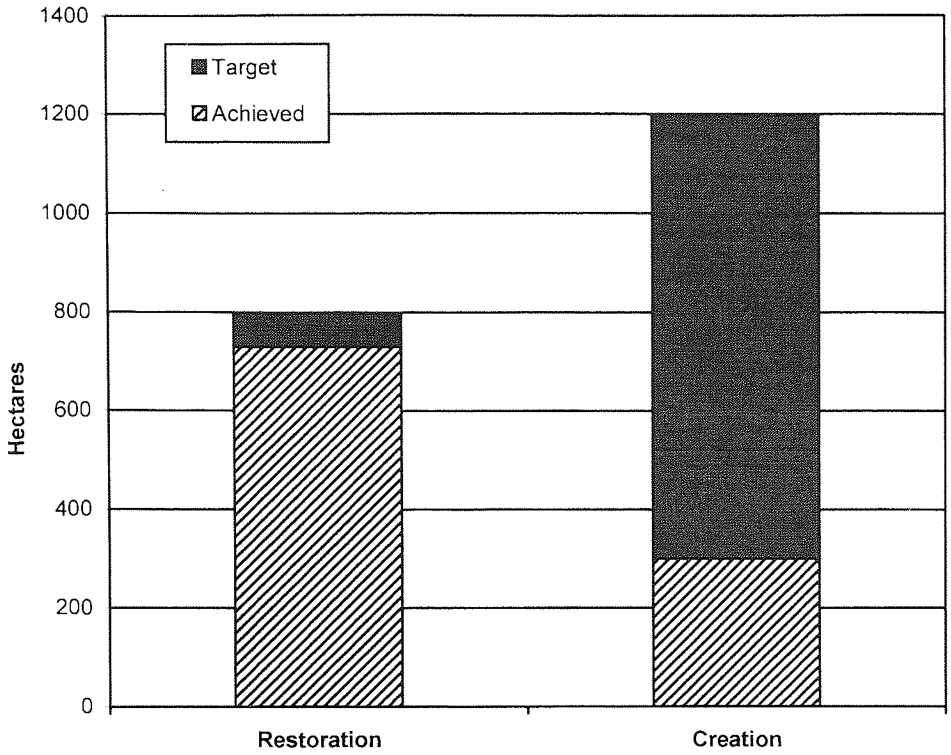

Fig. 3.1: UK HAP Targets for Reedbed Restoration and Creation
(after Bardsley, 2001)

To meet the Reedbed HAP targets, numerous organisations are aiming to create new reedbeds throughout the UK. One such scheme is a 30-year partnership project between Hanson plc and the Royal Society for the Protection of Birds (RSPB) to create one of the largest new wetlands in Europe comprising of reedbeds, open water and grassland on an ex-mineral extraction site. The sand and gravel extraction site in Cambridgeshire will be progressively donated to the RSPB as quarrying is completed. It is anticipated that the Ouse Fen nature reserve will eventually support breeding bitterns and will meet 40% of the HAP target for the creation of new reedbeds.

Gilbert and Smith (2001) stated that bitterns require 20 – 25 ha Phragmites dominated reedbeds containing a network of dykes and pools (which should make up 20% of the area) to breed. They concluded that those sites with more than one booming male were greater than 40 ha in size.

The common reed *Phragmites australis* is often used within 'constructed wetlands', i.e. wetlands that have been designed and built for the treatment of industrial, agricultural and domestic wastewater. Although they do provide some habitat for wildlife, they are often quite small in size (Nuttall *et al*, 1997) and are therefore not discussed further in this thesis.

3.5 PUBLISHED WATER USE RATES

Pribáň and Ondok (1986) stated that in general, wetlands are assumed to have high evapotranspiration rates, and cite a number of authors who suggest that evaporation from wetlands exceeds several times that from terrestrial ecosystems and even that from open water. Fermor (1997) presented a summary of ET(Wetland) and Kc(Wetland) values as derived by numerous authors.

There are a range of methods used for the determination of ET rates of different habitats and species. Hall et al (1996) suggested that the calculation of ET from a stand of vegetation usually involves one or more of the following techniques:

(1) measuring any reduction in the water content of the soil;
(2) measuring any increase in the water vapour content of the atmosphere which both surrounds and is above the vegetation;
(3) measuring the loss of water vapour from both a sufficient number and sufficiently well distributed range of leaf samples within the canopy.

Each of the techniques outlined above have their advantages and disadvantages, and it is often these that influence a project's chosen methodology.

A detailed review of the literature associated with the provision of values for ET(Reed) is presented in Fermor (1997) and Fermor et al (1999). Both of these studies concluded that there was a lack of relevant published data associated with the water use rates of reedbeds. Published ET(Reed) and Kc(Reed) values as researched by Fermor are presented in Table 3.3. This thesis presents additional data which has become available since Fermor finished his research in 1997.

Despite increased interest in reedbed habitats in recent years, Burba et al (1999a) concluded that there is:

> '*Very little reliable comparative information…on the ratio of the evapotranspiration from the emergent* [reedbed] *vegetation to evaporation from open water*.'

Until 1994, most ET experiments on reedbeds and *Phragmites australis* in particular had been of two types: those using Bowen ratio methods; and those using lysimeter methods (Gilman, 1994a). Recently the use of computer models as a method of estimating ET(Reed) has become more widespread in its use. A discussion of the different techniques used to determine reedbed water use rates and a summary of the results are given in Sections 3.5.1 to 3.5.4.

3.5.1 BOWEN RATIO

Burba et al (1999a) measured components of the surface energy balance using the Bowen ratio-energy balance method in three different communities (*Phragmites australis*, *Scirpus acutus* and open water) within a wetland. The study was conducted during the growing season of 1994 at Ballards Marsh, in the Sandhills region of north-central Nebraska, an area characterised as a semi-arid prairie consisting of grass-covered sand dunes and interdunal valleys occupied by marshes, lakes or wet meadows.

The Bowen ratio is a widely used micrometeorological method based on the heat-balance equation in which quantitatively unimportant components (heat storage, metabolic heat consumption and production) are neglected, and heat advection is assumed to be of negligible importance (Pribáň and Ondok, 1986). To determine ET(Reed) using the Bowen Ratio method, Burba et al (1999a) measured meteorological parameters which included: net radiation; incoming and outgoing short wave radiation; air temperature and humidity gradients (measured at two points above the vegetation cover); mean water temperature; soil heat flux; water depth; mean horizontal wind speed (measured at three points above the vegetation canopy); wind direction and atmospheric pressure. Latent heat flux (the measurement of ET) was calculated using Equation 3.1, with the Bowen ratio calculated using Equation 3.2.

$$\lambda ET = \frac{R_n - G}{1 + \beta} \tag{3.1}$$

where:

λET is the energy available for evapotranspiration in MJ m^{-2} d^{-1};

$R_n - G$ is the net radiation minus soil or water heat flux density in MJ m^{-2} d^{-1};

β is the Bowen ratio.

$$\beta = \frac{\gamma \Delta T}{\Delta e} \tag{3.2}$$

where:

β is the Bowen ratio;

γ is the psychometric constant;

ΔT is the vertical difference of temperature in ^{o}C; and,

Δe is the vertical difference of vapour pressure in kPa $^{o}C^{-1}$.

The authors stated that several prior studies concerned with energy fluxes in a single community wetland had reported the influence of meteorological factors (including: solar radiation; wind speed; air and water temperatures; vapour pressure deficit and albedo), and biological factors (including: leaf area; stomatal conductance; plant height; species composition and development), on ET rates.

Burba et al (1999a) presented average ET(Reed) values for the early to peak growth stages of 4.44 mm day^{-1} (with a range of 2.5 to 6.5 mm day^{-1}) and stated that this average fell to 2.5 mm day^{-1} between early September and late October. Average ET(Reed) and Eo values for the months of June to October were determined by the author of this thesis using a figure presented in Burba's paper. Table 3.3 presents the developed ET(Reed) and Kc(Reed) values.

Part of the same study is also presented in Burba et al (1999b), where the focus is purely on the surface energy fluxes of *Phragmites australis*. This paper presented the same basic data but also illustrated the relationship between actual evapotranspiration (ETa) and potential evapotranspiration (PET). The authors stateded that during the early and peak growth stages, ETa was 75-100% of PET, and during senescence ETa was considerably smaller (10-75% of PET). The exception to this was noted on cloudy days when both ETa and PET were small. Further investigation showed that the canopy stomatal resistance controlled the transpiration rate and therefore affected the ETa/PET ratio.

In a study recently completed at Cranfield University, the ET rates from a large reedbed in Kent (Stodmarsh SSSI) were calculated using a Bowen ratio station sited within the reedbed, as part of a water budget for the nature reserve. Despite technical problems with the equipment, preliminary results showed ET(Reed) was 2.0 mm day^{-1} in June 2001 and 2.1 mm day-1 in July 2001. These results correspond to 58% and 56% respectively of ET Penman Open Water (Peacock and Hess, 2001).

Gilman et al (1998, cited by Acreman et al, 2002), used a Bowen ratio station to calculate ET from an area of newly planted reeds at Hams Wall reserve in Somerset, UK. The authors calculated that reedbed ET was 5% less than Penman PET rates between April and July, but increased to 20% higher in August and fell again to 7% higher in September.

3.5.2 EDDY-CORRELATION

Acreman et al (2002) used an open-path eddy correlation device (Mark 2 "Hydra" system) for the direct measurement of evapotranspiration from a reedbed at Hams Wall reserve in Somerset, UK. Shuttleworth et al (1988) stated that eddy correlation represented '*the most elegant meteorological method for measuring surface atmospheric fluxes*' and concluded that the Mark 2 "Hydra" was specifically designed to provide routine measurements of surface energy flux with minimal supervision.

Oke (1987) stated that all atmospheric entities show short-period fluctuations about their longer term mean value. This is the result of turbulence which causes eddies to move continually around carrying with them their properties derived elsewhere. The properties contained by and therefore transported within an eddy are its mass, its vertical velocity and the volumetric content of any entity it possesses.

To calculate the surface energy flux the process is split into different components which can be measured using: a one-dimensional ultrasonic anemometer: a lightweight cup anemometer; a fine thermocouple; and infrared hygrometer. These instruments are sited above the crop being studied (5 m above the water surface at Ham Wall) and are coupled to an on-line computer. Fluxes are calculated hourly and are stored along with a quality control index which shows when the measurement might be in error (Acreman et al, 2002). In addition to the measurement of heat and water vapour fluxes, the system provides measurements of momentum flux, net radiation, air temperature, humidity and wind speed.

The data collected by the Mark 2 "Hydra" is then transferred to a computer via floppy disk and analysed using the HYDRAN program. This programme adjusts / corrects the data and provides a measurement of the latent heat flux (Equation 3.3).

$$\lambda E_m = (1 + 1.6r)\left(\lambda E_R + \frac{\lambda < \rho_v >}{\rho_a}\frac{Hf}{c_p T_k}\right)$$

(3.3)

where:

λET_m is the measured energy available for evapotranspiration;

λET_R is the raw energy available for evapotranspiration;

r is the mean mixing ratio;

λ is the latent heat vapourisation of water;

Hf is the sensible heat flux;

ρ_a is the density of air;

c_p is the specific heat of air; and,

ρ_v is the true humidity fluctuation;

T_k is the temperature of air (in degrees Kelvin).

The developed latent heat flux (energy available for evapotranspiration) is then corrected to give the true latent heat flux using Equations 3.4 and 3.5.

$$\lambda ET = \lambda ET_m + \frac{\lambda}{\rho_a c_p}\frac{B_o Q < \rho_v >}{B} Hf$$

(3.4)

and

$$B = [B_o Q(T - Ts)]$$

(3.5)

where:

λET_R is the true latent heat flux;

λET_m is the latent heat flux;

λ is the latent heat vapourisation of water;

ρ_a is the density of air;

c_p is the specific heat of air; and,

B_o is a calibration parameter (typically 0.3);

Q is a calibration parameter (typically 0.008);

ρ_v is the true humidity fluctuation;

Hf is the sensible heat flux;

T_s is the stabilised temperature for the detector and filter in the infrared hygrometer

Further details regarding the development, calibration and use of the Mark 2 "Hyrda" system for measuring eddy correlation are provided in Shuttleworth et al (1988).

The ET(Reed) data produced by Acreman et al (2002) was compared to Penman PET measured at the same site and the ratio of daily measured ET(Reed) to Penman PET was 1.19 between June and 4 October 1999 and 2.92 between 4 October and 25 November 1999. Measured ET(Reed) exceeded measured ET at a nearby grassland wetland by 14% (or 50 mm over the 5 month period). Acreman et al (2002) stated that this was due to the higher roughness length of the reedbed and the lower effective surface resistance of the reed / open water assemblage and went on the conclude that the:

> *'restoration of reedbeds may have important implications for local water resources, especially where wetlands are conserved by pumping from rivers or groundwater.'*

3.5.3 COMPUTER MODELS

Within the scientific community, the use of computer modelling to predict environmental parameters has increased, particularly within the last 10 years. Many researchers are now using empirical field data to create computer models which allow the user to investigate the effect of changing given parameters (such as species type, soil type, cultivation techniques) on the ET rates of a specified crop or habitat. A summary of the models discussed in this section is provided in Table 3.2.

Herbst and Kappen (1999) studied the transpiration and various components of evaporation from a reed (*Phragmites australis*) belt on the western shore of Lake Belau, in the Bornhoved lake district of northern Germany, a site which was chosen to represent a '*typical central European reed ecosystem*'. The authors used an evaporation model based on equations given by Shuttleworth and Wallace (1985, in Herbst and Kappen, 1999) and modified the 'two-layer approach' to take into account the process of interception evaporation (see Table 3.2 for details of model). Using the model, ET(Reed) was estimated from meteorological data collected between 1991 and 1993, which included: water and sediment temperatures; incoming solar radiation; gross precipitation; photosynthetic photon flux density; air temperature and relative humidity. In addition, leaf area index was estimated every two weeks between 1991 and 1994.

The authors stated that the annual evapotranspiration from the reed belt generally exceeded the annual evaporation from the open lake surface. Depending on the meteorological conditions, ET(Reed) ranged between 824 and 1324 mm annum^{-1} and the ratio of ET versus Eo ranged between 1.5 and 2.0. A more detailed breakdown of the results of this study is included in Table 3.4.

The study showed that the evaporation of intercepted rainfall was low compared to the transpiration rates of the reeds, but the evaporation from the water surface between the reed stalks was significant during the whole year. The authors concluded that, in 3 of the 4 study years, ET(Reed) exceeded annual gross precipitation, and state that this:

'emphasises the general significance of reed transpiration for the water balance of lakes and wetlands.'

Souch et al (2000) carried out a study to investigate the availability of surface water as an opportunity or a constraint on the creation or enhancement of those freshwater wetland habitats with biodiversity priority in the Environment Agency's Anglian region. One of the habitats with biodiversity priority used in this study was reedbeds. The authors used a daily soil water simulation model (WaSim model) to predict the water requirements for the winter (October – March) and summer (April – September) periods for NVC habitat S4 (Rodwell, 1991), for both 'ponding' soils and 'draining' soils which they define as:

(1) 'Ponding' soils are soils where the downward movement of water (seepage) is negligible and the soil water status is simply the result of inputs of water from rainfall and outputs of evapotranspiration; and,

(2) 'Draining' soils represent more permeable soils with a greater rate of seepage. The water supply to the site must meet the evapotranspiration demands of the plants and the seepage loss.

During the winter, NVC habitat S4 was predicted to require 90 mm in ponding soils and 312 mm in draining soils, whereas during summer the requirements were 116 mm in ponding soils and 287 mm in draining soils.

It should be noted that the water requirements for 'draining' soils do not relate to the amount of water lost by the habitat through ET as the values also include the amount of water required for seepage. Therefore the results for 'ponding' soils only are included in Table 3.3.

In addition, Souch et al (2000) used data made available to Cranfield HydroEcology Centre and presented an annual crop coefficient for S4 reedbeds of 1.2.

MODEL TITLE	REFERENCES	MODEL FOCUS	UNDERLYING PRINCIPLES	TIME PERIOD
Modified Shuttleworth-Wallace two-layer model approach	Herbst and Kappen (1999) Shuttleworth and Wallace (1985)	To determine transpiration and various components of evaporation from a reed-belt in north Germany	The Shuttleworth-Wallace two-layer model considers two layers of evaporation surfaces - vegetation and soil. It uses the Penman-Monteith equation and a detailed network of canopy, soil surface and aerodynamic resistances to calculate water vapour flux from standard hourly meteorological variables. Herbst and Kappen (1999) modified the approach to take into account the process of interception.	Meteorological parameters collected between 1991 and 1993. Model provided daily sums of ET and ETo.
WaSim	Souch et al (2000) Hess and Counsell (2000)	To calculate the water requirements of various wetland communities	The program calculates a daily soil water balance to predict the water table position and water content of the unsaturated zone on a daily basis. Rules are set for minimum soil water conditions for each month of the year. Whenever these conditions are exceeded, the program calculates the amount of water needed to bring the soil back to the minimum condition. The program was modified to allow timing of water application to be controlled by 'saturation deficits' or depth of ponding.	Daily

Table 3.2: Summary of Computer Models Used to Estimate ET(Reed)

3.5.4 LYSIMETER STUDIES

Gilman (1993) stated that there is considerable difficulty assigning catchment boundaries to wetlands, across which certain of the flows (e.g. groundwater and surface flow) will always be zero. This can be done however, by building physical barriers to prevent lateral flows, and therefore effectively removing these factors from the water budget (see Equation 2.1). The lysimeter method involves containing the elementary area in a watertight tank (Gilman, 1993), and therefore rendering the evapotranspiration process more accessible for measurement.

The research undertaken by Fermor (1997) was based on a technique developed by Bernatowicz et al (1976), and used lysimeters (referred to as phytometers) to measure monthly ET rates of *Phragmites australis* and develop monthly Kc(Reed) values. In Fermor's study ET(Reed) results for two sites within the UK: Teeside International Nature Reserve (TINR); and Himley Sewage Treatment Works (STW), were calculated. Experimental works at TINR were carried out between 1994 and 1997, and at Himley STW between 1996 and 1997.

The outcome of Fermor's research, supplemented by an additional study undertaken by Cranfield University, are presented in Fermor et al (2001). The additional site was Walton Lake, Milton Keynes, where experimental works were undertaken between 1994 and 1997. The values of ET(Reed) and Kc(Reed) for each month at each of the sites are summarised in Table 3.4.

Table 3.4 shows that ET(Reed) and Kc(Reed) values are much higher for the sites studied by Fermor (1997) with Kc(Reed) values at TINR and Himley STW above 1 between June and December, and July and November respectively. The Kc(Reed) values for the site at Walton Lake are less than 1 throughout the year apart from in January.

The authors suggested that the differences in Kc(Reed) are influenced by the age, size and shape of the reedbed in addition to the surrounding land-use and nutrient status and concluded that:

'The range of [Kc(Reed)] *values obtained indicate that a single crop coefficient for reed is not appropriate...A designer selecting Kc(Reed) values...for use in the hydrological design of a reedbed system should choose the series of values which most clearly reflect the characteristics of the site under consideration.'*

Bardsley (2001b) used a Kc(Reed) value of 1.4 as part of a wetland design case study in Worcestershire, UK. There is no discussion of how this value was determined.

3.5.5 DISCUSSION

Despite increased interest in the creation of reedbeds (particularly large reedbeds) within the last 5 years, there are still relatively few published studies concerned with their water use rates. Using data presented in Tables 3.3 and 3.4, Figure 3.2 was developed to present the mean monthly published ET(Reed) rates, with the bars showing the maximum and minimum ET(Reed) values.

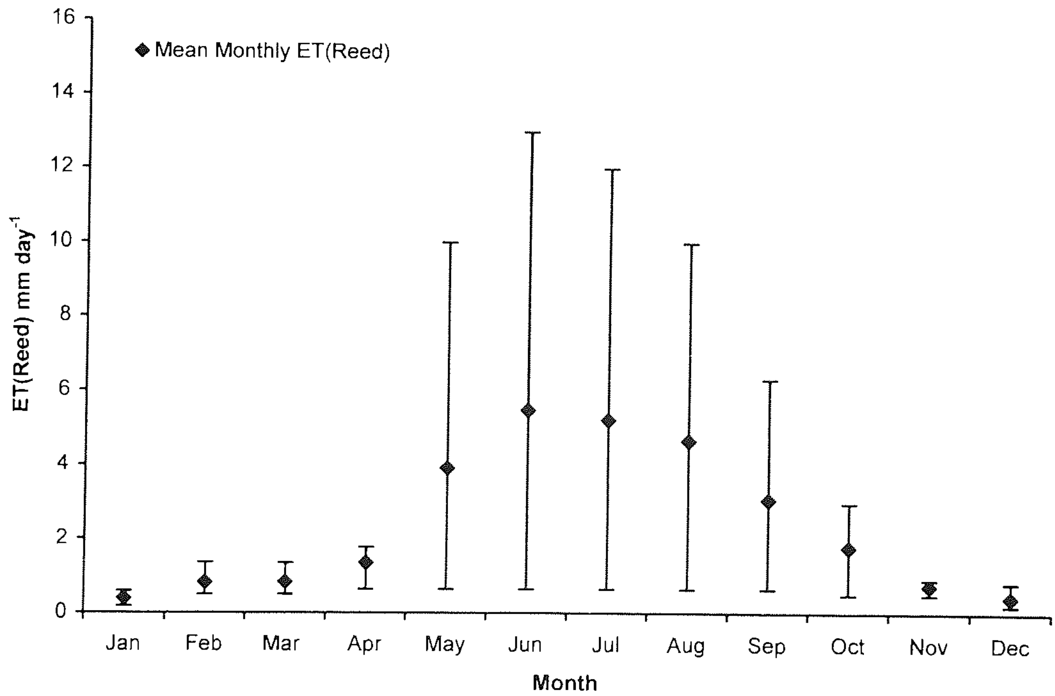

Fig. 3.2: Summary of Published Mean, Maximum and Minimum Monthly ET(Reed)

Figure 3.2 clearly shows that, despite the wide range of values published, mean ET(Reed) is minimal during the winter months, but increases significantly between April and May, reaching a peak in June and decreasing steadily from this point. From the values presented, it can be concluded that ET(Reed) is likely to be an important factor within a reedbed's water balance, particularly during summer months when rainfall input is likely to be lower.

The data presented in Figure 3.2 supports a statement by Haslam (1970) that evapotranspiration in reedbeds mostly occurs between May and September, being greatest in July and August. She concluded that annual losses are greatest in hot summers and with large biotypes.

Tables 3.3 and 3.4 show the range of reference crop evapotranspiration values used to create Kc(Reed) crop coefficients which include evaporation from an evaporation pan [E Pan]; potential evapotranspiration values determined using Penman equation [Penman PET]; evaporation from open water [Eo]; and, potential evapotranspiration from grass [PET Grass] calculated using the Penman-Monteith equation.

Annual Kc(Reed) values can be used to develop annual water budgets, but will not provide useful data for the monthly management of water and the calculation of monthly water deficits. Fermor et al (2001) are the only authors to present monthly Kc(Reed) values for the whole year, as other authors have focussed their attention during those months when the reedbeds are growing rapidly (June to September).

The measurement of ET(Reed) and subsequent calculation of monthly Kc(Reed) values will form part of the 'contribution to knowledge' made by this research project. Developed values will be focussed on large reedbeds and will provide monthly values covering the whole year.

RESEARCHER	STUDY SITE	TECHNIQUE	ET(Reed)	Kc(Reed)
Kuzencov (1949) cited by Bernatowicz (1976)	Not known	Lysimeter located on land	N/a	Kc (Reed) Pan 1.5 – 2.5
Uryvaev (1953) cited by Krowlikowska (1971)	Not known	Not known	N/a	Kc(Reed) Eo up to 3.0
Gel'bukh (1964)	Reedbed, Russia	Lysimeter within reedbed	N/a	Kc(Reed) Eo 0.8 – 2.5
Rudescu et al (1965) cited by Krowlikowska (1971)	Reedbelt, River Danube Stem density = 30 / m^2 Stem height = 4.5 m	Cut-stem weight changes	5 mm day^{-1}	N/a
Tuschhl (1970) cited by Smid (1975)	Reedbed, Austria	Cut-stem weight changes	13 mm day^{-1} (June)	N/a
Krowlikowska (1971)	Reedbed, Mikolajskie Lake Stem density = 54 / m^2 Stem height = 2.7 m	Cut-stem weight changes	2.23 mm day^{-1} (does not include Eo from within stand)	N/a
Gavenciak (1972) cited by Smid (1975)	Southern Slovakia	Lysimeter located within a lawn	17.9 to 27.8 mm day^{-1}	N/a
Kvet (1973) cited by Smid (1975)	Reedbed, Czechoslovakia	Cut-stem weight changes	7.8 mm day^{-1} (July)	N/a

Table 3.3: Summary of Findings of Fermor (1997) Literature Review - ET(Reed) and Kc(Reed)

RESEARCHER	STUDY SITE	TECHNIQUE	ET(Reed)	Kc(Reed)
Kvet and Rejmankova (unpublished) cited by Smid (1975)	Reedbed, Czechoslovakia	Lyismeter located within lawn, *Typha angustifolia*	10 to 12 mm day^{-1} (summer)	N/a
Smid (1975)	Reedbed, Czechoslovakia Stem density = 50-120 / m^2	Bowen Ratio	6.9 mm day^{-1} (July)	Kc(Reed) Eo > 1.0
Bernatowicz (1976)	Reedbed, Poland	Lysimeter within reedbed	N/a	Kc(Reed) Eo = 0.92 – 1.27
Gilman and Newson (1983) cited by Crundwell (1986)	Reedbed, UK	Lysimeter within reedbed	N/a	Kc(Reed) Eo = 1.2 – 2.0
Burgoon et al (1997)	Reedbed, USA	Mass water balance calculation	6.4 mm day^{-1} (May/June)	Kc(Reed) Grass = 1.0

Table 3.3 cont.: Summary of Findings of Fermor (1997) Literature Review - ET(Reed) and Kc(Reed)

RESEARCHER	STUDY SITE	TECHNIQUE	ET(Reed)	Kc(Reed)
Gilman et al, 1998 Cited by Acreman et al (2002)	Reedbed, Hams Wall, Somerset, UK. (reeds newly planted and not full height)	Bowen Ratio	N/a	Kc(Reed) Penman PET = 0.95 (Apr-Jul) 1.20 (Aug) 1.07 (Sep)
Burba et al (1999a)	Reedbed, North-central Nebraska	Bowen ratio-energy balance method	4.49 mm day^{-1} (Jun) 5.02 mm day^{-1} (Jul) 4.30 mm day^{-1} (Aug) 3.18 mm day^{-1} (Sep) 1.30 mm day^{-1} (Oct)	Kc(Reed) Eo = 0.68 (Jun) 0.98 (Jul) 0.91 (Aug) 1.10 (Sep)
Herbst and Kappen (1999)	Reedbed, Lake Belau, Bornhoved, Northern Germany	A two-layer evaporation model of the Shuttleworth-Wallace-type.	3.63 mm day^{-1} (1992) 2.26 mm day^{-1} (1993) 2.80 mm day^{-1} (1994) 3.44 mm day^{-1} (1995) Mean = 3.03 mm day^{-1}	Kc(Reed) Eo = 1.92 (1992) 1.53 (1993) 1.51 (1994) 1.72 (1995) Mean = 1.67
Souch et al (2000)	Environment Agency Anglian region (no specific study site)	ET rates – WaSim model Kc rates - Unknown	Ponding Soils (average) 0.49 mm day^{-1} (Oct-Mar) 0.63 mm day^{-1} (Apr-Sep)	Kc(Reed) = 1.2
Bardsley (2001b)	Not known	Not known	N/a	Kc(Reed) = 1.4

Table 3.4: Summary of Findings of Current Literature Review - ET(Reed) and Kc(Reed)

RESEARCHER	STUDY SITE	TECHNIQUE	ET(Reed)	Kc(Reed)
Fermor et al (2001)	Reedbed, Teeside International Nature Reserve, UK	Lysimeters installed within reedbed	0.29 mm day^{-1} (Jan) 1.36 mm day^{-1} (Feb) 1.34 mm day^{-1} (Mar) 1.76 mm day^{-1} (Apr) 2.25 mm day^{-1} (May) 4.22 mm day^{-1} (Jun) 4.12 mm day^{-1} (Jul) 4.35 mm day^{-1} (Aug) 3.24 mm day^{-1} (Sep) 2.75 mm day^{-1} (Oct) 0.90 mm day^{-1} (Nov) 0.81 mm day^{-1} (Dec)	Kc(Reed) MORECS Grass = 0.94 (Jan) 1.27 (Feb) 0.89 (Mar) 0.97 (Apr) 0.83 (May) 1.38 (Jun) 1.37 (Jul) 1.55 (Aug) 1.82 (Sep) 1.70 (Oct) 1.05 (Nov) 1.59 (Dec)
	Treatment Reedbed, Himley Sewage Treatment Works, West Midlands, UK	Lysimeters installed within reedbed	0.18 mm day^{-1} (Jan) 0.82 mm day^{-1} (Feb) 0.73 mm day^{-1} (Mar) 1.38 mm day^{-1} (Apr) 2.41 mm day^{-1} (May) 3.84 mm day^{-1} (Jun) 4.99 mm day^{-1} (Jul) 6.19 mm day^{-1} (Aug) 6.30 mm day^{-1} (Sep) 2.96 mm day^{-1} (Oct) 0.90 mm day^{-1} (Nov) 0.21 mm day^{-1} (Dec)	Kc(Reed) MORECS Grass = 0.67 (Jan) 0.75 (Feb) 0.50 (Mar) 0.96 (Apr) 0.81 (May) 1.04 (Jun) 1.19 (Jul) 1.47 (Aug) 2.10 (Sep) 1.50 (Oct) 1.27 (Nov) 0.60 (Dec)

Table 3.4 cont.: Summary of Findings of Current Literature Review - ET(Reed) and Kc(Reed)

RESEARCHER	STUDY SITE	TECHNIQUE	ET(Reed)	Kc(Reed)
Fermor et al (2001) cont.	Reedbelt, Walton Lake, Milton Keynes, UK	Lysimeters installed within reedbed	0.58 mm day^{-1} (Jan) 0.61 mm day^{-1} (Feb) 0.76 mm day^{-1} (Mar) 1.62 mm day^{-1} (Apr) 1.78 mm day^{-1} (May) 2.69 mm day^{-1} (Jun) 3.33 mm day^{-1} (Jul) 2.42 mm day^{-1} (Aug) 1.93 mm day^{-1} (Sep) 1.34 mm day^{-1} (Oct) 0.67 mm day^{-1} (Nov) 0.20 mm day^{-1} (Dec)	Kc(Reed) MORECS Grass = 1.09 (Jan) 0.46 (Feb) 0.48 (Mar) 0.78 (Apr) 0.63 (May) 0.77 (Jun) 0.86 (Jul) 0.72 (Aug) 0.75 (Sep) 0.82 (Oct) 0.76 (Nov) 0.97 (Dec)
Peacock and Hess (2001)	Reedbed, Stodmarsh SSSI, Kent, UK.	Bowen ratio	2.0 mm day^{-1} (Jun) 2.1 mm day^{-1} (Jul)	Kc(Reed) Penman Eo = 0.58 (Jun) 0.56 (Jul)
Acreman et al (2002)	Reebed, Hams Wall, Somerset, UK. (reeds full height)	Eddy Correlation	N/a	Kc(Reed) Penman PET = 1.19 (June – Sep) 2.29 (Oct – Nov)

Table 3.4 cont.: Summary of Findings of Current Literature Review - ET(Reed) and Kc(Reed)

CHAPTER 4. WET WOODLAND INTRODUCTION AND WATER USE RATES

4.1 WET WOODLAND INTRODUCTION

This chapter provides an introduction to wet woodland: its distribution (Section 4.2); current legal protection and identified threats (Section 4.3); and associated wildlife (Section 4.4). Section 4.5 focuses on wet woodland creation and restoration, with the current state of knowledge regarding the hydrology of wet woodland habitats presented in Section 4.6. This knowledge is summarised in Section 4.7. An extensive review of the different methods used to determine the water use rates of wet woodland habitats and species is included in Section 4.8.

The Wet Woodland HAP defines UK wet woodlands as those woodlands falling within the National Vegetation Classification (NVC) categories W1 - W7 (see Rodwell, 1991). Table 4.1 lists these communities and shows that the habitats are characterised by the dominance of alder (*Alnus glutinosa*), downy birch (*Betula pubescens*), and various willows, sallows and osiers (*Salix* sp.).

Wet woodlands often develop around open waters and on wet ground as part of the process of succession, where canopy tree species colonise the area first and as terrestrialisation increases and the canopy grows causing deeper shading at ground level, the field and ground layers develop (Rodwell and Patterson, 1994). This process results in the characteristic canopy and ground layer flora species associated with each habitat type (Table 4.2). Rodwell and Patterson (1994) concluded that the differences in species composition between wet woodland types and even within wet woodlands were related to: variations in the wetness of the ground; the base-richness of the soils and waters; and, the amount of nutrients in the system.

NVC CODE	HABITAT NAME
W1	*Salix cinerea – Galium palustre* woodland
W2	*Salix cinerea – Betula pubescens – Phragmites australis* woodland
W3	*Salix pentandra – Carex rostrata* woodland
W4c	*Betula pubescens – Molinia caerulea* woodland: Sphagnum sub-community
W5	*Alnus glutinosa – Carex paniculata* woodland
W6	*Alnus glutinosa – Urtica dioica* woodland
W7	*Alnus glutinosa – Fraxinus excelsior – Lysimachia nemorum* woodland

Table 4.1: NVC Classifications of Wet Woodland Habitats

4.2 WET WOODLAND DISTRIBUTION

Wet woodland occurs throughout Britain on poorly drained or seasonally wet soils, in situations where wetness of the ground is (or until recently has been) the overriding element of the environment (Rodwell, 1991). Thus, wet woodlands typically occur on: floodplains; as successional habitat on fens, mires and bogs; along streams and hillside flushes; and, in peaty hollows (UKBG, 1998).

Wilkinson et al (1999) suggested that wet woodland communities would have been common historically in Britain prior to forest clearance. Paleoecological studies (Bennet, 1989; Brown, 1988; as cited by Wilkinson et al, 1999) suggested that these woodlands covered large areas of the Wash, Severn estuary and Somerset Levels 5000 years ago, in addition to smaller wet woodland patches which would have occurred in river valleys and wetlands.

NVC CODE	CHARACTERISTIC SPECIES	
	Canopy / Field Layer	**Ground Layer**
W1	Grey sallow (*Salix cinerea*)	Soft rush (*Juncus effusus*) Common marsh bedstraw (*Galium palustre*) Water mint (*Mentha aquatica*)
W2	Alder (*Alnus glutinosa)*	Common reed (*Phragmites australis*) Meadowsweet (*Filipendula ulmaria*) Hemp agrimony (*Eupatorium cannabinum*) Wild angelica (*Angelica sylvestris*) Marsh thistle (*Cirsium palustre*) Yellow loosestrife (*Lysimachia vulgaris)* - locally Purple loosestrife (*Lythrum salicaria*) - locally
W3	Grey sallow (*Salix cinerea*) Northern bay willow (*Salix pentandra*)	Bottle sedge (*Carex rostrata*)
W4c	Downy birch (*Betula pubescens*) Grey sallow (*Salix cinerea*)	Purple moor-grass (*Molinia caerulea*) Bog mosses (*Sphagnum* spp.)
W5	Alder (*Alnus glutinosa)* Grey sallow (*Salix cinerea*)	Great tussock sedge (*Carex paniculata*) Lesser pond sedge (*Carex acutiformis*) Tufted sedge (*Carex elata*)
W6	Alder (*Alnus glutinosa*) Grey sallow (*Salix cinerea*) Goat willow (*Salix caprea*) Osier willow (*Salix viminalis*) Purple willow (*Salix purpurea*) Almond willow (*Salix triandra*) Crack willow (*Salix fragilis*)	Nettle (*Urtica dioica*) Great willowherb (*Epilobium hirsutum*) Bittersweet (*Solanum dulcamara*) Cleavers (*Galium aparine*)
W7	Alder (*Alnus glutinosa*) Ash (*Fraxinus excelsior*) Downy birch (*Betula pubescens*) Grey sallow (*Salix cinerea*)	Yellow pimpernel (*Lysimachia nemorum*) Creeping buttercup (*Rannunculus repens*) Meadowsweet (*Filipendula ulmaria*) Opposite-leaved golden saxifrage (*Chrysosplenium oppositifolium*) Lady fern (*Athyrium filix-femina*) Soft rush (*Juncus effusus*) Tufted hair-grass (*Deschampsia cespitosa*) Pendulous sedge (*Carex pendula*) Remote sedge (*Carex remota*) Smooth-stalked sedge (*Carex laevigata)*

Table 4.2: Characteristic Species of Wet Woodland NVC Habitat Types
(after Rodwell and Patterson, 1994)

Within the last 200 years, the riparian zone throughout Britain and Europe has been destroyed or damaged by river regulation, power generation, pollution and intensive agriculture (MacKenzie, 1996). Harper et al (1997) concluded that floodplain woodland loss in the UK accelerated after the Second World War as the result of agricultural intensification encouraged initially by the UK government, and latterly by EC agricultural policy. This loss was particularly high for riparian trees as lowland rivers were 'improved' for agricultural and flood-defence purposes and the extensive removal of trees occurred in both channel-straightening and re-alignment projects. Indeed Rackham (1995) stated that there are now no ancient woods to be found on river terraces, fens, or floodplains, as these areas were all too valuable as meadow.

Traditionally patches of wet woodland would have been coppiced and grazed and some wet woodlands along stream-sides are still managed as strips of coppice or pollards, the Forestry Commission (1994) concluded that many floodplain wet woodlands in lowland England have been reduced to a line of old pollarded willows on riverbanks.

The current distribution of wet woodlands within Britain is related to the pattern of occurrence of appropriate sites within the regions of broadly suitable climate and within these regions, wet woodlands mainly occur as small woods or localised patches in larger woods (Forestry Commission, 1994: Peterken, 1996). Survey information from the former Nature Conservancy Council estimated there to be 25,000 – 30,000 ha of ancient semi-natural woodland of this type (Forestry Commission, 1994). However, the UKBG (1998) suggested that the area of recent wet woodland may be at least as large again and a crude estimate of the total wet woodland area in the UK is therefore 50,000 – 70,000 ha.

Wet woodlands tend to occur either on fen peat or on alluvium and Figures 4.1a and 4.1b illustrate the main locations within the UK (Rodwell and Patterson, 1994). Table 4.3 details the typical location and habitat ranges of wet woodland within the UK. It should be noted that there appears to be some inconsistency between authors with respect to the base status and nutrient status for NVC habitat W3.

Wheeler et al (2001) studied the ecological relationships of wet woodlands, fens and associated habitats in Wales. Using species data collected from 141 wet woodland sites, the authors used a trait-based data processing procedure called WETSPEC (Wetland Species Prediction of Environmental Conditions) to develop estimates of the required environmental conditions of wet woodlands in Wales. The model is based on given environmental conditions associated with individual species and given 'functional' biological traits of species (both derived from databases held by the University of Sheffield). The developed broad environmental attributes for each wet woodland category in Wales are shown in Table 4.4. Although Rodwell (1991) suggested that W3 habitat had not been recorded in Wales he concluded that its natural range probably extends there which would explain why Wheeler et al (2001) presented information with respect to the environmental attributes of this habitat.

Fig. 4.1a: Main Zones of Wet Woodland on Alluvium
(Rodwell and Patterson, 1994)

Fig. 4.1b: Main Zones of Wet Woodland on Fen Peat
(Rodwell and Patterson, 1994)

NVC CODE	TYPICAL LOCATION	HABITAT RANGE IN THE UK
W1	On water-logged mineral soils[2], typically on flood-plain fens, open water transitions and basin mires[3].	Scattered throughout the lowlands. This woodland is especially well developed in more sheltered situations around the west, in clifftop flushes and around dune slacks.
W2	On flood-plain mires[3] and where the influence of base-rich waters remains strong in lowland fens, but where the peat surface is raised above the limit of winter flooding[2].	Extensive examples in East Anglia and around the Cheshire and Shropshire Meres.
W3	Typical of peat soils kept moist by base-rich and calcareous groundwater in open-water transitions and basin mires[1,3]. Around basin mires with more base poor and nutrient poor waters[2].	Locally throughout the sub-montane zone of northern Britain. Not recorded in Wales although its range probably extends there[1].
W4	Associated with moderately acid peats on a variety of mire types, for example drying ombrogenous peats and soligenous fens[3]. Their range extends into lowland valley bogs and into the water tracks and hill slope flushes of the upland fringe where peaty gleys are kept very wet by seepage of base-poor and nutrient-poor waters[2].	Locally throughout the lowlands and upland fringes.
W5	Usually on base-rich mesotrophic to eutrophic sites where fen peats accumulate in floodplains, basins and valley fens. W5c is typical of valley-side springs and seepage lines[3]. This woodland often develops early in the primary colonisation of swampy vegetation around standing or sluggish open waters[2].	Local but quite widespread in the English lowlands, with very few localities in Scotland and Wales.
W6	In nutrient-rich systems, where fen peats have been drained and disturbed, or the waters enriched by nutrients or where rich alluvium accumulates in mature river valleys or around silting water bodies[2]. Usually on flood-plain mires enriched by silt[3].	Widespread but locally in the lowlands.
W7	In base-rich flushes on valley sides and where surface-water gleys show some local nutrient enrichment[2].	In the wetter parts of southern Britain and more widely in the north and west.

[1] Rodwell (1991)
[2] Rodwell and Patterson (1995)
[3] Newbold and Mountford (1997)

Table 4.3: Typical UK Locations and Habitat Ranges of Wet Woodland
(after Rodwell, 1991; Rodwell and Patterson, 1995; Newbold and Mountford, 1997)

NVC CODE	PREDICTED ENVIRONMENTAL ATTRIBUTES					TYPICAL WOODLAND STRUCTURE
	Fertility	Base Status		Water Level	Light Indices	
		pH soil	pH water			
W1	High	5.94	5.81	Low	High	Open canopy woodland possibly reflecting fairly early seral stage
W2	High	6.01	5.90	Low	High	
W3	Low	5.62	5.57	High	High	Open, low canopy and low productivity woodland
W4	Low	5.57	5.48	High	High	
W5	High	6.14	6.06	Low	Low	Robust, closed canopy woodland
W6	High	6.16	6.08	Low	Low	
W7	High	6.06	5.91	Low	Low	

Table 4.4: Predicted Environmental Attributes of Wet Woodland Habitats in Wales – Data Produced by the WETSPEC Model
(after Wheeler et al, 2001)

4.3 WET WOODLAND PROTECTION

Statutory site protection plays an important part in the conservation of wet woodland habitats. Approximately 5–10 % of the more important areas of wet woodland are protected under designation as Sites of Special Scientific Interest (SSSI) or as Areas of Special Scientific Interest (ASSI) (Northern Ireland) (UKBG, 1998). Other wet woodlands may have additional protection as part of National Nature Reserves (NNR) or contain specimen trees which are protected through Tree Preservation Orders.

Certain UK wet woodlands include habitats (e.g. Bog Woodland and Residual Alluvial Forests) identified under Annex 1 of the EC Habitats Directive and a number of those sites have been designated as Special Areas of Conservation (SACs). Throughout the UK there are four sites containing bog woodland and six sites which include residual alluvial forest. Monadh Moor SAC in northern Scotland represents one of the largest areas of bog woodland in a single location in the UK. The New

Forest, in southern England, is designated as a SAC and contains, along with numerous other habitats, both bog woodland and residual alluvial forest.

The UK Wet Woodland HAP (UKBG, 1998) identifies numerous factors that impact directly or indirectly upon the current condition and dynamics of wet woodland. These identified threats to wet woodland habitats are included in Table A1.1 (Appendix 1).

4.4 WET WOODLAND WILDLIFE

Wet woodlands provide valuable habitats for endangered and vulnerable invertebrates such as: capsid bugs; caddis fly larvae; rove beetles; jewel beetles; and, leaf beetles which rely on specific habitats such as old willows, submerged roots, leaf litter and rotting wood for the completion of their life-cycle (Kenderdine, 2000). In addition, they provide habitat for lichens, otters, bats and bird species including lesser-spotted and green woodpeckers, siskin, redpoll and marsh tit.

Table A2.1 (Appendix 2) provides a list of species of conservation concern that are associated with wet woodland habitats.

4.5 WET WOODLAND CREATION

Due to the loss of wet woodland habitats the management of existing wet woodland, the restoration of degraded sites and the creation of new areas are of great conservation importance. Targets for wet woodland protection, restoration and creation were outlined in the Wet Woodland HAP and revised in the 2001 Targets Review. Table 4.5 presents the revised targets and details the extent to which they have been met as provided during the 2002 Reporting process (UKBG, no date). The current trend in the biological status of the habitat was recorded as increasing in England, Northern Ireland and Scotland, and is stable in Wales.

TARGET	START DATE	END DATE	PROGRESS IN 2002
Maintain the total extent (50,000 – 70,000 ha) and distribution of wet woodlands	1998	On-going	UK: some progress (behind schedule) E: some progress (behind schedule) NI: some progress (behind schedule) S: unknown W: unknown
Maintain the current area (currently estimated at 24,000 – 30,000 ha) of ancient semi-natural wet woodlands	1998	On-going	UK: unknown E: unknown NI: some progress (behind schedule) S: unknown W: unknown
Initiate measures intended to achieve favourable condition in 100% of wet woodlands within SSSI/ASSIs	1998	2004	UK: unknown E: unknown NI: some progress (behind schedule) S: unknown W: unknown
Initiate measures intended to achieve favourable condition in 80% of wet woodland of the total resource	1998	2004	UK: some progress (behind schedule) E: some progress (behind schedule) NI: some progress (behind schedule) S: some progress (behind schedule) W: some progress (behind schedule)
Achieve favourable condition over 50% of the total resource of wet woodlands	2004	2010	UK: some progress (behind schedule) E: not reported NI: some progress (behind schedule) S: not reported W: not reported
Achieve favourable conditions over 70% of the designated sites	1998	2010	UK: unknown E: unknown NI: some progress (behind schedule) S: unknown W: unknown
Complete restoration to site-native species of 1,600 ha of former native wet woodland that has been converted to non-native plantations on ancient woodland sites	1998	2010	UK: no progress E: no progress NI: some progress (behind schedule) S: no progress W: no progress
Complete restoration to site-native species of a further 1,600 ha of former native wet woodland that has been converted to non-native plantation on ancient woodland sites	2010	2015	UK: not reported E: not reported NI: not reported S: not reported W: not reported
Complete establishment of 3,375 ha of wet woodland on unwooded sites or by conversion of plantations	1998	2010	UK: some progress (behind schedule) E: some progress (on schedule) NI: some progress (behind schedule) S: some progress (behind schedule) W: some progress (behind schedule)
Complete establishment of a further 3,375 ha of wet woodland on unwooded sites or by conversion of plantations	2010	2015	UK: not reported E: not reported NI: not reported S: not reported W: not reported

UK – United Kingdom E – England NI – Northern Ireland
S – Scotland W – Wales

Table 4.5: Wet Woodland Management, Restoration and Creation Targets
(after UKBG, no date)

Table 4.5 highlights that overall, some progress has been made towards meeting HAP targets although in general works are behind schedule. The progress was assessed using partial or sample survey information and no quantitative data was available.

With respect to the potential for meeting the targets outlined in Table 4.5, Peterken and Hughes (1998) concluded that

> *'...floodplain forests and their restoration must be taken more seriously...opportunities now exist in association with river restoration initiatives for recreating lost floodplain forests, and thus restoring to the British landscape a characteristically rich and varied forest type.'*

This thesis is concerned mainly with the creation of new wetland habitats and therefore details of techniques associated with the restoration and management of existing wet woodlands are not presented here but are discussed in Read (2001).

The subject of woodland creation has been discussed in detail in numerous texts (Forestry Commission, 1990, 1991, 2000; Forestry Authority, 1992; Rodwell and Patterson, 1994; Gilbert and Anderson, 1998), as has the subject of wetland creation (Mitch and Gosselink, 2000; Bardsley, 2001a), therefore this thesis presents information with respect to the creation of wet woodland habitats only.

The creation of new wet woodlands is a two-stage process: selecting a site; and undertaking active measures. When selecting a potential creation site, the existing conservation value, size, location and physical, hydrological and chemical properties of the site must all be considered. Active measures include land profiling and planting. Further details associated with these processes are provided in Appendix 3.

4.6 WET WOODLAND HYDROLOGY

Hydrology is one of the most important parameters determining the distribution and species composition of wet woodland habitats. However, there is a paucity of information with respect to this subject, with those references specifically associated with riparian woodlands (e.g. Parrott and MacKenzie, 2000), having little discussion of the hydrology of the habitats. In an earlier publication, MacKenzie (1996) even stated that there was a shortage of information on the mechanisms of hydrological events in relation to riparian woodlands.

A few studies have been undertaken within the last 5 years that provide details with respect to wet woodland hydrology and these have been collated to produce a summary of the current state of knowledge. A review of published water-use rates of wet woodland habitats is presented in Section 4.8.

The water level regime of a site will affect the species that successfully grow and therefore the habitats that develop (Newbold and Mountford, 1997; Bardsley et al, 2001). Much of the literature associated with the creation of wetland habitats provides details of ideal water levels for a habitat type or species. For example, Newbold and Mountford (1997) provided values for the 'preferred' water levels (mean water levels that have not taken into consideration the effects of seasonality, soil type or soil moisture tension) for a range of wetland plant species. The authors asserted that any engineer designing a wetland scheme should place more emphasis on a plant's preferred water level than the extremes that it may tolerate.

Using water level data from Newbold and Mountford (1997) and species lists provided by Rodwell (1991), an attempt was made to determine the 'preferred' water table depths of W5 wet woodland habitat. The developed data were compared with water levels for W5 presented by Souch et al (2000) and were found to fall within the same broad range. However, it was decided that the inaccuracy within the method for determining 'preferred' water levels was high due to the number of plant species recorded within the habitat without corresponding water level data. The data is therefore not presented in this thesis.

NVC CODE	SOIL TYPE	HYDROLOGY
W1	Wet mineral soils	The habitat can tolerate a fair degree of winter water-logging but requires a seasonal water table fall after winter flooding and in particular needs to be free of surface standing water in early summer to ensure colonisation. Prolonged rising of the water table damages the habitat.
W2	Peaty soils	The habitat requires that the peat on which it develops be above the limit of the winter flood and that the water table falls in spring. Marked differences in winter and summer water tables may limit colonisation.
W3	Peaty soils	The habitat requires that the peat on which it develops be above the limit of the winter flood. However, some examples are prone to sudden and dramatic un-seasonal water level fluctuations after heavy rain due to the peaty substrate. The habitat generally grows on a raft of vegetation which rises and falls with the peat's water level, thus keeping the surface free from inundation.
W4	Peaty soils	This habitat requires that the water table to be sufficiently low enough for birch to establish. However, the habitat also needs high enough soil moisture levels to be maintained to ensure the growth of sphagnum.
W5	Wet to waterlogged organic soils	This habitat requires that the general fen surface is raised above the limit of winter flood. However, it can tolerate the presence of winter surface water, and some summer drying.
W6	Mineral soils	This habitat is tolerant of winter flooding where the ground may be submerged for weeks. Within the habitat, hollows may retain water throughout the summer.
W7	Moist to very wet mineral soils	The *Urtica* sub-community requires that the soils be kept moist by the high water table of associated streams or flushing from above. This community may experience some surface flooding in winter and small depressions may remain permanently wet. The *Carex-Cirsium* sub-community requires that the soils be kept permanently wet through groundwater inputs from springs or along seepage lines.

Table 4.6: Hydrological Requirements of Wet Woodland Habitats
(after Rodwell, 1991)

To provide a qualitative assessment, Rodwell's species lists from each habitat were compared and clearly showed that the percentage of wetland plants listed decreased from NVC habitat W1 to W7, suggesting a shift from wetland-oriented communities towards more terrestrial communities.

Within the descriptions of each habitat, Rodwell (1991) provided brief discussions with respect to the hydrological and soil requirements of each habitat. A summary of his observations is presented in Table 4.6.

Souch et al (2000) presented detailed water level data for NVC habitat W5. Using data collected as part of previous research (unpublished), typical examples of water table behaviour were determined for the target habitats. From these data, the required water table depths at the end of each of the summer months, and the end of the winter period (February) were developed (Table 4.7) for both ponding and draining soils (see Section 3.5.3 for definitions of soil types).

	WATER TABLE DEPTH (m)					SOIL MOISTURE DEFICIT IN UNSATURATED ZONE (mm)
COMMUNITY	**May**	**Jun**	**Jul**	**Aug**	**Feb**	
W5 Wet Woodland	-0.1	-0.6	-1.0	-1.0	0.0	60

Table 4.7: Water Table Requirements of W5 Wet Woodland in Ponding / Draining Conditions
(after Souch et al, 2000)

Table 4.7 shows that W5 requires a fluctuating water table throughout the year. Wet woodland habitats will not grow at their optimal rate with permanently saturated soil in the same way that reedbed habitats can. This is due to the requirement for oxygen around the roots of the vegetation during the growing season.

Shaw (1983) stated that a soil moisture deficit [SMD] is the volume of water required to return a soil to its field capacity and when soils are at field capacity ET from the vegetation occurs at the maximum possible rate determined by the meteorological conditions [PET]. During the summer months as rainfall inputs reduce, the SMD increases and ETa from the vegetation becomes less than PET. Shaw (1983) cited Grindley (1970), who suggested a maximum SMD of 250 mm for deep-rooted woodland, which is much greater than the SMD of 60 mm presented in Table 4.7. This difference can be attributed to the fact that W5 wet woodlands have a relatively shallow rooting depth of 1 m (Souch et al, 2000).

The volume of water that W5 can tolerate losing (through ET) over a period and the depth of water required to recharge the soil profile over winter are presented in Table 4.8. The latter figure was calculated as being the volume of water required to reinstate the water level fall plus the volume of water used by the habitat through ET.

Allowable saturation deficits for the habitat in ponding and draining conditions are given in Table 4.9. It should be noted that saturation deficits are cumulative.

	WATER LOSS TOLERATED BY HABITAT (mm)			DEPTH OF WINTER RECHARGE (mm)
COMMUNITY	Mar to Jun	Jun to Jul	Jul to Aug	
W5 Wet Woodland	60	48	Profile may dry	180

Table 4.8: Water Loss Tolerated by W5 Wet Woodland
(after Souch et al, 2000)

	ALLOWABLE SATURATION DEFICITS (mm)			
W5 WET WOODLAND	Mar to May	Jun	Jul	Aug
Ponding Soils	6	36	60	120
Draining Soils	12	56	88	148

Table 4.9: Allowable Saturation Deficits for W5 Wet Woodland
(after Souch et al, 2000)

Gowing (2002) concluded that the data presented in Tables 4.8 and 4.9 show that W5 does not require a summer supply of water, but that the soil moisture needs recharging during winter months.

Some studies undertaken on specific wet woodland sites provide actual water levels for existing habitats. One such example is a study of the hydrology of Coed y Cerrig SSSI / NNR in Monmouthshire, which has an area of alder-dominated wet woodland within the valley bottom, by Gilman (2000a). The aim of the study was to provide a hydrological basis for future management of the site and in particular the maintenance of high soil moisture levels within the alder woodland. An ecological survey classified the woodland as NVC W5 and W7, which are intermingled within the woodland cluster (Wheeler et al, 2001).

As part of the study a network of twelve dipwells and three WALRAG (WAter Level RAnge Gauge) maximum-minimum water level gauges were installed. The dipwells provided water level measurements during monitoring visits, and the WALRAG gauges showed the maximum and minimum water levels achieved between visits. The water levels for two of the dipwells and one of the WALRAG gauges located within the wettest part of the alder woodland are included in Table 4.10.

	WATER TABLE DEPTH (m)		
STATION	**Oct 1999**	**Mar 2000**	**Jul 2000**
Dipwell 1	0.00	0.01	-0.20
Dipwell 4	-0.04	-0.02	-0.04
WALRAG 5	0.00	Max 0.08 -0.01 Min -0.02	Max 0.03 -0.12 Min -0.12

NB – Negative values show water levels below ground level

Table 4.10: Measured Water Levels within the Alder Wet Woodland at Coed y Cerrig SSSI, Monmouthshire
(after Gilman, 2000a)

The data in Table 4.10 shows that during the winter months (October and March) there was little change in the water levels with water at or just below ground level. However, during the summer months (July) the water table fell as rainfall inputs decreased and ET increased.

Gilman (2000a) concluded that:

> *'the optimum water level regime* [within the wet woodland] *would require that the water level rise no further than a few centimetres above the average ground surface, and that the seasonal range should not exceed 0.5 m. Short periods of deeper inundation could be tolerated in winter, although summer flooding for long periods brings with it the risk of anoxia and excess nutrient levels.'*

The work of Wheeler et al (2001) has already been presented in Section 4.2 (see Table 4.4). The authors concluded that in summer W1, W2, W5, W6 and W7 habitats have low water tables whereas W3 and W4 have high water tables, although no data is presented to determine the relative depths of these water tables.

In Pribáň and Ondok (1986) a detailed graph showing the daily fluctuations of ground-water level within a willow carr at the Třeboň Biosphere Reserve in the Czech Republic is included. The author of this thesis interpreted this graph to determine the mean and range of water table depths (Table 4.11).

	WATER TABLE DEPTH (m)		
	Jul	**Aug**	**Sep**
Mean	-0.27	-0.25	-0.36
Range	-0.11 to -0.38	-0.11 to -0.42	-0.22 to -0.46

Table 4.11: Mean Monthly Water Levels of a Willow Carr in Summer
(after Pribáň and Ondok, 1986)

Table 4.11 shows the lowest water levels within the willow carr were recorded during September due to high ET demands and reduced rainfall in August. The graph presented by Pribáň and Ondok (1986) illustrates that the water levels increase towards the end of September as rainfall inputs become more frequent and ET falls.

Wicken Fen, Cambridgeshire is a nature reserve which comprises of fen vegetation with areas of naturally developed scrub wet woodland (comprised of alder / willow / alder buckthorn and silver birch). A network of dipwells has existed on the site since 1994, some of which provide water level data from within the scrub wet woodland areas. However, the data is recorded in such a way that the levels are presented in metres above sea level which makes the data difficult to compare and apply to other sites and is therefore not included in this thesis.

Newbold and Mountford (1997) highlighted the importance of the association between a wetland's soil properties and the hydrological requirements of a target species / habitat. This relationship was investigated by Souch et al (2000) who produced comprehensive details of the preferred soil types and associated hydrological requirements of numerous wetland habitats including: MG9 species poor tussocky pasture; MG10 species poor rush pasture; MG4 species rich flood meadow; MG8 species rich water meadow; MG13 inundation grassland; S4 reedbed; S25 fen; and W5 wet woodland (Table 4.12).

For the wetland designer, the information presented in Tables 4.7 to 4.12 can inform both the design process and site investigation requirements to determine a site's suitability for the creation of W5 habitats. To allow wetland designers to successfully carry out wet woodland creation projects, a similar level of scientific knowledge should be available for each target habitat.

4.7 WET WOODLAND SUMMARY

Sections 4.2 to 4.6 present an overview of the current knowledge relevant to the design, creation and restoration of wet woodland habitats. Data relating to their historical distribution comes mainly from paleoecological studies, with information pertaining to their current extent and characteristics from detailed surveys and data assimilation studies. The current widespread management regime of existing wet woodlands takes the form of 'non-intervention' wherever possible, probably partly as a result of the inaccessibility of many of the remaining woodlands, but also their characteristic as a successional habitat often dominated by patterns of disturbance (e.g. flooding events). Wet woodland restoration techniques often involve the removal of non-native species, additional planting and, wherever possible, positive water level management.

PARAMETER	REQUIREMENTS
Topographical Requirements	
Can the habitat be created on ploughed land?	Yes
Can the habitat be created on sloping land?	Yes
Soil Requirements	
Hydraulic conductivity (m day^{-1}) Drainable soil types - Pondable soil types -	 > 0.3 < = 0.3
Drainable porosity (%)	No preference
PH	> 5.5
Organic Carbon (%)	No preference
Nutrient Requirements	
Soil nutrient status tolerated	Moderate
Water nutrient content	Moderate
Hydrological Requirements	
Presence of winter surface water	Yes
Surface water source essential	No
Surface drainage required	No
Tolerance of summer drying	Some

Table 4.12: Topographical, Soil, Nutrient and Hydrological Requirements of W5 Wet Woodland
(after Souch et al, 2000)

The creation of new wet woodland habitats is targeted on: ancient woodland sites where former wet woodland on has been converted to non-native plantations; suitable sites with existing plantations; and unwooded sites. Some progress has been made to date with respect to meeting targets outlined in the wet woodland HAP, but on average this progress is behind schedule.

During the period of this project, there have been a number of large flooding incidents, and Hughes (2001) stated that '*evidence from climate models suggests that further flooding is more likely in the future, particularly in the southeast, due to* *global warming'*. As a consequence, interest in flood alleviation and floodplain restoration has grown. Indeed, the idea of restoring river floodplains to create areas that would combine the functions of flood storage and habitat has been promoted by researchers for a number of years. Peterken and Hughes (1995) suggested two features of floodplains that can be restored to a lesser or greater extent: (1) the fluvial processes and geomorphological features they generate; and, (2) the vegetation that grows on them. The authors concluded that these could be combined into four options for floodplain forest restoration (Table 4.13) and stated that these options represent extremes, between which many kinds of intermediate measures are possible.

		FOREST	
		Managed	**Not Managed**
RIVER	**Managed**	Option A Plant woodland on a floodplain whose river remains constrained within existing channels.	Option B Establish new native woodland, but leave it to develop naturally. The river remains constrained within existing channels.
	Not Managed	Option C Plant new woodland on a floodplain where the river is allowed to flood and meander without restraint.	Option D Establish new native woodland, but leave it to develop naturally on a floodplain where the river is allowed to flood and meander without restraint.

Table 4.13: Forms of Floodplain Restoration
(after Peterken and Hughes, 1995)

Peterken and Hughes (1995) suggested that there are three levels of floodplain forest restoration:

(1) **Managed** – Option A. This is the most realistic aim in most circumstances.

(2) **Semi-Natural** – Options B & C. This is intermediate restoration where one element is totally restored and the other is ignored. These options are either impractical (C) or pointless (B) in their extreme forms.

(3) **Natural** – Option D. This represents the complete restoration of a natural floodplain forest, with no management input to either the forest or the river. This option is unlikely to be suitable along large river sections.

The authors concluded that in practice, river and forest restoration should be linked, as the river and its floodplain form one hydrological unit, and the environmental benefits will only by maximised if vegetation and water regimes are managed in conjunction.

Sterba et al (1997) stressed the importance of forests for preserving the optimum ecological condition of river ecosystems and suggested that one of the main concerns of river restoration schemes should be the re-creation of forest along riverbanks and that these forests should be as similar as possible to the original forest type. In a recent article, Peterken (2001) promoted the theory of restored floodplains comprising of a mixture of buffer strips (narrow belts along or near to the river bank) and forest zones (more substantial tracts potentially stretching right across the floodplain). He suggested that both strips and zones should comprise of a mosaic of grassland, marsh and woodland, with the woodland occupying no more than 30% of the total ground area.

Mitch and Gosselink (2000) suggested that the most important considerations in floodplain wetland design are hydrological, as flooding patterns and nutrient additions to the floodplain will fundamentally affect the success of any restoration initiative. Despite this, Section 4.6 has highlighted the dearth of information with respect to the hydrological requirements of many wet woodland habitats.
Souch et al (2000) provided the most comprehensive data associated with NVC habitat W5 (Table 4.12), which could be used by wetland designers as guidelines for the creation of this specific habitat. To ensure effective creation of wet woodland habitats, additional research is required to improve scientific understanding of these habitats and hence to provide wetland designers with sound factual guidance.

The overall aim of the project (Section 1.2) is to refine water budget design methodology for wetland habitats, with a focus on large reedbed and wet woodland systems. Given the current interest in the creation and restoration of woodland habitats within floodplains (often on land currently used for agriculture), NVC habitat W6 *Alnus glutinosa – Urtica dioica* woodland was highlighted as a target habitat for investigation.

Rodwell (1991) asserted that W6 is usually located on moist, eutrophic soils, with examples often found on river levees, small terraces on river bends and uncultivated floodplains. To maintain the ground flora, W6 woodlands require supplies of major nutrients, which can come from fresh alluvium (from flooding events) enriching the substrate, or from fertiliser run-off and sewage effluent. These woodlands are often submerged for weeks on end during the winter floods, but will not tolerate excessive summer flooding.

4.8 PUBLISHED WATER USE RATES

The Environment Agency (1998) stated that there was a lack of information on the evaporative properties of different combinations of tree species and soil type and suggested that, at the time of publication, direct measurements of evaporative properties in the UK had been restricted mainly to mature ash trees growing on chalk and clay soils and mature beech trees growing on chalk soils. A literature review of published ET rates and crop coefficients of wet woodland was instigated which illustrated the dearth of information available with respect to this data, a finding that was confirmed by a number of leading researchers and specialists (e.g. Gilman, 2000b; Hughes, 2000; Kerby, 2000, Latham, 2000 and Peterken, 2000).

A limited number of authors provide ET and Kc rates for wet woodland specifically. Bardsley (2001b) employed Kc('Carr' Wet Woodland) values of 1.4 for October to March, and 1.7 for April to September as part of a water budget case study, although the origin of these values was not provided. A number of authors provide ET and Kc rates for woodland / species, which may be applicable to wet woodland habitats, details of which are presented in Sections 4.8.1 to 4.8.5.

4.8.1 BOWEN RATIO

Pribáň and Ondock (1986) studied the ET of willow carr (dominated by *Salix cinerea* L. and *Salix pentandra* L.), which had developed in patches within an area dominated by sedge-grass marsh on parts of the 'Wet Meadows' area of the Třeboň Biosphere Reserve, Czech Republic. ET was evaluated by the Bowen ratio method, using data collected between July and September 1983. The results from this study were compared with the results from earlier investigations (undertaken between 1977 and 1979) using the same technique at the same site, which provided ET rates for the sedge-grass marsh adjacent to the willow carr. The ET rates produced in these two studies are shown in Table 4.14.

	ET mm day^{-1}		
	Jul	**Aug**	**Sep**
ET(Sedge-Grass Marsh) 1977-79	4.65	3.07	2.28
ET(Willow Carr), 1983	3.70	3.10	2.30

Table 4.14: Measured ET(Sedge-Grass Marsh) and ET(Willow Carr) at Třeboň Biosphere Reserve, Czech Republic
(after Pribáň and Ondok, 1986)

A more detailed comparison of these data is presented in Pribáň and Ondok (2002) and despite differences in the meteorological conditions between the two sampling periods, the authors stated that '*On average, evapotranspiration was higher in the willow-carr than in the sedge-grass marsh'*. However, they concluded that the ET rates from both habitats appear to be low in view of the wet habitat and high ground-water level.

Iritz and Lindroth (1994) studied the contribution of night-time evaporation to daily ET rates using data collected from a Bowen ratio station installed in a short-rotation coppice [SRC] willow stand near Uppsala, Sweden in 1988. They discovered that night-time ET provided on average 4.3% of total ET throughout the growing season. The data for each month is presented in Table 4.15. The authors concluded that the contribution of night-time ET to total ET depends on climate, with windy and / or dry areas more likely to have substantially higher night-time ET than still and / or wet areas.

	ET(Willow SRC), mm day^{-1}					
	May	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**
Day-Time ET	2.00	3.60	4.00	2.70	2.40	1.40
Night-Time ET	0.09	0.09	0.09	0.02	0.21	0.36
Total ET	2.09	3.69	4.09	2.72	2.61	1.76

Table 4.15: Monthly Averages of Day-time and Night-time ET
(after Iritz and Lindroth, 1994)

4.8.2 COMPUTER MODELS

Within the scientific community, the use of computer modelling to predict environmental parameters has increased, particularly within the last 10 years. Many researchers are now using empirical field data to create computer models which allow the user to investigate the effect of changing given parameters (such as species type, soil type, cultivation techniques) on the ET rates of a specified crop or habitat. A summary of the models discussed in this section is provided in Table 4.21.

In a study by Grip et al (1989), field data collected by Grip (1981) was used to verify an application of the KAUSHA model. ET rates presented in the latter paper are discussed in Section 4.8.3. The model was used to assess the contribution of different components (transpiration, soil evaporation and interception evaporation) to total ET at different points in the growing season (Table 4.16). In addition, the authors determined the overall percentage contribution of each component during the growing season to the total ET (Table 4.17).

MONTH	MOST IMPORTANT COMPONENT OF ET	COMMENTS
May	Soil Evaporation	The leaf area of the tree is not fully developed yet so there is little transpiration. The leaves are therefore not shading the soil. The input of the soil evaporation is reduced to close to zero later in the season.
Jun	Transpiration	As the leaf area develops transpiration rates increase.
Aug	Transpiration and Interception Evaporation	As the leaf area reaches its greatest extent, the transpiration and interception rates increase.

Table 4.16: Analysis of the Input of Different Components to ET
(after Grip et al, 1989)

Persson and Lindroth (1994) applied the SOIL computer model, which '*has been widely used and adapted to different agricultural crops and forests*', to a short-rotation coppice stand of willow. The simulation utilised ET data collected (using the Bowen ratio method) from a site near Uppsala in southern Sweden in 1988. From data collected, simulated monthly ET rates were developed for May to October (presented in Table 4.18). In addition, Kc(*Salix viminalis*) values were determined using Penman PET as ETo. Kc rates varied between 0.7 to 1 at the initial and crop development stages, increased to between 1.2 and 1.6 at mid-season, and reached approximately 2 in late season.

The authors also used the model to study the contribution of the different components to the total ET value. Table 4.18 presents the data from their study, and compares it to the results obtained by Grip et al (1989). Both studies show that transpiration has the highest contribution to overall ET rates, with interception evaporation having the lowest contribution during the growing season.

COMPONENT	PERCENTAGE CONTRIBUTION (after Grip et al, 1989)	PERCENTAGE CONTRIBUTION (after Persson & Lindroth, 1994)
Transpiration	66%	71%
Soil Evaporation	23%	18%
Interception Evaporation	11%	11%

Table 4.17: Percentage Contribution of Different Components to ET during the Growing Season
(after Grip et al, 1989 and Persson and Lindroth, 1994)

Persson and Lindroth (1994) concluded that the

> *'Introduction* [of short-rotation coppice]*...should be carefully planned to be used in situations where the high water consumption* [of the trees] *is not opposed to other water use or where a high consumption could even be beneficial.'*

Persson (1995) used the same SOIL model parameterised for an intensively managed willow stand on clay soil and applied it to other willow stands on sandy, clay and organic soils in south-western Sweden. He investigated the effects of afforesting existing farmland with short-rotation coppice stands of willows or other species. The change in land-use was expected to alter the water balance of the area, as ET from willow SRC was expected to be higher than from agricultural land (Persson, 1995).

The simulated ET from the willow stands was 480 mm between May and October. Persson (1995) concluded that monthly ET increased from May (1.3 - 2.6 mm day^{-1}) until June / July (2.6 - 4.1 mm day^{-1}), and then decreased, with values for September being similar to those in May.

In addition to providing ET for the sites, Persson (1995) provided PET values calculated using the Penman-Moneith equation, and from this data, mean monthly Kc(Willow SRC) values were determined by the author of this thesis (Table 4.18).

	MONTHLY Kc(Willow SRC)				
	May	**Jun**	**Jul**	**Aug**	**Sep**
Mean	0.31	0.75	1.02	1.16	1.21
Standard Error	*0.05*	*0.06*	*0.06*	*0.06*	*0.06*

Table 4.18: Mean Monthly Kc(Willow SRC)
(after Persson, 1995)

The data in Table 4.18 show a seasonal pattern of increasing Kc(Willow SRC) values throughout the growing season. Persson (1995) concluded that:

> *'willow short-rotation forest...when amply supplied with water, evaporates considerably more than traditional agricultural crops and forests growing in the same climatic region.'*

and stated that

> *'The crop coefficients are also higher than those of many water-demanding species.'*

The Environment Agency (1998) presented data from a set of modelling studies (undertaken by Hall et al, 1996) designed to assess the water resource impacts from afforesting an area with a particular woodland habitat. The study predicted annual evapotranspiration and drainage under different land uses for three classes of annual rainfall: (a) above 700 mm, (b) between 600 and 700 mm, and (c) below 600 mm (Table 4.19).

The drainage values presented in Table 4.19 relate to the annual excess of water not used by the habitat. In natural systems this would be calculated as the total input of water minus the evapotranspiration. However, errors associated with the application of the model result in small inaccuracies in these values (the maximum error is 16 mm).

RAIN (mm)	ASPECT	ASH	BEECH	POPLAR SRC	PINE	GRASS
801 (a)	Evapotranspiration (mm)	467	501	629	676	436
	Drainage (mm)	318	242	131	52	368
676 (b)	Evapotranspiration (mm)	471	496	615	653	445
	Drainage (mm)	209	214	104	51	231
560 (c)	Evapotranspiration (mm)	467	481	519	605	411
	Drainage (mm)	110	128	63	27	144

(a) Average of 1967, 1968, 1970, 1974, 1977, 1979
(b) Average of 1969, 1971, 1980, 1981, 1982, 1983
(c) Average of 1972, 1973, 1975, 1976, 1978

Table 4.19: Predicted Annual Evaporation and Drainage under Different Land Uses for Three Classes of Annual Rainfall
(after Environment Agency, 1998)

Table 4.19 clearly shows that as rainfall increases, ET from the vegetation also increases. This can be attributed to an increased interception loss as more rain falls onto the vegetation's leaves and is subsequently evaporated. The Environment Agency (1998) concluded that any interception loss from vegetation would be dependent upon: the climate - primarily the rainfall regime and any evaporative demand during rainfall; and, the structure of the vegetation. They concluded that for broadleaf forests in the UK the interception ratio (the annual proportion of the total rainfall lost through interception) ranges from 10% to 36%. The lower values being comparable to those measured by Grip et al (1989) and Persson and Lindroth (1994) as shown in Table 4.17.

The 'Poplar SRC' data presented in Table 4.19 relates to short rotation coppice with poplar as the dominant species. Hall (1998) stated to Fermor (2000), that it would be applicable to use the 'Poplar SRC ' and 'Grass' values presented in Table 4.19 to create a crop coefficient for Poplar SRC. Thus, Kc(Poplar SRC) has been calculated as 1.44, 1.38 and 1.26 for areas with annual rainfall above 700 mm, between 600 and 700 mm and below 600 mm respectively.

Herbst et al (1999) modelled transpiration, interception evaporation and soil evaporation of neighbouring stands of beech (*Fagus sylvatica*) and black alder (*Alnus glutiosa*) using a two-layer evaporation model of the Shuttleworth and Wallace type (1985, in Herbst et al, 1999). The model uses the Penman-Montieth equation in association with a detailed network of canopy, soil surface and aerodynamic resistances to calculate the water vapour flux from hourly meteorological standard variables. Annual ET rates (Table 4.20) were calculated from the 60-year old alder woodland [ET(Alder)], which was situated on the shore of Lake Belau in northern Germany using meteorological data collected between 1992 and 1995.

YEAR	ET(Alder) (mm/annum)
1992	884
1993	612
1994	731
1995	846

Table 4.20: Annual ET(Alder) Rates from a Woodland in Northern Germany
(after Herbst et al, 1999)

Herbst et al (1999) stated that the range in ET(Alder) shown in Table 4.20 was due to the different weather conditions recorded during each year. They concluded that alder does not regulate its water consumption very strongly and suggested that alder trees have a strongly varying water consumption which depends on the tree's leaf cover, the radiation inputs and the evaporative demand of the atmosphere.

In the study by Souch et al (2000) (see Section 3.5.3), the authors highlighted wet woodland as a priority habitat for creation within the Anglian region. The authors used the WaSim model to predict NVC habitat W5 ET rates [ET(W5)] for winter and summer periods (Table 4.22) in both ponding and draining soils (see Section 3.5.3 for description of soil types). The authors presented an annual crop coefficient of 1.2, but provided no explanation as to how this was derived.

MODEL TITLE	REFERENCES	MODEL FOCUS	UNDERLYING PRINCIPLES	TIME PERIOD
KAUSHA	Grip et al (1989)	To provide estimates of evapotranspiration from a given habitat	The model was designed to work using weather data given once every 24 hours. In this model transpiration and interception evaporation are dealt with separately. • Unstressed transpiration was calculated with the Penman (1953) formula, supposed to be valid for the whole canopy. • The interceptions process was modelled as a threshold function where precipitation below a given threshold, identified as the storage capacity of the canopy, was assumed to be caught by the leaves, branches and stems and all subsequently evaporated. • Soil evaporation was important during the vegetation establishment year and in the early part of the growing season and was calculated using the Priestly-Taylor (1972) formula.	Model provided daily sums of ET
SOIL	Persson and lindroth (1994) Persson (1995)	Studies were initiated to compare stimulated and estimated soil water tension / ET/ water balance data and to provide estimates of contribution to ET by transpiration, soil evaporation and interception	The SOIL model represents , in one dimension, the water dynamics in a layered soil profile covered with vegetation. This study uses 12 soil layers as a base for calculations. The following data was used in the model. • Groundwater flow was calculated as a 'base flow' and a more rapid 'peak flow'. • Potential daily transpiration, evaporation from soil and potential evaporation of intercepted water were estimated independently using the Penman-Monteith combination equation. • Aerodynamic resistance was estimated using a formula based on the logarithmic wind profile (Monteith and Unsworth, 1990)	Model provided daily sums of ET

Table 4.21: Summary of Computer Models Used to Estimate ET(Woodland)

MODEL TITLE	REFERENCES	MODEL FOCUS	UNDERLYING PRINCIPLES	TIME PERIOD
WUCOP SIMWUCOP	Hall et al (1996) Environment Agency (1998)	To provides estimates of daily transpiration from poplar short rotation coppice	Both models are based on a water balance equation and calculate ET using the Penman-Monteith equation. • WUCOP requires ten-minute values of solar and net radiation, dry and wet-bulb temperature, windspeed and rainfall. • SIMWUCOP required daily values of rainfall and Penman ET. Calculations are made to provide transpiration, interception and evaporation totals.	WUCOP provides 10-minute intervals SIMWUCOP provides daily data
Modified Shuttleworth-Wallace two-layer model approach	Herbst and Kappen (1999) Shuttleworth and Wallace (1985)	To determine transpiration and various components of evaporation from a reed-belt in north Germany	The Shuttleworth-Wallace two-layer model considers two layers of evaporation surfaces - vegetation and soil. It uses the Penman-Monteith equation and a detailed network of canopy, soil surface and aerodynamic resistances to calculate water vapour flux from standard hourly meteorological variables. Herbst and Kappen (1999) modified the approach to take into account the process of interception.	Meteorological parameters collected between 1991 and 1993. Model provided daily sums of ET and ETo.
WaSim	Souch et al (2000) Hess and Counsell (2000)	To calculate the water requirements of various wetland communities	The program calculates a daily soil water balance to predict the water table position and water content of the unsaturated zone on a daily basis. Rules are set for minimum soil water conditions for each month of the year. Whenever these conditions are exceeded, the program calculates the amount of water needed to bring the soil back to the minimum condition. The program was modified to allow timing of water application to be controlled by 'saturation deficits' or depth of ponding.	Daily

Table 4.21 cont.: Summary of Computer Models Used to Estimate ET(Woodland)

	ET(W5) (mm)	
SOIL TYPE	**Winter (Oct – Mar)**	**Summer (Apr – Sep)**
Ponding Soils	44	186
Draining Soils	312	296

Table 4.22: ET(W5) Rates for Winter and Summer Periods
(after Souch et al, 2000)

4.8.3 LYSIMETERS

Lysimeters have been used to determine ET rates of a single tree or a woodland area extensively during the past 30 years. Lysimeter studies are based on a water balance equation (see Section 2.2), with one of the main difference between studies being the methodology used to determine the sum of the outputs from the lysimeter.

Pauliukonis and Schneider (2001) used a simple method whereby the volume of water required to restore water levels to a set point within a dipwell was recorded. Other techniques include: monitoring the change in the volume of water in a reservoir attached to the lysimeter (e.g. Grip, 1981; Kelerman, 1996); monitoring the change using soil moisture monitoring equipment (e.g. Cureton et al, 1991); measuring soil moisture and outputs (e.g. Roygard et al, 1999); and, weighing the lysimeter (e.g. Devitt et al, 1994).

In an early study by Grip (1981), lysimeters (1 m^2 area, 0.7 m deep) were used to develop ET rates of *Salix viminalis* and *Salix smithiana* in a study that was carried out in Sweden during parts of the growing seasons of 1978 to 1980. Using data presented in the paper, the author of this thesis calculated ET(*Salix* sp.) and developed Kc(*Salix* sp.) using Penman PET values (Table 4.23).

	Salix viminalis		*Salix smithiana*	
MONTH	**ET (mm day^{-1})**	**Kc**	**ET (mm day^{-1})**	**Kc**
Jun	2.15	0.65	1.10	0.33
Jul	2.67	1.05	2.71	1.07
Aug	2.69	1.31	2.37	1.16
Sep	1.39	1.14	1.45	1.19

Table 4.23: Monthly ET and Kc Rates for *Salix viminialis* and *Salix smithiana*
(after Grip, 1981)

Table 4.23 illustrates that during the latter part of the growing season, ET(*Salix* sp.) was higher than PET and Grip (1981) suggested that despite sparse data, the opposite appears to apply in the early part of the growing season.

The use of willow species in the phytoremediation of landfill leachate and wastewater has been the subject of a number of studies in recent years some of which have considered the ET rates of the chosen species. In a study by Cureton et al (1991), *Salix babylonica* L. specimens grown in lysimeters in Canada were irrigated with water or landfill leachate and the actual ET rates determined (Table 4.24). The authors studied a number of different species and the results show that for the whole season when irrigated with water, ET(*S. babylonica*) was 157% and 173% higher than the measured ET of reed canary grass *Phalaris arundinacea* and meadow foxtail *Alopeurus pratensis* respectively; and when irrigated with leachate ET(*S. babylonica*) was 107% and 147% higher than reed canary grass and meadow foxtail respectively.

In a similar study by Roygard et al (1999) in New Zealand, *Salix kinuyanagi* was included as part of an investigation into the land treatment of wastewater (dairy-farm effluent) using short rotation forestry. Lysimeters were installed in the ground and then the lysimeters and immediate environs were planted with trees. The study produced ET(*S. kinuyanagi*) rates of 1.10 mm day^{-1} in winter and 4.59 mm day^{-1} in summer. The authors cited another New Zealand study by Tungcul et al (1996, cited by Roygard et al, 1999) who reported ET values for *Salix* species receiving effluent application ranging from 3.8 mm day^{-1} to 9.65 mm day^{-1}. Roygard et al (1999) concluded that the lower ET values produced in their study may be attributed to limited soil water availability (volumetric soil moisture content averaged 10.4% for the study period).

Period	ET(*Salix babylonica*) (mm)	
	Irrigated with Water	Irrigated with Leachate
7 Jul – 13 Jul 1989 (before senescence)	185.5	214.4
7 Jul – 12 Sep 1989 (seasonal total)	620.6	639.9

Table 4.24: ET(*Salix babylonica*) Rates Under Different Irrigation Regimes
(after Cureton et al, 1991)

Kelerman (1996) used a lysimeter installed around a birch (*Betula pubescens*) tree to investigate the effects of birch encroachment on the water balance of Flinders Moss, a lowland raised mire in Scotland. Despite numerous problems with the operation of the lysimeter, ET and Kc rates (using PET as ETo) from the tree covered mire were calculated (Table 4.25).

PERIOD	ET(*B. pubescens*) (mm)	Kc(*B. pubescens*)
14 Mar – 19 Mar 1994	13.53	1.95
19 Mar – 5 Apr 1994	73.39	2.88
17 Apr – 27 Apr 1994	20.36	1.03
21 Jul – 10 Aug 1994	24.07	0.42
4 Sep – 15 Sep 1994	13.86	0.76

Table 4.25: ET and Kc Rates of a Tree Covered Raised Mire
(after Kelerman, 1996)

In a recent study, Pauliukonis and Schneider (2001) used lysimeters to determine ET rates of common wetland plant species including weeping willow (*Salix babylonica*) at a study site at the Cornell Biological Field Station on the southern shoreline of Lake Oneida, New York. In this study daily ET(*S. babylonica*) rates were calculated to be 16.35 ± 1.34 mm day^{-1} between 25th June and 14th August 1996. The authors presented Eo data which was converted to ET Penman using Table 2.3 by the author of this thesis and used to provide Kc(*S. babylonica*) Penman, determined as 6.35. This Kc value is very high compared with other studies. However, the authors stated that the ET rates in their study were maximised due to the position of the tree along the shoreline of the lake, but justify this on the grounds that it accurately portrays the natural habitat of this species.

4.8.4 MASS WATER BALANCE CALCULATIONS

Elowson (1999) carried out a study in Månstorp, south-west Sweden to establish a willow vegetation filter for nitrogen-polluted agricultural drainage which involved planting a field with basket willow (*Salix viminalis*) and water willow (*Salix dascyclados*). The study aimed to investigate the amount of nitrogen taken up by the plant from the irrigation water, but as part of the study the inputs (rainfall and irrigation) and changes in groundwater levels (in a series of dipwells) were recorded between May and October 1994 and 1995. ET(*Salix* sp.) was calculated using a water balance equation, and the authors concluded that mean ET from the plantation was 5 mm day^{-1}.

4.8.5 SAP FLOW

In an early study, Čermák et al (1984) used the tissue heat balance method to determine the diurnal course of the xylem water flow in a solitary 20 year old *Salix fragilis* L. tree at the Třeboň Biosphere Reserve in the Czech Republic. The trunk of the tree was heated using electrodes and the temperature changes in thermocouples situated at given points along the tree trunk were measured. The authors stated that the transpiration per projected crown area was approximately 4 mm day^{-1}.

Hall et al (1996) completed a study in the UK to determine the impact of poplar short rotation coppice establishment on water resources, by gaining a fuller understanding of the mechanisms controlling its water use and by quantifying the effect of SRC on groundwater quality. The project involved the collection of environmental and biometrical data from existing SRC plantations at Swanbourne in Buckinghamshire and Hunstrete in Avon, and subsequent data analysis using mathematical models. Transpiration rates from the SRC were calculated using a variety of techniques to determine the sap flow of the trees. The mass flow rate of sap in a sample of tree stems was scaled up to an average value on a land area basis. Different sap flow techniques used in this study are presented below (details from Hall et al, 1996).

The Stem Heat Balance method employs an instrument called a Dynagauge installed on the tree's stem. The Dynagauge consists of a flexible tube made of thermally-insulating foam rubber, which wraps around the stem. Around the inner surface is an electrical heater, which applies a constant amount of heat to the surface of the stem and temperature gauges mounted within the wall of the instrument enable the heat lost to the surrounding environment to be calculated. Data, recorded at regular intervals and stored on a data logger, was used to determine the sap flow rate using Equation 4.1.

$$\mathbf{s} = \frac{\mathbf{Q_f}}{\mathbf{c_s \Delta Ts}} \tag{4.1}$$

where:

s is the sap flow rate in g s^{-1};

Q_f is the amount of heat dissipated by heating the sap as it flows through the heated region;

c_s is the specific heat capacity of the sap in J g^{-1} K^{-1} (assumed to be equal to the value for water); and,

ΔTs is the temperature increase of the sap in Kelvin.

The Heat Pulse Velocity method measures the rate of sap flow by timing how long it takes short pulses of heat to travel over a known distance along the stem. The heat pulses are provided by an electrically-powered line heater (a metal probe), which is inserted radially into a small hole drilled in the stem. Two temperature probes (one 10 mm above and one 5 mm below the metal probe) measure the stem temperature after the heat pulse is released as it is moved upwards by the sap stream. The bottom temperature sensor compensates for the fact that the pulse spreads out as a result of heat conduction in the static wood. The pulse remains symmetrical, thus when both temperature sensors reach the same temperature after release, the pulse is halfway between them. The speed of heat pulse (sap flow) is given as the time between releasing the pulse and the measurement of zero temperature difference between the probes, divided by the distance of travel [(10 mm–5 mm)/2 = 2.5 mm].

The transpiration results from these studies were correlated with leaf area data and scaled up to provide an estimation of the transpiration from the plantation. Net rainfall rates were determined using a plastic-sheet net-rainfall gauge, which, when combined with gross rainfall data were used to provide an estimation of the interception rates. ET rates were calculated as the sum of the transpiration and interception rates. In addition, the soil moisture content beneath the plantations was determined using a neutron probe and puncture tensiometers.

These data were used to develop the 'Water Use of Coppice Poplar' (WUCOP) and 'Simplified Water Use of Coppice Poplar' (SIMWUCOP) models which produced a graph showing cumulative ET(Poplar SRC), PET(Poplar SRC) and ET Penman values, generated using data from the model for Hunstrete. Data extracted from the graph is shown in Table 4.26.

The data in Table 4.26 clearly illustrates the impact of available water on ET(Poplar SRC) rates. In August water use was 5 mm day^{-1} higher when there was unlimited soil water. The difference between actual ET and PET rates was greatest during the summer months when water reserves within the soil are depleted and there was little regeneration from rainfall. The data in Table 4.26 was used to calculate Kc(Poplar SRC) Penman values which are shown in Table 4.27.

MONITORING PERIOD	ET(Poplar SRC) (mm day^{-1})	PET(Poplar SRC) (mm day^{-1})	ET Penman (mm day^{-1})
16 May - 13 Jun 1995	3.21	3.57	2.86
13 Jun - 11 Jul 1995	5.71	6.25	3.93
11 Jul - 8 Aug 1995	3.57	7.32	3.93
8 Aug - 5 Sep 1995	1.07	6.07	3.39
5 Sep - 1 Oct 1995	2.69	3.08	1.73
1 Oct - 29 Oct 1995	1.43	1.43	1.43
29 Oct - 26 Nov 1995	0.36	0.36	0.36

Table 4.26: ET(Poplar SRC), PET(Poplar SRC) and ET Penman Values for Hunstrete, Kent
(after Hall et al, 1996)

Granier sap flow sensors were used by Lambs and Muller (2002) to monitor the water consumption of the two dominant European riparian trees, the black polar (*Populus nigra*) and the white willow (*Salix alba*), in the active floodplain of the Garonne River, France. Although the authors did not present any water use data suitable for presentation in this thesis, they did conclude that sap flow rates were highly variable and were dependant on species, tree age and size, local climate and environment. They stated that evapotranspiration did not cease during periods of high flood, but that sap flows were reduced during the summer drought by stomatal closing.

A summary of the ET and Kc data presented in Section 4.9 is given in Table 4.27.

4.8.6 SUMMARY OF PUBLISHED WATER USE RATES

Sections 4.8.1 to 4.8.5 have investigated the range of different techniques utilised in the determination of ET rates from either a woodland habitat or a single tree specimen. The review highlights that most of the studies relevant to UK wet woodland species have been conducted on *Salix* sp. or short-rotation coppice stands, with only a few studies on native alder, poplar and birch species. With respect to wet woodland habitats, only two references were found which provided appropriate water use rates.

Tables 4.28 and 4.29 summarise monthly ET and Kc rates respectively of those canopy species listed as being characteristic of wet woodland habitat in the UK (see Table 4.2). These tables illustrate the paucity of information available to UK wetland designers regarding wet woodland habitats and highlight that most studies provide data between May and October only.

4.8.7 DISCUSSION OF METHODOLOGIES

Section 4.8 has reviewed a range of established techniques for determining the water use rates of woodland habitats and species including: Bowen ratio; lysimeters; mass water balance calculations; and, sap flow. Data collected using these techniques has been widely used to develop computer programmes for modelling ET, often as part of a wider study. This section aims to provide an assessment of the advantages and disadvantages of each of these methodologies with respect to the suitability for use in this project.

The Bowen ratio method is known as a 'micrometeorological technique' and with respect to these, Hall et al (1996) stated that

> '*The use of micrometeorological techniques, which are frequently used to measure evaporation fluxes from vegetation when the site is suitable, require a uniform area of at least ~150 m in the direction of the prevailing wind.*'

There are very few remaining wet woodland habitats that can provide this distance of fetch and for this reason, the use of a Bowen ratio station was not deemed suitable for use in this study due to the small size and often fragmented composition of wet woodland in the UK and in the Midlands region in particular. Gilman (2000b) agreed with this premise and concluded that with smaller woodlands, the impact of advection and the edge effects are greatly increased and using a Bowen ratio station in these instances was likely to result in the production of inaccurate data.

The use of a mass water balance calculation was not appropriate for this project, as it would involve measuring the hydrological inputs and outputs across a given area and was deemed to be too complex to be undertaken as part of this study.

Sap flow sensor use has been widespread through the UK and Europe and they have been proven to work within riverine woodland habitats (e.g. Lambs and Miller, 2002) and therefore the use of this technique was investigated further to determine its suitability. Consultation with experts from the Centre for Ecology and Hydrology (Roberts, 2002) highlighted the processes required for determining ET rates.

There are two types of sap flow sensor available: Dynagauge sensors and Granier sensors. The former of these is used mainly on smaller stemmed trees. Roberts (2002) suggested that these gauges do not need calibrating but may damage the tree if they are left in situ for periods longer than 1-2 months. Granier probes are used on larger stemmed trees and although standard calibration data is available for these probes, Roberts (2002) discovered that these were not applicable and therefore recommended that a species-specific calibration be used. In their study, Roberts (2002) found that they had to move the probes every 2-3 weeks as the wood surrounding the probes died.

Both types of probe provide a rate per period (e.g. mm per hour) of sap flow. To convert to a volume per period, the cross sectional area of that part of the stem that is conducting sap must be known. This can be determined by taking a core from the tree and the area of sapwood is the total area of the cross section minus the area of the heartwood. Not all of the sapwood will be conducting, and therefore the conductive sapwood percentage must be determined using an appropriate dye. The transpirational flux is then given by multiplying the sap velocity by the area of conductive sapwood. Values are usually converted to grams per hour and summed to provide grams per day.

To provide transpiration data on a ground area basis, the Leaf Area Index [LAI] of the tree being studied must be determined. This can be done using a Leaf Area Meter in a laboratory, and either a set of sample branches are stripped of leaves and the results are scaled-up for the whole tree, or all the leaves that fall are collected and a representative sample (10%) is used which can again be scaled-up for the whole tree.

Not only are there considerable issues surrounding the use of sap flow sensors, but they only provide transpiration data for the tree that they are installed on. Interception and evaporation data would have to be separately determined if ET rates were to be provided. It was therefore decided that these probes would not provide a suitable method for use in this project. Further information regarding the measurement of sap flow in plants is given by Smith and Allen (1996).

Lysimeters have been used for the past 20 years in the determination of ET rates from woodlands and for this project there are various advantages of using them. Lysimeters can be installed within an existing wet woodland, are relatively cheap to install and maintain and the set up of each lysimeter is replicable. Within a large enough lysimeter, a representative wet woodland habitat can be established rather than just a single tree specimen, thus providing ET rates for the whole habitat. ET rates from a lysimeter can be calculated throughout the year, thus providing monthly Kc values to be used by wetland designers.

This thesis provides details of the development of a methodology for determining the ET rates of wet woodland habitat using lysimeters (Chapter 6).

RESEARCHER	LOCATION	TECHNIQUE	SPECIES	AGE	ET	Kc
Grip (1981)	Ultuna, near Uppsala, Sweden	Lysimeters (in ground, non-draining, 1m^2 area, 0.7 m deep)	*Salix viminalis* and *Salix smithiana*	Not exactly known (less than 5 yrs)	ET(*Salix viminalis*) = 2.15 mm day^{-1} (Jun) 2.67 mm day^{-1} (Jul) 2.69 mm day^{-1} (Aug) 1.39 mm day^{-1} (Sep) ET(*Salix smithiana*) = 1.10 mm day^{-1} (Jun) 2.71 mm day^{-1} (Jul) 2.37 mm day^{-1} (Aug) 1.45 mm day^{-1} (Sep)	Kc(*S. viminalis*) Penman = 0.65 (Jun) 1.05 (Jul) 1.31 (Aug) 1.14 (Sep) Kc(*S. smithiana*) Penman= 0.33 (Jun) 1.07 (Jul) 1.16 (Aug) 1.19 (Sep)
Cermák et al (1984)	Trebon Biosphere Reserve, Czech Republic	Tissue Heat-Balance	Solitary *Salix fragilis* tree	20 yrs	Transpiration per projected crown area = 4.1 mm m^{-2}	N/a
Pribán and Ondok (1986)	Trebon Biosphere Reserve, Czech Republic	Bowen ratio	Willow carr (stand of *Salix cinerea* and *Salix pentandra*)	+ 30 yrs	3.7 mm day^{-1} (Jul) 3.1 mm day^{-1} (Aug) 2.3 mm day^{-1} (Sep)	N/a
Cureton et al (1991)	University of Guelph, Ontario, Canada	Lysimeters (in-ground, bottom-draining, 1 m diameter, 1.3 m deep)	Weeping willow (*Salix babylonica*)	Saplings	Irrigated with water: 9.13 mm day^{-1} (Jul-Sep) Irrigated with Guelph leachate: 9.41 mm day^{-1} (Jul-Sep)	N/a

Table 4.27: Summary of Findings of the Literature Review – ET(Woodland) and Kc(Woodland)

RESEARCHER	LOCATION	TECHNIQUE	SPECIES	AGE	ET	Kc
Iritz and Lindroth (1994)	Ultuna, near Uppsala, Sweden	Bowen ratio	Well established short rotation stand of *Salix viminialis*	Planted 1984 - coppiced on 3 yr rotation	ET(*S. viminialis* SRC) = 2.09 mm day^{-1} (May) 3.69 mm day^{-1} (June) 4.09 mm day^{-1} (July) 2.72 mm day^{-1} (Aug) 2.61 mm day^{-1} (Sep) 1.76 mm day^{-1} (Oct)	N/a
Persson and Lindroth (1994)	Ultuna, near Uppsala, Sweden	'SOIL' computer model	Well established short rotation stand of *Salix viminialis*	Planted 1984 - coppiced on 3 yr rotation	ET(*S. viminialis* SRC) = 2.00 mm day^{-1} (May) 3.40 mm day^{-1} (June) 4.40 mm day^{-1} (July) 2.90 mm day^{-1} (Aug) 2.30 mm day^{-1} (Sep) 0.80 mm day^{-1} (Oct)	Kc(*S. viminialis* SRC) Penman = 0.7 – 1.0 (May-Jun) 1.2 – 1.6 (Jul-Aug) 2.0 (Sep)
Persson (1995)	Ultuna, near Uppsala, Sweden	'SOIL' computer model	Willow stand	Planted 1984 - coppiced on 3 yr rotation	ET(willow) = 2.6 mm day^{-1} (May – Sep)	Kc(willow) Penman = 0.31 ± 0.15 (May) 0.75 ± 0.18 (Jun) 1.02 ± 0.16 (Jul) 1.16 ± 0.17 (Aug) 1.12 ± 0.17 (Sep)

Table 4.27 cont.: Summary of Findings of the Literature Review – ET(Woodland) and Kc(Woodland)

RESEARCHER	LOCATION	TECHNIQUE	SPECIES	AGE	ET	Kc
Hall et al (1996)	UK	WUCOP model	Poplar (*Populus* sp.) dominated short rotation coppice (SRC)	11 yrs - coppiced on 3 & 5 yr cycles	ET(Poplar SRC) = 3.57 mm day^{-1} (mid May-mid Jun) 6.25 mm day^{-1} (mid Jun - mid Jul) 7.32 mm day^{-1} (mid Jul–end Jul) 6.07 mm day^{-1} (Aug) 3.08 mm day^{-1} (Sep) 1.43 mm day^{-1} (Oct) 0.36 mm day^{-1} (Nov)	Kc(Poplar SRC) Penman= 1.25 (mid May-mid Jun) 1.59 (mid Jun–mid Jul) 1.86 (mid–end Jul) 1.79 (Aug) 1.78 (Sep) 1.00 (Oct) 1.00 (Nov)
Kelerman (1996)	Flinders Moss, Scotland	Lysimeters	Birch (*Betula pendula*) covered moss	Not known	ET(*B. pendula*) = 2.71 mm day^{-1} (mid Mar) 4.32 mm day^{-1} (mid Mar-early Apr) 2.04 mm day^{-1} (mid Apr) 1.20 mm day^{-1} (mid Jul-mid Aug) 1.26 mm day^{-1} (early Sep)	Kc(*B. pendula*) Penman = 1.95 (mid Mar) 2.88 (mid Mar-early Apr) 1.03 (mid Apr) 0.42 (mid Jul-mid Aug) 0.76 (early Sep)
Tungcul et al (1996), cited by Roygard et al (1999)	Aokautere, near Palmerston North, New Zealand	Unknown	*Salix* sp.	Not known	ET(*Salix* sp.) = 3.8 to 9.65 mm day^{-1}	N/a

Table 4.27 cont.: Summary of Findings of the Literature Review – ET(Woodland) and Kc(Woodland)

RESEARCHER	LOCATION	TECHNIQUE	SPECIES	AGE	ET	Kc
Environment Agency (1998)	UK	Modelling studies carried out by Hall et al (1996)	Poplar (*Populus* sp.) dominated short rotation coppice (SRC)	11 yrs - coppiced on 3 & 5 yr cycles	ET(Poplar SRC) = 1.72 mm day^{-1} (annual rainfall >700 mm) 1.68 mm day^{-1} (annual rainfall 600-700 mm) 1.42 mm day^{-1} (annual rainfall <600 mm)	Kc(Poplar SRC) Penman= 1.44 (annual rainfall >700 mm) 1.38 (annual rainfall 600-700 mm) 1.26 (annual rainfall <600 mm)
Elowson (1999)	Månstorp, south-west Sweden	Mass water balance calculation	Plantation of basket willow (*Salix viminalis*) and water willow (*Salix dasyclados*)	3 yrs	ET(*Salix* sp.) = 5 mm day^{-1} (May-Oct)	N/a
Herbst et al (1999)	Lake Belau, northern Germany	Model based on Shuttleworth-Wallace type.	Black alder (*Alnus glutinosa*)	60 years	ET(*A. glutinosa*) = 2.42 mm day^{-1} (1992) 1.68 mm day^{-1} (1993) 2.00 mm day^{-1} (1994) 2.32 mm day^{-1} (1995)	N/a
Roygard et al (1999)	Aokautere, near Palmerston North, New Zealand	Lysimeters (in-ground, bottom-draining, 1.8 m diameter, 1.0 m deep)	*Salix kinuyanagi*	1-3 yrs	ET(*S. kinuyanagi*) = 1.10 mm day^{-1} (winter) 4.59 mm day^{-1} (summer)	N/a

Table 4.27 cont.: Summary of Findings of the Literature Review – ET(Woodland) and Kc(Woodland)

RESEARCHER	LOCATION	TECHNIQUE	SPECIES	AGE	ET	Kc
Souch *et al* (2000)	Anglian region, UK	ET rates – WaSim Model Kc rates - Unknown	W5 - *Alnus glutinosa* – *Carex paniculata* woodland	Not known	ET(W5) = Ponding Soils (average) 0.24 mm day^{-1} (Oct-Mar) 1.02 mm day^{-1} (Apr-Sep) Draining Soils (average) 1.62 mm day^{-1} (Oct-Mar) 1.71mm day^{-1} (Apr-Sep)	Kc(W5) = 1.2
Bardsley (2001b)	Not known	Not known	'Carr' Wet Woodland	Not known	N/a	Kc(Wet Woodland) 1.4 (Oct-Mar) 1.7 (Apr-Sep)
Pauliukonis and Schneider (2001)	Shoreline of Lake Oneida, New York, USA	Lysimeters (situated on a wooden frame, 68 litre capacity, 0.16 m^2 surface area)	Weeping willow (*Salix babylonica*)	Planted 1996 2.8-3.8 m high	ET(*S. babylonica*) = 16.35 ± 1.34 mm day^{-1} (25 Jun–14 Aug 1996)	Kc(*S. babylonica*) Penman = 6.35

Table 4.27 cont.: Summary of Findings of the Literature Review – ET(Woodland) and Kc(Woodland)

SCIENTIFIC NAME	COMMON NAME	NO. OF REFERENCES	MEAN MONTHLY ET, mm day^{-1}												
			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Alnus glutinosa	Alder	1	-	-	-	-	-	-	-	-	-	-	-	-	2.11
Betula pubescens	Downy birch	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fraxinus excelsior	Ash	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Salix caprea	Goat willow	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Salix cinerea	Grey sallow	1	-	-	-	-	-	-	3.70	3.10	2.30	-	-	-	-
Salix fragilis	Crack willow	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Salix pentandra	Northern bay willow	1	-	-	-	-	-	-	3.70	3.10	2.30	-	-	-	-
Salix purpurea	Purple willow	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Salix triandra	Almond willow	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Salix viminalis	Osier willow	4	-	-	-	-	3.03	3.56	4.04	3.33	2.83	2.52	-	-	-
W5 Wet Woodland	Draining soils	1	1.62	1.62	1.62	1.71	1.71	1.71	1.71	1.71	1.71	1.62	1.62	1.62	-
W5 Wet Woodland	Ponding soils	1	0.24	0.24	0.24	1.02	1.02	1.02	1.02	1.02	1.02	0.24	0.24	0.24	-

Table 4.28: Mean Monthly Published ET Rates of UK Wet Woodland Species

SCIENTIFIC NAME	COMMON NAME	NO. OF REFERENCES	MEAN MONTHLY Kc												
			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Alnus glutinosa	Alder	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Betula pubescens	Downy birch	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fraxinus excelsior	Ash	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Salix caprea	Goat willow	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Salix cinerea	Grey sallow	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Salix fragilis	Crack willow	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Salix pentandra	Northern bay willow	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Salix purpurea	Purple willow	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Salix triandra	Almond willow	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Salix viminalis	Osier willow	3	-	-	-	-	0.51	0.80	1.09	1.36	1.42		-	-	-
'Carr' Wet Woodland	N/a	1	1.40	1.40	1.40	1.70	1.70	1.70	1.70	1.70	1.70	1.40	1.40	1.40	1.55
W5 Wet Woodland	N/a	1	-	-	-	-	-	-	-	-	-	-	-	-	1.20

Table 4.29: Mean Monthly Published Kc Rates of UK Wet Woodland Species

CHAPTER 5. REEDBED SITES AND EXPERIMENTAL DESIGN AND ESTABLISHMENT

5.1 INTRODUCTION

This chapter provides: an introduction to the reedbed study sites; the experimental design associated with the development of ET(Reed); and, information regarding the establishment of the experiments.

To assist in the suitability assessment of potential reedbed study sites, a number of criteria were developed which are given below.

(1) **Geographical Location.** To develop nationally applicable crop coefficients study sites were required to be distributed throughout England. However, financial and practical limitations did have some influence on the location of the sites with respect to their proximity to Aston University.

(2) **Reedbed Size.** In order to minimise the 'edge effects' associated with small or fringe reedbeds, the chosen reedbeds were of a medium to large size (minimum 40 m x 40 m). Within each reedbed a suitable area for the installation of lysimeters had to be identified which would maximise the fetch over the reedbed from the predominant wind direction.

(3) **Reedbed Composition.** The reedbeds chosen for study should be dominated by common reed *Phragmites australis*.

(4) **Meteorological Equipment.** The sites were required to have an area suitable for the installation of meteorological equipment i.e. an area of open, flat ground. The potential for damage by animals / humans was also taken into consideration.

Using these criteria, three study sites were identified, details of which are given in Sections 5.2.1 to 5.2.3. A map showing the location of the study sites is presented in Figure 5.1.

Fig. 5.1: Location of Reedbed Study Sites

5.2 STUDY SITES

5.2.1 AQUALATE MERE

5.2.1.1 INTRODUCTION

Aqualate Mere is the largest of the natural meres in the north-west Midlands, and together with the Mosses, forms a nationally important series of wetland sites (the Midland and Mosses Ramsar site). The site is located at National Grid Reference SJ 770 205 and has a total area of 213.2 ha. Although the site is privately owned, the mere and associated habitats are managed by English Nature, as it is designated as a Site of Special Scientific Interest (SSSI) and a National Nature Reserve (NNR).

The Mere itself comprises of 72.5 ha of open water which is fed by three feeder streams, and drains westward to the River Meese. The Mere is surrounded by woodland fringes along the northern, western and part of the southern section of the shore and site the supports extensive reedswamps, alder and willow carr, damp grassland and fen communities (Coleshaw and Walker, 2001). Apart from the central area of the south shore, most of the periphery of the Mere is fringed with reedbed (totalling 4 ha). This reedbed has been classified as NVC habitat S4 (see Rodwell, 1991), and comprises stands of common reed *Phragmites australis* and lesser bullrush *Typha angustifolia*. The reedbed is well developed and reaches up to 40 m in width (Coleshaw and Walker, 2001).

Although it appears stable, reedbed is being lost on the landward side through the build-up of litter, drying out and invasion by willow and alder scrub. Despite this seral succession being natural within a wetland system, the reedbed has been deemed too important to lose and is therefore maintained by tree removal and scrub coppicing.

5.2.1.2 SITE CHARACTERISTICS

As part of a project undertaken at Aston University, Smallridge (2001) presented data associated with characteristics of the three reedbed sites used in this project. The information included data with respect to: meteorological conditions (rainfall, temperature and potential evapotranspiration); soil type; and, water quality.

Long-term average (1961-90) rainfall data was taken from the closest Met Office rain gauge to Aqualate Mere, located at Moreton (NGR: SJ 797 170). Average monthly temperature values and PET are presented for MORECS Square 124 (see Section 2.3.4) for the period 1995-2000. These data are summarised in Figure 5.2.

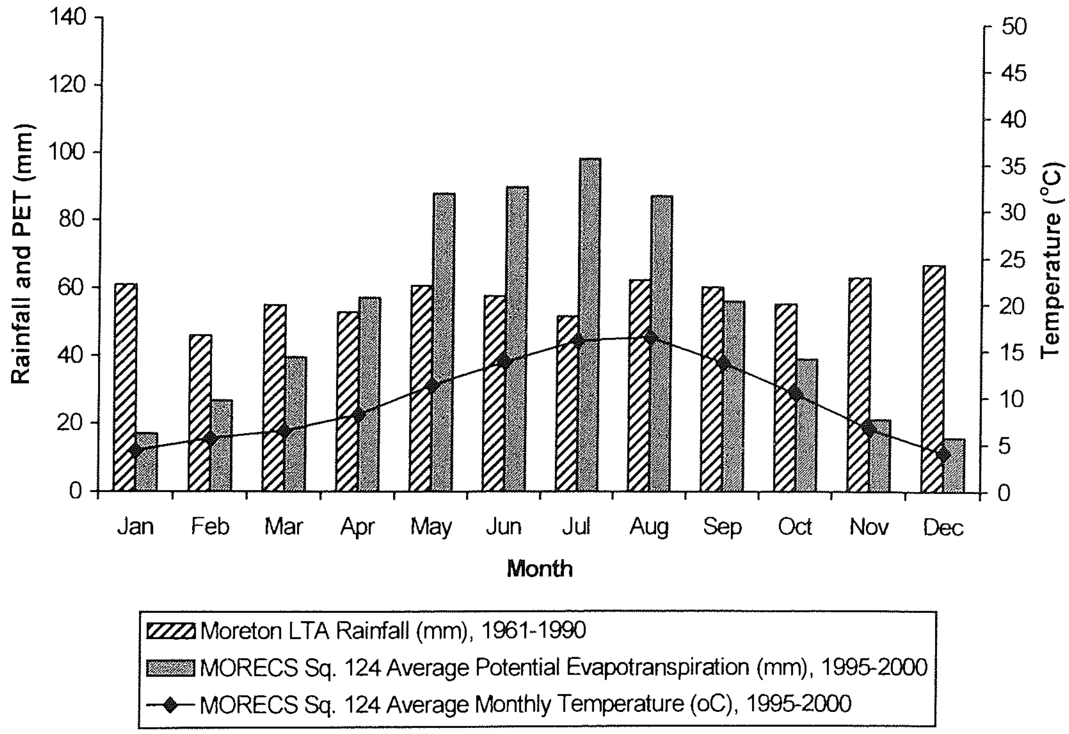

Fig. 5.2: Aqualate Mere Meteorological Data

Aqualate Mere has an annual long-term average rainfall of 698 mm and Figure 5.2 shows that that this rainfall is spread evenly throughout the year, with no significant reduction during the summer months. The annual average PET is 640.8 mm and PET exceeds rainfall between April and August. Average monthly temperatures ranged between 4 °C in the winter months and 16 °C in the summer months.

As a result of access restrictions placed on Aqualate Mere associated with the national outbreak of foot and mouth disease in 2001, it was not possible for Smallridge to complete soil analysis and water quality tests. Coleshaw and Walker (2001) concluded that to the east of the Mere (where the experimental area is situated), there are extensive peat deposits, and the Mere has a pH of 8.3 - 8.5.

5.2.1.3 EXPERIMENTAL AREA

The experimental area was situated within the extensive fringe of reed on the eastern shore of the Mere (Figure 5.3). The reedbed was wide enough to provide conditions similar to those of a large reedbed with extensive reed cover. Twelve lysimeters were installed within the reedbed, and meteorological equipment (see Section 5.3.1) was located elsewhere on the site. The location of experimental and meteorological equipment on the site is shown in Figure 5.4 (map supplied by Warwickshire Wildlife Trust).

Fig. 5.3: Aqualate Mere Reedbed Experimental Area, February 2000

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5.2.2 BRANDON MARSH

5.2.2.1 INTRODUCTION

Brandon Marsh is an 87 ha wetland reserve, located 3 miles east of Coventry at National Grid Reference SP 386 761, it is designated as a SSSI and comprises lakes, marsh, reedbeds, grassland and woodland. The site is held by the Warwickshire Wildlife Trust on 99-year leases from Lafarge Redland Aggregates Ltd and Coventry City Council.

The reserve is situated alongside the River Avon and has developed over the past 50 years as a result of mining subsidence and sand and gravel extraction. The site contains a number of reedbeds of varying size and age. A suitable reedbed was identified within Goose Pool, an old settling pool, which comprises open water with an expanse of reedbed along the northern edge. The reedbed is dominated by common reed *Phragmites australis* with some sedges *Carex* sp. and has developed as a result of succession during the last 10 years (Clark, 2000). The banks of the pool are lined with lombardy poplar to the east and west. Water levels are maintained by a small piped supply from a larger pool (Grebe Pool) to the east (BMVCT, 2000) and water outflows are controlled using a flexi-pipe situated in the south-western corner of the pool, through which water flows into a subsidiary settling bed to the west.

5.2.2.2 SITE CHARACTERISTICS

Long-term average monthly rainfall data was collected from Finham (NGR: SP 334 740), with temperature data and PET values provided by MORECS Square 137 (Figure 5.5). Average annual rainfall for Brandon Marsh is 658 mm and is distributed evenly throughout the year. Average annual PET totals 611.1 mm, and Figure 5.5 shows that PET generally exceeds rainfall between April and September. The average temperature falls to a minimum of 4.1 ^{o}C in winter and reaches a maximum of 17.2 ^{o}C in the summer.

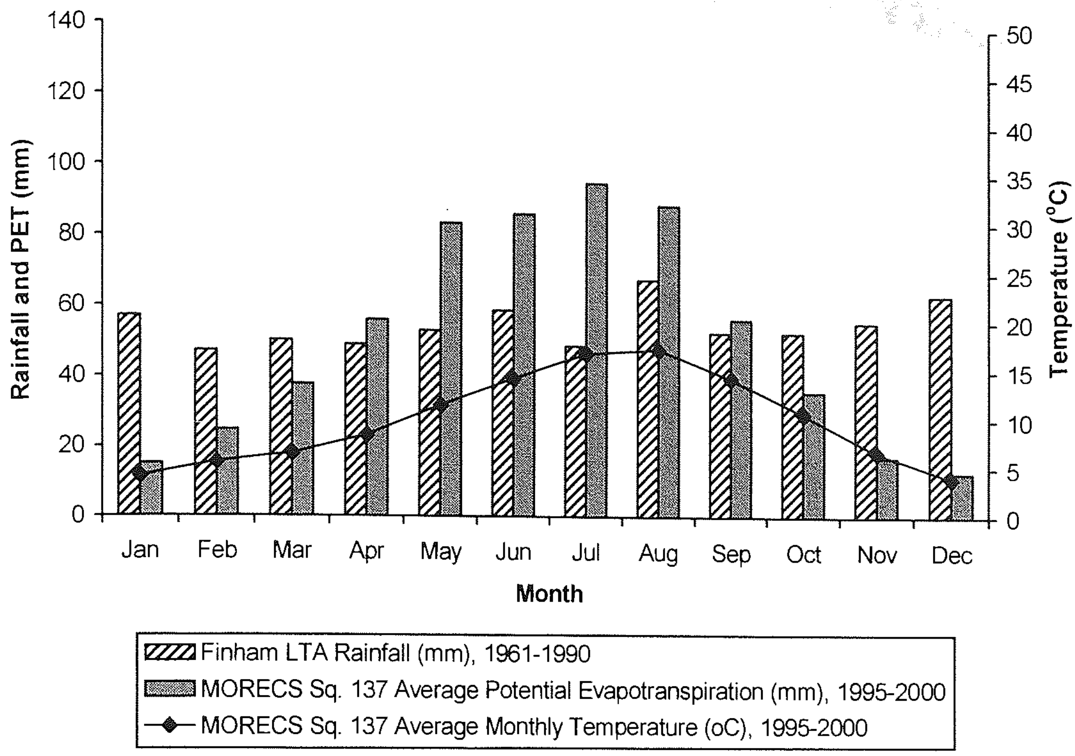

Fig. 5.5: Brandon Marsh Meteorological Data

Smallridge (2001) concluded that the soils in Goose Pool comprise of a humus layer to 0.1 metres below bed level [m.b.b.l.], underlain by very fine sands to 3.0 m.b.b.l., with clay below this. The pH of the water within the reedbed was recorded as 7.3 - 7.9, with low dissolved oxygen [DO] levels and nitrate levels. Smallridge (2001) concluded that the pH and DO levels recorded were within acceptable water quality ranges for non-flowing water and that the low nitrate levels suggest that there are no inputs from agricultural run-off into this system.

5.2.2.3 EXPERIMENTAL AREA

The reed bed in Goose Pool is shown in Figure 5.6. Ten lysimeters were installed within the reedbed and meteorological equipment was sited elsewhere within the reserve (see Figure 5.7). The base map was provided by English Nature.

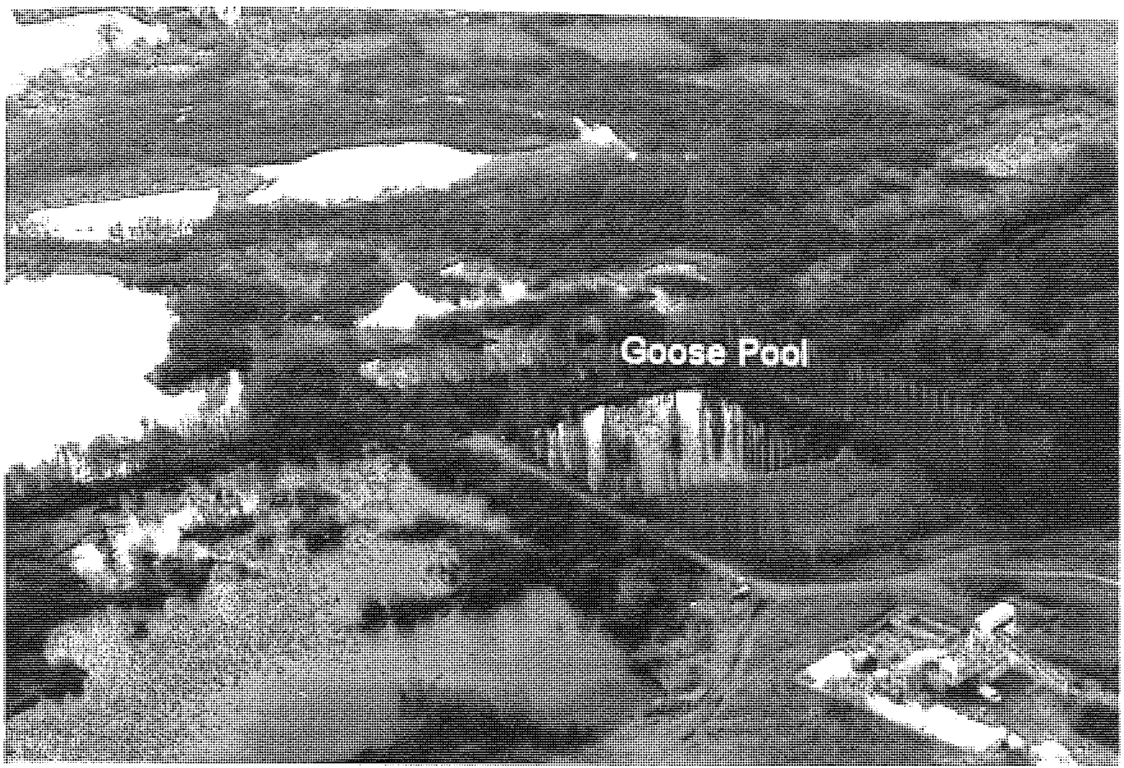

Fig. 5.6: Brandon Marsh – Showing the Location of Goose Pool

5.2.3 LEIGHTON MOSS

5.2.3.1 INTRODUCTION

Leighton Moss is located in Warton, Lancashire at National Grid Reference SD 483 746 and is owned and managed by the Royal Society for the Protection of Birds (RSPB). The reserve is located close to Morecambe Bay, and would historically have been tidal. The first drainage of the site was attempted at the end of the eighteenth century with the construction of flood banks and dykes, and the area was used for agricultural land until pumping stopped in 1917 due to World War I. This cessation of pumping lead to flooding of the Moss and started the natural succession which has lead to the freshwater shallow lakes and reedbed habitats that form the majority of the Moss today.

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Leighton Moss was awarded SSSI status in 1985; is classified as a 'Wetland of International Importance' under the Ramsar Convention; and has been designated as a Special Protection Area under the EEC Birds Directive. The reserve comprises 82 ha of *Phragmites* dominated reedbed (the largest reedbed in north-west England), which is dissected by a number of open water areas and channels throughout. Wilson et al (2000) stated that the reedbed has been classified as NVC habitat S4 (see Rodwell, 1991).

The site supports the only regularly breeding bittern population in England outside of East Anglia. Careful management of the reedbed has maintained the breeding population of bitterns and increased the numbers of breeding bearded tit, marsh harrier and water rail (Wilson et al, 2000). Reedbed management takes the form of winter and summer cutting and water level management.

5.2.3.2 SITE CHARACTERISTICS

Water enters the reserve as streams flowing from springs in the surrounding limestone, and from rainfall inputs. The water drains through the reserve and out to Morecambe Bay via a tidal sluice situated on the western boundary. The average mean water levels in the Main Mere from 1993-1998 in meters above ground level are presented in Table 5.1.

AVERAGE MEAN WATER LEVEL IN MAIN MERE (m)											
Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
0.74	0.77	0.78	0.73	0.70	0.64	0.57	0.54	0.56	0.58	0.69	0.75

Table 5.1: Average Mean Water Levels in Leighton Moss' Main Mere, 1993-1998 (after Wilson et al, 2000)

Long-term average monthly rainfall data was determined using the meteorological station at Beetham Hall (NGR: SD 499 790) with PET data provided from MORECS Square 91. Maximum and minimum temperatures for the reserve were provided by Wilson et al (2000) and are included in Figure 5.8.

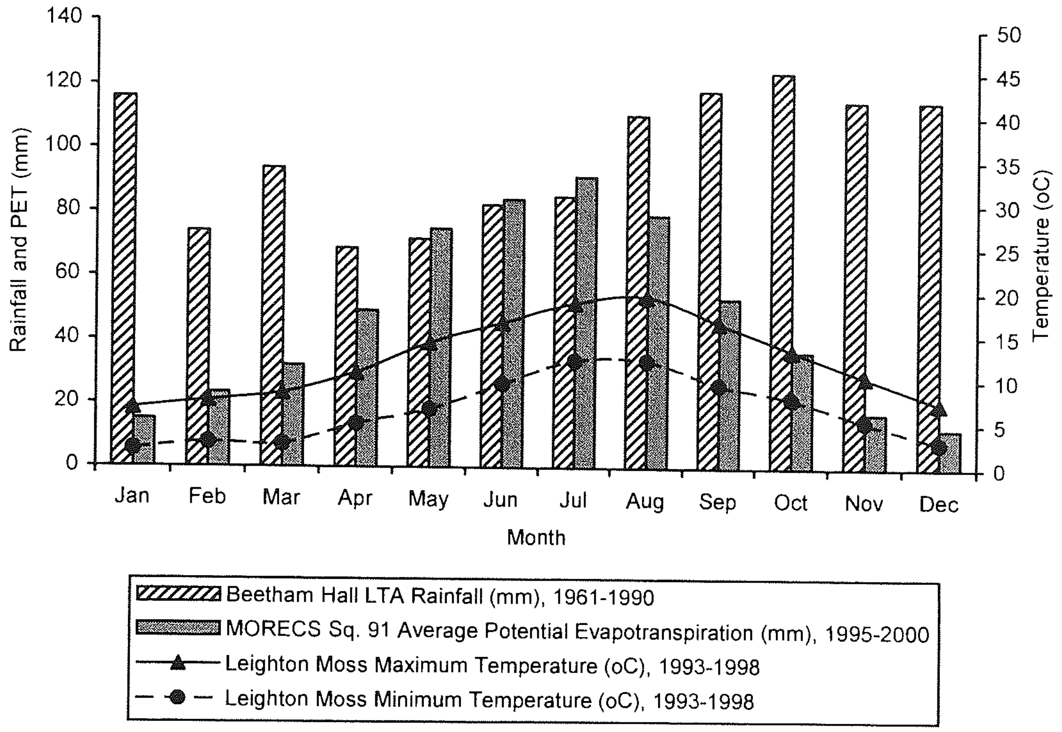


Fig. 5.8: Leighton Moss Meteorological Data

Average yearly rainfall at Beetham Hall was 1186 mm, 416.7 mm higher than that measured by a gauge at Leighton Moss between 1993 and 1998. On average, yearly rainfall at Leighton Moss is approximately 40% higher than that at Aqualate Mere and Brandon Marsh. The pattern of monthly rainfall also differs, and there is a significant reduction in rainfall between April and August. Annual PET totals 573.9 mm, and only exceeds rainfall between May and July. Minimum temperatures of 2.0 °C were recorded during winter increasing to 19.5 °C during summer.

Smallridge (2001) recorded that the soils were comprised of a humus top layer to 0.1 m.b.g.l., with peat beneath this to a depth of 2.0 m.b.g.l., below which the soil was clay. Within the humus and peat layers 40% organic matter was recorded at the surface, falling to 15-20% between 0.5 and 2.0 m.b.g.l. The soil at this site is comprised of mainly fine particles (<0.06 mm) such as coarse and fine silt and clay and Smallridge (2001) concluded that the finer the soil particles, the more likely the soil is to retain moisture, heat and nutrients and therefore the more suitable it is for reed growth as the soil looses less moisture during periods of dry weather.

Smallridge (2001) recorded pH of 7.1 – 7.9, with low dissolved oxygen and nitrate levels.

5.2.3.3 EXPERIMENTAL AREA

Within the study site, the experimental area spans either side of the main causeway with six lysimeters on each side of the causeway. Two of the lysimeters (L11 and L12) were located within a section of reedbed that had been cut the year before the experimental equipment was installed. The remainder were situated within an area of reedbed not subject to recent management. Figure 5.9 shows the reedbed either side of the main water channel that runs east to west through the site. Meteorological equipment was situated within an open part of the site towards the western boundary.

A deer-proof fence was erected around the equipment to protect it and to prevent deer drinking from the evaporation pan.

A map of Leighton Moss showing the location of the experimental and meteorological equipment is presented in Figure 5.10 (map provided by the RSPB).

Fig. 5.9: Leighton Moss Reedbed, February 2000

Fig. 5.10: Leighton Moss Site Map

5.2.4 SITE SUMMARY

A summary of the characteristics of the reedbed study sites is presented in Table 5.2.

CHARACTERISTIC	SITE		
	AQUALATE MERE	**BRANDON MARSH**	**LEIGHTON MOSS**
Site Characteristics			
Site history	Agricultural catchment	Quarry settling pond	Drained agricultural land to 1917
Current reedbed management	Minimal (occasional tree removal)	Ongoing	Ongoing
Meteorological Data			
Annual Rainfall LTA (mm)	698	658	1186
Annual PET LTA (mm)	640.8	611	573.8
Annual Temperature LTA (^{o}C)	9.71	9.95	9.5
Annual Temperature LT range (^{o}C)	4.1 - 16.4	4.1 - 17.2	4.3 - 15.9
Soil organic matter			
Surface	Not known	15%	40%
1.0 m deep	Not known	8%	17%
2.0 m deep	Not known	2%	20%
Sub surface soil			
Top horizon	Not known	Humus to 0.1m.b.b.l.	Humus to 0.1m.b.b.l.
Middle horizon	Not known	Fine sand to 3 m.b.b.l.	Peat to 2 m.b.b.l.
Bottom horizon	Not known	Clay >3 m	Clay > 2 m.b.b.l.
Water quality			
pH	8.3 - 8.54	7.3 - 7.6	7.1 - 7.9
DO (ppm)	Not known	1.8 - 5.4	3.3 - 7.2
NO_3 (mg/l)	Not known	0.57 – 2.2	0.87 - 1.37

Table 5.2: Reedbed Study Sites - Summary Data

5.3 EXPERIMENTAL DESIGN AND ESTABLISHMENT

5.3.1 INTRODUCTION

A summary of the equipment installed at each site is provided in Table 5.3. Equipment was installed at each site during February and April 2000 for two reasons:

(1) the ideal time to move reeds in rhizome sods is late winter (Hawke and Jose, 1996); and,

(2) by moving the reeds before they start significant growth, the reeds were able to establish within the lysimeters during the growing season of year 2000.

SITE	ESTABLISHMENT DATE	NUMBER OF LYSIMETERS	METEOROLOGICAL EQUIPMENT
Aqualate Mere	29th – 30th Feb 2000	12 (0.5 m diameter)	US Class 'A' Evaporation Pan Splayed-base Rain Gauge
Brandon Marsh	22nd – 23rd Feb 2000	10 (0.5 m diameter)	US Class 'A' Evaporation Pan Splayed-base Rain Gauge
Leighton Moss	3rd – 4th Apr 2000	12 (0.5 m diameter)	US Class 'A' Evaporation Pan Splayed-base Rain Gauge (sited within a 'deer-proof' fence)

Table 5.3: Summary of Reedbed Experimental Site Establishment and Equipment

5.3.2 INSTALLATION METHODOLOGY

The methodology used for the installation of the reedbed experimental equipment was developed from the technique used by Fermor (1997). During his research, Fermor used a hydraulic excavator to install the lysimeters within his study sites. However, this methodology was not deemed appropriate within ecologically sensitive sites and therefore all installation works were completed by hand. The lysimeters comprised of rigid plastic barrels (with no tops) with a surface area of approximately 0.25 m^2.

An outline layout of the lysimeters within each reedbed was developed prior to installation works based on the following factors:

(1) installation should cause minimal disturbance to the reedbed;
(2) each lysimeter should be independent and subject to the same conditions as the surrounding reedbed;
(3) the lysimeters should all radiate from a central pathway;
(4) there should be at least 5 m of reedbed between each lysimeter; and,
(5) the lysimeters should only be approached from one side.

Inevitably, during installation, some alterations were made to the proposed layouts due to local constraints (inappropriate substrate, water depth and other plant species present).

Once the position of each lysimeter was determined, a metal ring (650 mm high with a diameter of 750 mm) was dug into the substrate and the dead reed stems were broken off approximately 1 m above the substrate. Water was baled out from inside the ring and reeds were carefully dug up in sods (approximately 300 mm diameter and 400 mm depth) and placed to one side. Care was taken to ensure that the stems of the reeds were not broken and the rhizomes were kept as intact as possible. The substrate within the ring was excavated and placed in the lysimeter (depth of substrate ranged from 200 mm to 500 mm), which was then lifted into the ring and the reed sods replanted within the substrate. Enough water was added to the lysimeter to cover the reeds with approximately 200 mm of water and the ring was removed. Figure 5.11 illustrates the lysimeter installation process and Figure 5.12 shows an established lysimeter.

To ensure that the lysimeters did not to overtop or become inundated, the top rim was set 100 mm above the reedbed top water level (estimated using information supplied by site managers and collected during initial site visits). If the lip of the lysimeter was found to be too high the top was carefully sawn off in situ.

After a suitable period during which the lysimeter contents were allowed to settle and the surrounding reedbed recovered, a permanently sited hook gauge was attached to the side of each lysimeter. These hook gauges were designed so that the water depth within the lysimeters could be altered. Between March and September the hook gauges were set 80 mm below the top of the lysimeter at Aqualate Mere and Brandon Marsh and 100 mm at Leighton Moss, whereas between October and February the gauges were set 100 mm and 120 mm below.

During subsequent site visits, it was noted that at Aqualate Mere and Leighton Moss some of the reed sods were floating within the lysimeters and though they appeared to be growing at a similar rate to the secured clumps there was some concern with respect to root damage from water freezing during the winter months. The floating may have resulted from the twisting action used to secure the lysimeters into the substrate, thus loosening the sods. In addition, it was noted that the substrate surrounding the rhizomes had a high quantity of organic matter, thus making the sods very light. A number of techniques for pinning the reeds were tested, the most successful involving a wooden trellis-type mat laid over the reed sods, and held down using two metal strips clamped to the side of the lysimeter. Gowing (2002) stated that they had had similar problems at the study site at Walton Lake (see Section 3.5.4) and that it was solved by leaving the lysimeters with minimal water in during the first year to encourage the reeds to establish in the substrate.

5.3.3 COLLECTION OF HYDRO-METEOROLOGICAL DATA

At a suitable location, the meteorological equipment detailed in Table 5.3 was installed. Shaw (1983) suggested that the hook gauge on an evaporation pan be set 50 mm below the rim. However, in this instance it was set at the same depth as the lysimeters at each site (see Section 5.3.2) to ensure that the pan did not overtop in the intervening period between visits.

At each site a water level gauge was installed in the reedbed with zero datum sited at the top of the reedbed substrate.

Lysimeter and Hook Gauge

Insertion of the Metal Ring

Planting the Reed Clumps

The Newly Installed Lysimeter

Fig. 5.11: Reedbed Lysimeter Installation Process

Fig. 5.12: Successfully Established Lysimeter, Aqualate Mere, July 2002

5.3.4 MONITORING

Monitoring was undertaken once a month to allow monthly water use rates to be determined. In addition, practical considerations such as cost and time limited the frequency of site visits. During each visit the following data was recorded:

(1) the rainfall;

(2) the volume of water required to return the water levels within the evaporation pan to datum;

(3) the volume of water required to return the water levels within each lysimeter to datum; and,

(4) the phenological characteristics of the reeds, both within the lysimeters and within the surrounding reedbed (March – September).

ASCE (1996) stated that reasonable values for ET can only be obtained using lysimetry when plant density, height and leaf area of the vegetation inside the lysimeter are close to that of the surrounding vegetation. However, Gowing (2000) observed that due to the growth form of reeds, measurement of the leaf area was not a suitable method for comparison and concluded that stem density and maximum height of the reeds were more appropriate phenological characteristics for comparison. These data were recorded monthly between March and September. To enable this, four 0.5 m x 0.5 m fixed-point quadrats were established within each reedbed. The dimensions of the quadrats were chosen for two reasons: (1) each quadrat has the same approximate area (0.25 m^2) as each lysimeter; and, (2) by having four quadrats, a total area of 1 m^2 was studied which Carter (2000) judged as producing a representative sample of the reedbed.

Schematic diagrams showing the layout of the lysimeters and quadrats within the reedbeds at Aqualate Mere, Brandon Marsh and Leighton Moss are presented in Figures 5.13 to 5.15.

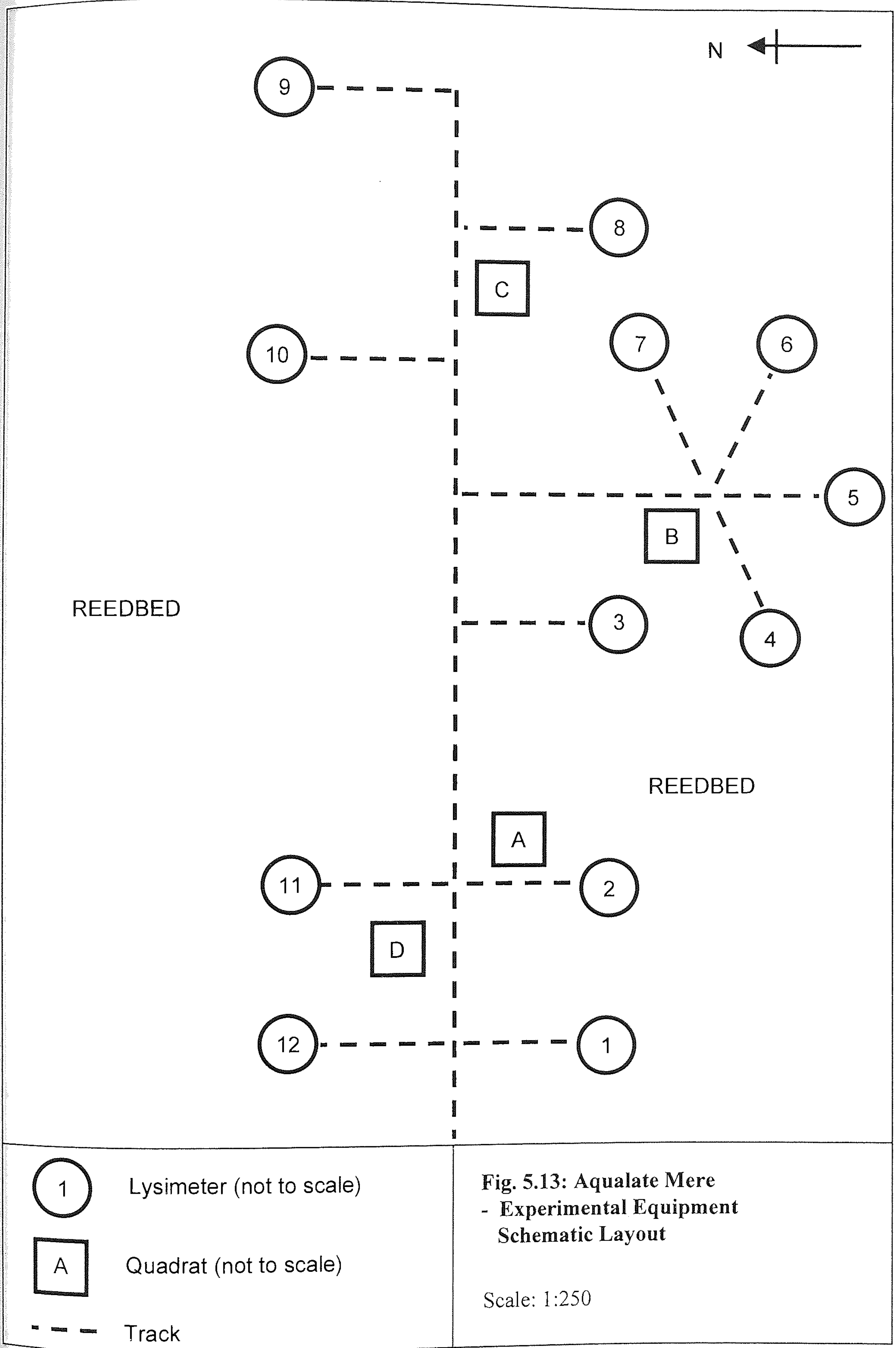
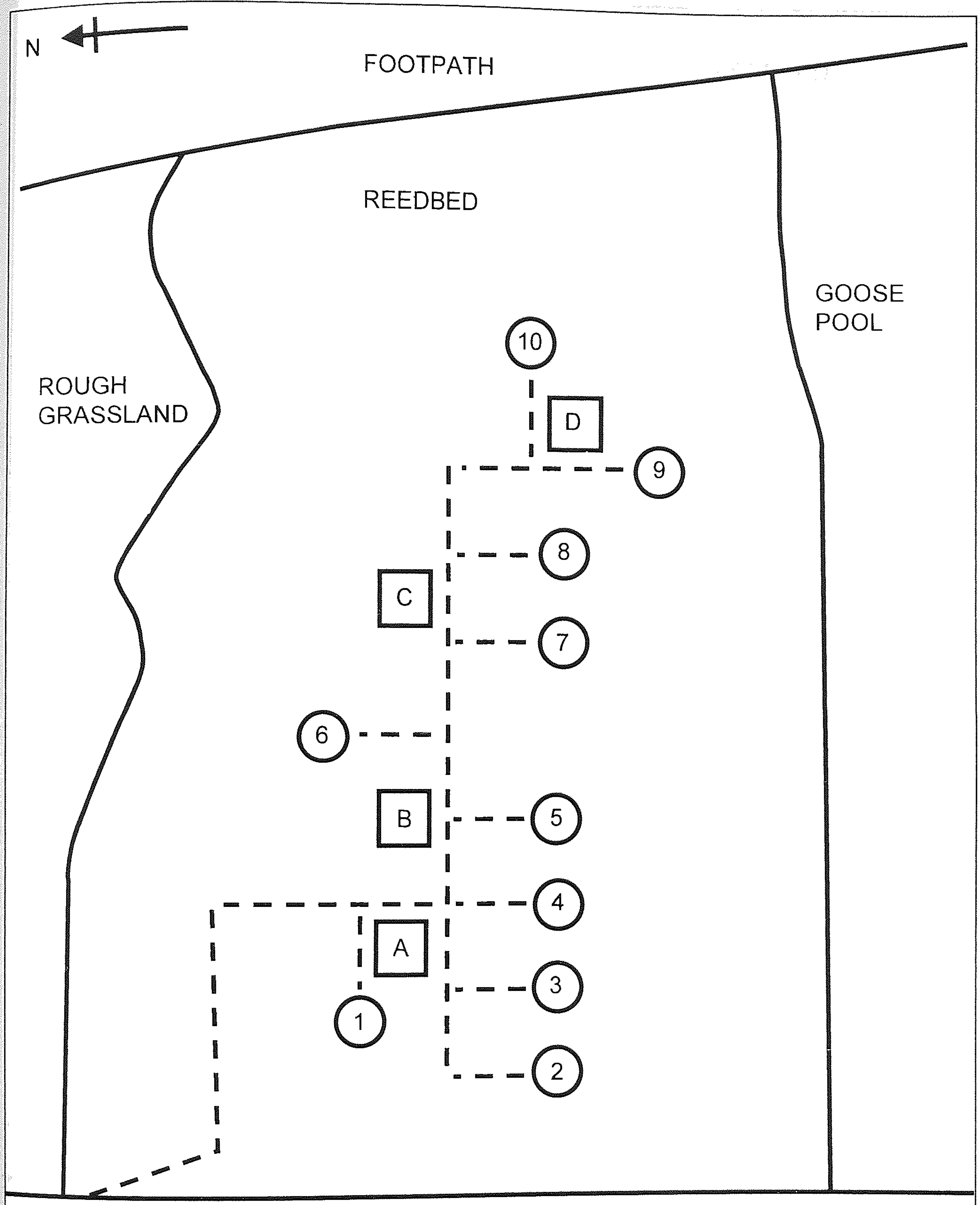


Fig. 5.13: Aqualate Mere - Experimental Equipment Schematic Layout

Scale: 1:250



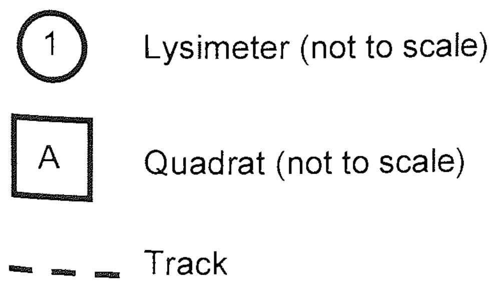


Fig. 5.14: Brandon Marsh
- Experimental Equipment
Schematic Layout

Scale: 1:500

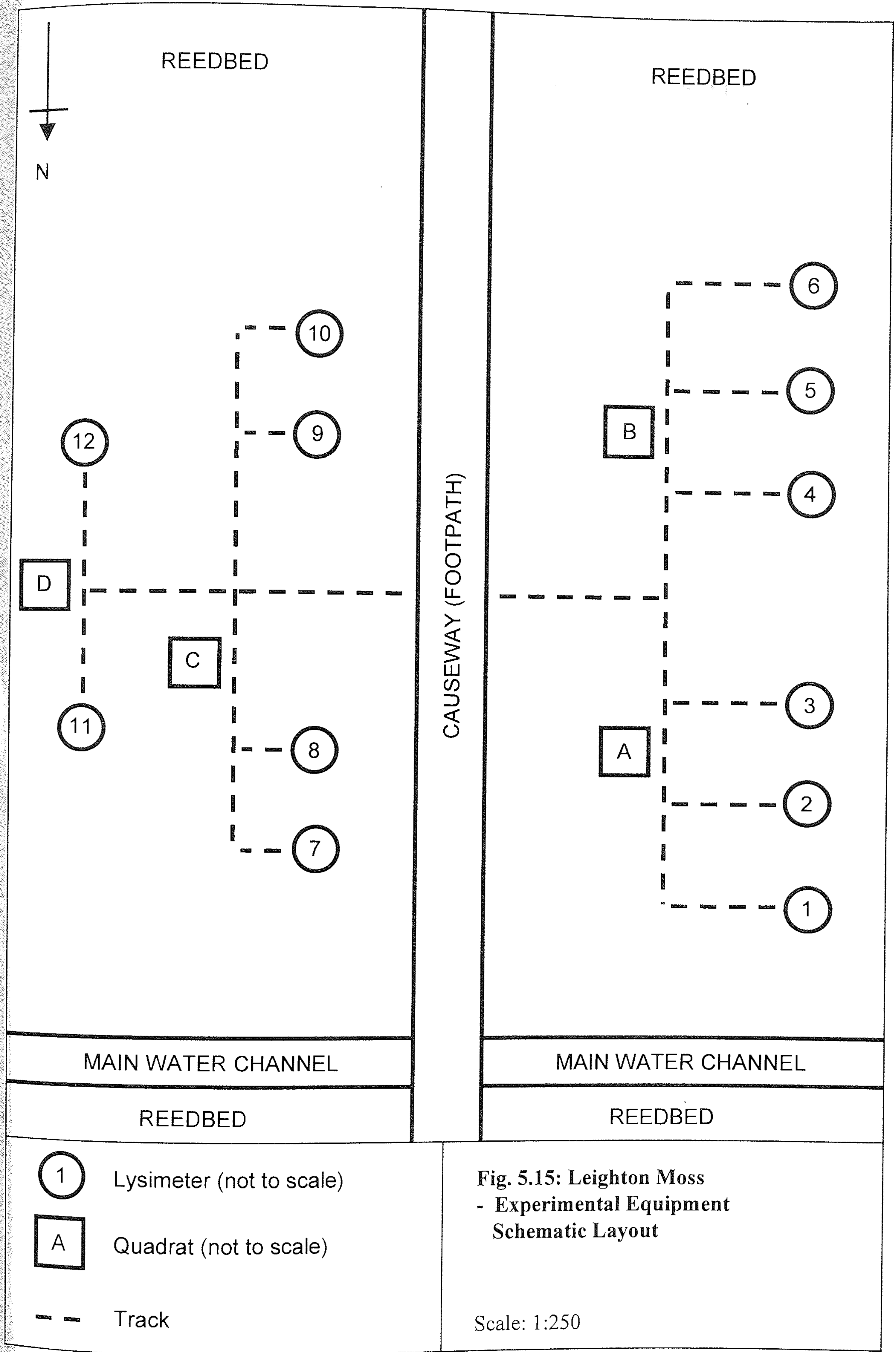


Fig. 5.15: Leighton Moss - Experimental Equipment Schematic Layout

Scale: 1:250

CHAPTER 6. WET WOODLAND STUDY SITES, EXPERIMENTAL DESIGN AND ESTABLISHMENT

6.1 INTRODUCTION

This chapter provides: an introduction to the wet woodland study sites; details of the experimental design associated with the development of ET(W6); and, information regarding the establishment of the experiments.

The criteria shown below were used to assist in the suitability assessment of each potential wet woodland study site.

(1) **Geographical Location.** Due to the frequency of site visits and associated financial and practical limitations, sites were chosen within a 50 mile radius of Aston University. To provide the required suitable meteorological and hydrological conditions, woodlands situated within a floodplain were chosen.

(2) **Accessibility.** To allow installation of experimental equipment, the study sites required access suitable for a hydraulic excavator to enter the woodland during the autumn / winter period.

(3) **Woodland Composition.** The sites were required to have suitable areas comprising of the target wet woodland NVC habitat W6.

(4) **Meteorological Equipment.** An area suitable for the installation of meteorological equipment i.e. an area of open, flat ground was necessary. The potential for damage by animals / humans was also taken into consideration.

Using these criteria, two study sites were identified, details of which are provided in Sections 6.2.1 and 6.2.2. The location of the study sites is shown in Figure 6.1.

Fig. 6.1: Location of Wet Woodland Study Sites

6.2 STUDY SITES

6.2.1 CHERRY HOLME WOODS

6.2.1.1 INTRODUCTION

Cherry Holme Woods is located at National Grid Reference SK 214 153, south of Walton-on-Trent, Staffordshire. The 8.1 ha woodland is part of the Catholme Estate and is located within the National Forest and the area covered by the 'OnTrent Project', and the 'Central Rivers Project'. These two projects were put in place to allow the strategic development of sections of the River Trent in accordance with the projects' aim and objectives. The vision of the 'OnTrent Project', which covers the whole of the River Trent floodplain, is

> '*A Trent Floodplain rich in wildlife habitats, landscape and historic features, for the benefit of all both now and in the future*'

The Central Rivers Project focuses on a smaller area with an overall aim of developing a strategy for 6,000 ha of land between Burton-on-Trent and Tamworth centred on the corridors of the Rivers Tame and Trent (the 'Study Area'). One of the specific aims is to:

> *'increase the level of habitat provision in the Study Area (e.g. of wetlands, reedbeds and appropriate woodlands) and specifically to meet habitat and species action plan targets as included within the Staffordshire and National Forest Biodiversity Action Plans; and create a habitat network throughout the Study Area.'*

ENTEC (1999)

The study site at Cherry Holme Woods was identified through discussions with the Forestry Commission (Woodcock, 2000) as a potential wet woodland restoration site as the woodland abuts the bank of the River Trent. Cherry Holme Woods was isolated from the surrounding arable land when the River Trent was diverted and spoil from the new river channel was deposited into the old river channel. When the river is in spate, the old river channel fills with water and cuts off the woodland, and if the volume of flood water is large enough, water floods out into the woodland area (Figure 6.2).

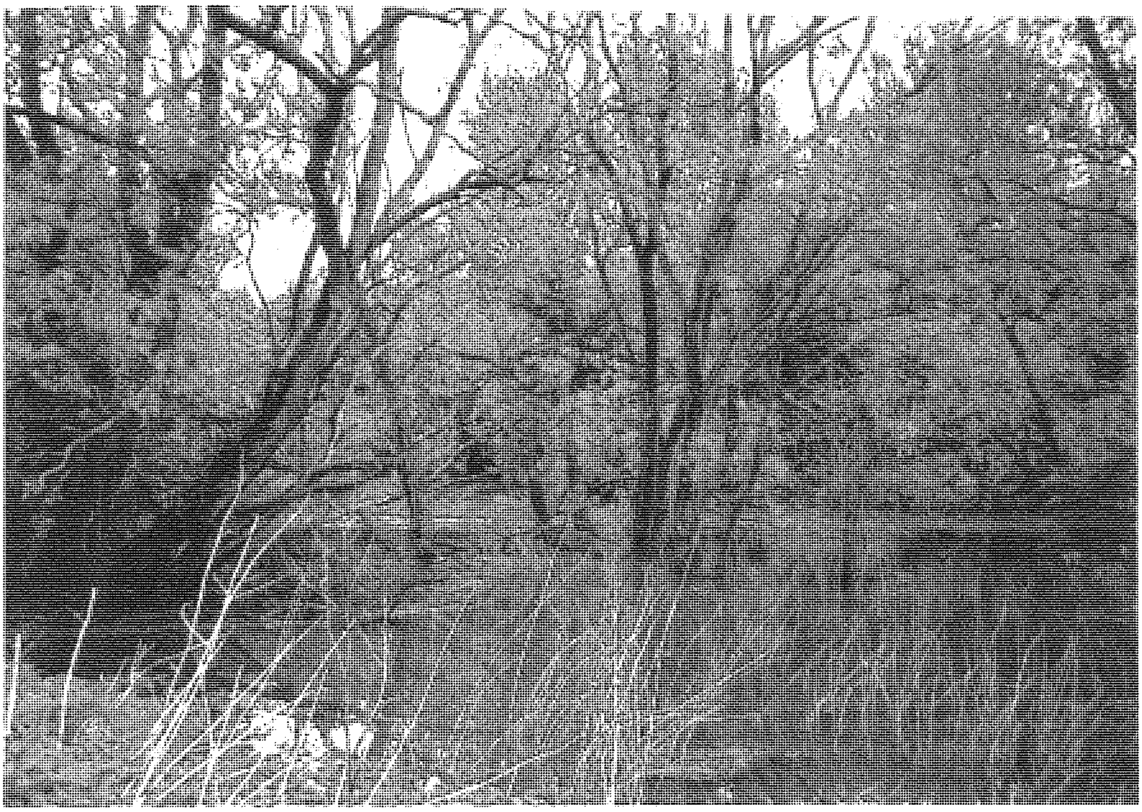


Fig. 6.2: Cherry Holme Woods in Flood Conditions, May 2001

6.2.1.2 SITE CHARACTERISTICS

Investigative trial holes were undertaken using a hand auger during August 2000. Within the experimental area the soils are composed of a loose brown sandy clayey topsoil to 0.30 Metres Below Ground Level [m.b.g.l.], below which exists a layer of stiff orange brown sandy clay extending to 1.40 m.b.g.l. Underneath this is a thin (0.10 m) layer of stiff grey sandy clay, which extends into a layer of loose brown sand with small to medium sub-rounded gravels (up to 50%). The soils within the profile were noted as being moist, with minimal lateral seepage.

Long-term average (1961-1990) rainfall and PET for MORECS Square 126 is presented in Figure 6.3.

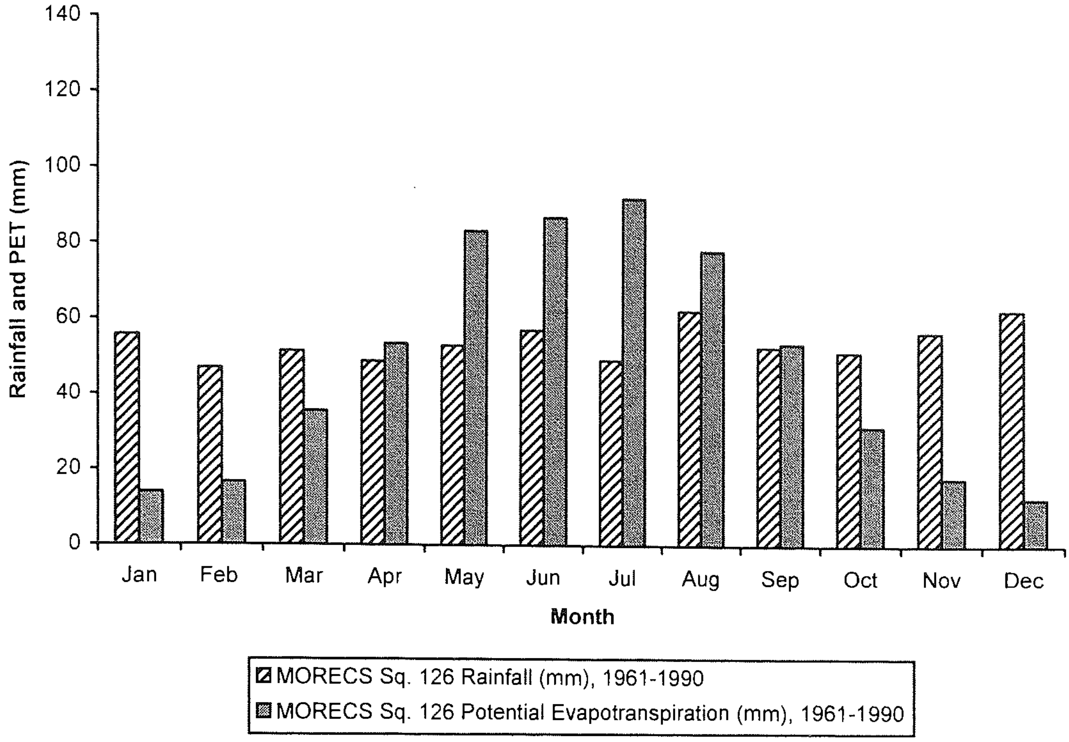


Fig. 6.3: Cherry Holme Woods Meteorological Data

The average annual rainfall at Cherry Holme Woods is 654.3 mm, with the annual PET totalling 581.5 mm. PET exceeds rainfall between April and September.

6.2.1.3 EXPERIMENTAL AREA

The experimental area was situated within an area of both planted and naturally developed W6 wet woodland. The woodland species recorded within the immediate environs of the experimental area are detailed in Table 6.1.

Within the interior of the woodland (away from the experimental area), large poplar trees (*Populus* sp.) had been removed and the area re-planted with woodland species including willow (*Salix* sp.), alder (*Alnus glutinosa*), guelder rose (*Viburnum opulus*), oak (*Quercus robar*) and ash (*Fraxinus excelsior*).

COMMON NAME	SCIENTIFIC NAME
Canopy Species	
Oak	*Quercus robar*
Goat willow	*Salix caprea*
Crack willow	*Salix fragilis*
Guelder rose	*Viburnum opulus*
Understorey Species	
Creeping bent	*Agrostis stolonifera*
Cow parsley	*Arthriscus sylvestris*
Burr dock	*Articum lapa*
Willowherb	*Epilobium montanum*
Cleavers	*Galium aparine*
Ground ivy	*Glechoma hederacea*
Yorkshire fog	*Holcus lanatus*
Creeping buttercup	*Rannunculus repens*
Broad-leaved dock	*Rumex obtusifolius*
Red campion	*Silene dioica*
Nettle	*Urtica dioica*

Table 6.1: Wet Woodland Species Recorded at Cherry Holme Woods

The meteorological equipment (see Section 6.3.2) was sited approximately 1.5 km away from the woodland for two reasons: (1) the equipment could not be sited in the woodland as it was too enclosed; and, (2) if situated within the adjacent fields, data / equipment may have been lost during floods that regularly cover the area. A suitable area was identified within a secure compound on Hanson plc land.

A site map of Cherry Holme Wood showing the location of the meteorological equipment and experimental area is provided in Figure 6.4. The map is based on OS map - Explorer 245 The National Forest.

6.2.2 LEAM VALLEY

6.2.2.1 INTRODUCTION

The Leam Valley Local Nature Reserve (LNR) is located to the east of Royal Leamington Spa, Warwickshire and is owned by Warwick District Council and managed by the Warwickshire Wildlife Trust. Within the reserve, at National Grid Reference SP 346 650, is an area that has recently been restored to provide a mosaic of floodplain wetland habitats. The total area of the wetland site is 4 ha, with wet woodland comprising approximately 0.7 ha.

Figure 6.5 shows the area of wet woodland which forms a 15 m wide ecotone along the northern boundary of the created wetland area and acts as a transition between the wetland vegetation and the existing terrestrial woodland.

Fig. 6.5: Leam Valley Wet Woodland Area, August 2002

6.2.2.2 SITE CHARACTERISTICS

Investigative trial holes were undertaken using a hand auger during September 2000. The site had no topsoil due to its removal during the wetland construction works. The top 1 m depth of soil was a stiff brown sandy clay (tending to red brown sandy clay below 0.60 m.b.g.l.). Below this, sub-angular to sub-rounded gravels were noted within the clay to a depth of 1.40 m.b.g.l., with a layer of red-brown very sandy clay with numerous gravels recorded to depth (1.85 m.b.g.l.).

The Leam Valley is located within MORECS Square 137 and long-term average (1961-1990) rainfall and PET data from this square is shown in Figure 6.3.

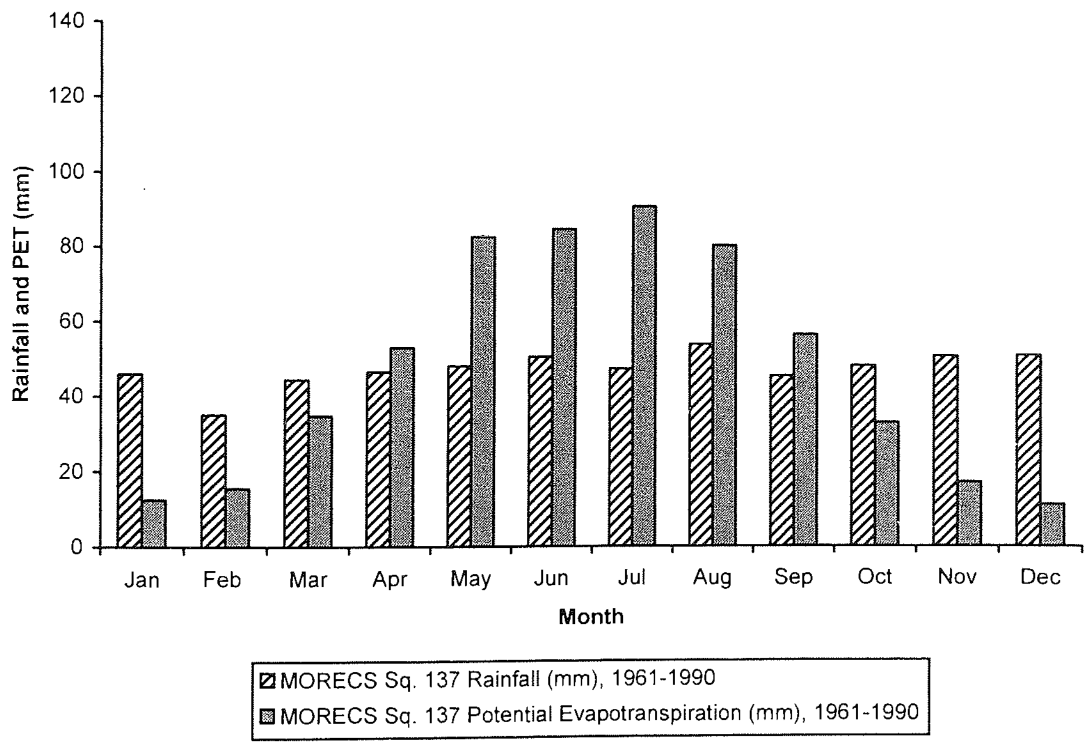


Fig. 6.6: Leam Valley Meteorological Data

Figure 6.6 shows that rainfall is distributed evenly throughout the year, with the annual rainfall totalling 567.9 mm. Annual PET exceeds this slightly, totalling 573.6 mm. PET exceeds rainfall between April and September.

6.2.2.3 EXPERIMENTAL AREA

The experimental area comprised of a 10 m x 15 m block situated within the newly established wet woodland area. Carter (2000) asserted that NVC habitat W6 was most appropriate for establishment on this site and therefore, the wet woodland area was planted up in November 2000 with the canopy species shown in Table 6.2. All species were planted as 600-800 mm high whips apart from a few 2-3 m tall alders and willows and two 2 m high goat willow specimens (planted in the lysimeters).

To establish a representative W6 woodland, understorey species were introduced into the experimental area. These works were planned to take place soon after the trees had been planted. However adverse weather conditions (flooding) and access restrictions due to the national outbreak of foot and mouth disease resulted in establishment taking place in September 2001. Plant plugs and seed were used to introduce target species (Table 6.2) into the lysimeters and the surrounding experimental area, with the addition of some turves from the adjacent woodland.

Meteorological equipment was situated within the wetland area on the northern part of a 10 m wide pipeline corridor that dissects the site (Fig 6.7). Map provided by Warwickshire Wildlife Trust.

CANOPY SPECIES		**UNDERSTOREY SPECIES**	
Common Name	**Scientific Name**	**Common Name**	**Scientific Name**
Alder	*Alnus glutinosa*	Wild angelica	*Angelica sylvestris*
Hawthorn	*Crataegus monogyna*	Meadowsweet	*Filipendula ulmaria*
Oak	*Quercus robar*	Cleavers	*Galium aparine*
Goat willow	*Salix caprea*	Yellow iris	*Iris pseudacorus*
Grey willow	*Salix cinerea*	Soft rush	*Juncus effuses*
Crack willow	*Salix fragilis*	Creeping buttercup	*Rannunculus repens*
Guelder rose	*Viburnum opulus*	Nettle	*Urtica dioica*

Table 6.2: Wet Woodland Species Planted at Leam Valley

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6.2.3 SUMMARY CHARACTERISTICS

A summary of the site characteristics associated with the wet woodland study sites is provided in Table 6.3.

	SITE	
CHARACTERISTIC	**CHERRY HOLME WOOD**	**LEAM VALLEY WETLAND AREA**
Site Characteristics		
Site history	Natural colonisation & planting	Newly created wetland
Current management	None	N/a
Canopy Vegetation	Naturally developed and planted W6 habitat. Dominated by crack willow and goat willow.	Planted W6 habitat. Dominated by alder, crack willow, goat willow and aspen.
Understorey Vegetation	Naturally colonised. Species include nettle, cleavers, dock, creeping bent, Yorkshire fog and red campion.	Planted. Species include nettle, clevers, wild angelica, red campion, meadowsweet, flag iris and reed.
Meteorological Data		
Annual Rainfall LTA (mm)	654.3 mm	567.9 mm
Annual PET LTA (mm)	581.8 mm	573.6 mm
Sub surface soil		
Top horizon	Topsoil to 0.30 m.b.g.l.	None
Medium horizon	Clay from 0.30 to 1.50 m.b.g.l.	Clay from 0.00 to 1.60 m.b.g.l.
Bottom horizon	Sand and gravel below 1.50 m.b.g.l.	Sand and gravel below 1.60 m.b.g.l.

Table 6.3: Wet Woodland Study Sites - Summary Data

6.3 EXPERIMENTAL DESIGN AND ESTABLISHMENT

6.3.1 INTRODUCTION

Experimental equipment was installed at the two wet woodland sites during October 2000 for the following reasons.

(1) Smith (2000) concluded that late October was the optimum time for tree transplantation works to ensure minimal impact on the tree and the greatest chance of survival. Tree transplantation was carried out at Cherry Holme Woods.

(2) Experimental equipment was installed before tree planting had to take place at Leam Valley (November 2000).

(3) Installation during October allowed the soil within the lysimeters to settle before soil moisture monitoring equipment was installed and monitoring could began in spring 2001.

A summary of the equipment installed at each site is given in Table 6.4.

6.3.2 LYSIMETER INSTALLATION AND VEGETATION ESTABLISHMENT

The lysimeters used in the wet woodland experiments comprised 2 m diameter, 2 m deep plastic water tanks which had had the tops removed. Lysimeter installation involved excavating pits within the experimental area, dropping the lysimeter into the excavation pit and re-instating the soil profile within the lysimeters, and was carried out using hydraulic excavators. At Cherry Holme Woods trees and associated ground flora were transplanted. Details of the methodology used to install the lysimeters at the two sites are given in Sections 6.3.2.1 and 6.3.2.2.

The species chosen for transplantation into the lysimeters was goat willow *Salix caprea* as this is one of the component species of NVC habitat W6 (see Table 4.2). Although *Salix caprea* tend to prefer drier localities than some other *Salix* sp. (Moff, 1914), their abundance throughout the woods and hedgerows of the UK mean that they are a species often included in wetland design projects as they will successfully survive within a wet woodland ecotone between terrestrial woodland and wetland habitats.

SITE	EQUIPMENT	INSTALLATION DATE	SPECIFICATION
Cherry Holme Woods	Lysimeters	25^{th} Oct 2001	2 no. (2 m diameter)
	Soil Moisture Monitoring Equipment	3^{rd} Apr 2001	Watermark Sensors
		3^{rd} Apr 2001	Profile Probe Access Tubes
		22^{nd} Nov 2001	Theta Probes
	Meteorological Equipment	9^{th} Apr 2001	Rain Gauge US Class 'A' Evaporation Pan
		18^{th} Dec 2001	Automatic Weather Station
Leam Valley	Lysimeters	27^{th} Oct 2000	2 no. (2 m diameter) 3 (0.5 m diameter)
	Soil Moisture Monitoring Equipment	18^{th} May 2001	Watermark Sensors
		18^{th} May 2001	Profile Probe Access Tubes
		31^{st} Jan 2002	Theta Probes
	Meteorological Equipment	18^{th} May 2001	Rain Gauge US Class 'A' Evaporation Pan

Table 6.4: Summary of Wet Woodland Experimental Site Establishment and Equipment

6.3.2.1 CHERRY HOLME WOODS

The working area was marked out (2.50 m by 2.50 m) and the turf carefully removed and temporarily stored to one side of the excavation area. The topsoil and sandy clay layers were excavated and stored in separate piles. Below the clay layer was a layer of sand and gravel which was excavated to a depth of 1.80 m.b.g.l. and stored to one side of the excavation.

Once all the material had been removed, the bottom of the excavation pit (2.50 m by 2.50 m wide and 1.80 m deep) was flattened and the lysimeter lowered into it. To prevent water entering the lysimeter during the experiment via over-land flow, the rim of the lysimeter was set 0.3 m above ground level.

To provide a suitable drainage layer for the dip wells, and a potential water reservoir, a layer of gravel 0.3 m thick was reinstated at the bottom of the lysimeter. Into this a dip well (90 mm diameter slotted drainage pipe) and two access tubes (250 mm diameter plastic pipes with holes drilled along its length) were installed and secured to the side of the lysimeter.

The sandy clay layer (0.8 m thick) was reinstated on top of the gravel. To ensure that the walls of the lysimeter were not damaged, soil was back-filled around the outside of the lysimeter during this phase. Where possible, the soils inside the lysimeter were compacted using the bucket of the excavator, with the soil around the dip well and access tubes being packed down by hand.

Suitable trees for transplantation into each lysimeter had been identified during a previous site visit. Both trees were approximately 5 years old and were 3.5 m and 4.0 m tall. The trees were situated in an open part of the woodland and could be moved without damaging the trees themselves or any of the surrounding habitat. To ensure that the tree was not damaged during transplantation, the branches were loosely tied to the trunk.

Patch (2000) and Faulk (2000) stated that 90% of a tree's roots are likely to be found within the top 0.6 m of soil. The soil around the tree's roots was loosened using the bucket of the excavator to a minimum depth of 0.6 m.b.g.l., the tree was scooped up in the bucket and ropes were used to secure it to the boom. The tree was then carefully manoeuvred into the lysimeter.

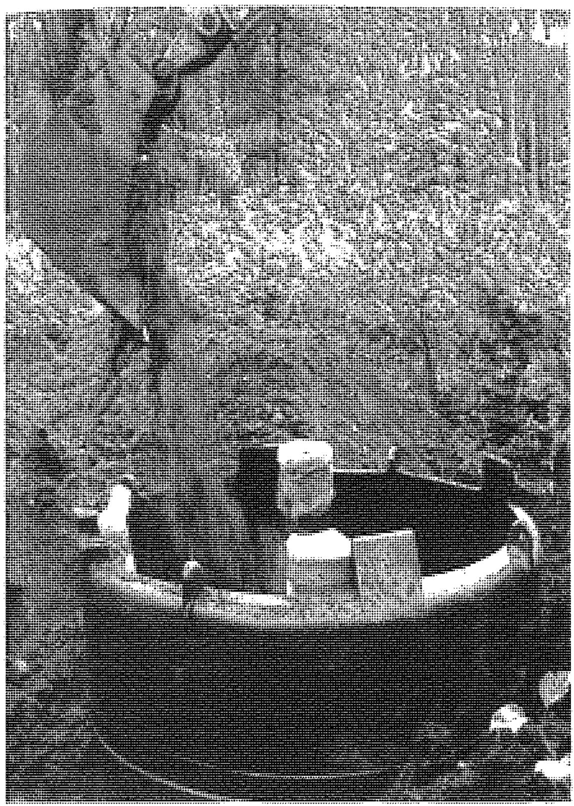
The tree was supported by ropes while the excavator back-filled the remainder of the lysimeter with the stored topsoil which was reinstated to a depth of 0.4 m around the tree. The tree was then staked to secure it. Turves were reinstated to depth of

0.2 m and any unwanted species (e.g. tall coarse grasses) were removed. To achieve appropriate soil moisture levels, the lysimeters were watered with approximately 135 litres of water.

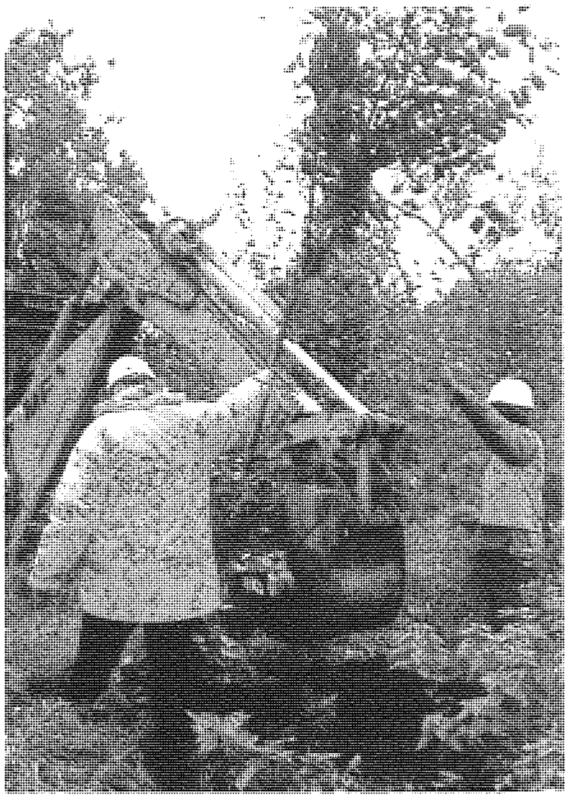
The installation process is shown in Figure 6.8, with a diagrammatic representation of the wet woodland lysimeters at Cherry Holme Woods provided in Figure 6.9.

During April 2001 it was noted that the tree in Lysimeter 1 was not growing well (there was reduced leaf cover and poor growth). Excessive flooding between October 2000 and March 2001 resulted in the lysimeters being repeatedly inundated with floodwater, which could not be removed due to restricted access to the woodland and this extended inundation could have resulted in the tree's death. Gowing (2002) stated that *Salix caprea* can withstand inundation during December and January as temperatures are low and bacteria is not active and anaerobic conditions within the soil are unlikely. However, if the soils are saturated during warmer months the anaerobic conditions in the soil can result in damage to the tree. Members of the Wet Woodland Research Steering Group (WWRSG, 2001) concluded that the lack of lateral water movement within the soil during periods when the lysimeter was standing in water could have resulted in the water around the tree roots having a low oxygen content. To counteract these problems, water was removed from the lysimeters during appropriate months and replaced with fresh water from the nearby rivers.

Smith (2001) recommended that the tree be left in situ throughout the summer as willows can regenerate successfully and may grow again. However, the tree did not re-grow and was therefore replaced with another specimen in November 2001.

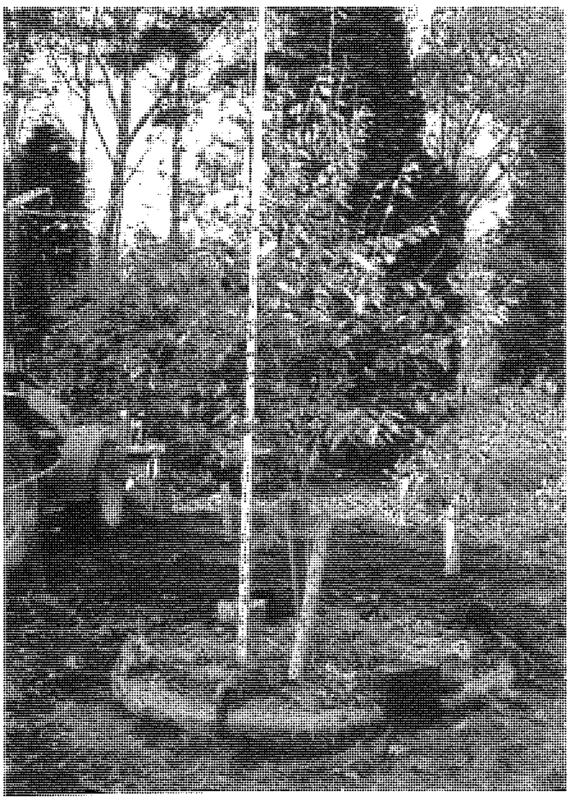


Reinstating the Soil Layers



Transplanting the Tree

Planting the Tree in the Lysimeter



The Completed Lysimeter

Fig. 6.8: Wet Woodland Lysimeter Installation Process

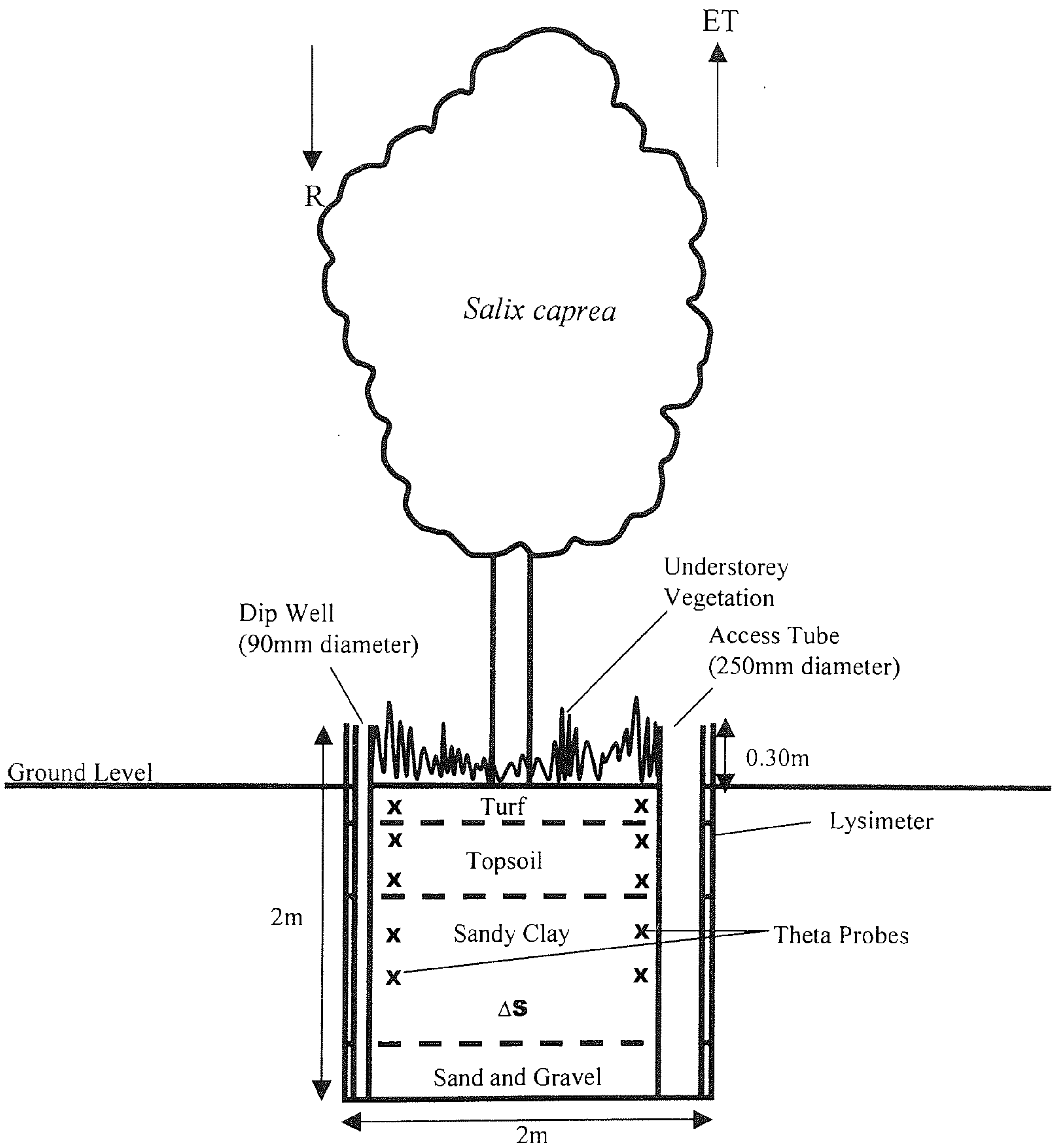


Fig. 6.9: Diagrammatic Representation of a Wet Woodland Lysimeter

6.3.2.2 LEAM VALLEY

The same installation methodology was used at the Leam Valley LNR. The Leam Valley wetland area was still under construction during the lysimeter installation and as such, there was no flora or topsoil covering the site.

The site had a water table that sits approximately 1.5 m.b.g.l. during the winter months. The lysimeters were therefore installed to a depth of 1.4 m.b.g.l. as a result of concerns about rising water tables affecting the lysimeter due to floatation resulting from an imbalance of hydrostatic pressure.

Soil from within the working area was removed in layers and stored to one side of the excavation. The gravel layer installed at the bottom of the lysimeters was 0.25 m thick and was won from another excavation on-site where gravel was found more than 2 m.b.g.l. A layer of topsoil was taken from the nearby alder woodland and spread 0.25 m deep over the clay layer.

In May 2001, the tree in Lysimeter 2 was noted to be dead, deemed to be the result of the same excessive inundation problems that were noted at Cherry Holme Woods. Again this tree was retained during the 2001 growing season and then replaced in November 2001. The tree in this lysimeter again suffered and was replaced with another specimen (already growing on the site) during April 2002. Although this was not the ideal time for replanting, this tree survived throughout the remainder of the experiment.

6.3.3 SOIL MOISTURE MONITORING EQUIPMENT

An appropriate technique for determining soil moisture content within the lysimeter was required. Details of a range of soil moisture monitoring equipment available and an assessment of their suitability for this project, is provided in Sections 6.3.3.1 to 6.3.3.7.

Soil moisture monitoring equipment can provide data with respect to either soil moisture content, or soil moisture potential, dependant on its design. Soil moisture content is the volume of water contained in the soil at a given time.

Soil moisture potential (also known as soil water suction) is measured in centibars or kiloPascals (kPa) and represents the amount of work (energy) required by a plant to extract water from the soil matrix indicating the availability of soil water. Skinner et al (1997) stated that most plants grow best when the soil water potential is less than 30 centibars (1 centibar = -1 kPa), but can grow quite happily at suctions up to 200 centibars. Although the soil moisture content of two different soils may be the same, the soil water potential may be vastly different, as some soils 'hold onto' their water more strongly than other. Table 6.5 provides an example of the relationship between soil water potential and the amount of clay in a soil (after Skinner et al, 1997).

SOIL TYPE	SOIL MOISTURE CONTENT	SOIL WATER POTENTIAL	EFFECT ON PLANT GROWTH
Loam	20 %	Low suction – 10 centibars	Ample water for plant growth
Clay	20 %	High suction – 500 centibars	Plant growth limited by water availability

Table 6.5: The Impact of Soil Type on Soil Water Potential and Plant Growth
(after Skinner et al, 1997)

6.3.3.1 ELECTRICAL RESISTANCE BLOCKS

The simplest of these is known as a gypsum block, which comprises two electrodes embedded in a block of gypsum, and is one of the oldest methods of soil moisture measurement. The block transmits water easily, and rapidly comes into equilibrium with the soil water potential in the surrounding soil. Measurements are taken by determining the electrical resistance between the electrodes in the block. When the soil is wet, pores in the gypsum block are filled, and the measured resistance is quite small. As the soil around the block dries, water migrates out of the block thus emptying the pores and increasing the resistance (Skinner et al, 1997).

Gypsum blocks provide a simple, low cost solution to the measurement of soil moisture but there are a number of disadvantages associated with them. The blocks suffer from hysteresis and when soils are dry, a large change in soil moisture is often only shown as a small change in resistance. Skinner et al (1997) concluded that the blocks measure soil water potential in the 60 to 600 centibar range. As the soil wets up and water enters into the pores in the block, the gypsum dissolves to form a solution of calcium sulphate which successfully buffers soil salinity (and therefore does not affect the measurement of resistance), however, as a result, the blocks do degrade over time. The rate of degradation is dependant on the soil conditions, but will be increased in soils with a high water content.

An alternative to gypsum blocks but based on the same principles are Watermark Soil Water Potential Sensors supplied by Delta-T Devices Ltd (1998) which provide soil water potential measurements between 10 and 200 centibars. The sensor includes internally installed gypsum which provides the required salinity buffer but does not dissolve in the soil. They are unaffected by freezing and need little maintenance and therefore can be left installed in the soil for longer periods of time. Data is collected using a hand-held meter which supplies the required power to the sensors.

Delta-T Devices Ltd (1998) provided a general guide for measured soil water potential in irrigated soils and the associated soil moisture regimes (Table 6.6). Evans (2000) stated that Watermark sensors provide information about soil water potential trends within the soil, but do not provide very accurate readings.

SOIL WATER POTENTIAL	SOIL MOISTURE REGIME
0 - 10 centibars	Soil is saturated
10 - 20 centibars	Soil is adequately wet (except coarse sands which are starting to lose water)
20 - 60 centibars	Soil is within the usual range to apply irrigation (except heavy clay soils)
60 - 100 centibars	Soil is within the usual range to apply irrigation for heavy clay soils
100 - 200 centibars	Soil is dangerously dry for maximum crop production.

Table 6.6: Measured Soil Moisture Potential and Associated Soil Moisture Regimes
(after Delta-T Devices Ltd, 1998)

6.3.3.2 TENSIOMETERS

Tensiometers also measure soil water potential and operate by allowing the soil solution to come into equilibrium with a reference pressure indicator through a permeable ceramic cup placed in contact with the soil. They are not affected by the osmotic potential of the soil solution as salts can move in and out of the ceramic cup. They measure soil water potential in the range 0 - 85 centibars, and are particularly actuate in more saturated soils but during dry periods, they can act locally as a source of water and therefore results become inaccurate.

Disadvantages include: having a slow reaction time; being prone to damage if the soil freezes; and requiring maintenance after dry periods (probes require refilling with water and degassing). There are also potential problems associated with installation, as the ceramic cup must be in constant contact with the soil, as air pockets result in an apparent 'lack of response' of the instrument.

To address some of the issues associated with using traditional tensiometers the 'Equitensiometer' (Figure 6.10) has been developed by Delta-T Devices Ltd (2001a). The sensor comprises a Theta Probe (see Section 6.3.3.6) embedded into a specially formulated matric material. The water content of this material rapidly reaches equilibrium with the matric potential of the surrounding soil, and the absorbed water is detected by the probe. Unlike traditional tensiometers this instrument does not require refilling, degassing, topping up or frost protection. Delta-T Devices Ltd (2001a) asserted that the best accuracy is achieved over the range 100 - 1000 centibars, but concluded that the instrument is not a rapid response, high accuracy device as it takes up to two days for equilibration.

Fig. 6.10: Equitensiometer Probe
(Delta-T Devices, 2001a)

6.3.3.3 NEUTRON PROBE

The neutron probe (Figure 6.11) measures soil moisture by the moderating effect of water on fast neutrons. The probe is inserted into an aluminium access tube and works by emitting fast neutrons into the soil from a radioactive source.

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Fig. 6.11: Diagram of a Neutron Probe
(SoWaCS, no date)

Bell (1976) provided information with respect to the basic principles of the probe and stated that the fast neutrons scatter, slow and lose energy when they collide with the nuclei of soil atoms predominantly those of hydrogen in the soil water. When the neutrons have slowed to a so-called 'thermal' energy level they are absorbed by other nuclear reactions and a 'cloud' of slow neutrons is generated within the soil around the source. The density of this cloud is largely a function of soil moisture content and is sampled by a slow neutron detector in the probe. The electrical pulses from the detector are then amplified and shaped and passed up to the counter unit where the mean count rate is displayed. The count rate is then translated into soil moisture content (by volume) using an appropriate calibration curve.

There are a number of disadvantages of using this instrument for the determination of soil water within plastic lysimeters. Not only will the probe measure any water that is present in the plant roots (which should not be included in the soil moisture content), but the lysimeter is made of a polymer which contains large numbers of hydrogen atoms. These would slow down the neutrons in the same way as water and therefore distort the soil moisture readings. SoWaCS (no date) stated that not only are there safety issues relating to the use of the neutron probe (due to its radioactivity), but it also does not provide accurate readings close to the soil surface due to the fact that the sphere of influence is not totally contained within the soil.

6.3.3.4 TIME DOMAIN REFLECTOMETERS

Time Domain Reflectometers (TDR) use electromagnetic waves to provide readings of volumetric soil moisture content. A fast-rise electromagnetic pulse is sent down two transmission lines (prongs) which are buried in the soil. The velocity at which the waves are reflected back is related to the water content in the soil as the presence of water causes the electromagnetic waves to slow down slightly. All electromagnetic waves are reflected back along the same transmission line and a microprocessor converts the travel time of the wave into a value of the dielectric constant of the soil (a measure of a material's response to polarisation in an electromagnetic field). For a given soil type a relationship exists between the soil's dielectric properties and the soil moisture content, and therefore soil moisture can be determined.

Advantages of using this technique include: an accuracy to within 1 or 2 % of volumetric water content; minimal calibration requirements; and, simple data collection. The main constraint is that the equipment has very complex electronics and is therefore expensive to purchase and maintain.

6.3.3.5 THETA PROBE

Theta Probes (Figure 6.12) were developed by Delta-T Devices Ltd (2001a) and work by using a simplified standing electromagnetic wave measurement to determine the impedance of a sensing rod array and hence the volumetric water content of the soil matrix (Miller and Gaskin, no date).

The input/output cable provides a connection to a suitable power source and for an analogue signal output. An oscillator, internal transmission line, and the measuring circuitry are housed within the probe body, with the sensing head comprising of four 60 mm rods. The three shield rods form an electrical shield around the central signal rod and behave as an additional section of transmission line, which has an impedance dependant on the dielectric constant of the soil matrix into which it is inserted. If the impedance differs from that of the internal transmission line (in the probe body) then a proportion of the signal is reflected back to the junction between the probe array and the transmission line (point J in Figure 6.12). The reflected component interferes with the incident signal causing variation of voltage amplitude along the length of the line. Measuring the amplitude gives the relative impedance of the probe, therefore a dielectric constant can be determined, and from this a measure of volumetric water content (Miller and Gaskin, no date).

The Theta Probes can either be wired into a datalogger that provides the required power and records the signal from the probe, or alternatively, a hand held Moisture Meter (Type HH2, Delta-T Devices Ltd, 2001a) could be connected to the probe and a reading taken manually.

Theta Probes provide an established method for the determination of soil moisture in a variety of soil types (Hanson et al, 1999). They can be installed in the soil for up to five years without requiring any maintenance, and provide a simple output reading of soil moisture. The probes will only provide readings from the immediate surrounding soil and therefore installation must be done carefully and a set of probes would have to be installed at varying depths to provide a soil moisture profile.

6.3.3.6 PROFILE PROBE

The Profile Probe (Figure 6.13) is also manufactured by Delta-T Devices Ltd (2001a) and works on the same principles as the Theta Probe but the device enables soil moisture content to be measured at different depths within the soil profile. The instrument consists of a sealed composite rod, approximately 25 mm diameter with electronic sensors (in the form of pairs of stainless steel rings) arranged at fixed intervals along its length. To take a reading, the probe is inserted into an access tube situated in the ground. The access tubes are thin-wall polymer tubes which allow maximum penetration of the electromagnetic field into the surrounding soil (Delta-T Devices Ltd, 2001b).

When power is applied to the probe it generates a 100 mHz signal which is applied to the pairs of stainless steel rings which in turn generate an electromagnetic field that extends approximately 100 mm into the soil. This field passes easily though the access tube walls, but less easily through any air gaps. The soil's dielectric properties are determined by the water content of the soil surrounding the rings and if the dielectric properties of the soil are different from the probe electronics, some of the signal gets reflected back. The reflected part of the signal combines with the applied signal to form a standing wave, the voltage of which acts as a simple, sensitive measure of soil moisture content. The soil moisture content is presented either as a voltage (mV), or as a percentage of the total volume of the soil or both.

The Profile Probe has sensors set at 0.10, 0.20, 0.30, 0.40, 0.60 and 1.00 m along its length (Figure 6.13), thus providing soil moisture readings at each of these depths within the profile. Readings from the probe are taken using either a datalogger or a hand-held Moisture Meter (Type HH2, Delta-T Devices Ltd, 2001a), which provides power to the probe and records the readings so that they can be downloaded onto a computer.

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Aston University

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Fig. 6.13: Diagram of a Profile Probe
(Delta-T Devices Ltd, 2001b)

6.3.3.7 SUMMARY AND INSTALLATION METHODOLOGY

The suitability of each of the soil moisture monitoring methodologies was evaluated with respect to this project. Instruments that measure soil water potential (electrical resistance blocks and tensiometers) would not provide a simple measurement of soil water content as the relationship between the two is dependant on soil type and would have to be calibrated for each study site. However, Watermark Soil Water Potential sensors were installed to test their suitability as a back-up system and provide an indication of the available water within the lysimeters.

The sensors were supplied by Delta-T Devices Ltd and were installed in the lysimeters during April and May 2001 to provide a soil moisture tension profile consisting of four sensors in each profile (Table 6.7). Readings from the Watermark sensors were taken with a hand-held meter during each monitoring visit.

CHERRY HOLME WOODS			LEAM VALLEY		
DEPTH (m.b.g.l.)	**LYSIMETER 1 SENSOR ID**	**LYSIMETER 2 SENSOR ID**	**DEPTH (m.b.g.l.)**	**LYSIMETER 1 SENSOR ID**	**LYSIMETER 2 SENSOR ID**
0.30	CH WS 01	CH WS 05	0.30	LV WS 01	LV WS 05
0.60	CH WS 02	CH WS 06	0.60	LV WS 02	LV WS 06
0.90	CH WS 03	CH WS 07	0.90	LV WS 03	LV WS 07
1.20	CH WS 04	CH WS 08	1.10	LV WS 04	LV WS 08

Table 6.7: Watermark Sensor Installation Depths

To provide data with respect to the soil water content within the soil, a review of the available techniques (see Sections 6.3.3.3 to 6.3.3.6) was completed. As a result of safety issues, problems associated with the measurement of soil moisture at the surface and concerns with respect to the impact of vegetation roots and the polymer walls of the lysimeter, the use of a neutron probe was rejected. The high purchase and maintenance costs of TDR technology linked with concerns about using sensitive electrical equipment in a floodplain situation deemed this method inappropriate for use in this project.

It was therefore decided that a Profile Probe (see Section 6.3.3.6) be used as it provided a cheap and simple way of directly measuring volumetric soil moisture content. Access tubes could be permanently installed in the soil and the probe inserted when a reading was required, thus allowing numerous readings to be taken using one instrument.

Access tubes were installed in the lysimeters using installation equipment supplied by the manufacturer during March and May 2001 at Cherry Holme Woods and Leam Valley respectively. Two access tubes were installed within each lysimeter and soil moisture readings were taken every two weeks.

Due to the different composition of some soils, the Moisture Meter allowed the selection of one of two manufacturer-calibrated soil types - either organic soil or mineral soil, the latter of which was used in this project. It is possible to carry out a soil specific calibration for each site; however, the overall error (including probe, calibration and sampling errors) for a sample using a soil-specific calibration is likely to be ± 0.047, compared to an overall error using the generalised calibration of ± 0.058 (Delta-T Devices Ltd, 2001b). Nichols (2001) concluded that in the clay soils found on the study sites, a soil-specific calibration would be difficult and was likely to produce greater overall errors than using the pre-installed calibrations in the Moisture Meter.

Soil moisture data was collected throughout May and June 2001, and during this time, a number of the readings appeared to be very high (up to 86.7 % soil moisture), particularly for a clay soil during spring/early summer. In comparison, Gavin and Agnew (2001) concluded that the London clay soil on their wet grassland site had a soil moisture content of 40% when saturated. To ensure that the anomalous results were not due to a fault with the Probe itself, the Probe was returned to the manufacturer for re-calibration. Their tests highlighted that Sensor 6 (1.00 m.b.g.l.) was reading incorrectly, but only by ± 4% and it was suggested that an installation error with the access tubes was causing the high readings (Nichols, 2001). However, most installation errors are associated with air gaps around the access tubes, which result in low rather than high readings although if the gaps were filled with water this may result in high readings. However, Delta-T Devices Ltd (2001b) suggested that a loose, gappy, access tube installation could lead to errors of ± 10%, which even if this had been taken into account, would still have resulted in high soil moisture readings. In addition, water table readings suggested that the water table within the lysimeters was significantly lower than the sensors providing the high readings and the soil, although wet, was not saturated.

To provide additional data against which the Profile Probe could be tested, comparative soil moisture readings were collected using three methodologies: Profile Probe; Theta Probe; and, gravimetric sampling, all applied to the same soil profile. To minimise damage to the wet woodland habitat within the lysimeters, these tests were carried out in ground adjacent to the lysimeters. Direct comparisons were achieved by installing an access tube in the ground (using a specially designed frame to minimise any movement of the auger, and ensure 'snug fit'), and taking soil moisture readings using the Profile Probe. A hole was excavated next to the access tube and readings taken at specified depths using the Theta Probe. A soil corer was used to collect soil samples at specified depths for use in the gravimetric sampling.

To determine the gravimetric soil moisture content (θm) of the samples taken using the corer, Equation 6.1 (HMSO, 1975) was applied. Gravimetric soil moisture content was then converted to volumetric soil moisture contact (θv) using the bulk density of the soil which was determined from laboratory experiments (Equation 6.2).

$$\theta \mathbf{m} = 100\left(\frac{\mathbf{m}_2 - \mathbf{m}_3}{\mathbf{m}_3 - \mathbf{m}_1}\right) \qquad \textbf{(6.1)}$$

where:

θm is the gravimetric moisture content of the sample;

m_1 is the mass of the container in g;

m_2 is the mass of the container and wet soil in g; and,

m_3 is the mass of container and dry soil in g.

$$\theta m = \theta v\left(\frac{\rho_b}{\rho_l}\right)$$

(6.2)

where:

θm is the gravimetric soil moisture content;

θv is the volumetric soil moisture content;

ρ_b is the bulk density of the sample; and,

ρ_l is the density of liquid.

Graphs showing the comparative results using the three different techniques at Cherry Holme Woods and Leam Valley are shown in Figures 6.14 and 6.15 respectively.

Figures 6.14 and 6.15 show that the Theta Probe and gravimetric sampling produced similar soil moisture profiles with Theta Probes being approximately 10% higher. The readings from the Profile Probe do not appear to have any relationship with the other instruments as they are very variable with large differences in soil moisture content measured within each profile (readings from the Leam Valley for example range between 25.93% and 70.93%).

From the results of these tests, and supplementary data collected in the field throughout 2001, it was decided that the soil moisture readings provided by the Profile Probe were not sufficiently reliable enough to be used in this project. The manufacturers ultimately confirmed that there was uncertainty regarding the Profile Probe's accuracy in saturated clay soils.

As Theta Probes had been proved to provide accurate soil moisture readings during the comparison tests, a profile of instruments were installed within the lysimeters. A number of Theta Probes and associated equipment was available on loan from the University of Central England and the New Energy Trust, which included:

- 40 no. Theta Probes (wired into junction boxes);
- 2 no. Dataloggers (Type DL2e, Delta-T Devices Ltd, Cambridge); and,
- 1 no. Automatic Weather Station (Delta-T Devices Ltd, Cambridge).

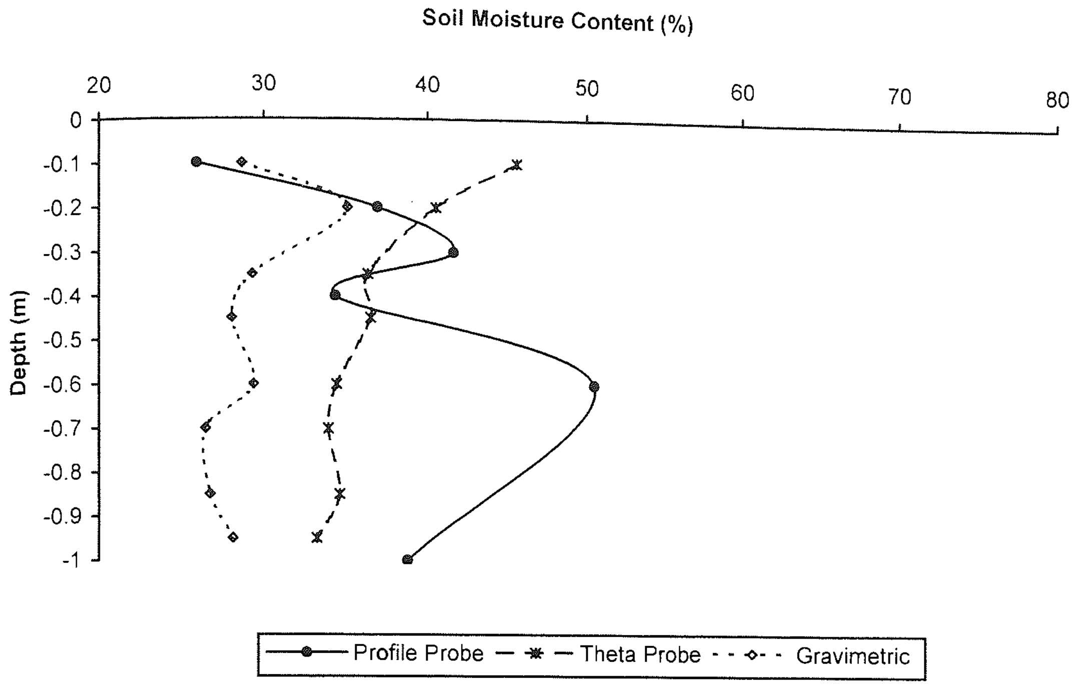


Fig. 6.14: Comparative Soil Moisture Profiles from Cherry Holme Woods

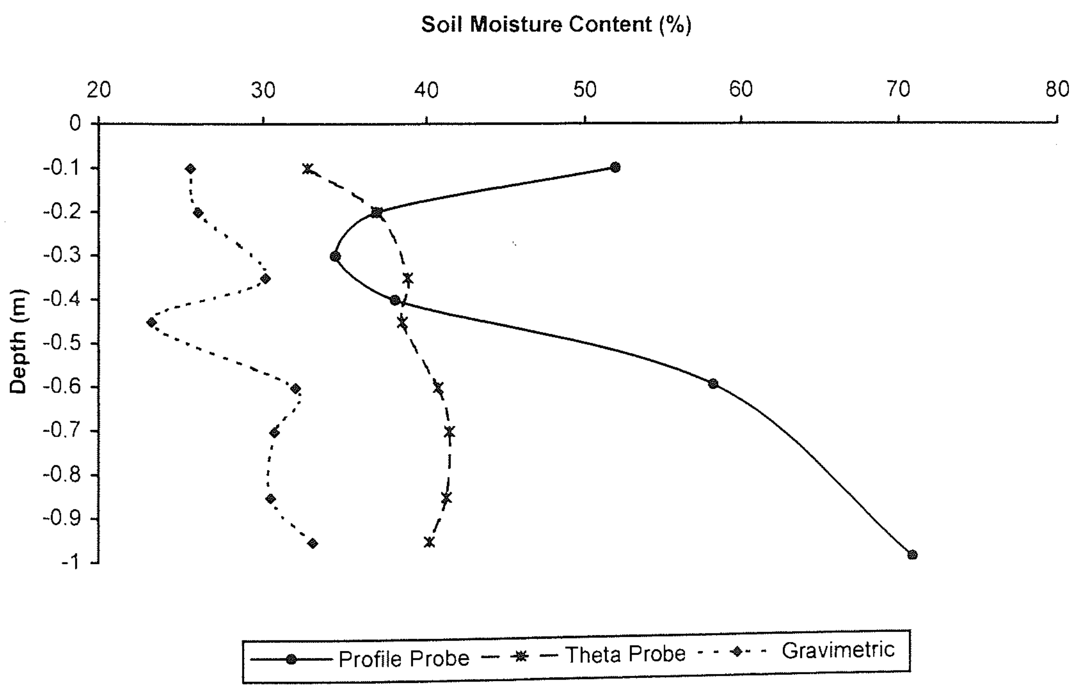


Fig. 6.15: Comparative Soil Moisture Profiles from Leam Valley

The dataloggers and automatic weather station were installed at Cherry Holme Woods for three reasons: (1) the woodland was more established and therefore provided data associated with a more developed wet woodland; (2) an open area suitable for erecting the weather station was identified; and, (3) as there is no public access to the site, the equipment was less likely to be subject to vandalism.

At Cherry Holme Woods, two profiles of five Theta Probes were installed during November 2001, at the depths shown in Table 6.8. These probes were wired into one of the dataloggers (Figure 6.16) which provided a pulse of power to the probes every 4 hours (starting at 00:00 hours each day) and recorded the soil water in $m^3.m^{-3}$. It should be noted that the soil moisture readings were recorded as 4-hourly time-steps and were not averaged by the datalogger. Data was stored within the logger and downloaded onto a laptop computer during monitoring visits. The soil moisture content of the surface layer was determined using a portable Theta Probe and the Moisture Meter, this probe was not left permanently sited on the surface as there was some concern about damage to the probe and rainfall flowing down the side of the probe and along the rods thus affecting the readings.

As there was no datalogger available for use at the Leam Valley, the Theta Probes were wired onto 25 pin D-sockets (suitable for use with the Moisture Meter) and located within a waterproof box (Figure 6.17). Readings from this site were collected during each monitoring visit, stored on the Moisture Meter and then downloaded onto a computer. Theta Probes were installed using the same layout at Leam Valley as had been adopted at Cherry Holme Woods (Table 6.8).

6.3.4 METEOROLOGICAL EQUIPMENT

Meteorological equipment installed at Cherry Holme Woods and Leam Valley included a standard Splayed Base Rain Gauge and a US Class 'A' Evaporation Pan (installation dates are provided in Table 6.4).

THETA PROBE DEPTH (m.b.g.l.)	SENSOR IDENTIFICATION	
	LYSIMETER 1	LYSIMETER 2
0.10	ML2 01 ML2 06	ML2 11 ML2 16
0.25	ML2 02 ML2 07	ML2 12 ML2 17
0.50	ML2 03 ML2 08	ML2 13 ML2 18
0.75	ML2 04 ML2 09	ML2 14 ML2 19
1.00	ML2 05 ML2 10	ML2 15 ML2 20

Table 6.8: Theta Probe Installation Depths at Cherry Holme Woods and Leam Valley

A weather station was erected at Cherry Holme Woods in December 2001 which provided readings every 4 hours of the following parameters: rainfall (mm); solar radiation ($kW.m^{-2}$); relative humidity (%); wind speed ($m.s^{-1}$); wind direction (degrees); soil temperature (^{o}C); and, air temperature (^{o}C). Readings were stored on a datalogger and downloaded onto a laptop computer during monitoring visits.

Data from the weather station was used to calculate daily ETo. The calculations were undertaken using the AWSET Version 3.0 computer programme developed by Cranfield University (1999) for this purpose. The programme offers the user alternative methods of evaporation / evapotranspiration calculation by combination equations from various sources. The method used in this project was the Penman-Monteith method based on the original form (Monteith, 1965 and 1981) and the equations recommended by the Food and Agriculture Organisation of the United National (FAO) using factors for a reference surface (Allen et al, 1999 cited by Cranfield, 1999). The programme allowed the calculation of daily PET Grass.

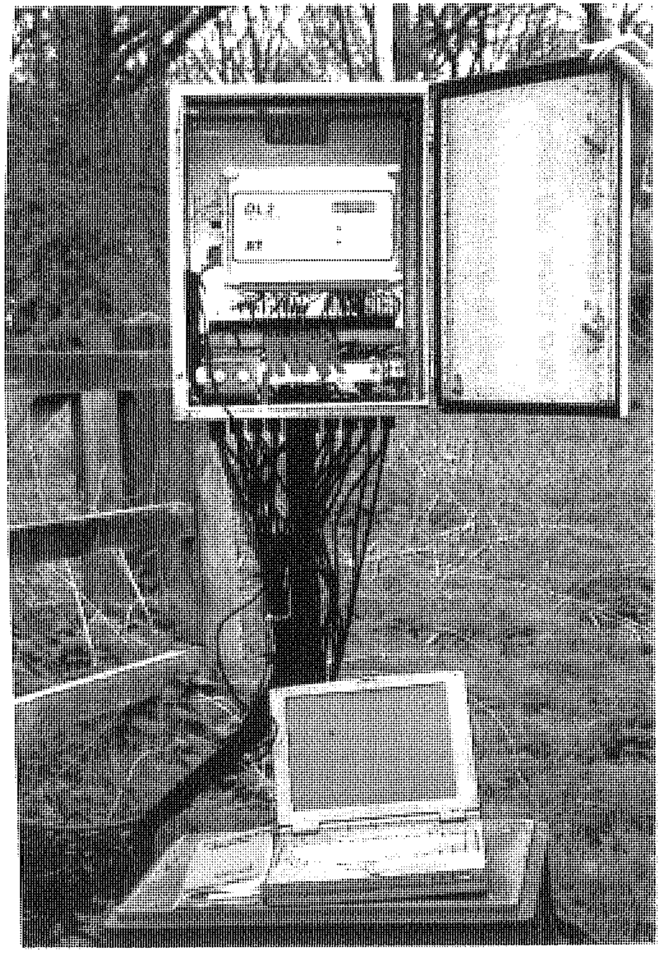


Fig. 6.16: Datalogger at Cherry Holme Woods

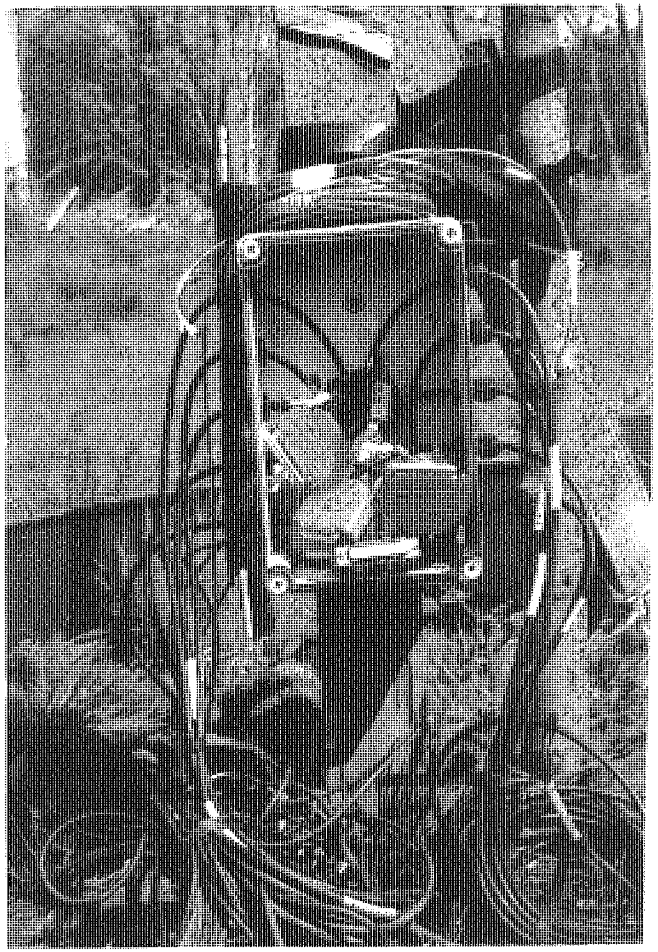


Fig. 6.17: Theta Probe Connections at Leam Valley

6.4 DETERMINATION OF ET(W6) AND Kc(W6)

To determine ET(W6) and Kc(W6) values from the empirical data a computer model was developed using Microsoft Excel. The model was designed to be used during monitoring visits to manage the soil moisture levels within the lysimeters to ensure that: (1) the habitat was continuing to transpire at its potential rate; and (2) the water levels within the lysimeters replicated a natural wet woodland system.

This section provides an introduction to the model and details how it was developed and its limitations. The model itself is split into five different worksheets: raw data entry; known data entry; the calculation of E Pan and ET(W6); generation of Kc(W6); and water level change model. Example worksheets are shown in Figures A4.1 to A4.9 in Appendix 4.

The empirical data shown below was entered into the worksheet entitled 'Raw Data' (see Figures A4.1 to A4.3 in Appendix 4).

(1) Previous and current survey dates.
(2) Rainfall for the period (mm).
(3) The volume of water added / removed from the evaporation pan to restore it to datum (litres). A positive value shows water was removed, a negative value shows the water was added.
(4) Measurement of the depth of water above (positive) or below (negative) the datum point in the evaporation pan (mm).
(5) ETo values for MORECS Grass, Local Meteorological Station and Automatic Meteorological Station.
(6) The measured water levels within the lysimeters during previous and current monitoring visits (m.b.g.l.).
(7) The volume of water added (negative) or removed (positive) from the lysimeters during the previous monitoring visit (litres).
(8) Soil moisture readings from the top surface of the soil (% soil moisture).
(9) Soil moisture readings from the Theta Probes. At Cherry Holme Woods data from the previous 24 hours (6 datasets) was used to provide mean values).
(10) The volume of water in the lysimeters during the previous survey visit.

The 'Known Data' worksheet (see Figure A4.4 in Appendix 4) contained data which did not change between monitoring visits such as the area of the evaporation pan and lysimeters. To allow the conversion of volumetric soil moisture to a total volume of water within the lysimeter, the top 1 m of the profile was split into 5 theoretical 'slices' (Figure 6.18), the total volume of which was calculated within this worksheet.

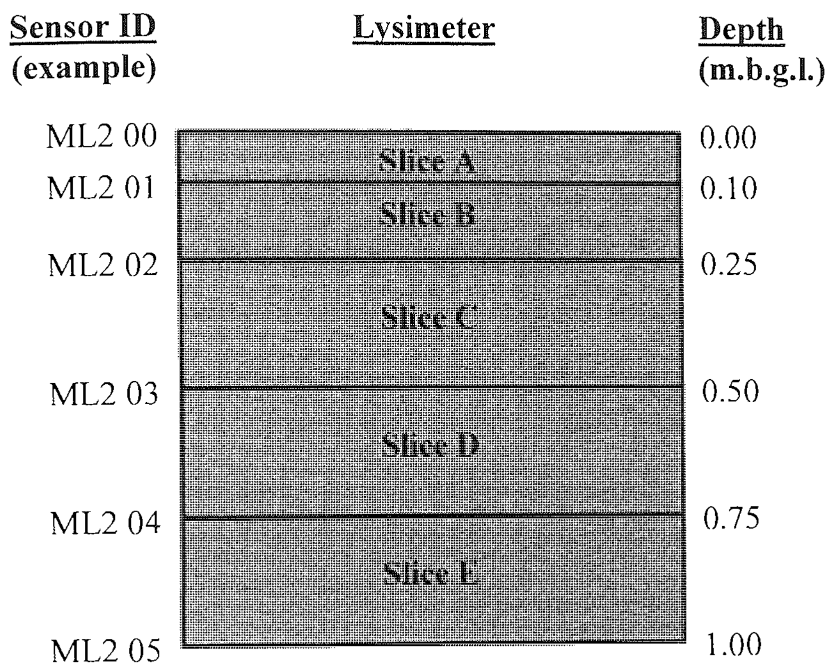


Fig. 6.18: Soil Moisture 'Slices' and Theta Probe Sensor Depths

The 'EPan and ET(W6)' worksheet enables the calculation of ETo Pan (using the method outlined in Section 2.3.1) and ET(W6) for each lysimeter. Evaporation pan data was verified to ensure accurate data entry using an on-site measurement of the depth to the water above / below the gauge point (see Figure A4.5 in Appendix 4).

Mean soil moisture readings at each sensor depth for each profile were generated, these readings were used to create mean soil moisture contents for each slice and the volume of water in each 'slice' was calculated (see Figure A4.6 in Appendix 4).

The change in volume of water within the soil between two monitoring visits was determined and summed to give a total water change in the profile. These volumes represented the change in storage and to replace the ET losses these volumes had to be replaced (see Figure A4.7 in Appendix 4).

To calculate the actual change in water storage within the lysimeter during the period between monitoring visits the volumes of water added / removed during the previous monitoring visit to return the soil moisture to the desired profile were taken into consideration. Figure 6.19 provides an example showing three soil moisture profiles: Profile (x) when the soils are saturated; Profile (y) recorded during the first monitoring visit; and Profile (z) recorded during the second monitoring visit. During monitoring visit (y) the volume of water added to return the soil moisture to Profile (x) is the area between Profiles (x) and (y), shown on Figure 6.19 as Vw(y). During monitoring visit (z) the volume required to return the soil moisture to Profile (y) is Vw(z). The actual change in storage (Δs) within the lysimeter between monitoring visits (y) and (z) is therefore: $\Delta s = Vw(y) + Vw(z)$.

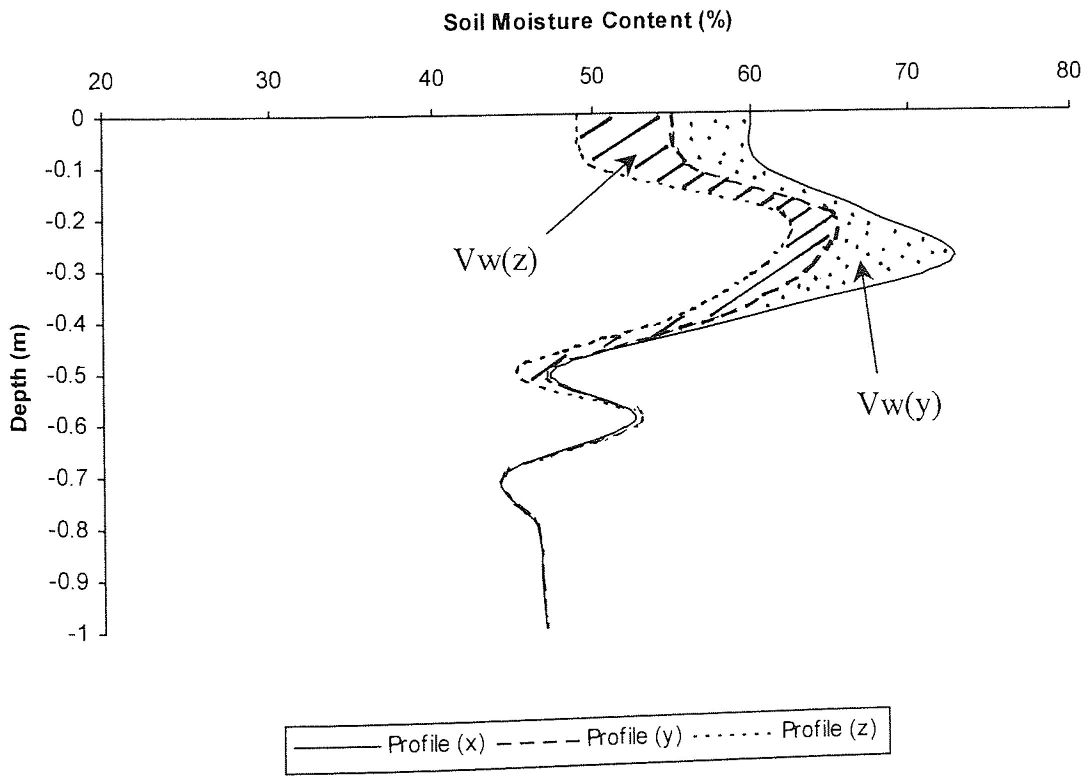


Fig. 6.19: Theoretical Soil Moisture Profiles within Lysimeters

ET(W6) for each lysimeter for the period between visits was calculated using Equation 6.3 (see Figure A4.8 in Appendix 4).

$$\mathbf{ET(W6)} = \frac{\mathbf{R} - \mathbf{\Delta s}}{\mathbf{n}} \tag{6.3}$$

where:

ET(W6) is the evapotranspiration from the lysimeter in mm day^{-1};

R is the rainfall in mm;

Δs is the change in total water storage in mm; and,

n is the number of days in the sampling period.

Kc(W6) was subsequently calculated in worksheet 'Kc(W6)' using Equation 2.2 (Section 2.2) for each of the different ETo sources (see Figure A4.9 in Appendix 4).

Section 4.6 highlighted that wet woodland habitats naturally have a fluctuating water table. To simulate the conditions for a W6 habitat within the lysimeters, a predictive water level model was developed. This provided the user with details of the volumes of water necessary to raise / lower the water levels a required distance.

An initial graph showing the proposed water level regime within the lysimeters was developed (Figure 6.20) using published data and advice from relevant experts (WWRSG, 2001). These initial water levels were used until June 2002, when further consultation and investigation resulted in the creation of the final water level regime shown in Figure 6.20, which was used for the remainder of the monitoring period. During the period when the initial regime was being implemented, it was noted that it was often not possible to remove the total volume of water required from the lysimeters due to the relatively slow lateral movement of water within the lysimeters. To ensure that the total volume required was removed, the lysimeters would have had to have been left over night to allow the access tubes to re-fill with water. As this was not practicable, the final regime used a time-step of approximately two weeks between water level changes, rather than one month.

The proposed water regimes ensured that the habitat within the lysimeters was not short of water, but the soils were not waterlogged between February and October. During installation the tree roots extended to 0.60 m.b.g.l. and it was decided that this should be the maximum water level depth to allow a sufficient water supply to the roots. Gowing (2002) stated that this would also allow the soils at the surface to remain damp through the water being drawn up through the profile by capillary action and a suction gradient produced by the vegetation roots.

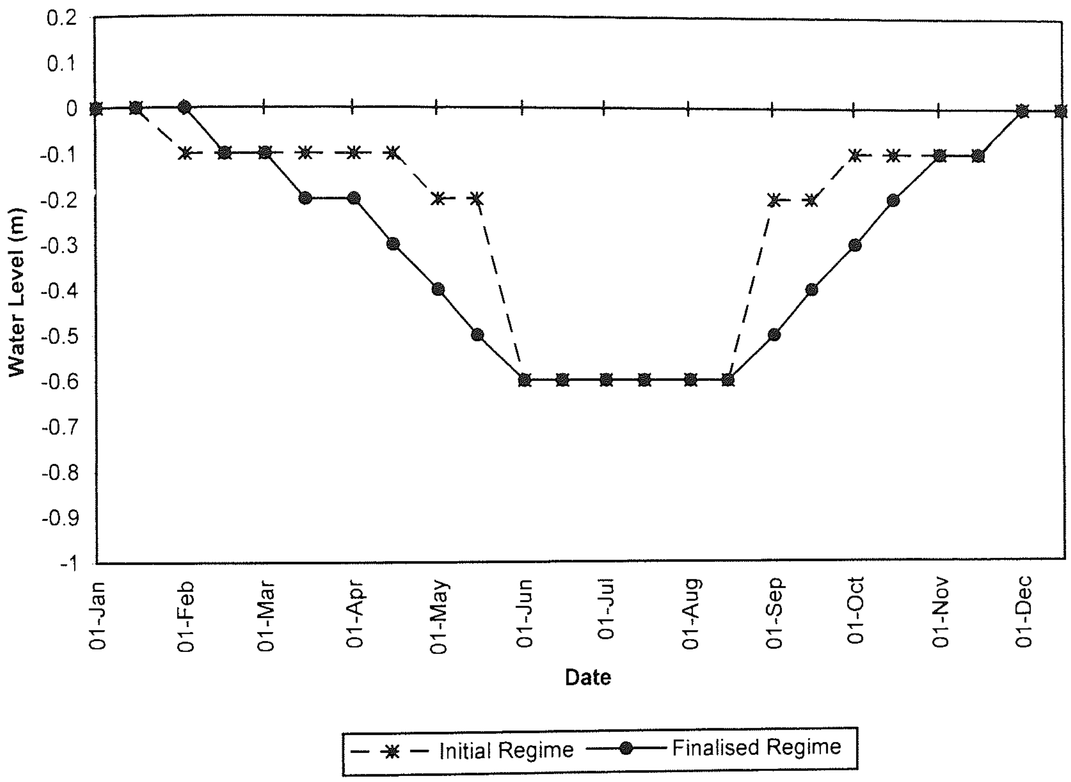


Fig. 6.20: Proposed Water Levels within Lysimeters

To manage the water levels within each lysimeter, the volume of water required to raise / lower the water table a given distance to accord with the design criteria was calculated. During the period when the initial water regime was implemented, this was completed by determining the total volume of water in each soil 'slice' (see Figure 6.18) during monitoring and subtracting this from the required volume of water in each slice. Those slices below the required water table depths shown in Figure 6.20 were assumed to be saturated, whereas those slices above the water table were assumed to be at field capacity. Using soil moisture data from the lysimeters collected during between December and February, the mean soil moisture content when the soils were saturated were calculated (Table 6.10). Shaw (1983) stated that soils comprising of approximately 47% clay had an approximate soil moisture content at field capacity of 41%. These data were used to calculate the required volume of water within the lysimeter at the start of each sampling interval using Equation 6.4.

$$V_{W\,REQ} = \mathbf{n}_1\left(\theta\mathbf{m}_{(FC)} \,.\, V_{SLICE}\right) + \mathbf{n}_2\left(\theta\mathbf{m}_{(SAT)} \,.\, V_{SLICE}\right) \tag{6.4}$$

where:

$V_{W\,REQ}$ is the required volume of water in the lysimeter in m^3;

n_1 and n_2 are the number of 0.1 m slices above and below the water table respectively;

$\theta m_{(FC)}$ is the soil moisture content at field capacity in $m^3.m^{-3}$;

$\theta m_{(SAT)}$ is the soil moisture content at saturation in $m^3.m^{-3}$; and,

V_{SLICE} is the volume of a 0.1 m deep slice in m^3.

The volume of water to be added / removed from the lysimeter in order to achieve the desired water level was the difference between the required volume of water and the calculated volume of water in the lysimeter. This method was tested between January and May 2002. The results showed that the approach did not provide the required degree of accuracy due to the potential for errors when soils were below field capacity.

An alternative method was implemented in June 2002 which utilised the concept of specific yield (SY). This latter is defined (Ward, 1975) as the quantity of water given up by a unit volume of a soil when drained by gravity, i.e. the difference between the soil when saturated and at field capacity.

Gowing (2002) suggested two ways of determining the specific yield from the lysimeters used in this experiment.

(1) Extract soil cores from the lysimeter and obtain a soil moisture release curve showing soil moisture content versus tension. This curve would provide soil moisture values at saturation and field capacity from which the difference in

water volume can be calculated. This method would involve taking numerous soil cores from each lysimeter to ensure that a representative graph was produced (due to the fact that the soil had been disturbed during installation), and was therefore not deemed practical due to the damage this could cause to the integrity of the lysimeter.

(2) The second method involved adding a known volume of water directly into the water table within a lysimeter (via the access tubes), and measuring the resultant change in water table level once equilibrium had been reached. To ensure that the water table had reached equilibrium, measurements would be taken over a 24 hour period. Ideally this experiment would need to be carried out without additional hydrological outputs (transpiration from vegetation) or inputs (rainfall). Due to the vegetation being already established within the lysimeters, the experiment would have had to have been carried out during a period of guaranteed no rainfall, low temperatures and no sunshine, i.e. during a dry night. If the water level had not reached equilibrium by daybreak, the lysimeter and associated vegetation would have to be covered in plastic to stop any water being lost via transpiration. This method would only provide specific yield values for those slices with a similar soil characteristics.

Since neither of these approaches was deemed practicable a method for estimating specific yield based on Option (1) was developed. This involved determining the mean soil moisture content of the topsoil and subsoil layers at each site when the soils were at field capacity and saturation.

It is possible to estimate the moisture content of a soil at field capacity using a diagram (Figure 6.21) presented in Hall et al (1977) once the percentage of clay in the soil was known. The Anderson Pipette Method (BSI, 1977) was used to determine the clay content of soil samples taken from the lysimeters at each site. At Cherry Holme Woods, soil samples were taken from the centre of the topsoil layer (0 - 0.3 m.b.g.l.) and from the centre of the subsoil layer (0.3 - 0.1 m.b.g.l.), whereas soil samples from the Leam Valley were taken from the centre of the subsoil layer which extended throughout the profile (0 - 1.0 m.b.g.l.). Table 6.9 details the composition of the soils.

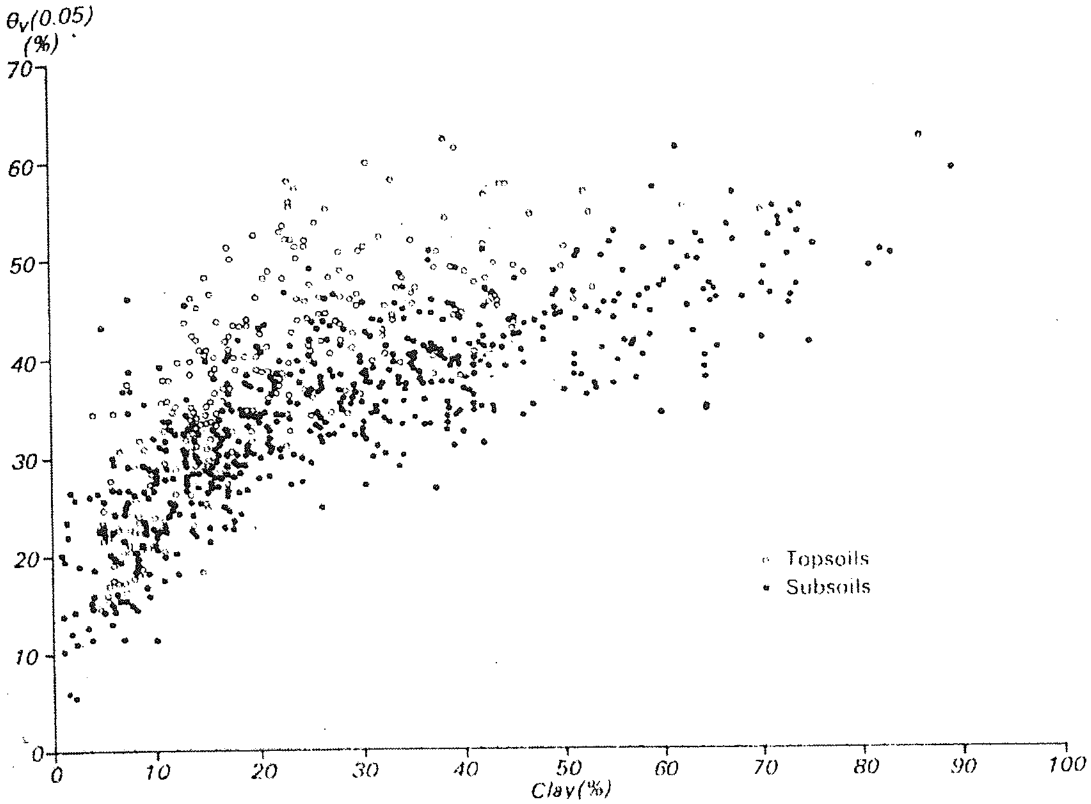


Figure 6.21: Water Retention at Field Capacity in Relation to Clay Content
(Hall et al, 1977)

SOIL COMPOSITION	CHERRY HOLME WOODS		LEAM VALLEY
	TOPSOIL	SUBSOIL	SUBSOIL
Sand	18.5%	34.3%	45.4%
Silt	35.0%	23.3%	13.6%
Clay	46.5%	42.5%	41.0%

Table 6.9: Soil Composition within the Wet Woodland Lysimeters

Using the clay percentage data the mean soil moisture content at field capacity was estimated from Figure 6.21. Mean soil moisture content of the soil when saturated and at field capacity are presented in Table 6.10. The difference between the two soil moisture contents equated to the specific yield (Table 6.10).

SAMPLE	$\theta v_{(SAT)}$ ($m^3.m^{-3}$)	$\theta v_{(FC)}$ ($m^3.m^{-3}$)	SY
Cherry Holme Woods Topsoil	0.62	0.51	**0.11**
Cherry Holme Woods Subsoil	0.49	0.40	**0.09**
Leam Valley Subsoil	0.47	0.39	**0.08**

Table 6.10: Soil Moisture Content at Saturation and Field Capacity and Specific Yield of Soils in the Lysimeters at Cherry Holme Woods and Leam Valley

The data for specific yield presented in Table 6.10 is comparable with data presented by Souch et al (2000) for W5 wet woodland; i.e. a SY of 0.12 at a depth of 0.15 m.b.g.l. In addition, Gowing (2002) stated that he would expect the specific yield from the sandy clay soils at the research sites to equal approximately 0.1.

Equation 6.5 gives the volume of water required to move the water table within the lysimeters a specified distance.

$$V_{W\,REQ} = SY\,.\,\Delta d\,.\,A_L \tag{6.5}$$

where:

$V_{W\,REQ}$ is the volume of water required to move the water table within the lysimeter distance Δd;

SY is the specific yield of the soil;

Δd is the change in depth of the water table in m; and,

A_L is the area of the lysimeter in m^2.

Using Equation 6.5, Tables 6.11 and 6.12 were developed, which provide details of the volumes of water to be added / removed from the lysimeters given monthly and bi-monthly monitoring visits respectively in order that the water table follows the pattern given in Figure 6.20. The volumes presented assume no rainfall inputs or evapotranspiration outputs from the lysimeter as these are dealt with elsewhere within the model.

During each monitoring visit therefore, the total volume of water to be added / removed from the lysimeter was the sum of: (a) the volume of water required to replace ET losses (Figure A4.7 in Appendix 4); and (b) the volume of water required to alter the water level (Tables 6.11 and 6.12).

The computer model was tested in its initial form between December and May 2002, and in its revised form between June 2002 and January 2003. An assessment of the success and limitations of the method employed to determine wet woodland water use rates and initial water use data is presented in Chapter 8.

		CHERRY HOLME WOODS		LEAM VALLEY	
SURVEY DATE	REQUIRED WATER LEVEL (m.b.g.l.)	ACTION	VOLUME	ACTION	VOLUME
01-Jan	0	-	0	-	0
01-Feb	0	Remove	33 litres	Remove	24 litres
01-Mar	0.1	Remove	33 litres	Remove	24 litres
01-Apr	0.2	Remove	60 litres	Remove	48 litres
01-May	0.4	Remove	54 litres	Remove	48 litres
01-Jun	0.6	-	0	-	0
01-Jul	0.6	-	0	-	0
01-Aug	0.6	Add	27 litres	Add	24 litres
01-Sep	0.5	Add	54 litres	Add	48 litres
01-Oct	0.2	Add	66 litres	Add	48 litres
01-Nov	0.1	Add	33 litres	Add	24 litres
01-Dec	0	-	0	-	0

NB – These volumes assume no rainfall inputs or ET outputs from the lysimeter

Table 6.11: Details of the Water Management Regime Required to Facilitate Designed Water Levels within Lysimeters - Monthly Monitoring

		CHERRY HOLME WOODS		LEAM VALLEY	
SITE VISIT DATE	REQUIRED WATER LEVEL (m.b.g.l.)	ACTION	VOLUME	ACTION	VOLUME
01-Jan	0	-	0	-	0
15-Jan	0	-	0	-	0
01-Feb	0	Remove	33 litres	Remove	24 litres
15-Feb	0.1	-	0	-	0
01-Mar	0.1	Remove	33 litres	Remove	24 litres
15-Mar	0.2	-	0	-	0
01-Apr	0.2	Remove	33 litres	Remove	24 litres
15-Apr	0.3	Remove	27 litres	Remove	24 litres
01-May	0.4	Remove	27 litres	Remove	24 litres
15-May	0.5	Remove	27 litres	Remove	24 litres
01-Jun	0.6	-	0	-	0
15-Jun	0.6	-	0	-	0
01-Jul	0.6	-	0	-	0
15-Jul	0.6	-	0	-	0
01-Aug	0.6	-	0	-	0
15-Aug	0.6	Add	27 litres	Add	24 litres
01-Sep	0.5	Add	27 litres	Add	24 litres
15-Sep	0.4	Add	27 litres	Add	24 litres
01-Oct	0.3	Add	33 litres	Add	24 litres
15-Oct	0.2	Add	33 litres	Add	24 litres
01-Nov	0.1	-	0	-	0
15-Nov	0.1	Add	33 litres	Add	24 litres
01-Dec	0	-	0	-	0
15-Dec	0	-	0	-	0

NB – These volumes assume no rainfall inputs or ET outputs from the lysimeter

Table 6.12: Details of the Water Management Regime Required to Facilitate Designed Water Levels within Lysimeters - Bi-Monthly Monitoring

CHAPTER 7. REEDBED RESULTS

7.1 INTRODUCTION

This chapter presents the results from the reedbed experiments at Aqualate Mere, Brandon Marsh and Leighton Moss. Phenological data was used to determine which lysimeters were representative of the surrounding reedbed (Section 7.2) and from these ET(Reed) was calculated (Section 7.3). Reference Crop Evapotranspiration are presented in Section 7.4, with developed Kc(Reed) presented in Section 7.5. A discussion of the experimental design, the results and their application is provided in Section 7.6.

7.2 PHENOLOGICAL DATA AND DETERMINATION OF 'SUCCESSFUL' LYSIMETERS

To determine whether the reeds growing in the lysimeters were representative of a natural reedbed, phenological data (crop height, stem number, and number of flowering shoots) were collected from each lysimeter and from fixed-point quadrats within each reedbed (see Section 5.3.4) throughout the growing season (March to September), 2000 to 2002.

The maximum stem height was measured from the lowest point where the vertical stem protruded above the substrate surface, to the highest point at the break of the youngest leaf (after Fermor, 1997).

The stem number was measured directly as the number of individual stems occurring within each lysimeter or quadrat. The method followed Fermor (1997) where all growing stems were counted, but reed 'stubble' shorter than 250 mm was excluded. The stem number was adjusted for the area of each lysimeter or quadrat to provide a crop density (stems m^{-2}).

Crop height and density data were combined (Equation 7.1) to provide an estimation of the 'standing crop' within each of the lysimeters or quadrats.

$$\textbf{Mean Standing Crop (m stems}^{-1}\textbf{ m}^{-2}\textbf{)} = \textbf{Mean Crop Height (m)} \cdot \textbf{Mean Crop Density (stems m}^{-2}\textbf{)} \qquad \textbf{(7.1)}$$

The monthly standing crop data from the quadrats was averaged and the 95% confidence limit determined. If the standing crop value from a given lysimeter fell within the 95% confidence limits of the quadrat data between June and August, the lysimeter was classed as being 'successful' in replicating the natural reedbed system in which it was located.

Standing crop data from the lysimeters during 2000 showed that the reeds within all lysimeters had not established well enough during their first year to be representative of the surrounding reedbed and therefore data collected during 2000 was not included in subsequent calculations. In response to the reduced reed growth within the lysimeters, additional reed planting was undertaken at each of the sites during March 2001. As a result of the ecologically sensitive nature of the sites, the additional planting could not utilise reed plugs due to the potential introduction of non-native reed onto the nature reserves. Additional reed planting involved the transplantation of reed rhizomes and clumps using the methodology described in Section 5.3.2.

The number of flowering shoots (inflorescence) within each lysimeter and quadrat was determined through direct counting. Very few inflorescences were noted within the lysimeters during the sampling period (maximum of 3 per lysimeter) and therefore this data is not considered further. Inflorescence data for the quadrats and lysimeters are presented in Tables A5.1 and A5.5, Appendix 5 (Aqualate Mere); Tables A6.1 and A6.5, Appendix 6 (Brandon Marsh); and, Tables A7.1 and A7.5, Appendix 7 (Leighton Moss).

7.2.1 AQUALATE MERE

Monthly crop height, crop density and standing crop values for each quadrat from Aqualate Mere in 2001 and 2002 are presented in Tables A5.2, A5.3 and A5.4 in Appendix 5. Crop characteristic data from the lysimeters is included in Tables A5.6, A5.7 and A5.8 in Appendix 5.

Mean standing crop data were compared with lysimeter standing crop data to determine the 'successful' lysimeters shown in Table 7.1, which shows a 33% success rate during 2001 and a 50% success rate during 2002. Table 7.1 highlights that the success of the reed growth within the lysimeters increased over time as the reeds became more established.

	2001	2002
SUCCESSFUL LYSIMETER NUMBER	L1	L1
	L3	L3
	-	L4
	L5	L5
	-	L6
	L9	L9

Table 7.1: Aqualate Mere 'Successful' Lysimeters

The poor reed establishment within the unsuccessful lysimeters can be attributed to excessive shading from the surrounding reedbed. Where the crop density within the reedbed was highest, reduced amounts of sunlight fell onto the reeds within the lysimeters thus impeding their growth.

Mean crop height and crop density data from the successful lysimeters was compared with mean quadrat data and the results are presented in Figures 7.1 and 7.2 respectively.

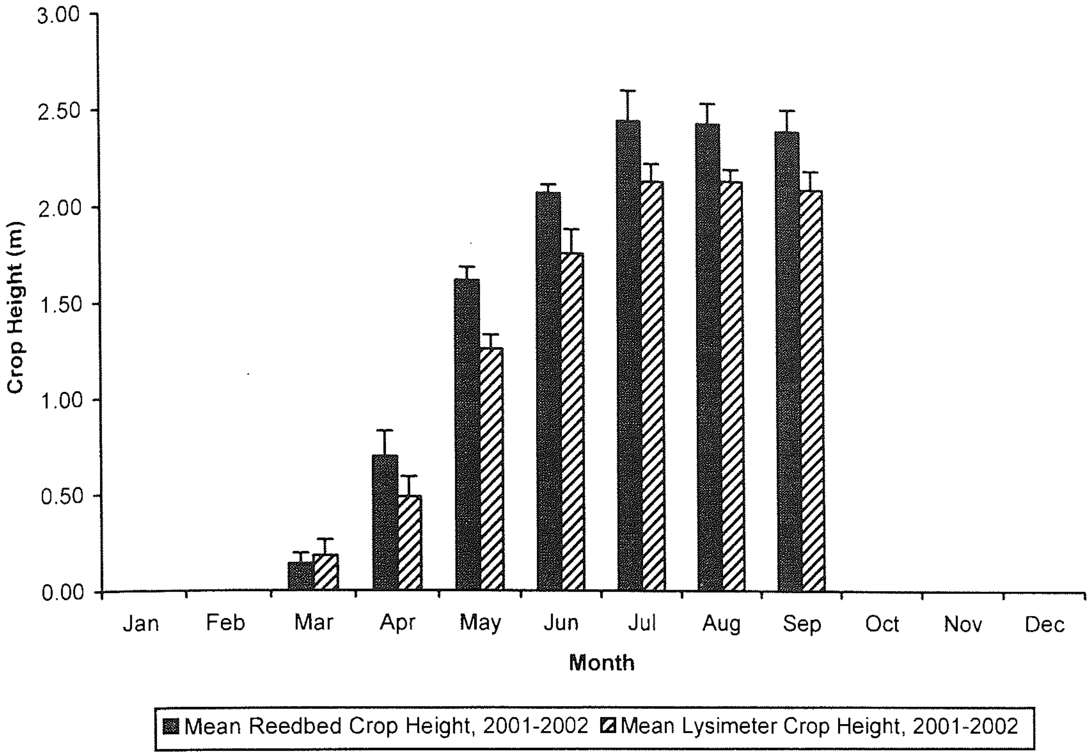


Fig. 7.1: Aqualate Mere Reedbed and Successful Lysimeters Mean Crop Height Including 95% Confidence Limits

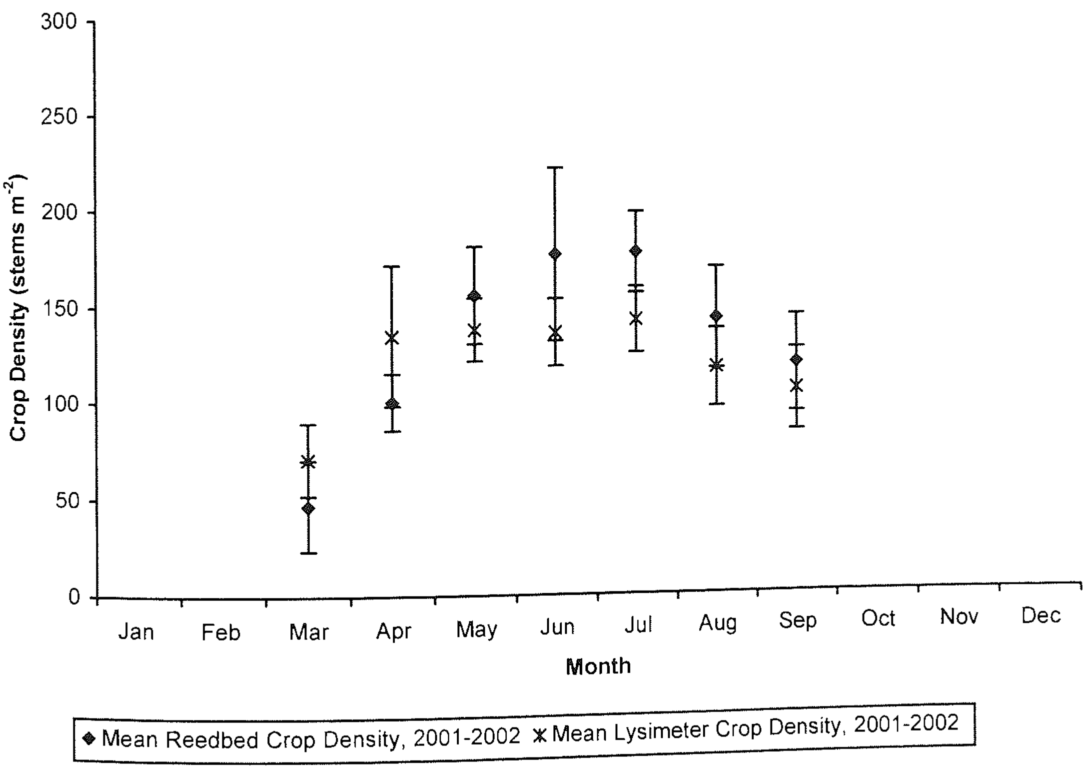


Fig. 7.2: Aqualate Mere Reedbed and Successful Lysimeters Mean Crop Density Including 95% Confidence Limits

Figure 7.1 shows a rapid increase in mean crop height during May and June in both the reedbed and lysimeters, with the mean maximum height in the reedbed (2.45 m) and lysimeters (2.00 m) being reached in July and August respectively. The increase in crop height during March was faster in the lysimeters than the reedbed, but by April reedbed growth had overtaken the growth within the lysimeters. On average, the reeds within the lysimeters were approximately 0.5 m shorter than those within the reedbed.

Figure 7.2 portrays a similar trend, with the mean crop density greatest in the lysimeters during March and April, but falling to approximately 50 stems m^{-2} lower than the reedbed by June. Maximum crop density was recorded in July for both the reedbed and the lysimeters. The 95% confidence limits show the variability within the crop density measurements, particularly within the reedbed.

To investigate whether there was any significant difference between the crop height and crop density of the reeds from the quadrats and those within the successful lysimeters a T-Test was performed, with the resulting probabilities presented in Table 7.2. Table 7.2 shows that there was no significant difference between the crop height and crop densities of the reedbed and the lysimeters at the 99% confidence level.

	PROBABILITY (t)						
	Mar	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
Crop Height	0.481	0.045	0.001	0.048	0.007	0.015	0.025
Crop Density	0.139	0.136	0.232	0.080	0.708	0.131	0.426

Table 7.2: T-Test Probabilities of Crop Height and Crop Density Between the Reedbed and Lysimeters at Aqualate Mere

7.2.2 BRANDON MARSH

Monthly crop height, crop density and standing crop values for each quadrat from Brandon Marsh in 2001 and 2002 are presented in Tables A6.2, A6.3 and A6.4 in Appendix 6. Crop characteristic data from the lysimeters is included in Tables A6.6, A6.7 and A6.8 in Appendix 6.

Mean standing crop data were compared with lysimeter standing crop data to determine the 'successful' lysimeters (Table 7.3), and this reveals a 10% success rate during 2001 and a 60% success rate during 2002. Table 7.3 highlights that the success of the reed growth within the lysimeters increased over time as the reeds became more established.

The reduced reed establishment within the unsuccessful lysimeters can again be attributed to excessive shading from the surrounding reedbed.

Mean crop height and crop density data from the successful lysimeters was compared with mean quadrat data and are presented in Figures 7.3 and 7.4 respectively.

	2001	**2002**
SUCCESSFUL LYSIMETER NUMBER	L2	L2
	-	L3
	-	L5
	-	L6
	-	L7
	-	L9

Table 7.3: Brandon Marsh 'Successful' Lysimeters

To investigate whether there was any significant difference between the crop height and crop density of the reeds from the quadrats and those within the successful lysimeters a T-Test was performed, with the resulting probabilities presented in Table 7.4. Table 7.4 shows that there was no significant difference between the crop height and crop densities of the reedbed and the lysimeters at the 99% confidence level. No data is presented for July to September as there was only one successful lysimeter during 2001 and monitoring had ceased during 2002.

	PROBABILITY (t)						
	Mar	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
Crop Height	0.002	0.058	0.032	0.203	n/a	n/a	n/a
Crop Density	0.720	0.122	0.094	0.017	n/a	n/a	n/a

Table 7.4: T-Test Probabilities of Crop Height and Crop Density Between the Reedbed and Lysimeters at Brandon Marsh

During June 2001 it was noted that the reeds within both the reedbed and lysimeters were turning brown and dying from the top. Small holes were found in the reed stem synonymous with insect burrowing and stem samples were sent to the invertebrate specialist at Warwick Museum, who confirmed that the holes were likely to be caused by 'reedbug' - reed-boring larvae of wainscot moths (Faulk, 2001).

Wainscot moths are widespread and common, and are likely to occur in most reedbeds (Hawke and José, 1996). The species can be damaging to reed if they occur in large numbers, but can be controlled by single wale cutting, which removes the overwintering microhabitat for most species (Hawke and José, 1996).

The impact of reedbug on the reedbed at Brandon Marsh is apparent from the data shown in Figure 7.3 where the crop height was significantly reduced in June due to reed death. In response to the damage by the reedbug, the reed stems sprouted secondary growth from a node close to the water level near the base of the stem. The secondary stems were noticeably thinner than the original reed stems and it is this secondary growth that accounts for the increase in crop height in July and August.

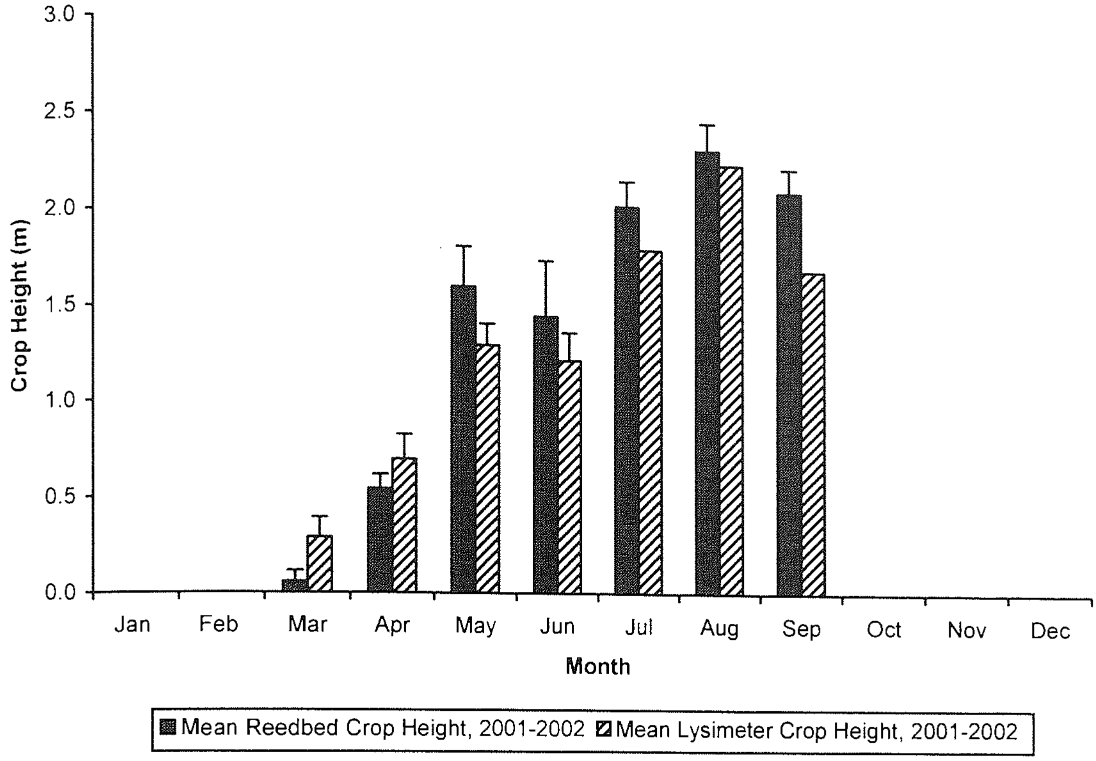


Fig. 7.3: Brandon Marsh Reedbed and Successful Lysimeters Mean Crop Height Including 95% Confidence Limits

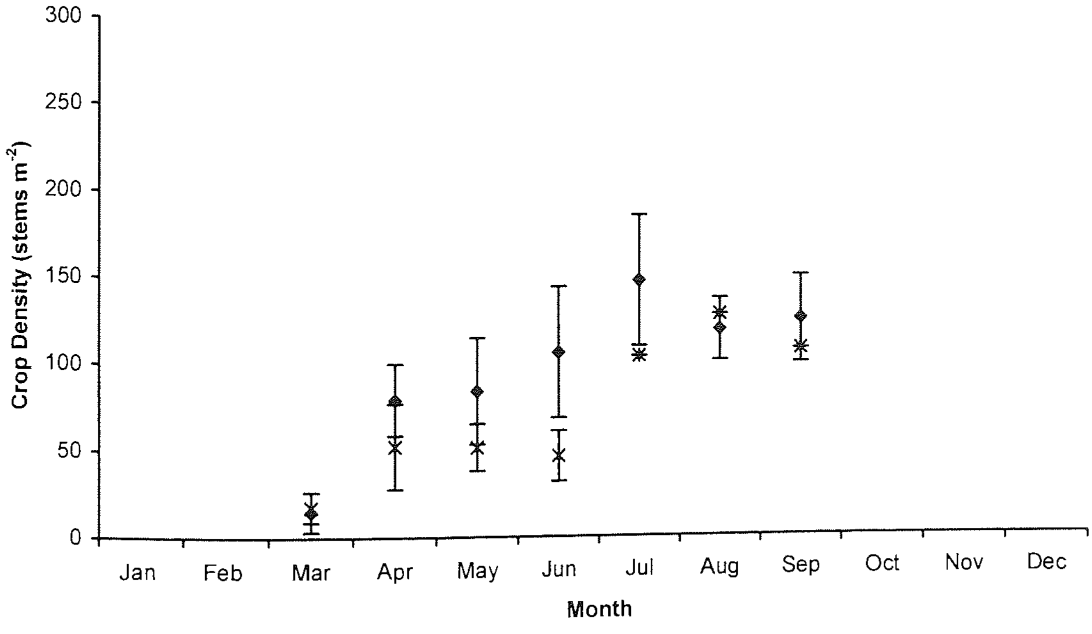


Fig. 7.4: Brandon Marsh Reedbed and Successful Lysimeters Mean Crop Density Including 95% Confidence Limits

Once the cause of the reedbed damage had been determined, consultation was carried out with the Warwickshire Wildlife Trust and the Brandon Marsh Voluntary Conservation Team with regards to the potential for appropriate management (single wale cutting) to ensure that reedbug damage would not impact on the experiments during 2002. However, Thompson (2001) concluded that as the presence of reedbug was a natural phenomenon, management of the reedbed would not be carried out.

Data collection continued in the hope that reedbug would not detrimentally affect the reedbed during 2002. However, during June 2002 reed stem death was noted throughout the reedbed and monitoring was stopped. Due to the cessation of monitoring in June 2002, the crop characteristic data presented in Figures 7.3 and 7.4 for July, August and September contain only one year's results.

7.2.3 LEIGHTON MOSS

Monthly crop height, crop density and standing crop values for each quadrat from Leighton Moss in 2001 and 2002 are presented in Tables A7.2, A7.3 and A7.4 in Appendix 7. Crop characteristic data from the lysimeters is included in Tables A7.6, A7.7 and A7.8 in Appendix 7.

Mean standing crop data were compared with lysimeter standing crop data to determine the 'successful' lysimeters. At this site there were no successful lysimeters during 2001 and 2002 and therefore phenological data is not discussed further.

The lack of reed establishment may be attributed to prolonged flooding during the winter of 2000 in response to the high rainfall experienced across the UK. During this time, the reeds growing within the lysimeters were permanently inundated which may have impacted on the development of the reed stems within the lysimeters.

Additional planting of the lysimeters was carried out during March 2001. However, the reeds did not establish well and were continually shaded out by the surrounding reedbed. During January 2002, a sea wall was breached and saline water was pushed onto the site. Due to high tides it was not possible for the sea wall to be repaired and so the lysimeters were permanently inundated again between January 2002 and March 2002.

Due to the lack of appropriate data, monitoring at Leighton Moss ceased at the end of June 2002.

7.3 ET(Reed)

This section presents calculated monthly ET(Reed) from the successful lysimeters at Aqualate Mere (Section 7.3.1) and Brandon Marsh (Section 7.3.2). As there were no successful lysimeters from Leighton Moss ET(Reed) data from this site is not included in this section. Leighton Moss survey dates are shown in Table A7.9 with calculated ET(Reed) from each lysimeter presented in Tables A7.10 and A7.11 in Appendix 7.

An investigation of the correlation between ET(Reed) and crop characteristic data and application of the resulting equations is provided in Section 7.3.3.

7.3.1 AQUALATE MERE

Calculated mean monthly ET(Reed) from the 10 successful lysimeters at Aqualate Mere are shown in Figure 7.5 and presented in Table 7.5 (Section 7.3.3). Details of the survey dates are included in Table A5.9 with ET(Reed) data from each lysimeter included in Tables A5.10 and A5.11 in Appendix 5.

Between February and April 2001, ET(Reed) data could not be collected due to site access restrictions associated with a nationwide outbreak of foot and mouth disease. Site access was gained again at the end of April 2001 and the lysimeters were re-set, providing monthly data for May 2001.

Figure 7.5 shows the calculated mean monthly ET(Reed) which was low in January and steadily increased to reach a peak of 2.75 mm day^{-1} in June, with July and August values being similar. ET(Reed) then fell steadily between September and December when ET(Reed) reached 0.30 mm day^{-1}. It should be noted that the presented February, March and April values include data from 2002 only.

Table 7.5 presents the range of calculated ET(Reed) values for each month and shows that during some months (e.g. September) there was a large variation in ET(Reed). This data highlights the need for having as many replicates as possible when carrying out ET(Reed) studies using lysimeters.

7.3.2 BRANDON MARSH

Calculated mean monthly ET(Reed) from the 7 successful lysimeters at Brandon Marsh are shown in Figure 7.6 and presented in Table 7.5 (Section 7.3.3). Details of the survey dates are included in Table A6.9 with ET(Reed) data from each lysimeter included in Tables A6.10 and A6.11 in Appendix 6.

ET(Reed) data for 2001 was calculated from only one lysimeter due to the lack of successful reed establishment. In addition, data was lost during March and May as the lysimeter overtopped. Data for 2002 was collected between January and June, but ceased in July as a result of the damage to the reedbed caused by reedbug (see Section 7.2.2).

Figure 7.6 shows monthly ET(Reed) increased throughout the year to a maximum of 1.91 mm day^{-1} in July. The lower values recorded for June was associated with the reedbug damage. During July and August 2001 secondary growth was recorded on most reed stems, which was reflected in the increased water use.

Table 7.5 presents the range of calculated ET(Reed) values for each month and shows that during some months (e.g. February) there was a large variation in ET(Reed).

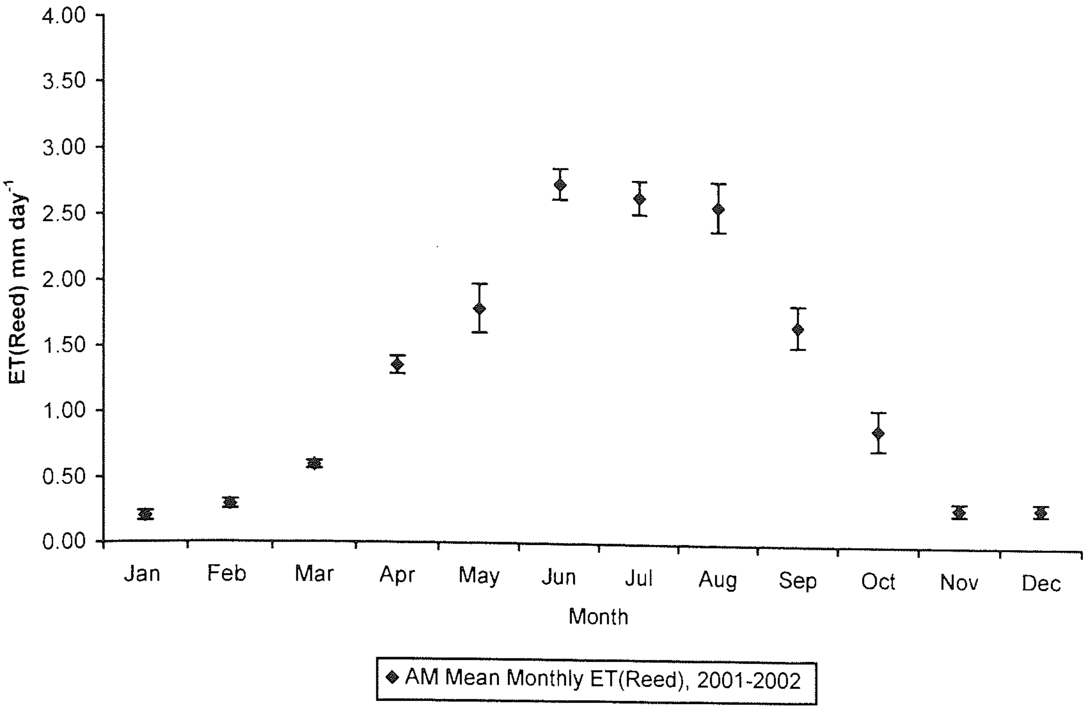


Fig. 7.5: Aqualate Mere Mean Monthly ET(Reed) Including Standard Error Bars, 2001-2002

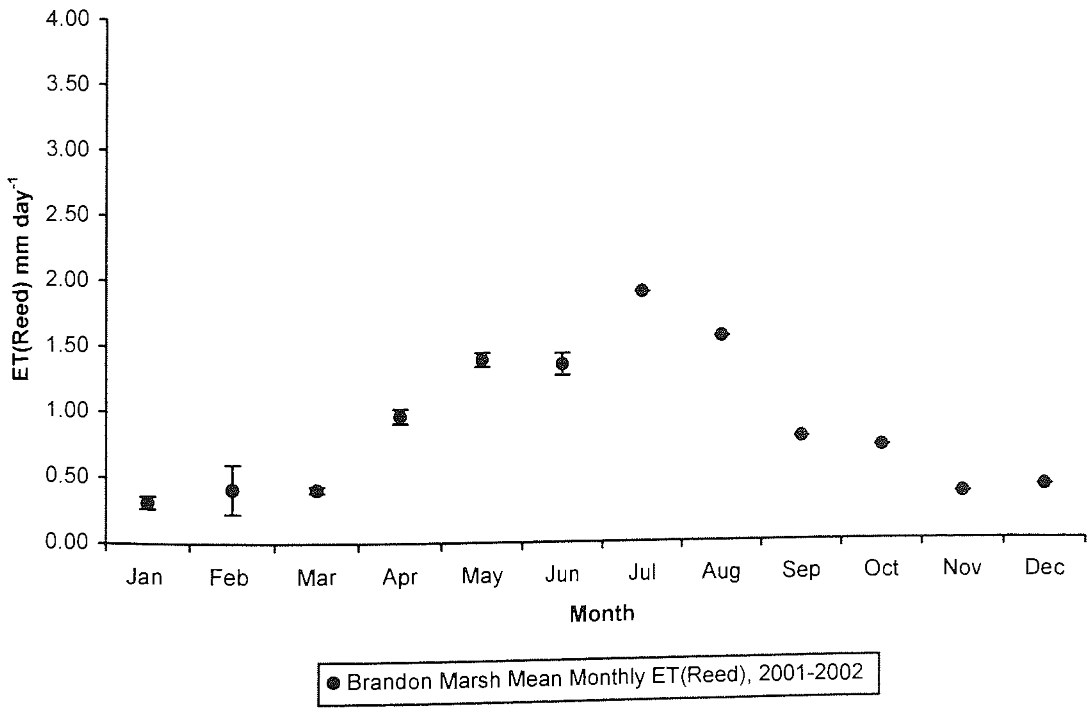


Fig. 7.6: Brandon Marsh Mean Monthly ET(Reed) Including Standard Error Bars, 2001-2002

	ET(Reed), mm day^{-1}												
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
Aqualate Mere 2001-2002 Mean	**0.20**	**0.29**	**0.60**	**1.36**	**1.80**	**2.75**	**2.67**	**2.61**	**1.70**	**1.02**	**0.30**	**0.30**	**1.29**
Aqualate Mere 2001-2002 SE	*0.04*	*0.04*	*0.03*	*0.07*	*0.18*	*0.12*	*0.13*	*0.19*	*0.16*	*0.15*	*0.05*	*0.05*	*0.08*
Aqualate Mere 2001-2002 Max	0.39	0.42	0.71	1.66	2.76	3.15	3.31	3.45	2.66	1.40	0.49	0.55	1.84
Aqualate Mere 2001-2002 Min	0.10	0.19	0.50	1.18	1.19	1.84	1.73	1.41	0.68	0.63	0.02	0.04	0.98
Brandon Marsh 2001-2002 Mean	**0.31**	**0.41**	**0.41**	**0.96**	**1.39**	**1.36**	**1.91**	**1.57**	**0.79**	**0.72**	**0.36**	**0.41**	**0.88**
Brandon Marsh 2001-2002 SE	*0.05*	*0.19*	*0.02*	*0.06*	*0.05*	*0.08*	-	-	-	-	-	-	-
Brandon Marsh 2001-2002 Max	0.47	1.13	0.48	1.12	1.56	1.76	-	-	-	-	-	-	-
Brandon Marsh 2001-2002 Min	0.13	0.09	0.34	0.68	1.18	1.12	-	-	-	-	-	-	-
Percentage Difference [1]	55%	41%	-32%	-29%	-23%	-49%	-28%	-40%	-54%	-30%	20%	37%	32%

SE Standard Error
[1] Percentage Difference = (Brandon Marsh Mean ET(Reed) / Aqualate Mere Mean ET(Reed) *100)-100
Positive percentage difference Brandon Marsh ET(Reed) was higher than Aqualate Mere ET(Reed)
Negative percentage difference Brandon Marsh ET(Reed) was lower than Aqualate Mere ET(Reed)

Table 7.5: Comparison Between Aqualate Mere and Brandon Marsh Mean Monthly ET(Reed), 2001-2002

7.3.3 ET(Reed) COMPARISONS

Crop characteristic data (Section 7.2.2) showed that reed growth at Brandon Marsh had been stunted by the reedbug damage when compared with data from Aqualate Mere (Section 7.2.1). To determine whether this was reflected in the ET(Reed) values, data from Brandon Marsh and Aqualate Mere were compared (Table 7.5) and the monthly percentage difference was determined.

Table 7.5 shows that between November and February, ET(Reed) was approximately 38% higher at Brandon Marsh than Aqualate Mere. However, between March and September Brandon Marsh ET(Reed) dropped to between 23% and 54% lower than Aqualate Mere. Annually ET(Reed) was 31% lower at Brandon Marsh. Although there cannot be a true comparison between the two data sets due to variations in local meteorological conditions and microclimate, the data provides an indication of the difference.

The crop characteristic and water use data suggested that the reedbed at Brandon Marsh was not growing at its optimal rate due to the damage caused by the reedbug infestation, a conclusion supported by visual inspections of the reedbed. Thus, the calculated ET(Reed) from this site does not represent PET and therefore the data are not applicable for use in the design of sustainable reedbed systems.

7.3.4 MODELLING ET(Reed) USING PHENOLOGICAL DATA

In this section the potential for modelling ET(Reed) from a reedbed's phenological data is investigated. A model of this type would act as a tool in the hydrological management of an existing reedbed where direct measurements or determination from meteorological data was too costly / time consuming.

The data used in this exercise included ET(Reed) and crop characteristic data from all lysimeters at Aqualate Mere. Data from Brandon Marsh was not included due to the sub-optimal growth of the reedbed and neither was data from Leighton Moss as no lysimeters were representative of the reedbed.

Dorrenbos and Pruitt (1977) divided the crop growing season into four stages as detailed in Table 7.6 (after Fermor, 1997). Phenological data from Aqualate Mere was analysed to determine the relevant monthly data relating to each stage.

STAGE	CRITERIA	AQUALATE MERE DATA FROM:
Initial Stage	Germination and early growth, when the soil surface is not or is hardly covered by the crop (groundcover <10%)	March
Crop Development Stage	From the end of initial stage to attainment of effective full groundcover (groundcover = 70-80%)[1]	April – May
Mid-Season Stage	From attainment of effective full groundcover to start of maturing as indicated by the discolouring of leaves	June – August
Late-Season Stage	From the end of mid-season stage until full maturity or harvest	September – October

[1] The start of mid-season can be recognised in the field when the crop has reached 70-80% groundcover which does not mean that the crop has reached its mature height. Effective full groundcover refers to cover when Kc is approaching a maximum.

Table 7.6: Determination of Crop Development Stages
(after Fermor, 1997)

Initial and Crop Development Stages

Data from March was initially analysed separately to that from April and May to provide information associated with each crop development stage. However, as the resulting equations were so similar the data was eventually combined to provide a single equation for both the initial and crop development stages. The analysis included data from May 2001 and March, April and May 2002, no data from March and April 2001 was available due to site restrictions associated the national outbreak of foot and mouth disease.

A regression analysis between crop height, crop density and standing crop against ET(Reed) was carried out (Figure A5.1 in Appendix 5 presents the data). In addition, a multiple regression was completed between ET(Reed), crop height and crop density.

The regression equations for each of the correlation parameters are provided in Table 7.7. To determine which of the regression equations provided the most suitable model, the degree of the relationship between the correlation parameters was determined using Pearson's Product Moment Correlation Coefficient (*r*).

REGRESSION EQUATION	PEARSON PRODUCT MOMENT COEFFICIENT OF CORRELATION (*r*)
ET(Reed) = 0.997.CH + 0.487	0.706
ET(Reed) = 0.008.CD + 0.548	0.539
ET(Reed) = 0.007.SC + 0.659	0.742
ET(Reed) = 0.827.CH + 0.005.CD + 0.196	0.763

CH - Crop Height CD - Crop Density SC - Standing Crop

Table 7.7: Regression Equations and Pearson Correlation Coefficients Developed Between ET(Reed) and Crop Characteristics for Initial and Crop Development Stages at Aqualate Mere, 2001-2002

Table 7.7 highlights that the strongest correlation was provided using multiple regression Crop Height:Crop Density:ET(Reed) where $r = 0.763$. Statistical tables (White et al, 1994) were used to determine the significance of this r value, and showed that the correlation was highly significant at the 1% significance level. Indeed, all of the correlations presented in Table 7.7 were highly significant.

Therefore it can be concluded that ET(Reed) in mm day^{-1} for March to May can be estimated from crop characteristic data using Equation 7.2.

$$\mathbf{ET(Reed) = 0.827.CH + 0.005.CD + 1.016} \qquad \mathbf{(7.2)}$$

where:

ET(Reed) is the evapotranspiration from the reedbed in mm day^{-1};

CH is the crop height in m; and,

CD is the crop density in stems m^{-2}.

Mid-Season

The mid-season included data from June, July and August 2001 and 2002.
Figure A5.2 (Appendix 5) shows the crop height, crop density and standing crop data plotted against ET(Reed). The regression equations and Correlation Coefficients for each of the correlation parameters are provided in Table 7.8.

REGRESSION EQUATION	PEARSON PRODUCT MOMENT COEFFICIENT OF CORRELATION (*r*)
ET(Reed) = 1.166.CH + 0.042	0.451
ET(Reed) = 0.008.CD + 1.363	0.493
ET(Reed) = 0.005.SC + 1.016	0.674
ET(Reed) = 0.970.CH + 0.007.CD - 0.325	0.616

CH - Crop Height CD - Crop Density SC - Standing Crop

Table 7.8: Regression Equations and Pearson Correlation Coefficients Developed Between ET(Reed) and Crop Characteristics for Mid-Season at Aqualate Mere, 2001-2002

Table 7.8 shows the strongest correlation was between Standing Crop:ET(Reed) where $r = 0.674$ which was highly significant at the 1% significance level. Indeed, all of the correlations presented in Table 7.8 were highly significant.

Therefore during the mid-season (June to August), ET(Reed) in mm day^{-1} can be determined from standing crop data using Equation 7.3.

$$\mathbf{ET(Reed) = 0.005.SC + 1.016} \qquad \textbf{(7.3)}$$

where:

ET(Reed) is the evapotranspiration from the reedbed in mm day^{-1};

SC is the standing crop value in height (m) stems^{-1} m^{-2}.

Late-Season

The late-season included data from September 2001 and 2002. Figure A5.3 (Appendix 5) shows the crop height, crop density and standing crop data plotted against ET(Reed). The regression equations and Correlation Coefficients for each of the correlation parameters are provided in Table 7.9.

REGRESSION EQUATION	PEARSON PRODUCT MOMENT COEFFICIENT OF CORRELATION (r)
ET(Reed) = 0.860.CH – 0.273	0.516
ET(Reed) = 0.008.CD + 0.683	0.578
ET(Reed) = 0.004.SC + 0.712	0.666
ET(Reed) = 0.006.CH – 0.007.CD + 0.839	0.685

Table 7.9: Regression Equations and Pearson Correlation Coefficients Developed Between ET(Reed) and Crop Characteristics for Late-Season at Aqualate Mere, 2001-2002

Table 7.9 shows the strongest correlation was between Crop Height: Crop Density:ET(Reed) where $r = 0.685$ which was highly significant at the 1% significance level. Indeed, all of the correlations presented in Table 7.9 were highly significant.

Therefore during the late-season (September), ET(Reed) in mm day^{-1} can be determined from crop height and crop density data using Equation 7.4.

$$\mathbf{ET(Reed) = 0.006.CD - 0.007.CH + 0.839} \tag{7.4}$$

where:

ET(Reed) is the evapotranspiration from the reedbed in mm day^{-1};

CH is the crop height in m; and,

CD is the crop density in stems m^{-2}.

Fermor (1997) developed a regression equation using August data from his research sites (Equation 7.5).

$$\mathbf{ET(Reed) = 0.005.SC + 1.800} \tag{7.5}$$

where:

ET(Reed) is the evapotranspiration from the reedbed in mm day^{-1};

SC is the standing crop value in height (m) stems^{-1} m^{-2}.

Using the equations developed by the author and by Fermor (1997), ET(Reed) values have been calculated using mean crop characteristic data from the reedbeds at Leighton Moss and Aqualate Mere (Table 7.10). Actual mean ET(Reed) rates from Aqualate Mere are presented for comparison. It should be noted that Fermor's equation was developed using August data and is therefore only applicable during this month.

The data presented in Table 7.10 clearly shows that during most months, the model developed by the author provides ET(Reed) closely comparable to that recorded at Aqualate Mere, the only exception being May, when the model appears to overestimate ET. To rectify this problem a regression analysis of ET(Reed) and crop characteristic data using data from May only was carried out. However, when the regression equation was applied ET(Reed) was again overestimated by a similar value. A specific regression equation for May was therefore not deemed appropriate.

DATA	ET(Reed), mm day^{-1}						
	Initial Stage	Crop Development Stage		Mid-Season Stage			Late-Season Stage
	Mar	Apr	May	Jun	Jul	Aug	Sep
Estimated data for Leighton Moss using Eqs. 7.2, 7.3 & 7.4 (Author, 2003)	0.66	1.35	2.51	2.66	3.07	2.83	1.56
Estimated data for Leighton Moss using Eq. 7.5 (Fermor, 1997)	-	-	-	-	-	3.61	-
Estimated data for Aqualate Mere using Eqs. 7.2, 7.3 & 7.4 (Author, 2003)	0.55	1.27	2.31	2.87	2.79	2.78	1.54
Estimated data for Aqualate Mere using Eq. 7.5 (Fermor, 1997)	-	-	-	-	-	3.56	-
Actual data from Aqualate Mere	0.47	1.59	2.35	2.62	3.07	2.83	1.56

Table 7.10: Estimated ET(Reed) for Aqualate Mere and Leighton Moss

Table 7.10 shows that estimated ET(Reed) data for August developed using Fermor's equation was significantly higher than that developed using the author's. This is the result of the higher ET(Reed) rates recorded by Fermor (see Table 3.4) from his fringe reedbed study sites which were subject to increased advection. It is recommended that Fermor's equation be used for fringe / edge reedbeds only, and the author's equations be applied to large reedbeds. It should also be noted that the regression equations presented here only apply to reedbeds in the UK or similar climate areas.

7.4 REFERENCE CROP EVAPOTRANSPIRATION

This section presents the three different forms of reference crop evapotranspiration [ETo] used in the determination of Kc(Reed): ETo Pan; ETo LMS Grass; and ETo MORECS Grass.

Evaporation pan data [E Pan] was collected during monitoring visits and ETo Pan was calculated as outlined in Section 2.3.1. Monthly PE Grass data was purchased from the Met Office for the relevant MORECS Square (see Section 2.3.3). Monthly PE Grass and rainfall totals were supplied and were adjusted to provide values in mm day^{-1}. In addition, site-specific PE Grass was calculated by and purchased from the Met Office using relevant data from local meteorological stations (see Section 2.3.4) and again adjusted accordingly.

7.4.1 AQUALATE MERE

With respect to data from the on-site rain gauge and evaporation pan, site access restrictions at Aqualate Mere associated with the national outbreak of foot and mouth disease between February and April 2001 resulted in no data collection during this period. In addition, sampling errors associated with ice in the evaporation pan in January and December 2001 and January 2002, resulted in negative ETo Pan values and are therefore not included. During October 2002, the evaporation pan overtopped and data was lost.

MORECS site-specific data was provided by the Met Office where the following local meteorological stations were used to obtain the relevant data: Shawbury (SJ 552 221); Coalbrookdale (SJ 667 048); Newport (SJ 711 203); and, Weston Park (SJ 806 108). Aqualate Mere is located within MORECS Square 124 (see Section 2.3.4).

Figures 7.7 and 7.8 present the monthly rainfall and ETo in mm day^{-1} from each source for 2001 and 2002 respectively (monthly rainfall and ETo totals are included in Tables A5.11 and A5.12 respectively in Appendix 5). The data has been presented in mm day^{-1} to provide direct comparison between the data sources as monitoring visits did not always fall on the first day of each month (see Table A5.9 in Appendix 5). On average, the number of days between monitoring visits was 30 days, however in December 2001 and 2002 this was reduced to 16 days, providing the anomalous rainfall data shown in December 2002 (Figure 7.8) where the main period of rainfall must have occurred after the monitoring visit on 19 December 2002.

Figure 7.7 shows that on average the rainfall data from the three sources provided similar rainfall patterns throughout 2001, the exception being June, when rainfall from MORECS Square 124 was approximately 1 mm day^{-1} higher than both the on-site rain gauge and local met station. ETo data showed a greater variation, with ETo Pan lower than the other two sources throughout the year. ETo MORECS Grass was lower than ETo LMS Grass between January and June, but higher throughout the remainder of the year.

Figure 7.8 highlights that rainfall from MORECS Square 124 exceeded other sources during six months of the year in 2002, the most extreme record being in May 2002 when the rainfall was recorded as being approximately 0.7 mm day^{-1} higher. With the exception of December 2002, rainfall records were similar from the three sources. ETo Pan was again lower throughout the year than both other sources particularly in May 2002 which was very low and was therefore not used in subsequent calculations. ETo MORECS Grass and ETo LMS Grass were very similar throughout the year.

Figures 7.7 and 7.8 illustrate that PET exceeded rainfall between May and July in 2001 and between March and September in 2002. Annually rainfall exceeded PET in both years (see Tables A5.11 and A5.12 in Appendix 5). Rainfall in 2001 and 2002 were not representative of the trends shown by long-term average data (see Figure 5.2), although PET was similar to long-term average data.

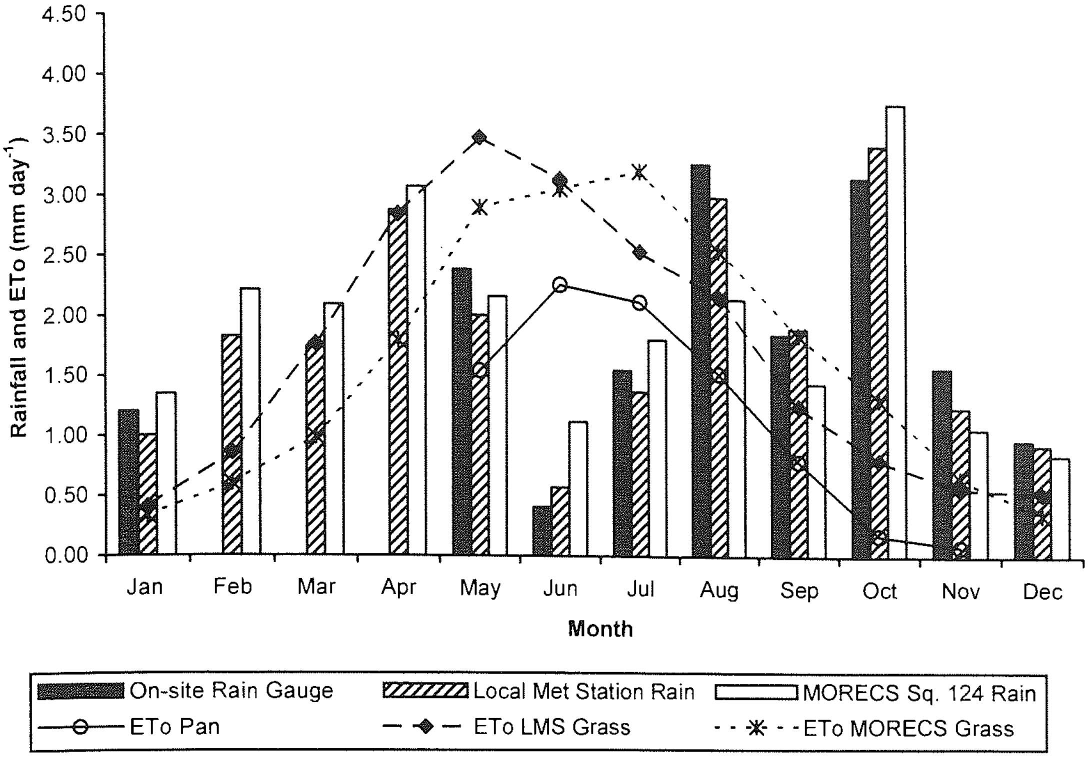


Fig. 7.7: Monthly Rainfall and ETo at Aqualate Mere from Various Sources, 2001

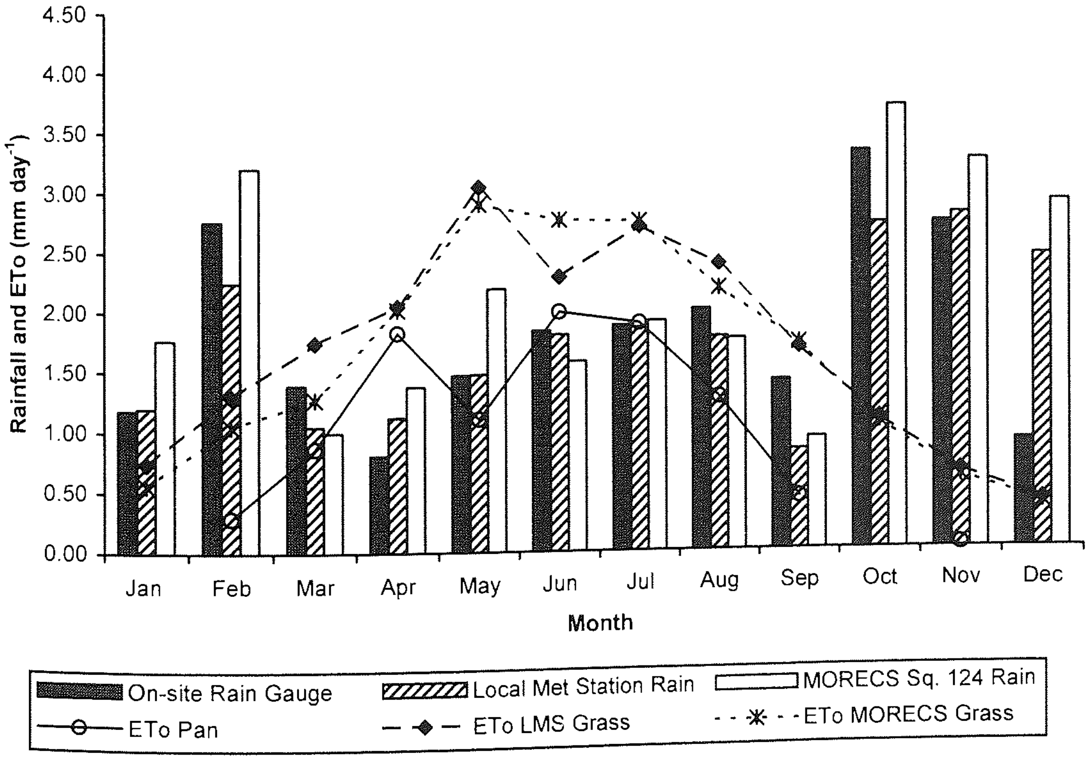


Fig. 7.8: Monthly Rainfall and ETo at Aqualate Mere from Various Sources, 2002

7.4.2 BRANDON MARSH

With respect to data from the evaporation pan at Brandon Marsh, sampling errors associated with ice in the evaporation pan in January and December 2001 resulted in negative ETo Pan values which are not included.

Site-specific MORECS data was provided by the Met Office where the following local meteorological stations were used to obtain the relevant data: Church Lawford (SP 456 736); Coleshill (SP 4211 869); and, Finham Water Reclamation Works (SP 334 739). Brandon Marsh is located within MORECS Square 137 (see Section 2.3.4).

Figures 7.9 and 7.10 present the monthly rainfall and ETo in mm day^{-1} from each source for 2001 and 2002 respectively (monthly rainfall and ETo totals are included in Tables A6.11 and A6.12 respectively in Appendix 6).

The rainfall data from this site was more variable throughout both years with some high values provided by the site-specific MORECS data and from local meteorological stations. Indeed the site-specific MORECS data provided by the Met Office for February 2002 was judged to be anomalous as it was so high (10.67 mm day^{-1}) and is therefore not shown in Figure 7.10. On average, the rainfall data from the on-site rain gauge and MORECS Square 137 were in agreement throughout 2001-2002 and rainfall was evenly distributed throughout the year.

ETo data from the three sources in 2001 and 2002 was in good agreement. Although ETo Pan data for July 2001 and February 2002 appeared to be very low in comparison with the other data, and was therefore not used in subsequent calculations.

PET exceeded rainfall between May and August 2001 and April and September 2002. Annually rainfall was greater than PET (see Tables A6.11 and A6.12 in Appendix 6). The meteorological data shown in Figures 7.9 and 7.10 are similar to long-term average data shown in Figure 5.5.

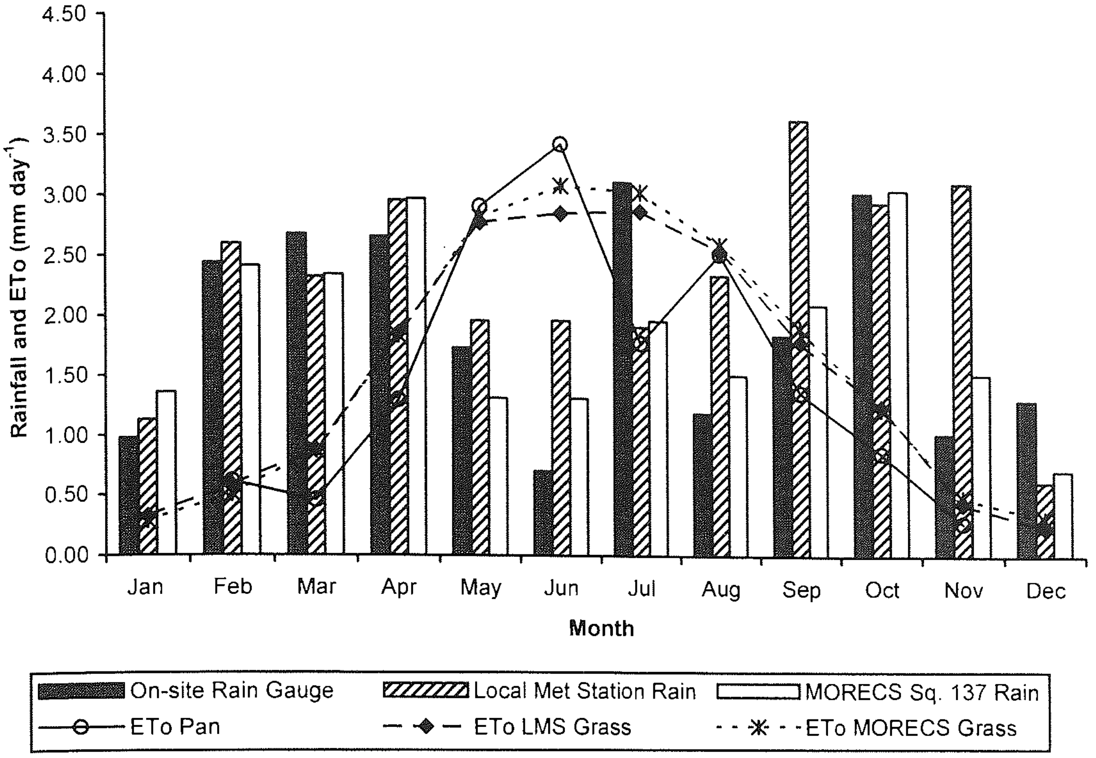


Fig. 7.9: Monthly Rainfall and ETo at Brandon Marsh from Various Sources, 2001

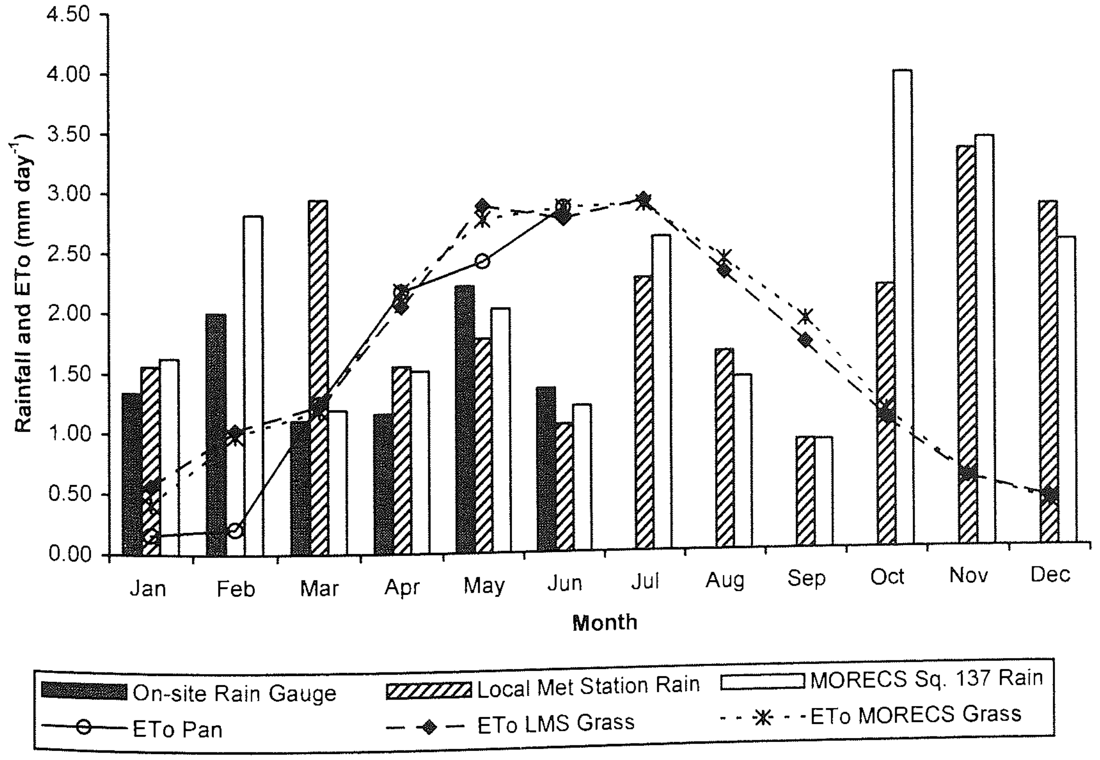


Fig. 7.10: Monthly Rainfall and ETo at Brandon Marsh from Various Sources, 2002

7.4.3 LEIGHTON MOSS

With respect to data from the evaporation pan at Leighton Moss, sampling errors associated with ice in the evaporation pan in January and December 2001 resulted in negative ETo Pan values and are therefore not included. In addition, during January and February 2002 the whole site was flooded due to a sea wall breach and experimental equipment was inaccessible.

Site-specific MORECS data from local meteorological stations was provided by the Met Office where the following local meteorological stations were used to obtain the relevant data: Levens Hall (SD 494 850); Casterton (SD 630 794); Morecambe (SD 438 648); Beetham Hall (SD 498 791); Carnforth, Pedder Potts Reservoir. No.2 (SD 535 705); Meathop, Ulpha Farm (SD 453 814); and, Merlewood (SD 409 796). Leighton Moss is located within MORECS Square 91 (see Section 2.3.4).

Figures 7.11 and 7.12 present the monthly rainfall and ETo in mm day^{-1} from each source for 2001 and 2002 respectively (monthly rainfall and ETo totals are included in Tables A7.11 and A7.12 respectively in Appendix 7).

The rainfall data provided by the three sources are in agreement throughout 2001 and 2002 apart from the data provided by the local meteorological stations for February 2001 which was very high. There is no explanation for this aside from the effect of different local meteorological conditions at the site and the station which recorded the rainfall.

With respect to the ETo data, site-specific MORECS and MORECS Square 91 data are similar, with ETo MORECS Grass being consistently slightly lower than ETo LMS Grass. ETo Pan values were approximately 0.8 mm day^{-1} lower than the other two sources.

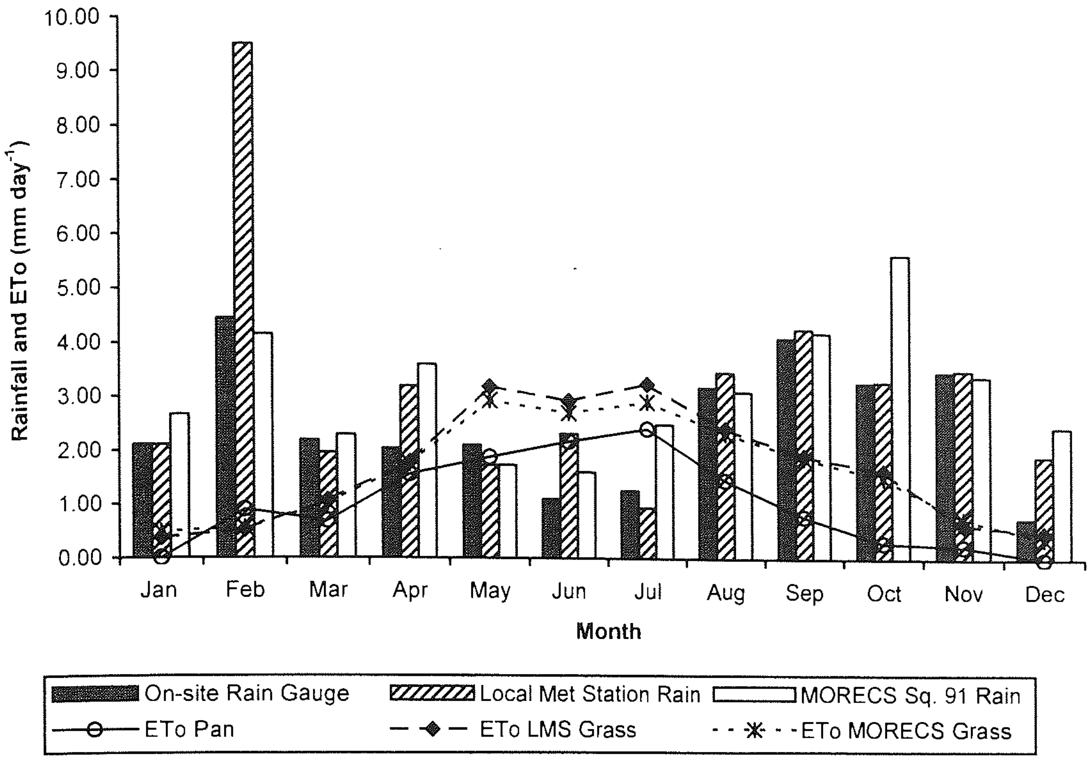


Fig. 7.11: Monthly Rainfall and ETo at Leighton Moss from Various Sources, 2001

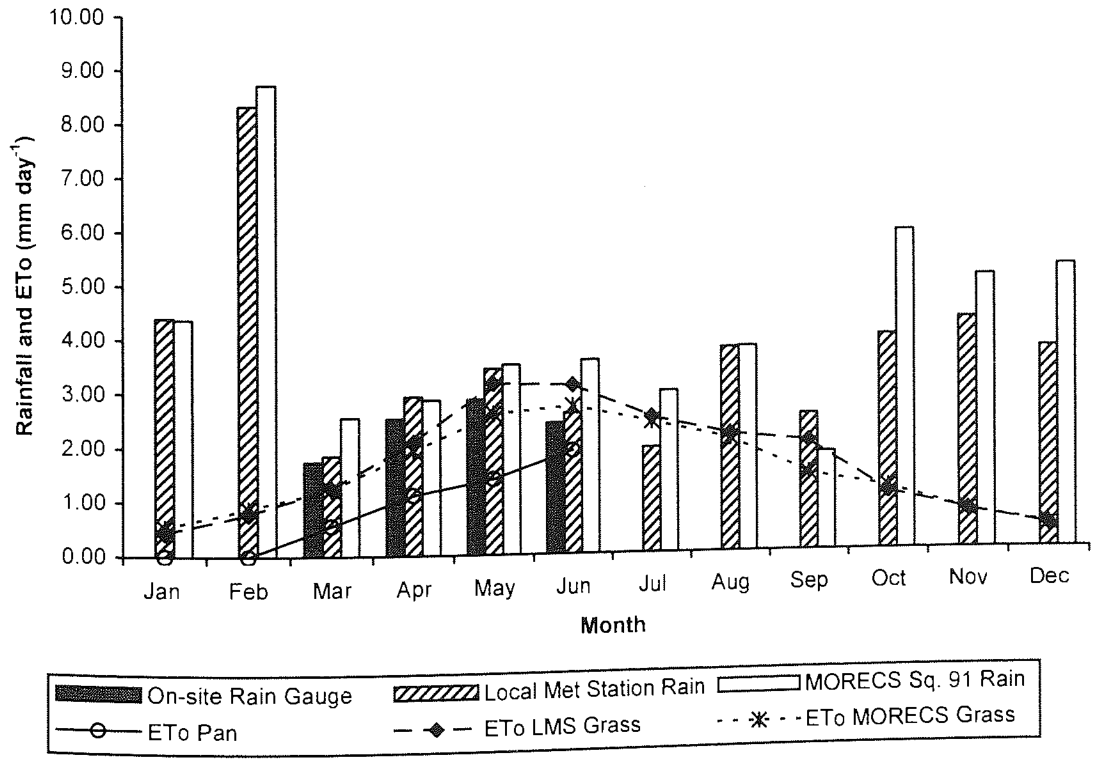


Fig. 7.12: Monthly Rainfall and ETo at Leighton Moss from Various Sources, 2002

On average, PET exceeded rainfall between May and July 2001, and was approximately equal to rainfall in June and July 2002 but lower throughout the remainder of the year. Annually rainfall exceeded PET (see Tables A7.11 and A7.12 in Appendix 7). The meteorological data collected in 2001 and 2002 follows the same patterns as the long-term average data for the site as shown in Figure 5.8.

7.4.4 COMPARISON OF METEOROLOGICAL DATA

From the data presented in Sections 7.4.1 to 7.4.3 the following conclusions with respect to the different sources of meteorological data can be drawn.

Data from the evaporation pan is not directly comparable with ETo LMS Grass and ETo MORECS Grass as they provide evapotranspiration rates associated with grass as a reference crop, whereas the evaporation pan is based on open water as the reference.

The lower values recorded using the evaporation pan at Aqualate Mere and Leighton Moss could be attributed to the height of the surrounding vegetation within the area where the pan was situated. At Aqualate Mere the pan was situated adjacent to an area where *Salix fragilis* whips had been planted during autumn 1999. These had grown to a height of approximately 2 m by the end of 2002 and may have caused extensive shading and sheltering of the evaporation pan. At Leighton Moss the pan was situated in an open area within the environs of the reedbed, which could have resulted in the pan being too sheltered. The data from Brandon Marsh would suggest that if sited correctly, ETo Pan is in close agreement with ETo LMS Grass and ETo MORECS Grass.

Fermor (1997) similarly recorded ETo Pan values being lower than comparable MORECS values and concluded that this was likely to be the result of the effects of surrounding vegetation and the fact that measurements and adjustments were undertaken on a monthly basis.

ETo LMS Grass and ETo MORECS Grass were both developed using calculations based on the Penman-Monteith equation. The differences between the values can be attributed to the effect of the different meteorological parameters data used in the calculations.

Figures 7.7 to 7.12 show that potential variability of rainfall data that can be used. For this project rainfall from the on-site gauges was used in Kc(Reed) calculations.

7.5 Kc(Reed)

Monthly Kc(Reed) data was developed using calculated ET(Reed) and ETo from Aqualate Mere (Section 7.5.1). In addition, estimated ET(Reed) was used to provide estimated monthly Kc(Reed) during the growing season from Aqualate Mere (Section 7.5.2) and Leighton Moss (Section 7.5.3). Kc(Reed) data from Brandon Marsh is not presented in this section due to the inappropriate ET(Reed) data collected. However, mean 2001 and 2002 Kc(Reed) data are included in Tables A6.13 to A6.18 in Appendix 6.

7.5.1 AQUALATE MERE (MEASURED DATA)

Mean monthly and maximum and minimum Kc(Reed) Pan, Kc(Reed) LMS Grass and Kc(Reed) MORECS Grass for the successful lysimeters at Aqualate Mere from 2001-2002 are presented in Table 7.11 and shown in Figure 7.13. In addition, the range of Kc(Reed) values calculated using each ETo source are included. Monthly Kc(Reed) data from all lysimeters are included in Tables A5.13 to A5.18 in Appendix 5.

Table 7.11 shows high mean Kc(Reed) Pan between October and February, which was the result of low ETo Pan recorded during this time. The data from these months has therefore been discounted from further consideration and is not shown in Figure 7.13. Figure 7.13 shows Kc(Reed) Pan for March and April was 0.71 increasing to 1.34 throughout the period May to July, and reaching a peak of 1.90 during August.

Both mean Kc(Reed) LMS Grass and Kc(Reed) MORECS Grass increased steadily from 0.07 in January to reach their respective peaks of 0.92 and 0.98 during June. These Kc values were maintained throughout July and August and then fell steadily from September to approximately 0.1 in December. The similarity of the two data sets are clearly shown in Figure 7.13.

7.5.2 AQUALATE MERE (ESTIMATED DATA)

Kc(Reed) data was calculated using estimated ET(Reed) data developed from the crop characteristics of the quadrats in 2001 and 2002. The data from each quadrat is presented in Tables A5.19 to A5.21 in Appendix 5 with summary data for estimated Kc(Reed) included in Table 7.12 and presented in Figure 7.14.

Table 7.12 shows Kc(Reed) Pan increasing from 0.49 in March to a peak of 1.78 in June, July and August, and falling to 0.99 in September. The estimated Kc(Reed) Pan values were again high as a result of low recorded ETo Pan. Kc(Reed) LMS Grass and Kc(Reed) MORECS Grass had lower values which increased from approximately 0.18 in March to reach their respective peaks of 0.92 and 0.96 in June. Data throughout the mid-season were similar, falling again in September to approximately 0.50.

Figure 7.14 illustrates that Kc(Reed) values developed using estimated ET(Reed) data are very similar to those produced using measured ET(Reed) data. This is a function of the fact that the model was developed using data from Aqualate Mere.

7.5.3 LEIGHTON MOSS (ESTIMATED DATA)

Estimated Kc(Reed) for each lysimeter are included in Tables A7.13 to A7.18 in Appendix 7, with 2001-2002 data presented in Table 7.13 and shown in Figure 7.15.

	Mean Kc(Reed)												
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
Kc(Reed) Pan Mean	**error**	**(0.99)**	**0.69**	**0.74**	**1.37**	**1.31**	**1.34**	**1.90**	**(3.10)**	**(4.99)**	**(6.25)**	**error**	**n/a**
Kc(Reed) Pan SE	-	*(0.13)*	*0.03*	*0.04*	*0.07*	*0.06*	*0.07*	*0.15*	*(0.40)*	*(0.95)*	*(1.26)*	-	-
Kc(Reed) Pan Maximum	-	(0.43)	0.82	0.91	1.78	1.57	1.51	2.70	(6.07)	(7.72)	(12.03)	-	-
Kc(Reed) Pan Minimum	-	(0.65)	0.62	0.65	1.07	0.92	0.91	1.11	(1.55)	(3.48)	(0.67)	-	-
Kc(Reed) LMS Grass Mean	**0.07**	**0.11**	**0.22**	**0.50**	**0.58**	**0.92**	**0.90**	**0.87**	**0.56**	**0.32**	**0.10**	**0.10**	**0.44**
Kc(Reed) LMS Grass SE	*0.01*	*0.01*	*0.01*	*0.02*	*0.04*	*0.05*	*0.06*	*0.07*	*0.06*	*0.07*	*0.02*	*0.02*	-
Kc(Reed) LMS Grass Maximum	0.11	0.15	0.26	0.61	0.79	1.14	1.22	1.27	0.98	0.40	0.15	0.20	-
Kc(Reed) LMS Grass Minimum	0.04	0.07	0.18	0.43	0.44	0.68	0.64	0.52	0.25	0.18	0.03	0.03	-

error - a sampling error resulted in a negative value and is therefore not presented
no data - no data collected due to site restrictions associated with outbreak of foot and mouth disease
over - the lysimeter / evaporation pan overtopped and data was lost
SE - Standard Error
( ) - discounted data

Table 7.11: Aqualate Mere Mean Monthly Kc(Reed), 2001-2002

	Mean Kc(Reed)												
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
Kc(Reed) MORECS Grass Mean	**0.07**	**0.11**	**0.22**	**0.49**	**0.63**	**0.98**	**0.95**	**0.93**	**0.60**	**0.36**	**0.10**	**0.11**	**0.46**
Kc(Reed) MORECS Grass SE	*0.01*	*0.01*	*0.01*	*0.02*	*0.06*	*0.04*	*0.05*	*0.07*	*0.06*	*0.06*	*0.02*	*0.02*	-
Kc(Reed) MORECS Grass Maximum	0.13	0.15	0.26	0.60	0.95	1.14	1.20	1.25	0.96	0.54	0.17	0.20	-
Kc(Reed) MORESC Grass Minimum	0.04	0.07	0.18	0.43	0.43	0.67	0.63	0.51	0.25	0.22	0.01	0.01	-

error - a sampling error resulted in a negative value and is therefore not presented
no data - no data collected due to site restrictions associated with outbreak of foot and mouth disease
over - the lysimeter / evaporation pan overtopped and data was lost
SE - Standard Error
( ) - discounted data

Table 7.11 cont.: Aqualate Mere Mean Monthly Kc(Reed), 2001-2002

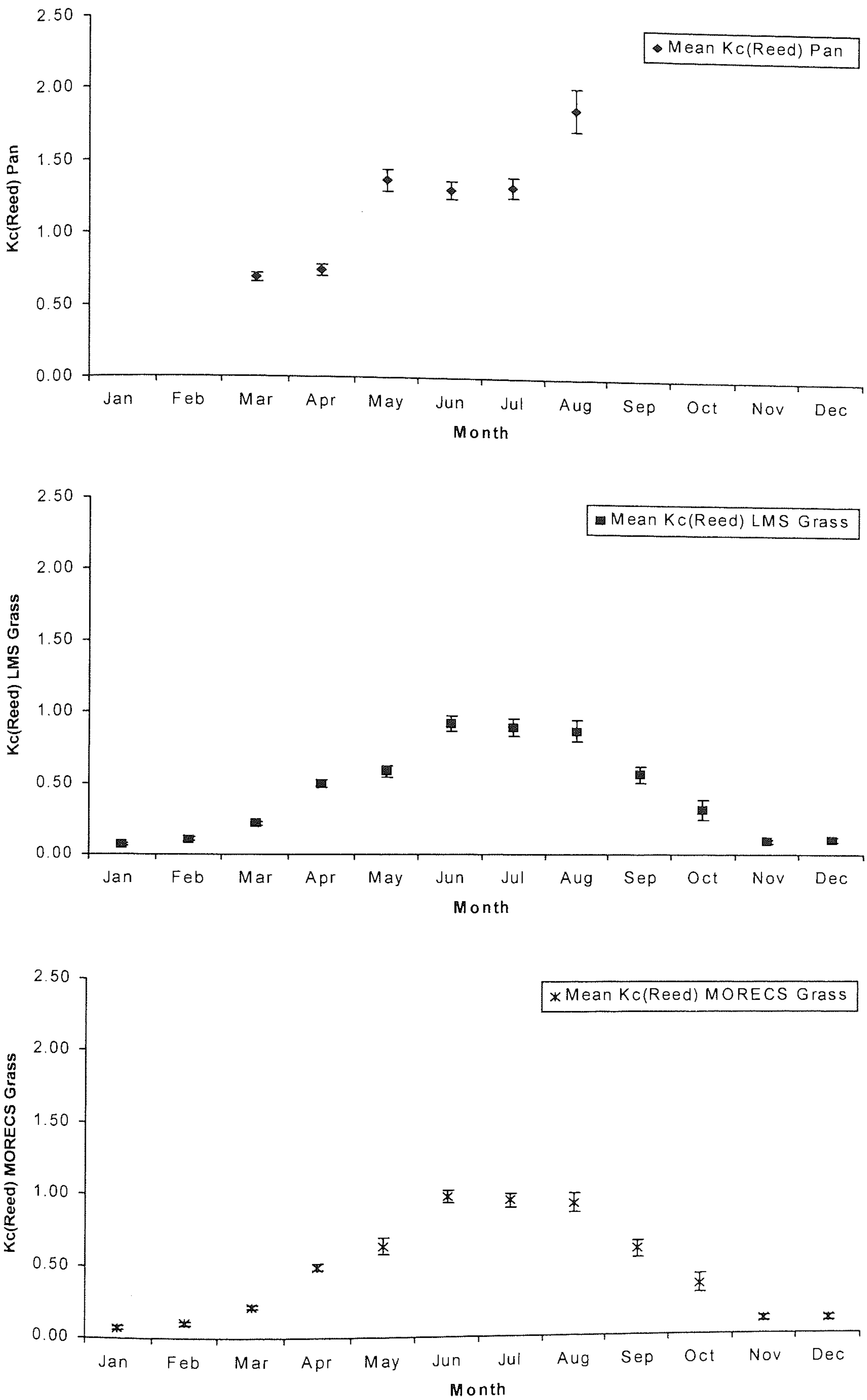


Fig. 7.13: Mean Kc(Reed) Including Standard Error Bars for Aqualate Mere, 2001-2002

	Mean Kc(Reed)												
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
Kc(Reed) Pan Mean	-	-	0.49	0.86	1.52	1.78	1.78	1.78	0.99	-	-	-	-
Kc(Reed) Pan SE	-	-	*0.07*	*0.13*	*0.17*	*0.11*	*0.15*	*0.17*	*0.09*	-	-	-	-
Kc(Reed) LMS Grass Mean	-	-	0.18	0.41	0.75	0.92	0.90	0.89	0.50	-	-	-	-
Kc(Reed) LMS Grass SE	-	-	*0.03*	*0.03*	*0.02*	*0.08*	*0.06*	*0.06*	*0.02*	-	-	-	-
Kc(Reed) MORECS Grass Mean	-	-	0.19	0.43	0.77	0.96	0.93	0.93	0.51	-	-	-	-
Kc(Reed) MORECS Grass SE	-	-	*0.03*	*0.03*	*0.02*	*0.08*	*0.06*	*0.05*	*0.02*	-	-	-	-

SE Standard Error

Table 7.12: Aqualate Mere Estimated Mean Monthly Kc(Reed), 2001-2002

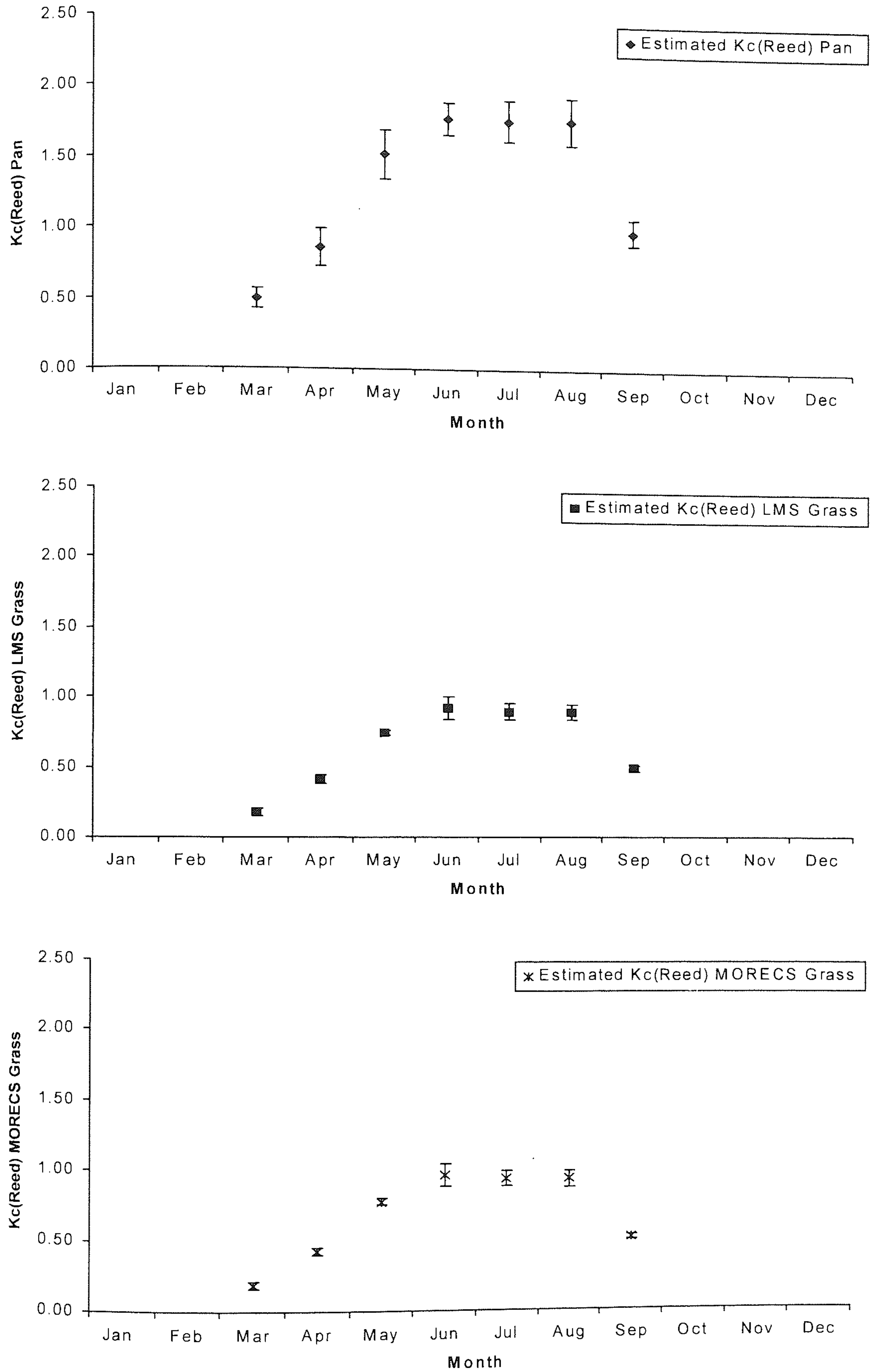


Fig. 7.14: Estimated Kc(Reed) Including Standard Error Bars for Aqualate Mere, 2001-2002

	Mean Kc(Reed)												
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
Kc(Reed) Pan 2001-2002 Mean	-	-	0.30	0.90	1.37	1.47	1.40	1.29	0.71	-	-	-	-
Kc(Reed) Pan 2001-2002 SE	-	-	*0.07*	*0.06*	*0.12*	*0.07*	*0.04*	*0.01*	*0.02*	-	-	-	-
Kc(Reed) LMS Grass 2001-2002 Mean	-	-	0.15	0.52	0.77	0.87	1.04	0.96	0.53	-	-	-	-
Kc(Reed) LMS Grass 2001-2002 SE	-	-	*0.02*	*0.06*	*0.05*	*0.09*	*0.03*	*0.01*	*0.02*	-	-	-	-
Kc(Reed) MORECS Grass 201-2002 Mean	-	-	0.18	0.59	0.88	0.98	1.13	1.04	0.57	-	-	-	-
Kc(Reed) MORECS Grass 2001-2002 SE	-	-	*0.03*	*0.06*	*0.04*	*0.08*	*0.03*	*0.01*	*0.02*	-	-	-	-

SE Standard Error

Table 7.13: Leighton Moss Estimated Mean Monthly Kc(Reed), 2001-2002

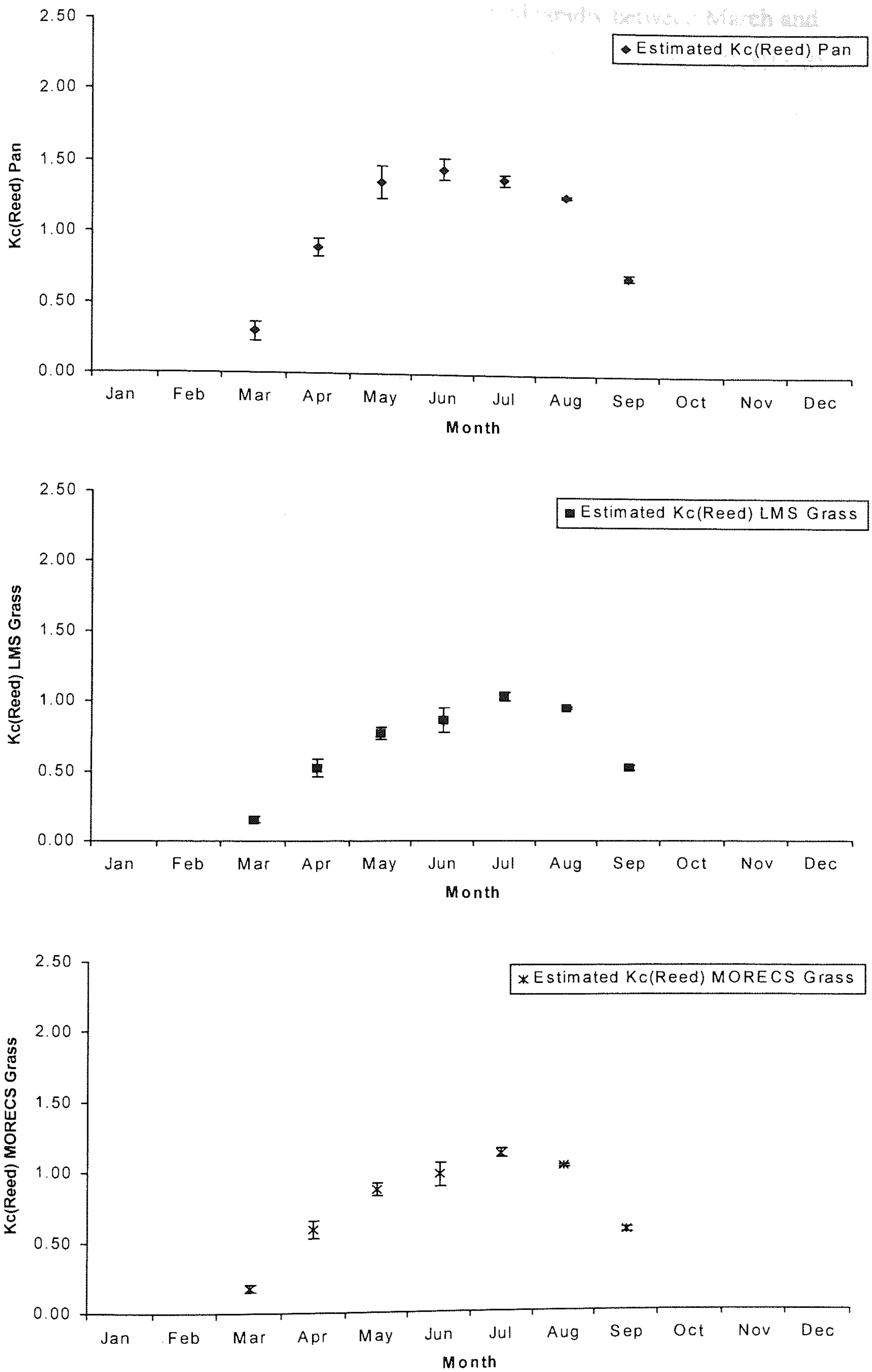


Fig. 7.15: Estimated Kc(Reed) Including Standard Error Bars for Leighton Moss, 2001-2002

Table 7.13 shows estimated Kc(Reed) Pan increased rapidly between March and April and reached a peak in June at 1.47, falling to 0.71 in September. Kc(Reed) LMS Grass provided lower values with a peak of 1.04 recorded in July. A similar pattern was recorded Kc(Reed) MORECS Grass which peaked in July at 1.13. On average, Kc(Reed) values developed using the modelled ET(Reed) values from Leighton Moss were higher than both the measured and modelled Kc(Reed) data from Aqualate Mere.

7.6 DISCUSSION

7.6.1 METHODOLOGY

The methodology used to install the lysimeters within the reedbed on the whole was very successful. In undertaking the work without the use of hydraulic excavators, the damage to the reedbed was minimal and within one growing season the reeds surrounding the lysimeters were growing successfully again. The use of adjustable hook gauges on the lysimeters minimised the potential for the lysimeters to overtop during the winter or dry out during the summer. In addition they allowed the gauges at Leighton Moss to be set in such a way that the potential for the heightened rainfall (Leighton Moss received approximately twice as much rainfall as the other sites) to overtop the lysimeters was reduced.

The main problems were associated with the establishment of the reeds within the lysimeters. In attempting to ensure that the lysimeters replicated a large natural reedbed system by locating them within the centre of the reed stand, the lysimeters were subjected to excessive shading from the surrounding reeds during the growing season, and therefore reed establishment within the lysimeters was limited. Despite repeated attempts to add reed clumps to the lysimeters, establishment problems continued throughout the duration of the project.

The higher establishment success rate within the lysimeters at Aqualate Mere can be attributed to the fact the reedbed's position at the edge of the mere resulted in the reedbed being occasionally slightly flattened by the prevailing wind. Reeds within those lysimeters located in the areas more prone to the reedbed being flattened established more successfully than those where the lysimeters were shaded for most of the growing season.

Due to the ecologically sensitive nature of the research sites it was not possible to add artificial fertilisers or reed plugs to the lysimeters to encourage strong reed growth, and nor was it possible to cut down the reeds surrounding the lysimeters to ensure adequate light was available.

Other problems associated with carrying out research in natural wetland environments were encountered, including reedbed damage from reedbug infestation at Brandon Marsh and excessive flooding at Leighton Moss.

7.6.2 ET(Reed)

Table 7.14 presents a summary of published and calculated monthly ET(Reed) data compared with ET(Reed) developed during this project. The data has been sorted using ET(Reed) for July with the lowest values presented at the top of the table.

Table 7.14 clearly shows that the ET(Reed) rates recorded in this project are lower than most published values. Low ET(Reed) data for June and July was recorded by Peacock and Hess (2001) using a Bowen ratio station, although it should be noted that these data are initial data only as the data from the whole project (2001 and 2002) has not yet been published.

Souch et al (2002) provided ET(Reed) for the growing season and winter seasons which have been averaged to provide monthly ET(Reed) and for this reason these data are not directly comparable with ET(Reed) generated in this project.

Measured ET(Reed) from Aqualate Mere was lower than the estimated data from both Aqualate Mere and Leighton Moss as a result of the crop height and crop density within the reedbeds being higher than those from the lysimeters. ET(Reed) data calculated in this project are comparable with those presented by Fermor et al (2001) for Walton Lake. The reedbed at Walton Lake was similar to that at Aqualate Mere in that it was a wide expanse of reedbed along one edge of the lake into which lysimeters were installed.

ET(Reed) recorded by Fermor et al (2001) at TINR and Himley STW were expected to be higher than those recorded in this project due to their nature as a 'fringe' reedbed and a small treatment reedbed respectively where increased advection resulted in higher water use. This expectation is reflected in the data shown in Table 7.12.

The highest ET(Reed) data was recorded from fringe reedbeds (e.g. Burba et al, 1999a) and wastewater treatment reedbeds (e.g. Burgoon et al, 1997) in the USA; and from larger dense reedbed stands in continental Europe. These data support the supposition that different types of reedbed will use water at different rates.

Some of the variation between ET(Reed) data can be attributed to the differences in meteorological conditions at the study sites. It is therefore probably more appropriate to compare calculated Kc(Reed) data with published values as the underlying differences between meteorological conditions are removed.

7.6.3 Kc(Reed)

Using data from Aqualate Mere a crop coefficient curve (see Doorenbos and Pruitt, 1977) was developed (Figure 7.16) showing mean Kc(Reed) for each crop growth stage. Kc(Reed) MORECS Grass is most likely to be used by UK wetland designers due to its availability from the Met Office and is therefore the only form of Kc(Reed) considered throughout the remainder of this chapter.

RESEARCHER	REEDBED TYPE	ET(Reed), mm day^{-1}											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Souch et al (2000)	Not known, UK	0.49	0.49	0.49	0.63	0.63	0.63	0.63	0.63	0.63	0.49	0.49	0.49
Peacock and Hess (2001)	Large, UK	-	-	-	-	-	2.00	2.10	-	-	-	-	-
Author - Aqualate Mere (measured)	Large, UK	0.20	0.29	0.60	1.36	1.80	2.75	2.67	2.61	1.70	0.91	0.30	0.30
Author - Aqualate Mere (estimated)	Large, UK	-	-	0.37	1.27	2.31	2.87	2.79	2.78	1.54	-	-	-
Author - Leighton Moss (estimated)	Large, UK	-	-	0.47	1.59	2.35	2.62	3.07	2.83	1.56	-	-	-
Fermor et al (2001) Walton Lake	Large, UK	0.58	0.61	0.76	1.62	1.78	2.69	3.33	2.42	1.93	1.34	0.67	0.20
Fermor et al (2001) TINR	Fringe, UK	0.29	1.36	1.34	1.76	2.25	4.22	4.12	4.35	3.24	2.75	0.90	0.81
Fermor et al (2001) Himley STW	Treatment, UK	0.18	0.82	0.73	1.38	2.41	3.84	4.99	6.19	6.30	2.96	0.90	0.21
Burba et al (1999a)	Fringe, USA	-	-	-	-		4.49	5.02	4.30	3.18	1.30	-	-
Smid (1975)	Dense, Czech Rep.	-	-	-	-	-	-	6.90	-	-	-	-	-
Kvet (1973), cited by Smid (1975)	Reedbed, Czech Rep.	-	-	-	-	-	-	7.80	-	-	-	-	-
Burgoon et al (1997)	Treatment, USA	-	-	-	-	6.40	6.40	-	-	-	-	-	-
Tuschhl (1970), cited by Smid (1975)	Reedbed, Austria	-	-	-	-	-	13.00	-	-	-	-	-	-

Table 7.14: Mean Monthly ET(Reed) Summary

Figure 7.16 shows Kc(Reed) increased steadily from dormancy where Kc(Reed) = 0.10, through the initial and crop development stages where Kc(Reed) = 0.22 and 0.55 respectively, to reach a plateau of 0.94 during the mid-season stage. From here Kc(Reed) fell steadily throughout the late-season back to dormancy in November.

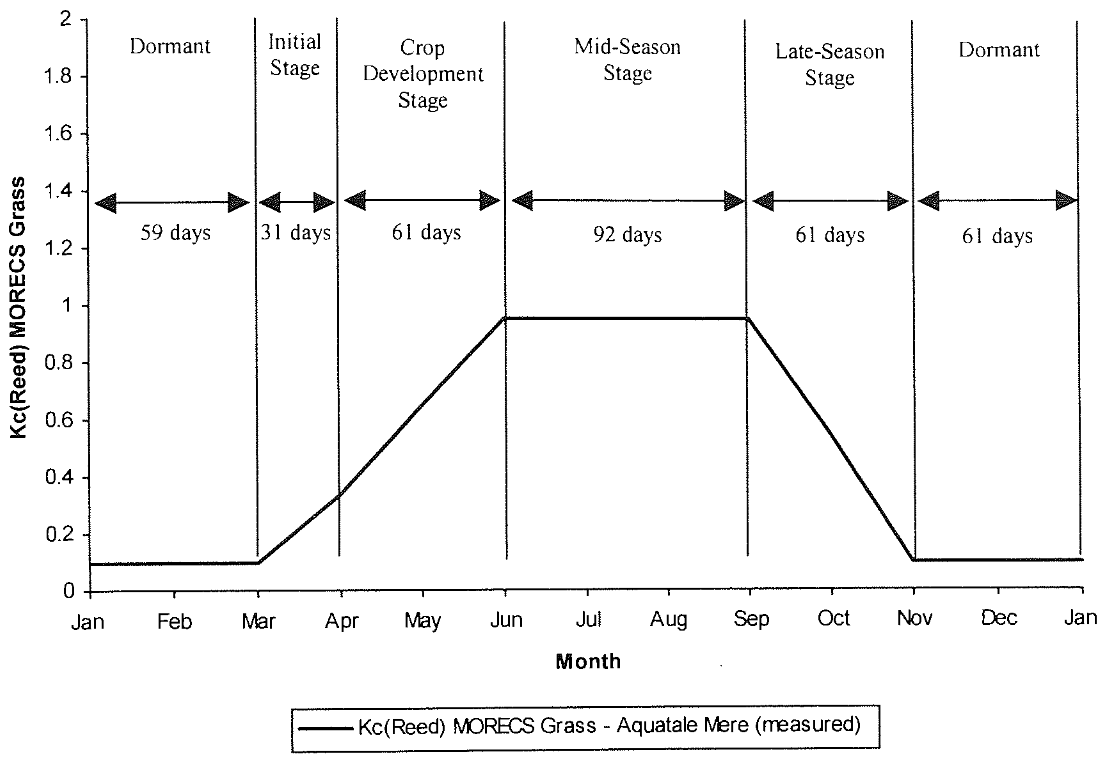


Fig. 7.16: Reedbed Crop Coefficient Curve for Aqualate Mere, 2001-2002

Table 7.15 provides a summary of published Kc(Reed) compared with the data developed during this project. The ETo source from which Kc(Reed) values were developed is included, as Kc is not directly comparable unless the same ETo data have been used. Again the data has been presented with the lowest July Kc(Reed) values at the top of the table.

RESEARCHER	REEDBED TYPE	ETo SOURCE	MEAN MONTHLY Kc(Reed)											
			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Peacock and Hess (2001)	Large, UK	Penman Open Water	-	-	-	-	-	0.58	0.56	-	-	-	-	-
Author - Aqualate Mere (measured)	Large, UK	MORECS Grass	0.50	0.29	0.43	0.68	0.63	0.88	0.82	0.99	0.82	0.66	0.56	0.66
Fermor et al (2001) Walton Lake	Large, UK	MORECS Grass	1.09	0.46	0.48	0.78	0.63	0.77	0.86	0.72	0.75	0.82	0.76	0.97
Author - Aqualate Mere (estimated)	Large, UK	MORECS Grass	-	-	0.19	0.43	0.77	0.96	0.93	0.93	0.51	-	-	-
Gilman et al (1998), cited by Acreman et al (2002)	Large, UK	Penman PET	-	-	-	0.95	0.95	0.95	0.95	1.20	1.07	-	-	-
Burba et al (1999a)	Fringe, USA	Open Water	-	-	-	-	-	0.68	0.98	0.91	1.10	-	-	-
Smid (1975)	Dense, Czech Rep.	Open Water	-	-	-	-	-	-	>1.0	-	-	-	-	-
Author - Leighton Moss (estimated)	Large, UK	MORECS Grass	-	-	0.18	0.59	0.88	0.91	1.13	1.04	0.57	-	-	-
Fermor et al (2001) Himley STW	Treatment, UK	MORECS Grass	0.67	0.75	0.50	0.96	0.81	1.04	1.19	1.47	2.10	1.50	1.27	0.60
Acreman et al (2002)	Large, UK	Penman PET	-	-	-	-	-	1.19	1.19	1.19	1.19	2.29	2.29	-
Fermor et al (2001) TINR	Fringe, UK	MORECS Grass	0.94	1.27	0.89	0.97	0.83	1.38	1.37	1.55	1.82	1.70	1.05	1.59
Burgoon et al (1997)	Treatment, USA	Grass	-	-	-	-	1.00	1.00	-	-	-	-	-	-

Table 7.15: Mean Monthly Kc(Reed) Summary

The lowest Kc(Reed) values were calculated by Peacock and Hess (2001) and were significantly lower than those from Aqualate Mere (measured). The data presented by Fermor et al (2001) for Walton Lake compares favourably with Aqualate Mere, with similar values throughout the growing season. Kc(Reed) between November and February was lower at Aqualate Mere than Walton Lake, although data from January and December compares favourably with data from Himley STW (Fermor et al, 2001).

Table 7.15 illustrates that during March Kc(Reed) data from the two estimated data sets (Aqualate Mere and Leighton Moss) was very low as a result of low ET(Reed) values (see Table 7.14). During March the reeds started to use water for initial growth, although often only small above ground stems were seen. Due to the model developed in Section 7.3.3 using crop height and density to estimate ET(Reed), minimal above ground growth data resulted in the estimated water use values being low.

Table 7.16 presents comparative annual Kc(Reed) data. It should be noted that only those studies which presented Kc(Reed) for each month have been used to calculate annual values. In addition, some authors presented annual rates as opposed to monthly rates and these have been included.

RESEARCHER	REEDBED TYPE	ETo SOURCE	ANNUAL Kc(Reed)
Author - Aqualate Mere (measured)	Large, UK	MORECS Grass	0.66
Fermor et al (2001) Walton Lake	Large, UK	MORECS Grass	0.76
Fermor et al (2001) Himley STW	Treatment, UK	MORECS Grass	1.07
Souch et al (2000)	Not known, UK	Not known	1.20
Fermor et al (2001) TINR	Fringe, UK	MORECS Grass	1.28
Bardsley (2001b)	Fringe, UK	Not known	1.40
Herbst and Kappen (1999)	Fringe, Germany	Open Water	1.67

Table 7.16: Annual Kc(Reed) Summary

Table 7.16 clearly highlights the difference in Kc(Reed) values that have been recorded. Annual Kc(Reed) calculated in this project has the lowest value of 0.66 which is comparable to that presented by Fermor et al (2001) for Walton Lake. If the low ET values recorded at Aqualate Mere during February and November were increased to values similar to those presented by Fermor et al (2001) for Walton Lake the two annual Kc(Reed) values would be very similar.

As the source of the values from Souch et al (2000) are not known, it is not appropriate to discuss a reason for these data being higher.

Fermor et al (2001) recorded annual Kc(Reed) = 1.28 at the TINR and this can be attributed to the fact that the lysimeters were located within a fringe reedbed and the water use from the plants was therefore elevated through the 'clothes-line' effect of increased advection. Although the source of the data from Bardsley (2001b) is not known, the design of the wetland for which the data were applied would suggest that the reedbed was a fringe reedbed which would account for the high Kc rates used. The highest rates (Kc(Reed) = 1.67) were produced by Herbst and Kappen (1999) and can be attributed to the meteorological conditions associated with the reed-belt in which the studies were undertaken, associated with the effect of the different climate of continental Europe, when compared to the maritime climate experienced by the UK.

CHAPTER 8. WET WOODLAND RESULTS

8.1 INTRODUCTION

This chapter presents results from the wet woodland experiments. Section 8.2 provides an analysis of the methodology for determining the water use rates of wet woodland habitats, including discussions associated with: equipment installation and vegetation establishment; soil moisture monitoring equipment; and measured water levels within the lysimeters. Section 8.3 provides the initial developed ET(W6) values, with reference crop evapotranspiration data for each site included in Section 8.4. Information with respect to Kc(W6) is included in Section 8.5 with a discussion presented in Section 8.6.

8.2 EVALUATION OF EXPERIMENTAL DESIGN

8.2.1 INSTALLATION METHODOLOGY AND VEGETATION ESTABLISHMENT

The installation methodology involved two processes: installing the lysimeter at the study sites; and inserting soil moisture monitoring equipment into the lysimeters. The lysimeters were successfully installed and backfilled using a hydraulic excavator (see Figure 6.8). The dipwells were used to measure water levels in each lysimeter (see Section 8.2.4), although towards the end of the project it was noted that at Leam Valley silt was starting to build up within them. This did not affect the water level readings, but if the project was extended for more than an additional 1-2 years, this may become an issue.

Silting was also noted within the water access tubes towards the end of the project at both of the sites (but particularly at Leam Valley), and again this may become a consideration for a longer project. The tubes provided a means for the removal of water from the system with the 30 mm diameter holes drilled through the sides of the water access tubes allowing water to move laterally into them from the soil. These holes were drilled 300 mm apart, and it may have been more appropriate to drill them closer together to allow more rapid dispersal, particularly during the winter months to ensure that the correct volumes of water were removed - water had to be drained from the tubes, allowed to fill up and then drained again.

Two types of soil moisture sensor were installed within the lysimeters: Watermark sensors; and Theta Probes, and Sections 8.2.2 and 8.2.3 provide details of the data collected. With respect to the installation of the probes, both types were inserted into an augered hole, which was back-filled once the probe had been inserted.

Table 8.1 details the flooding events at Cherry Holme Woods and Leam Valley during the period of the research and highlights one of the potential problems of working with sensitive electronic equipment (soil moisture probes) in wetland environments. The soil moisture monitoring equipment installed was chosen to minimise adverse affects of flooding, and no problems with the equipment associated with the flooding events were noted.

STUDY SITE	DATE	FLOODING RECORDED		
		OLD RIVER CHANNEL	**WET WOODLAND**	**LYSIMETERS**
Cherry Holme Woods	Nov 2000	✓	✓	✓
	May 2001	✓		
	Feb 2002	✓		
Leam Valley		**WETLAND AREA**	**WET WOODLAND**	**LYSIMETERS**
	Dec 2000	✓	✓	✓
	Jan 2002	✓		

Table 8.1: Flooding Events Noted at Cherry Holme Woods and Leam Valley

The flooding events had a significant impact on the establishment of vegetation within the lysimeters. Table 8.2 provides a summary of the activities undertaken to successfully establish the vegetation.

LYSIMETER	DATE	VEGETATION ESTABLISHMENT ACTIVITIES
Cherry Holme Woods Lysimeter 1	Oct 2000	Tree and understorey transplanted
	Nov 2001	Dead tree removed and replaced with new specimen
	mid May 2001	Understorey vegetation accidentally sprayed off during woodland management works
	end May 2001	Understorey vegetation replanted using turves from surrounding woodland
Cherry Holme Woods Lysimeter 2	Oct 2000	Tree and understorey transplanted
Leam Valley Lysimeter 1	Nov 2000	Tree planted
	Sep 2001	Understorey vegetation planted using turves from adjacent woodland and plug plants
Leam Valley Lysimeter 2	Nov 2000	Tree planted
	Sep 2001	Understorey vegetation planted using turves from adjacent woodland and plug plants
	Nov 2001	Dead tree removed and replaced with new specimen
	Apr 2002	Dead tree removed and replaced with new specimen

Table 8.2: Summary of Wet Woodland Vegetation Establishment Activities

Table 8.2 highlights the fact that vegetation establishment within the lysimeters was a significant factor in the success of the methodology. For Lysimeter 2 at Cherry Holme Woods the vegetation was successfully transplanted during October 2000, established during 2001, and was therefore well established during monitoring in 2002. The death of the tree in Lysimeter 1 at Cherry Holme Woods was associated with frequent flooding between November 2000 and January 2001 as the top level of the lysimeter was below that of Lysimeter 2 and was therefore inundated more often. It was not apparent until April 2001 that the tree was suffering, and by November 2001 the tree had died. The replacement tree was planted in November 2001 and established throughout 2002. The accidental spraying of the understorey in May 2002 with herbicide necessitated the transplantation of additional turves in early June 2002 and the vegetation established throughout the remainder of 2002.

At Leam Valley, the tree within Lysimeter 1 was planted during November 2000 and was therefore fully established during monitoring in 2002, however, the understorey was still establishing during 2002. In Lysimeter 2 the death of the first tree can be attributed to the extensive flooding between November 2000 and January 2001, although there is no explanation for the death of the second tree. Consequentially both the tree and the understorey were still establishing during monitoring in 2002.

Photographs showing the vegetation differences in each lysimeter in July 2002 are provided in Figure 8.1.

8.2.2 WATERMARK SOIL WATER POTENTIAL SENSORS

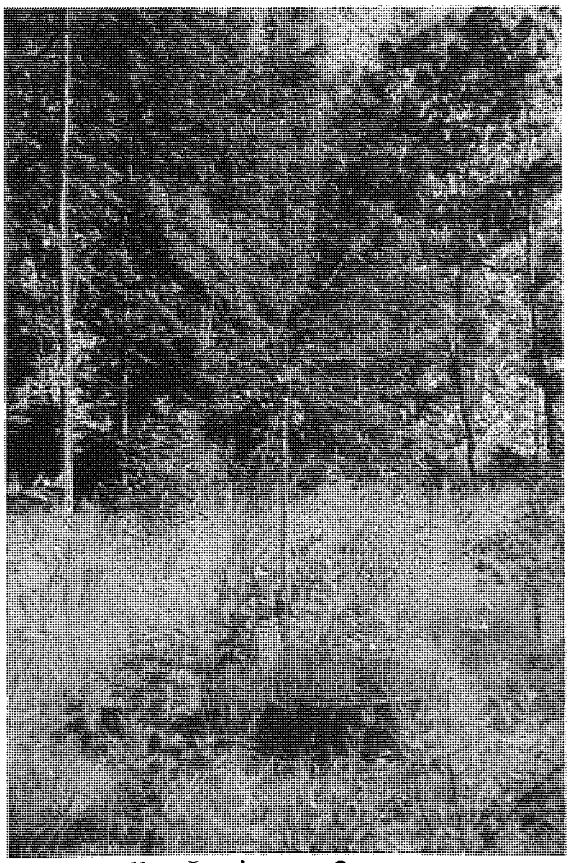
Watermark soil water potential sensors were installed to provide a back-up system for determining soil moisture if the Theta Probes failed. Evans (2000) stated that the watermark sensors were not very sensitive and would only supply information with respect to the trends in soil tension within the lysimeters. The measured soil water potential data presented in Table A8.1 (Appendix 8) and Table A9.1 (Appendix 9) supports this as there was little variation in the data throughout 2002. Brady (1974) stated that a soil reached its field capacity when the soil water tension was between 10 – 20 centibars and that at soil moisture tensions below this the soils were above field capacity. Table 8.3 details those months of the year when the soils in the lysimeters were below field capacity. The soil suction at which the habitat would reach its wilting point is approximately 1,500 centibars (Brady, 1974) and Tables A8.1 (Appendix 8) and A9.1 (Appendix 9) illustrate that at no point was the soil tension low enough to significantly affect the transpiration of the habitat.

The measured soil water potential data was not converted to soil moisture content as this would have involved soil specific calibrations for each of the soil layers within each lysimeter and the lack of sensitivity in the probes would have resulted in data which was not accurate enough for use in this study.

Cherry Holme Woods Lysimeter 1

Cherry Holme Woods Lysimeter 2

Leam Valley Lysimeter 1



Leam Valley Lysimeter 2

Figure 8.1: Vegetation Establishment Within the Wet Woodland Lysimeters, July 2002

SENSOR DEPTH (m.b.g.l.)	MONTHS WHEN SOILS WITHIN LYSIMETERS WERE BELOW FIELD CAPACITY			
	Cherry Holme Woods		Leam Valley	
	Lysimeter 1	Lysimeter 2	Lysimeter 1	Lysimeter 2
0.3	Aug & Sep	Aug & Sep	Jun, Jul, Aug Sep & Oct	Aug, Sep
0.6	N/a	Sep	Jul, Aug & Sep	Aug
0.9	N/a	Sep	Sep	N/a
1.2	N/a	N/a	Sep	Sep

Table 8.3: Months When the Soils Within the Wet Woodland Lysimeters Were Below Field Capacity

8.2.3 THETA PROBES

Theta Probes were used throughout 2002 to measure the moisture content of the soil. The soil moisture content recorded by each probe is presented in Tables A8.2 to A8.5 (Appendix 8) and A9.2 to A9.5 (Appendix 9) for Cherry Holme Woods and Leam Valley respectively. During the project, a technical problem was encountered in January 2002 with one of the probes (ML2 06) at Cherry Holme Woods providing negative data as the result of a loose wire connection in a junction box. The problem was fixed in February 2002.

To assess whether the soil moisture readings from the probes at each depth within each lysimeter (see Table 6.8) were providing consistent values, the data were compared by determining the percentage difference between the two readings. Where the percentage difference was greater than 10%, the probe that showed the inconsistency (e.g. very high or very low data, or data with considerable variation between sampling visits) was not included in subsequent ET(W6) calculations. Tables 8.4 and 8.5 detail the decisions taken regarding the probes highlighted during this exercise at Cherry Holme Woods and Leam Valley respectively (see Table 6.7 for information regarding sensor ID and associated installation depth).

CHERRY HOLME WOODS	THETA PROBES WITH > 10% DIFFERENCE ON AVERAGE	DECISION
Lysimeter 1	ML2 01 (Profile A) ML2 06 (Profile B)	Soil moisture readings from ML2 01 not included in ET(W6) calculations
	ML2 02 (Profile A) ML2 07 (Profile B)	Soil moisture readings from ML2 02 not included in ET(W6) calculations
Lysimeter 2	ML2 11 (Profile A) ML2 16 (Profile B)	Soil moisture readings from ML2 11 not included in ET(W6) calculations
	ML2 12 (Profile A) ML2 17 (Profile B)	Soil moisture readings from ML2 17 not included in ET(W6) calculations

Table 8.4: Details of Inaccurate Theta Probes at Cherry Holme Woods

LEAM VALLEY	THETA PROBES WITH > 10% DIFFERENCE ON AVERAGE	DECISION
Lysimeter 1	ML2 01 (Profile A) ML2 06 (Profile B)	Soil moisture readings from ML2 06 not included in ET(W6) calculations
Lysimeter 2	ML2 13 (Profile A) ML2 18 (Profile B) 02-Sep and 01-Oct only	Soil moisture readings from ML2 18 not included in relevant ET(W6) calculations

Table 8.5: Details of Inaccurate Theta Probes at Leam Valley

At both sites the most noticeable variations between the probes occurred within the topsoil in the lysimeters (0.10 m.b.g.l. and 0.25 m.b.g.l.), likely to be the result of the different soil structure and root system. Roots within this layer could have grown into the small space within the soil generated by the insertion of the Theta Probe as this would offer the roots the path of least resistance. Any space surrounding the instrument's probes would result in inaccurate soil moisture readings as the spaces would fill with water as the soils reached saturation and would drain again as the soils dried out admitting air. This would result in higher readings during the winter and spring and lower readings during the summer and autumn.

At Leam Valley Lysimeter 1 the spurious data from Theta Probe ML2 06 (Table 8.5) were caused by a technical problem with the probe. The soil moisture readings were consistently recorded as being between 0.25 and 0.31 $m^3\ m^{-3}$ throughout the whole sampling period and the readings increased during the drier months. Within Lysimeter 2, low soil moisture readings were recorded by Theta Probe ML2 18 on 02 September 2002 and 01 October 2002 and this data was not used in subsequent ET(W6) calculations. It is not known why this occurred, and as readings throughout the remainder of the monitoring period were consistent, data from this probe was included in calculations in most instances.

As the probes had been installed within a vertical column with each one directly above another, it was not deemed appropriate to try to remove the probes providing the inaccurate data and replace them as the action would either have disturbed other probes or the habitat within the lysimeter.

The variation between the soil moisture readings taken at the surface (0 m.b.g.l.) using a portable Theta Probe was often considerable (see Tables A8.2 and A9.2) as a result of the sampling procedure whereby the probe was inserted randomly into the soil during each visit, thus increasing the likelihood of variation between the four samples. The data was considered valid and a mean of the values was therefore used in all ET(W6) calculations.

To reduce the problems of variation additional profiles of Theta Probes could have been installed. However, financial limitations and the requirement to minimise the disturbance within the lysimeters rendered this impractical.

8.2.4 SOIL MOISTURE PROFILES

Figures 8.2 and 8.3 present the mean soil moisture profiles during representative summer (mid August 2002) and winter (mid December 2002) monitoring visits at Cherry Holme Woods and Leam Valley respectively.

Figure 8.2 shows that within Cherry Holme Woods Lysimeter 1, the greatest seasonal variation was within the top 0.1 m of the profile, likely to be the result of the top 0.1 m of the soil drying during the summer period. The similar summer and winter values at 0.1 m.b.g.l. were surprising, but may be attributed to the understorey vegetation being killed off during May and taking a few months to recover. The tree roots would be extracting water from the soils between 0.1 and 0.5 m.b.g.l. resulting in the soil moisture profiles shown. Below this depth, the soil moisture remained constant throughout the year.

The profiles exhibited by Cherry Holme Woods Lysimeter 2 (Figure 8.2) are quite different, the majority of which can be attributed to the better establishment of the tree and understorey. During the summer months, the tree and understorey were extracting water consistently throughout the top 0.5 m of the profile. In addition, the soils in Lysimeter 2 were noted to be more sandy than those in Lysimeter 1 which would allow for easier extraction of water by the vegetation within this layer.

Figure 8.3 illustrates that the saturated profiles within both lysimeters at Leam Valley were similar, with little variation throughout the profile itself. During the summer, the greatest drying was recorded within Lysimeter 1 due to the fact that the tree was more established than within Lysimeter 2. As a result of the understorey in both lysimeters still establishing during 2002, the majority of water loss from the lysimeters was via the trees during this period. This is reflected in the greatest decrease in soil moisture occurring at a depth of 0.5 m.b.g.l. The soil moisture lost from the surface during the summer months was primarily due to evaporation.

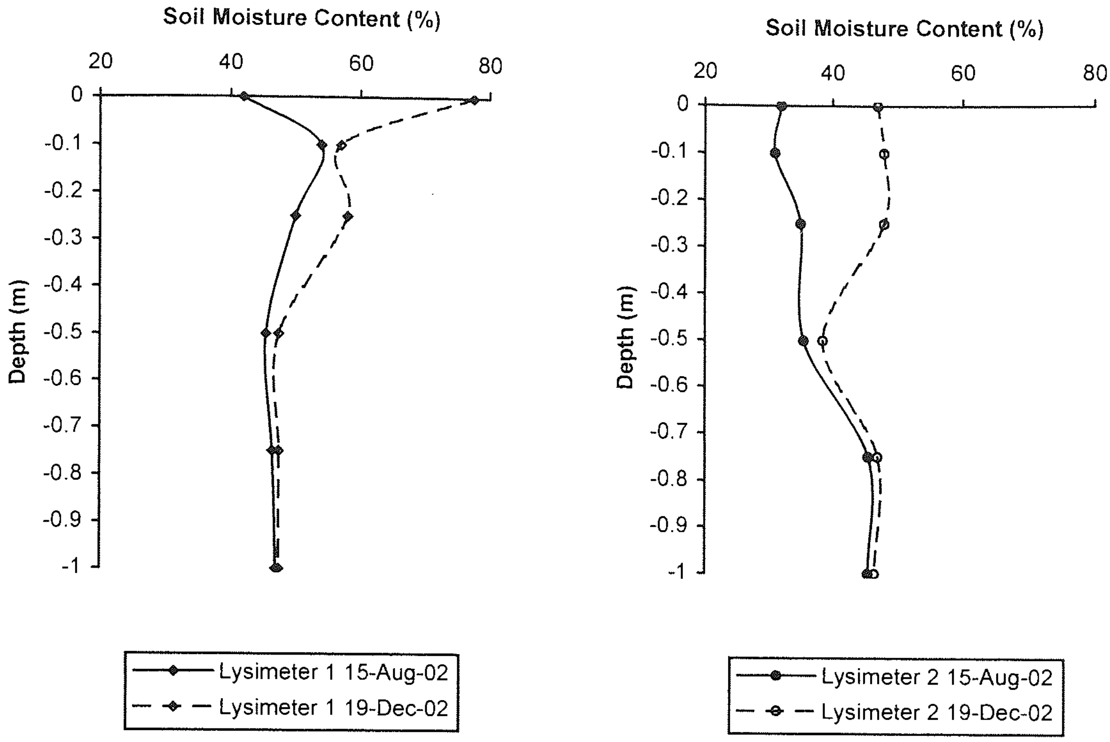


Fig. 8.2: Winter and Summer Soil Moisture Profiles at Cherry Holme Woods

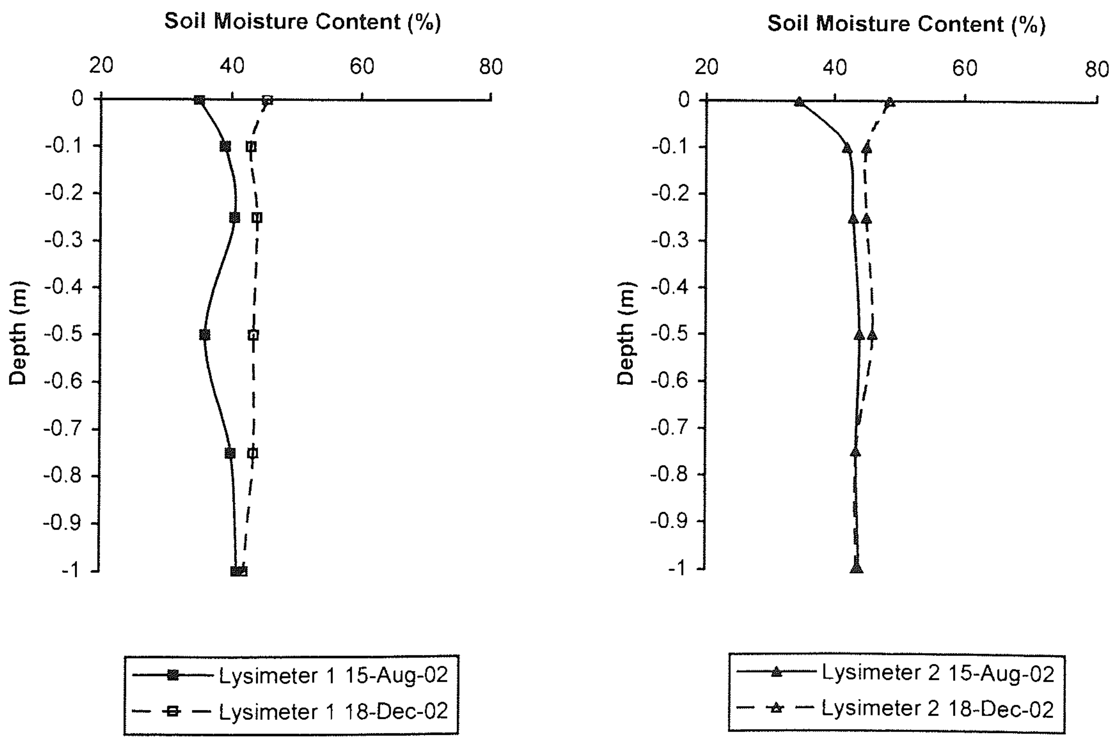


Fig. 8.3: Winter and Summer Soil Moisture Profiles at Leam Valley

Within Leam Valley Lysimeter 2 (Figure 8.3) the most significant soil moisture loss was from the surface as a result of evaporation. The tree within this lysimeter was re-planted in April 2002 (see Table 8.2) so was still establishing itself during the growing season.

It should be noted that the saturated water level within the lysimeters was controlled (see Section 6.4.5) and therefore it was not expected that there would be moisture loss below the controlled level.

8.2.5 DIPWELLS AND WATER LEVELS

During each monitoring visit the water levels within the lysimeters were recorded. To determine whether the water level in the dipwell was representative of the level at which the soil was saturated, measured water levels were compared with the soil moisture profiles obtained from the Theta Probes. Ideally, the depths at which the monthly soil profiles meet the saturated soil profile (see Section 6.4.5) should correspond to the recorded water level assuming that water moves laterally within the soils quite freely. The recorded soil moisture profiles for February, April, June and August and dipwell water levels are shown in Figures 8.4 to 8.7.

Figure 8.4 shows that within Lysimeter 1 at Cherry Holme Woods, the measured water levels provided a good indication of the point below which the soils were saturated. The relationship is particularly strong during February and June, with the data for August showing the point below which the soil was saturated approximately 0.15 m lower than that recorded in the dipwell.

Lysimeter 2 at Cherry Holme Woods (Figure 8.5) again shows that the measured water levels corresponded to the depth below which the soils are saturated during the months presented. The saturated curve within this lysimeter was very different to that for Lysimeter 1. The saturated soil moisture content was similar at the surface, but at depths between 0.1 and 0.3 m.b.g.l. was markedly greater reading 79%. This is likely to be due to the sandier nature of the substrate within this lysimeter. In addition, Figure 8.4 illustrates that the soils do not follow the same soil moisture profile pattern as they dry out, but appeared to dry most rapidly between 0.2 and 0.6 m.b.g.l., probably due to preferential moisture demand by plant roots at these depths.

Figure 8.6 details the soil moisture profiles and water levels from Lysimeter 1 at Leam Valley. The saturated profile shows that within this lysimeter the soils were saturated at approximately 45% soil moisture content throughout the profile. During the wetter months (February and April) the soil moisture profiles were very similar to the saturated profile throughout the depth. Data for June shows the profile significantly drier at the surface (0 to 0.2 m.b.g.l.), but only slightly drier than saturation throughout the remainder of the profile. By the end of August the soil was much drier (approximately 20% soil moisture) at the surface and approximately 10% drier throughout the remainder of the profile. During August the measured water level did not correspond directly with the saturated profile.

Figure 8.7 shows that in Lysimeter 2 at Leam Valley the measured water levels were representative of the saturation levels within the soils. Indeed the profiles follow a similar pattern to those shown in Lysimeter 1 suggesting that the soils within these two lysimeters have a very similar composition, and that the vegetation was extracting water from similar depths within the soil profile.

This exercise has been completed to provide information with respect to the appropriateness of using the dipwell water levels to assess the depth of soil saturation. Many wetland scientists (e.g. Fermor, 2000) concluded that measuring water tables in clay soils was meaningless due to the lack of lateral water movement through the soils. This assessment has established that within the lysimeters there is a relationship between the two and therefore the measured water levels can be used to investigate the effectiveness of the predictive water level model (see Section 6.4.5), by comparing the recorded water levels with the intended water levels (Figure 6.29).

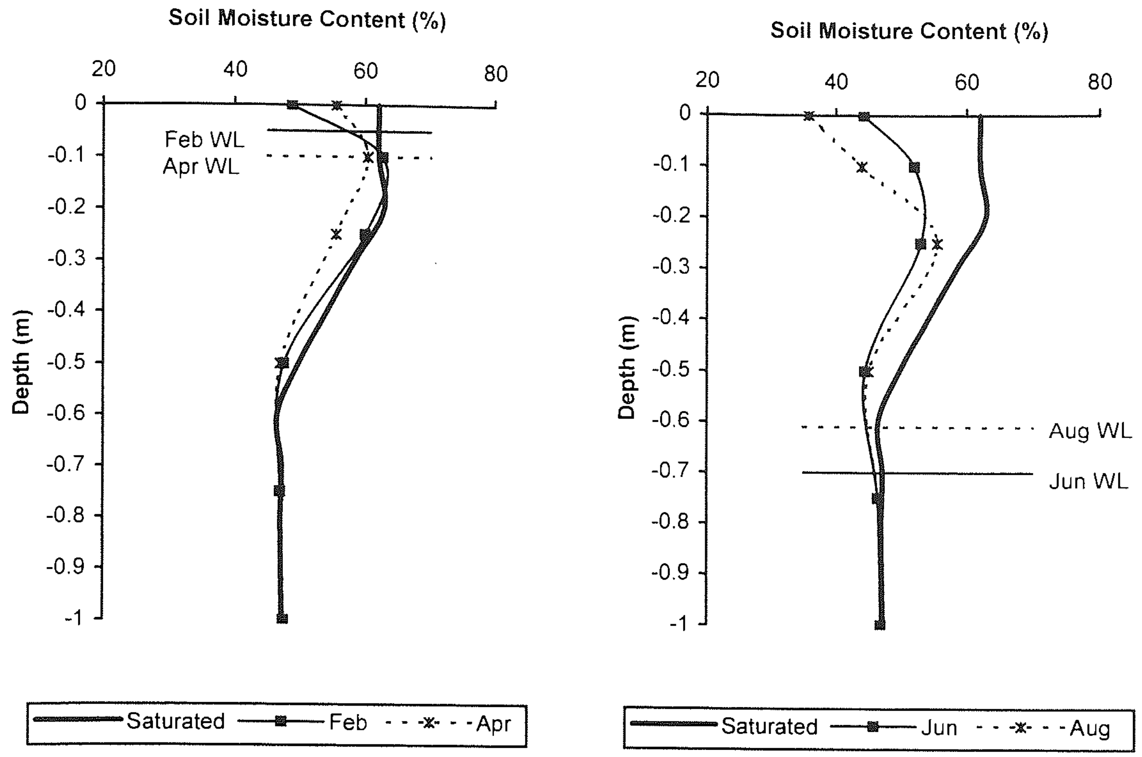


Fig. 8.4: Soil Moisture Profiles and Water Levels for Lysimeter 1 at Cherry Holme Woods

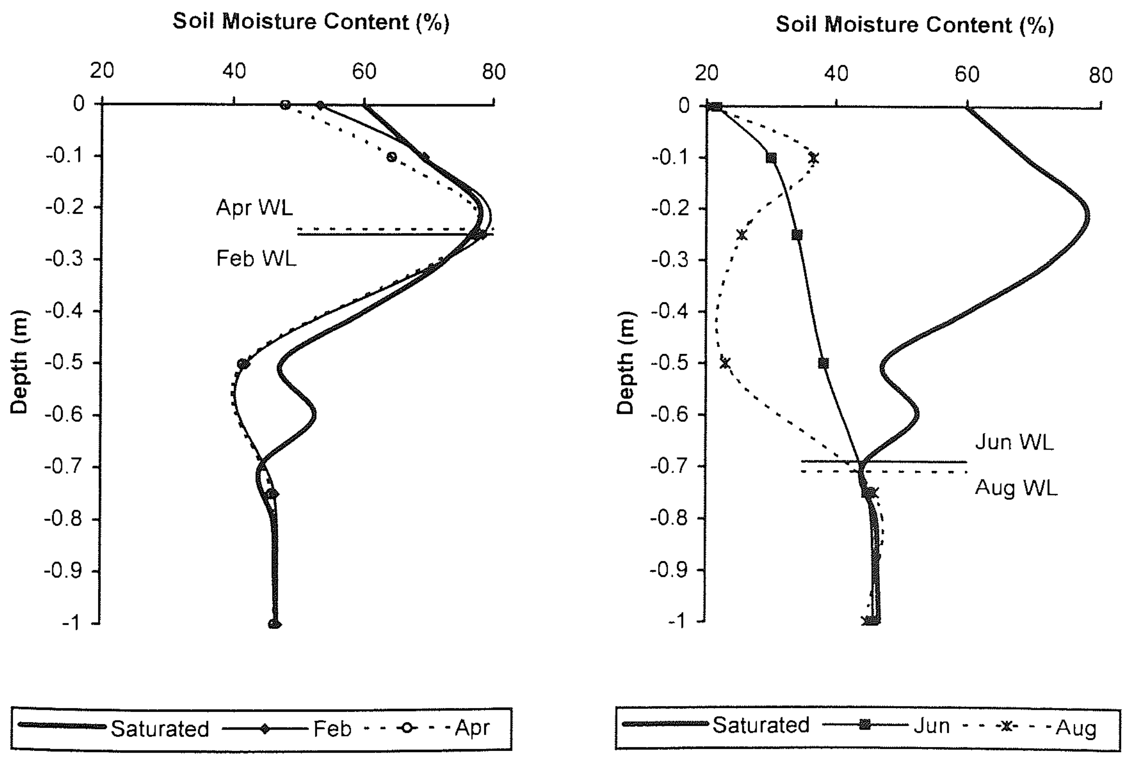


Fig. 8.5: Soil Moisture Profiles and Water Levels for Lysimeter 2 at Cherry Holme Woods

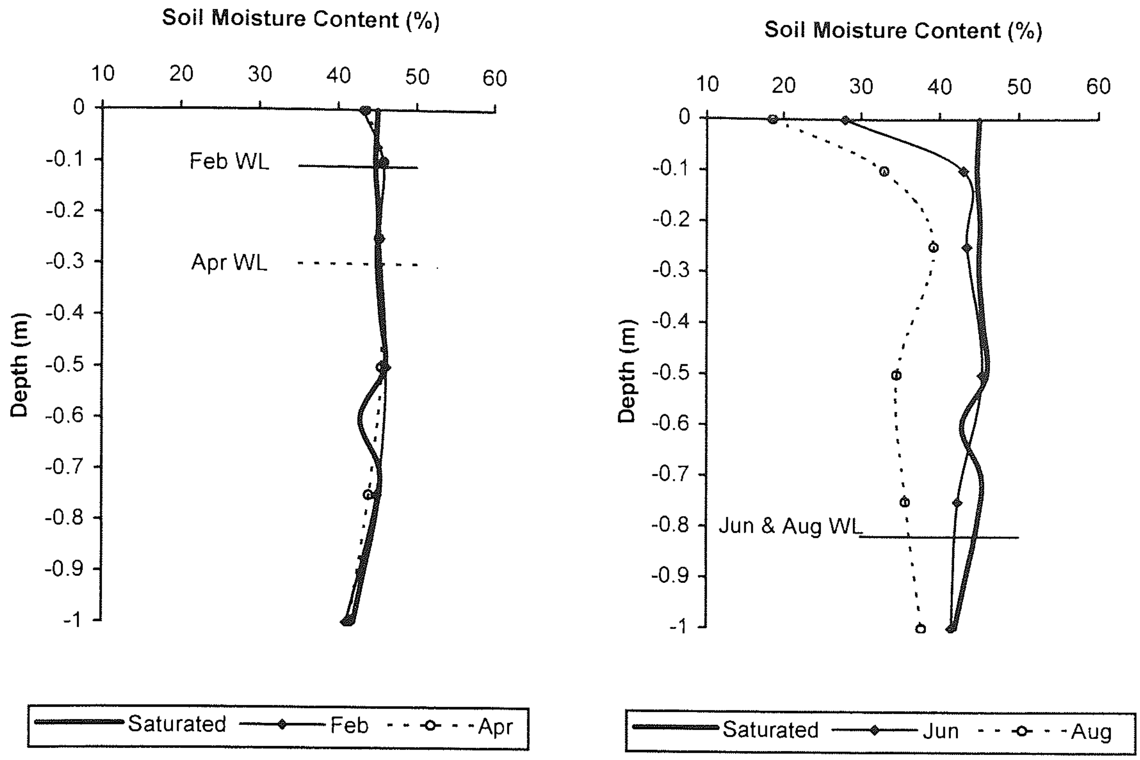


Fig. 8.6: Soil Moisture Profiles and Water Levels for Lysimeter 1 at Leam Valley

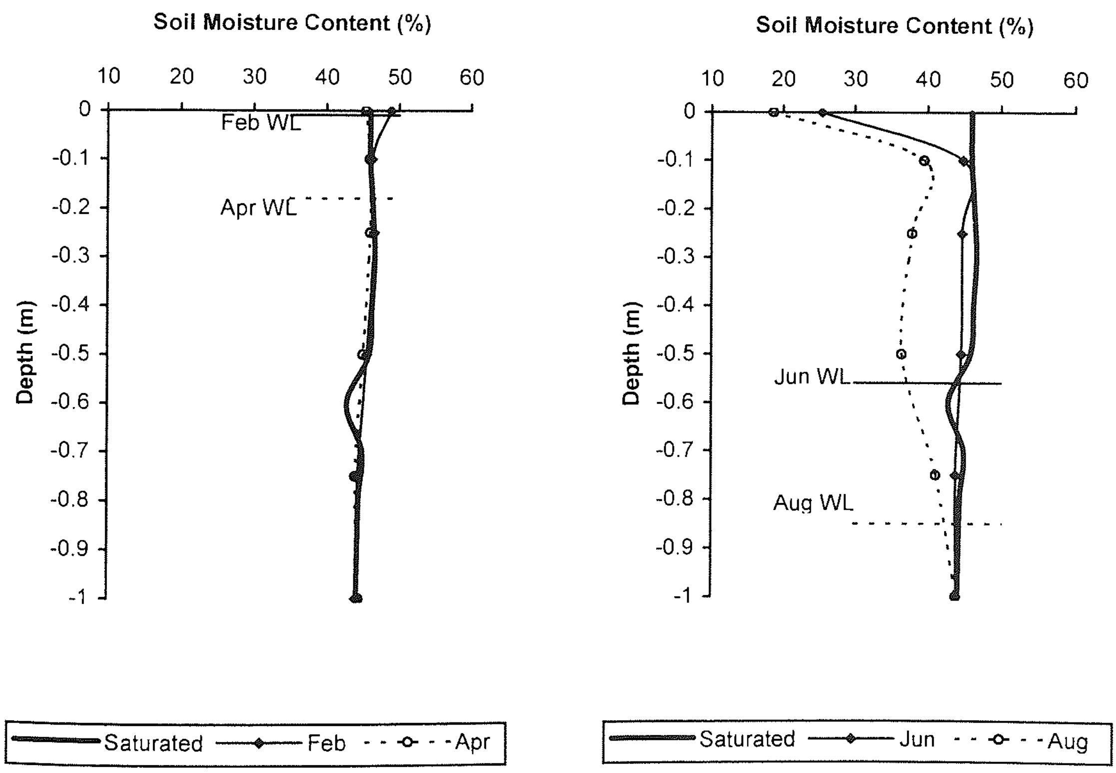


Fig. 8.7: Soil Moisture Profiles and Water Levels for Lysimeter 2 at Leam Valley

Figures 8.8 and 8.9 show the measured and proposed water levels within the lysimeters at Cherry Holme Woods and Leam Valley. Measured water level data are presented in Tables A8.6 (Appendix 8) and A9.6 (Appendix 9) for Cherry Holme Woods and Leam Valley respectively.

Figure 8.8 shows that between January and March 2002, the water levels within the Lysimeter 1 and Lysimeter 2 at Cherry Holme Woods were approximately 0.2 m and 0.4 m respectively lower than the intended water level for that period as a result of intentionally keeping the levels low to assist with tree establishment. Throughout April measured and proposed water levels were similar although during May and June measured levels were higher than proposed levels, as a result of additional inputs due to abnormally high (76 mm) rainfall in May (see Section 8.3.1). During July, August and September the levels in Lysimeter 1 were approximately 0.25 m higher than planned. Lysimeter 2 showed water levels approximately 0.2 m lower than intended but followed a similar fluctuating pattern as Lysimeter 1. From the beginning of October, water levels steadily rose in both lysimeters, with Lysimeter 1 reaching saturation at the beginning of November.

Figure 8.9 presents data for Leam Valley and shows that on average, the measured water levels were similar to the proposed levels between February and mid April. The lower levels measured in mid March can be attributed to low rainfall (28.2 mm) (see Section 8.3.2). Between mid April and the end of June the water levels followed the pattern of the proposed levels with a lag of approximately 2 weeks, likely to be the result of the water level management regime. In Lysimeter 1 the levels dropped to approximately 0.2 m lower than planned between the end July and December, but in Lysimeter 2 they only fell below the proposed level between September and December.

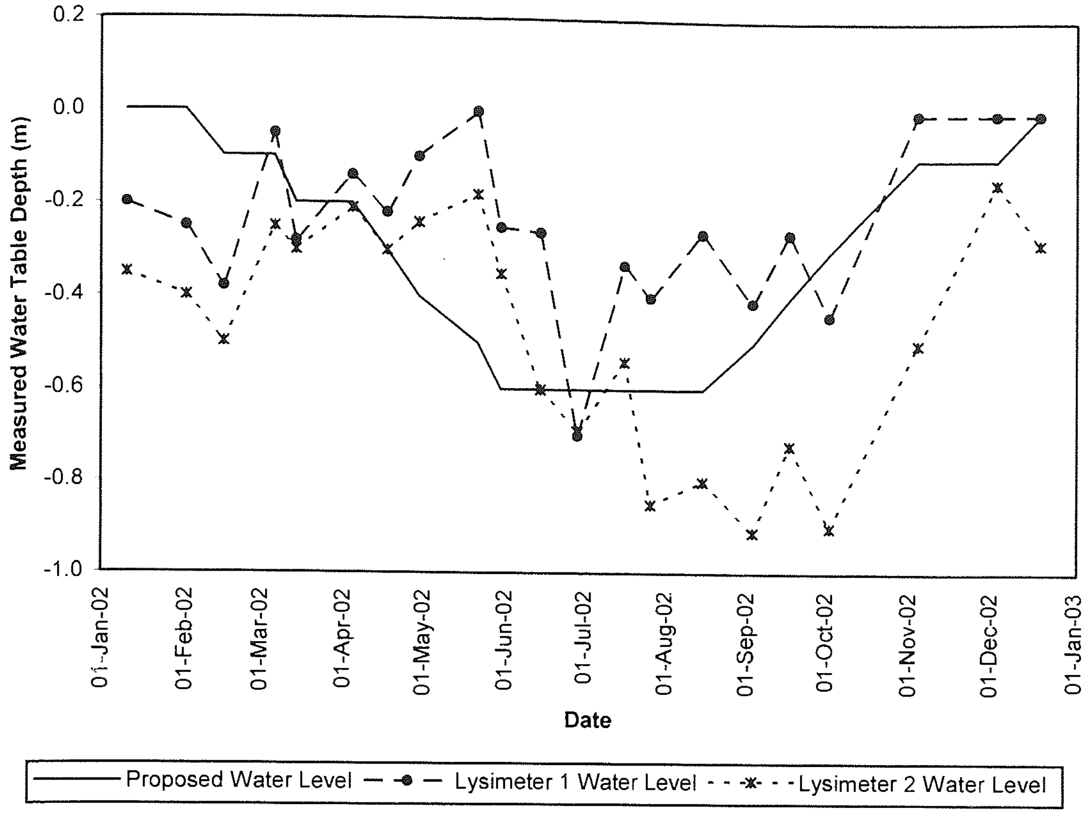


Fig. 8.8: Measured Water Levels within the Lysimeters at Cherry Holme Woods

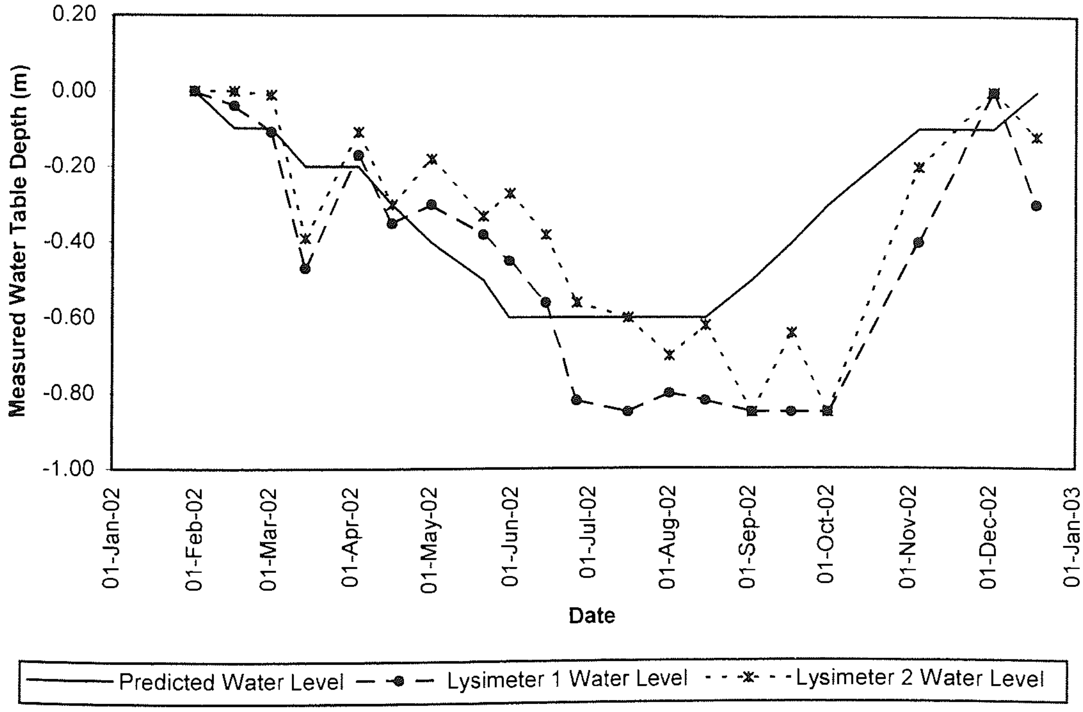


Fig. 8.9: Measured Water Levels within the Lysimeters at Leam Valley

Fluctuations in the measured water levels can be attributed to the method employed to determine the additional inputs / outputs from the lysimeter during each monitoring visit. If soil moisture content was low during the visit (and therefore water levels were low) the model would detail the volumes of water to add to the lysimeter. During the summer months, these volumes of water were quite large (150 litres for example) and would therefore cause the water levels within the lysimeter to rise between that visit and the next. During the next visit the soil moisture content would be higher and therefore less water would be added, causing water levels to fall.

8.3 ET(W6)

ET(W6) was calculated using the method outlined in Section 6.4.3. During those months when the sites were visited twice, calculated ET(W6) values were averaged to provide the mean monthly values presented in Table 8.6. It was not possible to derive mean values for each site due to the differences in tree and understorey growth within the different lysimeters. However, the results provide an insight into the effect of tree and understorey development on the water use of the habitat.

Within each of the lysimeters, the ET(W6) rates between October and February appeared to be unusually high given the time of year. This is believed to be associated with the effectiveness of the soil moisture model during periods of the year when the soils were saturated.

Whilst the soil profile was saturated, minimal changes in soil moisture content were recorded by the Theta Probes (see Tables A8.2 to A8.5 Appendix 8 and Tables A9.2 to A9.5 in Appendix 9). During this period the lysimeters were subject to rainfall inputs which were entering the system without altering the soil moisture readings as the soils had already reached saturation. Some of this water was ponding on the surface of the soil and was potentially subject to surface evaporation. The soil moisture readings on the surface did not show surface water as they continued to measure soil moisture at saturation.

The high ET(W6) rates shown in Table 8.6 between October and February were the result of the model assuming that as the rainfall inputs were resulting in no change to the soil moisture content, the excess water was being used as ET. In reality, the excess water was ponding within the lysimeter and being removed during monitoring visits in order to maintain the lysimeter's required water levels. Various attempts were made at justifying the volumes of water associated with this process and excluding them from subsequent ET(W6) calculations. However, the margins of error associated with doing this were large and therefore the inaccuracy within the results was too high to justify altering the data in this way.

It has therefore been assumed that the accuracy of the ET(W6) data between October and February cannot be confirmed and should not be used in further analysis. Figure 8.10 presents ET(W6) from each lysimeter between March and September 2002.

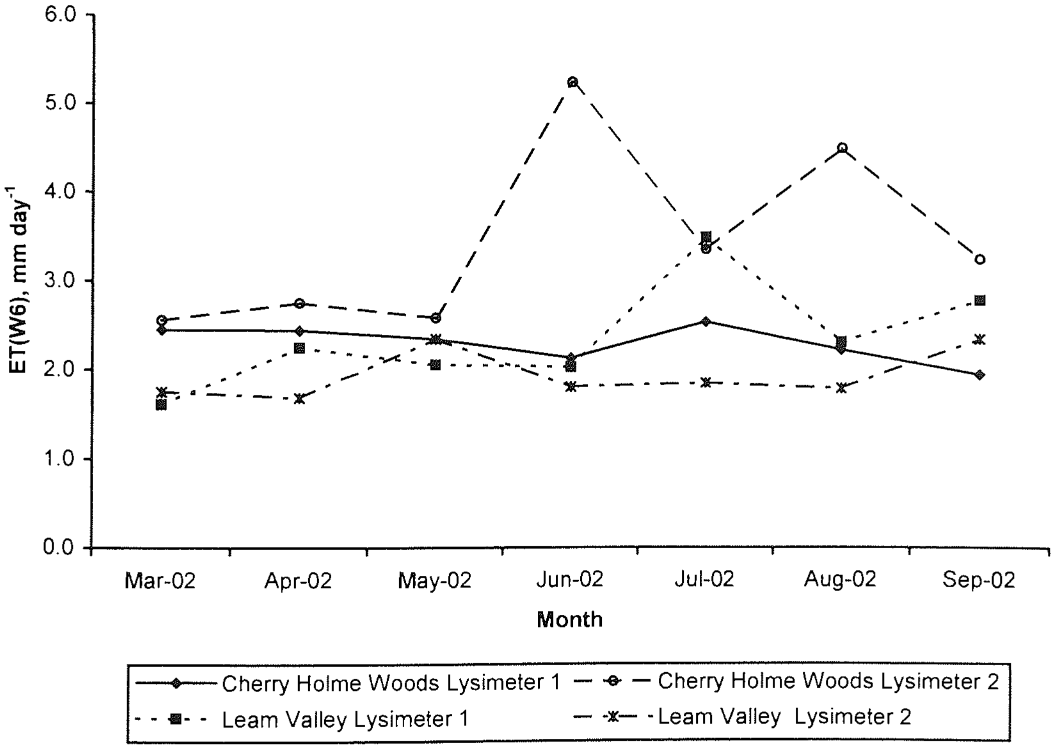


Fig. 8.10: Summary of Mean ET(W6) for all Lysimeters between March and September 2002

	Mean ET(W6), mm day^{-1}												
SITE	**Jan-02**	**Feb-02**	**Mar-02**	**Apr-02**	**May-02**	**Jun-02**	**Jul-02**	**Aug-02**	**Sep-02**	**Oct-02**	**Nov-02**	**Dec-02**	**Annual**
Cherry Holme Woods Lysimeter 1	error	error	2.45	2.44	2.35	2.14	2.55	2.24	1.96	error	error	neg.	n/a
Cherry Holme Woods Lysimeter 2	error	error	2.56	2.75	2.59	5.27	3.37	4.53	3.27	error	error	error	2.77
Leam Valley Lysimeter 1	no data	error	1.61	2.25	2.06	2.04	3.51	2.33	2.80	error	error	neg.	n/a
Leam Valley Lysimeter 2	no data	error	1.75	1.69	2.35	1.82	1.86	1.81	2.36	error	error	neg.	n/a

no data - Theta Probes not installed
neg. - sampling error resulted in a negative value
error - accuracy of data not confirmed

Table 8.6: Mean Monthly ET(W6) from Cherry Holme Woods and Leam Valley, 2002

Figure 8.10 shows that the water use from Lysimeter 1 at Cherry Holme Woods was relatively constant (approximately 2.3 mm day^{-1}) with a maximum of 2.55 mm day^{-1} recorded in July 2002. This can be attributed to the fact that the tree and understorey within the lysimeter were establishing throughout this period (see Table 8.2) and that the tree's energy would have been focussed on establishing a root system rather than the production of leaves. Reduced leaf cover results in fewer stomata to facilitate the release of water into the atmosphere.

Lysimeter 2 at Cherry Holme Woods had the greatest water use due to the well established understorey and large tree within the lysimeter. Between March and May ET(W6) was approximately 2.6 mm day^{-1}, which increased rapidly in June to reach a peak of 5.27 mm day^{-1}. This sudden increase may be the result of the warm temperatures, minimal rainfall and increased sunshine levels that occurred towards the end of the month. Water use fell in July to 3.37 mm day^{-1}, then increased to 4.53 mm day^{-1} throughout August, and fell again to 3.27 mm day^{-1} in September.

At Leam Valley, the tree within Lysimeter 1 was well established by 2002, although the understorey vegetation was still in the process of developing. Within this lysimeter the water use was relatively constant between March and June (approximately 2 mm day^{-1}), increasing in July to reach its peak of 3.51 mm day^{-1} and falling again during August. Water use increased slightly in September to 2.8 mm day^{-1} which can be attributed to the low rainfall recorded at the site (see Section 8.4.2) and the fact that September had been the sunniest on record since 1991.

On average, the lowest water use was recorded in Lysimeter 2 at Leam Valley where both the understorey and the tree were establishing throughout 2002. Water use was fairly constant between March and September with a mean value of 1.95 mm day^{-1}.

Section 8.2.2 concluded that at no point during the study were the habitats within the lysimeters suffering from lack of available water. Although the soils were shown to be below field capacity during August and September, on average the water use data presented in Table 8.6 is representative of a W6 wet woodland habitat transpiring at its potential rate.

8.4 REFERENCE CROP EVAPOTRANSPIRATION

Evaporation pan data [E Pan] was collected during each monitoring visit and ETo Pan calculated as outlined in Section 2.3.1. The UK Met Office provided PE Grass and rainfall data from appropriate local meteorological stations and relevant MORECS Squares. In addition, data from the on-site automatic meteorological station at Cherry Holme Woods was used to calculate ETo Grass.

8.4.1 CHERRY HOLME WOODS

Figure 8.11 provides a comparison of the various sources of calculated monthly rainfall and ETo data for Cherry Holme Woods (monthly totals are included in Tables A8.7 and A8.8 in Appendix 8) and showed that on-average the on-site rain gauge recorded higher rainfall than the other methods. Throughout the year there was a close agreement between the different rainfall datasets with the exception of July 2002, when the on-site rain gauge and on-site automatic meteorological station recorded similar rainfall (approximately 2.3 mm day^{-1}), but the data from the local meteorological station and MORECS Square 126 were both significantly higher (approximately 4.8 mm day^{-1}). This anomaly could be due to differences in localised meteorological conditions as Loudon (2003) concluded that if a different local meteorological station was used to provide rainfall data, the data were similar to that recorded by the on-site equipment.

The monthly rainfall totals (Table A8.7 in Appendix 8) show an irregular rainfall pattern recorded throughout the monitoring period with low rainfall (<45 mm/month) recorded in January, March, April and September 2002 and maximum rainfall (124 mm) recorded by the on-site rain gauge in October 2002. When compared with long-term average MORECS Square 126 data (Section 6.2.1.2) which shows monthly rainfall between 50 and 60 mm/month throughout the year, it is apparent that the rainfall recorded during the monitoring period was characterised by high rainfall in July, October and November and lower rainfall throughout the remainder of the year. It should be noted however, that the long-term average data covers a wide area

(40 x 40 km square) whereas on-site data will be very specific and locally variable.

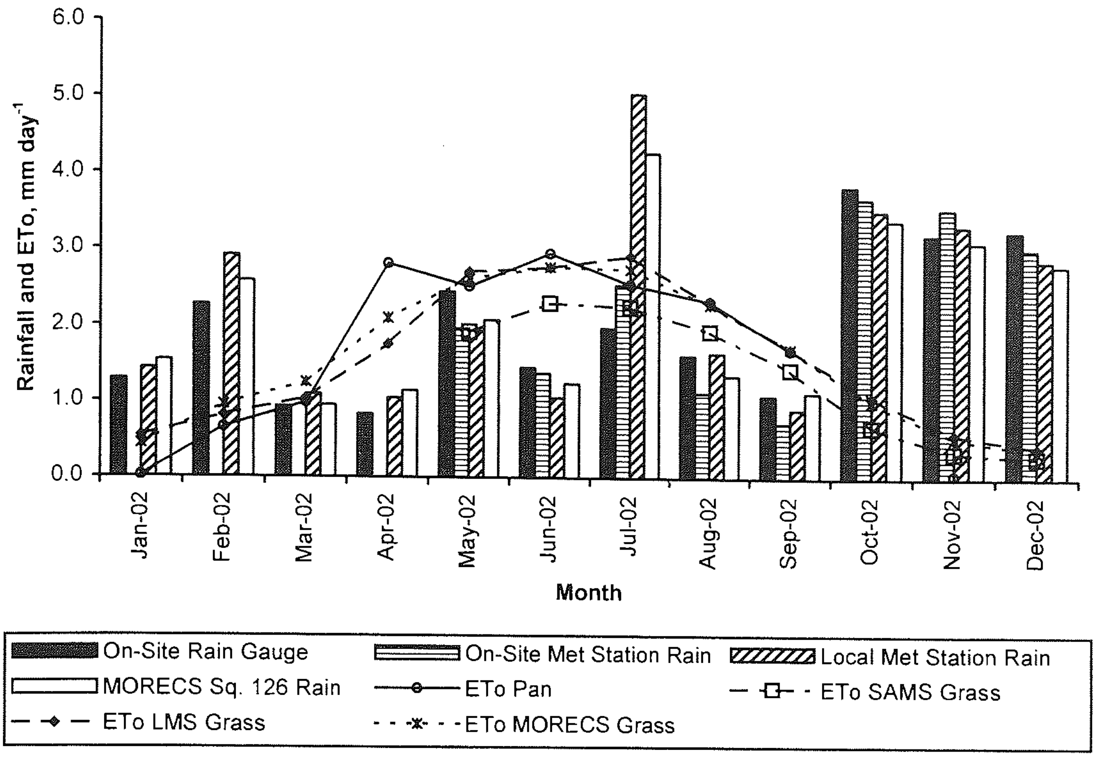


Fig. 8.11: Monthly Rainfall and ETo data for Cherry Holme Woods 2002

Figure 8.11 shows that ETo Pan was lower than ETo LMS Grass and ETo MORECS Grass between January and March 2002, but higher during April 2002. For the remainder of the year, the three data sets are very similar, with ETo Pan and ETo MORECS Grass reaching their respective peaks (2.96 mm day^{-1} and 2.78 mm day^{-1}) in June 2002, and ETo LMS Grass and reaching its peak (2.93 mm day^{-1}) in July 2002. ETo then fell steadily to reach its minimum (approximately 0.3 mm day^{-1}) in December.

Due to a problem with the electronics of the on-site automatic meteorological station providing inaccurate relative humidity data, ETo SAMS Grass was only available between May and December 2002. The data follows the same pattern as the three previous ETo data sets although the values are approximately 0.45 mm day^{-1} lower between May and August and approximately 0.25 mm day^{-1} lower between September and December. ETo SAM Grass reached a peak of 2.31 mm day^{-1} in June.

Throughout the monitoring period ETo exceeded rainfall in April, May, June, August and September.

8.4.2 LEAM VALLEY

Figure 8.12 provides a comparison of the various sources of calculated monthly rainfall and ETo data for Leam Valley (monthly rainfall and ETo totals are included in Table A9.7 and A9.8 in Appendix 9) and shows that the rainfall data was similar throughout the year. The data provided by both the local meteorological stations and the MORECS square was generally between 0.3 and 0.4 mm day^{-1} higher than that recorded using the on-site gauge, with the exception of December 2002 when they were approximately 1.3 mm day^{-1} higher.

Table A9.7 (Appendix 9) presents the monthly rainfall totals recorded from the on-site splayed-base rain gauge at Leam Valley and shows an irregular rainfall pattern, with maximum rainfall (146.8 mm) recorded in October 2002, and low rainfall (<45 mm/month) recorded in March, April, June, August and September 2002. As with Cherry Holme Woods, the rainfall data recorded during monitoring was significantly different from the long-term average MORECS Square 137 data presented in Section 6.2.2.2 which had a mean monthly rainfall between 50 and 60 mm/month throughout the year.

ETo data presented in Figure 8.12 shows that the data from each source is similar between February and April 2002, but between May and September 2002 ETo Pan is consistently approximately 0.6 mm day^{-1} lower than the other two data sets. Data from ETo Pan was not available in October and December 2002 due to the evaporation pan overtopping and data being lost. A negative value was obtained due to ice on the pan in November.

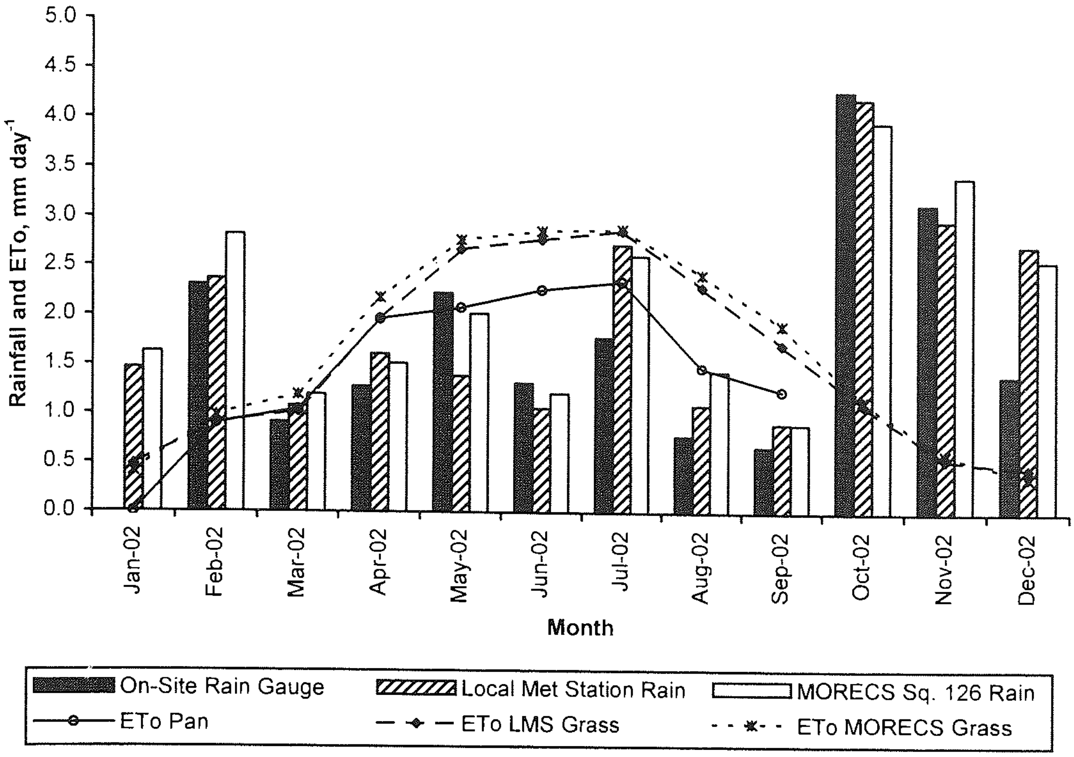


Fig. 8.12: Monthly Rainfall and ETo Data for Leam Valley 2002

ETo data from the local meteorological station and MORECS Square 137 are very similar throughout the year. ETo MORECS Grass data was approximately 0.1 mm day^{-1} higher than ETo LMS Grass data throughout the year. Maximum values were recorded in July 2002 by all forms of ETo where maximum ETo Pan = 2.36 mm day^{-1}; and ETo LMS Grass and ETo MORECS Grass was 2.90 mm day^{-1}. At Leam Valley, ETo exceeded rainfall between April and September in 2002.

8.5 Kc(W6)

For the reasons discussed in Section 8.3 the only viable ET(W6) data available are for March to September 2002. Using these data and the compatible ETo data from Section 8.4, Kc(W6) values have been developed using the methodology outlined in Section 2.2 and are presented in Figures 8.13 to 8.16 and Tables 8.8 to 8.11.

Figure 8.13 shows the derived Kc(W6) Pan rates. A combination of the high ET(W6) rates and low ETo Pan during March resulted in very high Kc values for Cherry Holme Woods in particular. As with the ET(W6) rates, the highest Kc data was provided by Cherry Holme Woods Lysimeter 2 with the lowest values from Leam Valley Lysimeter 2.

Kc(W6) SAMS Grass values are presented in Figure 8.14 for the lysimeters from Cherry Holme Woods. These data clearly illustrate the difference in water use between the two lysimeters; the establishing vegetation in Lysimeter 1 showed a relatively constant water use throughout the period with an increase in September, whereas Lysimeter 2 showed a very different pattern of increasing and falling water use throughout the period.

The data presented in Figures 8.15 and 8.16 show similar patterns due to the similarities between the ETo data from the two sources. Kc rates for March are high, which may be the result of the energy required by the tree to facilitate the initial growth of catkins and subsequently leaves. In addition the higher September rates can be attributed to the fact that the leaves remain on the trees throughout this month and are maintaining their transpiration rates.

The 'peak and trough' nature of the data presented in Figures 8.13 to 8.16 is associated with the ET(W6) rates rather than the ETo data as the same patterns were shown in Figure 8.10. Apart from the value for July 2002 from Cherry Holme Woods Lysimeter 2, Kc(W6) increases steadily from June to September in all lysimeters. The ET(W6) data from Cherry Holme Woods Lysimeter 2 may be anomalous as it does not fit the pattern shown by the other lysimeters. However, given that the data is only from one year, it was not possible to prove that the data is anomalous or to provide an explanation for the values recorded.

The Kc(W6) data recorded during 2002 does not fit a standard crop coefficient curve (see Doorenbos and Pruitt, 1977). This is likely to be the result of the data being initial data, collected during a period when the experimental design was being developed and tested.

Although no formal phenological data was collected, a photographic record allows an initial assessment of the crop stages within the lysimeters at the two research sites. The collection of relevant phenological data would involve the determination of leaf area index values throughout the year and it was not possible to complete these studies within the remit of this project.

STAGE	MONTH	NOTES
Initial Stage	February	Catkins on tree branches and leaf buds starting to appear. No understorey growth.
Crop Development Stage	March – April	Leaf cover developing on tree. Understorey cover growing.
Mid-Season Stage	May – September	Tree leaf cover complete. Understorey fully developed.
Late-Season Stage	October	Tree leaves starting to turn brown. Understorey turning brown.
Dormant Stage	November – January	No leaves on tree. Understorey dormant.

Table 8.7: Crop Stages at Cherry Holme Woods and Leam Valley, 2002

	Kc(W6) Pan												
SITE	Jan-02	Feb-02	Mar-02	Apr-02	May-02	Jun-02	Jul-02	Aug-02	Sep-02	Oct-02	Nov-02	Dec-02	Annual
Cherry Holme Woods Lysimeter 1	neg.	error	2.56	0.86	0.93	0.77	0.99	0.98	1.09	over	error	neg.	n/a
Cherry Holme Woods Lysimeter 2	neg.	error	2.77	0.97	1.03	1.79	1.31	1.95	1.90	over	error	neg.	n/a
Leam Valley Lysimeter 1	no data	error	1.56	1.09	0.97	0.98	1.49	1.76	1.44	over	neg.	neg.	n/a
Leam Valley Lysimeter 2	no data	error	1.69	0.77	1.10	0.87	0.79	1.32	1.16	over	neg.	neg.	n/a

no data - Theta Probes not installed
neg. - sampling error resulted in a negative value
error - accuracy of data not confirmed

Table 8.8: Monthly Kc(W6) Pan from Cherry Holme Woods and Leam Valley, 2002

	Kc(W6) SAMS Grass												
SITE	**Jan-02**	**Feb-02**	**Mar-02**	**Apr-02**	**May-02**	**Jun-02**	**Jul-02**	**Aug-02**	**Sep-02**	**Oct-02**	**Nov-02**	**Dec-02**	**Annual**
Cherry Holme Woods Lysimeter 1	-	-	-	1.64	1.20	0.98	1.14	1.09	1.35	error	error	neg.	n/a
Cherry Holme Woods Lysimeter 2	-	-	-	1.85	1.34	2.31	1.51	2.25	2.35	error	error	error	n/a

no data - Weather station not installed
neg. - sampling error resulted in a negative value
error - accuracy of data not confirmed

Table 8.9: Monthly Kc(W6) SAMS Grass from Cherry Holme Woods, 2002

	Kc(W6) LMS Grass												
SITE	Jan-02	Feb-02	Mar-02	Apr-02	May-02	Jun-02	Jul-02	Aug-02	Sep-02	Oct-02	Nov-02	Dec-02	Annual
Cherry Holme Woods Lysimeter 1	error	error	2.21	1.39	0.87	0.77	0.87	0.93	1.19	error	error	neg.	n/a
Cherry Holme Woods Lysimeter 2	error	error	2.33	1.57	0.96	1.90	1.15	1.92	2.02	error	error	error	n/a
Leam Valley Lysimeter 1	no data	error	1.50	1.12	0.77	0.73	1.23	1.02	1.62	error	error	neg.	n/a
Leam Valley Lysimeter 2	no data	error	1.63	0.84	0.88	0.65	0.65	0.79	1.37	error	error	neg.	n/a

no data - Theta Probes not installed
neg. - sampling error resulted in a negative value
error - accuracy of data not confirmed

Table 8.10: Monthly Kc(W6) LMS Grass from Cherry Holme Woods and Leam Valley, 2002

	Kc(W6) MORECS Grass												
SITE	**Jan-02**	**Feb-02**	**Mar-02**	**Apr-02**	**May-02**	**Jun-02**	**Jul-02**	**Aug-02**	**Sep-02**	**Oct-02**	**Nov-02**	**Dec-02**	**Annual**
Cherry Holme Woods Lysimeter 1	error	error	1.83	1.16	0.90	0.77	0.92	0.95	1.22	error	error	neg.	n/a
Cherry Holme Woods Lysimeter 2	error	error	1.93	1.31	0.99	1.90	1.22	1.95	2.20	error	error	error	n/a
Leam Valley Lysimeter 1	no data	error	1.29	1.02	0.74	0.71	1.22	0.97	1.46	error	error	neg.	n/a
Leam Valley Lysimeter 2	no data	error	1.40	0.76	0.85	0.63	0.65	0.75	1.23	error	error	neg.	n/a

no data - Theta Probes not installed
neg. - sampling error resulted in a negative value
error - accuracy of data not confirmed

Table 8.11: Monthly Kc(W6) MORECS Grass from Cherry Holme Woods and Leam Valley, 2002

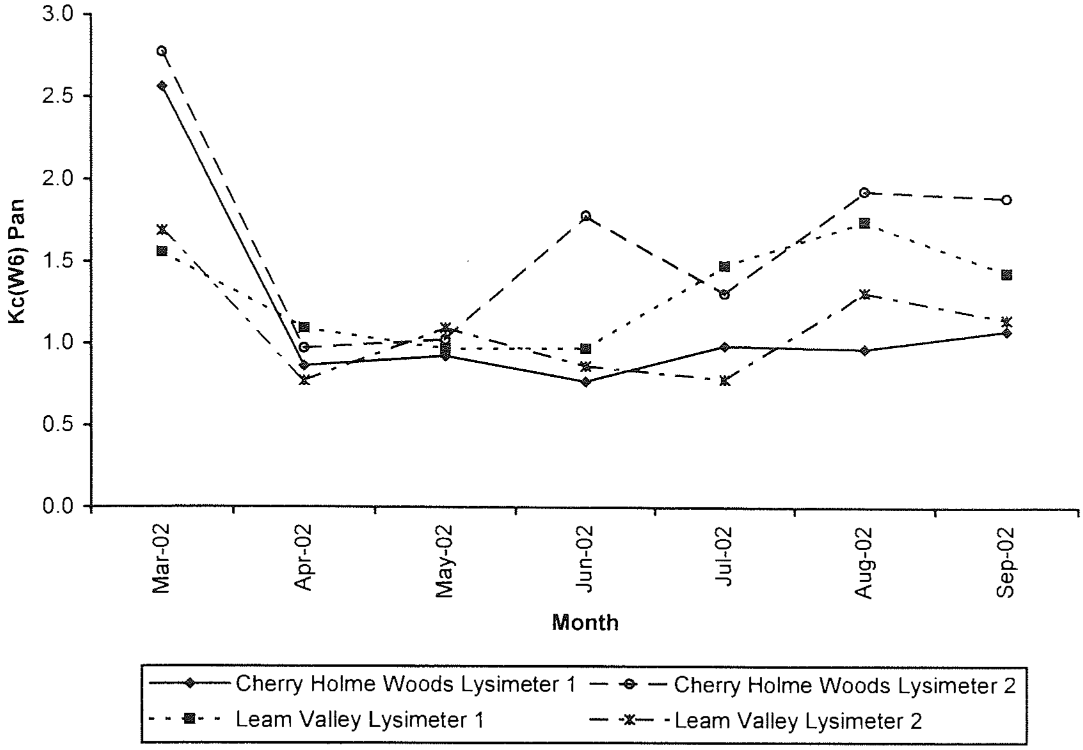


Fig. 8.13: Kc(W6) Pan from Cherry Holme Woods and Leam Valley 2002

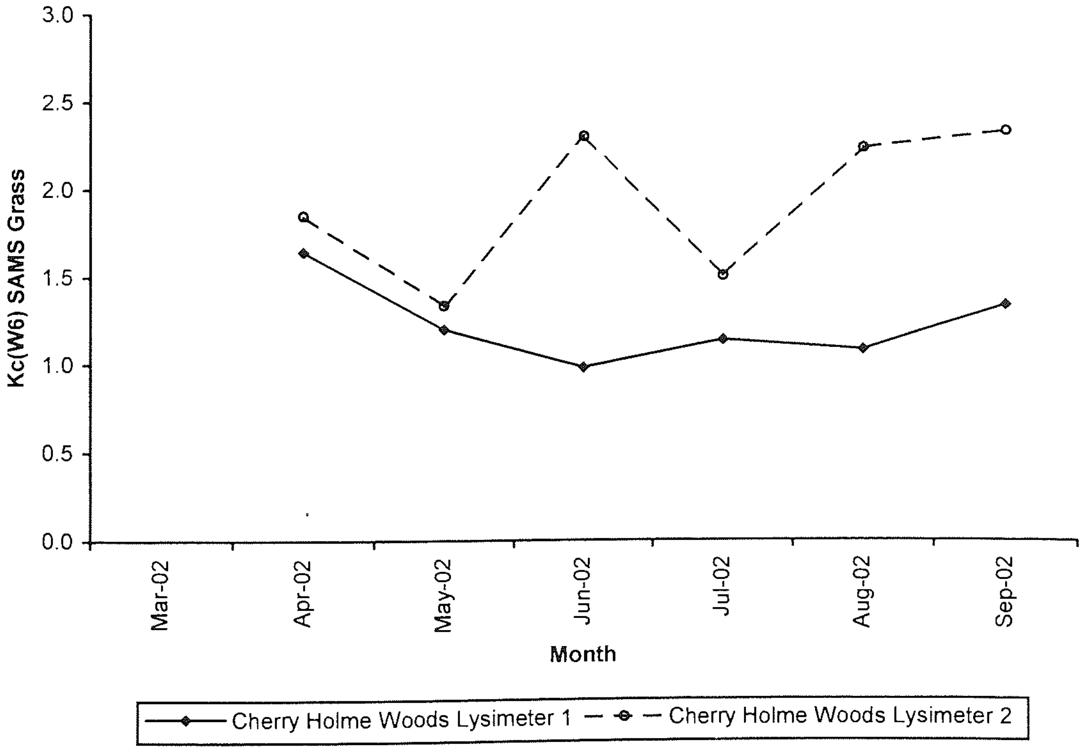


Fig. 8.14: Kc(W6) SAMS Grass from Cherry Holme Woods 2002

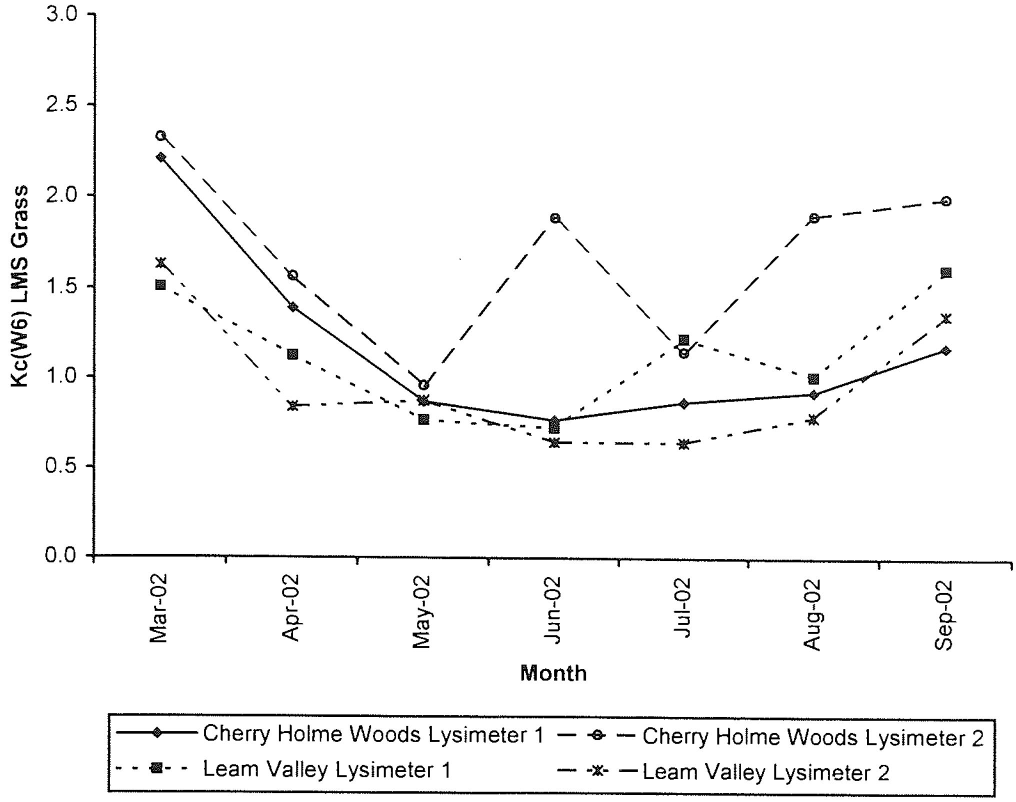


Fig. 8.15: Kc(W6) LMS Grass from Cherry Holme Woods and Leam Valley 2002

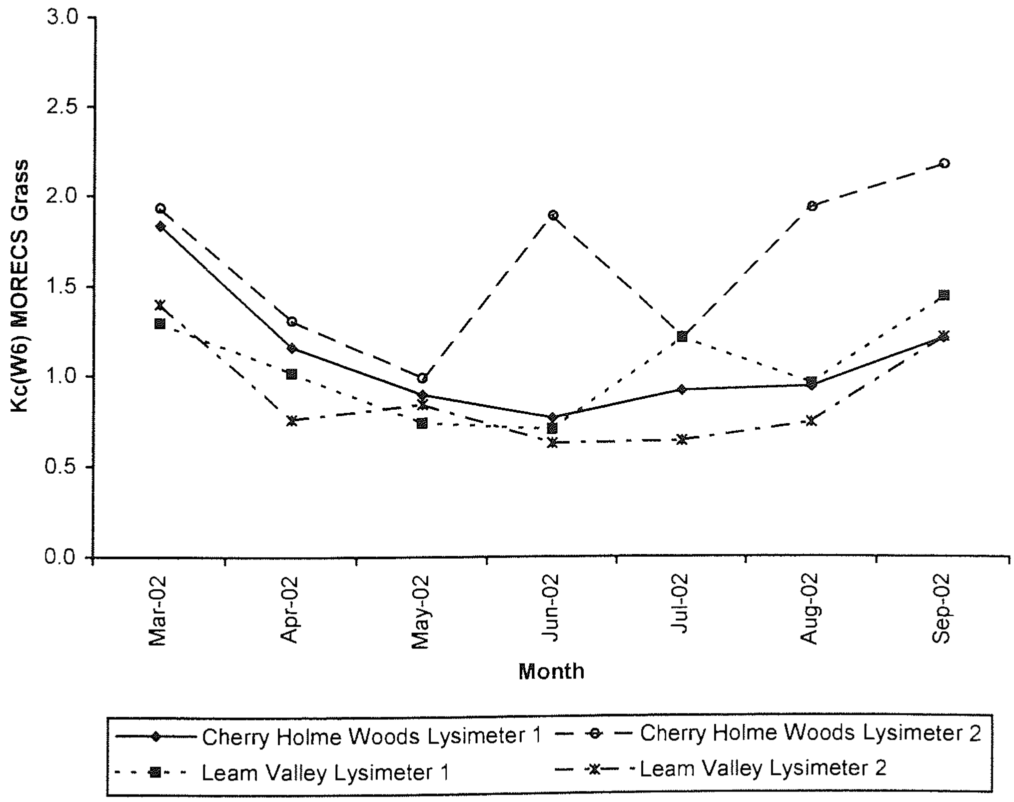


Fig. 8.16: Kc(W6) MORECS Grass from Cherry Holme Woods and Leam Valley 2002

8.6 DISCUSSION

8.6.1 METHODOLOGY

The installation of the lysimeters and ancillary equipment was successful and no problems were noted with this equipment during the project. There were problems associated with vegetation establishment which may have been solved if the vegetation had been given a year to establish before any experiments were instigated. During this year, additional monitoring visits and appropriate water level management regimes would have reduced the potential for vegetation death.

The Watermark soil water potential sensors were not very sensitive and the soil water tension readings were therefore not converted to soil moisture content. Minimal problems were experienced with respect to the installation and maintenance of the Theta Probes and the data provided by most probes was used in subsequent ET calculations.

With respect to the developed soil moisture profiles, there may be inaccuracies associated with the fact that the Theta Probes were at spaced locations within the lysimeter profile and a linear variation is assumed between the measured points. The potential inaccuracy could have been reduced by the installation of additional Theta Probes but financial limitations precluded this activity.

The adjustment of the lysimeter water levels was also prone to error as it was managed by a method of calculating the volumes of water to be removed / added to restore to water levels to a given point.

One of the main criticisms of the water level model was that it was reactionary rather than predictive. The water lost through ET was replaced during each monitoring visit regardless of what the water inputs were likely to be during the forthcoming period. This often resulted in the lysimeters being either too wet or too dry dependant on the rainfall inputs between monitoring visits. No attempts were made to predict what the rainfall inputs would be due to the potential for error. The effect of this approach is shown in the pattern of fluctuating water levels shown in Figures 8.8 and 8.9.

Given the limited data set, it was not possible to solve the inaccuracy problems with the water use model during the period of the year when the soils were saturated.

8.6.2 ET(W6)

To provide an indication of the effect of vegetation growth and establishment on the measured water use rates from the different lysimeters, mean ET(W6) values from each lysimeter between March and September have been determined (Table 8.12).

SITE	**Mean ET(W6), mm day^{-1} (Mar - Sep)**
Cherry Holme Lysimeter 1	2.30
Cherry Holme Lysimeter 2	3.48
Leam Valley Lysimeter 1	2.37
Leam Valley Lysimeter 2	1.95

Table 8.12: Mean ET(W6) Between March and September 2002

The data in Table 8.12 clearly illustrates that the greatest volumes of water were used by the habitat which was most successfully established, and with the tallest tree (Cherry Holme Woods Lysimeter 2). The second highest water user was the habitat in Lysimeter 1 at Leam Valley, where the tree was successfully established but smaller and the understorey vegetation was establishing. Similar mean data was recorded from Cherry Holme Woods Lysimeter 1 as the tree within this lysimeter was approximately 1.5 m taller than Leam Valley Lysimeter 1, but not as well established and the understorey vegetation had been recently re-planted. The lysimeter containing the recently established tree and understorey at Leam Valley was the lowest user of water.

These data clearly show that the water use of the habitat is related to the age (and therefore the height and leaf area) of the canopy trees, and the level of establishment of the understorey vegetation. Therefore as would be expected a newly planted wet woodland area is likely to require less water to sustain it than a more established area.

Table 8.13 presents a summary of published wet woodland and *Salix* sp. ET rates compared with those produced in this project. The data has been presented in ascending order with the highest ET rates in July at the top of the table. The highest rates were recorded by three different studies on *Salix viminalis* short-rotation coppice cut on a 3-year rotation located at research sites in continental Europe. The three studies all used different techniques to calculate ET but produced similar results. The high water use of the trees are associated with the increased biomass that results from coppicing the trees on a 3-year rotation. The root systems of the trees are allowed to establish and then they are coppiced close to ground level and re-growth takes the form of a fast-growing multi-stemmed tree with an increased leaf area.

The data presented by Pribán and Ondock (1986) for *Salix cinerea* and *Salix pentandra* is comparable with the data recorded within the two more established lysimeters (Cherry Holme Woods Lysimeter 2 and Leam Valley Lysimeter 1) in this study. Although the techniques for determining the water use were different, both studies considered the habitat as a whole rather than just the tree specimens, although the age of the habitats was considerably different as Pribán and Ondock (1986) studied a habitat comprised of 30-year old trees whereas in this study the trees were between 4 and 7-years old. It may be that as the trees pass a critical age at which their water use peaks, the water use falls again as the amount of yearly growth is reduced, although given the variations between the two studies this cannot be confirmed.

One of the most comparable studies was that by Grip (1981) who used lysimeters and trees of a similar age to those in this study, although the species of willow was different. The water use data calculated by Grip (1981) is very similar to that produced by the two lysimeters containing the establishing vegetation (Cherry Holme Woods Lysimeter 1 and Leam Valley Lysimeter 2). Grip (1981) stated that in his study the trees were established in 1978 and reached an approximate height of 3 m by the end of the 1980 growing season. Although these trees were slightly younger than those used in this study their height was similar, they were artificially fertilised and were more established within the lysimeters by the time that experimental data was collected, which accounts for the slightly higher water use rates calculated.

The lowest values were those provided by Souch et al (2000) using their modelled data, the source of which is not known. It should be noted that the data from Souch et al (2000) was provided as total values for the dormant and growing periods and has been averaged by the author of this thesis to provide a mean monthly data in mm day^{-1}.

Lambs and Muller (2002) stated that the water uptake of willows was not a simple process as they were able to regulate their uptake dependant on the available water. They concluded that during periods of flood, the evapotranspiration from riverine willows did not cease and in fact they were able to increase sap fluxes (and therefore water use) during this period. During the summer drought the trees were able to reduce the water use via stomatal closing. In this study the soils within the lysimeters were maintained close to field capacity throughout the majority of the monitoring period (see Section 8.2.2) and so the trees should have been transpiring at their potential rate. However, if these species can increase their water use in response to the volumes of water available it could be concluded that the water use data provided by this study does not represent the maximum use for the habitat.

RESEARCHER	SPECIES / HABITAT	TREE / HABITAT DETAILS	TYPE OF STUDY	ET, mm day^{-1}											
				Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Elowson (1999)	*Salix viminalis*	3-year old plantation	Mass water balance calculation	-	-	-	-	5.00	5.00	5.00	5.00	5.00	5.00	-	-
Persson and Lindroth (1994)	*Salix viminalis*	Short-rotation coppice on 3-year cut	'SOIL' computer model	-	-	-	-	2.00	3.40	4.40	2.90	2.30	0.80	-	-
Iritz and Lindroth (1994)	*Salix viminalis*	Short-rotation coppice on 3-year cut	Bowen ratio	-	-	-	-	2.09	3.69	4.09	2.72	2.61	1.76	-	-
Pribán and Ondock (1986)	*Salix cinerea* and *Salix pentandra*	+30-year old willow carr habitat	Bowen ratio	-	-	-	-	-	-	3.70	3.10	2.30	-	-	-
Author – Leam Valley Lysimeter 1	W6 Wet Woodland	4-year old tree establishing understorey	Lysimeter	-	-	1.61	2.25	2.06	2.04	3.51	2.33	2.80	-	-	-
Author – Cherry Holme Woods Lysimeter 2	W6 Wet Woodland	7-year old tree, 2-year old understorey	Lysimeter	-	-	2.56	2.75	2.59	5.27	3.37	4.53	3.27	-	-	-
Grip (1981)	Salix viminalis	3-years old single trees	Lysimeters	-	-	-	-	-	2.15	2.67	2.69	1.39	-	-	-

Table 8.13: Summary of ET Rates for Wet Woodland Habitats and *Salix* Species

RESEARCHER	SPECIES / HABITAT	TREE / HABITAT DETAILS	TYPE OF STUDY	ET, mm day^{-1}											
				Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Author – Cherry Holme Woods Lysimeter 1	W6 Wet Woodland	Establishing – 4-year old tree & understorey	Lysimeter	-	-	2.45	2.44	2.35	2.14	2.55	2.24	1.96	-	-	-
Author – Leam Valley Lysimeter 2	W6 Wet Woodland	Establishing – 4-year old tree & understorey	Lysimeter	-	-	1.75	1.69	2.35	1.82	1.86	1.81	2.36	-	-	-
Souch et al (2000)	W5 Wet Woodland (draining soils)	W5 woodland (age not known)	Not known	1.62	1.62	1.62	1.71	1.71	1.71	1.71	1.71	1.71	1.62	1.62	1.62
Souch et al (2000)	W5 Wet Woodland (ponding soils)	W5 woodland (age not known)	Not known	0.24	0.24	0.24	1.02	1.02	1.02	1.02	1.02	1.02	0.24	0.24	0.24

Table 8.13 cont.: Summary of ET Rates for Wet Woodland Habitats and *Salix* Species

8.6.3 Kc(W6)

Table 8.14 presents the average Kc(W6) MORECS Grass data between March and September and shows the range of mean Kc(W6) MORECS Grass values being between 0.89 and 1.64 and again supports the conclusion that the older and taller the vegetation, the greater the water use requirements of the habitat.

SITE	Mean Kc(W6) MORECS Grass (Mar - Sep)
Cherry Holme Lysimeter 1	1.11
Cherry Holme Lysimeter 2	1.64
Leam Valley Lysimeter 1	1.06
Leam Valley Lysimeter 2	0.89

Table 8.14: Mean Kc(W6) MORECS Grass Between March and September 2002

It should be noted that although mean ET(W6) between March and September was greater in Leam Valley Lysimeter 2 than Cherry Holme Woods Lysimeter 1 (Table 8.12), the Kc(W6) MORECS Grass data do not reflect this.

Data presented by Bardsley (2001b) can be averaged to provide a mean March to September Kc('Carr' Wet Woodland) value of 1.66, which is similar to that shown in Table 8.14 for Cherry Holme Woods Lysimeter 2. Souch et al (2000) published an annual Kc(W5) value of 1.2 which is comparable with the data from Cherry Holme Woods Lysimeter 1.

A summary of published and calculated (see Section 4.8) mean monthly Kc data for wet woodland and *Salix* species are presented in Table 8.15 which has been sorted in ascending order using July Kc data.

RESEARCHER	SPECIES / HABITAT	TREE / HABITAT DETAILS	TYPE OF STUDY	ETo	Kc											
					Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Barsley (2001b)	'Carr' Wet Woodland	Not known	Not known	Not known	1.40	1.40	1.40	1.70	1.70	1.70	1.70	1.70	1.70	1.40	1.40	1.40
Persson and Lindroth (1994)	*Salix viminalis*	Short-rotation coppice on 3-year cut	'SOIL' computer model	Penman	-	-	-	0.70	1.00	1.20	1.60	2.00	-	-	-	-
Grip (1981)	*Salix viminalis*	3-years old single trees	Lysimeters	Penman	-	-	-	-	0.65	1.05	1.31	1.14	-	-	-	-
Author – Cherry Holme Woods Lysimeter 2	W6 Wet Woodland	7-year old tree, 2-year old understorey	Lysimeter	MORECS Grass	-	-	1.93	1.31	0.99	1.90	1.22	1.95	2.20	-	-	-
Author – Leam Valley Lysimeter 1	W6 Wet Woodland	4-year old tree establishing understorey	Lysimeter	MORECS Grass	-	-	1.29	1.02	0.74	0.71	1.22	0.97	1.46	-	-	-
Elowson (1999)	*Salix viminalis*	3-year old plantation	Mass water balance calculation	Not known	-	-	-	0.31	0.75	1.02	1.16	1.12	-	-	-	-
Author – Cherry Holme Woods Lysimeter 1	W6 Wet Woodland	Establishing - 4-year old tree & understorey	Lysimeter	MORECS Grass	-	-	1.83	1.16	0.90	0.77	0.92	0.95	1.22	-	-	-
Author – Leam Valley Lysimeter 2	W6 Wet Woodland	Establishing - 4-year old tree & understorey	Lysimeter	MORECS Grass	-	-	1.40	0.76	0.85	0.63	0.65	0.75	1.23	-	-	-

Table 8.15: Summary of Kc Rates for Wet Woodland Habitats and *Salix* Species

Given the effect of the habitat's growth on the resulting Kc data determined in this study, consideration should be given to which calculated dataset (i.e. from which lysimeter) be used to provide Kc(W6) rates suitable for use in a water budget.

If data from the recently established lysimeters were used, the water budget may provide water use rates applicable within the first few years of vegetation establishment. However, once the habitat was established the water use requirements would increase putting additional pressure on the water resources of the site. To provide information with respect to the water use required to sustain the habitat it is therefore recommended that monthly Kc(W6) rates from Cherry Holme Woods Lysimeter 2 be used between March and September.

Section 8.4 showed that for the sites used in this study the MORECS square data was comparable with both the local meteorological station data and on-site data. In terms of ease of use and cost it is therefore recommended that MORECS square data be used as the ETo values and therefore Kc(W6) MORECS Grass be used as the crop coefficient.

CHAPTER 9. WATER BUDGET CASE STUDY

9.1 INTRODUCTION

This chapter presents a theoretical case study using both published water use data and data calculated during this project. The chapter aims to provide a simple example that highlights the criticality of the use of appropriate crop coefficients when undertaking water budgets.

It should be noted that the water budgets presented in this section relate solely to the atmospheric fluxes (ET) associated with a feasibility assessment for a proposed wetland design project and do not consider other aspects of the hydrological design of a wetland system (see Figure 2.1 for all parameters required for a complete water budget).

9.2 CASE STUDY INTRODUCTION

This case study provides information with respect to a theoretical wetland design project located within the floodplain of the River Trent in Staffordshire. Within this region there are numerous sand and gravel extraction sites within river floodplains, the majority of which are restored to wetland habitats once mineral extraction has ceased (Southgate, 2003). Given the extensive areas of some of these sites, the creation of large areas of wetland habitat is commonplace and, therefore in this example it is assumed that the area for wetland creation totals 50 ha. The design and composition of the target wetland habitats are appropriate for the floodplain environment and comprise a mosaic of habitats.

Table 9.1 details the proposed wetland habitats and provides justification with respect to the designed habitat areas.

HABITAT	PERCENTAGE OF AREA	AREA (ha)	JUSTIFICATION
Reedbed	40%	20 ha	Required to meet UK BAP targets for the creation of large reedbed habitats.
Wet Woodland	28%	14 ha	Peterken (2001) stated that woodland should occupy no more than 30% of a floodplain.
Wet Grassland	10%	5 ha	Peterken (2001) concluded that floodplains should comprise of grassland and marsh areas to complement other wetland habitats.
Sedge / Marsh	6%	3 ha	Peterken (2001) concluded that floodplains should comprise of grassland and marsh areas to complement other wetland habitats.
Open Water	16%	8 ha	Required to provide an area for winter water storage. Increases diversity of habitats and encourages areas for waterfowl.
TOTAL	**100%**	**50 ha**	N/a

Table 9.1: Proposed Wetland Habitat Creation Areas

9.3 CROP COEFFICIENTS AND METEOROLOGICAL DATA

9.3.1 CROP COEFFICIENTS

Table 9.2 presents monthly crop coefficients for various wetland habitats that are likely to be included in a wetland design project. The values have been derived from published literature and from data collected during this project.

The Kc data for large reedbeds presented in Table 9.2 is an average of the data developed during this project from Aqualate Mere and the data presented by Fermor et al (2001) for Walton Lake as both studies provide crop coefficients associated with a large reedbed system.

Fermor et al (2001) derived crop coefficients associated with fringe reedbeds from his research site at the Teeside International Nature Reserve and Williams et al (1995) informed the coefficients for wet grassland, sedge and marsh.

The Kc values for W6 wet woodland include the March to September data from Cherry Holme Woods Lysimeter 2 calculated during this project. As the accuracy of the data from October to February was not confirmed, a Kc rate of 1.0 has been substituted for this period. The coefficients for 'carr' wet woodland were provided by Bardsley (2001b).

During his research, Fermor (1997) held discussions with Hough (1997) who provided the coefficients for open water presented in Table 9.2. Hough (1997) stated that water depth and size of water surface might have an effect on open water evaporation. Large lakes strongly influence the water vapour content of the air moving across them, consequently reducing evaporation. Shallow water bodies have seasonal temperature regimes that closely approximate to the seasonal air temperature, whereas deep water bodies often have a large heat storage capacity which may distort the seasonal trend. As the target habitats shown in Table 9.1 are dominated by shallow water bodies, anomalies of evaporation from deep water are not included in this case study.

Hough (1997) concluded that the turbidity of the water may have a minor impact on evaporation as increased turbidity may have an indirect correlation with evaporation. By increasing the albedo of the water, turbidity may reduce evaporation. However, this effect is deemed to be minimal and is therefore not considered within this case study.

HABITAT	DATA SOURCE	Kc(Habitat)											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Open Water	Hough (1997)	0.60	1.10	1.10	1.30	1.30	1.30	1.30	1.30	1.30	1.20	0.90	0.60
Marsh	Williams et al (1995)	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
Wet Grassland	Williams et al (1995)	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
Fringe Reedbed	Fermor et al (2001)	0.94	1.27	0.89	0.97	0.83	1.38	1.37	1.55	1.82	1.70	1.05	1.59
Large Reedbed	Fermor et al (2001) and Author	0.80	0.46	0.45	0.73	0.63	0.82	0.84	0.85	0.78	0.74	0.66	0.81
W6 Wet Woodland	Author	1.00	1.00	1.93	1.31	0.99	1.90	1.22	1.95	2.20	1.00	1.00	1.00
'Carr' Wet Woodland	Bardsley (2001b)	1.40	1.40	1.40	1.70	1.70	1.70	1.70	1.70	1.70	1.40	1.40	1.40

Table 9.2: Kc Rates for Wetland Habitats

9.3.2 METEOROLOGICAL DATA

MORECS 30-year mean data (1961-1990) for Square 126 (see Section 2.3.4) was used to provide rainfall and grass evapotranspiration (ETo MORECS Grass) data that might be expected from the case study locality. Table 9.3 presents the data and shows that on an annual basis, MORECS rainfall inputs (654.3 mm) exceed annual ETo MORECS Grass outputs (581.8 mm).

Using the meteorological data presented in Table 9.3 and the crop coefficients shown in Table 9.2, the evapotranspiration rates for each target habitat in mm per month were calculated (Table 9.4).

Table 9.4 clearly shows that the habitat with the highest annual water requirements is wet woodland (870.6 mm/annum), with open water also using a significant volume (716.7 mm/annum). The lowest evapotranspiration demands were from the reedbed (434.3 mm/annum), with marsh and wet grassland evapotranspiration being slightly lower than that from ETo MORECS Grass.

9.4 WATER BUDGET – ATMOSPHERIC FLUXES

Table 9.5 presents the actual volume of water that each target habitat will require for a given area (m^3 ha^{-1}). Table 9.6 presents both the monthly totals and the annual water budget volumes per ha for each target habitat.

In Table 9.6 a negative water budget volume implies a net deficit, which would require the provision of an additional water source other than direct precipitation to meet the water requirements. Within this case study, the wet woodland and open water habitats are subject to an annual net deficit, where the other habitats are not. On a monthly basis, there will be a water deficit within the majority of the habitats in May and in all of the habitats between June and August as ET demands increase (see Table 9.5).

Using the target habitat areas provided in Table 9.1, the actual change in water storage within each habitat is presented in Table 9.7 and shows that, assuming that there is winter storage, there will be an annual surplus of water within the reedbed, wet grassland and marsh habitats, but that within the wet woodland and open water areas, there will be a net deficit. Assuming that the wetland scheme is designed as a mosaic of habitats that are hydrologically linked with winter water surpluses stored in the areas of open water and reedbed, and with an appropriate positive water level management regime, there will be a surplus of 35 mm of water across the wetland creation area on an annual basis.

These data provide an indication of the likely maximum water requirements of the target habitats, however, once established, the habitats may be sustainable without these volumes of water. Water level data collected from within the reedbeds at Aqualate Mere, Brandon Marsh and Leighton Moss are presented in Tables A5.22 (Appendix 5), A6.19 (Appendix 6) and A7.22 (Appendix 7) respectively. These data show that during the months of June, July and August, the water levels within the reedbed fall below the ground surface suggesting that in a natural reedbed system, water levels above the surface need not be maintained throughout the whole summer period and therefore the water demand from the habitat may be met by extracting water from the soil rather than from the surface. The water use of the habitat is then dependant on the available water within the soil.

Figure 9.1 presents an idealised annual soil moisture cycle for grassland and woodland vegetation, and highlights that throughout the summer and autumn months the vegetation is likely to be transpiring at a rate which is less than its potential as the soils fall below field capacity. Although the diagram presented is related to a terrestrial habitat rather than a wetland one, it provides an indication of the likely annual soil moisture regime and its impact on a habitat's water use. If the same diagram were applied to a wetland habitat the soils would be unlikely to experience a soil moisture deficit until early summer.

MORECS Square No. 126	Units	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
MORECS Rainfall	mm	55.7	47.0	51.5	49.0	53.3	57.6	49.8	63.2	53.6	52.3	57.7	63.6	654.3
ETo MORECS Grass	mm	13.9	16.6	35.7	53.7	83.9	87.7	93.1	79.3	54.5	32.3	18.3	12.8	581.8

Table 9.3: 30-Year Mean Monthly Rainfall and Evapotranspiration for Grass

MORECS Square No. 126	Units	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
ET(Reedbed)	mm	11.1	7.6	16.2	39.3	52.8	72.2	78.2	67.6	42.7	23.9	12.1	10.4	434.3
ET(Wet Woodland)	mm	13.9	16.6	69.0	70.2	83.2	166.3	113.7	154.6	119.7	32.3	18.3	12.8	870.6
ET(Wet Grassland)	mm	13.2	15.8	33.9	51.0	79.7	83.3	88.4	75.3	51.8	30.7	17.4	12.2	552.7
ET(Marsh)	mm	12.5	14.9	32.1	48.3	75.5	78.9	83.8	71.4	49.1	29.1	16.5	11.5	523.6
ET(Open Water)	mm	8.3	18.3	39.2	69.8	109.1	114.0	121.1	103.1	70.9	38.8	16.5	7.7	716.7

Table 9.4: Monthly Evapotranspiration for Target Habitats (mm)

MORECS Square No. 126	Units	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
ET(Reedbed)	$m^3\ ha^{-1}$	111	76	162	393	528	722	782	676	427	239	121	104	4343
ET(Wet Woodland)	$m^3\ ha^{-1}$	139	166	690	702	832	1663	1137	1546	1197	323	183	128	8706
ET(Wet Grassland)	$m^3\ ha^{-1}$	132	158	339	510	797	833	884	753	518	307	174	122	5527
ET(Marsh)	$m^3\ ha^{-1}$	125	149	321	483	755	789	838	714	491	291	165	115	5236
ET(Open Water)	$m^3\ ha^{-1}$	83	183	392	698	1091	1140	1211	1031	709	388	165	77	7167

Table 9.5: Monthly Evapotranspiration for Target Habitats ($m^3\ ha^{-1}$)

MORECS Square No. 126	Units	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
ΔV(Reedbed)	$m^3\ ha^{-1}$	446	394	353	97	5	-146	-284	-44	109	284	456	532	2200
ΔV(Wet Woodland)	$m^3\ ha^{-1}$	418	304	-175	-212	-299	-1087	-639	-914	-661	200	394	508	-2163
ΔV(Wet Grassland)	$m^3\ ha^{-1}$	425	312	176	-20	-264	-257	-386	-121	18	216	403	514	1016
ΔV(Marsh)	$m^3\ ha^{-1}$	432	321	194	7	-222	-213	-340	-82	45	232	412	521	1307
ΔV(Open Water)	$m^3\ ha^{-1}$	474	287	123	-208	-558	-564	-713	-399	-173	135	412	559	-624

NB - negative values show a net water deficit

Table 9.6: Water Budget Volumes for Target Habitats ($m^3\ ha^{-1}$)

MORECS Square No. 126	Units	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
ΔV(Reedbed)	m^3	8928	7873	7056	1937	101	-2925	-5681	-881	2175	5670	9119	10634	44007
ΔV(Wet Woodland)	m^3	5852	4256	-2449	-2969	-4188	-15223	-8946	-12796	-9249	2800	5516	7112	-30284
ΔV(Wet Grassland)	m^3	2125	1562	879	-101	-1320	-1286	-1932	-607	91	1081	2016	2572	5080
ΔV(Marsh)	m^3	1296	962	581	20	-666	-640	-1020	-245	137	697	1237	1562	3920
ΔV(Open Water)	m^3	3792	2298	981	-1665	-4460	-4514	-5700	-3195	-1380	1082	3297	4475	-4990
														17733

Table 9.7: Calculated Target Habitat Water Budgets (m^3)

Cherry Holme Woods provides an example of a natural floodplain W6 wet woodland system and sedimentological investigations (see Section 6.2.1.2) highlighted that beneath the layer of topsoil and clay (approximately 1.5 m.b.g.l.) was an extensive layer of sand and gravel. Once the roots of the canopy species extended into this sand and gravel layer, they would be able to extract water from it thus supplying them with an external source of water other than precipitation inputs.

This additional source of water could only be exploited once the habitat was mature enough for the tree roots to extend far enough into the soil and therefore the water budget information presented in Table 9.7 would be vital within the habitats establishment stage. Hughes (2000) concluded that with respect to the natural establishment of riparian trees, the hydrology of the site within the first few years of growth was critical to the successful development of the species. Ireland (2003) also confirmed that the hydrology of a site was critical to the establishment of planted ground flora, particularly marsh flora and wet woodland understorey species.

Fermor (1997) recommended the use of 'worst case scenario' water budgets using MORECS data from a drought period (e.g. 1976-1977) to provide information with respect to the likely water deficit during these periods. Although these data may not be applicable within an established wetland system, the occurrence of such an extreme dry period during the planting and establishment phase of some wetland habitats may be detrimental to the success of the project. Financial limitations precluded the purchase of this data for this project and therefore 'worst case scenario' data is not presented in this thesis.

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Fig. 9.1: Idealised Annual Soil Moisture Cycle of Grassland and Woodland Vegetation

(after Shaw, 1983)

CHAPTER 10. PROJECT EVALUATION AND FURTHER RESEARCH REQUIREMENTS

10.1 INTRODUCTION

This chapter provides an evaluation of the successes and limitations of the project (Section 10.2) and highlights areas of study which require further research (Section 10.3).

10.2 PROJECT EVALUATION

10.2.1 THE PROJECT

This project was completed on a full-time basis which limited the duration of the project to three-years. Although these three years encompassed three complete growing seasons, due to problems with vegetation establishment within both the reedbed and wet woodland habitats, the volume of accurate water use data that was generated was disappointing.

Much of the allocated fieldwork time was spent visiting the five research sites and carrying out the standard monthly / bi-monthly monitoring. Given the health and safety issues associated with working in wetland environments, each monitoring visit involved two people which resulted in the project having a high fieldwork demand. The stringent monitoring programme and financial limitations from the available travel budgets limited the potential for additional on-site investigations (for example water quality data was not investigated at the reedbed sites) and increased monitoring visits. Had the number of research sites been smaller, it may have been possible to carry out more regular visits which may have reduced the problems encountered with the vegetation establishment.

10.2.2 VEGETATION ESTABLISHMENT AND EXPERIMENTAL DESIGN

Reedbeds

Section 7.2 highlighted the fact that the reed growth within the lysimeters increased each year thus becoming more representative of the reedbed in which the lysimeters were located. It is anticipated that had the project continued for longer, the reed growth within the lysimeters would have continued to increase until it reached a stage were the reed growth could be managed to provide an exact replica of the surrounding natural reedbed system.

The detrimental effect of the reedbug infestation at Brandon Marsh illustrates the unpredictable nature of working within the natural environment rather than within controlled laboratory conditions.

Apart from the vegetation establishment problems, no other major problems were encountered with the experimental design used in this study. Minor problems were noted with respect to the sourcing of water to re-fill the lysimeters during that period of the year when the surrounding reedbed was dry (July and August). The water used was sourced from deep channels and pools within or adjacent to the reedbed. This limitation should be considered when investigating the potential of a reedbed site for undertaking water use studies using lysimeters.

Wet Woodland

During the verification of the experimental design various problems were encountered. Problems with the soil moisture monitoring equipment in 2001 resulted in a year's worth of data being lost. In choosing to use the Profile Probe, the project was in effect testing out a recently released piece of equipment in addition to developing and verifying an experimental design. In hindsight, it would have been more advisable to use 'tried and tested' soil moisture monitoring equipment from the start as this would have generated two years worth of data that could be used to verify the experimental design.

As a result of the limited dataset, problems with the wet woodland water use model during the time when the soils were saturated were only identified towards the end of 2002. Despite numerous attempts to modify the model to account for the problem, the errors involved were too large for the process to be scientifically accurate. Given a more extensive dataset it may have been possible to determine the source of the error and to modify the model accordingly.

The vegetation establishment problems in 2000 / 2001 were exacerbated by access restrictions associated with the national outbreak of foot and mouth disease and inaccessibility due to flooding. The death of the initial trees in two of the lysimeters (Cherry Holme Woods Lysimeter 1 and Leam Valley Lysimeter 2) may have been prevented had excess water within the lysimeters been removed on a regular basis throughout the winter period.

10.2.3 METEOROLOGICAL DATA

Various forms of meteorological data were used in this study to provide ETo values suitable in the calculation of Kc(Reed) and Kc(W6). The Met Office provided rainfall and PET data from the relevant MORECS squares and from Local Meteorological Stations based on the Penman-Montieth calculation. At the five research sites the values provided from these sources were similar, although this would not always be the case. MORECS data is widely used by wetland designers (Fermor, 2000) but is only really appropriate if the potential creation site is representative of the 40 x 40 km MORECS square. Local Meteorological Station data may therefore be more appropriate for use assuming that finances are not limited. It should be noted that these data sources are only available within the UK.

The technical problems associated with the on-site Automatic Meteorological Station highlighted the issues arising from relying on this equipment to provide a source of ETo data. The difference in the data from the Met Office and the on-site station shows the potential for inaccuracy associated with purchased data.

However, unless the on-site station can be regularly monitored and any problems fixed quickly, this source of ETo is prone to having gaps in the data.

Minimal problems were noted with the on-site rain gauges apart from occasional flooding and cracking of glass sampling bottles during the winter period. The gauges are simple to monitor and assuming that they are sited appropriately, provide an excellent record of on-site rainfall. The evaporation pan was prone to sampling error during the winter months due to ice forming on the pan, but otherwise provided a simple measurement of ETo. However, unless the site has been monitored for a number of years prior to wetland creation, these sources are unlikely to be able to assist in the provision of long-term average data for a site.

10.2.4 ET and Kc DATA

ET(Reed) and Kc(Reed) data compared favourably with published water use data, particularly with respect to large reedbeds. Although some studies were completed in parts of the world with different climatic conditions (e.g. USA) the studies completed in the UK allowed the direct comparison of the water use rates developed in this study with previous studies.

Initial ET(W6) and Kc(W6) data was harder to verify as there was minimal published data against which it could be compared directly. Comparisons with other studies on willow species and willow short-rotation coppice have concluded that the developed data is within the expected ranges for both ET(W6) and Kc(W6). Comparison was made more difficult by the variability of species, technique and tree ages used in other studies.

During the completion of this project numerous wetland creation schemes have been launched throughout the UK highlighting the increased interest in these habitats and re-enforcing the requirement for accurate water use data for use in water budgets.

10.3 REQUIREMENTS FOR FURTHER RESEARCH

Throughout this project requirements for future research have been identified through literature reviews, discussions with other researchers and experimental works.

10.3.1 REEDBEDS

Reduced reed development within the lysimeters was the main experimental problem noted during this project. Further research to develop a technique for ensuring successful reed establishment within the lysimeters would improve the experimental design presented in this thesis.

To provide a direct comparison of the ET(Reed) results produced using different established techniques (e.g. lysimeters, Bowen Ratio, Eddy Correlation) the establishment of a research site at which the various methods could be tested in parallel would be a valuable resource. The research would allow an assessment of each technique's advantages and limitations and would provide a large data source from which Kc(Reed) data could be developed. An ideal site to complete these studies would be Leighton Moss as it contains a large expanse of naturally developed Phragmites dominated reedbed.

10.3.2 WET WOODLAND

On a broad scale, the hydrology of the seven wet woodland habitats identified by the UK BAP (see Table 4.1) is very poorly understood with respect to: their water level requirements; hydrological management; and water use rates. Most of the existing data is not widely available and is often not in a format that would make it useful to practitioners. Further research into these aspects of the habitats, which could be presented in a useable format (e.g. Best Practice Guide) and utilised by practicioners managing, restoring and creating wet woodland would fill an important gap in the knowledge.

On a more specific scale, additional research is required to confirm the wet woodland coefficients developed in this thesis. Monitoring of the two wet woodland sites established during this project will continue throughout 2003 providing an additional year's data. After this time, the canopy trees within the habitat are likely to become pot-bound which would detrimentally effect the tree's growth and therefore impact on the measured water use rates.

An important area of research would be to verify the water use results developed using the lysimeters with a different method. The most appropriate technique would be to use sap flow sensors, although the experiments would only be viable for a couple of months each year due to the nature of the equipment used.

Detailed investigation of the relationship between water use and phenological characteristics of the wet woodland habitat should be completed. It is anticipated that this would involve the determination of the habitat's leaf area index throughout the year as simple height measurements are not appropriate for the canopy trees.

CHAPTER 11. CONCLUSIONS

11.1 INTRODUCTION

This chapter provides a summary of the conclusions that have been reached during this research project including: the published water use rates of wetland habitats (Section 11.2); conclusions from the water use studies of large reedbeds and W6 wet woodland (Section 11.3): a summary of how the project's aims and objectives have been met (Section 11.4).

This project has successfully developed monthly crop coefficients for large reedbeds and has presented an innovative approach to the determination of water-use rates from wet woodland habitats. In studying two wetland habitats in parallel the criticality of available, accurate, water-use data for a range of habitats to ensure the successful design of sustainable wetland systems has been highlighted.

11.2 PUBLISHED WATER USE RATES

An extensive literature review focussed on the published water use rates (and particularly crop coefficients) associated with a range of wetland habitats likely to be targeted within a lowland wetland mosaic creation project. The review highlighted the dearth of information with respect to the water use of large reedbed systems and wet woodland habitats. In particular the lack of monthly data which covered a whole year was highlighted, as many researchers provided either annual coefficients or focused their studies during the height of the growing season.

The review identified available and useful data for wet grassland, marsh / sedge, open water and fringe reedbed habitats. Annual crop coefficients for W5 wet woodland were available, but no data associated with W6 was located.

In response to this lack of information, field experiments were established to develop water use rates for large reedbeds and W6 wet woodland habitats.

11.3 DEVELOPED WATER USE RATES

This thesis presents a series of monthly Kc(Reed) values associated with large reedbed systems. It can be concluded that Kc(Reed) Grass from large reedbeds was less than 1 during the growing season (March to September), ranging between 0.22 in March to reach a peak of 0.98 in June. The developed crop coefficients followed the pattern of a standard crop coefficient curve (see Dorennbos and Pruitt, 1977: Allen et al, 1998). The developed Kc(Reed) data compare favourably with published Kc(Reed) values from within the UK, continental Europe and the USA. It can be concluded that large reedbed systems have lower water requirements than small fringe reedbeds within the same location, but that they are still likely to form an important part of a wetland water budget due to the fact that their highest water use is between June and August when rainfall inputs are likely to be at their lowest.

The wet woodland studies were focussed on successfully developing a methodology for determining the water use rates from wet woodland habitats, an objective which has been achieved. Given the limited data set (January to December 2002) the developed Kc(W6) rates are provisional rates and should only be used in this capacity. In addition, problems associated with the developed wet woodland water use model when soils were saturated (January to February and October to December) resulted in these months data being discarded and not used in subsequent water budget calculations. Provisional data suggested that the water use rates of the wet woodland habitat are high compared with other wetland habitats (maximum recorded water-use was 5.27 mm day^{-1} in June 2002) and are directly associated with the growth stage of the habitat, and in particular the age of the canopy tree species. Mean provisional Kc(W6) rates for the growing season (March to September) ranged between 0.89 and 1.64.

11.4 AIM AND OBJECTIVES

Throughout the project, the aims and objectives of the research have remained constant with the exception of those changes highlighted in Section 1.2. In satisfying each objective particular goals have been achieved, details of which are provided in Section 11.4.2.

11.4.1 AIM

The overall aim of the project was

> *'To refine water budget design methodology for wetland habitats to enable the maintenance of the biodiversity of target species in created wetland systems'*

This aim has been achieved through the calculation of water use rates and the development of crop coefficients for two wetland habitats included in the National Biodiversity Action Plan. In addition, literature reviews highlighted available monthly crop coefficients for other wetland habitats and Table 9.2 presents a summary of the crop coefficients currently available to wetland designers for a range of wetland habitats.

Although the design of water budgets has not been refined, the project has developed appropriate water use parameters to be used in the feasibility assessment for wetland habitat creation. The calculated Kc(Reed) data is appropriate for use in the assessment of water budgets associated with the creation of large areas of reedbed. It should be noted that the developed Kc(W6) data provides only provisional values based on a limited data set but could be used if no alternative data was available.

The experiments were designed in such a way that the developed water use rates were associated with the potential maximum water use of the habitat. When applied to a water budget the crop coefficients provide water use calculations which should represent the maximum water volumes required to sustain the habitat. If properly designed therefore the hydrological maintenance of newly created wetland systems should be achievable.

11.4.2 OBJECTIVES

This section provides an assessment of the extent to which each of the seven objectives outlined in Section 1.2.2 have been achieved.

(1) The installation of lysimeters in a series of large reedbeds, and the subsequent monitoring of phenological characteristics, hydrometeorological and water quality parameters.

Three large, natural reedbed research sites were identified and between ten and twelve lysimeters were installed at each site. Monitoring was initiated in May 2000 and extended until July 2002 at Brandon Marsh and Leighton Moss, and December 2002 at Aqualate Mere. Meteorological parameters were monitored monthly using an on-site rain gauge and evaporation pan with reedbed water levels provided using a water level gauge situated within the reedbed. During monitoring visits the change in the volume of water within each lysimeter was measured.

Monthly monitoring of the phenological characteristics (stem height, stem density, inflorescence numbers) of each lysimeter and of the surrounding reedbed was carried out between March and September 2000-2002. These data were used to provide a method for determining which of the lysimeters were successfully replicating the natural reedbed system in which they were located. In addition, the data was subsequently used to develop a model which allowed the estimation of ET(Reed) from the crop characteristics of an existing reedbed system.

Basic water quality data from the reedbeds at Brandon Marsh and Leighton Moss was provided by Smallridge (2001). Due to the problems associated with reed establishment within the lysimeters throughout the 2000 and 2001, water quality data was not collected during this period. During 2002 the fieldwork requirements associated with monitoring all five research sites precluded any additional fieldwork time for completing water quality analysis and so this aspect of Objective (1) was only met in part.

(2) The determination of design water use parameters for the monitored reedbeds.

This objective was achieved through the calculation of mean monthly reedbed water use rates [ET(Reed)] using a simple water balance equation (Equation 11.1). ET(Reed) was calculated using data from the successful lysimeters at Aqualate Mere. As there were no successful lysimeters at Leighton Moss due to reed establishment problems and the reedbed at Brandon Marsh was damaged by an infestation of reedbug, data from these sites was not used to develop ET(Reed). Calculated ET(Reed) data from Aqualate Mere is presented in Table 7.12.

$$\textbf{Rainfall [R]} = \textbf{Evapotranspiration [ET(Reed)] - Change in Water Storage [}\Delta\textbf{s]} \qquad \textbf{(11.1)}$$

Using meteorological data collected from an on-site rain gauge and evaporation pan in addition to data purchased from the UK Met Office, monthly reference crop evapotranspiration [ETo] data was developed for Aqualate Mere and subsequently monthly reedbed crop coefficients [Kc(Reed)] were determined by re-arranging Equation 11.2. The developed Kc(Reed) data is presented in Table 7.13.

$$\textbf{ET(Reed)} = \textbf{ETo . Kc(Reed)} \qquad \textbf{(11.2)}$$

(3) The development and application of field methods for determining water use rates from other wetland habitats, primarily wet woodland.

This objective was met through the completion of an extensive literature review of available methodologies for determining the water use rates from woodland habitats and single tree specimens (Section 4.8). The review highlighted numerous available techniques ranging from lysimeters through to the use of sap flow sensors and micro-meteorological studies. An assessment of each technique with respect to its suitability within wet woodland habitats was completed (Section 6.3.3.7).

Using information collected during the literature review, a methodology applicable to 3 to 5-year study of wet woodland water use based on lysimetry was developed (Section 6.3). To test the methodology, two suitable research sites at Cherry Holme Woods and Leam Valley were identified and established during October 2000 (Section 6.2). Soil moisture monitoring equipment was installed in April and May 2001 and the developed method was tested. Problems with the soil moisture monitoring equipment were identified during July 2001 and the equipment was replaced with a different set of instruments during November 2001 and January 2002. Successful monitoring of the two research sites continued until December 2002.

Provisional water use rates [ET(W6)] and crop coefficients [Kc(W6)] from the wet woodland experiments were developed (Table 8.13 and Table 8.15 respectively). It should be noted that these data represent provisional data based on a limited data set and should be used accordingly.

(4) Investigation of the relationship between phenological parameters and water use rates for the habitats studied.

With respect to the reedbed sites, the calculated water use data and measured phenological characteristics of the reedbed were used to develop a crop coefficient curve (Figure 7.16, Section 7.6.3) using the criteria outlined by

Doorenbos and Pruitt (1977). This curve clearly shows the relationship between a large reedbed's water requirements and the growth stage of the habitat. Calculated ET(Reed) and measured phenological data were used to develop a model which allowed the estimation of water use values from a reedbed's crop height and stem density. The model proved that there was a strong relationship at the 1% significance level between the phenological characteristics and water use. The model would be of use to managers of existing large reedbed habitats to estimate the likely water use of the habitat throughout the growing season.

As the main aim of the wet woodland studies was to successfully develop a suitable methodology for determining water use rates, minimal phenological data was collected from the sites. A summary of the phenological observations (recorded using a photographic record) is presented in Table 8.7. The provisional crop coefficients for W6 habitats did not fit into a standard crop coefficient curve.

(5) The development of a procedure for enabling the calculation of water budgets for wetlands containing a variety of habitats.

This objective was achieved in Chapter Nine which presents a case study water budget associated with the creation of a 50 ha wetland mosaic on an ex-mineral extraction site within the floodplain of the River Trent in Staffordshire. The case study provides design areas for five target wetland habitats: large reedbeds; W6 wet woodland; wet grassland; marsh; and, open water and illustrates the methodology associated with developing a water budget based on atmospheric fluxes only.

(6) Research into the water use rates of other wetland habitats which are likely to be found as part of a wetland mosaic (wet grassland, sedge beds and marsh).

Monthly crop coefficients of different wetland habitats likely to be included in the design of a lowland wetland mosaic are presented in Table 9.2. This table provides the current knowledge available to wetland designers with respect to the water use requirements of a target habitat.

Water use rates of other wetland habitats (e.g. sphagnum bogs and raised mires) have been developed by different researchers, however, as these habitats are not likely to be included in a lowland wetland mosaic design this data has not been included in this project.

(7) Presentation of a sample water budget for sites with a mosaic of wetland habitats.

The case study presented in Chapter Nine highlights the need for wetland designers to have access to monthly crop coefficients for a range of wetland habitats. The potential summer water deficit calculated within the case study shows the criticality of completing these hydro-meteorological assessments as part of the feasibility investigation of a wetland creation project. The water budget informs whether the wetland creation project is: (1) hydrologically sustainable from precipitation inputs alone; (2) hydrologically sustainable assuming that there is winter water storage on site; or (3) not hydrologically sustainable if water inputs are from precipitation alone. This information is valuable with respect to the wetland design process and will encourage the creation of wetlands within appropriate areas where the water requirements of the habitat will not result in the long-term failure of the project.

11.5 SUMMATION

The overall aim of this project has been successfully achieved: field experiments have allowed the calculation of monthly crop coefficients associated with large reedbed systems; and a methodology suitable for the determination of water use rates from wet woodland habitats has been developed and implemented. To verify and confirm the provisional crop coefficients developed for W6 wet woodlands it is recommended that further research be undertaken. It is anticipated that the methodology developed for the determination of water use rates can be applied to different wet woodland habitats assuming that the project's timescale allows for woodland establishment within the lysimeters.

The data required to calculate the atmospheric fluxes associated with the successful completion of water budgets for a wetland creation site encompassing a mosaic of wetland habitats has been presented and it is anticipated that this model can be applied to wetland creation projects throughout the UK.

In conclusion, this thesis presents monthly Kc(Reed) values for large reedbed habitats in addition to provisional Kc(W6) values for W6 wet woodland habitats. These data provide a contribution to knowledge and can be used by wetland designers attempting to meet the UK Biodiversity Action Plan wetland creation targets.

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APPENDICES

APPENDIX 1.

IDENTIFIED THREATS TO WET WOODLAND HABITATS

Table A1.1 details the threats to existing wet woodland habitats identified in the Wet Woodland Habitat Action Plan (UKBG, 1998).

THREAT	COMMENTS
Loss of habitat and habitat limitations	Wet woodlands are subject to clearance and conversion to other land-uses, particularly in woods recently established on wetland sites. Land pressure from agriculture, industrial or residential development can form a constraint on the spread of woodland from conservation sites onto adjacent areas, and can lead to greater uniformity of structure within the woodland.
Cessation of management	A cessation of management in formerly coppiced wet woodland sites may encourage succession to drier woodland types.
Lowering of water tables	The lowering of water tables through drainage or water abstraction will alter the species composition of the habitats and may result in a change to drier woodland types.
Damage by grazing animals	Inappropriate grazing levels and poaching of the soil by sheep, cattle and deer leads to a change in the woodland structure which can reduce ground flora biodiversity and is particularly damaging to sensitive species such as ragged robin (*Lychnis flos-cuculi*) and wild garlic (*Allium usinum*). Over-grazing may also lead to difficulties in woodland regeneration as seedlings cannot become established.
Flood prevention measures	Flood prevention measures, river control and canalisation, lead to a loss of the dynamic disturbance-succession systems, which results in the natural loss and gain of wet woodland habitats. Flood defence schemes may simply reduce the size of wet woodlands or they may impact on the colonisation of wet woodlands by flora and fauna.
Poor water quality	Poor water quality arising from eutrophication, industrial effluents or rubbish dumping may result in changes in the composition of ground flora and invertebrate communities within the habitat, leading to the loss of more sensitive species.
Air pollution	Air pollution may detrimentally influence important bryophyte and lichen communities within the woodland.
Invasion by introduced species	Introduced invasive plants can rapidly colonise a wetland out-competing native species, as they have few or no native grazers. Non-native species which colonise wet woodlands include Indian balsam (*Impatiens glandulifera*), sycamore (*Acer pseudoplantus*), rhododendron (*Rhododendron* spp). and Japanese knotweed (*Fallopia japonica*).
Diseases	Alder woodlands are potentially under threat from diseases such as *Phytophthora* root disease of alder.
Climate Change	Climate change may potentially result in changes in the vegetation communities, ranging from an increased rate of successional drying to changes in flooding events.

Table A1.1: Direct and Indirect Threats to Wet Woodlands

APPENDIX 2.

SPECIES OF CONSERVATION CONCERN ASSOCIATED WITH WET WOODLAND HABITATS

Table A2.1 details species of conservation concern which are associated with wet woodland habitats. A key showing the status code used in Table A2.1 and the associated protection / legislation is given below.

Status Code	**Protection / Legislation**
BAP	Biodiversity priority species included on the Wet Woodlands HAP as an associated species. NB – all species included in the list are UK BAP species.
Bern Con	Species listed in Appendix II of the Convention on the Conservation of European Wildlife and Natural Heritage (Bern Convention), 1979.
Bonn Con	Species protected by the Convention on the Conservation of Migratory Species (Bonn Convention), 1979.
EC Birds	Species protected by the Directive on the Conservation of Wild Birds (EC Birds Directive), 1979.
EC Hab	Species protected under the EC Directive on the Conservation of Natural Habitats and Wild Flora and Fauna (EC Habitats Directive), 1994.
CITES	Species protected under the Convention of International Trade in Endangered Species.
Cons Reg	Species protected by the Conservation (Natural Habitats etc) Regulations, 1994.
RDB	Species included on Great Britain Red Data Book Lists. EN – Endangered, VN – Vulnerable, ns – nationally scarce
WCA	Species listed under the Wildlife and Countryside Act, 1981.

SPECIES	LATIN NAME	STATUS	HABITAT REQUIREMENTS / NOTES
PLANTS			
A lichen	*Arthothelium dictyosporum*	WCA	Grows on the smooth bark of willow in ancient semi-natural woodlands.
A lichen	*Graphina pauciloculata*	RDB VN WCA	Grows on the smooth bark of trees such as hazel, holly and young oak in willow carr.
Veilwort	*Pallavicinia lyellii*	WCA	Grows mainly on bare, acid peaty soils in lowland bogs and damp woodland.
Marsh fern	*Thelypteris palustris*	BAP	May exist in wet woodlands as a relict species from former open wetlands.
Tiny fern-moss	*Fissidens exiguus*	WCA	Grows on wet or submerged acidic sandstone in lowland streams and small rivers usually where shaded e.g. in ravines and woodlands.
Spruce's bristle-moss	*Orthotrichum sprucei*	WCA	Grows on the bark of trees within the flood-zones of streams and rivers, at levels which remain dry for much of the year but which are inundated at times of peak discharge.
Prostrate feather-moss	*Sematophyllum demissum*	RDB EN WCA	Grows on shady rocks in humid places, such as wooded streamsides.
BIRDS			
Marsh warbler	*Acrocephalus palustris*	WCA EC Birds Bern Con	Occurs in riparian habitats. Summer migrant.
MAMMALS			
Barbastrelle bat	*Barbastella barbastellus*	Bern Con Bonn Con EC Hab RDB VN WCA	Riparian woodland forms an important habitat in some areas.
Otter	*Lutra lutra*	BAP Bern Con CITES Cons Reg EC Hab WCA	Otter holts are often situated on the edges of floodplain wet woodland habitat. Wet woodlands provide ideal areas for mothers with young.

Table A2.1: Species of Conservation Concern Associated with Wet Woodland Habitats

SPECIES	LATIN NAME	STATUS	HABITAT REQUIREMENTS / NOTES
INVERTEBRATES			
A cranefly	*Lipsothrix ecucullata*	RDB VN	Found on or close to wet seepages in damp, deciduous woodlands. They avoid acid conditions and breed in very soft, well-decayed wood lying partially immersed in water.
A cranefly	*Lipsothrix errans*	BAP RDB ns	A species of wet rotting fallen trees and branches in shaded woodland streams.
A cranefly	*Lipsothrix nervosa*	BAP	A species of wet, rotting twigs and branches in seepages in deciduous woodland. Believed to require continuous shade and a constant supply of rotting timber.
A cranefly	*Lipsothrix nigristigma*	BAP RDB EN	Associated with woodland streams, where larvae live in wet, rotting, fallen trees and branches lying in the stream.
A weevil	*Melanapion minimum*	BAP	Occurs on willows and sallows in woodland, on the margins of woods, along the sides of ponds, rivers and other watercourses, and in carr.
A jumping weevil	*Rhynchaenus testaceus*	BAP RDB VN	Associated with alder where its larvae mine the leaves.
Netted carpet moth	*Eustromia reticulata*	RDB VN	The sole larval food plant, yellow balsam *Impatiens noli-tangere*, is found in wet woodland, by streams, seepages and lakesides.
Waved carpet moth	*Hydrelia sylvata*	RDB ns	Occurs in coppiced woods with a long history of active coppice and in open sunny areas with younger growth of larval foodplants (inc. alder, birch, sallow).
White-line snout moth	*Schraki taenialis*	RDB ns	Recorded from a number of habitats including wet woodland.
Tadpole shrimp	*Triops cancriformis*	RDB EN WCA	Occurs in seasonally flooded ponds which dry out completely in summer.

Table A2.1 cont.: Species of Conservation Concern Associated with Wet Woodland Habitats

APPENDIX 3.

ASPECTS OF WET WOODLAND CREATION

This section presents details of the two-stages involved in creating new wet woodlands: selecting a site (Section A3.1) and undertaking active measures (Section A3.2).

A3.1 SELECTING A SITE

The existing conservation value, size, location and physical, hydrological and chemical properties of a potential creation site must all be considered as part of the design process.

A3.1.1 EXISTING CONSERVATION VALUE

The site should be of low conservation and archaeological value, and therefore intensive agricultural land, disused industrial land and gravel works are all suitable for wet woodland creation. A site survey and desk study should be performed prior to any creation work to determine the current conservation status of the land.

A3.1.2 ARCHAEOLOGY

Trees planted on archaeological remains can cause damage to the remains as the tree roots grow. Woodcock (2000a) suggested that as part of the site selection process, the County archaeologist should be contacted to determine whether there are any features of archaeological significance on the site.

A3.1.3 LOCATION

New woodlands should be created as close to existing wet woodlands as possible as many of the important species associated with these habitats (for example the lichens *Anthathelium dictyosparum* and *Graphina paucilocilata*), have limited dispersal ranges.

The Environment Agency's conservation section supports and encourages the creation of wet woodlands within river floodplain zones as part of well designed wetland creation projects. However, certain sites may be subject to constraints due to flood defence issues such as the maintenance of flood storage and flow capacity (Heaton, 2000) and the planting of trees within the floodplain in England and Wales must involve prior consultation with the Environment Agency. Woodcock (2000a) states that trees can affect flooding in three main ways:

(1) by reducing the speed of flood flows - water flowing through a smooth sided channel moves faster than through a rough channel and trees increase the 'roughness' of flood channels;

(2) by acting as a 'net' collecting flood transported debris – this can build up into a semi-permeable dam which holds back and re-directs flood flows; and,

(3) by occupying volume within a floodplain which could potentially be occupied by water.

Woodcock (2000b) suggests that newly created wet woodlands should form part of a matrix of floodplain habitats, which might include wet grassland, reedbeds and wet woodland, and schemes should provide provision for conventional farming and short rotation coppice land should be made within the floodplain habitat mosaic. The requirements of species using adjacent habitats should also be considered, for example, some birds which frequent wet grasslands, will not use sites which are located too close to trees that can provide perches for their predators.

A3.1.4 SIZE

At present wet woodland creation is often undertaken as part of broader wetland habitat creation schemes. As a result, created wet woodlands often form part of a mosaic of wetland habitats on a single site. These small patches of wet woodland are still valuable habitats, particularly if they form a connection with other wet woodland patches.

A3.1.5 PHYSICAL HYDROLOGY

A potential creation site must have suitable hydrology and topography (land shape) for the establishment of a high water table and/or water level management. A survey of the water movement across the site, the land profile and any existing water control structures will allow the feasibility of wet woodland creation to be assessed.

A3.1.6 FUTURE MANAGEMENT

The future management of a site must be considered at the planning stage. The chosen site must be accessible for future management and the required resources for this management must be considered.

Once a suitable site has been selected and a detailed design undertaken, asctive measures can be carried out. These include land profiling and planting, details of which are included below.

A3.2 ACTIVE MEASURES

A3.2.1 LAND PROFILING

Re-profiling involves altering the shape of the ground and is usually the first physical task undertaken in woodland creation. Re-profiling large areas requires heavy machinery, which is expensive but careful and detailed design at the planning stage can limit the quantity of earth to move, which in turn will reduce the cost of the project. Access for heavy machinery may prove difficult if the land is already wet, therefore work should be carried out in late summer when sites are at their driest.

Most wet woodland habitats occur on topogeneous sites (Newbold and Mountford, 1997). However, Smith (2000) suggested that in order to produce a more diverse habitat, different micro-habitats within a wet woodland may be created during land profiling works and may involve micro-profiling of the land prior to planting to create wetter areas and small ponds. The Forestry Commission (2000) stated that when establishing new native woodlands, minimal cultivation of the land is especially important as severe cultivation can detrimentally alter the soil structure, thus making it more difficult for target woodland species to grow.

A3.2.2 VEGETATION ESTABLISHMENT

There are many references available detailing standard woodland planting techniques and operational guidelines (Forestry Commission, 1990; Rodwell and Patterson, 1994; Gilbert and Anderson, 1998; Forestry Commission, 2000) and therefore these techniques are not discussed in great detail here.

Canopy / Shrub Layer Establishment

Planting in new native woodlands should be designed to develop a species composition and structure appropriate to the woodland types which it is intended to encourage. The land form should be followed and the impact of tree planting on the aesthetics of an area should be considered.

Table A3.1 provides a list of trees and shrubs suitable for planting in each climatic zone (shown in Figure A3.1) on wet sites. When creating new native woodlands care should be taken not to plant trees and shrubs outside of their natural range and even within these ranges care should be taken to respect local patterns of distribution. Trees should be of local provenance, particularly where the new woodlands are situated close to long-established semi-natural woodlands of the same type (Rodwell and Patterson, 1994). Local trees should be used to provide seedlings of local provenance wherever possible.

Understorey Establishment

Wet woodlands have an interesting and important ground flora and when creating new habitats there should be some attempts to introduce desirable species. Dixie and Francis (no date) suggested that woodland ground flora does not appear to readily colonise newly planted woodland areas. They concluded that this is due to the fact that woodland herbaceous plants are mainly found in mature woodlands; they have poor dispersal mechanisms; are slow colonisers; and relatively weak competitors. They suggest that without some assistance, the development of typical woodland layers may take hundreds of years. The establishment of a wet woodland understorey can be achieved using a number of techniques including the following.

(1) Transplantation of turfs from a donor site. This should only be done if the removal of vegetation from the donor site will not result in irreparable damage to the woodland. Transplantation cannot take place from any woodlands which are protected by legislation (e.g. SSSI, NNR) without permission from English Nature.

(2) Sowing seed mixtures. Some of the species found within the understorey of wet woodland habitats are commercially available. If possible, the seed should be of local provenance.

(3) Planting using plugs. Many herbaceous wet woodland species can be introduced using plant plugs. These plugs may be available from commercial sources, but plants of local provenance should be used wherever possible.

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Fig. A3.1: Main Climatic Zones in the UK
(Forestry Commission, 1990)

	CLIMATIC ZONE											SOILS		
	1	2	3	4	5	6	7	8	9	10	11	a	b	c
Large and medium sized trees														
Alder (*Alnus glutinosa*)	•	•	•	•	•	•	•	•	•	•	L		•	
Ash (*Fraxinus excelsior*)	•	•	•	•	•	•	•	•	•	•	L		•	•
Downy birch (*Betula pubescens*)	•	•	•	•	•	•	•	•	•	•	L	•	•	•
Bird cherry (*Prunus padus*)	•	•	•	•		L					L		•	
Common oak (*Quercus robar*)		•	•	•	•	•	•	•	•	•	L	•	•	•
Black poplar (*Populus nigra var betulifolia*)					L	L	L	L	L				•	
Grey poplar (*Populus canescens*)					•	•	•	•	•				•	
Crack willow (*Salix fragilis*)			•	•	•	•	•	•	•	•			•	•
Goat willow (*Salix caprea*)	•	•	•	•	•	•	•	•	•	•	L		•	•
White willow (*Salix alba*)			•	•	•	•	•	•	•	•	L		•	•
Small trees and shrubs														
Blackthorn (*Prunus spinosa*)	•	•	•	•	•	•	•	•	•	•	L		•	•
Alder buckthorn (*Frangula alnus*)				•	•	•	•	•	•	•		•	•	
Guelder-rose (*Viburnum opulus*)	•	•	•	•	•	•	•	•	•	•	L		•	
Almond willow (*Salix triandra*)				•	•	•	•	•					•	
Bay willow (*Salix pentandra*)			•	•							L		•	
Eared willow (*Salix aurita*)	•	•	•	•	•	•	•	•	•	•	L	•	•	•
Grey willow (*Salix cinerea*)	•	•	•	•	•	•	•	•	•	•	L	•	•	•
Osier willow (*Salix viminalis*)	•	•	•	•	•	•	•	•	•	•			•	
Purple willow (*Salix purpurea*)			•	•	•	•	•	•	•	•	L		•	•

NB – This matrix is not intended for use in the management of ancient and semi-natural woodland.
• = suitable for use
L = only stock of local origin should be used
a = acid soil
b = neutral or alkaline soil
c = exposed sites

Table A3.1: Recommended Tree and Shrub Species for Planting on Wet Sites and Associated Soil Requirements
(after Forestry Commission, 1990)

APPENDIX 3 REFERENCES

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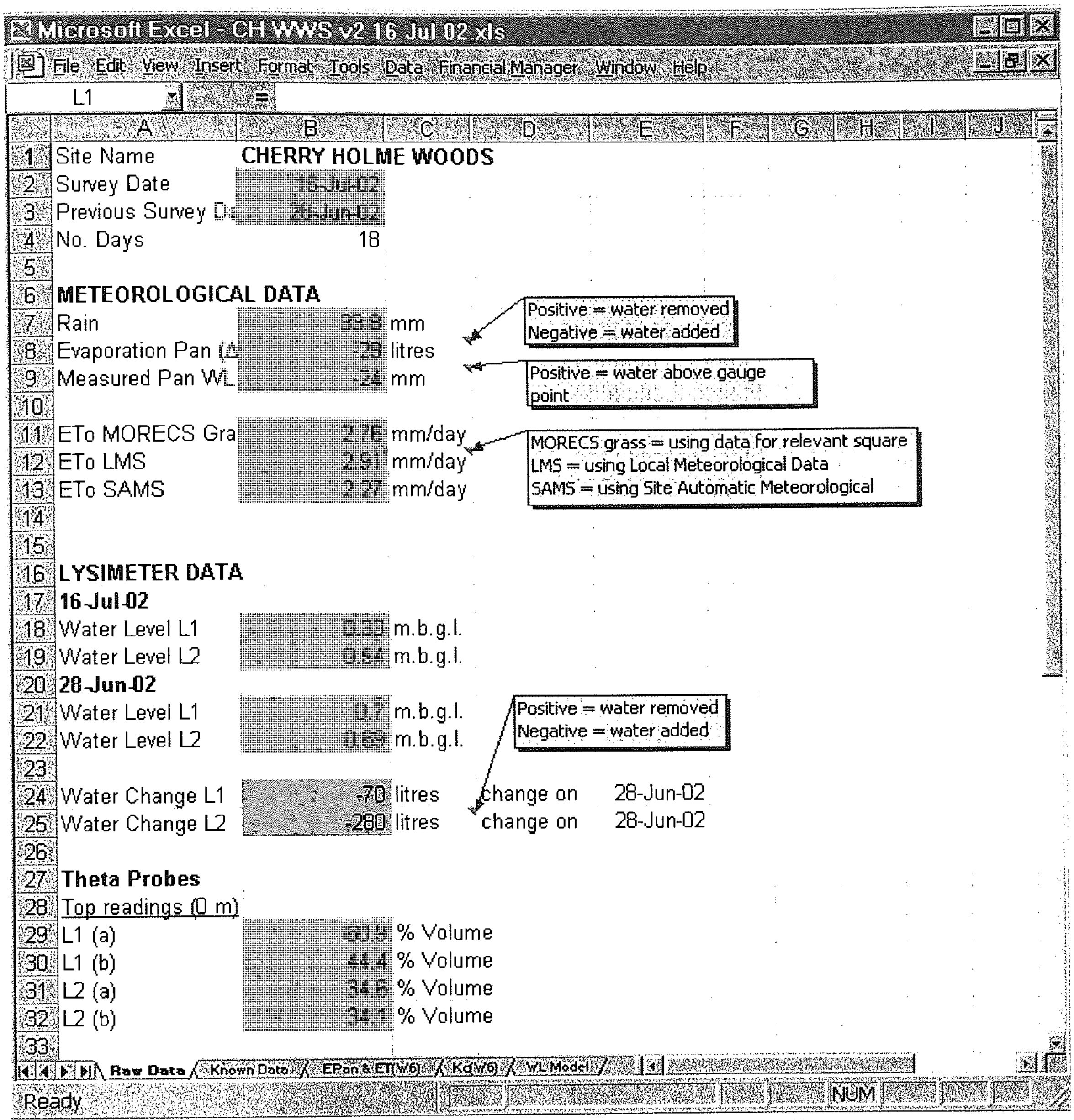
APPENDIX 4.
WET WOODLAND WATER USE MODEL

A4.1 'RAW DATA'

Figure A4.1 shows Part 1 of the 'Raw Data' worksheet within the Wet Woodland Water Use Model. This section of the model was the same for both cherry Holme Woods and Leam Valley. Figure A4.2 shows Part 2 of the worksheet which contains the soil moisture content data from Cherry Holme Woods. Due to the different methods of recording the soil moisture data between the two sites (datalogger and hand-held Moisture Meter), this section of the worksheet is different for each site. Figure A4.3 shows this section of the worksheet for Leam Valley.



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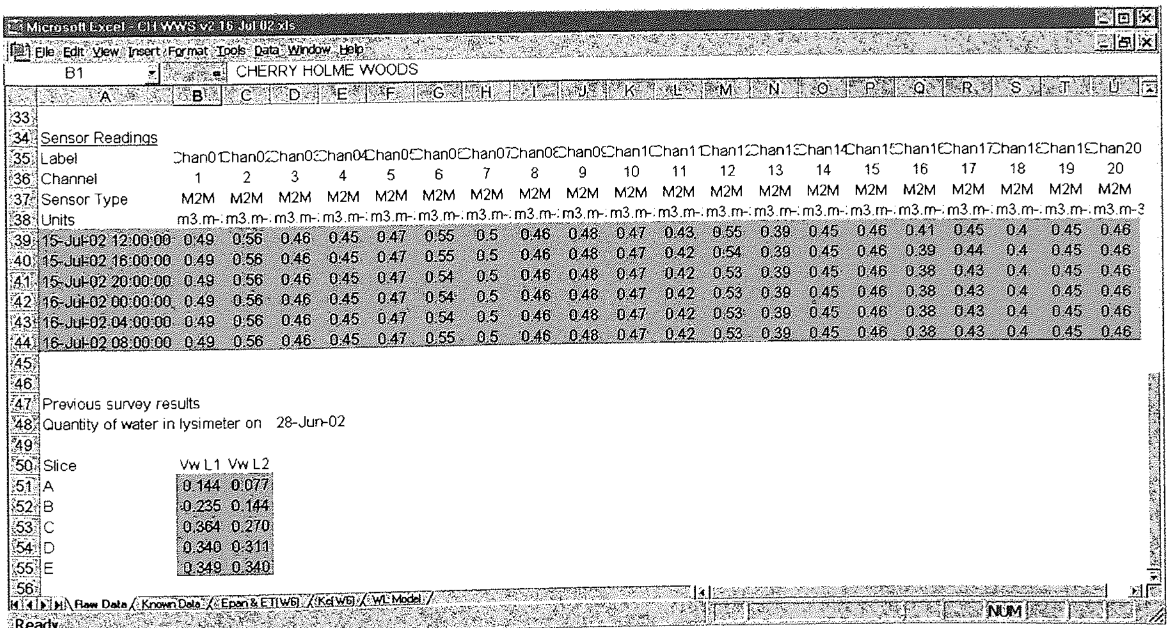
L1 =

Row	A	B	C	D
1	Site Name	CHERRY HOLME WOODS		
2	Survey Date	16-Jul-02		
3	Previous Survey D	28-Jun-02		
4	No. Days	18		
5				
6	**METEOROLOGICAL DATA**			
7	Rain	33.8	mm	
8	Evaporation Pan (A	-23	litres	
9	Measured Pan WL	-24	mm	
10				
11	ETo MORECS Gra	2.76	mm/day	
12	ETo LMS	2.91	mm/day	
13	ETo SAMS	2.27	mm/day	
14				
15				
16	**LYSIMETER DATA**			
17	**16-Jul-02**			
18	Water Level L1	0.33	m.b.g.l.	
19	Water Level L2	0.54	m.b.g.l.	
20	**28-Jun-02**			
21	Water Level L1	0.7	m.b.g.l.	
22	Water Level L2	0.69	m.b.g.l.	
23				
24	Water Change L1	-70	litres	change on 28-Jun-02
25	Water Change L2	-280	litres	change on 28-Jun-02
26				
27	**Theta Probes**			
28	Top readings (0 m)			
29	L1 (a)	60.9	% Volume	
30	L1 (b)	44.4	% Volume	
31	L2 (a)	34.6	% Volume	
32	L2 (b)	34.1	% Volume	
33				

Fig. A4.1: 'Raw Data' Worksheet (Part 1)



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B1 = CHERRY HOLME WOODS

34 Sensor Readings

Row	A	B	C	D	E	F	G	H	I	J	K
35	Label	Chan01	Chan02	Chan03	Chan04	Chan05	Chan06	Chan07	Chan08	Chan09	Chan10
36	Channel	1	2	3	4	5	6	7	8	9	10
37	Sensor Type	M2M	M2M	M2M	M2M	M2M	M2M	M2M	M2M	M2M	M2M
38	Units	m3.m-	m3.m-	m3.m-	m3.m-	m3.m-	m3.m-	m3.m-	m3.m-	m3.m-	m3.m-
39	15-Jul-02 12:00:00	0.49	0.56	0.46	0.45	0.47	0.55	0.5	0.46	0.48	0.47
40	15-Jul-02 16:00:00	0.49	0.56	0.46	0.45	0.47	0.55	0.5	0.46	0.48	0.47
41	15-Jul-02 20:00:00	0.49	0.56	0.46	0.45	0.47	0.54	0.5	0.46	0.48	0.47
42	16-Jul-02 00:00:00	0.49	0.56	0.46	0.45	0.47	0.54	0.5	0.46	0.48	0.47
43	16-Jul-02 04:00:00	0.49	0.56	0.46	0.45	0.47	0.54	0.5	0.46	0.48	0.47
44	16-Jul-02 08:00:00	0.49	0.56	0.46	0.45	0.47	0.55	0.5	0.46	0.48	0.47

Row	A	L	M	N	O	P	Q	R	S	T	U
35	Label	Chan11	Chan12	Chan13	Chan14	Chan15	Chan16	Chan17	Chan18	Chan19	Chan20
36	Channel	11	12	13	14	15	16	17	18	19	20
37	Sensor Type	M2M	M2M	M2M	M2M	M2M	M2M	M2M	M2M	M2M	M2M
38	Units	m3.m-	m3.m-	m3.m-	m3.m-	m3.m-	m3.m-	m3.m-	m3.m-	m3.m-	m3.m-3
39	15-Jul-02 12:00:00	0.43	0.55	0.39	0.45	0.46	0.41	0.45	0.4	0.45	0.46
40	15-Jul-02 16:00:00	0.42	0.54	0.39	0.45	0.46	0.39	0.44	0.4	0.45	0.46
41	15-Jul-02 20:00:00	0.42	0.53	0.39	0.45	0.46	0.38	0.43	0.4	0.45	0.46
42	16-Jul-02 00:00:00	0.42	0.53	0.38	0.45	0.46	0.38	0.43	0.4	0.45	0.46
43	16-Jul-02 04:00:00	0.42	0.53	0.39	0.45	0.46	0.38	0.43	0.4	0.45	0.46
44	16-Jul-02 08:00:00	0.42	0.53	0.39	0.45	0.46	0.38	0.43	0.4	0.45	0.46

47 Previous survey results

48 Quantity of water in lysimeter on 28-Jun-02

Row	Slice	Vw L1	Vw L2
51	A	0.144	0.077
52	B	0.235	0.144
53	C	0.364	0.270
54	D	0.340	0.311
55	E	0.349	0.340

Fig. A4.2: 'Raw Data' Worksheet (Part 2) – Cherry Holme Woods

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B1 = LEAM VALLEY

	A	B	C	D	E	F
34	Sensor Readings					
35						
36	Device >>	ML2				
37	Root Depth >>				0	
38	Sensor Depth >>				0	
39	Soil >>				Mineral	
40	Time	Sample	Plot	Device	% Vol	Error
41	16/07/02 14:33	1	A	0	38	
42	16/07/02 14:33	2	A	0	42.4	
43	16/07/02 14:33	3	A	0	42.3	
44	16/07/02 14:33	4	A	0	42.8	
45	16/07/02 14:33	5	A	0	42.4	
46	16/07/02 14:34	6	A	0	31.4	
47	16/07/02 14:34	7	A	0	40.4	
48	16/07/02 14:34	8	A	0	39.9	
49	16/07/02 14:34	9	A	0	39.6	
50	16/07/02 14:34	10	A	0	40.7	
51	16/07/02 14:36	1	B	0	44.7	
52	16/07/02 14:36	2	B	0	44.5	
53	16/07/02 14:36	3	B	0	44.6	
54	16/07/02 14:36	4	B	0	42.3	
55	16/07/02 14:36	5	B	0	45.2	
56	16/07/02 14:36	6	B	0	43.7	
57	16/07/02 14:37	7	B	0	44.4	
58	16/07/02 14:37	8	B	0	44.4	
59	16/07/02 14:37	9	B	0	45	
60	16/07/02 14:38	10	B	0	42.7	
61						
62						
63	**Previous survey results**					
64	Quantity of water in lysimeter on		26-Jun-02			
65						
66	Slice	Vw L1	Vw L2			
67	A	0.106	0.105			
68	B	0.194	0.201			
69	C	0.332	0.333			
70	D	0.327	0.330			
71	E	0.313	0.327			

Raw Data / Known Data / ET(W6) Model / Kc(W6) / WL Model /

Ready NUM

Fig. A4.3: 'Raw Data' Worksheet (Part 2) – Leam Valley

A4.2 'KNOWN DATA'

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K1 =

Site Name	**CHERRY HOLME WOODS**	
Survey Date	16-Jul-02	
Previous Survey Date	28-Jun-02	
No. Days	18	

METEOROLOGICAL EQUIPMENT

Evaporation Pan area

Area =	Πr^2	
Radius r =	0.6	m
Pan Area (A_p) =	1.131	m^2
Pan Coefficient (Kp) =	0.8	(after Dorrhenbos & Pruitt, 1977)

LYSIMETERS

Lysimeter area

Area =	Πr^2	
Radius r =	0.975	m
Pan Area (A_L) =	2.987	m^2

Theta Probes

Installation Depths of Theta Probe Sensors

Lysimeter	Depth (m.b.g.l.)	Profile 1 Channel	Profile 2 Channel
L1	0.00	n/a	n/a
	0.10	1	6
	0.25	2	7
	0.50	3	8
	0.75	4	9
	1.00	5	10
L2	0.00	n/a	n/a
	0.10	11	16
	0.25	12	17
	0.50	13	18
	0.75	14	19
	1.00	15	20

Lysimeter Slices

Total Volume of slice (V_T) = A_L * H

Slice	Depth Range	Height (m)	V_T (m^3)
A	0.00 - 0.10	0.10	0.299
B	0.10 - 0.25	0.15	0.448
C	0.25 - 0.50	0.25	0.747
D	0.50 - 0.75	0.25	0.747
E	0.75 - 1.00	0.25	0.747
		Total	2.987

Notation

A_p	Evap Pan area
A_L	Lysimeter area
H	Height of slice
Kp	Pan Coefficient
V	Total volume
V_T	Total volume of slice
ΔS	Change in water storage
R	Rainfall

Raw Data / Known Data / EPan & ET(W6) / Kc(W6) / WL Model

Ready NUM

Fig. A4.4: 'Known Data' Worksheet

A4.3 'EPan & ET(W6)'

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A26 =

	A	B	C	D	E	F	G	H
1	Site Name	CHERRY HOLME WOODS						
2	Survey Date	16-Jul-02						
3	Previous Survey Date	28-Jun-02						
4	No. Days	18						
5								
6	ETo PAN	2.60	mm/day					
7	ET(W6) L1	2.76	mm/day					
8	ET(W6) L2	4.23	mm/day					
9								
10								
11	**METEOROLOGICAL EQUIPMENT**							
12								
13	Determination of ETo PAN							
14	Epan =	R - ΔS						
15	R =	0.038	m^3		**VERIFICATION**			
16	ΔS =	-0.028	m^3		ΔS =	24.75	mm	
17	Epan =	0.066	m^3		Measured WL =	24.00	mm	
18								
19	ETo PAN =	Epan * Kp						
20	ETo PAN (period) =	0.053	m^3					
21	ETo PAN (period) =	46.843	mm					
22	**ETo PAN =**	**2.60**	**mm/day**					
23								

Raw Data / Known Data / **Epan & ET(W6)** / Kc(W6) / WL Model /

Ready NUM

Fig. A4.5: 'EPan & ET(W6)' Worksheet (Part 1)

LYSIMETERS

Determine volumetric soil moisture content (θv) at each sample point

Sample Point (m)	L1 (a) ($m^3.m^{-3}$)	L1 (b) ($m^3.m^{-3}$)	L1 ($m^3.m^{-3}$)	L2 (a) ($m^3.m^{-3}$)	L2 (b) ($m^3.m^{-3}$)	L2 ($m^3.m^{-3}$)
0.00	0.609	0.444	0.527	0.346	0.341	0.344
0.10	0.490	0.545	0.545	0.422	0.387	0.387
0.25	0.560	0.500	0.500	0.535	0.435	0.535
0.50	0.460	0.460	0.460	0.390	0.400	0.395
0.75	0.450	0.480	0.465	0.450	0.450	0.450
1.00	0.470	0.470	0.470	0.460	0.460	0.460

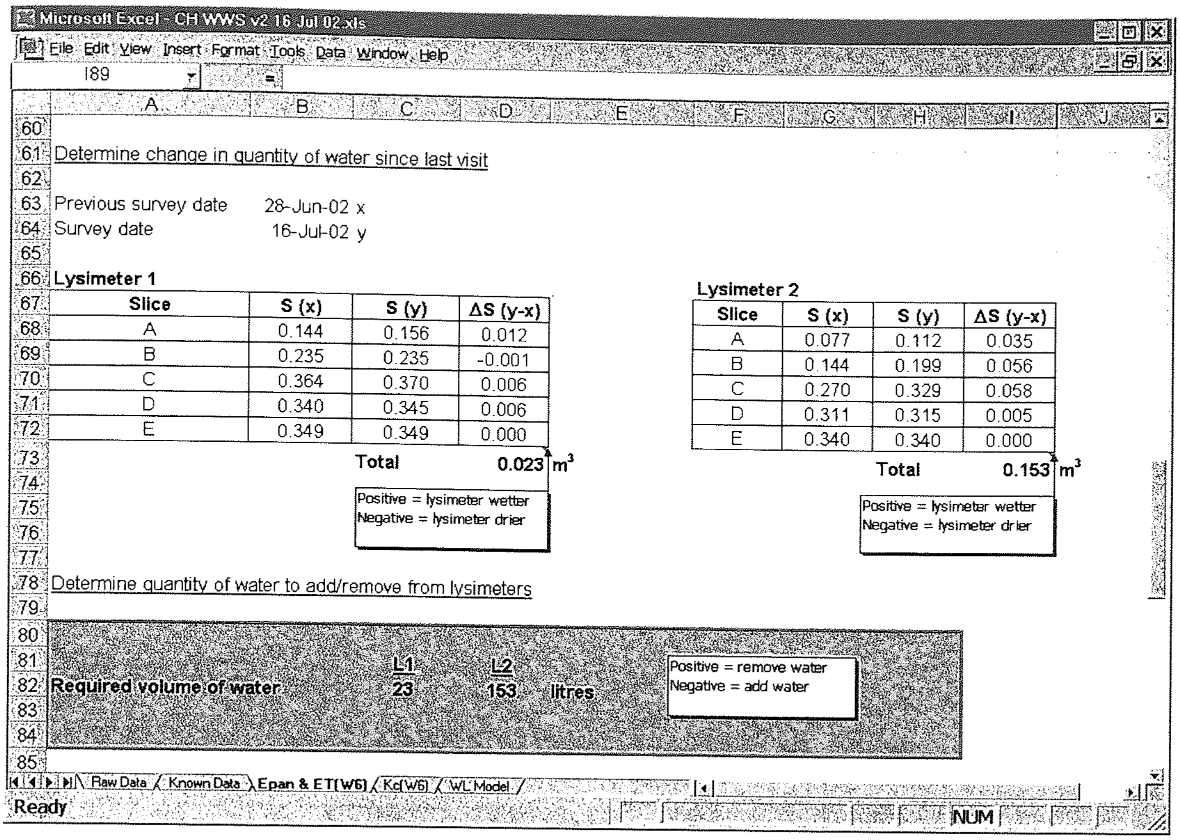
Determine mean volumetric soil moisture content (θv) for each slice

Slice	θv ($m^3.m^{-3}$) L1	θv ($m^3.m^{-3}$) L2
A	0.536	0.365
B	0.523	0.461
C	0.480	0.465
D	0.463	0.423
E	0.468	0.455

Determine quantity of water in each slice

Slice	Vw (m^3) L1	Vw (m^3) L2
A	0.160	0.109
B	0.234	0.206
C	0.358	0.347
D	0.345	0.315
E	0.349	0.340

Fig. A4.6: 'EPan & ET(W6)' Worksheet (Part 2)



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Determine change in quantity of water since last visit

Previous survey date 28-Jun-02 x

Survey date 16-Jul-02 y

Lysimeter 1

Slice	S (x)	S (y)	ΔS (y-x)
A	0.144	0.156	0.012
B	0.235	0.235	-0.001
C	0.364	0.370	0.006
D	0.340	0.345	0.006
E	0.349	0.349	0.000
		Total	0.023 m^3

Positive = lysimeter wetter
Negative = lysimeter drier

Lysimeter 2

Slice	S (x)	S (y)	ΔS (y-x)
A	0.077	0.112	0.035
B	0.144	0.199	0.056
C	0.270	0.329	0.058
D	0.311	0.315	0.005
E	0.340	0.340	0.000
		Total	0.153 m^3

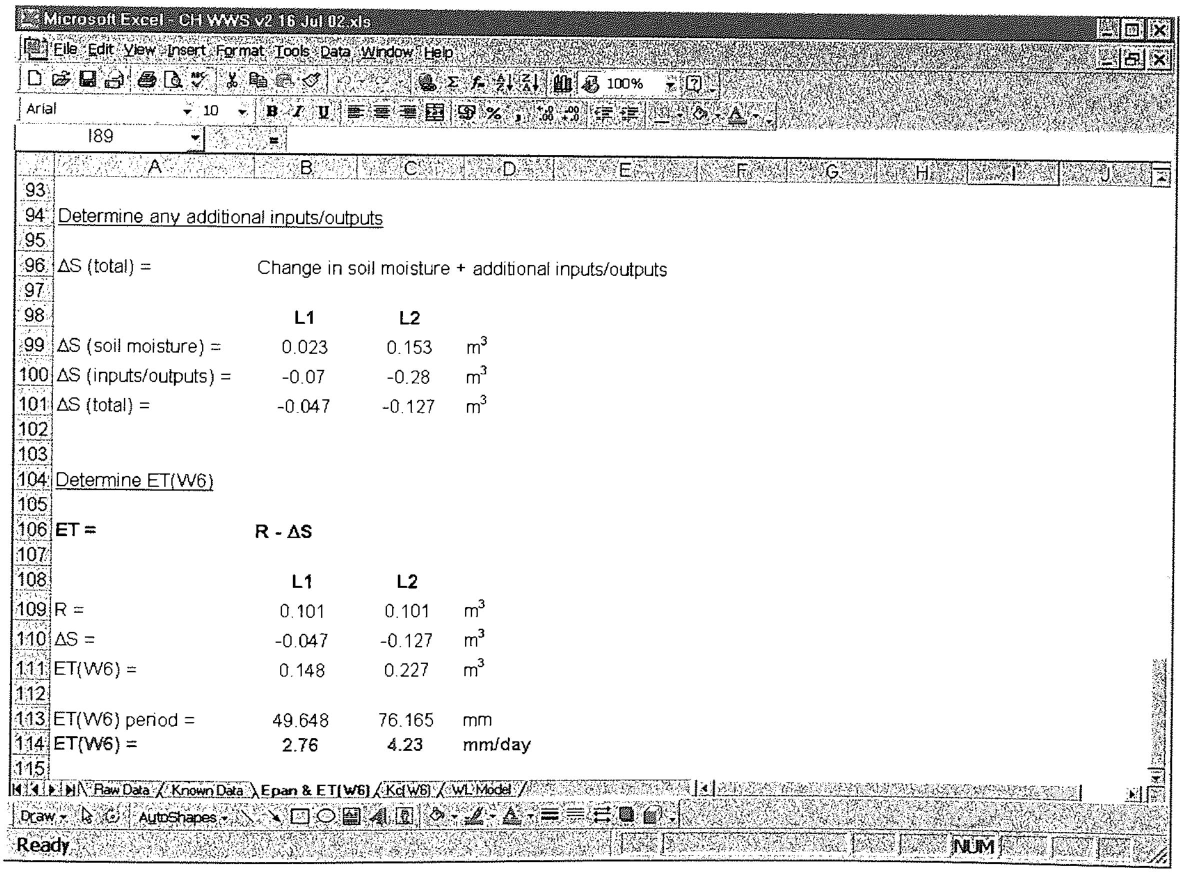
Positive = lysimeter wetter
Negative = lysimeter drier

Determine quantity of water to add/remove from lysimeters

	L1	L2	
Required volume of water	23	153	litres

Positive = remove water
Negative = add water

Fig. A4.7: 'EPan & ET(W6)' Worksheet (Part 3)



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Determine any additional inputs/outputs

ΔS (total) = Change in soil moisture + additional inputs/outputs

	L1	L2	
ΔS (soil moisture) =	0.023	0.153	m^3
ΔS (inputs/outputs) =	-0.07	-0.28	m^3
ΔS (total) =	-0.047	-0.127	m^3

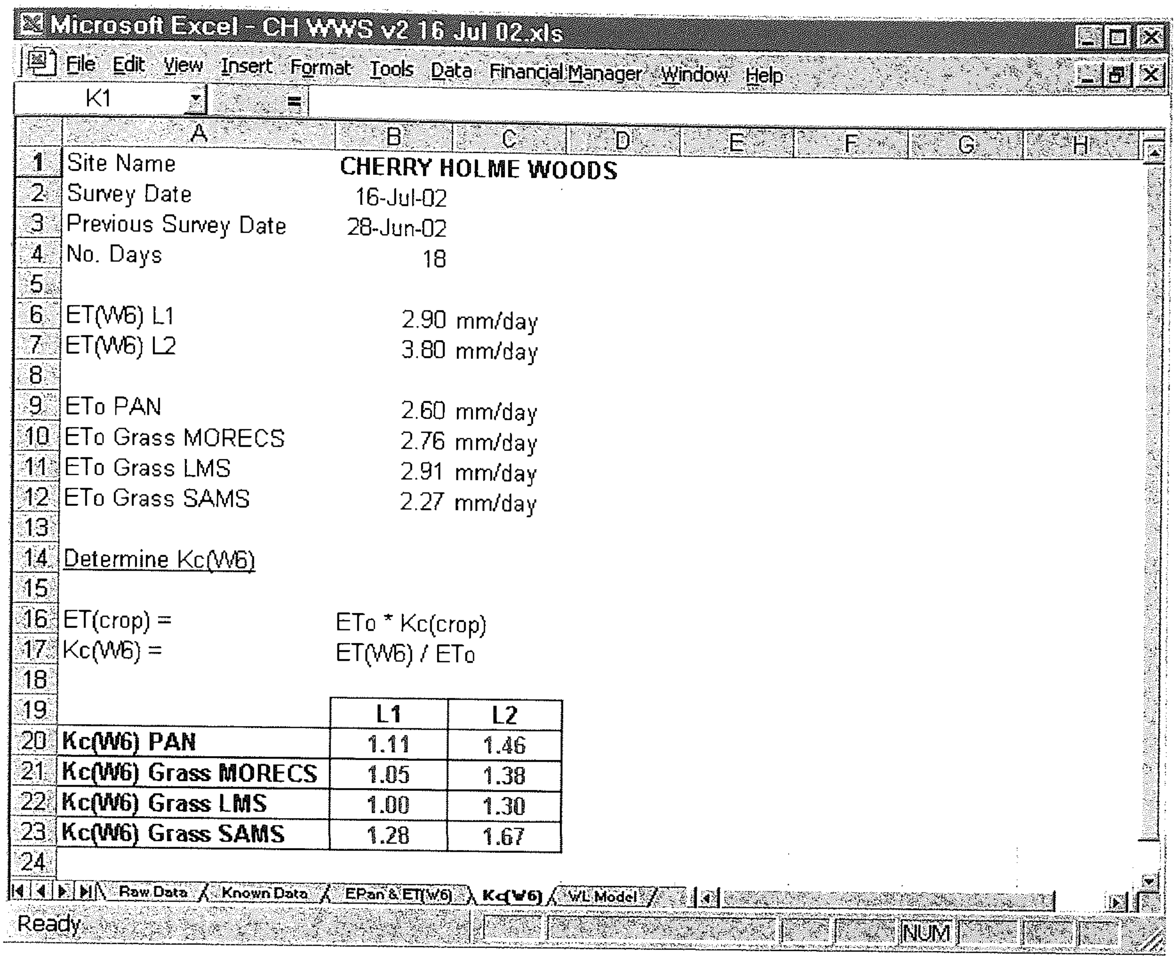
Determine ET(W6)

ET = **R - ΔS**

	L1	L2	
R =	0.101	0.101	m^3
ΔS =	-0.047	-0.127	m^3
ET(W6) =	0.148	0.227	m^3
ET(W6) period =	49.648	76.165	mm
ET(W6) =	2.76	4.23	mm/day

Fig. A4.8: 'EPan & ET(W6)' Worksheet (Part 4)

A4.4 'Kc(W6)'



	A	B	C
1	Site Name	CHERRY HOLME WOODS	
2	Survey Date	16-Jul-02	
3	Previous Survey Date	28-Jun-02	
4	No. Days	18	
5			
6	ET(W6) L1	2.90	mm/day
7	ET(W6) L2	3.80	mm/day
8			
9	ETo PAN	2.60	mm/day
10	ETo Grass MORECS	2.76	mm/day
11	ETo Grass LMS	2.91	mm/day
12	ETo Grass SAMS	2.27	mm/day
13			
14	Determine Kc(W6)		
15			
16	ET(crop) =	ETo * Kc(crop)	
17	Kc(W6) =	ET(W6) / ETo	
18			
19		**L1**	**L2**
20	**Kc(W6) PAN**	1.11	1.46
21	**Kc(W6) Grass MORECS**	1.05	1.38
22	**Kc(W6) Grass LMS**	1.00	1.30
23	**Kc(W6) Grass SAMS**	1.28	1.67
24			

Fig. A4.9: 'Kc(W6)' Worksheet

APPENDIX 5.
AQUALATE MERE DATA

A5.1 QUADRAT CROP CHARACTERISTIC DATA

The total number of inflorescence recorded in each quadrat is presented in Table A5.1. Tables A5.2, A5.3 and A5.4 present the crop height, crop density and standing crop values of the quadrats within the reedbed. Crop characteristic data was measured between March and September.

QUADRAT	YEAR	TOTAL NO. OF INFLORESCENCE RECORDED
A	2001	10
B	2001	14
C	2001	20
D	2001	18
A	2002	9
B	2002	7
C	2002	5
D	2002	7

Table A5.1: Aqualate Mere Reedbed Inflorescence Data

QUADRAT	YEAR	CROP HEIGHT (m)						
		Mar	Apr	May	Jun	Jul	Aug	Sep
A	2001	no data	0.80	1.55	2.05	2.39	2.40	2.60
B	2001	no data	0.40	1.55	2.00	2.25	2.30	2.20
C	2001	no data	0.85	1.72	2.35	2.60	2.55	2.50
D	2001	no data	0.62	1.60	2.15	2.56	2.60	2.50
A	2002	0.20	0.75	1.50	1.70	2.15	2.70	2.60
B	2002	0.07	0.45	1.60	2.10	2.30	2.30	2.20
C	2002	0.13	0.96	1.80	2.20	2.30	2.40	2.40
D	2002	0.16	0.74	1.60	2.00	2.40	2.30	2.30
Mean		0.14	0.70	1.62	2.07	2.45	2.44	2.41
Standard Dev.		0.05	0.19	0.10	0.19	0.16	0.15	0.16
95% Conf. Limit		0.05	0.13	0.07	0.05	0.16	0.11	0.11

Table A5.2: Aqualate Mere Reedbed Crop Height

QUADRAT	YEAR	CROP DENSITY (stems m^{-2})						
		Mar	Apr	May	Jun	Jul	Aug	Sep
A	2001	no data	76	148	184	148	128	120
B	2001	no data	80	176	240	168	172	156
C	2001	no data	136	188	224	176	168	128
D	2001	no data	100	220	280	220	216	188
A	2002	64	120	120	104	136	120	100
B	2002	16	80	112	132	104	112	88
C	2002	68	104	136	120	124	104	80
D	2002	40	108	148	132	112	128	96
Mean		47.0	100.5	156.0	177.0	178.0	143.5	119.5
Standard Dev.		24.1	21.2	36.4	64.9	30.4	38.3	37.0
95% Conf. Limit		23.6	14.7	25.2	45.0	21.0	26.5	25.6

Table A5.3: Aqualate Mere Reedbed Crop Density

QUADRAT	YEAR	STANDING CROP Mar	Apr	May	Jun	Jul	Aug	Sep
A	2001	no data	60.8	229.4	377.2	353.72	307.2	312.0
B	2001	no data	32.0	272.8	480.0	378.0	395.6	343.2
C	2001	no data	115.6	323.4	526.4	457.6	428.4	320.0
D	2001	no data	62.0	352.0	602.0	563.2	561.6	470.0
A	2002	12.8	90.0	180.0	176.8	292.4	324.0	260.0
B	2002	1.1	36.0	179.2	277.2	239.2	257.6	193.6
C	2002	8.8	99.8	244.8	264.0	285.2	249.6	192.0
D	2002	6.4	79.9	236.8	264.0	268.8	294.4	220.8
Mean		7.3	72.0	252.3	371.0	354.8	352.3	289.0
Standard Dev.		4.9	29.7	61.9	150.6	109.6	105.0	93.5
95% Conf. Limit		4.8	20.6	42.9	104.4	75.9	72.8	64.8

Table A5.4: Aqualate Mere Reedbed Standing Crop Values

A5.2 LYSIMETER CROP CHARACTERISTIC DATA

The total number of inflorescence recorded in each lysimeter is presented in Table A5.5. Tables A5.6, A5.7 and A5.8 present the crop height, crop density and standing crop values of the lysimeters. Crop characteristic data was measured between March and September.

QUADRAT	YEAR	TOTAL NO. OF INFLORESCENCE RECORDED
1	**2001**	**8**
2	2001	5
3	**2001**	**8**
4	2001	0
5	**2001**	**0**
6	2001	0
7	2001	1
8	2001	0
9	**2001**	**7**
10	2001	0
11	2001	1
12	2001	0
1	**2002**	**5**
2	2002	3
3	**2002**	**4**
4	**2002**	**4**
5	**2002**	**5**
6	**2002**	**1**
7	2002	0
8	2002	2
9	**2002**	**6**
10	2002	5
11	2002	0
12	2002	2

NB – Lysimeters in bold are 'successful'

Table A5.5: Aqualate Mere Lysimeters Inflorescence Data

LYSIMETER	YEAR	CROP HEIGHT (m) Mar	Apr	May	Jun	Jul	Aug	Sep
1	**2001**	**no data**	**0**	**1.32**	**2**	**2.1**	**2.18**	**2.2**
2	2001	no data	0	1.4	1.9	2.23	2.29	2.4
3	**2001**	**no data**	**0.47**	**1.28**	**2**	**2.17**	**2.13**	**2.2**
4	2001	no data	0.41	1.1	1.25	1.79	1.7	1.6
5	**2001**	**no data**	**0.58**	**1.38**	**1.6**	**2.15**	**1.94**	**1.8**
6	2001	no data	0.57	1.17	1.8	1.6	1.57	1.3
7	2001	no data	0.4	1.13	1.54	1.67	2.2	2.2
8	2001	no data	0.59	1.09	1.5	1.51	1.6	1.6
9	**2001**	**no data**	**0.53**	**1.29**	**1.8**	**2.13**	**2.15**	**2.2**
10	2001	no data	0.57	1.18	1.33	1.68	1.84	1.5
11	2001	no data	0.55	1.07	1.47	1.81	1.81	1.6
12	2001	no data	0.69	1.22	1.57	1.87	1.76	1.7
1	**2002**	**0.39**	**0.53**	**1.00**	**1.45**	**1.80**	**2.20**	**2.20**
2	2002	0.07	0.29	0.90	1.50	1.70	2.10	2.00
3	**2002**	**0.15**	**0.55**	**1.34**	**1.85**	**2.20**	**2.30**	**2.20**
4	**2002**	**0.11**	**0.61**	**1.17**	**1.60**	**1.90**	**2.20**	**2.20**
5	**2002**	**0.07**	**0.45**	**1.40**	**1.97**	**2.15**	**2.20**	**2.10**
6	**2002**	**0.21**	**0.54**	**1.18**	**1.64**	**2.00**	**1.60**	**1.40**
7	2002	0.15	0.37	1.04	1.55	1.95	2.00	2.00
8	2002	0.25	0.77	1.50	1.80	1.90	1.90	1.70
9	**2002**	**0.15**	**0.51**	**1.25**	**1.90**	**2.00**	**2.20**	**2.10**
10	2002	0.20	0.71	1.44	1.78	1.90	2.00	2.00
11	2002	0.18	0.55	1.25	1.70	2.00	1.90	1.80
12	2002	0.19	0.58	1.26	1.55	1.80	2.10	2.00
Successful Lysimeters Mean		**0.18**	**0.48**	**1.26**	**1.78**	**2.06**	**2.11**	**2.06**
Successful Lysimeters Standard Dev.		**0.11**	**0.17**	**0.12**	**0.20**	**0.13**	**0.20**	**0.26**
Successful Lysimeters 95% Conf. Limit		**0.09**	**0.11**	**0.07**	**0.12**	**0.08**	**0.12**	**0.16**

NB – Lysimeters in bold are 'successful'

Table A5.6: Aqualate Mere Lysimeters Reed Height

LYSIMETER	YEAR	CROP DENSITY (stems m^{-2}) Mar	Apr	May	Jun	Jul	Aug	Sep
1	**2001**	**no data**	**0**	**112**	**152**	**140**	**148**	**167**
2	2001	no data	0	154	122	138	134	122
3	**2001**	**no data**	**162**	**162**	**158**	**179**	**130**	**110**
4	2001	no data	135	118	157	140	162	114
5	**2001**	**no data**	**175**	**175**	**183**	**187**	**126**	**118**
6	2001	no data	103	103	163	124	94	94
7	2001	no data	41	65	85	41	37	41
8	2001	no data	32	72	116	100	104	84
9	**2001**	**no data**	**60**	**112**	**148**	**170**	**150**	**100**
10	2001	no data	92	100	152	148	140	120
11	2001	no data	17	45	54	50	41	45
12	2001	no data	48	84	124	111	88	64
1	**2002**	**60**	**140**	**128**	**152**	**175**	**179**	**179**
2	2002	41	53	69	49	49	77	61
3	**2002**	**61**	**171**	**150**	**101**	**134**	**89**	**81**
4	**2002**	**79**	**166**	**153**	**114**	**122**	**109**	**109**
5	**2002**	**69**	**195**	**134**	**134**	**110**	**89**	**85**
6	**2002**	**73**	**141**	**120**	**124**	**137**	**90**	**86**
7	2002	49	45	41	37	53	53	53
8	2002	20	72	64	56	72	40	40
9	**2002**	**116**	**175**	**175**	**152**	**152**	**144**	**136**
10	2002	40	100	108	76	76	68	68
11	2002	33	33	37	33	50	45	41
12	2002	40	100	100	84	104	64	60
Successful Lysimeters Mean		**76.1**	**138.5**	**142.0**	**141.6**	**150.5**	**125.4**	**117.1**
Successful Lysimeters Standard Dev.		**20.6**	**61.1**	**24.4**	**23.7**	**26.1**	**30.7**	**34.1**
Successful Lysimeters 95% Conf. Limit		**16.5**	**37.9**	**15.1**	**14.7**	**16.2**	**19.0**	**21.2**

NB – Lysimeters in bold are 'successful'

Table A5.7: Aqualate Mere Lysimeters Crop Density

LYSIMETER	YEAR	STANDING CROP						
		Mar	Apr	May	Jun	Jul	Aug	Sep
1	**2001**	**no data**	**0.0**	**147.4**	**303.1**	**293.1**	**321.7**	**368.5**
2	2001	no data	0.0	216.0	231.4	307.8	306.8	292.3
3	**2001**	**no data**	**76.3**	**207.8**	**316.6**	**387.6**	**276.7**	**241.1**
4	2001	no data	55.5	129.7	196.5	250.1	274.6	181.6
5	**2001**	**no data**	**101.2**	**240.9**	**292.3**	**401.5**	**244.1**	**211.9**
6	2001	no data	58.6	120.4	293.2	198.9	148.0	122.6
7	2001	no data	16.2	73.4	131.3	67.8	80.4	89.3
8	2001	no data	18.8	78.2	173.5	150.5	165.9	134.0
9	**2001**	**no data**	**31.7**	**144.0**	**265.6**	**362.1**	**322.5**	**219.3**
10	2001	no data	52.3	117.6	201.6	247.9	256.8	179.5
11	2001	no data	9.1	48.6	79.0	89.8	74.8	72.7
12	2001	no data	33.0	102.2	194.1	207.6	154.4	108.5
1	**2002**	**23.3**	**74.0**	**127.6**	**219.7**	**315.9**	**394.8**	**394.8**
2	2002	2.8	15.3	62.1	73.1	82.8	162.0	121.8
3	**2002**	**9.1**	**93.8**	**201.3**	**187.8**	294.7	**205.4**	**178.6**
4	**2002**	**8.6**	**101.2**	**178.8**	**181.6**	**232.3**	**240.1**	**240.1**
5	**2002**	**4.8**	**87.7**	**187.6**	**263.9**	**235.7**	**196.5**	**179.0**
6	**2002**	**15.3**	**76.4**	**141.6**	**203.8**	**274.3**	**144.0**	**120.0**
7	2002	7.3	16.5	42.2	56.6	102.9	105.5	105.5
8	2002	5.0	55.3	95.7	100.5	136.4	75.8	67.8
9	**2002**	**17.3**	**89.5**	**219.3**	**287.9**	**303.1**	**315.9**	**284.7**
10	2002	8.0	70.8	155.1	134.9	144.0	135.6	135.6
11	2002	6.0	18.2	46.5	56.2	99.2	86.4	74.4
12	2002	7.6	57.8	125.6	129.8	186.6	134.0	119.6
Successful Lysimeters Mean		**13.1**	**73.2**	**179.6**	**252.2**	**310.0**	**266.2**	**243.8**
Successful Lysimeters Standard Dev.		**6.8**	**32.6**	**38.2**	**50.0**	**58.3**	**74.5**	**85.3**
Successful Lysimeters 95% Conf. Limit		**5.4**	**20.2**	**23.7**	**31.0**	**36.1**	**46.2**	**52.8**

NB – Lysimeters in bold are 'successful'

Table A5.8: Aqualate Mere Lysimeters Standing Crop Values

A5.3 SURVEY DATES

Table A5.9 presents the actual survey dates and the months for which the monitoring period provided data

MONTH	MONITORING PERIOD		NUMBER OF DAYS
	FROM	TO	
Jan-01	3-Jan-01	1-Feb-01	29
Feb-01	no access	no access	n/a
Mar-01	no access	no access	n/a
Apr-01	no access	no access	n/a
May-01	10-May-01	4-Jun-01	25
Jun-01	4-Jun-01	1-Jul-01	27
Jul-01	1-Jul-01	3-Aug-01	33
Aug-01	3-Aug-01	3-Sep-01	31
Sep-01	3-Sep-01	5-Oct-01	32
Oct-01	5-Oct-01	5-Nov-01	31
Nov-01	5-Nov-01	30-Nov-01	25
Dec-01	30-Nov-01	19-Dec-01	19
Jan-02	19-Dec-01	30-Jan-02	42
Feb-02	30-Jan-02	27-Feb-02	28
Mar-02	27-Feb-02	27-Mar-02	28
Apr-02	27-Mar-02	29-Apr-02	33
May-02	29-Apr-02	30-May-02	31
Jun-02	30-May-02	28-Jun-02	29
Jul-02	28-Jun-02	26-Jul-02	28
Aug-02	26-Jul-02	3-Sep-02	39
Sep-02	3-Sep-02	2-Oct-02	29
Oct-02	2-Oct-02	2-Nov-02	31
Nov-02	2-Nov-02	3-Dec-02	31
Dec-02	3-Dec-02	19-Dec-02	16

Table A5.9: Survey Dates for Aqualate Mere, 2001-2002

A5.4 ET(Reed) DATA

LYSIMETER	ET(Reed) mm day^{-1} Jan-01	Feb-01	Mar-01	Apr-01	May-01	Jun-01	Jul-01	Aug-01	Sep-01	Oct-01	Nov-01	Dec-01	Annual
1	**error**	**no data**	**no data**	**no data**	**2.18**	**2.86**	**2.77**	**2.86**	**1.94**	**1.40**	**0.42**	**0.25**	**n/a**
2	error	no data	no data	no data	2.47	3.65	3.14	1.99	1.88	1.26	0.47	0.13	n/a
3	**0.22**	**no data**	**no data**	**no data**	**2.76**	**2.90**	**2.67**	**1.95**	**1.62**	**0.63**	**0.41**	**0.12**	**n/a**
4	error	no data	no data	no data	2.56	1.92	1.83	2.05	1.49	0.67	0.38	0.22	n/a
5	**0.39**	**no data**	**no data**	**no data**	**2.67**	**2.72**	**2.55**	**2.47**	**1.78**	**0.71**	**0.37**	**0.23**	**n/a**
6	0.25	no data	no data	no data	1.90	1.97	1.82	1.40	1.00	over	0.23	0.09	n/a
7	0.36	no data	no data	no data	2.35	1.69	1.66	over	1.11	over	0.45	0.13	n/a
8	0.29	no data	no data	no data	2.07	0.93	1.75	1.97	1.33	1.27	0.57	0.36	n/a
9	**error**	**no data**	**no data**	**no data**	**2.07**	**2.73**	**2.41**	**3.30**	**2.12**	**0.88**	**0.49**	**0.36**	**n/a**
10	error	no data	no data	no data	1.75	1.53	1.54	1.88	0.88	1.40	0.40	0.36	n/a
11	error	no data	no data	no data	1.73	1.40	1.15	over	0.84	0.48	0.28	0.34	n/a
12	error	no data	no data	no data	1.80	1.83	1.38	over	1.38	0.83	0.33	0.36	n/a
Mean (Successful)	0.31	no data	no data	no data	2.42	2.80	2.60	2.65	1.87	0.91	0.42	0.24	n/a
SE (Successful)	*0.09*	-	-	-	*0.17*	*0.05*	*0.08*	*0.29*	*0.11*	*0.17*	*0.02*	*0.05*	*0.09*

error - a sampling error resulted in a negative value and is therefore not presented
no data - no data collected due to site restrictions associated with outbreak of foot and mouth disease
SE - Standard Error

over - the lysimeter overtopped and data was lost
Lysimeters in bold are 'successful'

Table A5.10: Aqualate Mere Mean Monthly ET(Reed), 2001

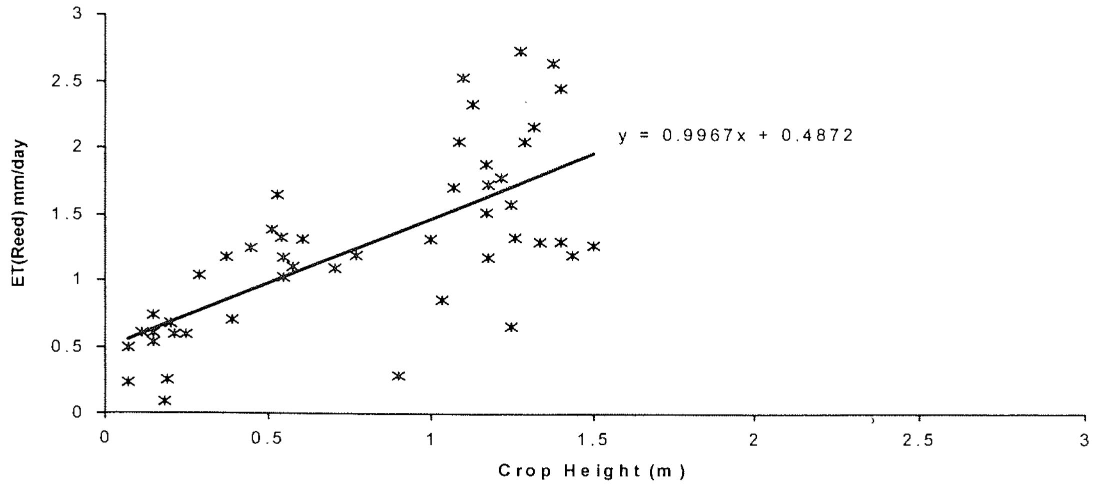
	ET(Reed) mm day^{-1}												
LYSIMETER	**Jan-02**	**Feb-02**	**Mar-02**	**Apr-02**	**May-02**	**Jun-02**	**Jul-02**	**Aug-02**	**Sep-02**	**Oct-02**	**Nov-02**	**Dec-02**	**Annual**
1	**0.16**	**0.34**	**0.71**	**1.66**	**1.33**	**2.53**	**2.88**	**2.53**	**1.50**	**over**	**0.40**	**0.29**	**n/a**
2	0.19	0.10	0.23	1.04	0.29	1.84	1.35	1.61	0.86	1.63	0.44	0.20	0.82
3	**0.10**	**0.42**	**0.61**	**1.18**	**1.31**	**3.10**	**2.76**	**2.75**	**1.43**	**over**	**0.36**	**0.35**	**n/a**
4	**0.24**	**0.19**	**0.61**	**1.32**	**1.54**	**2.74**	**2.74**	**2.47**	**1.65**	**over**	**0.09**	**0.04**	**n/a**
5	**0.19**	**0.23**	**0.50**	**1.25**	**1.31**	**2.96**	**2.83**	**2.86**	**1.59**	**over**	**0.15**	**0.41**	**n/a**
6	**error**	**0.22**	**0.60**	**1.33**	**1.19**	**1.84**	**1.73**	**1.42**	**0.68**	**over**	**0.25**	**0.55**	**n/a**
7	0.22	0.48	0.74	1.18	0.87	1.84	1.16	1.45	0.86	1.27	0.59	0.56	0.93
8	0.10	0.38	0.60	1.20	1.28	2.25	2.10	2.53	1.63	1.77	0.58	0.55	1.25
9	**0.12**	**0.34**	**0.54**	**1.39**	**1.60**	**3.15**	**3.31**	**3.45**	**2.66**	**1.49**	**0.02**	**0.41**	**1.54**
10	error	error	0.68	1.10	1.21	2.53	2.60	2.43	1.01	over	0.49	0.46	n/a
11	error	0.25	0.09	1.03	0.67	1.41	1.00	1.28	0.48	over	over	0.40	n/a
12	0.19	0.34	0.25	1.11	1.34	2.53	2.03	1.72	1.28	1.54	0.35	0.41	1.09
Mean (Successful)	0.16	0.29	0.60	1.36	1.38	2.72	2.71	2.58	1.59	1.49	0.21	0.34	1.29
SE (Successful)	*0.02*	*0.04*	*0.03*	*0.07*	*0.06*	*0.20*	*0.21*	*0.27*	*0.26*	*n/a*	*0.06*	*0.07*	*0.07*

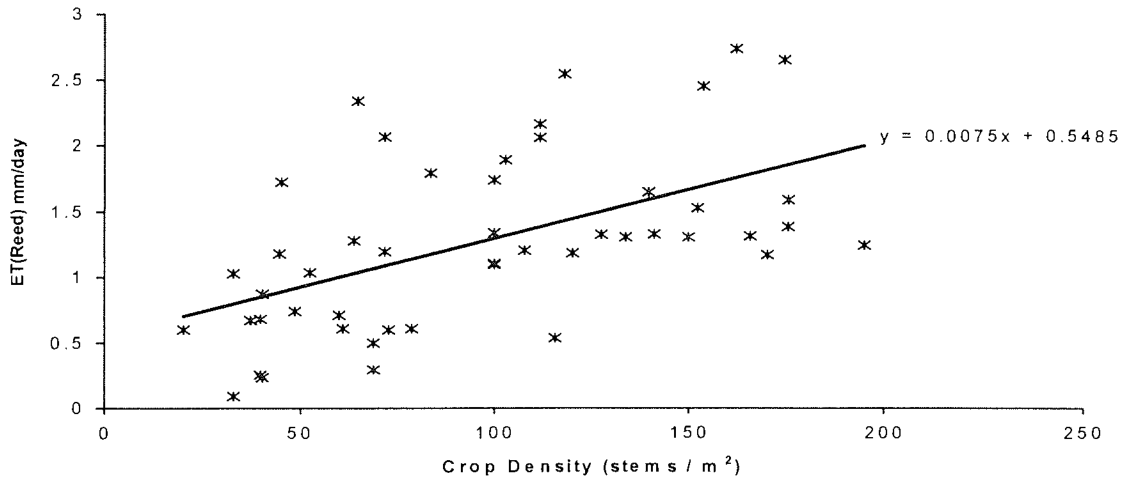
error - a sampling error resulted in a negative value and is therefore not presented
no data - no data collected due to site restrictions associated with outbreak of foot and mouth disease
SE - Standard Error

over - the lysimeter overtopped and data was lost
Lysimeters in bold are 'successful'

Table A5.11: Aqualate Mere Mean Monthly ET(Reed), 2002

A5.5 COMPARISON BETWEEN ET(Reed) AND CROP CHARACTERISTICS





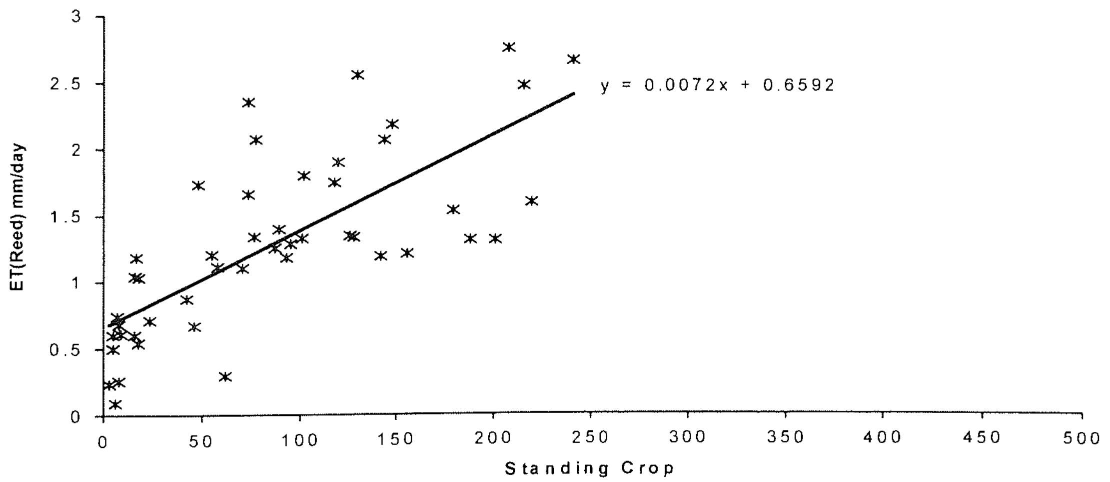


Fig. A5.1: Comparison Between Crop Characteristic and ET(Reed) Data for Initial Development Stage (Mar-May) at Aqualate Mere, 2001-2002

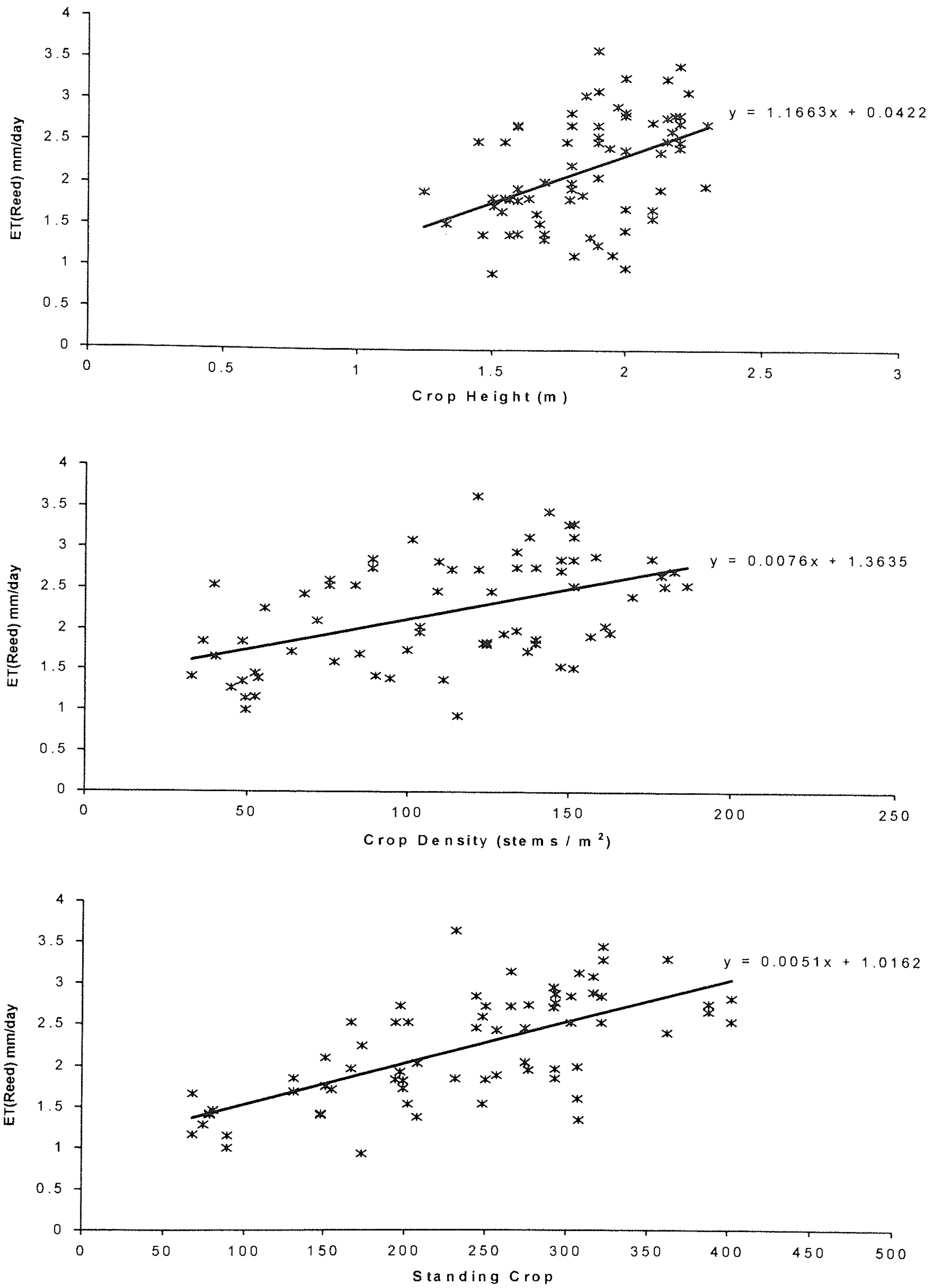
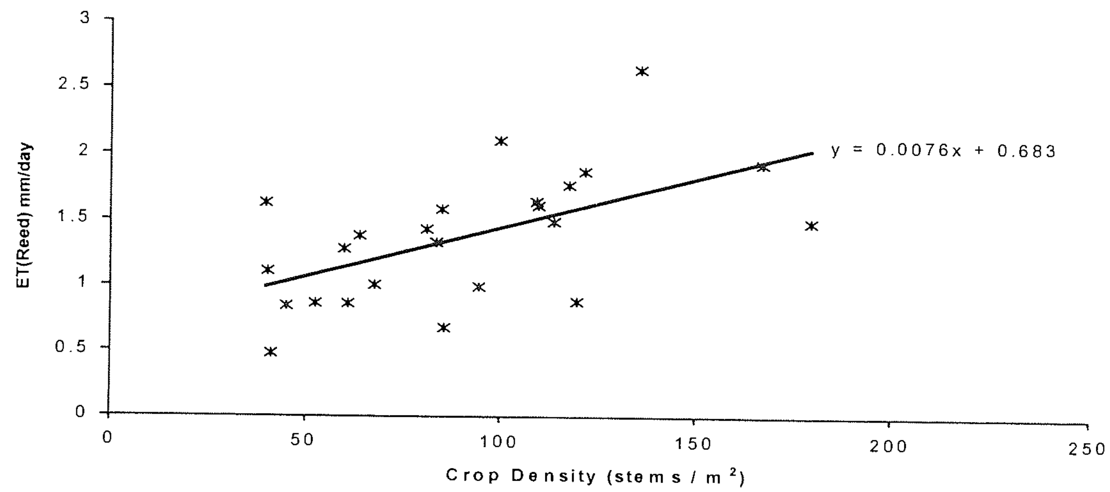


Fig. A5.2: Comparison Between Crop Characteristic and ET(Reed) Data for Mid-Season (Jun-Aug) at Aqualate Mere, 2001-2002



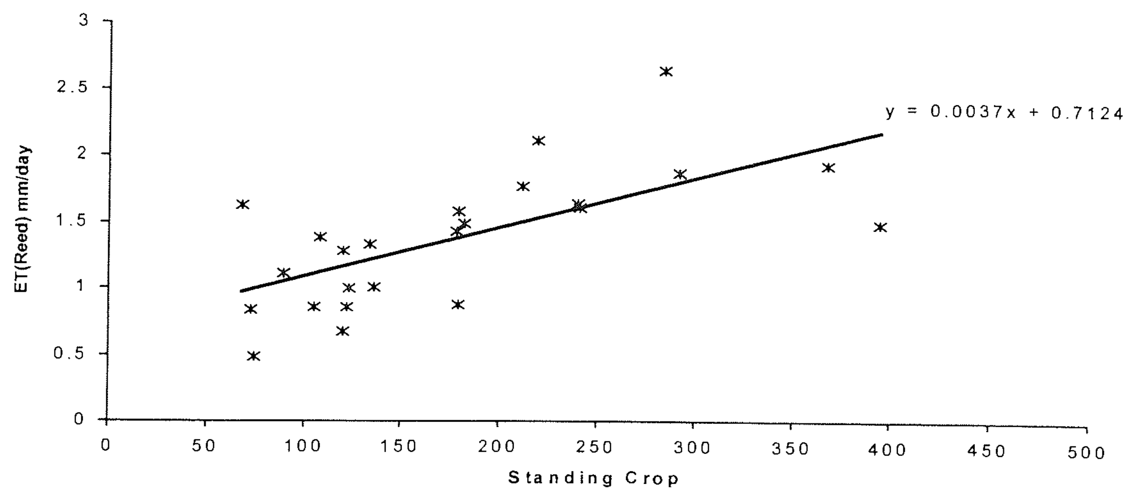


Fig. A5.3: Comparison Between Crop Characteristic and ET(Reed) Data for Late-Season (Sep) at Aqualate Mere, 2001-2002

A5.6 RAINFALL DATA

		RAINFALL (mm)												
Source	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
On-site Rain Gauge	2001	34.9	no data	no data	no data	59.7	21.4	51.6	102.3	60.0	99.2	40.1	18.8	n/a
	2002	49.7	77.2	39	26.7	45.6	53.4	52.8	78.9	41.2	104.1	85.5	14.6	668.7
Local Met Station	2001	31.0	51.1	54.1	86.2	62.3	17.3	42.9	93.7	57.8	107.7	38.0	29.4	671.5
	2002	37.2	62.9	32.5	33.8	45.8	54.2	57.8	55.4	25.0	85.2	84.9	76.9	651.6
MORECS Sq. 124	2001	41.7	61.8	64.8	92.1	67.2	33.9	56.6	67.2	43.9	118.7	32.6	26.8	707.3
	2002	54.7	89.6	30.9	41.3	68.0	47.5	59.6	54.9	28.1	115.9	98.7	91.1	780.3

Table A5.12: Monthly Rainfall Totals from Various Sources at Aqualate Mere, 2001-2002

A5.7 ETo DATA

Source	Year	ETo (mm)												
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Evaporation Pan	2001	error	no data	no data	no data	38.7	61.3	70.5	47.8	25.7	5.6	2.2	error	n/a
	2002	error	8.2	24.2	60.3	34.4	58.0	53.4	49.9	12.7	error	0.9	error	n/a
Local Met Station	2001	12.7	24.1	54.8	85.3	108.1	94.5	79.3	67.8	38.2	25.4	17.3	16.9	624.4
	2002	22.9	36.4	54.1	61.5	94.5	68.8	84.3	74.5	51.0	34.1	19.7	12.6	614.4
MORECS Sq. 124	2001	10.4	16.9	30.7	54.0	90.0	92.1	100.1	79.8	56.4	41.4	20.0	11.3	603.1
	2002	17.4	29.4	39.5	60.7	90.0	83.2	85.6	68.2	52.0	33.1	18.2	11.9	589.2

error - a sampling error resulted in a negative value and is therefore not presented
no data - no data collected due to site restrictions associated with outbreak of foot and mouth disease

Table A5.13: Monthly ETo Totals from Various Sources at Aqualate Mere, 2001-2002

A5.8 Kc(Reed) DATA

LYSIMETER	Kc(Reed) Pan												
	Jan-01	Feb-01	Mar-01	Apr-01	May-01	Jun-01	Jul-01	Aug-01	Sep-01	Oct-01	Nov-01	Dec-01	Annual
1	**error**	**no data**	**no data**	**no data**	**1.41**	**1.26**	**1.30**	**1.86**	**2.41**	7.72	**4.84**	**error**	**n/a**
2	error	no data	no data	no data	1.59	1.61	1.47	1.29	2.34	6.95	5.41	error	n/a
3	**error**	**no data**	**no data**	**no data**	**1.78**	**1.28**	**1.25**	**1.27**	**2.01**	**3.48**	**4.72**	**error**	**n/a**
4	error	no data	no data	no data	1.65	0.85	0.86	1.33	1.85	3.70	4.38	error	n/a
5	**error**	**no data**	**no data**	**no data**	**1.72**	**1.20**	**1.19**	**1.60**	**2.21**	**3.92**	**4.26**	**error**	**n/a**
6	error	no data	no data	no data	1.23	0.87	0.85	0.91	1.24	over	2.65	error	n/a
7	error	no data	no data	no data	1.52	0.74	0.78	over	1.38	over	5.18	error	n/a
8	error	no data	no data	no data	1.34	0.41	0.82	1.28	1.65	7.01	6.57	error	n/a
9	**error**	**no data**	**no data**	**no data**	**1.34**	**1.20**	**1.13**	**2.14**	**2.64**	**4.85**	**5.65**	**error**	**n/a**
10	error	no data	no data	no data	1.13	0.67	0.72	1.22	1.09	7.72	4.61	error	n/a
11	error	no data	no data	no data	1.12	0.62	0.54	over	1.04	2.65	3.23	error	n/a
12	error	no data	no data	no data	1.16	0.81	0.65	over	1.72	4.58	3.80	error	n/a
Mean (Successful)	error	no data	no data	no data	1.56	1.23	1.22	1.72	2.32	4.99	4.87	error	n/a
SE (Successful)	-	-	-	-	*0.11*	*0.02*	*0.04*	*0.19*	*0.13*	*0.95*	*0.29*	-	-

error - a sampling error resulted in a negative value and is therefore not presented
no data - no data collected due to site restrictions associated with outbreak of foot and mouth disease
SE - Standard Error
over - the lysimeter overtopped and data was lost
Lysimeters in bold are 'successful'

Table A5.13: Aqualate Mere Mean Monthly Kc(Reed) Pan, 2001

	Kc(Reed) Pan												
LYSIMETER	**Jan-02**	**Feb-02**	**Mar-02**	**Apr-02**	**May-02**	**Jun-02**	**Jul-02**	**Aug-02**	**Sep-02**	**Oct-02**	**Nov-02**	**Dec-02**	**Annual**
1	**error**	**1.16**	**0.82**	**0.91**	**1.20**	**1.26**	**1.51**	**1.98**	**3.43**	**over**	**13.63**	**error**	**n/a**
2	error	0.34	0.27	0.57	0.26	0.92	0.71	1.26	1.96	over	14.96	error	n/a
3	**error**	**1.43**	**0.70**	**0.65**	**1.18**	**1.55**	**1.45**	**2.15**	**3.27**	**over**	**12.03**	**error**	**n/a**
4	**error**	**0.65**	**0.70**	**0.72**	**1.39**	**1.37**	**1.44**	**1.93**	**3.77**	**over**	**3.07**	**error**	**n/a**
5	**error**	**0.79**	**0.58**	**0.68**	**1.18**	**1.48**	**1.48**	**2.23**	**3.63**	**over**	**5.19**	**error**	**n/a**
6	**error**	**0.75**	**0.69**	**0.73**	**1.07**	**0.92**	**0.91**	**1.11**	**1.55**	**over**	**8.50**	**error**	**n/a**
7	error	1.64	0.85	0.65	0.78	0.92	0.61	1.13	1.96	over	19.84	error	n/a
8	error	1.30	0.69	0.66	1.15	1.12	1.10	1.98	3.72	over	19.39	error	n/a
9	**error**	**1.16**	**0.62**	**0.76**	**1.44**	**1.57**	**1.74**	**2.70**	**6.07**	**over**	**0.67**	**error**	**n/a**
10	error	error	0.79	0.60	1.09	1.26	1.36	1.90	2.31	over	16.51	error	n/a
11	error	0.85	0.10	0.56	0.60	0.70	0.52	1.00	1.10	over	over	error	n/a
12	error	1.16	0.29	0.61	1.21	1.26	1.07	1.34	2.92	over	11.71	error	n/a
Mean (Successful)	error	0.99	0.69	0.74	n/a	1.36	1.42	2.02	3.62	over	7.18	error	n/a
SE (Successful)	-	*0.13*	*0.03*	*0.04*	-	*0.10*	*0.11*	*0.21*	*0.59*	-	*2.08*	-	-

error - a sampling error resulted in a negative value and is therefore not presented
Lysimeters in bold are 'successful'

over - the lysimeter overtopped and data was lost
SE - Standard Error

Table A5.14: Aqualate Mere Mean Monthly Kc(Reed) Pan, 2002

	Kc(Reed) LMS Grass												
LYSIMETER	**Jan-01**	**Feb-01**	**Mar-01**	**Apr-01**	**May-01**	**Jun-01**	**Jul-01**	**Aug-01**	**Sep-01**	**Oct-01**	**Nov-01**	**Dec-01**	**Annual**
1	**error**	**no data**	**no data**	**no data**	**0.63**	**0.82**	**0.79**	**0.82**	**0.56**	**0.40**	**0.12**	**0.07**	**n/a**
2	error	no data	no data	no data	0.71	1.05	0.90	0.57	0.54	0.36	0.13	0.04	n/a
3	**0.06**	**no data**	**no data**	**no data**	**0.79**	**0.83**	**0.77**	**0.56**	**0.46**	**0.18**	**0.12**	**0.03**	**n/a**
4	error	no data	no data	no data	0.73	0.55	0.52	0.59	0.43	0.19	0.11	0.06	n/a
5	**0.11**	**no data**	**no data**	**no data**	**0.77**	**0.78**	**0.73**	**0.71**	**0.51**	**0.20**	**0.11**	**0.07**	**n/a**
6	0.07	no data	no data	no data	0.54	0.56	0.52	0.40	0.29	over	0.07	0.03	n/a
7	0.10	no data	no data	no data	0.67	0.48	0.48	over	0.32	over	0.13	0.04	n/a
8	0.08	no data	no data	no data	0.59	0.27	0.50	0.56	0.38	0.36	0.16	0.10	n/a
9	**error**	**no data**	**no data**	**no data**	**0.59**	**0.78**	**0.69**	**0.95**	**0.61**	**0.25**	**0.14**	**0.10**	**n/a**
10	error	no data	no data	no data	0.50	0.44	0.44	0.54	0.25	0.40	0.11	0.10	n/a
11	error	no data	no data	no data	0.50	0.40	0.33	over	0.24	0.14	0.08	0.10	n/a
12	error	no data	no data	no data	0.52	0.52	0.40	over	0.40	0.24	0.09	0.10	n/a
Mean (Successful)	0.09	no data	no data	no data	0.69	0.80	0.75	0.76	0.53	0.26	0.12	0.07	n/a
SE (Successful)	*0.02*	-	-	-	*0.05*	*0.01*	*0.02*	*0.08*	*0.03*	*0.05*	*0.01*	*0.01*	-

error - a sampling error resulted in a negative value and is therefore not presented
no data - no data collected due to site restrictions associated with outbreak of foot and mouth disease
SE - Standard Error
over - the lysimeter overtopped and data was lost
Lysimeters in bold are 'successful'

Table A5.15: Aqualate Mere Mean Monthly Kc(Reed) LMS Grass, 2001

	Kc(Reed) LMS Grass												
LYSIMETER	**Jan-02**	**Feb-02**	**Mar-02**	**Apr-02**	**May-02**	**Jun-02**	**Jul-02**	**Aug-02**	**Sep-02**	**Oct-02**	**Nov-02**	**Dec-02**	**Annual**
1	**0.06**	**0.13**	**0.26**	**0.61**	**0.49**	**0.93**	**1.06**	**0.93**	**0.55**	**over**	**0.15**	**0.11**	**n/a**
2	0.07	0.04	0.08	0.38	0.11	0.68	0.50	0.59	0.32	0.60	0.16	0.07	0.30
3	**0.04**	**0.15**	**0.22**	**0.43**	**0.48**	**1.14**	**1.01**	**1.01**	**0.53**	**over**	**0.13**	**0.13**	**n/a**
4	**0.09**	**0.07**	**0.22**	**0.49**	**0.57**	**1.01**	**1.01**	**0.91**	**0.61**	**over**	**0.03**	**0.01**	**n/a**
5	**0.07**	**0.08**	**0.18**	**0.46**	**0.48**	**1.09**	**1.04**	**1.05**	**0.58**	**over**	**0.06**	**0.15**	**n/a**
6	**error**	**0.08**	**0.22**	**0.49**	**0.44**	**0.68**	**0.64**	**0.52**	**0.25**	**over**	**0.09**	**0.20**	**n/a**
7	0.08	0.18	0.27	0.43	0.32	0.68	0.43	0.53	0.32	0.47	0.22	0.20	0.34
8	0.04	0.14	0.22	0.44	0.47	0.83	0.77	0.93	0.60	0.65	0.21	0.20	0.46
9	**0.04**	**0.13**	**0.20**	**0.51**	**0.59**	**1.16**	**1.22**	**1.27**	**0.98**	**0.55**	**0.01**	**0.15**	**0.57**
10	error	error	0.25	0.40	0.44	0.93	0.96	0.89	0.37	over	0.18	0.17	n/a
11	error	0.09	0.03	0.38	0.25	0.52	0.37	0.47	0.18	over	over	0.15	n/a
12	0.07	0.13	0.09	0.41	0.49	0.93	0.75	0.63	0.47	0.57	0.13	0.15	0.40
Mean (Successful)	0.06	0.11	0.22	0.50	0.51	1.00	1.00	0.95	0.58	0.55	0.08	0.13	0.47
SE (Successful)	*0.01*	*0.01*	*0.01*	*0.02*	*0.02*	*0.07*	*0.08*	*0.10*	*0.10*	-	*0.02*	*0.03*	-

error - a sampling error resulted in a negative value and is therefore not presented
no data - no data collected due to site restrictions associated with outbreak of foot and mouth disease
SE - Standard Error
over - the lysimeter overtopped and data was lost
Lysimeters in bold are 'successful'

Table A5.16: Aqualate Mere Mean Monthly Kc(Reed) LMS Grass, 2002

	Kc(Reed) MORECS Grass												
LYSIMETER	**Jan-01**	**Feb-01**	**Mar-01**	**Apr-01**	**May-01**	**Jun-01**	**Jul-01**	**Aug-01**	**Sep-01**	**Oct-01**	**Nov-01**	**Dec-01**	**Annual**
1	**error**	**no data**	**no data**	**no data**	**0.75**	**0.99**	**0.95**	**0.99**	**0.67**	**0.48**	**0.14**	**0.09**	**n/a**
2	error	no data	no data	no data	0.85	1.26	1.08	0.69	0.65	0.43	0.16	0.04	n/a
3	**0.08**	**no data**	**no data**	**no data**	**0.95**	**1.00**	**0.92**	**0.67**	**0.56**	**0.22**	**0.14**	**0.04**	**n/a**
4	error	no data	no data	no data	0.88	0.66	0.63	0.71	0.51	0.23	0.13	0.08	n/a
5	**0.13**	**no data**	**no data**	**no data**	**0.92**	**0.94**	**0.88**	**0.85**	**0.61**	**0.24**	**0.13**	**0.08**	**n/a**
6	0.09	no data	no data	no data	0.65	0.68	0.63	0.48	0.34	over	0.08	0.03	n/a
7	0.12	no data	no data	no data	0.81	0.58	0.57	over	0.38	over	0.16	0.04	n/a
8	0.10	no data	no data	no data	0.71	0.32	0.60	0.68	0.46	0.44	0.20	0.12	n/a
9	**error**	**no data**	**no data**	**no data**	**0.71**	**0.94**	**0.83**	**1.14**	**0.73**	**0.30**	**0.17**	**0.12**	**n/a**
10	error	no data	no data	no data	0.60	0.53	0.53	0.65	0.30	0.48	0.14	0.12	n/a
11	error	no data	no data	no data	0.60	0.48	0.40	over	0.29	0.17	0.10	0.12	n/a
12	error	no data	no data	no data	0.62	0.63	0.48	over	0.48	0.29	0.11	0.12	n/a
Mean (Successful)	0.11	no data	no data	no data	0.83	0.97	0.90	0.91	0.64	0.31	0.15	0.08	n/a
SE (Successful)	*0.03*	-	-	-	*0.06*	*0.02*	*0.03*	*0.10*	*0.04*	*0.06*	*0.01*	*0.02*	-

error - a sampling error resulted in a negative value and is therefore not presented
no data - no data collected due to site restrictions associated with outbreak of foot and mouth disease
SE - Standard Error

over - the lysimeter overtopped and data was lost
Lysimeters in bold are 'successful'

Table A5.17: Aqualate Mere Mean Monthly Kc(Reed) MORECS Grass, 2001

	Kc(Reed) MORECS Grass												
LYSIMETER	**Jan-02**	**Feb-02**	**Mar-02**	**Apr-02**	**May-02**	**Jun-02**	**Jul-02**	**Aug-02**	**Sep-02**	**Oct-02**	**Nov-02**	**Dec-02**	**Annual**
1	**0.06**	**0.12**	**0.26**	**0.60**	**0.48**	**0.92**	**1.04**	**0.92**	**0.54**	**over**	**0.15**	**0.10**	**n/a**
2	0.07	0.04	0.08	0.38	0.11	0.67	0.49	0.58	0.31	0.59	0.16	0.07	0.30
3	**0.04**	**0.15**	**0.22**	**0.43**	**0.47**	**1.12**	**1.00**	**1.00**	**0.52**	**over**	**0.13**	**0.13**	**n/a**
4	**0.09**	**0.07**	**0.22**	**0.48**	**0.56**	**0.99**	**0.99**	**0.89**	**0.60**	**over**	**0.03**	**0.01**	**n/a**
5	**0.07**	**0.08**	**0.18**	**0.45**	**0.47**	**1.07**	**1.02**	**1.03**	**0.58**	**over**	**0.06**	**0.15**	**n/a**
6	**error**	**0.08**	**0.22**	**0.48**	**0.43**	**0.67**	**0.63**	**0.51**	**0.25**	**over**	**0.09**	**0.20**	**n/a**
7	0.08	0.17	0.27	0.43	0.32	0.67	0.42	0.53	0.31	0.46	0.21	0.20	0.34
8	0.04	0.14	0.22	0.43	0.46	0.81	0.76	0.92	0.59	0.64	0.21	0.20	0.45
9	**0.04**	**0.12**	**0.20**	**0.50**	**0.58**	**1.14**	**1.20**	**1.25**	**0.96**	**0.54**	**0.01**	**0.15**	**0.56**
10	error	error	0.25	0.40	0.44	0.92	0.94	0.88	0.37	over	0.18	0.17	n/a
11	error	0.09	0.03	0.37	0.24	0.51	0.36	0.46	0.17	over	over	0.14	n/a
12	0.07	0.12	0.09	0.40	0.49	0.92	0.74	0.62	0.46	0.56	0.13	0.15	0.39
Mean (Successful)	0.06	0.11	0.22	0.49	0.50	0.99	0.98	0.93	0.57	0.54	0.08	0.12	0.47
SE (Successful)	*0.01*	*0.01*	*0.01*	*0.02*	*0.02*	*0.07*	*0.08*	*0.10*	*0.09*	-	*0.02*	*0.03*	-

error - a sampling error resulted in a negative value and is therefore not presented
no data - no data collected due to site restrictions associated with outbreak of foot and mouth disease
SE - Standard Error

over - the lysimeter overtopped and data was lost
Lysimeters in bold are 'successful'

Table A5.18: Aqualate Mere Mean Monthly Kc(Reed) MORECS Grass, 2002

	Kc(Reed) Pan												
QUADRAT	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
A – 2001	-	-	no data	0.55	0.98	1.28	1.23	1.12	0.68	-	-	-	-
B – 2001	-	-	no data	0.41	1.04	1.50	1.28	1.32	0.77	-	-	-	-
C – 2001	-	-	no data	0.70	1.13	1.61	1.46	1.39	0.70	-	-	-	-
D – 2001	-	-	no data	0.53	1.15	1.77	1.69	1.68	0.86	-	-	-	-
Mean – 2001	-	-	**no data**	**0.55**	**1.07**	**1.54**	**1.41**	**1.38**	**0.75**	-	-	-	-
SE – 2001	-	-	-	*0.06*	*0.04*	*0.10*	*0.10*	*0.12*	*0.04*	-	-	-	-
A – 2002	-	-	0.61	1.28	1.84	1.71	2.23	2.38	1.28	-	-	-	-
B – 2002	-	-	0.30	0.87	1.87	2.17	1.99	2.08	1.22	-	-	-	-
C – 2002	-	-	0.58	1.36	2.13	2.11	2.20	2.04	1.17	-	-	-	-
D – 2002	-	-	0.48	1.22	2.04	2.11	2.13	2.24	1.26	-	-	-	-
Mean – 2002	-	-	**0.49**	**1.18**	**1.97**	**2.02**	**2.14**	**2.18**	**1.23**	-	-	-	-
SE – 2002	-	-	*0.07*	*0.11*	*0.07*	*0.10*	*0.05*	*0.08*	*0.02*	-	-	-	-

no data - no data collected due to site restrictions associated with outbreak of foot and mouth disease
SE - Standard Error

Table A5.19: Aqualate Mere Estimated Monthly Kc(Reed) Pan, 2001-2002

	Estimated Kc(Reed) LMS Grass												
QUADRAT	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
A – 2001	-	-	no data	0.39	0.70	0.92	0.88	0.81	0.49	-	-	-	-
B – 2001	-	-	no data	0.29	0.75	1.08	0.92	0.95	0.56	-	-	-	-
C – 2001	-	-	no data	0.50	0.81	1.16	1.05	1.00	0.50	-	-	-	-
D – 2001	-	-	no data	0.38	0.83	1.28	1.22	1.21	0.62	-	-	-	-
Mean – 2001	-	-	**no data**	**0.39**	**0.77**	**1.11**	**1.02**	**0.99**	**0.54**	-	-	-	-
SE – 2001	-	-	-	*0.04*	*0.03*	*0.07*	*0.07*	*0.08*	*0.03*	-	-	-	-
A – 2002	-	-	0.22	0.46	0.67	0.62	0.81	0.86	0.47	-	-	-	-
B – 2002	-	-	0.11	0.32	0.68	0.79	0.73	0.76	0.44	-	-	-	-
C – 2002	-	-	0.21	0.50	0.78	0.77	0.80	0.74	0.43	-	-	-	-
D – 2002	-	-	0.17	0.44	0.74	0.77	0.77	0.82	0.46	-	-	-	-
Mean – 2002	-	-	**0.18**	**0.43**	**0.72**	**0.74**	**0.78**	**0.79**	**0.45**	-	-	-	-
SE – 2002	-	-	*0.03*	*0.04*	*0.03*	*0.04*	*0.02*	*0.03*	*0.01*	-	-	-	-

no data - no data collected due to site restrictions associated with outbreak of foot and mouth disease
SE - Standard Error

Table A5.20: Aqualate Mere Estimated Monthly Kc(Reed) LMS Grass, 2001-2002

	Estimated Kc(Reed) MORECS Grass												
QUADRAT	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
A – 2001	-	-	no data	0.40	0.72	0.95	0.91	0.83	0.50	-	-	-	-
B – 2001	-	-	no data	0.30	0.77	1.11	0.95	0.98	0.57	-	-	-	-
C – 2001	-	-	no data	0.51	0.83	1.19	1.08	1.03	0.52	-	-	-	-
D – 2001	-	-	no data	0.39	0.85	1.31	1.25	1.25	0.64	-	-	-	-
Mean – 2001	-	-	**no data**	**0.40**	**0.79**	**1.14**	**1.04**	**1.02**	**0.56**	-	-	-	-
SE – 2001	-	-	-	*0.04*	*0.03*	*0.08*	*0.08*	*0.09*	*0.03*	-	-	-	-
A – 2002	-	-	0.23	0.49	0.70	0.65	0.85	0.91	0.49	-	-	-	-
B – 2002	-	-	0.12	0.33	0.72	0.83	0.76	0.79	0.47	-	-	-	-
C – 2002	-	-	0.22	0.52	0.81	0.80	0.84	0.78	0.45	-	-	-	-
D – 2002	-	-	0.18	0.46	0.78	0.80	0.81	0.86	0.48	-	-	-	-
Mean – 2001	-	-	**0.19**	**0.45**	**0.75**	**0.77**	**0.82**	**0.83**	**0.47**	-	-	-	-
SE – 2001	-	-	*0.03*	*0.04*	*0.03*	*0.04*	*0.02*	*0.03*	*0.01*	-	-	-	-

no data - no data collected due to site restrictions associated with outbreak of foot and mouth disease
SE - Standard Error

Table A5.21: Aqualate Mere Estimated Monthly Kc(Reed) MORECS Grass, 2001-2002

A5.8 MEASURED REEDBED WATER LEVELS

	MEASURED REEDBED WATER LEVEL (m.a.g.l.)											
YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2001	0.21	no data	no data	no data	0.06	Dry	Dry	Dry	0.06	0.11	0.16	0.08
2002	0.16	0.30	0.10	0.07	0.08	Dry	Dry	Dry	Dry	0.21	0.24	0.16

no data - no data collected due to site restrictions associated with outbreak of foot and mouth disease

Table A5.22: Aqualate Mere Measured Reedbed Water Levels, 2001-2002

APPENDIX 6.
BRANDON MARSH DATA

A6.1 QUADRAT CROP CHARACTERISTIC DATA

The total number of inflorescence recorded in each quadrat is presented in Table A6.1. Tables A6.2, A6.3 and A6.4 present the crop height, crop density and standing crop values of the quadrats within the reedbed. Crop characteristics were measured between March and September.

QUADRAT	YEAR	TOTAL NO. OF INFLORESCENCE RECORDED
A	2001	13
B	2001	23
C	2001	16
D	2001	21
A	2002	no data
B	2002	no data
C	2002	no data
D	2002	no data

NB – no data due to cessation of sampling in June 2002

Table A6.1: Brandon Marsh Reedbed Inflorescence Data

		CROP HEIGHT (m)						
QUADRAT	YEAR	Mar	Apr	May	Jun	Jul	Aug	Sep
A	2001	0.00	0.40	1.84	1.74	1.90	2.50	2.20
B	2001	0.00	0.48	1.80	1.94	2.30	2.50	2.30
C	2001	0.00	0.44	1.90	1.70	2.00	2.10	1.90
D	2001	0.00	0.59	1.78	1.70	1.90	2.20	2.05
A	2002	0.17	0.64	1.10	0.80	no data	no data	no data
B	2002	0.15	0.50	1.30	1.30	no data	no data	no data
C	2002	0.14	0.56	1.35	0.90	no data	no data	no data
D	2002	0.00	0.73	1.70	1.50	no data	no data	no data
Mean		**0.06**	**0.54**	**1.60**	**1.45**	**2.03**	**2.33**	**2.11**
Standard Dev.		0.08	0.11	0.30	0.41	0.19	0.21	0.18
95% Conf. Limit		0.06	0.08	0.21	0.29	0.13	0.14	0.12

NB – no data due to cessation of sampling in June 2002

Table A6.2: Brandon Marsh Reedbed Crop Height

		CROP DENSITY (stems m^{-2})						
QUADRAT	YEAR	Mar	Apr	May	Jun	Jul	Aug	Sep
A	2001	0	48	96	112	112	100	108
B	2001	0	64	35	148	128	108	128
C	2001	0	92	33	208	200	140	160
D	2001	0	32	32	116	148	128	104
A	2002	24	100	104	56	no data	no data	no data
B	2002	40	100	112	40	no data	no data	no data
C	2002	32	76	120	68	no data	no data	no data
D	2002	24	120	140	100	no data	no data	no data
Mean		**15.0**	**79.0**	**84.0**	**106.0**	**147.0**	**119.0**	**125.0**
Standard Dev.		16.8	29.6	43.9	54.3	38.3	18.3	25.6
95% Conf. Limit		11.6	20.5	30.4	37.6	37.5	17.9	25.1

NB – no data due to cessation of sampling in June 2002

Table A6.3: Brandon Marsh Reedbed Crop Density

		STANDING CROP						
QUADRAT	**YEAR**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
A	2001	0.0	19.2	176.6	194.9	212.8	250.0	237.6
B	2001	0.0	30.7	63.0	287.1	294.4	270.0	294.4
C	2001	0.0	40.5	62.7	353.6	400.0	294.0	304.0
D	2001	0.0	18.9	57.0	197.2	281.2	281.6	213.2
A	2002	4.1	64.0	114.4	44.8	no data	no data	no data
B	2002	6.0	50.0	145.6	52.0	no data	no data	no data
C	2002	4.5	42.6	162.0	61.2	no data	no data	no data
D	2002	0.0	87.6	238.0	150.0	no data	no data	no data
Mean		**1.8**	**44.2**	**127.4**	**167.6**	**297.1**	**273.9**	**262.3**
Standard Dev.		2.6	23.2	65.1	113.8	77.4	18.7	43.9
95% Conf. Limit		1.8	16.1	45.1	78.8	75.8	18.3	43.1

NB – no data due to cessation of sampling in June 2002

Table A6.4: Brandon Marsh Reedbed Standing Crop Values

A6.2 LYSIMETER CROP CHARACTERISTIC DATA

The total number of inflorescence recorded in each lysimeter is presented in Table A6.5. Tables A6.6, A6.7 and A6.8 present the crop height, crop density and standing crop values of the quadrats within the reedbed. Phenological data was measured between March and September.

LYSIMETER	YEAR	TOTAL NO. OF INFLORESCENCE RECORDED
1	2001	0
2	**2001**	**2**
3	2001	6
4	2001	2
5	2001	0
6	2001	0
7	2001	0
8	2001	0
9	2001	0
10	2001	0
1	2002	no data
2	**2002**	**no data**
3	**2002**	**no data**
4	2002	no data
5	**2002**	**no data**
6	**2002**	**no data**
7	**2002**	**no data**
8	2002	no data
9	**2002**	**no data**
10	2002	no data

NB – Lysimeters in bold are 'successful'
no data due to cessation of sampling in June 2002

Table A4.5: Brandon Marsh Lysimeters Inflorescence Data

		CROP HEIGHT (m)						
LYSIMETER	YEAR	Mar	Apr	May	Jun	Jul	Aug	Sep
1	2001	0.00	0.00	0.50	1.00	1.13	1.14	1.20
2	**2001**	**0.22**	**0.50**	**1.20**	**1.42**	**1.80**	**2.25**	**1.70**
3	2001	0.25	0.43	1.30	1.05	1.10	1.40	1.80
4	2001	0.00	0.46	1.26	1.40	1.86	2.30	2.00
5	2001	0.27	0.55	0.87	1.43	1.42	1.80	1.90
6	2001	0.00	0.00	1.10	1.10	1.70	1.91	1.40
7	2001	0.33	0.54	1.40	1.30	1.43	1.92	1.90
8	2001	0.00	0.36	0.82	1.20	1.74	1.95	1.80
9	2001	0.00	0.00	0.90	1.40	1.65	1.85	1.90
10	2001	0.00	0.00	0.25	0.45	0.00	0.00	0.00
1	2002	0.00	0.27	0.80	1.30	no data	no data	no data
2	**2002**	**0.40**	**0.88**	**1.35**	**0.95**	**no data**	**no data**	**no data**
3	**2002**	**0.00**	**0.45**	**1.13**	**1.30**	**no data**	**no data**	**no data**
4	2002	0.35	0.86	1.00	0.90	no data	no data	no data
5	**2002**	**0.34**	**0.68**	**1.40**	**1.35**	**no data**	**no data**	**no data**
6	**2002**	**0.31**	**0.71**	**1.28**	**1.10**	**no data**	**no data**	**no data**
7	**2002**	**0.32**	**0.74**	**1.15**	**1.00**	**no data**	**no data**	**no data**
8	2002	0.39	0.89	1.30	0.90	no data	no data	no data
9	**2002**	**0.41**	**0.91**	**1.55**	**1.40**	**no data**	**no data**	**no data**
10	2002	0.00	0.00	0.00	0.00	no data	no data	no data
Successful Lysimeter Mean		**0.29**	**0.70**	**1.29**	**1.22**	**1.80**	**2.25**	**1.70**
Successful Lysimeter Standard Dev.		0.14	0.17	0.15	0.20	N/a	N/a	N/a
Successful Lysimeter 95% Conf. Limit		0.14	0.17	0.15	0.19	N/a	N/a	N/a

NB – Lysimeters in bold are 'successful'
no data due to cessation of sampling in June 2002

Table A6.6: Brandon Marsh Lysimeters Reed Height

		CROP DENSITY (stems m^{-2})						
LYSIMETER	YEAR	Mar	Apr	May	Jun	Jul	Aug	Sep
1	2001	0	0	16	12	16	12	12
2	**2001**	**20**	**39**	**47**	**86**	**102**	**125**	**106**
3	2001	7	29	26	26	44	37	55
4	2001	0	13	35	65	96	105	118
5	2001	8	28	41	45	65	69	73
6	2001	0	0	12	12	28	45	53
7	2001	16	51	74	67	82	63	71
8	2001	0	20	24	35	86	82	90
9	2001	0	0	17	12	29	54	45
10	2001	0	0	4	8	0	0	0
1	2002	0	12	8	12	no data	no data	no data
2	**2002**	**27**	**121**	**90**	**47**	**no data**	**no data**	**no data**
3	**2002**	**29**	**40**	**40**	**26**	**no data**	**no data**	**no data**
4	2002	4	48	48	13	no data	no data	no data
5	**2002**	**20**	**45**	**41**	**41**	**no data**	**no data**	**no data**
6	**2002**	**0**	**20**	**45**	**85**	**no data**	**no data**	**no data**
7	**2002**	**20**	**47**	**51**	**35**	**no data**	**no data**	**no data**
8	2002	16	39	39	31	no data	no data	no data
9	**2002**	**4**	**45**	**41**	**37**	**no data**	**no data**	**no data**
10	2002	0	0	0	0	no data	no data	no data
Successful Lysimeter Mean		**17.8**	**52.4**	**51.8**	**46.7**	**103.7**	**127.6**	**107.7**
Successful Lysimeter Standard Dev.		11.7	32.8	18.1	19.5	N/a	N/a	N/a
Successful Lysimeter 95% Conf. Limit		11.4	31.9	17.6	18.9	N/a	N/a	N/a

NB – Lysimeters in bold are 'successful'
no data due to cessation of sampling in June 2002

Table A6.7: Brandon Marsh Lysimeters Crop Density

		STANDING CROP						
LYSIMETER	YEAR	Mar	Apr	May	Jun	Jul	Aug	Sep
1	2001	0.0	0.0	8.0	12.0	18.0	13.6	14.4
2	**2001**	**4.3**	**19.6**	**56.4**	**122.4**	**183.4**	**282.1**	**179.9**
3	2001	1.8	12.6	33.3	26.9	48.3	51.2	98.7
4	2001	0.0	6.0	44.0	91.7	178.6	241.0	235.8
5	2001	2.2	15.6	35.3	63.9	92.2	124.2	138.8
6	2001	0.0	0.0	13.4	13.4	48.3	85.3	73.9
7	2001	5.2	27.5	104.2	86.6	117.7	120.4	134.0
8	2001	0.0	7.1	19.3	42.3	150.0	160.5	162.2
9	2001	0.0	0.0	14.9	17.4	47.7	99.4	86.4
10	2001	0.0	0.0	1.1	3.8	0.0	0.0	0.0
1	2002	0.0	3.2	6.4	15.6	no data	no data	no data
2	**2002**	**8.8**	**89.9**	**103.6**	**47.0**	**no data**	**no data**	**no data**
3	**2002**	**12.0**	**36.6**	**62.4**	**35.8**	**no data**	**no data**	**no data**
4	2002	1.5	41.3	48.0	11.8	no data	no data	no data
5	**2002**	**8.1**	**39.3**	**54.8**	**38.6**	**no data**	**no data**	**no data**
6	**2002**	**0.0**	**9.1**	**50.5**	**110.8**	**no data**	**no data**	**no data**
7	**2002**	**6.7**	**32.0**	**71.3**	**47.6**	**no data**	**no data**	**no data**
8	2002	6.1	34.9	50.9	28.2	no data	no data	no data
9	**2002**	**1.6**	**32.3**	**52.9**	**40.9**	**no data**	**no data**	**no data**
10	2002	0.0	0.0	0.0	0.0	no data	no data	no data
Successful Lysimeter Mean		**6.1**	**37.9**	**66.1**	**57.7**	**186.6**	**287.1**	**183.0**
Successful Lysimeter Standard Dev.		4.6	26.1	19.3	30.7	N/a	N/a	N/a
Successful Lysimeter 95% Conf. Limit		4.4	25.4	18.8	29.9	N/a	N/a	N/a

NB – Lysimeters in bold are 'successful'
no data due to cessation of sampling in June 2002

Table A6.8: Brandon Marsh Lysimeters Standing Crop Values

6.3 SURVEY DATES

able A6.9 presents the actual survey dates and the months for which the monitoring eriod provided data.

MONTH	MONITORING PERIOD		NUMBER OF DAYS
	FROM	TO	
Jan-01	04-Jan-01	01-Feb-01	28
Feb-01	02-Feb-01	26-Feb-01	24
Mar-01	26-Feb-01	05-Apr-01	38
Apr-01	05-Apr-01	30-Apr-01	25
May-01	30-Apr-01	31-May-01	31
Jun-01	31-May-01	29-Jun-01	29
Jul-01	29-Jun-01	31-Jul-01	32
Aug-01	31-Jul-01	29-Aug-01	29
Sep-01	29-Aug-01	01-Oct-01	33
Oct-01	01-Oct-01	31-Oct-01	30
Nov-01	31-Oct-01	28-Nov-01	28
Dec-01	28-Nov-01	20-Dec-01	22
Jan-02	20-Dec-01	31-Jan-02	42
Feb-02	31-Jan-02	01-Mar-02	29
Mar-02	01-Mar-02	03-Apr-02	33
Apr-02	03-Apr-02	01-May-02	28
May-02	01-May-02	31-May-02	30
Jun-02	31-May-02	26-Jun-02	26

Table A6.9: Survey Dates for Brandon Marsh, 2001-2002

A6.4 ET(Reed) DATA

	ET(Reed) mm day^{-1}												
LYSIMETER	**Jan-01**	**Feb-01**	**Mar-01**	**Apr-01**	**May-01**	**Jun-01**	**Jul-01**	**Aug-01**	**Sep-01**	**Oct-01**	**Nov-01**	**Dec-01**	**Annual**
1	0.09	0.31	0.41	0.72	0.96	0.90	1.31	0.24	0.14	0.41	0.42	0.55	0.54
2	**0.35**	**1.13**	**over**	**0.93**	**over**	**1.76**	**1.91**	**1.57**	**0.79**	**0.72**	**0.36**	**0.41**	**n/a**
3	0.07	0.53	over	0.89	over	1.39	1.53	0.76	0.33	0.95	0.40	0.39	n/a
4	error	0.25	0.40	0.71	1.31	1.87	1.71	1.44	0.67	0.59	0.18	0.34	n/a
5	0.14	0.48	0.54	0.87	1.21	1.23	1.61	0.73	0.34	0.63	0.31	0.22	0.69
6	0.04	0.51	0.54	0.67	1.08	1.31	1.23	0.60	0.53	0.50	0.08	0.04	0.59
7	error	0.03	0.25	0.62	1.31	1.59	1.54	1.28	0.67	0.49	0.09	0.12	n/a
8	0.03	0.30	0.49	0.54	1.13	1.40	1.56	0.87	0.32	0.95	0.34	0.23	0.68
9	0.08	0.37	0.56	0.89	1.34	1.65	1.40	0.78	0.48	0.59	0.30	0.20	0.72
10	error	0.25	0.36	0.80	1.26	1.74	1.32	0.19	0.33	0.50	0.13	0.18	n/a
Mean (Successful)	**0.35**	**1.13**	**over**	**0.93**	**over**	**1.76**	**1.91**	**1.57**	**0.79**	**0.72**	**0.36**	**0.41**	**n/a**
SE (Successful)	-	-	-	-	-	-	-	-	-	-	-	-	-

error - a sampling error resulted in a negative value and is therefore not presented
no data - no data collected due to site restrictions associated with outbreak of foot and mouth disease
SE - Standard Error

over - the lysimeter overtopped and data was lost
Lysimeters in bold are 'successful'

Table A6.10: Brandon Marsh Mean Monthly ET(Reed), 2001

	ET(Reed) mm day^{-1}												
LYSIMETER	**Jan-02**	**Feb-02**	**Mar-02**	**Apr-02**	**May-02**	**Jun-02**	**Jul-02**	**Aug-02**	**Sep-02**	**Oct-02**	**Nov-02**	**Dec-02**	**Annual**
1	0.49	0.40	0.46	0.92	1.02	0.97	no data	no data	no data	no data	no data	no data	n/a
2	**0.41**	**0.23**	**0.45**	**1.08**	**1.56**	**1.43**	**no data**	**no data**	**no data**	**no data**	**no data**	**no data**	**n/a**
3	**0.34**	**0.36**	**0.44**	**1.05**	**1.49**	**1.44**	**no data**	**no data**	**no data**	**no data**	**no data**	**no data**	**n/a**
4	0.29	error	0.39	0.99	1.34	1.25	no data	no data	no data	no data	no data	no data	n/a
5	**0.47**	**0.23**	**0.37**	**0.87**	**1.38**	**1.12**	**no data**	**no data**	**no data**	**no data**	**no data**	**no data**	**n/a**
6	**0.13**	**error**	**0.34**	**0.68**	**1.18**	**1.12**	**no data**	**no data**	**no data**	**no data**	**no data**	**no data**	**n/a**
7	**0.16**	**error**	**0.35**	**0.99**	**1.33**	**1.28**	**no data**	**no data**	**no data**	**no data**	**no data**	**no data**	**n/a**
8	0.44	error	0.30	0.88	1.22	1.13	no data	no data	no data	no data	no data	no data	n/a
9	**0.31**	**0.09**	**0.48**	**1.12**	**1.42**	**1.35**	**no data**	**no data**	**no data**	**no data**	**no data**	**no data**	**n/a**
10	0.04	error	0.47	1.16	1.23	1.10	no data	no data	no data	no data	no data	no data	n/a
Mean (Successful)	**0.30**	**0.23**	**0.41**	**0.97**	**1.39**	**1.29**	**no data**	**no data**	**no data**	**no data**	**no data**	**no data**	**n/a**
SE (Successful)	*0.06*	*0.06*	*0.02*	*0.07*	*0.05*	*0.06*	*no data*	*no data*	*no data*	*no data*	*no data*	*no data*	-

error - a sampling error resulted in a negative value and is therefore not presented
no data - no data collected due to site restrictions associated with outbreak of foot and mouth disease
SE - Standard Error

over - the lysimeter overtopped and data was lost
Lysimeters in bold are 'successful'

Table A6.11: Brandon Marsh Mean Monthly ET(Reed), 2002

A6.5 RAINFALL DATA

		RAINFALL (mm)												
Source	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
On-site Rain Gauge	2001	28.4	58.4	101.6	66.4	53.8	42.1	100.2	34.9	61.4	92.0	29.0	29.2	697.4
	2002	56.3	58.0	36.5	32.5	66.5	35.5	no data	no data	no data	no data	no data	no data	n/a
Local Met Station	2001	35.1	72.6	71.8	88.7	60.8	59.0	59.6	73.3	110.4	92.6	94.7	19.4	838.0
	2002	48.3	298.7	91.3	46.6	55.2	31.8	70.6	51.4	27.4	68.2	100.6	89.4	979.5
MORECS Sq. 137	2001	42.2	67.4	72.5	89.1	40.9	39.6	61.2	47.2	63.7	95.9	46.3	22.4	688.4
	2002	50.4	78.9	37.0	45.5	62.8	36.5	81.3	44.9	27.2	124.0	103.4	80.0	771.9

no data - no data collected due to cessation of sampling in June 2002

Table A6.12: Monthly Rainfall Totals from Various Sources at Brandon Marsh, 2001-2002

A6.6 ETo DATA

Source	Year	ETo (mm)												
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Evaporation Pan	2001	error	14.7	17.3	32.5	90.3	99.8	57.2	73.8	45.6	27.0	7.9	error	n/a
	2002	6.8	6.1	41.3	60.8	72.7	74.7	no data	no data	no data	no data	no data	no data	n/a
Local Met Station	2001	10.0	16.3	27.2	55.6	86.2	85.9	89.7	79.7	54.3	39.3	13.2	7.6	565.0
	2002	17.5	28.7	38.2	61.5	89.6	83.3	90.9	72.0	51.8	33.6	17.7	12.7	597.5
MORECS Sq. 137	2001	8.9	14.2	27.0	55.1	87.5	92.8	94.6	81.3	57.8	38.7	14.9	9.9	582.7
	2002	12.8	27.4	37.0	65.4	86.0	86.2	89.9	75.5	57.7	35.8	18.0	11.6	603.3

error - a sampling error resulted in a negative value and is therefore not presented
no data - no data collected due to cessation of sampling in June 2002

Table A6.13: Monthly ETo Totals from Various Sources at Brandon Marsh, 2001-2002

A6.7 Kc(Reed) DATA

	Kc(Reed) Pan												
LYSIMETER	**Jan-01**	**Feb-01**	**Mar-01**	**Apr-01**	**May-01**	**Jun-01**	**Jul-01**	**Aug-01**	**Sep-01**	**Oct-01**	**Nov-01**	**Dec-01**	**Annual**
1	0.03	0.09	0.12	0.21	0.28	0.26	-	0.07	0.04	0.12	0.12	0.16	n/a
2	**0.10**	**0.33**	**over**	**0.27**	**over**	**0.51**	-	**0.46**	**0.23**	**0.21**	**0.10**	**0.12**	**n/a**
3	0.02	0.15	over	0.26	over	0.40	-	0.22	0.10	0.28	0.12	0.11	n/a
4	error	0.07	0.12	0.21	0.38	0.54	-	0.42	0.19	0.17	0.05	0.10	n/a
5	0.04	0.14	0.16	0.25	0.35	0.36	-	0.21	0.10	0.18	0.09	0.06	n/a
6	0.01	0.15	0.16	0.19	0.31	0.38	-	0.17	0.15	0.15	0.02	0.01	n/a
7	error	0.01	0.07	0.18	0.38	0.46	-	0.37	0.19	0.14	0.03	0.03	n/a
8	0.01	0.09	0.14	0.16	0.33	0.41	-	0.25	0.09	0.28	0.10	0.07	n/a
9	0.02	0.11	0.16	0.26	0.39	0.48	-	0.23	0.14	0.17	0.09	0.06	n/a
10	error	0.07	0.10	0.23	0.37	0.51	-	0.06	0.10	0.15	0.04	0.05	n/a
Mean (Successful)	**0.10**	**0.33**	**over**	**0.27**	**over**	**0.51**	-	**0.46**	**0.23**	**0.21**	**0.10**	**0.12**	**n/a**
SE (Successful)	-	-	-	-	-	-	-	-	-	-	-	-	-

error - a sampling error resulted in a negative value and is therefore not presented
over - the lysimeter overtopped and data was lost
SE - Standard Error
Lysimeters in bold are 'successful'

Table A6.13: Brandon Marsh Mean Monthly Kc(Reed) Pan, 2001

	Kc(Reed) Pan												
LYSIMETER	**Jan-02**	**Feb-02**	**Mar-02**	**Apr-02**	**May-02**	**Jun-02**	**Jul-02**	**Aug-02**	**Sep-02**	**Oct-02**	**Nov-02**	**Dec-02**	**Annual**
1	0.20	0.17	0.19	0.38	0.42	0.40	no data	no data	no data	no data	no data	no data	n/a
2	**0.17**	**0.09**	**0.19**	**0.45**	**0.64**	**0.59**	**no data**	**no data**	**no data**	**no data**	**no data**	**no data**	**n/a**
3	**0.14**	**0.15**	**0.18**	**0.43**	**0.62**	**0.59**	**no data**	**no data**	**no data**	**no data**	**no data**	**no data**	**n/a**
4	0.12	error	0.16	0.41	0.55	0.52	no data	no data	no data	no data	no data	no data	n/a
5	**0.19**	**0.09**	**0.15**	**0.36**	**0.57**	**0.46**	**no data**	**no data**	**no data**	**no data**	**no data**	**no data**	**n/a**
6	**0.05**	**error**	**0.14**	**0.28**	**0.49**	**0.46**	**no data**	**no data**	**no data**	**no data**	**no data**	**no data**	**n/a**
7	**0.07**	**error**	**0.14**	**0.41**	**0.55**	**0.53**	**no data**	**no data**	**no data**	**no data**	**no data**	**no data**	**n/a**
8	0.18	error	0.12	0.36	0.50	0.47	no data	no data	no data	no data	no data	no data	n/a
9	**0.13**	**0.04**	**0.20**	**0.46**	**0.59**	**0.56**	**no data**	**no data**	**no data**	**no data**	**no data**	**no data**	**n/a**
10	0.02	error	0.19	0.48	0.51	0.45	no data	no data	no data	no data	no data	no data	n/a
Mean (Successful)	**0.13**	**0.09**	**0.17**	**0.40**	**0.58**	**0.53**	**no data**	**no data**	**no data**	**no data**	**no data**	**no data**	**n/a**
SE (Successful)	*0.02*	*0.02*	*0.01*	*0.03*	*0.02*	*0.02*	-	-	-	-	-	-	

error - a sampling error resulted in a negative value and is therefore not presented
no data - no data collected due to cessation of sampling in June 2002
SE - Standard Error
Lysimeters in bold are 'successful'

Table A6.14: Brandon Marsh Mean Monthly Kc(Reed) Pan, 2002

	Kc(Reed) LMS Grass												
LYSIMETER	**Jan-01**	**Feb-01**	**Mar-01**	**Apr-01**	**May-01**	**Jun-01**	**Jul-01**	**Aug-01**	**Sep-01**	**Oct-01**	**Nov-01**	**Dec-01**	**Annual**
1	0.03	0.11	0.15	0.26	0.35	0.32	0.47	0.09	0.05	0.15	0.15	0.20	0.19
2	**0.13**	**0.41**	**over**	**0.33**	**over**	**0.63**	**0.69**	**0.56**	**0.28**	**0.26**	**0.13**	**0.15**	**n/a**
3	0.03	0.19	over	0.32	over	0.50	0.55	0.27	0.12	0.34	0.14	0.14	n/a
4	error	0.09	0.14	0.26	0.47	0.67	0.61	0.52	0.24	0.21	0.06	0.12	n/a
5	0.05	0.17	0.19	0.31	0.44	0.44	0.58	0.26	0.12	0.23	0.11	0.08	0.25
6	0.01	0.18	0.19	0.24	0.39	0.47	0.44	0.22	0.19	0.18	0.03	0.01	0.21
7	error	0.01	0.09	0.22	0.47	0.57	0.55	0.46	0.24	0.18	0.03	0.04	n/a
8	0.01	0.11	0.18	0.19	0.41	0.50	0.56	0.31	0.12	0.34	0.12	0.08	0.24
9	0.03	0.13	0.20	0.32	0.48	0.59	0.50	0.28	0.17	0.21	0.11	0.07	0.26
10	error	0.09	0.13	0.29	0.45	0.63	0.47	0.07	0.12	0.18	0.05	0.06	n/a
Mean (Successful)	**0.13**	**0.41**	**over**	**0.33**	**over**	**0.63**	**0.69**	**0.56**	**0.28**	**0.26**	**0.13**	**0.15**	**n/a**
SE (Successful)	-	-	-	-	-	-	-	-	-	-	-	-	-

error - a sampling error resulted in a negative value and is therefore not presented
over - the lysimeter overtopped and data was lost
SE - Standard Error
Lysimeters in bold are 'successful'

Table A6.15: Brandon Marsh Mean Monthly Kc(Reed) LMS Grass, 2001

	Kc(Reed) LMS Grass												
LYSIMETER	**Jan-02**	**Feb-02**	**Mar-02**	**Apr-02**	**May-02**	**Jun-02**	**Jul-02**	**Aug-02**	**Sep-02**	**Oct-02**	**Nov-02**	**Dec-02**	**Annual**
1	0.17	0.14	0.16	0.31	0.35	0.33	no data	no data	no data	no data	no data	no data	n/a
2	**0.14**	**0.08**	**0.15**	**0.37**	**0.53**	**0.49**	**no data**	**no data**	**no data**	**no data**	**no data**	**no data**	**n/a**
3	**0.12**	**0.12**	**0.15**	**0.36**	**0.51**	**0.49**	**no data**	**no data**	**no data**	**no data**	**no data**	**no data**	**n/a**
4	0.10	error	0.13	0.34	0.46	0.43	no data	no data	no data	no data	no data	no data	n/a
5	**0.16**	**0.08**	**0.13**	**0.30**	**0.47**	**0.38**	**no data**	**no data**	**no data**	**no data**	**no data**	**no data**	**n/a**
6	**0.04**	**error**	**0.12**	**0.23**	**0.40**	**0.38**	**no data**	**no data**	**no data**	**no data**	**no data**	**no data**	**n/a**
7	**0.05**	**error**	**0.12**	**0.34**	**0.45**	**0.44**	**no data**	**no data**	**no data**	**no data**	**no data**	**no data**	**n/a**
8	0.15	error	0.10	0.30	0.42	0.39	no data	no data	no data	no data	no data	no data	n/a
9	**0.11**	**0.03**	**0.16**	**0.38**	**0.48**	**0.46**	**no data**	**no data**	**no data**	**no data**	**no data**	**no data**	**n/a**
10	0.01	error	0.16	0.40	0.42	0.38	no data	no data	no data	no data	no data	no data	n/a
Mean (Successful)	**0.10**	**0.08**	**0.14**	**0.33**	**0.48**	**0.44**	**no data**	**no data**	**no data**	**no data**	**no data**	**no data**	**n/a**
SE (Successful)	*0.02*	*0.02*	*0.01*	*0.02*	*0.02*	*0.02*	-	-	-	-	-	-	-

error - a sampling error resulted in a negative value and is therefore not presented
no data - no data collected due to cessation of sampling in June 2002
SE - Standard Error
Lysimeters in bold are 'successful'

Table A6.16: Brandon Marsh Mean Monthly Kc(Reed) LMS Grass, 2002

	Kc(Reed) MORECS Grass												
LYSIMETER	**Jan-01**	**Feb-01**	**Mar-01**	**Apr-01**	**May-01**	**Jun-01**	**Jul-01**	**Aug-01**	**Sep-01**	**Oct-01**	**Nov-01**	**Dec-01**	**Annual**
1	0.03	0.11	0.15	0.26	0.34	0.32	0.46	0.09	0.05	0.15	0.15	0.19	0.19
2	**0.12**	**0.40**	**over**	**0.33**	**over**	**0.62**	**0.68**	**0.56**	**0.28**	**0.26**	**0.13**	**0.15**	**n/a**
3	0.02	0.19	over	0.32	over	0.49	0.54	0.27	0.12	0.34	0.14	0.14	n/a
4	error	0.09	0.14	0.25	0.46	0.66	0.61	0.51	0.24	0.21	0.06	0.12	n/a
5	0.05	0.17	0.19	0.31	0.43	0.44	0.57	0.26	0.12	0.22	0.11	0.08	0.25
6	0.01	0.18	0.19	0.24	0.38	0.46	0.44	0.21	0.19	0.18	0.03	0.01	0.21
7	error	0.01	0.09	0.22	0.46	0.56	0.55	0.45	0.24	0.17	0.03	0.04	n/a
8	0.01	0.11	0.17	0.19	0.40	0.50	0.55	0.31	0.11	0.34	0.12	0.08	0.24
9	0.03	0.13	0.20	0.32	0.47	0.58	0.50	0.28	0.17	0.21	0.11	0.07	0.26
10	error	0.09	0.13	0.28	0.45	0.62	0.47	0.07	0.12	0.18	0.05	0.06	n/a
Mean (Successful)	**0.12**	**0.40**	**over**	**0.33**	**over**	**0.62**	**0.68**	**0.56**	**0.28**	**0.26**	**0.13**	**0.15**	**n/a**
SE (Successful)	-	-	-	-	-	-	-	-	-	-	-	-	-

error - a sampling error resulted in a negative value and is therefore not presented
over - the lysimeter overtopped and data was lost
SE - Standard Error
Lysimeters in bold are 'successful'

Table A6.17: Brandon Marsh Mean Monthly Kc(Reed) MORECS Grass, 2001

	Kc(Reed) MORECS Grass												
LYSIMETER	**Jan-02**	**Feb-02**	**Mar-02**	**Apr-02**	**May-02**	**Jun-02**	**Jul-02**	**Aug-02**	**Sep-02**	**Oct-02**	**Nov-02**	**Dec-02**	**Annual**
1	0.17	0.14	0.16	0.32	0.35	0.33	no data	no data	no data	no data	no data	no data	n/a
2	**0.14**	**0.08**	**0.16**	**0.37**	**0.54**	**0.49**	**no data**	**no data**	**no data**	**no data**	**no data**	**no data**	**n/a**
3	**0.12**	**0.12**	**0.15**	**0.36**	**0.51**	**0.50**	**no data**	**no data**	**no data**	**no data**	**no data**	**no data**	**n/a**
4	0.10	error	0.13	0.34	0.46	0.43	no data	no data	no data	no data	no data	no data	n/a
5	**0.16**	**0.08**	**0.13**	**0.30**	**0.48**	**0.39**	**no data**	**no data**	**no data**	**no data**	**no data**	**no data**	**n/a**
6	**0.04**	**error**	**0.12**	**0.23**	**0.41**	**0.39**	**no data**	**no data**	**no data**	**no data**	**no data**	**no data**	**n/a**
7	**0.06**	**error**	**0.12**	**0.34**	**0.46**	**0.44**	**no data**	**no data**	**no data**	**no data**	**no data**	**no data**	**n/a**
8	0.15	error	0.10	0.30	0.42	0.39	no data	no data	no data	no data	no data	no data	n/a
9	**0.11**	**0.03**	**0.17**	**0.39**	**0.49**	**0.47**	**no data**	**no data**	**no data**	**no data**	**no data**	**no data**	**n/a**
10	0.01	error	0.16	0.40	0.42	0.38	no data	no data	no data	no data	no data	no data	n/a
Mean (Successful)	**0.10**	**0.08**	**0.14**	**0.33**	**0.48**	**0.44**	**no data**	**no data**	**no data**	**no data**	**no data**	**no data**	**n/a**
SE (Successful)	*0.02*	*0.02*	*0.01*	*0.02*	*0.02*	*0.02*	-	-	-	-	-	-	-

error - a sampling error resulted in a negative value and is therefore not presented
no data - no data collected due to cessation of sampling in June 2002
SE - Standard Error
Lysimeters in bold are 'successful'

Table A6.18: Brandon Marsh Mean Monthly Kc(Reed) MORECS Grass, 2002

A6.8 MEASURED REEDBED WATER LEVELS

	MEASURED REEDBED WATER LEVEL (m.a.g.l.)											
YEAR	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
2001	0.31	0.31	0.36	0.31	0.28	0.18	0.12	Dry	0.00	0.00	0.00	0.00
2002	0.06	0.130	0.19	0.16	0.12	0.06	no data	no data	no data	no data	no data	no data

no data - no data collected due to cessation of sampling in June 2002

Table A6.19: Brandon Marsh Measured Reedbed Water Levels, 2001-2002

APPENDIX 7.
LEIGHTON MOSS DATA

A7.1 QUADRAT CROP CHARACTERISTIC DATA

The total number of inflorescence recorded in each quadrat is presented in Table A7.1. Tables A7.2, A7.3 and A7.4 present the crop height, crop density and standing crop values of the quadrats within the reedbed. Crop characteristics were measured between March and September.

QUADRAT	YEAR	TOTAL NO. OF INFLORESCENCE RECORDED
A	2001	26
B	2001	23
C	2001	17
D	2001	22
A	2002	no data
B	2002	no data
C	2002	no data
D	2002	no data

NB – no data due to cessation of monitoring in June 2002

Table A7.1: Leighton Moss Reedbed Inflorescence Data

		CROP HEIGHT (m)						
QUADRAT	YEAR	Mar	Apr	May	Jun	Jul	Aug	Sep
A	2001	0.15	1.01	2.00	2.10	2.40	2.35	2.10
B	2001	0.20	0.97	1.76	2.31	2.28	2.30	2.30
C	2001	0.00	1.24	1.74	2.23	2.40	2.46	2.40
D	2001	0.00	1.06	1.72	2.23	2.30	2.29	2.35
A	2002	0.27	0.86	1.69	2.10	no data	no data	no data
B	2002	0.25	0.82	1.68	1.90	no data	no data	no data
C	2002	0.22	0.93	1.63	1.90	no data	no data	no data
D	2002	0.32	0.87	1.70	1.90	no data	no data	no data
Mean		**0.27**	**0.48**	**1.74**	**2.08**	**2.35**	**2.35**	**2.29**
Standard Dev.		0.04	0.42	0.11	0.17	0.06	0.08	0.13
95% Conf. Limit		0.03	0.29	0.08	0.12	0.06	0.08	0.13

NB – no data due to cessation of monitoring in June 2002

Table A7.2: Leighton Moss Reedbed Crop Height

		CROP DENSITY (stems m^{-2})						
QUADRAT	YEAR	Mar	Apr	May	Jun	Jul	Aug	Sep
A	2001	8	204	196	160	180	152	140
B	2001	4	272	260	228	188	156	112
C	2001	0	192	176	184	176	152	136
D	2001	0	212	204	180	156	156	104
A	2002	60	108	112	112	no data	no data	no data
B	2002	40	76	136	112	no data	no data	no data
C	2002	56	76	160	144	no data	no data	no data
D	2002	36	72	152	120	no data	no data	no data
Mean		**48.0**	**151.5**	**174.5**	**155.0**	**175.0**	**154.0**	**123.0**
Standard Dev.		11.8	77.6	45.9	41.2	13.6	2.3	17.7
95% Conf. Limit		8.2	53.8	31.8	28.5	13.3	2.3	17.3

NB – no data due to cessation of monitoring in June 2002

Table A7.3: Leighton Moss Reedbed Crop Density

		STANDING CROP						
QUADRAT	**YEAR**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
A	2001	1.2	206.45	392	336	432	357.2	294
B	2001	0.8	262.75	457.6	526.68	428.64	358.8	257.6
C	2001	0	238.46	306.24	410.32	422.4	373.92	326.4
D	2001	0	224.3	350.88	401.4	358.8	357.24	244.4
A	2002	16.2	92.9	189.3	235.2	no data	no data	no data
B	2002	10.0	62.3	228.5	212.8	no data	no data	no data
C	2002	12.3	70.7	260.8	273.6	no data	no data	no data
D	2002	11.5	62.6	258.4	228.0	no data	no data	no data
Mean		**6.5**	**152.6**	**305.5**	**328.0**	**410.5**	**361.8**	**280.6**
Standard Dev.		6.7	87.9	89.7	111.2	34.7	8.1	37.0
95% Conf. Limit		4.6	60.9	62.2	77.0	34.0	8.0	36.3

NB – no data due to cessation of monitoring in June 2002

Table A7.4: Leighton Moss Reedbed Standing Crop Values

A7.2 LYSIMETER CROP CHARACTERISTIC DATA

The total number of inflorescence recorded in each lysimeter is presented in Table A7.5. Tables A7.6, A7.7 and A7.8 present the crop height, crop density and standing crop values of the lysimeters. Crop characteristic data was measured between March and September.

QUADRAT	YEAR	TOTAL NO. OF INFLORESCENCE RECORDED
1	2001	1
2	2001	2
3	2001	5
4	2001	0
5	2001	3
6	2001	2
7	2001	3
8	2001	4
9	2001	4
10	2001	2
11	2001	4
12	2001	1
1	2002	no data
2	2002	no data
3	2002	no data
4	2002	no data
5	2002	no data
6	2002	no data
7	2002	no data
8	2002	no data
9	2002	no data
10	2002	no data
11	2002	no data
12	2002	no data

NB – no data due to cessation of sampling in June 2002
Lysimeters in bold are 'successful'

Table A7.5: Leighton Moss Lysimeters Inflorescence Data

		CROP HEIGHT (m)						
LYSIMETER	YEAR	Mar	Apr	May	Jun	Jul	Aug	Sep
1	2001	0.10	1.01	1.09	1.44	1.65	1.89	1.67
2	2001	0.09	1.15	1.24	1.74	1.95	1.95	2.15
3	2001	0.10	0.85	1.15	1.55	1.70	1.78	1.60
4	2001	0.09	0.97	1.18	1.75	1.77	1.77	1.40
5	2001	0.11	1.04	1.14	1.86	1.73	2.45	1.90
6	2001	0.08	1.10	1.60	1.41	1.90	1.95	1.96
7	2001	0.00	0.00	1.15	1.71	2.10	1.94	1.50
8	2001	0.12	0.92	1.38	1.97	2.05	2.04	2.05
9	2001	0.13	1.08	1.47	2.05	2.10	2.08	2.10
10	2001	0.12	1.06	1.33	1.87	1.80	2.10	1.95
11	2001	0.09	0.46	1.08	1.65	1.68	1.80	1.80
12	2001	0.16	0.81	1.10	1.36	1.60	1.50	1.40
1	2002	0.15	0.40	0.71	0.75	no data	no data	no data
2	2002	0.00	0.27	0.77	1.10	no data	no data	no data
3	2002	0.16	0.20	1.15	1.70	no data	no data	no data
4	2002	0.20	0.46	0.94	1.50	no data	no data	no data
5	2002	0.00	0.52	0.88	1.10	no data	no data	no data
6	2002	0.90	0.30	0.63	1.05	no data	no data	no data
7	2002	0.16	0.46	0.97	1.27	no data	no data	no data
8	2002	0.36	0.75	0.92	1.15	no data	no data	no data
9	2002	0.19	0.44	1.09	1.45	no data	no data	no data
10	2002	0.34	0.60	0.99	1.40	no data	no data	no data
11	2002	0.19	0.40	1.10	1.50	no data	no data	no data
12	2002	0.10	0.30	0.59	0.65	no data	no data	no data
Successful Lysimeters Mean		**N/a**	**N/a**	**N/a**	**N/a**	**N/a**	**N/a**	**N/a**
Successful Lysimeters Standard Dev.		N/a	N/a	N/a	N/a	N/a	N/a	N/a
Successful Lysimeters 95% Conf. Limit		N/a	N/a	N/a	N/a	N/a	N/a	N/a

NB – no data due to cessation of sampling in June 2002
Lysimeters in bold are 'successful'

Table A7.6: Leighton Moss Lysimeters Reed Height

LYSIMETER	YEAR	CROP DENSITY (stems m^{-2}) Mar	Apr	May	Jun	Jul	Aug	Sep
1	2001	20	48	28	16	16	16	8
2	2001	37	53	61	73	41	41	24
3	2001	69	106	101	130	97	61	53
4	2001	26	26	65	70	52	35	39
5	2001	24	20	65	57	41	49	28
6	2001	13	13	64	64	51	43	30
7	2001	0	0	85	81	53	53	37
8	2001	20	8	96	72	64	48	24
9	2001	16	16	96	104	60	44	32
10	2001	84	44	84	76	64	56	36
11	2001	99	149	132	161	132	95	83
12	2001	28	44	64	80	48	44	8
1	2002	4	4	8	8	no data	no data	no data
2	2002	0	4	4	8	no data	no data	no data
3	2002	57	81	73	69	no data	no data	no data
4	2002	13	13	13	13	no data	no data	no data
5	2002	0	4	8	16	no data	no data	no data
6	2002	39	39	43	34	no data	no data	no data
7	2002	20	28	32	28	no data	no data	no data
8	2002	12	8	20	8	no data	no data	no data
9	2002	56	52	60	64	no data	no data	no data
10	2002	24	16	16	24	no data	no data	no data
11	2002	33	62	70	70	no data	no data	no data
12	2002	16	20	24	16	no data	no data	no data
Successful Lysimeters Mean		**N/a**	**N/a**	**N/a**	**N/a**	**N/a**	**N/a**	**N/a**
Successful Lysimeters Standard Dev.		N/a	N/a	N/a	N/a	N/a	N/a	N/a
Successful Lysimeters 95% Conf. Limit		N/a	N/a	N/a	N/a	N/a	N/a	N/a

NB – no data due to cessation of sampling in June 2002
Lysimeters in bold are 'successful'

Table A7.7: Leighton Moss Lysimeters Crop Density

		STANDING CROP						
LYSIMETER	**YEAR**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
1	2001	2.0	48.3	30.4	23.0	26.3	30.1	13.3
2	2001	3.3	60.7	75.5	127.1	79.2	79.2	52.4
3	2001	6.9	89.7	116.7	201.4	165.6	108.4	84.4
4	2001	2.4	25.4	77.3	122.2	92.7	61.8	55.0
5	2001	2.7	21.1	74.0	105.7	70.2	119.4	54.0
6	2001	1.0	14.1	102.9	90.7	97.7	83.6	58.8
7	2001	0.0	0.0	98.0	138.8	110.8	102.4	54.8
8	2001	2.4	7.3	132.1	141.4	130.8	97.6	49.1
9	2001	2.1	17.2	140.7	212.6	125.6	91.2	67.0
10	2001	10.0	46.5	111.4	141.7	114.9	117.2	70.0
11	2001	8.9	68.4	142.8	266.0	222.2	171.1	148.8
12	2001	4.5	35.5	70.2	108.5	76.6	65.8	11.2
1	2002	0.6	1.6	5.7	6.0	no data	no data	no data
2	2002	0.0	1.1	3.1	8.9	no data	no data	no data
3	2002	9.1	16.2	84.0	117.3	no data	no data	no data
4	2002	2.6	6.0	12.3	19.6	no data	no data	no data
5	2002	0.0	2.1	7.1	17.9	no data	no data	no data
6	2002	34.7	11.6	27.0	36.0	no data	no data	no data
7	2002	3.2	13.1	31.5	36.1	no data	no data	no data
8	2002	4.3	6.0	18.3	9.2	no data	no data	no data
9	2002	10.6	22.8	65.2	92.5	no data	no data	no data
10	2002	8.1	9.6	15.8	33.5	no data	no data	no data
11	2002	6.3	24.8	77.3	105.4	no data	no data	no data
12	2002	1.6	6.0	14.1	10.4	no data	no data	no data
Successful Lysimeters Mean		**N/a**	**N/a**	**N/a**	**N/a**	**N/a**	**N/a**	**N/a**
Successful Lysimeters Standard Dev.		N/a	N/a	N/a	N/a	N/a	N/a	N/a
Successful Lysimeters 95% Conf. Limit		N/a	N/a	N/a	N/a	N/a	N/a	N/a

NB – no data due to cessation of sampling in June 2002
Lysimeters in bold are 'successful'

Table A7.8: Leighton Moss Lysimeters Standing Crop Values

A7.3 SURVEY DATES

Table A7.9 presents the actual survey dates and the months for which the monitoring period provided data.

MONTH	MONITORING PERIOD		NUMBER OF DAYS
	FROM	TO	
Jan-01	26-Dec-00	31-Jan-01	36
Feb-01	31-Jan-01	28-Feb-01	28
Mar-01	28-Feb-01	04-Apr-01	35
Apr-01	04-Apr-01	14-May-01	40
May-01	14-May-01	05-Jun-01	22
Jun-01	05-Jun-01	03-Jul-01	28
Jul-01	03-Jul-01	02-Aug-01	30
Aug-01	02-Aug-01	04-Sep-01	33
Sep-01	04-Sep-01	04-Oct-01	30
Oct-01	04-Oct-01	01-Nov-01	28
Nov-01	01-Nov-01	05-Dec-01	34
Dec-01	05-Dec-01	22-Dec-01	17
Jan-02	22-Dec-01	flooded	n/a
Feb-02	flooded	03-Mar-02	n/a
Mar-02	03-Mar-02	05-Apr-02	33
Apr-02	05-Apr-02	02-May-02	27
May-02	02-May-02	27-May-02	25
Jun-02	27-May-02	27-Jun-02	31

Table A7.9: Survey Dates for Leighton Moss, 2001-2002

A7.4 ET(Reed) DATA

	ET(Reed) mm day^{-1}												
LYSIMETER	**Jan-01**	**Feb-01**	**Mar-01**	**Apr-01**	**May-01**	**Jun-01**	**Jul-01**	**Aug-01**	**Sep-01**	**Oct-01**	**Nov-01**	**Dec-01**	**Annual**
1	0.28	over	0.67	1.22	0.07	0.82	0.85	1.13	1.85	0.98	over	0.31	n/a
2	0.31	over	0.77	1.26	0.16	1.18	1.23	1.30	1.71	1.19	over	0.38	n/a
3	0.41	over	0.68	1.36	1.40	1.70	1.56	1.81	2.02	1.22	over	0.47	n/a
4	0.28	over	0.69	1.34	error	1.05	1.11	1.11	1.77	0.94	over	0.33	n/a
5	0.38	over	0.74	1.37	0.35	1.14	1.32	1.55	1.91	0.95	over	0.24	n/a
6	0.15	over	0.60	1.34	1.13	1.42	1.34	1.22	2.03	0.83	over	0.32	n/a
7	0.26	over	0.60	1.18	0.18	0.96	1.20	2.02	2.58	1.08	over	error	n/a
8	0.30	over	0.77	1.53	0.38	1.45	1.52	1.50	2.00	0.87	over	0.41	n/a
9	0.01	over	0.57	1.19	0.64	1.56	1.40	1.84	2.51	1.64	over	0.42	n/a
10	0.31	over	0.74	1.64	0.46	1.48	1.27	1.43	1.74	1.18	over	0.35	n/a
11	0.44	over	0.75	2.78	1.84	1.99	1.59	2.27	2.86	1.36	over	0.40	n/a
12	0.39	over	0.79	1.44	1.01	1.23	1.23	2.05	2.48	1.55	over	error	n/a

error - a sampling error resulted in a negative value and is therefore not presented
over - the lysimeter overtopped and data was lost
Lysimeters in bold are 'successful'

Table A7.9: Leighton Moss Mean Monthly ET(Reed), 2001

	ET(Reed) mm day^{-1}												
LYSIMETER	**Jan-02**	**Feb-02**	**Mar-02**	**Apr-02**	**May-02**	**Jun-02**	**Jul-02**	**Aug-02**	**Sep-02**	**Oct-02**	**Nov-02**	**Dec-02**	**Annual**
1	no data	no data	no data	1.43	1.58	1.43	no data	no data	no data	no data	no data	no data	n/a
2	no data	no data	no data	1.49	1.58	1.39	no data	no data	no data	no data	no data	no data	n/a
3	no data	no data	no data	1.52	1.81	1.86	no data	no data	no data	no data	no data	no data	n/a
4	no data	no data	no data	1.41	1.57	1.18	no data	no data	no data	no data	no data	no data	n/a
5	no data	no data	no data	1.52	1.53	1.31	no data	no data	no data	no data	no data	no data	n/a
6	no data	no data	no data	1.36	1.50	1.51	no data	no data	no data	no data	no data	no data	n/a
7	no data	no data	no data	1.38	1.63	1.30	no data	no data	no data	no data	no data	no data	n/a
8	no data	no data	no data	1.40	1.56	1.40	no data	no data	no data	no data	no data	no data	n/a
9	no data	no data	no data	1.28	1.40	1.32	no data	no data	no data	no data	no data	no data	n/a
10	no data	no data	no data	1.46	1.45	1.39	no data	no data	no data	no data	no data	no data	n/a
11	no data	no data	no data	1.68	1.87	2.00	no data	no data	no data	no data	no data	no data	n/a
12	no data	no data	no data	1.54	1.66	1.46	no data	no data	no data	no data	no data	no data	n/a

no data - no data collected due to site flooding and cessation of sampling in June 2002
Lysimeters in bold are 'successful'

Table A7.10: Leighton Moss Mean Monthly ET(Reed), 2002

A7.5 RAINFALL DATA

		RAINFALL (mm)												
Source	**Year**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
On-site Rain Gauge	2001	76.1	124.2	76.6	81.7	46.5	55.5	38.1	106.0	124.5	92.9	120.0	13.0	955.1
	2002	no data	no data	57.5	68.6	72.0	75.6	no data	no data	no data	no data	no data	no data	n/a
Local Met Station	2001	65.4	265.4	60.8	95.8	54.0	69.8	29.4	108.6	129.6	103.4	106.8	60.4	1149.4
	2002	136.4	233.0	57.4	88.0	106.6	78.3	60.6	117.6	76.4	124.4	129.8	117.1	1325.6
MORECS Sq. 91	2001	82.4	116.0	71.1	108.1	54.1	48.5	77.9	97.1	127.5	177.3	103.4	77.4	1140.8
	2002	135.4	243.9	79.3	86.1	109.0	107.5	92.9	118.2	54.9	185.3	154.1	165.2	1531.8

no data - no data collected due to site flooding and cessation of sampling in June 2002

Table A7.12: Monthly Rainfall Totals from Various Sources at Leighton Moss, 2001-2002

A7.6 ETo DATA

Source	Year	ETo (mm)												
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Evaporation Pan	2001	error	25.1	24.2	62.5	41.6	61.4	72.9	48.7	23.9	8.5	8.3	error	n/a
	2002	no data	no data	18.6	30.1	35.0	59.5	no data	no data	no data	no data	no data	no data	n/a
Local Met Station	2001	11.6	14.7	33.1	53.8	99.1	88.3	101.5	75.7	58.5	51.8	19.4	15.5	623.0
	2002	13.5	21.8	38.9	63.3	98.1	93.7	78.1	68.0	61.3	33.1	21.6	13.5	604.9
MORECS Sq. 91	2001	15.0	15.7	31.4	53.1	91.2	81.5	91.0	73.2	57.2	47.7	23.0	12.3	592.3
	2002	16.6	24.6	38.2	58.0	81.0	82.1	75.5	65.3	42.9	36.2	21.5	14.0	555.9

error - a sampling error resulted in a negative value and is therefore not presented
no data - no data collected due to site flooding and cessation of sampling in June 2002

Table A7.13: Monthly ETo Totals from Various Sources at Leighton Moss, 2001-2002

A7.7 Kc(Reed) DATA

LYSIMETER	Kc(Reed) Pan												
	Jan-01	**Feb-01**	**Mar-01**	**Apr-01**	**May-01**	**Jun-01**	**Jul-01**	**Aug-01**	**Sep-01**	**Oct-01**	**Nov-01**	**Dec-01**	**Annual**
1	0.15	over	0.35	0.65	0.04	0.43	0.45	0.60	0.98	0.52	over	0.16	n/a
2	0.16	over	0.41	0.67	0.08	0.62	0.65	0.69	0.90	0.63	over	0.20	n/a
3	0.22	over	0.36	0.72	0.74	0.90	0.82	0.96	1.07	0.65	over	0.25	n/a
4	0.15	over	0.36	0.71	error	0.56	0.59	0.59	0.94	0.50	over	0.17	n/a
5	0.20	over	0.39	0.72	0.19	0.60	0.70	0.82	1.01	0.50	over	0.13	n/a
6	0.08	over	0.32	0.71	0.60	0.75	0.71	0.65	1.07	0.44	over	0.17	n/a
7	0.14	over	0.32	0.62	0.10	0.51	0.64	1.07	1.36	0.57	over	error	n/a
8	0.16	over	0.41	0.81	0.20	0.77	0.80	0.79	1.06	0.46	over	0.22	n/a
9	0.01	over	0.30	0.63	0.34	0.83	0.74	0.97	1.33	0.87	over	0.22	n/a
10	0.16	over	0.39	0.87	0.24	0.78	0.67	0.76	0.92	0.62	over	0.19	n/a
11	0.23	over	0.40	1.47	0.97	1.05	0.84	1.20	1.51	0.72	over	0.21	n/a
12	0.21	over	0.42	0.76	0.53	0.65	0.65	0.62	1.31	0.82	over	error	n/a

error - a sampling error resulted in a negative value and is therefore not presented
over - the lysimeter / evaporation pan overtopped and data was lost
Lysimeters in bold are 'successful'

Table A7.13: Leighton Moss Mean Monthly Kc(Reed) Pan, 2001

	Kc(Reed) Pan												
LYSIMETER	**Jan-02**	**Feb-02**	**Mar-02**	**Apr-02**	**May-02**	**Jun-02**	**Jul-02**	**Aug-02**	**Sep-02**	**Oct-02**	**Nov-02**	**Dec-02**	**Annual**
1	no data	no data	no data	1.02	1.13	1.02	no data	no data	no data	no data	no data	no data	n/a
2	no data	no data	no data	1.07	1.13	0.99	no data	no data	no data	no data	no data	no data	n/a
3	no data	no data	no data	1.09	1.29	1.33	no data	no data	no data	no data	no data	no data	n/a
4	no data	no data	no data	1.01	1.12	0.84	no data	no data	no data	no data	no data	no data	n/a
5	no data	no data	no data	1.09	1.09	0.94	no data	no data	no data	no data	no data	no data	n/a
6	no data	no data	no data	0.97	1.07	1.08	no data	no data	no data	no data	no data	no data	n/a
7	no data	no data	no data	0.99	1.17	0.93	no data	no data	no data	no data	no data	no data	n/a
8	no data	no data	no data	1.00	1.12	1.00	no data	no data	no data	no data	no data	no data	n/a
9	no data	no data	no data	0.92	1.00	0.94	no data	no data	no data	no data	no data	no data	n/a
10	no data	no data	no data	1.04	1.04	0.99	no data	no data	no data	no data	no data	no data	n/a
11	no data	no data	no data	1.20	1.34	1.43	no data	no data	no data	no data	no data	no data	n/a
12	no data	no data	no data	1.10	1.19	1.04	no data	no data	no data	no data	no data	no data	n/a

no data - no data collected due to site flooding and cessation of sampling in June 2002
Lysimeters in bold are 'successful'

Table A7.14: Leighton Moss Mean Monthly Kc(Reed) Pan, 2002

	Kc(Reed) LMS Grass												
LYSIMETER	Jan-01	Feb-01	Mar-01	Apr-01	May-01	Jun-01	Jul-01	Aug-01	Sep-01	Oct-01	Nov-01	Dec-01	Annual
1	0.09	over	0.21	0.38	0.02	0.26	0.27	0.35	0.58	0.31	over	0.10	n/a
2	0.10	over	0.24	0.39	0.05	0.37	0.38	0.41	0.53	0.37	over	0.12	n/a
3	0.13	over	0.21	0.43	0.44	0.53	0.49	0.57	0.63	0.38	over	0.15	n/a
4	0.09	over	0.22	0.42	error	0.33	0.35	0.35	0.55	0.29	over	0.10	n/a
5	0.12	over	0.23	0.43	0.11	0.36	0.41	0.48	0.60	0.30	over	0.08	n/a
6	0.05	over	0.19	0.42	0.35	0.44	0.42	0.38	0.64	0.26	over	0.10	n/a
7	0.08	over	0.19	0.37	0.06	0.30	0.38	0.63	0.81	0.34	over	error	n/a
8	0.09	over	0.24	0.48	0.12	0.45	0.47	0.47	0.63	0.27	over	0.13	n/a
9	0.00	over	0.18	0.37	0.20	0.49	0.44	0.58	0.79	0.51	over	0.13	n/a
10	0.10	over	0.23	0.51	0.14	0.46	0.40	0.45	0.54	0.37	over	0.11	n/a
11	0.14	over	0.23	0.87	0.58	0.62	0.50	0.71	0.89	0.43	over	0.13	n/a
12	0.12	over	0.25	0.45	0.32	0.38	0.38	0.37	0.78	0.48	over	error	n/a

error - a sampling error resulted in a negative value and is therefore not presented
over - the lysimeter overtopped and data was lost
Lysimeters in bold are 'successful'

Table A7.15: Leighton Moss Mean Monthly Kc(Reed) LMS Grass, 2001

	Kc(Reed) LMS Grass												
LYSIMETER	Jan-02	Feb-02	Mar-02	Apr-02	May-02	Jun-02	Jul-02	Aug-02	Sep-02	Oct-02	Nov-02	Dec-02	Annual
1	no data	no data	no data	0.57	0.63	0.57	no data	no data	no data	no data	no data	no data	n/a
2	no data	no data	no data	0.59	0.63	0.55	no data	no data	no data	no data	no data	no data	n/a
3	no data	no data	no data	0.60	0.72	0.74	no data	no data	no data	no data	no data	no data	n/a
4	no data	no data	no data	0.56	0.62	0.47	no data	no data	no data	no data	no data	no data	n/a
5	no data	no data	no data	0.60	0.61	0.52	no data	no data	no data	no data	no data	no data	n/a
6	no data	no data	no data	0.54	0.60	0.60	no data	no data	no data	no data	no data	no data	n/a
7	no data	no data	no data	0.55	0.65	0.52	no data	no data	no data	no data	no data	no data	n/a
8	no data	no data	no data	0.56	0.62	0.56	no data	no data	no data	no data	no data	no data	n/a
9	no data	no data	no data	0.51	0.56	0.52	no data	no data	no data	no data	no data	no data	n/a
10	no data	no data	no data	0.58	0.58	0.55	no data	no data	no data	no data	no data	no data	n/a
11	no data	no data	no data	0.67	0.74	0.79	no data	no data	no data	no data	no data	no data	n/a
12	no data	no data	no data	0.61	0.66	0.58	no data	no data	no data	no data	no data	no data	n/a

no data - no data collected due to site flooding and cessation of sampling in June 2002
Lysimeters in bold are 'successful'

Table A7.16: Leighton Moss Mean Monthly Kc(Reed) LMS Grass, 2002

	Kc(Reed) MORECS Grass												
LYSIMETER	**Jan-01**	**Feb-01**	**Mar-01**	**Apr-01**	**May-01**	**Jun-01**	**Jul-01**	**Aug-01**	**Sep-01**	**Oct-01**	**Nov-01**	**Dec-01**	**Annual**
1	0.10	over	0.23	0.41	0.02	0.28	0.29	0.38	0.63	0.33	over	0.11	n/a
2	0.11	over	0.26	0.43	0.05	0.40	0.42	0.44	0.58	0.40	over	0.13	n/a
3	0.14	over	0.23	0.46	0.48	0.58	0.53	0.62	0.69	0.41	over	0.16	n/a
4	0.10	over	0.23	0.46	error	0.36	0.38	0.38	0.60	0.32	over	0.11	n/a
5	0.13	over	0.25	0.47	0.12	0.39	0.45	0.53	0.65	0.32	over	0.08	n/a
6	0.05	over	0.20	0.46	0.38	0.48	0.46	0.41	0.69	0.28	over	0.11	n/a
7	0.09	over	0.20	0.40	0.06	0.33	0.41	0.69	0.88	0.37	over	error	n/a
8	0.10	over	0.26	0.52	0.13	0.49	0.51	0.51	0.68	0.30	over	0.14	n/a
9	0.00	over	0.19	0.40	0.22	0.53	0.48	0.63	0.85	0.56	over	0.14	n/a
10	0.11	over	0.25	0.56	0.16	0.50	0.43	0.49	0.59	0.40	over	0.12	n/a
11	0.15	over	0.25	0.94	0.63	0.68	0.54	0.77	0.97	0.46	over	0.14	n/a
12	0.13	over	0.27	0.49	0.34	0.42	0.42	0.40	0.84	0.53	over	error	n/a

error - a sampling error resulted in a negative value and is therefore not presented
over - the lysimeter overtopped and data was lost
Lysimeters in bold are 'successful'

Table A7.17: Leighton Moss Mean Monthly Kc(Reed) MORECS Grass, 2001

	Kc(Reed) MORECS Grass												
LYSIMETER	**Jan-02**	**Feb-02**	**Mar-02**	**Apr-02**	**May-02**	**Jun-02**	**Jul-02**	**Aug-02**	**Sep-02**	**Oct-02**	**Nov-02**	**Dec-02**	**Annual**
1	no data	no data	no data	0.59	0.65	0.59	no data	no data	no data	no data	no data	no data	n/a
2	no data	no data	no data	0.61	0.65	0.57	no data	no data	no data	no data	no data	no data	n/a
3	no data	no data	no data	0.62	0.74	0.76	no data	no data	no data	no data	no data	no data	n/a
4	no data	no data	no data	0.58	0.64	0.48	no data	no data	no data	no data	no data	no data	n/a
5	no data	no data	no data	0.62	0.63	0.54	no data	no data	no data	no data	no data	no data	n/a
6	no data	no data	no data	0.56	0.62	0.62	no data	no data	no data	no data	no data	no data	n/a
7	no data	no data	no data	0.57	0.67	0.53	no data	no data	no data	no data	no data	no data	n/a
8	no data	no data	no data	0.57	0.64	0.57	no data	no data	no data	no data	no data	no data	n/a
9	no data	no data	no data	0.53	0.57	0.54	no data	no data	no data	no data	no data	no data	n/a
10	no data	no data	no data	0.60	0.60	0.57	no data	no data	no data	no data	no data	no data	n/a
11	no data	no data	no data	0.69	0.77	0.82	no data	no data	no data	no data	no data	no data	n/a
12	no data	no data	no data	0.63	0.68	0.60	no data	no data	no data	no data	no data	no data	n/a

no data - no data collected due to site flooding and cessation of sampling in June 2002
Lysimeters in bold are 'successful'

Table A7.18: Leighton Moss Mean Monthly Kc(Reed) MORECS Grass, 2002

	Kc(Reed) Pan												
QUADRAT	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
A – 2001	-	-	0.16	0.94	1.29	1.23	1.45	1.28	0.76	-	-	-	-
B – 2001	-	-	0.17	0.46	0.76	1.75	1.44	1.28	0.68	-	-	-	-
C – 2001	-	-	0.09	1.00	1.15	1.40	1.43	1.32	0.75	-	-	-	-
D – 2001	-	-	0.09	0.97	1.20	1.38	1.28	1.28	0.66	-	-	-	-
Mean – 2001	-	-	**0.13**	**0.84**	**1.10**	**1.44**	**1.40**	**1.29**	**0.71**	-	-	-	-
SE – 2001	-	-	*0.02*	*0.13*	*0.12*	*0.11*	*0.04*	*0.01*	*0.02*	-	-	-	-
A – 2002	-	-	0.51	1.03	1.54	1.57	no data	no data	no data	-	-	-	-
B – 2002	-	-	0.43	0.90	1.62	1.16	no data	no data	no data	-	-	-	-
C – 2002	-	-	0.47	0.96	1.68	1.70	no data	no data	no data	-	-	-	-
D – 2002	-	-	0.46	0.91	1.69	1.54	no data	no data	no data	-	-	-	-
Mean – 2002	-	-	**0.47**	**0.95**	**1.63**	**1.49**	**no data**	**no data**	**no data**	-	-	-	-
SE – 2002	-	-	*0.02*	*0.03*	*0.03*	*0.12*	-	-	-	-	-	-	-

no data - no data collected due to cessation of sampling in June 2002
SE - Standard Error

Table A7.19: Leighton Moss Estimated Monthly Kc(Reed) Pan, 2001-2002

	Estimated Kc(Reed) LMS Grass												
QUADRAT	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
A – 2001	-	-	0.12	0.70	0.96	0.92	1.08	0.95	0.57	-	-	-	-
B – 2001	-	-	0.13	0.34	0.57	1.30	1.07	0.95	0.51	-	-	-	-
C – 2001	-	-	0.07	0.74	0.85	1.04	1.06	0.98	0.56	-	-	-	-
D – 2001	-	-	0.07	0.72	0.90	1.03	0.95	0.95	0.49	-	-	-	-
Mean – 2001	-	-	**0.10**	**0.63**	**0.82**	**1.07**	**1.04**	**0.96**	**0.53**	-	-	-	-
SE – 2001	-	-	*0.02*	*0.09*	*0.09*	*0.08*	*0.03*	*0.01*	*0.02*	-	-	-	-
A – 2002	-	-	0.23	0.46	0.68	0.69	no data	no data	no data	-	-	-	-
B – 2002	-	-	0.19	0.40	0.72	0.51	no data	no data	no data	-	-	-	-
C – 2002	-	-	0.21	0.43	0.74	0.75	no data	no data	no data	-	-	-	-
D – 2002	-	-	0.20	0.40	0.75	0.68	no data	no data	no data	-	-	-	-
Mean – 2002	-	-	**0.21**	**0.42**	**0.72**	**0.66**	**no data**	**no data**	**no data**	-	-	-	-
SE – 2002	-	-	*0.01*	*0.01*	*0.01*	*0.05*	-	-	-	-	-	-	-

no data - no data collected due to cessation of sampling in June 2002

Table A7.20: Leighton Moss Estimated Monthly Kc(Reed) LMS Grass, 2001-2002

	Estimated Kc(Reed) MORECS Grass												
QUADRAT	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
A – 2001	-	-	0.13	0.76	1.04	0.99	1.17	1.03	0.61	-	-	-	-
B – 2001	-	-	0.14	0.37	0.61	1.41	1.16	1.03	0.55	-	-	-	-
C – 2001	-	-	0.07	0.80	0.93	1.13	1.15	1.06	0.60	-	-	-	-
D – 2001	-	-	0.07	0.79	0.97	1.11	1.03	1.03	0.53	-	-	-	-
Mean – 2001	**-**	**-**	**0.10**	**0.68**	**0.89**	**1.16**	**1.13**	**1.04**	**0.57**	**-**	**-**	**-**	**-**
SE – 2001	-	-	*0.02*	*0.10*	*0.09*	*0.09*	*0.03*	*0.01*	*0.02*	-	-	-	-
A – 2002	-	-	0.28	0.55	0.82	0.84	no data	no data	no data	-	-	-	-
B – 2002	-	-	0.23	0.48	0.87	0.62	no data	no data	no data	-	-	-	-
C – 2002	-	-	0.25	0.51	0.90	0.91	no data	no data	no data	-	-	-	-
D – 2002	-	-	0.25	0.49	0.90	0.83	no data	no data	no data	-	-	-	-
Mean – 2001	**-**	**-**	**0.25**	**0.51**	**0.87**	**0.80**	**no data**	**no data**	**no data**	**-**	**-**	**-**	**-**
SE – 2001	-	-	*0.01*	*0.02*	*0.02*	*0.06*	-	-	-	-	-	-	-

no data - no data collected due to cessation of sampling in June 2002
SE - Standard Error

Table A7.21: Leighton Moss Estimated Monthly Kc(Reed) MORECS Grass, 2001-2002

A7.8 MEASURED REEDBED WATER LEVELS

	MEASURED REEDBED WATER LEVEL (m.a.g.l.)											
YEAR	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
2001	0.11	0.24	0.25	0.21	0.21	0.18	Dry	Dry	0.14	0.10	0.27	0.07
2002	no data	no data	0.23	0.22	0.24	0.16	no data	no data	no data	no data	no data	no data

no data - no data collected due to flooding and cessation of sampling in June 2002

Table A7.22: Leighton Moss Measured Reedbed Water Levels, 2001-2002

APPENDIX 8.
CHERRY HOLME WOODS DATA

A8.1 WATERMARK SENSORS - SOIL WATER POTENTIAL DATA

	MEASURED SOIL WATER POTENTIAL (centibars)							
	LYSIMETER 1				LYSIMETER 2			
SENSOR DEPTH (m)	0.3	0.6	0.9	1.2	0.3	0.6	0.9	1.2
03-Apr-01	6	6	6	7	4	5	6	7
20-Apr-01	1	4	3	3	3	3	3	4
05-May-01	2	3	3	4	0	3	3	4
15-May-01	0	0	3	4	0	0	2	4
01-Jun-01	0	1	2	3	0	1	2	3
15-Jun-01	0	2	2	3	0	0	2	2
04-Jul-01	0	1	1	3	0	1	2	2
17-Jul-01	0	0	1	2	0	0	1	2
01-Aug-01	0	0	0	2	0	0	0	1
17-Aug-01	0	0	0	1	0	0	0	1
30-Aug-01	0	0	0	1	0	0	0	0
17-Sep-01	0	0	0	0	0	0	0	1
03-Oct-01	0	0	0	1	0	0	1	1
29-Oct-01	0	0	0	1	0	0	0	1
29-Nov-01	0	0	0	1	0	0	0	1
18-Dec-01	0	0	0	1	0	0	2	1

Table A8.1: Measured Soil Water Potential from Watermark Sensors at Cherry Holme Woods, Apr 2001 – Jan 2003

	MEASURED SOIL WATER POTENTIAL (centibars)							
	LYSIMETER 1				LYSIMETER 2			
SENSOR DEPTH (m)	0.3	0.6	0.9	1.2	0.3	0.6	0.9	1.2
10-Jan-02	0	0	0	1	0	0	1	1
01-Feb-02	0	0	0	1	1	0	1	1
15-Feb-02	0	0	0	2	1	0	0	1
06-Mar-02	0	0	0	1	0	0	1	1
14-Mar-02	0	0	0	1	0	0	1	0
04-Apr-02	0	0	0	1	0	0	0	0
17-Apr-02	0	0	0	1	0	0	0	0
29-Apr-02	0	0	0	1	0	0	0	0
21-May-02	0	0	0	0	0	0	0	0
30-May-02	0	0	0	1	0	0	2	2
14-Jun-02	0	0	1	2	0	1	0	2
28-Jun-02	0	1	1	2	0	0	1	2
16-Jul-02	0	0	0	3	0	20	0	0
26-Jul-02	3	0	0	1	47	0	0	0
15-Aug-02	10	0	0	0	20	0	0	0
03-Sep-02	28	0	0	0	138	28	18	0
17-Sep-02	20	0	0	0	59	0	3	0
03-Oct-02	17	5	0	0	111	56	97	0
04-Nov-02	3	0	0	0	2	1	3	8
03-Dec-02	2	0	0	0	2	1	2	0
19-Dec-02	3	11	0	0	4	1	3	0

Watermark sensors showing soil moisture below field capacity (10 centibars)

Table A8.1 cont.: Measured Soil Water Potential from Watermark Sensors at Cherry Holme Woods, Apr 2001 – Jan 2003

A8.2 THETA PROBE SOIL MOISTURE READINGS

	SOIL MOISTURE CONTENT ($m^3\ m^{-3}$)					
	Surface	**ML2 01**	**ML2 02**	**ML2 03**	**ML2 04**	**ML2 05**
Probe Depth (m)	**0.00**	**0.10**	**0.25**	**0.50**	**0.75**	**1.00**
18-Dec-01	0.65	*0.67*	*0.66*	0.48	0.45	0.48
10-Jan-02	0.67	0.77	*0.60*	0.49	0.46	0.48
01-Feb-02	0.60	0.61	*0.64*	0.48	0.45	0.48
15-Feb-02	0.59	0.67	*0.58*	0.48	0.45	0.48
06-Mar-02	0.40	*0.67*	*0.65*	0.48	0.45	0.48
14-Mar-02	0.47	*0.64*	*0.64*	0.48	0.45	0.48
04-Apr-02	0.55	*0.62*	*0.59*	0.48	0.45	0.48
17-Apr-02	0.49	*0.60*	*0.60*	0.48	0.45	0.48
29-Apr-02	0.57	*0.64*	*0.58*	0.47	0.45	0.48
21-May-02	0.65	*0.59*	*0.57*	0.47	0.45	0.48
30-May-02	0.60	*0.58*	*0.57*	0.47	0.45	0.47
14-Jun-02	0.65	*0.58*	*0.58*	0.49	0.45	0.47
28-Jun-02	0.42	*0.49*	*0.56*	0.43	0.45	0.47
16-Jul-02	0.61	*0.49*	*0.56*	0.46	0.45	0.47
26-Jul-02	0.44	*0.49*	*0.57*	0.46	0.45	0.47
15-Aug-02	0.43	*0.48*	*0.57*	0.45	0.45	0.47
03-Sep-02	0.30	*0.44*	*0.57*	0.44	0.45	0.47
17-Sep-02	0.33	*0.44*	*0.59*	0.46	0.45	0.47
03-Oct-02	0.37	*0.44*	*0.58*	0.46	0.45	0.47
04-Nov-02	0.78	*0.67*	*0.65*	0.47	0.45	0.48
03-Dec-02	0.75	*0.76*	*0.67*	0.47	0.46	0.48
19-Dec-02	0.77	*0.94*	*0.74*	0.48	0.46	0.48

NB – Data in italics was not used in ET(W6) calculations

Table A8.2: Soil Moisture Readings from Theta Probes in Profile A, Lysimeter 1 at Cherry Holme Woods, 2002

	SOIL MOISTURE CONTENT (m^3 m^{-3})					
	Surface	ML2 06	ML2 07	ML2 08	ML2 09	ML2 10
Probe Depth (m)	**0.00**	**0.10**	**0.25**	**0.50**	**0.75**	**1.00**
18-Dec-01	0.60	0.53	0.55	0.47	0.49	0.47
10-Jan-02	*0.63*	*-0.02*	0.56	0.47	0.49	0.47
01-Feb-02	*0.59*	*-0.03*	0.54	0.47	0.49	0.47
15-Feb-02	*0.68*	*-0.03*	0.55	0.47	0.49	0.47
06-Mar-02	0.52	0.58	0.55	0.47	0.49	0.47
14-Mar-02	0.46	0.58	0.55	0.47	0.49	0.47
04-Apr-02	0.60	0.57	0.53	0.47	0.49	0.47
17-Apr-02	0.58	0.58	0.54	0.47	0.49	0.47
29-Apr-02	0.53	0.57	0.53	0.47	0.49	0.47
21-May-02	0.65	0.56	0.51	0.47	0.49	0.47
30-May-02	0.64	0.56	0.51	0.46	0.48	0.47
14-Jun-02	0.61	0.56	0.50	0.46	0.48	0.47
28-Jun-02	0.47	0.55	0.50	0.46	0.48	0.47
16-Jul-02	0.44	0.55	0.50	0.46	0.48	0.47
26-Jul-02	0.39	0.54	0.50	0.46	0.48	0.47
15-Aug-02	0.41	0.54	0.50	0.46	0.48	0.47
03-Sep-02	0.42	0.44	0.54	0.46	0.48	0.47
17-Sep-02	0.29	0.44	0.56	0.46	0.48	0.47
03-Oct-02	0.33	0.42	0.57	0.46	0.48	0.47
04-Nov-02	0.77	0.55	0.58	0.47	0.49	0.47
03-Dec-02	0.70	0.56	0.57	0.47	0.49	0.47
19-Dec-02	0.78	0.57	0.58	0.47	0.49	0.47

NB – Data in italics was not used in ET(W6) calculations

Table A8.3: Soil Moisture Readings from Theta Probes in Profile B, Lysimeter 1 at Cherry Holme Woods, 2002

	SOIL MOISTURE CONTENT ($m^3\ m^{-3}$)					
	Surface	**ML2 11**	**ML2 12**	**ML2 13**	**ML2 14**	**ML2 15**
Probe Depth (m)	**0.00**	**0.10**	**0.25**	**0.50**	**0.75**	**1.00**
18-Dec-01	0.49	*0.68*	0.66	0.41	0.46	0.48
10-Jan-02	*0.53*	*0.68*	0.65	0.39	0.46	0.48
01-Feb-02	*0.59*	*0.64*	0.64	0.43	0.46	0.48
15-Feb-02	*0.44*	*0.65*	0.64	0.40	0.47	0.48
06-Mar-02	0.57	*0.76*	0.76	0.43	0.47	0.48
14-Mar-02	0.56	*0.76*	0.75	0.43	0.47	0.48
04-Apr-02	0.53	*0.73*	0.75	0.43	0.46	0.47
17-Apr-02	0.36	*0.74*	0.76	0.43	0.46	0.47
29-Apr-02	0.46	*0.70*	0.76	0.43	0.46	0.47
21-May-02	0.44	*0.67*	0.76	0.42	0.46	0.47
30-May-02	0.51	*0.67*	0.76	0.42	0.46	0.47
14-Jun-02	0.50	*0.51*	0.57	0.39	0.45	0.46
28-Jun-02	0.23	*0.29*	0.37	0.37	0.45	0.46
16-Jul-02	0.35	*0.42*	0.54	0.39	0.45	0.46
26-Jul-02	0.30	*0.35*	0.43	0.34	0.45	0.46
15-Aug-02	0.32	*0.32*	0.35	0.31	0.46	0.46
03-Sep-02	0.22	*0.28*	0.28	0.19	0.47	0.45
17-Sep-02	0.25	*0.28*	0.29	0.27	0.47	0.45
03-Oct-02	0.28	*0.27*	0.28	0.20	0.35	0.45
04-Nov-02	0.46	*0.29*	0.30	0.32	0.47	0.46
03-Dec-02	0.48	*0.42*	0.67	0.38	0.47	0.46
19-Dec-02	0.48	*0.41*	0.48	0.38	0.47	0.47

NB – Data in italics was not used in ET(W6) calculations

Table A8.4: Soil Moisture Readings from Theta Probes in Profile A, Lysimeter 2 at Cherry Holme Woods, 2002

	SOIL MOISTURE CONTENT ($m^3\ m^{-3}$)					
	Surface	ML2 16	ML2 17	ML2 18	ML2 19	ML2 20
Probe Depth (m)	**0.00**	**0.10**	**0.25**	**0.50**	**0.75**	**1.00**
18-Dec-01	0.61	0.61	*0.78*	0.41	0.46	0.46
10-Jan-02	*0.51*	0.61	*0.87*	0.41	0.47	0.47
01-Feb-02	*0.63*	0.63	*0.72*	0.41	0.46	0.46
15-Feb-02	*0.52*	0.62	*0.76*	0.41	0.46	0.46
06-Mar-02	0.55	0.63	*0.81*	0.41	0.46	0.46
14-Mar-02	0.45	0.63	*0.78*	0.41	0.46	0.46
04-Apr-02	0.58	0.63	*0.80*	0.41	0.46	0.46
17-Apr-02	0.55	0.59	*0.73*	0.41	0.46	0.46
29-Apr-02	0.50	0.59	*0.78*	0.40	0.46	0.46
21-May-02	0.48	0.59	*0.71*	0.40	0.46	0.46
30-May-02	0.48	0.58	*0.73*	0.40	0.46	0.46
14-Jun-02	0.55	0.57	*0.59*	0.40	0.45	0.46
28-Jun-02	0.20	0.31	*0.31*	0.40	0.45	0.46
16-Jul-02	0.34	0.39	*0.44*	0.40	0.45	0.46
26-Jul-02	0.26	0.33	*0.33*	0.40	0.45	0.45
15-Aug-02	0.32	0.31	*0.28*	0.40	0.45	0.45
03-Sep-02	0.20	0.27	*0.23*	0.26	0.45	0.45
17-Sep-02	0.26	0.29	*0.26*	0.35	0.46	0.45
03-Oct-02	0.20	0.27	*0.23*	0.27	0.44	0.45
04-Nov-02	0.39	0.46	*0.46*	0.38	0.47	0.46
03-Dec-02	0.50	0.53	*0.85*	0.39	0.47	0.46
19-Dec-02	0.46	0.48	*0.56*	0.39	0.47	0.46

NB – Data in italics was not used in ET(W6) calculations

Table A8.5: Soil Moisture Readings from Theta Probes in Profile B, Lysimeter 2 at Cherry Holme Woods, 2002

A8.3 MEASURED WATER LEVELS

SURVEY DATE	MEASURED WATER DEPTH (m)	
	Lysimeter 1	Lysimeter 2
18-Dec-01	-0.23	-0.38
10-Jan-02	-0.20	-0.35
01-Feb-02	-0.25	-0.40
15-Feb-02	-0.38	-0.50
06-Mar-02	-0.05	-0.25
14-Mar-02	-0.28	-0.30
04-Apr-02	-0.14	-0.21
17-Apr-02	-0.22	-0.30
29-Apr-02	-0.10	-0.24
21-May-02	0.00	-0.18
30-May-02	-0.25	-0.35
14-Jun-02	-0.26	-0.60
28-Jun-02	-0.70	-0.69
16-Jul-02	-0.33	-0.54
26-Jul-02	-0.40	-0.85
15-Aug-02	-0.26	-0.80
03-Sep-02	-0.41	-0.91
17-Sep-02	-0.26	-0.72
02-Oct-02	-0.44	-0.90
04-Nov-02	0.00	-0.50
03-Dec-02	0.00	-0.15
19-Dec-02	0.00	-0.28
31-Jan-03	0.02	0.00

Table A8.6: Measured Water Levels within the Lysimeters at Cherry Holme Woods, Dec 2001 – Jan 2003

A8.4 RAINFALL DATA

Source	Year	RAINFALL (mm)												
		Jan-02	Feb-02	Mar-02	Apr-02	May-02	Jun-02	Jul-02	Aug-02	Sep-02	Oct-02	Nov-02	Dec-02	Annual
On-Site Rain Gauge	2002	28.9	37.7	17.2	10.0	34.3	21.8	27.4	32.3	15.6	124.0	93.8	52.5	495.4
Automatic Met Station	2002	no data	no data	no data	no data	61.0	41.4	79.2	35.0	21.8	115.2	107.4	94.2	n/a
Local Met Station	2002	44.3	81.4	34.0	31.4	60.2	31.8	157.5	51.4	27.4	110.2	100.6	89.4	819.6
MORECS Sq. 126	2002	47.7	72.1	29.4	34.3	64.6	37.4	133.3	42.2	34.1	106.2	93.9	87.4	782.6

no data - no data presented due to inaccurate data

Table A8.7: Monthly Rainfall Totals from Various Sources at Cherry Holme Woods, 2002

A8.5 ETo DATA

		RAINFALL (mm)												
Source	**Year**	**Jan-02**	**Feb-02**	**Mar-02**	**Apr-02**	**May-02**	**Jun-02**	**Jul-02**	**Aug-02**	**Sep-02**	**Oct-02**	**Nov-02**	**Dec-02**	**Annual**
On-Site Rain Gauge	2002	error	10.8	15.6	35.1	38.8	42.5	36.0	45.6	25.3	over	1.5	error	n/a
Automatic Met Station	2002	no data	no data	no data	no data	59.7	69.2	70.2	60.4	43.4	21.2	10.3	8.7	n/a
Local Met Station	2002	16.8	22.8	32.1	52.7	84.1	83.3	90.9	72.0	51.8	33.6	17.7	12.7	570.5
MORECS Sq. 126	2002	13.4	26.7	38.7	63.1	81.3	83.4	85.5	71.4	51.8	31.6	16.1	11.3	574.3

error - a sampling error resulted in a negative value and is therefore not presented
over - the evaporation pan overtopped and data was lost
no data - no data presented due to inaccurate data

Table A8.8: Monthly ETo Totals from Various Sources at Cherry Holme Woods, 2002

APPENDIX 9.
LEAM VALLEY DATA

A9.1 WATERMARK SENSORS - SOIL WATER POTENTIAL DATA

	MEASURED SOIL WATER POTENTIAL (centibars)							
	LYSIMETER 1				LYSIMETER 2			
SENSOR DEPTH (m)	**0.3**	**0.6**	**0.9**	**1.1**	**0.3**	**0.6**	**0.9**	**1.1**
18-May-01	6	2	4	5	3	3	5	3
31-May-01	3	2	2	3	2	2	2	2
14-Jun-01	2	1	0	0	2	2	1	1
29-Jun-01	2	1	1	1	1	2	2	1
16-Jul-01	2	1	1	1	2	2	1	1
31-Jul-01	1	0	0	0	0	1	0	0
16-Aug-01	1	0	0	0	0	1	0	0
29-Aug-01	2	4	0	0	0	2	0	0
14-Sep-01	2	0	0	0	0	2	3	0
01-Oct-01	2	1	0	0	1	2	0	0
31-Oct-01	2	0	0	0	0	2	0	1
28-Nov-01	3	1	1	1	2	3	0	1
20-Dec-01	4	1	1	0	2	3	2	0

Table A9.1: Measured Soil Water Potential from Watermark Sensors at Leam Valley, May 2001 – Dec 2002

	MEASURED SOIL WATER POTENTIAL (centibars)							
	LYSIMETER 1				LYSIMETER 2			
SENSOR DEPTH (m)	**0.3**	**0.6**	**0.9**	**1.1**	**0.3**	**0.6**	**0.9**	**1.1**
31-Jan-02	3	1	1	0	3	2	0	2
15-Feb-02	3	0	1	0	1	2	1	2
01-Mar-02	3	2	4	2	2	3	0	3
14-Mar-02	4	1	1	1	1	4	4	2
03-Apr-02	1	1	0	2	0	2	0	2
16-Apr-02	1	2	2	0	6	2	0	2
01-May-02	1	0	1	0	0	2	0	1
21-May-02	8	0	0	0	0	0	2	0
31-May-02	10	0	0	0	1	0	2	0
14-Jun-02	15	5	1	0	3	0	2	1
26-Jun-02	30	10	0	1	8	2	1	0
16-Jul-02	50	16	0	0	12	2	1	1
01-Aug-02	10	30	0	0	4	0	7	1
15-Aug-02	36	35	0	0	19	6	6	0
02-Sep-02	126	92	18	11	50	21	4	0
17-Sep-02	70	60	27	17	43	3	6	0
01-Oct-02	135	118	error	40	0	25	0	24
04-Nov-02	40	30	5	10	2	10	0	15
02-Dec-02	2	2	0	2	3	1	0	17
18-Dec-02	5	2	2	2	3	3	0	1

Watermark sensors showing soil moisture below field capacity (10 centibars)

Table A9.1 cont.: Measured Soil Water Potential from Watermark Sensors at Leam Valley, May 2001 – Dec 2002

A9.2 THETA PROBE SOIL MOISTURE READINGS

	SOIL MOISTURE CONTENT ($m^3\ m^{-3}$)					
	Surface	ML2 01	ML2 02	ML2 03	ML2 04	ML2 05
Probe Depth (m)	**0.00**	**0.10**	**0.25**	**0.50**	**0.75**	**1.00**
15-Feb-02	0.49	0.46	0.45	0.46	0.43	0.41
01-Mar-02	0.40	0.44	0.43	0.47	0.42	0.41
14-Mar-02	0.43	0.46	0.44	0.45	0.43	0.41
03-Apr-02	0.53	0.45	0.44	0.45	0.43	0.42
16-Apr-02	0.41	0.45	0.44	0.46	0.43	0.41
01-May-02	0.47	0.45	0.44	0.45	0.42	0.41
21-May-02	0.43	0.46	0.44	0.45	0.41	0.41
31-May-02	0.43	0.46	0.45	0.46	0.42	0.41
14-Jun-02	0.43	0.46	0.44	0.46	0.44	0.41
26-Jun-02	0.21	0.45	0.44	0.45	0.42	0.42
16-Jul-02	0.28	0.43	0.44	0.45	0.43	0.42
01-Aug-02	0.37	0.38	0.42	0.42	0.43	0.42
15-Aug-02	0.35	0.39	0.41	0.36	0.42	0.40
02-Sep-02	0.20	0.38	0.41	0.36	0.42	0.38
17-Sep-02	0.33	0.36	0.40	0.34	0.35	0.35
01-Oct-02	0.23	0.35	0.39	0.33	0.31	0.34
04-Nov-02	0.47	0.44	0.43	0.40	0.42	0.42
02-Dec-02	0.62	0.46	0.44	0.45	0.41	0.45
18-Dec-02	0.45	0.43	0.44	0.44	0.42	0.44

NB – Data in italics was not used in ET(W6) calculations

Table A9.2: Soil Moisture Readings from Theta Probes in Profile A, Lysimeter 1 at Leam Valley, 2002

	SOIL MOISTURE CONTENT ($m^3 m^{-3}$)					
	Surface	**ML2 06**	**ML2 07**	**ML2 08**	**ML2 09**	**ML2 10**
Probe Depth (m)	**0.00**	**0.10**	**0.25**	**0.50**	**0.75**	**1.00**
15-Feb-02	0.53	*0.27*	0.47	0.47	0.48	0.42
01-Mar-02	0.46	*0.25*	0.45	0.46	0.46	0.41
14-Mar-02	0.37	*0.26*	0.47	0.47	0.47	0.41
03-Apr-02	0.42	*0.24*	0.46	0.47	0.46	0.42
16-Apr-02	0.29	*0.32*	0.47	0.46	0.46	0.42
01-May-02	0.40	*0.31*	0.48	0.48	0.46	0.41
21-May-02	0.39	*0.30*	0.46	0.46	0.47	0.42
31-May-02	0.40	*0.31*	0.47	0.46	0.46	0.43
14-Jun-02	0.45	*0.31*	0.47	0.47	0.47	0.42
26-Jun-02	0.35	*0.32*	0.47	0.47	0.46	0.41
16-Jul-02	0.24	*0.32*	0.43	0.45	0.42	0.41
01-Aug-02	0.40	*0.31*	0.40	0.40	0.40	0.41
15-Aug-02	0.35	*0.31*	0.40	0.36	0.38	0.42
02-Sep-02	0.17	*0.31*	0.40	0.36	0.38	0.41
17-Sep-02	0.24	*0.30*	0.39	0.35	0.37	0.40
01-Oct-02	0.25	*0.29*	0.39	0.34	0.36	0.32
04-Nov-02	0.38	*0.28*	0.42	0.41	0.44	0.38
02-Dec-02	0.50	*0.28*	0.43	0.44	0.45	0.39
18-Dec-02	0.46	*0.27*	0.44	0.43	0.45	0.40

NB – Data in italics was not used in ET(W6) calculations

Table A9.3: Soil Moisture Readings from Theta Probes in Profile B, Lysimeter 1 at Leam Valley, 2002

	SOIL MOISTURE CONTENT ($m^3\ m^{-3}$)					
	Surface	**ML2 11**	**ML2 12**	**ML2 13**	**ML2 14**	**ML2 15**
Probe Depth (m)	**0.00**	**0.10**	**0.25**	**0.50**	**0.75**	**1.00**
15-Feb-02	0.51	0.47	0.48	0.47	0.44	0.47
01-Mar-02	0.47	0.47	0.47	0.46	0.43	0.46
14-Mar-02	0.31	0.47	0.47	0.46	0.43	0.46
03-Apr-02	0.48	0.47	0.47	0.46	0.43	0.46
16-Apr-02	0.40	0.46	0.47	0.45	0.43	0.46
01-May-02	0.47	0.46	0.47	0.45	0.43	0.46
21-May-02	0.42	0.46	0.47	0.45	0.43	0.45
31-May-02	0.36	0.46	0.46	0.45	0.43	0.46
14-Jun-02	0.39	0.46	0.46	0.45	0.43	0.46
26-Jun-02	0.25	0.46	0.46	0.45	0.43	0.46
16-Jul-02	0.23	0.45	0.45	0.45	0.43	0.45
01-Aug-02	0.42	0.45	0.45	0.45	0.42	0.45
15-Aug-02	0.36	0.43	0.44	0.44	0.42	0.45
02-Sep-02	0.16	0.43	0.44	0.45	0.42	0.45
17-Sep-02	0.21	0.40	0.37	0.44	0.42	0.45
01-Oct-02	0.21	0.39	0.33	0.44	0.42	0.45
04-Nov-02	0.40	0.44	0.44	0.45	0.43	0.45
02-Dec-02	0.60	0.45	0.45	0.46	0.43	0.46
18-Dec-02	0.47	0.45	0.45	0.46	0.43	0.45

NB – Data in italics was not used in ET(W6) calculations

Table A9.4: Soil Moisture Readings from Theta Probes in Profile A, Lysimeter 2 at Leam Valley, 2002

	SOIL MOISTURE CONTENT (m^3 m^{-3})					
	Surface	**ML2 16**	**ML2 17**	**ML2 18**	**ML2 19**	**ML2 20**
Probe Depth (m)	**0.00**	**0.10**	**0.25**	**0.50**	**0.75**	**1.00**
15-Feb-02	0.50	0.46	0.46	0.45	0.45	0.42
01-Mar-02	0.51	0.46	0.46	0.45	0.46	0.42
14-Mar-02	0.39	0.46	0.46	0.45	0.45	0.42
03-Apr-02	0.48	0.46	0.46	0.45	0.45	0.42
16-Apr-02	0.40	0.46	0.46	0.45	0.45	0.42
01-May-02	0.44	0.45	0.46	0.45	0.45	0.43
21-May-02	0.42	0.45	0.45	0.45	0.45	0.44
31-May-02	0.42	0.46	0.45	0.45	0.45	0.43
14-Jun-02	0.40	0.46	0.46	0.45	0.45	0.43
26-Jun-02	0.26	0.45	0.45	0.45	0.45	0.42
16-Jul-02	0.37	0.45	0.45	0.45	0.45	0.43
01-Aug-02	0.38	0.44	0.44	0.44	0.45	0.43
15-Aug-02	0.33	0.41	0.42	0.44	0.45	0.43
02-Sep-02	0.21	0.41	0.42	*0.44*	0.45	0.42
17-Sep-02	0.33	0.39	0.39	0.29	0.40	0.43
01-Oct-02	0.26	0.39	0.39	*0.28*	0.40	0.42
04-Nov-02	0.44	0.44	0.44	0.46	0.44	0.42
02-Dec-02	0.56	0.45	0.45	0.46	0.44	0.42
18-Dec-02	0.50	0.45	0.45	0.46	0.44	0.42

NB – Data in italics was not used in ET(W6) calculations

Table A9.5: Soil Moisture Readings from Theta Probes in Profile B, Lysimeter 2 at Leam Valley, 2002

A9.3 MEASURED WATER LEVELS

SURVEY DATE	MEASURED WATER DEPTH (m)	
	Lysimeter 1	Lysimeter 2
31-Jan-02	0.00	0.00
15-Feb-02	-0.04	0.00
01-Mar-02	-0.11	-0.01
14-Mar-02	-0.47	-0.39
03-Apr-02	-0.17	-0.11
16-Apr-02	-0.35	-0.30
01-May-02	-0.30	-0.18
21-May-02	-0.38	-0.33
31-May-02	-0.45	-0.27
14-Jun-02	-0.56	-0.38
26-Jun-02	-0.82	-0.56
16-Jul-02	-0.85	-0.60
01-Aug-02	-0.80	-0.70
15-Aug-02	-0.82	-0.62
02-Sep-02	-0.85	-0.85
17-Sep-02	-0.85	-0.64
01-Oct-02	-0.85	-0.85
04-Nov-02	-0.40	-0.20
02-Dec-02	0.00	0.00
18-Dec-02	-0.30	-0.12

Table A9.6: Measured Water Levels within the Lysimeters at Leam Valley, Jan 2002 – Dec 2002

A9.4 RAINFALL DATA

Source	Year	RAINFALL (mm)												
		Jan-02	Feb-02	Mar-02	Apr-02	May-02	Jun-02	Jul-02	Aug-02	Sep-02	Oct-02	Nov-02	Dec-02	Annual
On-Site Rain Gauge	2002	no data	33.16	17.55	19.20	29.35	18.30	31.90	11.35	10.10	146.80	88.70	22.50	n/a
Local Met Station	2002	45.30	66.20	33.40	48.30	43.10	31.80	84.80	34.10	27.40	131.50	90.00	84.90	720.80
MORECS Sq. 126	2002	50.40	78.90	37.00	45.50	62.80	36.50	81.30	44.90	27.20	124.00	103.40	80.00	771.90

no data - no data presented due to inaccurate data

Table A9.7: Monthly Rainfall Totals from Various Sources at Leam Valley, 2002

A9.5 ETo DATA

Source	Year	RAINFALL (mm)												
		Jan-02	Feb-02	Mar-02	Apr-02	May-02	Jun-02	Jul-02	Aug-02	Sep-02	Oct-02	Nov-02	Dec-02	Annual
On-Site Rain Gauge	2002	no data	12.84	17.23	27.74	29.50	29.16	42.48	24.65	18.20	over	error	error	n/a
Local Met Station	2002	14.80	25.10	31.60	58.90	83.00	83.60	89.40	71.60	51.80	34.60	16.60	14.20	575.20
MORECS Sq. 126	2002	12.80	27.40	37.00	65.40	86.00	86.20	89.90	75.50	57.70	35.80	18.00	11.60	603.30

error - a sampling error resulted in a negative value and is therefore not presented
over - the evaporation pan overtopped and data was lost
no data - no data presented due to inaccurate data

Table A9.8: Monthly ETo Totals from Various Sources at Leam Valley, 2002