ESTABLISHMENT OF A REEDBED WITHIN A CREATED SURFACE WATER FED WETLAND NATURE RESERVE

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SUMMARY.

In the early 1990's, outline designs for two wetland nature reserves were being prepared: the Teesside International Nature Reserve (TINR) and the Cardiff Bay Barrage Environmental Compensation Measures at Redwick, Gwent. The initial design for both proposals identified reedbed as a desirable habitat for establishment. The initial design works identified the importance of reedbed evapotranspiration [ET(Reed)] within the water budget, however, literature searches identified a paucity of information on this parameter.

Field experiments for the measurement of ET(Reed) from *Phragmites australis* are described for three sites distributed across England and Wales. Reference Crop Evapotranspiration (ETo) was calculated using techniques recommended by the Food and Agriculture Organisation. A technique for the calculation of a reedbed crop coefficient [Kc(Reed)], from ET(Reed) and ETo data is discussed. Kc(Reed) values produced in the project were found to be similar to those developed previously in continental Europe. Mean monthly and crop development stage Kc(Reed) values are presented which are applicable in the UK and possibly worldwide.

A conceptual hydrological model of surface water fed reedbed systems is developed, and used to calculate the hydrological sustainability of reedbed creation areas in the UK. Finally, the water budget model is verified using data from a small clay catchment located on the TINR. In addition, a methodology is developed for the hydrological design of surface water fed reedbed systems, and recommendations are made for the acquisition of essential hydrological information required for the feasibility, design, and establishment stage of reedbed creation sites. Further research needs are also identified.

KEY WORDS:

REEDBED, EVAPOTRANSPIRATION, CROP COEFFICIENT, WATER BUDGET, WETLAND CREATION.

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NOTATION.

A	measurement of habitat areas (m^2).
$\overline{A}$	mean surface water area (m^2).
AE	actual evapotranspiration rate (mm/day).
A_G	area of grassland (m^2).
A_R	area of reedbed (m^2).
A_W	area of waterbody (m^2).
C	channel flow.
c	adjustment factor for minimum relative humidity, % sunshine hours, and daytime wind estimate.
Ce	flux density of open channel flow output.
Ci	flux density of open channel flow input.
Cp	specific heat of air at constant pressure (1005 J kg^{-1}).
D	total surface and sub-surface discharge (m^3).
D	the rate of discharge from the system.
$\frac{ds}{dt}$	the rate of change of water stored in the system.
E	evaporation in mm/day.
E'	rate of water loss (kg m^{-2} s^{-1}).
e	screen vapour pressure (mb).
Ein	water vapour gain.
Eout	water vapour loss.
Ea	value of Eo obtained by putting $e_s = e_a$ in sink strength formula.
(ea-ed)	difference between saturated vapour pressure at mean air temperature and the mean actual vapour pressure of the air (mbar).
ed	average vapour pressure.
Eo	open water evaporation (m).
Epan	evaporation rate from a US Class A evaporation pan (mm/day).
E(Phyto)	evaporation rate from unplanted phytometer (mm/day).

es	saturation vapour pressure at screen temperature (mb).
ET	evapotranspiration rate (mm/day).
ET'	mean annual potential evapotranspiration (mm).
ET(Crop)	crop evapotranspiration rate (mm/day).
ETd	flux density of evapotranspiration.
ET_G	grassland evapotranspiration (m).
ET(Grass)	grassland evapotranspiration (mm/day).
ETo	reference crop evapotranspiration.
ETo CROPWAT	reference crop evapotranspiration calculated using CROPWAT.
ETo MORECS Eo	reference crop evapotranspiration calculated using MORECS Eo.
ETo MORECS Grass	reference crop evapotranspiration calculated using MORECS Grass.
ETo Pan	reference crop evapotranspiration calculated using evaporation pan data.
ET(Reed)	reedbed evapotranspiration (mm/day).
$ET(Reed)_{\text{Within-stand}}$	reedbed evapotranspiration from within-stand (mm/day).
$ET(Reed)_{\text{Not Within-stand}}$	reedbed evapotranspiration from not within-stand (mm/day).
ET(Wetland)	evapotranspiration rate from a wetland area (mm/day).
f	Penman (1948) crop coefficient.
f(u)	wind related function.
G	soil heat flux (W m^{-2}).
Gi	groundwater inflow (m^3).
Go	groundwater outflow (m^3).
H	water level (mAOD).
h	net radiation energy available at surface.
I	the rate of inflow to the system.
Kco	potential crop coefficient.
Kc(Reed)	reedbed crop coefficient.

Kc(Reed) CROPWAT	reedbed crop coefficient calculated using ETo CROPWAT data.
Kc(Reed) Eo	reedbed crop coefficient calculated using Eo data.
Kc(Reed) Grass	reedbed crop coefficient calculated using ET from grass.
Kc(Reed) MORECS Grass	reedbed crop coefficient calculated using ETo MORECS Grass.
Kc(Reed) MORECS Eo	reedbed crop coefficient calculated using ETo MORECS Eo.
Kc(Reed) Pan	reedbed crop coefficient calculated using ETo Pan data.
Kc(Rice)	crop coefficients used in the calculation of evapotranspiration from rice.
Kp	pan coefficient.
L	$300 + 25T + 0.05T^3$.
mAOD	metres above Ordnance Datum.
N	total surface and sub-surface recharge (m^3).
n	duration of bright sunshine.
ne	error (m^3).
P'	mean annual precipitation (mm).
P	precipitation (m^3).
p	mean daily % of total annual daytime hours.
Pd	flux density of precipitation.
PE	potential evapotranspiration rate (mm/day).
PERC	% runoff volume.
Q	lateral migration of surface water into surrounding catchment.
Q'	lateral migration of surface water into surrounding catchment (minimal in clay catchments).
Qe	flux density of diffuse surface flow output.
Qi	flux density of diffuse surface flow input.
R	rainfall input (mm/day).
r	Pearson product-moment coefficient of correlation (Harper, 1977).

r^2	coefficient of determination (Owen and Jones, 1983).
ra	bulk aerodynamic resistance (s m^{-1}).
R_n	net radiation (W m^{-2}).
Rn	net radiation in equivalent evaporation (mm/day).
Ro	runoff.
Rs	solar radiation in equivalent evaporation (mm/day).
rs	bulk surface (canopy) resistance (s m^{-1}).
S	seepage.
$S_{1....5}$	WRAP Classes 1 to 5.
Si	surface inflow (m^3).
SMD	soil moisture deficit (mm).
So	surface outflow (m^3).
T	mean daily temperature (°C).
Ta	mean air temperature (°C).
Ti	tidal inflow (+) or outflow (-) (m^3).
Tr	transpiration.
U_2	wind speed at 2m.
Ue	flux density of seepage output.
Ui	flux density of seepage input.
Ve	flux density of pipe flow output.
Vi	flux density of pipe flow input.
W	stored water.
w	temperature related weighting factor.
β	runoff coefficient.
Δ	rate of change of saturated vapour pressure with temperature (mb $°C^{-1}$).
Δ'	de_a/dT_a (Penman, 1948).

ΔA_W	change in waterbody area (m^2) over a given time.
ΔH	the change in surface water level (m).
ΔV	change in the volume of water storage (m^3).
$\Delta V_{reedbed}$	change in volume of water storage within a reedbed (m^3/ha). It is assumed that the winter water budget surplus is stored within the reedbed ecosystem.
$\Delta V_{reedbed\ nws}$	change in volume of water storage within a reedbed (m^3/ha) where all surpluses ignored. Provides a water budget deficit based on no winter surplus.
ρ	air density (kg m^{-3}).
λ	latent heat of vaporisation (=2465000 J kg^{-1}).
γ	psychometric constant (= 0.66 for temperature in ^{O}C and vapour pressure in mb).
γ'	constant of wet and dry bulb hygrometer equation; in ^{O}F and mm. Hg, ($\gamma' = 0.27$).

Chapter 1. INTRODUCTION.

An examination of wetland loss statistics and characteristic bird populations gathered by many authorities indicate that past management policies and practices have led to catastrophic loss of wetlands. Attitudes to the environment and specifically to wetlands have changed over recent years. This is reflected in both the content of international conventions and in national laws to protect and create wetland environments. This thesis is the result of a research programme undertaken in response to the need for environmental science increasingly to develop practicable plans in the context of more positive attitudes towards it.

Within this thesis, a conceptual hydrological model of surface water fed reedbed systems is developed and a water budget equation is derived to calculate the hydrological feasibility of reedbed creation in the UK. The model highlights the importance of reedbed evapotranspiration [ET(Reed)] within the water budget, however, literature searches identified a paucity of information on this parameter. As a result, ET(Reed) was directly measured at three experimental sites distributed across England and Wales. Reference Crop Evapotranspiration (ETo) is used in conjunction with the measured ET(Reed) data in the development of monthly reedbed crop coefficients [Kc(Reed)].

The Kc(Reed) values are used in the determination of ET(Reed) across the UK. It is shown that extensive reedbed creation requires a water budget input greater than that of an open water body, as ET(Reed) is greater than Eo. The research highlights those parts of the UK where direct rainfall inputs are insufficient to compensate for ET(Reed) losses, with respect to both annual and accumulated summer deficits where no winter surplus storage is possible.

A methodology is developed which enables the hydrological design of surface water fed reedbed systems. Strategies are given to inform the natural hydrologically sustainable ratio of reedbed to surrounding catchment area for a site without groundwater or additional imported water supply, using standard, accessible meteorological data. The need for additional water supplies is discussed with reference made to the form and source of these supplies: e.g. treated effluent.

In summary, the thesis primarily gives:-

- a set of monthly Kc(Reed) values applicable in the UK and continental Europe, and;

- a methodology for the hydrological design of surface water fed reedbed systems.

1.1 THE ORIGINS OF THE PROJECT.

In the early 1990's, outline designs for two wetland nature reserves were being prepared: the Teesside International Nature Reserve (TINR); and, the Cardiff Bay Barrage Environmental Compensation Measures at Redwick, Gwent. The initial design for these two projects identified both reedbed and flooded/wet grasslands to be desirable habitats for establishment.

The hydrological design and hydrometeorological monitoring programmes undertaken on each of the sites was the responsibility of Environmental & Hydrological Consultants (EHC). EHC form part of the wetland design teams contracted by both the Teesside Development Corporation (TDC) and Cardiff Bay Development Corporation (CBDC). It was this involvement of both the author and Dr Pam Brown at EHC that identified the need for research into the hydrology of reedbeds.

During 1991 and 1992 attempts were made to develop a conceptual water budget model for use within the initial design works for the TINR. The proposed wetland ecosystems identified were 50% wet and dry reedbed with open water areas, and 50% wet and flooded grasslands. It soon became apparent that the derived water budget equations required the accurate determination of ET(Reed). However, extensive literature searches identified a dearth of information to facilitate the design and establishment of the reedbeds. The data and conclusions of the published research were confusing and often conflicting.

As a result, field studies were undertaken to gain a better understanding of the hydrometeorological processes at work within surface water fed reedbed systems. The TDC agreed to the use of a created reedbed for research purposes, with the field studies beginning in 1993. This work has focused in particular on determining ET(Reed).

Research registration began as part-time, external, in October 1992, changing to full-time, internal in January 1997.

1.2 AIMS AND OBJECTIVES.

Initially, the aim of the project was to develop a methodology for the hydrological design, creation and establishment of surface water fed wetland habitats with an emphasis on reedbeds. However, as the project progressed the focus on reedbeds became absolute and thus the aim was adjusted accordingly. In addition, the original concept, which included not only design but also creation and establishment, proved to be to broad and the project was limited to the hydrological design. It should be noted that since the project commenced a manual dealing with the creation and establishment of reedbeds has been produced by Hawke and José (1996).

The original objectives outlined in the qualifying report (Fermor, 1994) included wet grassland habitats within the research remit. However, after a brief review of the literature it became apparent that the parameters necessary to calculate grassland water budgets were already well understood and estimation equations (e.g. Penman, 1948) had been fully validated. Therefore, no further research was undertaken on this habitat type.

AIM

The aim of the research project is to develop a methodology for the hydrological design of surface water fed reedbed habitats.

OBJECTIVES

In order to establish the methodology, a detailed understanding of the function of existing reedbed systems is necessary, with reference to the associated hydrological regimes. With this in mind the following objectives were identified:

1) undertake a comprehensive review of published literature, focused on the hydrological functioning of wetland systems, primarily reedbeds.

2) formulate a conceptual hydrological model of surface water fed reedbed systems.

3) design and undertake a monitoring programme to enable the components of the conceptual model to be quantified and hence facilitate design.

4) create a hydrological design methodology applicable to surface water fed reedbed creation.

1.3 THESIS STRUCTURE.

Chapter Two provides an historical background of the changing attitudes to, and characteristics of, wetlands, together with details of reedbed ecosystems including their: distribution; habitat characteristics; flora and fauna; and commercial use.

Chapter Three discusses wetland hydrology, including the hydrological requirements of reedbeds and the species that depend upon them. It also develops a conceptual model of surface water fed reedbed ecosystems. From this, a water budget equation is derived which is applicable to the study sites. These sites are described in Chapter Five.

Chapter Four includes an introduction to the underlying evapotranspiration theory, which provides the theoretical background upon which the field studies were based. Crop evapotranspiration is discussed and methods of calculating Reference Crop Evapotranspiration (ETo) are presented. A literature review of wetland evapotranspiration studies is undertaken with specific reference to ET(Reed) research.

Chapter Six describes the design and siting of experimental apparatus, the experimental procedures, and the results of the ET(Reed) studies. The analysis of the ET(Reed) results is undertaken in Chapter Eight. A list of notations is provided at the beginning of the thesis and a glossary of terms is provided in Appendix 8.

Chapter Seven details the development of four forms of ETo, discussing the relationship between each of the forms, and their inter-site variation. In Chapter Nine, the ETo's are used in conjunction with ET(Reed) to develop a series of monthly reedbed crop coefficients [Kc(Reed)] for each of the experimental sites. The seasonal variation in Kc(Reed) is discussed with reference to growth stages. Mean monthly Kc(Reed) values are developed, which, after comparison with works of other researchers are presented for application across the UK and continental Europe. The impact of ET(Reed) on the long term sustainability of created reedbeds is assessed, informing the need for additional water supplies.

Chapter Ten describes the methodology for the hydrological design of surface water fed reedbed ecosystems, and verifies the derived water budget model.

The research itself is evaluated in Chapter Eleven, and the areas requiring further study are identified. Finally, the conclusions are presented in Chapter Twelve, in which the success of the project in meeting the aims and objectives is assessed.

Chapter 2. WHAT IS A WETLAND?

2.1 INTRODUCTION.

Most people have a vague idea of what constitutes a wetland, but this idea varies from person to person (Hammer, 1988). Wetlands have been described as an "edge" habitat or ecotone, constituting a transition zone between dry land and deep water. Hammer states that several classification systems have been devised for wetlands, with more than 50 definitions in use worldwide. Table 2.1 contains a selection of definitions, among which the most widely referenced (Dugan, 1993) was provided by the Ramsar Convention (1971) on "Wetlands of International Importance, Especially as Waterfowl Habitat". This definition has been adopted throughout this research project.

Reference	Definition
Shaw and Fredine (1956) (cited by Kent, 1994)	*Lowlands covered with shallow and sometimes temporary or intermittent waters. They are referred to by such names as marshes, swamps, bogs, wet meadows, potholes, sloughs and river overflow lands.*
Ramsar Convention (1971)	*Areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres.*
Hammer and Bastian (1988)	*Shallow water or saturated areas dominated by water tolerant woody plants and trees are generally considered marshes; and, those with mosses are bogs.*
Gardiner (1994)	*Areas of waterlogged and periodically inundated land which support a distinctive and characteristic wetland vegetation type (marsh grass, rushes, sedges etc.)*

Table 2.1 Wetland Definitions

Tammi (1994) states that three characteristics have been selected to distinguish wetlands from uplands:

1) water, typically from a surface or groundwater source;
2) unique soils which are diagnostic of wetland conditions;
3) wetland vegetation which possess morphological adaptations that enable them to tolerate frequent root zone saturation or inundation, and anaerobic conditions.

These are very similar to those cited by Hammer and Bastian (1988), developed in 1979 by the US Fish and Wildlife Service.

Each wetland is unique with respect to its size, shape, hydrology, soil, vegetation and its position in the landscape (Kent, 1994), with detailed nomenclature developed by Goode (1972), Goode and Ratcliffe (1977) and Wheeler (1980). Maltby (1986) states that part of the definitional confusion is due to the differing terminology used, predominantly because individuals develop their own classification systems, and these tend to be incompatible with the systems of other workers. The group of ecosystems that are described collectively as wetlands are not uniform, but heterogeneous. Cowardin et al (1979) recognised five wetland systems including marine, estuarine, riverine, lacustrine and palustrine; whereas Dugan (1990) identifies seven wetland landscape units (see Appendix One). Dugan concludes that each unit can include a wide range of different wetland types, with several occurring in more than one unit. Further categorisation becomes tedious and provides opportunities for additional nomenclature for the same habitats (Maltby, 1986). Many wetlands have also developed under pastoral management, adding to the categories. For example, in the UK, wet grasslands are of five main types: flood meadows, washes, water meadows, grazing levels, and wet heaths (British Trust for Conservation Volunteers, 1976).

Natural wetlands are an ephemeral component of the landscape, which without tectonic or hydrologic disturbances gradually progress through a succession of stages to relatively dry upland type ecosystems (Hammer and Bastian, 1988). There is often a self destruct process in which successive plant communities alter environmental conditions in a way that makes the habitat more suited to different communities. Often lakes gradually fill with organic detritus and inorganic sediments washed in from the catchment area, allowing emergent species to establish, which often trap additional sediment. Trees such as alder or willow may establish themselves resulting in a 'carr woodland', eventually leading to the establishment of a terrestrial woodland ecosystem. Thus, ecological succession produces wetlands with a dynamic character, making them vulnerable to environmental change (Maltby, 1992). D'Avanzo (1990) concludes that the present structure of a wetland may be a "momentary expression of the wetland of the future".

Human society is commonly found along the margins of water. The first period of man's approach to wetlands was one of coexistence, with local communities harvesting the bountiful wetland productivity in sustainable ways (Maltby, 1992). Williams (1994) concludes that this was, until perhaps a generation ago, the way most people lived with and perceived wetlands.

For many the traditional view of wetlands was that they were wastelands associated with disease, difficulty and danger, and which should be 'reclaimed' for agriculture or building, transforming them into dryland. This second period of man's view of wetland areas produced formidable efforts to drain them in response to increases in population. In the USA, George Washington set up a company in 1763 to drain the 'dismal swamp of Virginia'. Widespread drainage was implemented following the Swampland Act (USA) of the mid nineteenth century, which encouraged wetland drainage in order that "wastelands might soon bear the fruits of sustained agriculture" (Mitchell, 1992). In England, drainage of the fens began in the seventeenth century. The pace of destruction has accelerated in the last few decades with advances in drainage technology and the construction of great dams (Williams, 1994). This has also been stimulated by the EEC's Common Agricultural Policy which artificially subsidised crop prices (Dugan, 1990). Drainage grants were available until 1985, for converting land to higher intensity agriculture (Gardiner, 1994).

Many authors (e.g. Maltby, 1986, Dahl, 1990, Mitchell, 1992, Dugan, 1993, and Hollis, 1994) provide countless examples of wetland loss statistics and population declines in associated flora and fauna (e.g. Gibbons et al, 1993), indicating the catastrophic impact of past policies and practices. Meadows et al (1992) state that the world's wetland areas have been reduced from 6% of the Earth's surface to 3% through dredging, filling, draining, and ditching, concluding that wetlands are probably more endangered than forests. Buisson and Bradley (1994) undertook a detailed review of loss statistics prepared by other authors (see Table 2.2) to show that in all cases losses are substantial. Jones and Hughes (1992) state that:

"the most common wetland type ..... is probably the lost wetland".

Country	Locality	Wetland Type	Timescale		% Loss	Rate of Loss (ha/ann.)	Reference
			Start	Finish			
USA	Lower 48 states	All wetlands	1780	1980	53%	188000	Dahl, 1990
USA	Lower 48 states	All wetlands	1950	1970		185000	Tiner, 1984
USA	Lower 48 states	Freshwater	1974	1983	3%	116000	Dahl & Johnson, 1991
USA	Lower 48 states	Saltwater	1974	1983	2%	3150	Dahl & Johnson, 1992
USA	Florida	Everglades	1900	1990	50%		Dugan, 1993
USA	California	Central Valley	1850	1990	99%	113000	Dugan, 1993
USA	California	Central Valley	1939	1985		435	Dugan, 1993
Canada	Lake Ontario	Shoreline wet.	1850	1990	90%		Dugan, 1993
Canada	Fraser river delta		1950	1990	28%		Dugan, 1993
Canada	Atlantic coast	Saltmarsh	1800	1990	66%		Environment Canada
Colombia	Cauca River	Floodplain wet.	1950	1990	88%	336	Naranjo, 1993
Colombia	Magdelana delta	Mangroves	1970	1987	80%	3450	
France	Brittany	coastal wet.	1960	1990	40%		Dugan, 1993
France	Camargue	wetlands	1942	1984		100	Anon. 1992
Greece		All wetlands	1920	1990	60%		Anon. 1992
Greece	Macedonia	Marshland	1930	1990	94%	1550	Anon. 1992
Italy		All wetlands	1881	1991	77%	10000	Anon. 1992
Tunisia		All wetlands	1881	1991	15%	190	Anon. 1992
Denmark		Freshwater wet.	1840	1990	75%		Dugan, 1993
Holland		All wetlands	1950	1985	55%		Jones & Hughes, 1993
Germany		Bogs and fens	1981	1985	9%	2500	Dugan, 1993
Belgium		All wetlands	1960	1990		1000	Dugan, 1993
Belgium	Flanders	Floodplain pasture	1960	1990	90%		Dugan, 1993
UK		Raised bog	1870	1990	94%		RSPB & Plantlife, 1993
England	Lancashire	Peat "mosses"	1948	1975	95%		NCC, 1984
England	Thames Estuary	Coastal pastures	1930	1980	64%		Ekins, 1990
N. Ireland	Belfast Lough	Intertidal Flats	1750	1990	85%		Wells, 1988
Kazakhstan	Aral Sea	Open water	1950	1990	66%	106000	Dugan, 1993
Cambodia	Mekong river	Floodplain forest	1970	1990	20%	6800	Dugan, 1993
Vietnam	Mekong delta	Mangrove & Melale	1960	1975	54%	10100	Dugan, 1993
Vietnam	Mekong delta	Mangrove & Melale	1918	1987	78%		Scott, 1993
Thailand		Mangroves	1961	1979	21%	4330	Dugan, 1993
Japan		Intertidal flats	1979	1985	7%	679	Takahashi, 1993
New Zealand		All wetlands	1840	1990	90%		Dugan, 1993
New Zealand		Freshwater wet.	1979	1983	14%		Dugan, 1993
Australia	Victoria	All wetlands	1830	1990	33%		Dugan, 1993

Table 2.2 A Summary of Wetland Loss Statistics (Buisson and Bradley, 1994).

Mountford's (1988) study showed that approximately thirty wetland bird species had been lost worldwide since 1600 AD. In the USA, 26% of the plants and 45% of the animals listed as threatened or endangered are either directly or indirectly dependant on wetlands for survival (Hammer and Bastian, 1988). Wetlands provide a home for one third of the USA resident bird species, and one third of all flora and fauna listed on the Federal Registry of Endangered and Threatened Species (Mitchell, 1992). In the UK, some species have come close to extinction or exist in such small numbers that they are vulnerable to extinction. These species are listed in "Red Data Books" with some 16% of vulnerable birds being wetland species. Gibbons et al (1993) carried out a detail breeding bird survey in Great Britain and Ireland between 1968-1972 and repeated it in 1988-1991. The survey highlighted the dramatic decline in breeding waders on lowland wet grasslands, including Snipe which have disappeared from 60% of the areas where they occurred at the time of the first survey.

An awareness of these less tangible costs, have led to a growing realisation of the ecological destruction associated with the drainage of the wetland landscape. Man's approach to wetlands entered a third period about 75 years ago in both the UK and USA. Individuals and pressure groups (e.g. RSPB) attempted to protect the remaining areas of wetland habitat. In the USA this resulted in the first National Wildlife Refuge being established in the Florida Everglades in 1934, whilst, in the UK, the Norfolk Naturalists Society acquired wetland areas in the early 1920's. With the advent of the European Union there has also been attempts to instigate wetland conservation policies (Williams, 1994).

Recent changes in attitudes have been reflected in international conventions and national laws to protect the environment in general and wetlands in particular (see section 2.3.1). This fourth period, one of wetland restoration and creation, began in the USA in the early 1970's, when restoration was seen primarily as compensation. This lead to the concept of "No Net Loss" (NNL) developed to compensate for unavoidable losses due to projects of significant public value for which no alternative site is feasible (Mitchell, 1990). Larson (1992) concludes by suggesting it is unrealistic to stop all wetland loss, but that NNL is a useful concept on which to base a wetland protection programme. In addition to NNL active long-term restoration initiatives have been articulated in the US National Research Council Report "The Restoration of Aquatic Ecosystems" which calls for the restoration of 10 million acres in the USA in the next 20 years (Williams, 1994).

However, these policies have not stopped wetland loss and degradation (Buisson and Bradley, 1994). Competing government priorities and institutional weakness contribute to this. For example, agricultural policy to drain land is often favoured against explicit government commitment to wetland conservation. Maltby (1992) states that the rate of loss of wetlands in the USA, despite major legislation and regulation, still exceeds 125,000ha per annum, and estimates that over 900million hectares of wetlands worldwide are also at risk. Most European countries are 'Contracting Parties' to the Ramsar Convention. However, Hollis and Jones' (1992) data for all European Ramsar sites, reveals that only 58 of the 318 wetlands (18%) are definitely not under threat. Dugan (1990) concludes that some wetland loss is inevitable and can even benefit man; however, much is both 'detrimental and avoidable', and that in many countries the rate of wetland loss has reached the 'proportion of a national crisis'. In addition, Bellamy (in Dugan, 1993) states that:

> "The continual destruction of wetlands by drainage, exploitation, and pollution is the worst act of environmental vandalism being committed on a worldwide scale today."

Grenell (1994) asserts that as population increases and urbanisation spreads, pressures on wetlands will increase. Williams (1994) concludes that it is now time to restore and create wetlands, defining the task as "the art of directing the great sources of power in mankind for the benefit of nature", perhaps to support Mitchell's (1990) vision that once again;

> "Wild birds will flood the sky, drawn to a sanctuary wet and priceless".

2.2 WETLAND FUNCTIONS AND VALUES.

So, much of the wetland loss has been deliberate, but other losses are the result of decisions taken in ignorance of the full value of wetlands in their natural state. Many authors (e.g. Mitsch and Gosselink, 1993, Hollis, 1994) have detailed descriptions of the various functions of wetland ecosystems. In general, wetlands provide natural storage for flood waters, reducing inundation damage downstream, whilst also encouraging recharge of underlying aquifers. Hollis (1994) states that wetlands provide improvements to water quality, both by reducing nitrogen and phosphorus and degrading/trapping organic material. Mitsch and Gosselink (1993) refer to wetlands as the "kidneys of the landscape".

The economic and non-economic value of wetlands has also been the subject of recent research papers with Zedler and Weller (1990) concluding that:

> "the complexity, integrity and uniqueness of natural wetlands are undervalued."

Wetland science has recently shown that far from being wastelands, they are among the most productive ecosystems in the world (Mitchell, 1990). Hollis (1994) quotes the works of Barbier et al (1993), whose studies in the Nigerian Hadejia (Nguru wetlands) show that wetlands are six times more valuable per hectare than formally irrigated cropland. Many coastal wetlands support lucrative fisheries, with the Wadden Sea acting as a major nursery area for valuable North Sea fish (Maltby, 1986). In addition, many wetland plants are global food staples. For example, rice is the primary food resource of over half of the world's population, and occupies 11% of all arable land. Wetlands are also a major source of non-food plants, e.g. *Phragmites australis* is used in thatching.

The value of wetlands to a large variety of wildlife cannot be overlooked (see Section 2.4.5). Mitchell (1990) states that wetlands "are libraries of nature that contain volumes of priceless genetic information". The recognition of the conservation value of reedbed habitats has produced a drive to restore and create these ecosystems (see Section 2.5.3).

2.3 WETLAND PROTECTION, POLICY, LEGISLATION, AND ADMINISTRATION.

2.3.1 INTRODUCTION.

Recent changes in attitude towards wetlands and their associated habitats have led to attempts to reduce their catastrophic loss. This section briefly outlines the major policy and legislation which has been implemented to protect them in the UK, as part of the European Community, and the policies adopted in the USA.

Effective protection depends on a government's capacity and will to prevent wetland losses. The legislative framework must be comprehensive, and able to protect all significant wetland values and functions from a wide range of likely impacts. However, Dugan (1990) found that in many countries relevant law is marked by "gaps, duplication and even conflicts".

In 1971, the 'Convention on Wetlands of International Importance, Especially as Waterfowl Habitat' was drafted at Ramsar, Iran. It produced criteria to identify wetlands of international importance. The Ramsar Convention has since provided the key intergovernmental forum for the promotion of international co-operation for wetland conservation (Dugan, 1990). Its signatories agree to include wetland conservation in their national planning and to promote sound utilisation (Maltby, 1986). At the start of the 1990s, 30million ha of wetlands throughout the world were listed, a striking testimony to the international recognition of the importance of wetlands and of national commitment to managing these so as to maintain their value (Dugan, 1990).

The World Conservation Union (1985) identified eight major categories which give degrees of protection to sites: Scientific Reserve/Strict Nature Reserve; National Park; Natural Monument/Natural Landmark; Managed Nature Reserve/Wildlife Sanctuary; Protected Landscape; Resource Reserve; Natural Biotic Area/Anthropological Reserve; Multiple Use Management Area/ Managed Resource Area.

Hollis and Jones (1992) found that not all legislation which beneficially impacts on wetland areas is directly related to conservation, asserting that the EEC's Farm Structures Regulations states that;

> "in protected areas such as nature or national parks, measures should be taken in order to support farmers following agricultural practices which meet the needs of protection and improvement of the environment".

Hollis and Jones ironically conclude that probably the greatest contribution to wetland conservation by the EC was the removal of direct and indirect subsides for drainage for land "improvement" e.g. under the Common Agricultural Policy.

Denny (1994) asserts that wetlands were given additional protection under the 'action programme' of the Convention on Biological Diversity (United Nations Conference on Environment and Development, 1992), which requires each contracting party to 'develop national strategies, plans or programmes for the conservation and sustainable use of biological diversity'. Denny states that this is 'directly pertinent' to wetland conservation. European wetlands have also been protected under the European Union LIFE programme (see Section 2.5.3).

2.3.2 UNITED KINGDOM.

Within the UK, wetland sites may be designated within a legislative and administrative framework, which includes: Sites of Special Scientific Interest (SSSIs); Special Protection Areas for Birds (SPAs); and European Special Areas of Conservation (SACs). SSSIs are areas of land or land covered by water which in the opinion of English Nature are of special interest for any of their flora, fauna or geological or physiographical features. SSSIs are notified under Section 28 of the Wildlife and Countryside Act, 1981 (HMSO, 1981), with approximately 900 wetland areas designated (English Nature, 1997). The UK Government's statutory nature conservation advisers have prepared a list of sites meeting the waterbird criteria for designation as Wetlands of International Importance under the Ramsar Convention and/or as Special Protection Areas (SPA's) under the European Community Directive on the Conservation of Wild Birds (79/409/EEC) (Jones and Hughes, 1992). The UK presently has 115 SPAs, many of which are also Ramsar sites (English Nature, 1997). On SACs, the Government is required to prevent deterioration or disturbance (except where there are overriding economic, social, health or safety considerations). A small number of river, fen and lake habitats are due to be designated as SACs by 1998 (English Nature, 1997).

Wetlands restored within agricultural areas involve a loss of income and it may be necessary to offer financial inducement for farmers to adopt the "sub economic" practices required for ecological aims. Section 39 of the Wildlife and Countryside Act (HMSO, 1981) allows farmers to receive payments for maintaining grazing marshland by undertaking 'profits-forgone' management agreements.

Armstrong et al (1994) provide a list of a variety of schemes under which further compensation is available in England and Wales, among them:

1) management agreements with English Nature for SSSI's;
2) Countryside Stewardship Schemes;
3) Environmentally Sensitive Areas (ESA) Payments from MAFF.

Grants have become available to farmers in recent years through the UK Government's decision in 1986 to establish Environmentally Sensitive Areas (ESAs) under Section 18(1) of the Agriculture Act 1986 (HMSO, 1986). Fourteen regions were identified in England and Wales by the Countryside Commission and the Nature Conservancy Council for consideration under the ESA scheme, with initially five ESAs established in December 1986. Within an ESA, if the landowner is to receive the maximum grant payment, he or she must actively manage the land to the benefit of nature conservation. Armstrong et al (1994) and Tidy (1994) provide details of wetland restoration under the ESA scheme.

In 1992, the UK signed the Convention on Biological Diversity (UNCED, 1992), and in May 1996, the UK Biodiversity Steering Group's report detailed plans for 14 key habitats (e.g. reedbeds) and 116 species of plants and animals (e.g. the bittern) (see Section 2.5.3). In response to the UK Biodiversity Action Plan, English Nature (1997) have produced an action plan to conserve SSSIs prioritising rivers, lakes, fens and marshes. The document states that the:

> "legislation and structures ....in England already exist" and that "now is the time to make a special effort on wildlife and fresh water".

2.3.3 USA.

In the mid 1980s explicit federal wetland policies began to emerge. Table 2.3 summarises the legislation and policy directives which have been implemented, and indicates the successful application of wetland protection legislation in the USA.

Legislation	Comments
Water Bank Act (1970)	Pays farmers to preserve wetland habitat for waterfowl.
Clean Water Act (1977)	Nearly all wetlands are considered "waters of the US" and, as such, are protected under several provisions of this Act. Recognises the importance of wetlands to society.
Section 404	Prohibits the sediment infilling of any portion of the US waters and ensures moneys for mitigation projects of over $15,000/ha. A set of 'Wetland Regulations' were included within the Federal Regulations Code in January 1994.
Section 319	Provides funding to implement management projects to reduce the impact of non point source pollution on wetlands.
Executive Order No. 11990 - Protection of Wetlands (1977)	Issued by President Carter - made wetland conservation a policy for all federal agencies.
Food Security Act (1985)	"Swampbuster" discourages wetland drainage by denying farm program benefits on all land the farm operator manages if the operator converts any wetland land.
North American Waterfowl Management Plan (1986)	An agreement between USA, Canada and Mexico to restore waterfowl populations to 1970 levels, with 0.5 million ha of priority habitat identified in North Central States.
Emergency Wetlands Resources Act (1986)	Requires states to include wetland priority plans in their state comprehensive outdoor recreation plans, doubling the amount of funding for federal acquisitions.
Tax Reform Act (1986)	Reduces the attractiveness of drainage schemes by eliminating tax allowances on drainage expenses.
Garrison Reform Act	Includes mitigation provisions to replace wetlands converted by project construction, providing moneys in wetland trust to be used for the preservation, enhancement, restoration and management of wetlands ($1 million/yr).
National Wetlands Policy Forum (1988)	Stated the aim of 'No Net Loss' and to increase the quantity and quality of the nation's wetlands resource base in the long term.
North American Wetland Conservation Act (1989)	Seeks to protect existing wetland and restore former wetlands. Greatly expanded wetland restoration by providing $25 million annually in federal matching funds for co-operative efforts with states and private individuals. In June 1993, a $4.2 million scheme was launched to protect 220ha of wetland and enhance a further 900ha.
Food, Agriculture, Conservation, and Trade Act (1990)	Modified some of the "swampbuster" provisions, includes fines up to $10,000. Provides 75% of the costs of permanently restoring wetlands on privately owned land.
Wetland Reserve Program & Environmental Easement Program.	Recently enacted as part of the Act, establishing a national goal of restoring and protecting 0.5 million ha of wetland by 1995, primarily critical wildlife habitat for threatened and endangered species. Maximum payments up to $50,000/yr for 30yr easements. Mean payments in 1992 were $435/ha.

Table 2.3 Wetland Legislation in the USA.
(Kusler and Kentula 1990, Heimlich 1991, Mitchell 1992, Fields 1992, Hollis 1992, Leitch and Baltezore 1992, Beck 1994, and Lant et al 1995)

2.3.4 WETLAND ADMINISTRATION.

In the UK and USA, the organisations and remits involved in the administration of wetland areas are shown in Tables 2.4 and 2.5 respectively.

Organisation	**Remit**
Ministry of Agriculture, Fish & Food	Policy
Dept. of the Environment	Legislation Commitments
Environment Agency	Operational Authority with conservation duties
Internal Drainage Board	Operational
English Nature	Site Designations and Management
Voluntary Bodies (RSPB, WWT etc.)	Site Management and conservation advice

Table 2.4 Wetland Administration in the UK. (after Gardiner, 1994)

Organisation	**Remit**
US Army Corps of Engineers	Wetland determination and delineation. Section 404 Permit Approval and Conditions
Environmental Protection Agency	Operational Authority Conservation Guidelines
US Fish and Wildlife Service	Wetland advice/research Management of National Wildlife Refuge System Development of National Wetland Inventory Maps
Non-profit Organisations (e.g. Association of State Wetland Managers)	Research/Management advice
Ducks Unlimited	Site Management

Table 2.5 Wetland Administration in the USA

2.3.5 CONSERVATION BODIES AND VOLUNTARY ORGANISATIONS.

Many UK conservation bodies and voluntary organisations both manage and own large areas of wetland habitat. Wildlife Trusts are involved in the day-to-day running of many wetland areas, and are often assisted by the British Trust for Conservation Volunteers (BTCV), a voluntary organisation which helps to rejuvenate wetland habitats.

The Wildfowl and Wetlands Trust works to save wetlands and conserve their wildlife through conservation, research and education activities, and through recreation, bringing people and wildfowl together in wetland settings. The Trust has eight Centres covering some 2,000 ha of wetland habitat, natural and created, (Davis, 1992).

The Royal Society for the Protection of Birds (RSPB), granted a Royal Charter in 1904, has long been the largest nature conservation charity in Europe. In recent years the RSPB has begun drawing up 'action plans' for threatened and internationally important birds and habitats in the UK. Each plan outlines the needs of the bird or habitat, the threats to its survival and the action required for improvement. Many directly focus on wetland habitats and the rare birds which inhabit them. The RSPB are responsible for the management of 24% of the regularly flooded lowland grasslands in the UK, and over 10% of the total British reedbed area (Gilbert et al, 1996). The RSPB management of *Phragmites australis* dominated reedbed is directed towards increasing the number of birds which rely on this habitat e.g. the bittern (see Section 2.4.5).

2.4 REEDBED SWAMPS.

2.4.1 INTRODUCTION.

Reedbed swamps exist across much of the world, dominated by tall emergent plants such as *Phragmites australis communis Trin.*. *Phragmites australis* has a worldwide distribution and, where conditions are suitable, it is highly successful and a rapid colonist of newly-created shallow water habitats. In optimum conditions, it forms large, single species swamps known variously as reedbed, reedswamp or reedmarsh. Rodwell (1995) distinguishes four main types of reedswamp community and defines twenty one communities of swamp as being:

> "characterised as generally species-poor vegetation types, each overwhelmingly dominated by an often tall or bulky monocotyledon and with a usually ill defined understorey element or none".

These twenty one communities include most of the emergent herbaceous vegetation in open-water transitions and flooded sites around British fresh (and some brackish) waters. Rodwell describes in detail the community 'S4 -

Phragmites australis swamps and reedbeds', as being characterised by an overwhelming dominance of *Phragmites australis.*

Reedbeds support their own distinct ecology. Hawke and José (1996) found that the conservation interest of a reedbed is influenced by the physical and chemical characteristics of the water environment. They conclude that reedbed habitats within the UK have been seriously damaged by poor water quality, over exploitation of water for abstraction, and drainage. English Nature (1994) assert that the loss of reedbed habitat, and neglect of remaining reedbeds has focused concern on the reduced wildlife interest of this threatened habitat. Gummer (1996) highlights the outstanding importance of reedbeds, that provide a home to some of our rarest and most spectacular wildlife.

2.4.2 HABITAT CHARACTERISTICS.

In the UK, the majority of the reedswamp communities occur on the floodplains of lowland rivers, with the focus on coastal floodplains protected from incursion by the sea. The most extensive reedbeds are found in two main localities: river floodplains and low lying coastal plains (Hawke and José, 1996). Reedbeds often occur on the margins of standing waters, both in natural lakes and pools and around man-made water bodies. Both organic and mineral soils are colonised and waters can range from oligotrophic to highly eutrophic. Everett (1989) reported that many reedswamps are relatively "young" with over half of those which could be aged formed this century.

Phragmites australis is a tall perennial and flood tolerant grass, forming extensive individual stands. Its reedswamp communities are typically very species-poor and no other species attains even occasional frequency throughout. In the UK, it is principally a lowland plant, commonest below 150 mAOD, intolerant of much water movement, but otherwise is a remarkably adaptable species which will grow successfully in brackish water (e.g. Tay Estuary, Scotland) but is most commonly associated with nutrient-rich freshwater. Haslam (1970) stated that it can also survive a wide variety of water regimes, with water-tables which range between 2 m above the substrate to more than 1m below and with various patterns of fluctuation. She also stated that the best performance is attained where the water level ranges from +500 mm to

-200 mm and where flooding persists for several months of the year. Everett (1989) observed that *Phragmites australis* thrives in water depths between 300-500 mm. The artificial dominance maintained by cropping extends the occurrence of *Phragmites australis* into naturally drier situations.

The characteristic of monodominant species changes where the hydroperiod is non-ideal. This produces an open 'ecotone' between the reedswamp zone and the aquatic and terrestrial zones. These fringing reedswamps appear to have a distinct boundary with open water, however the two habitats have much influence upon each other, with reedswamps often providing cover for oviposition sites, for birds and fish who spend most of their time in open water.

2.4.3 REEDBED AREA, DISTRIBUTION, AND PROTECTION STATUS IN THE UK.

Everett (1989) suggested that reedswamp was a widespread habitat in the UK prior to the major drainage programmes. Today, it is decidedly scarce, and recently man has had an important role in preserving it, with the traditional commercial use of reeds (thatching etc.) being particularly important (see Section 2.4.6). Bibby and Lunn (1982) provided an assessment of the number, distribution, size, and type of reedbeds existing in England and Wales, and attempted to classify all reedbeds that were >2 ha. Gilbert et al (1996) also studied smaller reedbeds (>0.1 ha) and reedbeds in Scotland, identifying 922 reedbed sites with a total area of 6,542 ha, including nearly 600 reedbeds >2 ha, and only 30 reedbeds larger than 40 ha (see Figure 2.1). Gilbert et al state that reedbed is more scarce than Caledonian pine forest, lowland heath, and lowland raised peat bogs, and that the reedbeds are mostly fragmented into small blocks of <1 ha.

Reedbeds are concentrated in East Anglia. Other important areas are Anglesey and the south coast. Gilbert et al (1996) state that 36% of the total reedbed area occurs in Norfolk and Suffolk. The most extensive area of reedbed is tidal, located on the Inner Tay estuary in Scotland, at 410 ha. Gilbert et al found that since the survey undertaken by Bibby and Lunn (1982), in 25 sites surveyed not in the control of the RSPB, there had been a net loss of reedbed of 13.2% (primarily due to saltwater incursion). However, on the RSPB reserves there had been a 2.8% net gain in area.

Aston University

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Figure 2.1 Reedbed Distribution in the UK (Gilbert et al, 1996)

Gilbert et al (1996) also conclude that 91% of the English reedbeds (>10ha) had some form of site protection, with the figures for Scotland and Wales being 98% and 84% respectively. In Britain, 5,788 ha of reedbed were designated as SSSIs, with 679 ha contained within RSPB reserves, and 347 ha within National Nature Reserves.

2.4.4 PHENOLOGICAL CHARACTERISTICS OF PHRAGMITES AUSTRALIS.

In the early 1970s, Haslam undertook a detailed study of the phenological characteristics and ecology of *Phragmites australis* (e.g. Haslam, 1970). Haslam (1972a) suggested that *Phragmites australis* grows best on cohesive soils, and to a decreasing degree on peat soils and non-cohesive sediments, particularly gravel. Hawke and José (1996) suggest that peat soils that have undergone prolonged oxidation, may experience a marked fall in the pH value when flooded, producing unfavourable conditions for the growth of *Phragmites australis*. Experiments undertaken by the author to assess the impact of varying sediment types on the establishment of *Phragmites australis* are detailed in Section 5.2.5.

The number of seeds which are present in any one inflorescence varies throughout the geographical range of *Phragmites australis* (White, 1993). Hawke and José (1996) state that mean seed numbers vary between 5 - 285 per inflorescence, with up to 2,300 seeds per inflorescence recorded at Strumpshaw Fen. In general, seed number and viability reduces in the north of the UK (Self, 1997), with subsequent seedling survival in natural habitats in the UK being poor (Haslam, 1971).

The dominant success of *Phragmites australis* in such diverse habitats is dependent on its growth habit (see Table 2.6). Once a reed has established from seed, it spreads by vegetative propagation from a rhizomatous root, the rhizome growing both horizontally and vertically through the soil. New shoots emerge in April, growing vertically to produce stem, leaves and flower, setting seed by November (Hawke and José, 1996). Most of the annual growth cycle takes place between April and September. Warmer temperatures influence the attainment of the height potential in aerial shoots by stimulating intercalary and apical growth (Haslam, 1969). Spence (1964) calculated a regression of the height of flowering shoots on the mean temperature of the warmest months.

Phragmites australis has a system of lacunae in its stems and rhizomes enabling it to translocate oxygen to its roots to provide aeration in the biochemically reducing conditions which result from waterlogging. This process continues even when the aerial stems are dead. Any damage to this system may prejudice the plant's ability to survive (George, 1992).

Crook et al (1983) discussed two distinct growth forms;

Littoral reed - the horizontal rhizomes are embedded in the sediment, forming a physically stable community.

Hover reed - the horizontal rhizomes are immersed in the water, consisting of a floating raft of roots and rhizomes often 0.5m thick. Intolerant of wave action or tidal induced water level variation.

When growing well *Phragmites australis* is amongst the most productive of all swamp species, with productivity reported by various authors shown in Table 2.7. In the UK, the modal density is more than 100 shoots/m^2 and the modal height is usually over 1m, but apparently stable stands can be found with over 200 shorter shoots/m^2 or as few as 30 shoots/m^2 with a modal height of 2.5 m (Haslam, 1971). Stem density may be affected by stem breakage which reduces the submerged bud inception in late summer, whilst spring frosts may increase bud density and lengthen the period of emergence.

2.4.5 FAUNAL SPECIES.

In general, the number of faunal species breeding in pure reedswamp is low, however, those species that have a close association with large reedbeds are rare (Everett, 1989). Some 40 species of insect feed solely on reed (Fojt and Foster, 1992), with at least nine species of moth specific to reed. Hawke and José (1996) report that 700 species of invertebrate have been found to be associated with the UK reedbed. Wet reedbeds may support a high population density of the harvest mouse, which exploits the aerial habitat offered by reed and the abundant supply of insects (summer) and seed (winter) (Jowitt and Perrow, 1993).

The number of breeding bird species associated with reedbeds is very low. Reed warblers are often regarded as the most typical small bird, but the presence of *Phragmites australis* is not vital for this species. Savi's warbler was absent in the UK for over a century until it was noted in 1954 in Cambridgeshire. The breeding population, never high, reached up to 30 pairs in the late 1970's. Cetti's warbler was not recorded in the UK until 1961, with the breeding population of 313 pairs peaking in 1984 (Everett, 1989).

Period	Growth Activity
Late March/Early April	Young shoot (colt) emerges and continues to grow for 1- 3 months. Larger buds sprout first and grow tallest. As shoot extends the leaves unfurl. Around the vertical rhizomes and shoot bases there is an extension of thick felted mass of roots.
Late June	Maximum shoot density achieved.
Late July	Inflorescence appear from aerial shoots.
Late Summer	Inflorescence flower. Stems start to harden and lower leaf blades drop. Bud growth from previous year's vertical rhizome extending horizontally for some distance. Its apex turns upwards and the tip becomes dormant. Several smaller buds form on the upper regions of the vertical rhizome, which will produce a cluster of smaller shoots, which are less likely to flower.
November	Fruits ripen and are shed through the Winter and early Spring. Senescence occurs. Leaf abscission continues into the winter.
January	Most leaf blades have been shed and stems are dead and brittle.
General	Stems may remain standing for two or more seasons, after which they break off close to the ground leaving a stubble which can persist for several years. After about three seasons the rhizome system begins to die from behind.

Table 2.6 Growth Activity of Phragmites australis (after Haslam, 1970)

Reference	Standing Crop/Net Productivity (kg/m^2)
Haslam (1972b)	up to 1.0
Wheeler and Giller (1982)	0.404 to 1.932
Mason and Bryant (1975)	1.08

Table 2.7 Reported Productivity of Phragmites australis

None of the aforementioned bird species are reedbed specialists. However, three species, bearded tits, bittern, and marsh harrier depend on reedbed habitat. Bearded tits nest in reedbeds, finding a rich supply of insects in reedbeds in summer, and turning to reedseeds in winter as their main food. Bitterns have declined in numbers since 1970 throughout southern and central Europe, and also in the UK with drainage, habitat destruction, and hunting all implicated. Bitterns require large, wet, freshwater reedbeds with dykes and open water, to provide plentiful reed/water interface necessary for feeding. Marsh harriers require large reedbeds for nesting and feeding (Everett, 1989).

Bibby and Lunn (1982) estimated that over 1.1 million birds use reedbed roost sites in England and Wales. In particular, many reedbeds are used as huge autumn roosts by passerines, which provide a food resource exploited by sparrowhawks and hobbies.

2.4.6 COMMERCIAL USE.

Harvesting reed from around the margins of the broads, and from sites where no control over the water regime is possible is difficult. Commercial reed production requires controlled conditions. Commercial reedbeds consist predominantly of managed monodominant stands of *Phragmites australis* growing in areas that are flooded to a depth of 150 mm as soon as possible after reed-cutting has ended in early April. Water flows through the reed stand throughout the summer to avoid stagnation, with inflow cut off in August or early September to allow the site to drain off ready for the beginning of the reed cutting season in late December (George, 1992). Hawke and José (1996) state that "some 1,000 people are employed in the 'reed' industry" in the UK.

Phragmites australis has been used as a roofing material for many centuries. In 1989, the total UK thatching reed production was estimated at 336,555 bundles, with approximately 1.5 million additional bundles imported from Europe (Bateman et al, 1990). There is a large market for thatching reed most of which is not yet met by home production. The management, rehabilitation and creation of reedbeds could help to redress this balance (Hawke and José, 1996).

The development and construction of *Phragmites australis* dominated stands for the treatment of wastewater is discussed in Section 2.5.2.

2.5 WETLAND HABITAT RESTORATION AND CREATION.

2.5.1 INTRODUCTION.

As wetlands have been lost and pressures have increased on both government and the private sector to take remedial action, considerable attention has been focused upon the potential of restoring degraded wetlands or creating new ones. The goal of restoration and creation is a progressive increase in both wetland area and the values derived from its functions (Hollis, 1992). However, a range of factors, including the dynamics of wetland systems make this difficult to achieve (Dugan, 1990).

Zedler and Weller (1990) state that most wetland restoration/creation projects are stimulated as part of wetland loss mitigation policies, whilst Kusler and Kentula (1990) assert that restoration and creation have been advocated to: reduce the impacts of activities in or near wetlands; compensate for additional losses; restore or replace wetlands already degraded or destroyed; serve various new functions such as wastewater treatment, aquaculture, and waterfowl habitat. Kusler and Kentula conclude that restored or created wetlands should be designed as self-sustaining or self-managing systems.

Much of the creation and restoration undertaken in the South-eastern USA has occurred primarily as a direct result of the need to fulfil conditions set out under Section 404 of the Clean Water Act of 1977, or under Chapter 177-4 of the Florida Administrative Code and Henderson Wetlands Act of the State of Florida (Mitchell, 1992). The Everglades Project seeks to restore Pre-1900 conditions to the Everglades systems (Erwin, 1990). In the USA, projects involve a variety of ecosystems and many kinds of target species. Most of the freshwater projects have been in palustrine or open marsh wetlands. Conservation of shrub-dominated wetlands to herbaceous marshes has been common particularly in North-eastern USA. However, little work has been undertaken on bogs and fens to date. Zedler and Weller (1990) found that most projects have involved the modifications of degraded wetlands with few projects replacing lost wetlands by upland conversion.

In the UK, much has been undertaken within areas of pump drainage schemes that are the responsibility of the Internal Drainage Boards. Other projects have been undertaken by, or on behalf of, the Environment Agency (EA), whose responsibility for main river courses requires it to give consent for the diversion of river flows to maintain the wet status of recreated and restored wetlands in summer (Armstrong et al, 1994).

Hollis and Jones (1992) conclude that probably the most dynamic aspect of wetland management in Europe is wetland restoration. They present numerous Europe-wide examples of schemes which have attempted to restore wetland function and form. Williams (1994) states that in the Netherlands there have been experiments to restore the Polderlands to wetlands, however, early failures have led many to question the value of restoration.

Restored wetlands generally fall into two major categories: reserves and normal agricultural land. Reserves are managed primarily for ecological aims and do not generally include the need to generate a financial return from the land. Wetland restoration on agricultural land was discussed in Section 2.3.2.

George (1992) observes that not all restoration has resulted from a desire to increase wetland area, stating that much of the East Anglian Broads which had previously been embanked and drained for grazing, have fallen into disuse and reverted to reed-dominated fen e.g. Reedham Marsh.

Wetland creation typically involves the removal of upland soils to elevations which will support growth of wetland species (Weller, 1990). Normally the objective of wetland creation is to establish a new, persistent, functional ecology, "native" to the region. Given ecoenvironmental change, there is considerable choice in the type of wetland community for suitable "targets" (Armstrong et al, 1994). The creation of wetlands includes the utilisation of reservoirs, ponds and lagoons, extraction pits, waterways, brinefields, rice paddies, and other large areas dominated by anthropogenic activities, e.g. the Norfolk Broads. Man-made wetlands in the UK also include artificial gravel pits which have become an important wildlife habitat, with approximately one half of the UK breeding bird species present. Indeed, the little ringed plover (*Charadrius dubius*) has become established as a breeding species largely because of artificial gravel pit habitats (Maltby, 1986).

Typically, because of the problems associated with wetland creation, it is given lower priority than restoration (Hollis, 1992). As many created wetlands are close to dense population concentrations they also bring educational, and recreational value. Such schemes undertaken as part of the Teesside International Nature Reserve and the Cardiff Bay Barrage Environmental Compensation Measures are discussed in detail in Chapter Five.

Merritt (1994) states that industrial land in the UK is a great potential wetland landbank. He found that land policy changes helped the popularity of wetland creation and construction, with three categories most widespread; reedbed treatment systems, flood storage wetlands, and reclamation schemes.

2.5.2 CREATED WETLANDS FOR WASTEWATER TREATMENT.

Wetland construction for wastewater treatment has been heavily researched during the last decade, with a view to its commercial application. There is a large volume of work available (e.g. Hammer, 1988, Cooper et al, 1996, etc.), and specialist groups have also developed, for example the 'Specialist Group on the use of Macrophytes in Water Pollution Control', a part of the International Association on Water Quality. Thus, only a brief overview follows.

Constructed wetlands for wastewater treatment emulate marshes as opposed to bogs and swamps, primarily due to the quicker establishment of marshes, and partially because herbaceous emergents are more tolerant of high pollutant concentrations (Hammer and Bastion, 1988). Constructed wetland systems provide wastewater treatment by significantly reducing BOD and ammonia, suspended solids, nutrients such as nitrogen and phosphorus and other pollutants such as metals (Corbitt and Bowen, 1994). Widespread use of constructed wetlands for this purpose may provide a relatively simple and inexpensive solution for controlling many water pollution problems facing small communities, industries and agricultural operations. Table 2.8 outlines a comparison between constructed wetlands and 'traditional concrete' treatment plants.

Advantages of Constructed Wetlands	Easy to maintain. Relatively inexpensive to construct and operate. Relatively tolerant of fluctuating hydrologic and contaminant loading rates. Provide indirect benefits: green space; wildlife habitats; recreational and educational areas. Support of neighbouring people. Planning consent more often granted.
Disadvantages of Constructed Wetlands	Require larger land areas. Full operational performance in not reached in the first two-three growing seasons.

Table 2.8 Comparison Between Constructed Wetlands for Wastewater Treatment and 'Traditional Concrete' Treatment Plants (after Hammer and Bastion, 1988, & Green, 1995).

Cooper and Hobson (1988) detailed the development of constructed wetland effluent treatment systems based primarily upon *Phragmites australis* (root zone treatment). The first root zone treatment reedbeds in the UK were built in Acle (Anglian Water) and St Paul's Walden (Thames Water) in October 1985, with 24 reedbed treatment systems constructed by 1988. The *Phragmites australis* beds are planted at densities of 2-4 rhizomes or stems per m^2, with most UK root zone treatment reedbeds having bed depths of 0.6 m. To accommodate an anticipated accumulation of sediment/reedbed litter (25 mm/year), a 0.5 m head is provided over the bed surface to the top of the bund walls. This allows a 20 year operational life before the front end of the beds need skimming (Cooper and Hobson, 1988).

2.5.3 REEDBED HABITAT CREATION.

Reedbed habitat creation is not new. Indeed, George (1992) comments that prisoners of the Napoleonic War are thought to have planted the Inner Tay reedbed to reduce mudflat erosion. There are many examples of reedbeds created during the 20th century, with one of the earliest undertaken by Cator in the early 1920's near Ranworth, where reed eventually colonised an area of 35 ha (George, 1992). Prior to World War II an area of reedbed was planted at Blacktoft Sands, Lincolnshire, in an unsuccessful attempt to claim the land for agriculture. During

World War II, the Minsmere Levels were flooded as an anti-invasion measure, encouraging the development of a large reedbed. Both the site at Blacktoft Sands and at Minsmere have been designated as SSSIs and are currently under the management of the RSPB.

The primary reasons for reedbed creation are:

1) the supply the thatching industry (see Section 2.4.6);
2) the treatment of wastewater (see Section 2.5.2);
3) the reduction of wave erosion.
4) the replacement of lost habitat for wildlife conservation;

Phragmites australis stands have been created in an attempt to cushion the effect of wave action generated by wind or boats on the Broadlands, UK. Bonham (1980) stated that up to 60% of the energy of boat wash is dissipated by a stand of reed 2 m wide. Bonham created a reed stand using old car tyres, to protect two 30 m long sections of rapidly eroding riverbank from wave action. The area behind the tyres was backfilled with riverine sediments to facilitate the establishment of reeds. This prototype was not widely adopted because the backfilled material was partially washed out leaving unsightly tyres. Other later experiments were distorted by heavy grazing of the reeds by feral geese.

Hawke and José (1996) state that reedbed creation for wildlife conservation in the UK dates back at least 20 years, with the majority of these schemes undertaken in the 1990's. They assert that reedbed creation enables reed to establish more quickly than by natural expansion, often with full reed cover taking less than 5 years. The most common types of land used are:

1) unused/disused industrial land e.g. Haverton Hole, Teesside.
2) arable land and improved pasture e.g. Hickling, Norfolk.
3) disused mining or gravel workings e.g. East Chevington, Northumberland.

Self et al (1996) give the key criteria for potential reedbed sites (see Table 2.9).

Much of the reedbed restoration/creation in the UK is being undertaken to increase the numbers of reedbed bird species. The RSPB and English Nature have set a target of 100 booming bitterns in the UK by the year 2020. Hawke and José (1996) conclude that to achieve this aim requires a further 1,600 ha of suitable reedbed habitat to be available in the UK, requiring:

1) the rehabilitation and enhancement of 560 ha of existing UK reedbeds (potential to support an additional 32 bitterns);

2) the creation of a further 1040 ha of reedbed habitat (potential to support an additional 52 bitterns).

This target was supported by the UK government, which is giving high priority to halting the decline of the bittern.

Self et al (1996) suggest that greater target species success would be achieved if creation schemes are focused in traditional heartland areas (e.g. East Anglia). Gilbert et al (1996) observe that the RSPB is presently attempting to create new reedbeds throughout the UK, producing approximately 400 ha of new habitat (Self et al, 1996).

A document entitled "Urgent Conservation Action for the Bittern *Botautus stellaris* in the UK - Bittern LIFE Project" (RSPB, 1996) was presented by the RSPB on behalf of a partnership of seven conservation organisations (3 statutory and 4 non-government organisations) in the UK, as an application for funding under the European Union LIFE programme, in March 1996 (see Appendix 2),. The Bittern LIFE Project identified thirteen existing reedbed habitat areas (see Figure 2.2) where additional creation/restoration projects could be targeted to increase the area of reedbed, producing large habitat units.

Land Form	Flat, or with very gentle gradient to minimise the need for grading and/or bunding. No possibility of flooding neighbouring land.
Water	Adequate supply to compensate for seepage and evaporation. Acceptable quality.
Habitat	No existing habitat that would be damaged by flooding. Existing reedswamp (e.g. in ditches) to assist early colonisation and provide material for establishment.
Infrastructure	Existing ditches, pools, sluices.
Consents	Likely consent to abstract, impound, change land-use.

Table 2.9 Key Criteria for Identifying Potential Reedbed Sites (Self et al, 1996).

2.5.4 CRITERIA FOR THE SUCCESS OF WETLAND RESTORATION AND CREATION.

Upland conversion is complex and expensive, and less likely to achieve agreed goals than enhancement of degraded sites. Mitchell (1990) discusses the question of how effectively restored or created wetlands compensate for the destruction of existing naturally functioning wetlands, concluding that "wetland policy....must recognise the limits of scientific knowledge about restoration and creation." This factor is also observed by Zedler and Weller (1990), who recognise that "duplication is impossible and simulation is improbable", while Kusler and Kentula (1990) state that it is particularly difficult to restore or create habitats for ecologically sensitive animal or plant species.

Feierabend (1988) concluded that the key to the increased success of constructed wetlands for wildlife incorporates proper planning, implementation, maintenance, and important design considerations including the maximising of edge, providing transition zones into uplands, and use of existing wildlife corridors. Zedler and Weller (1990) state that it is vital to study the interactions that occur in wetlands among hydrologic elements, soils, water quality and plant communities, and this has rarely been done in depth.

Figure 2.2 Bittern LIFE Project - Site Locations

Significant statistical analysis has not been undertaken with respect to the long-term success of wetland habitat creation schemes. This is in part due to the limited period of time that such projects have been in progress. In addition, there is an overall lack of post-construction monitoring and assessment reporting. Kusler and Kentula (1990) stated that many restoration and creation schemes have yet to prove their long-term viability. However, D'Avanzo (1990) found positive reports from wetland creation projects in the USA, based on dredged material stabilisation, and observed that when an artificial wetland is built as a mitigation for a lost wetland, decades may pass before the created project assumes the structure and function of the lost habitat. Kusler and Kentula expanded upon this by stating that the revegetation of a restored or created wetland over a short period of time is no guarantee that the area will continue to function in the long term. Zedler and Weller (1990) conclude that the persistence of constructed wetlands is 'imperative'. Weller (1990) continues this theme by suggesting that;

> "We must not become over-confident that we can "create" a normally functioning and naturally diverse system. In most situations, we can provide the environmental needs to allow dominant wetland plants and animals to succeed, and the product will satisfy many if not most viewers. We cannot, however, expect to replace the complex and diverse natural systems that are a product of many centuries of evolution and randomness, and we should not let the case of creating the structure and simple features of a wetland for mitigation lead us to accept unnecessary and perhaps unsatisfactory substitutes".

Table 2.10 contains the key elements to successfully constructing a functional freshwater marsh system.

The success of a project depends upon careful attention to the wetland hydrology needed in design. Kusler and Kentula (1990) state that:

> "long-term success depends upon the ability to assess, recreate, and manipulate hydrology".

Unanticipated fluctuations in hydrology are a particularly serious problem for efforts to restore or create wetland types with very sensitive elevation or hydroperiod requirement. Droughts or floods may destroy or change the targeted species composition.

No.	Element
1	Realistic goals and measurable success criteria.
2	Proper pre-construction design evaluation including a hydrological analysis.
3	Contour design.
4	Construction technique.
5	Proper water quality.
6	Compatibility of adjacent existing and future land uses.
7	Appropriate substrate characteristics.
8	Re-vegetation techniques.
9	Re-introduction of fauna.
10	Upland buffers and protective structures.
11	Supervision by an experienced professional.
12	Post construction long term management.
13	Monitoring and reporting criteria.

Table 2.10 Key Elements to Successfully Constructing a Functional Freshwater Marsh System (Erwin, 1990).

Armstrong et al (1994) conclude that the creation of wetland habitats requires deliberate intervention in site hydrology to establish the desired degree of wetness. Only after the ecological objectives have been turned into water level requirements is it possible to design the hydrological operations necessary to achieve the desired degree of wetness. Normally this is achieved by the use of structures that already exist to control the wetness of the site. Three main options are generally available:

1) control of flooding;
2) control of outlet structures;
3) importation of water to replace losses due to evapotranspiration.

Weller (1990) suggests that the development of the correct elevation and establishment of a proper hydroperiod is the critical factor in the success of created wetlands, with one of the most common errors in site construction being incorrect topography. Zedler and Weller (1990) state that site grading must be very precise; a few centimetres too high or too low will prevent the desired community developing.

Many creation projects fail because of inappropriate hydrology. Basic to the entire concept of wetland creation is the existence of a functional hydrologic regime appropriate for the establishment and development of the specific wetland species (D'Avanzo, 1990). Any wetland project should be constructed in an area of suitable land use with an adequate catchment to provide the proper hydroperiod to meet the established goals (Erwin, 1990). Erwin stresses the need to develop a water budget or model to assure that the catchment area will create the proper hydroperiods to attain the goals of the selected habitat type. Erwin concludes that;

> "Hydrology is the ultimate limiting factor on the ability to create the wetland."

Chapter 3. WETLAND HYDROLOGY.

3.1 INTRODUCTION.

> "Hydrology is the driving force and essential common element in wetlands. It is hydrology that puts the 'wet' in wetlands" (Hollis, 1994).

Hydrology directly influences the characteristics of wetland ecosystems, driving the complex interactions between biota, soils, and water which create the unique bio-physical and physio-chemical conditions that distinguish the wetland ecosystem from either terrestrial or deep water habitats (Hammer and Kadlec, 1986). Mitsch and Gosselink (1993) assert that;

> "Hydrology is probably the single most important determinant for the establishment and maintenance of specific types of wetlands and wetland processes...when hydrologic conditions in wetlands change even slightly, the biota may respond with massive changes in species richness and ecosystem productivity. When hydrologic patterns remains similar from year to year, a wetland's structural and functional integrity may persist for many years".

Zedler and Weller (1990) conclude;

> "we need to understand wetland hydrology before we can effectively understand any of the other interactions or processes that occur in wetlands."

Hollis (1994) concludes that the main hydrological parameters which act as wetland controls are water balance (see Section 3.2) and water level regime (see Section 3.3). The hydrological processes of wetland ecosystems are discussed in Section 3.4, whilst Section 3.5 focuses on the hydrology and water level management of reedbeds.

To evaluate the relative importance of the various components of the wetland hydrological system, a conceptual water balance model may be used to aid the formulation of a water budget equation. An introduction to wetland modelling is undertaken in Section 3.6, with a conceptual model of the hydrology of wetland ecosystems presented in Section 3.6.2. Previously documented wetland hydrological models are discussed in Section 3.6.4.

Erwin (1990) states that;

> "The wetland's relationship to the surrounding groundwater system should be identified when constructing a hydrological model".

However, the areas identified for reedbed creation at both the TINR and Redwick sites were located within impermeable clay substrates, and had no groundwater component. The models were therefore adapted to focus attention on the parameters required to provide a water budget equation applicable to the two creation sites. A conceptual model of a surface water fed wetland system is presented in Section 3.8. Water budget equations are presented for use in the wetland hydrological flux calculations required to inform the creation of reedbed habitat on the designated study sites. The water budget model was used to design the monitoring programme necessary to fulfil the reedbed hydrological design and also identify the need for an additional water supply to meet the design criteria.

Despite the importance of hydrology to the understanding of wetland ecosystems, many researchers (e.g. Hollis, 1994) working in both the 'developed' and 'developing' world state that there is often no formal hydrological data available for a wetland, with often only rainfall data from a gauge some distance away.

3.2 WATER BALANCE.

The dynamics of water supply and loss are fundamental to the development, maintenance and functioning of wetlands (Maltby, 1992). Winter and Woo (1990) suggest that the water balance offers a useful summary of the hydrological processes that control the gains, losses, and storage changes that depend on the environmental controls of the chosen wetland regions. The water balance equation is commonly expressed as:

$$I - D = \frac{ds}{dt} \qquad (3.1)$$

where
- I = the rate of inflow to the system;
- D = the rate of discharge from the system;
- $\frac{ds}{dt}$ = the rate of change of water stored in the system.

Ingram (1981) provided a summary of the interlinked processes within a wetland water balance (see Figure 3.1). Hollis (1994) states that a wetland water balance usually requires attention to the full range of variables including; precipitation, river and surface water runoff inputs, groundwater inputs and/or outputs, evaporation and evapotranspiration including that from hydrophytes, river runoff from wetland, any tidal exchanges in coastal sites, and abstraction of water or returns of effluent. Which of these values are used in the construction of a wetland water balance equation should correspond to the features of the ecosystem considered (Shebeko and Ivanov, 1972).

From their studies, Winter and Woo (1990) state that many wetlands are not integrated into a drainage network, interacting only with atmospheric water and groundwater. The water balance of such wetlands is generally dominated by atmospheric-water interchange, and the relative volume of water exchange with groundwater varies widely. Ingram (1981) asserted that for mire ecosystems the total input of water is equal to precipitation plus total surface, and sub-surface recharge. However, in ecosystems with no telluric supply the total input is equal to precipitation only. Eisenlohr et al (1972) stated that precipitation was the basic source of water to prairie potholes, with the rainfall falling directly on its surface, being the only source of inflow that is sure to occur from every storm. Eisenlohr et al, concluded that the ratio of average annual precipitation to average annual lake evaporation is a measure of the extent to which ponds will be present in the potholes over the years. Winter and Woo (1990) conclude that studies of the hydrology of prairie lakes indicate that the water balances of these systems are dominated by precipitation and evaporation, and that stream inflow and outflow are not major components of the water balance, except for the overland flow of snowmelt into the depressions.

Thus, primarily the water budgets for reedbed ecosystems created within an impermeable clay catchment exist as precipitation (principal input) and evaporation/evapotranspiration (principal output). This can be summarised using a simple equation;

$$\Delta \mathbf{V} = \mathbf{P} - [\mathbf{Eo} + \mathbf{ET(Reed)}] \qquad (3.2)$$

where;
ΔV = the change in water storage
P = precipitation
Eo = open water evaporation
ET(Reed) = reedbed evapotranspiration

Figure 3.1 Schematic Diagram of the Water Relations of a Mire, Showing the Compartments in which Storage Occurs and the Fluxes of Water Involved in their Recharge and Discharge (Ingram, 1981).

3.3 WATER LEVEL REGIME/HYDROPERIOD.

Creating a wetland area requires an understanding of the macroscale hydrological conditions which make up the water balance equation. Some major freshwater wetland systems exist as a result of relatively well-documented macroscale hydrologic conditions. However, differences in wetland community types or even the existence of numerous wetlands are dependent on much smaller hydrologic phenomena (Duever, 1988). Many of the large wetland ecosystems are dependent on a complex pattern of relatively microscale water movements. Very large total amounts of water may be involved, but because of the spatial extent of the wetland, water depths are shallow and water flows are very slow, e.g. Cypress Swamps, (Duever, 1988). The microscale hydrological processes existing on a site determine the inherent water level regime and the occurrence of the annual period of inundation, or hydroperiod.

The hydroperiod of a wetland area describes the combination of water level (e.g. surface water depth), the length of time that level is maintained, and at what time of the year (Hawke and José, 1996), being the summed expression of the temporal factors that control wetland water levels. Hollis (1994) states that the water level regime reflects the pattern of inflows and outflows, and the critical relationships between water depth, flooded area and water volumes in the wetland, producing a hydrological signature for each wetland type. At a site specific level, the character and extent of wetlands are determined by depths and duration of inundation, which are in turn influenced by each site's microtopography, soil type, and vegetative cover (Duever, 1988).

Hydroperiod has been shown to be the dominant factor controlling both the existence and composition of the plant communities of many wetlands (Duever, 1986). It has the effect of eliminating species which are intolerant of extended inundation.

Tammi (1994) states that all wetlands are dynamic systems from a hydrological viewpoint with associated hydroperiods which may vary annually (e.g. flooded grassland), seasonally, daily (e.g. tidally influenced wetlands), or may even be permanent in shallow water bodies. Duever (1988) found that the optimum hydroperiod for development of wetland in the Corkscrew Swamp in South Florida was, 7 to 9 months for marsh and 9 to 10 months for swamp, although wetlands existing at a higher latitude would require shorter hydroperiods to produce similar wetland habitats. Mitsch et al (1982) concluded that alteration of the hydroperiod can cause severe changes in the wetland over a relatively short period.

Duever (1988) stated that the microscale hydrological processes are poorly documented. It is these processes which are readily alterable and so form the prime focus for managers of 'successful' wetland nature reserves.

3.4 HYDROLOGICAL PROCESSES OF WETLAND ECOSYSTEMS.

A detailed description of the hydrological processes occurring within wetland ecosystems is not presented here. However, a review of these processes has been undertaken by many researchers (see, Ingram, 1981 and Duever, 1988). Duever (1988) asserted that although physical processes dominate wetland hydrology, biological processes can also significantly influence the pathways involved and the rates at which water moves. Eisenlohr et al (1972) summarised the hydrological inflow and outflow processes occurring within the prairie pothole wetlands they studied (see Table 3.1). Although runoff from the drainage basin was small and highly variable, it was the key source that determined whether a pond would persist.

Group	Inflow	Outflow
Above the ground (or water surface)	Precipitation Condensation	Evaporation Transpiration
On the ground	Runoff	Overflow
In the ground	Seepage inflow	Seepage outflow

Table 3.1 The Hydrological Processes Occurring in Prairie Pothole Wetlands (Eisenlohr et al, 1972).

Wetlands commonly retain part of their surface inflow, quickly absorbing water inputs and only slowly releasing them during an extended period (Teesside International Nature Reserve, 1990). The resulting outflow hydrographs are generally smooth, and peak flow lags behind the initial peak runoff into the wetland. The degree of flow modification related to storage depends both on the extent of the wetland, and the characteristics of the flow through them (Winter and Woo, 1990). Mitsch et al (1982) stated that in many cases wetlands are water conservation ecosystems and their removal could lead to lower streamflows in dry seasons, and higher floods in wet seasons.

Winter and Woo (1990) state that water storage in wetlands is primarily within surface depressions, or underground in nonsaturated peat based areas. Estimation of surface water storage requires a knowledge of site microtopography. Wetland water depths are frequently less than 1 m, even during high water periods, and microtopographic data with 0.1-0.2 m contours are probably necessary for reasonably detailed estimates of surface water quantities (Duever, 1988). The most efficient means of deriving these data over extensive areas is by correlating major vegetation types with water depths and then using aerial photography to map and quantify the areas occupied by the different vegetation types (Duever, 1988).

3.5 THE HYDROLOGICAL MANAGEMENT OF REEDBED ECOSYSTEMS.

3.5.1 INTRODUCTION.

Minimal detail was presented in Section 2.6 with respect to the hydrology and hydrological management of reedbed ecosystems. The importance of understanding the hydrology of reedbeds is expressed by many researchers (e.g. Haslam, 1969, Andrews and Ward, 1991). The relative scale of the hydrology and hydrological management may vary from water retention within a small pool, to the construction of large-scale sea defences necessary to prevent the incursion of saline water into freshwater reedbeds. This section outlines the importance of hydrological management, and discusses water level regimes appropriate to fulfil various reedbed management objectives.

Hawke and José (1996) state that the hydrology of a reedbed ecosystem may be influenced by both natural processes and by management, including water supply (rainfall, groundwater, surface flows and evapotranspiration) and water distribution (sluices, dams and bunds, pumps). Hydrological management is the most important factor in managing a reedbed for both wildlife and commercial gains, determining the longevity of the reedbed, what other forms of management can be implemented, and what machinery can be used. The precise regime employed in any reedbed will therefore in part depend on the requirements of the other management methods employed and is dependant primarily on the amount of water available (Ward, 1991). Ward states that sufficient water must be available to maintain a satisfactory management regime. Winter and Woo (1990) assert that the water supply must also be 'persistent'. Ward found that the summer was the crucial period for water supply limitations when not only is the supply limited, but it is the period of maximum evapotranspiration. So the maintenance of a water supply/level may only be guaranteed if an abstraction licence is granted to pump water from a nearby water resource.

Andrews and Ward (1991) state that for all reedbed sites hydrological management is invaluable. A large bed should be divided into four or more independent units, allowing the site to be managed in several different ways to provide a variety of different water levels and facilitate rotational management. They conclude that as the control of water levels is of the utmost importance in reedbed management, that new sites should not be constructed without provision for the drainage and re-flooding of individual compartments at any season.

The precise regime adopted may depend on individual species requirements, or the prevention of the excessive build up of reed litter. Management at Leighton Moss (RSPB Reedbed Reserve, Lancaster, UK.) controls water levels to a depth of 100-200 mm in spring, and allows water levels to drop between July and October to aid oxidation of the reed litter, preventing excessive build up (Ward, 1991). *Phragmites australis* is usually most vigorous in beds flooded to a depth of approximately 1m (Haslam, 1969), with a considerable depth of water required throughout much of the year to prevent the invasion of scrub (Ward, 1991). Haslam (1972a) and Andrews and Ward (1991) state that reeds do not normally thrive in water bodies with erratic fluctuations in water level e.g. reservoirs. Hawke and José (1996) provide example water level regimes for reedbeds managed for different objectives (see Table 3.2)

Bitterns require more precise control of water depths (< 200 mm) throughout the summer. Summer flooding, although beneficial for bitterns, may prevent the development of the carr-reed interface required by Cetti's warblers (Ward, 1991). The maximum and minimum water depth provided within a reedbed ecosystem may become critical.

Management Objective	Season	Water Level (Depth, m)	Additional Information
A) Optimum for Reedbed Wildlife	Summer	0.05 to 0.30 m	Some areas shallower and deeper.
	Winter	1.00 m max.	0.30 m enables bitterns and other wildlife to use reedbed for feeding.
B) Optimum for Reed Harvest	Summer	High as possible, 1.00 m max.	Enhances reed growth. Reduces weed competition
	Winter	At or below ground level	Harvesting facilitated by complete draw-down of water level, ensuring use of cutting machinery.
C) Integration for Wildlife and Reed Harvest	Summer	0.30 m max.	Where possible water depths should range across the reedbed, 0.00 to 0.50 m.
	Winter	At or below ground level	Surface water retained on separate hydrological units.
D) Wildlife and Commercial (reed, saw-sedge and Marsh hay)	Summer	At or below ground level	Draw-down facilitates cutting and removal, minimising machinery impact.
	Winter	0.30 m max.	Water level set to ensure cut ends of saw-sedge are not submerged.

Table 3.2 Example Water Level Regimes for Different Objectives (Hawke and José, 1996).

3.5.2 OPEN WATER AND DYKES.

Ward (1991) states that open water is an important feature in any reedbed, and that the "consensus of opinion" is that a reedbed should contain 15% of this habitat type, including shallow meres (0.05 - 0.3 m below summer water level), which provide valuable areas for waders and dabbling ducks. The open water areas contained within a reedbed ecosystem are often interconnected via dykes, which facilitate the movement of fish and eels, and ensure that water can both be applied to a site and removed again efficiently to allow management to take place. They can also provide a permanent reed/water interface essential for species such as bittern (Andrews and Ward, 1991).

As *Phragmites australis* will grow in water up to 1 m deep, and other emergents in water up to 1.5 m, open water features and dykes should be 1.5 - 2.0 m deep in order to prevent reed colonising the whole of the water course, and to reduce the impact of siltation (Ward, 1991). If the slope of dyke margins is set at 1:10 down to a depth of 1.5 m, reed will grow down to 1.0 m and the dyke centre will remain open. This has the added advantage that if a bed is drained for cutting in winter there will still be flooded dyke margins where bitterns can fish (Andrews and Ward, 1991).

3.5.3 COMMERCIAL REEDBEDS.

Haslam (1969) stated that the correct hydrological management regime is the primary requirement for a commercial thatching reedbed. Most of these reedbeds have water levels fluctuating around ground level for much of the year. High yields of thatching reed can come from many different water regimes provided they are repetitive from year to year. Thatching reedbeds require dry conditions to facilitate cutting during the winter. Water levels are kept low following cutting preventing die-back of the reeds caused by flooding stubble. Levels are gradually raised to follow the growth of the reed with shallow flooding in summer to enhance reed growth (Ward, 1991). To be effective the summer flooding should be at least 50 mm deep, reducing the growth of weed species which otherwise make profitable activity impossible (Haslam, 1969).

3.6 WETLAND MODELLING.

3.6.1 INTRODUCTION.

Constanza and Sklar (1985) asserted that the explanatory power of a model is a function of both "how much it attempts to explain (articulation)" and "how well it explains what was attempted (descriptive accuracy)". In the past, scientists have attempted to answer very 'narrow' questions, leading to models with low articulation but high descriptive accuracy. However, more recently, scientists have begun to adopt a more holistic, 'systems view' leading to more highly articulated models which are generally less accurate. Jorgensen (1994) concludes that it is necessary to find a balance between "elegant simplicity and realistic detail".

Jorgensen (1994) strongly recommends that the dynamics of all state variables are considered before the data collection programme is determined, concluding that, if the objective of the model is to give a good description of one state variable, it is essential that the data can show the dynamics of just that variable. The World Meteorological Organisation (1975) stated that the accuracy of a model not only depends its characteristics, but also on the accuracy and quantity of data input parameters, concluding that;

> "a lack of sufficiently long and reasonably accurate input data constitutes a major problem in the development of conceptual models".

The monitoring equipment and the frequency of data collection must therefore reflect the dynamics of the state variable being monitored. The World Meteorological Organisation concluded that for the successful calibration and operation of a catchment model, it is necessary to have data sets which are;

> "reliable, consistent, accurate and continuous, which are of sufficient length and cover all the required observations".

Using conceptual models within site-based projects helps appropriate monitoring to be well designed and implemented.

3.6.2 CONCEPTUAL MODELS.

Many researchers (Stone et al, 1978, Hopkinson et al, 1988, Jorgensen, 1994 etc.) conclude that the function of any complex ecosystem is most clearly and concisely described through the use of a conceptual model in which all of the major components, processes, and external variables are shown schematically. Lloyd et al (1979) stated that conceptual hydrologic models present a:

> "simple arrangement of simple elements whose structure and parameter values are chosen to simulate the behaviour of the catchment under study".

Jorgensen (1994) discovered that many authors have published different modelling procedures, but that the differences are only minor. The first modelling step is a 'definition of the problem', which establishes the model complexity, and allows the optimum number of subsystems in the model to be ascertained. The conceptual model can then be presented in diagrammatic form. Jorgensen (1994) presents ten examples of conceptual model layout used in varying applications. For example, 'Box Models' are simple and commonly used designs for conceptual ecosystem models with each 'box' representing a component in the model, with the arrows between boxes indicating processes.

The formulation of a conceptual hydrological model shows how these elements are connected by processes, allowing the development of mathematical equations e.g. water budget equations.

3.6.3 MATHEMATICAL MODELS.

Costanza and Sklar (1985) stated that mathematical models represent a simplification of the actual situation but that they are;

> "essential tools for understanding and managing ecosystems".

Jorgensen (1994) presents five components of a mathematical model in environmental sciences which are summarised in Table 3.3.

Within the modelling procedure the formulation of mathematical equations and the accurate measurement of all input parameters allows calibration, verification, and validation, of the developed model. Definitions of these significant steps in the modelling procedure are presented in Table 3.4.

No.	Component
1	External variables, which influence the state of the ecosystem (e.g. climatic variables).
2	State variables, which describe the state of the ecosystem.
3	Mathematical equations, which are used to represent the biological, chemical and physical processes, describing the relationship between external and state variables.
4	Processes, which may vary both spatially and/or temporally (e.g. evapotranspiration rate).
5	Universal constants (e.g. gravitational attraction).

Table 3.3 Components of a Mathematical Model in Environmental Sciences (after Jorgensen, 1994)

Step	Procedure
Calibration	An attempt to find the best accordance between computed and observed data by variation of a selected parameter.
Verification	A test of the internal logic of the model, e.g. does the model react as expected ?
Validation	An objective test of how well the model outputs accurate data.

Table 3.4 Significant Steps in the Modelling Procedure (after Jorgensen, 1994).

3.6.4 REVIEW OF WETLAND MODELS.

Wetland modelling began in the mid-1970's when sufficient data on the functioning of wetland ecosystems became available (Mitsch et al, 1988). Prior to this, the modelling efforts had been hampered by the diversity of wetland types and problems associated with wetland classification, producing wetland models limited to specific regions or types of wetlands (Constanza and Sklar, 1985). Mitsch et al (1988) stated that models of freshwater marshes and swamps are "primitive" whilst coastal marsh models are "well developed". Wetland modelling has changed markedly during the last decade, with Jorgensen (1994) asserting that this is "due to an increasing interest for these ecosystems as habitats for birds and amphibians", and that many models have been developed in response to the need to understand the role of wetland's in wastewater treatment.

Mitsch et al (1982) undertook a review of models of freshwater wetlands, stating that many were developed to organise: concepts; theories; and data collection, and have been constructed to present energy, nutrient and water budgets. Hopkinson et al (1988) concluded that the most successful models of marsh/estuarine systems are useful tools for formulating new hypotheses, for guiding large ecosystem-level research programmes and for guiding management of coastal habitats. Mitsch et al (1988) and Jorgensen (1994) conclude that modelling is one of the only tools available for managing quantitatively or semiquantitatively such complex systems as wetlands. However, Mitsch et al (1988) stated that without a reasonable amount of site-specific data to verify where there needs to be modification, wetland models are 'rarely adequate' for addressing management problems.

Many researchers have attempted to provide models for various wetland ecosystems. Mitsch et al (1982) presented a list of seven major types of models used for wetlands: energy/nutrient ecosystem models; hydrology models; spatial ecosystem models; tree growth models; process models; causal models; and regional energy models. Hammer and Kadlec (1986) developed a spatially distributed hydrology model to provide a means by which the response of natural or constructed wetlands can be predicted using sparse site information. Jorgensen (1994) presents conceptual wetland models for both a cypress swamp, and a water hyacinth marsh in Florida.

Stone et al (1978) and Duever (1988) produced a conceptual model which identified the most important features and functions of the freshwater marsh ecosystem, and there interdependency, allowing them to assign research priorities. The conceptual model was derived from existing data on freshwater marshes and from their many years of combined field experience. Duever's model illustrated major system components and their relationship to each other in the form of a 'box model' (see Figure 3.2), describing generalities rather than specific mathematical formulations.

Zentner (1994) highlighted the use of two wetland models for estimating wetland hydroperiod and depth of inundation. The first was applicable to wetlands abutting a river or lake where high surface water inputs produced seasonally varying water level with no implied storage. Zentner concluded that this model required accurate data, generally very expensive to generate. The second was a catchment model developed by the US Army Corps of Engineers in 1981, applicable to most wetlands. This model is based upon channelised streamflow equations, which when used in conjunction with an accurate topographical site map can predict the depth of water and duration of flooding at a specific elevation for a specific storm event.

Mitsch et al (1988) asserted because of its criticality wetland models require accurate descriptions of the hydrologic budget. Mitsch et al (1982) stated that there are several types of hydrology models applicable for wetlands, examples of which are shown in Table 3.5.

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Figure 3.2 A Conceptual Hydrological Model of Wetland Ecosystems (Duever, 1988).

Model	Form
Ecosystem	These describe a water budget for a homogeneous individual wetland and do not consider uplands or other bodies of water as part of the model.
Regional	These present overall gains and losses for a large scale region or catchment that includes wetland areas. Regional models differ from ecosystem models in that water storage in adjacent groundwater and surface water are considered as part of the model, not external to it.
Hydrodynamic transport	These are popular for streamflow and runoff calculations.

Table 3.5 Examples of Hydrology Models Applicable to Wetlands (after Mitsch et al, 1982).

Stone et al (1978) concluded that wetland modelling will enable decision makers: to identify the major impacts of an economic activity on wetland ecosystems; to form initial rough estimates of these impacts; and possibly to design mitigation procedure. Mitsch et al (1988) stated that:

> "with proper modelling efforts focused on wetland management and theory, the benefits will be to humanity and wetlands alike".

3.7 WETLAND WATER BALANCE MODELS AND DERIVED WATER BUDGETS EQUATIONS.

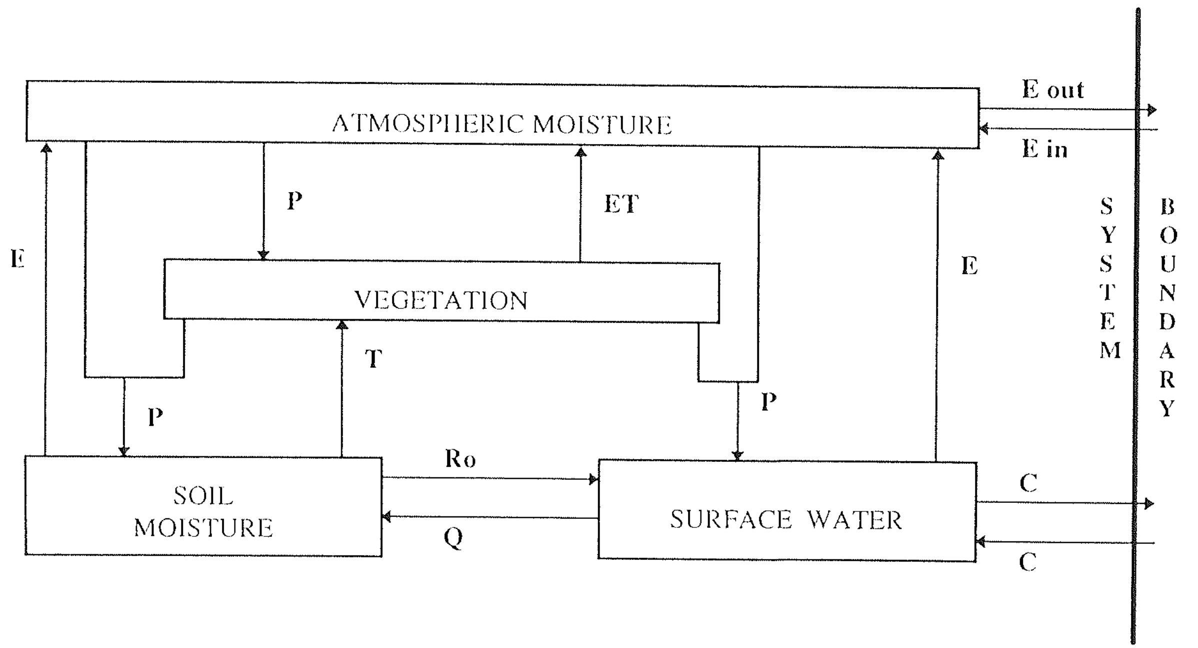
3.7.1 INTRODUCTION.

Objective 2 of this research is the formulation of a conceptual hydrological model of surface water fed reedbed systems, based on published literature. Section 3.7.2 briefly outlines the model synthesis from an understanding of the major processes important to wetland hydrology, and the discussion of wetland modelling undertaken in Section 3.6. Section 3.7.3 presents a water budget equation applicable to the small created reedbed area within the clay catchment of the Pilot Pool, Teesside International Nature Reserve (TINR) (see Section 5.2.4).

3.7.2 CONCEPTUAL MODELS OF SURFACE WATER FED WETLAND ECOSYSTEMS.

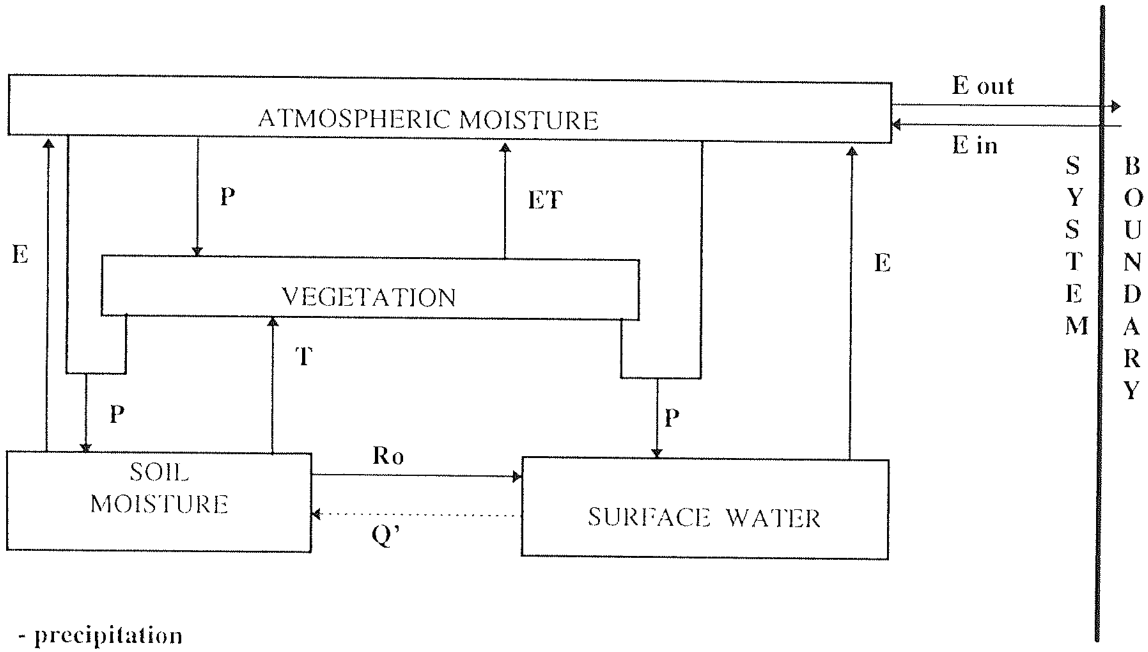
The model displayed in Figure 3.2 is applicable to the majority of wetland ecosystems both natural and anthropogenically altered. The majority of wetlands occur where the water table is close to the ground surface for much of the year and the resulting water balance is influenced by the seasonal variations in the groundwater fluxes. However, the study sites chosen in this project for the creation of wetland habitat are located in areas where the influence of groundwater is minimal. Hence a conceptual hydrological model of surface water fed reedbed systems is required that has relevance both to available field data and for informing design of the study sites (see Figure 3.3).

A study of the Pilot Pool catchment area identified no streamflow or surface outflow fluxes, requiring the removal of the streamflow component from the conceptual model developed for surface water fed reedbed systems. In addition, within the impermeable clay catchment the recharge of soil moisture from the surface waterbody is minimal. The resultant model applicable within the Pilot Pool catchment area is displayed in Figure 3.4.



P	- precipitation
E	- evaporation
T	- transpiration
ET	- evapotranspiration
C	- channel flow
Q	- lateral migration of surface water into surrounding catchment
Eout	- water vapour loss
Ein	- water vapour gain
Ro	- runoff

Figure 3.3 Proposed Conceptual Hydrological Model of a Surface Water Fed Reedbed Ecosystem.



P	- precipitation
E	- evaporation
T	- transpiration
ET	- evapotranspiration
C	- channel flow
Q'	- lateral migration of surface water into surrounding catchment (minimal in clay catchments)
Eout	- water vapour loss
Ein	- water vapour gain
Ro	- runoff

Figure 3.4 Proposed Conceptual Hydrological Model of the Pilot Pool Catchment Area, TINR.

3.7.3 WATER BUDGET EQUATIONS.

The water volume available to create and maintain various wetland habitats can be ascertained using a range of widely accepted water budget equations, based upon hydrometeorological data available from a site. From Figure 3.2, it is possible to identify a water budget equation applicable to the majority of wetland ecosystems. Ingram (1981) provides a more complex version of Equation 3.1 for the water balance of a mire ecosystem;

$$\mathbf{P} + \mathbf{N} - \mathbf{D} - \mathbf{ET} - \Delta\mathbf{V} - \mathbf{ne} = 0 \qquad (3.3)$$

where;

- **P** = precipitation (m^3),
- **N** = total surface and sub-surface recharge (m^3),
- **D** = total surface and sub-surface discharge (m^3),
- **ET** = evapotranspiration (m^3),
- **ΔV** = change in the volume of water storage (m^3),
- **ne** = error (m^3).

Mitsch and Gosselink (1993) also summarised their understanding of wetland hydrology in terms of a water budget containing similar parameters to those of Equation 3.3:

$$\Delta\mathbf{V} = \mathbf{P} + \mathbf{Si} + \mathbf{Gi} - \mathbf{ET} - \mathbf{So} - \mathbf{Go} +/- \mathbf{Ti} \qquad (3.4)$$

where;

- **ΔV** = change in the volume of water storage (m^3)
- **P** = precipitation (m^3)
- **Si** = surface inflow (m^3)
- **Gi** = groundwater inflow (m^3)
- **ET** = evapotranspiration (m^3)
- **So** = surface outflow (m^3)
- **Go** = groundwater outflow (m^3)
- **Ti** = tidal inflow (+) or outflow (-) (m^3)

A water budget equation applicable to surface water fed reedbed ecosystems can be synthesised from the parameters determined by Mitsch and Gosselink (1993) as;

$$\Delta\mathbf{V} = \mathbf{P} + \mathbf{Si} - \mathbf{ET} - \mathbf{So} \qquad (3.5)$$

This equation should be applicable to the majority of reedbed ecosystems where groundwater fluxes are minimal. Thus Equation 3.5 is applicable to the study sites at both the TINR and Redwick.

As already discussed in Section 3.7.2, a detailed study of the small clay catchment of the Pilot Pool showed that the water body seldom overflows, surface inflow occurs only after heavy rains, there is no streamflow component, and seepage is minimal. To model the Pilot Pool, Equation 3.5 can therefore be rewritten without **So** as;

$$\Delta \mathbf{V} = \mathbf{P} + \mathbf{Si} - \mathbf{ET} \qquad (3.6)$$

The surface inflow (**Si**) to the Pilot Pool is a function of the surface water runoff from the surrounding vegetated clay catchment. Runoff will be controlled by the infiltration capacity of the soil, occurring only when the precipitation rate exceeds the infiltration rate. Painter (1971) stated that the runoff can be estimated by the use of a coefficient applied to net precipitation. A technique was developed by Thomasson (1978) to determine the winter rain acceptance potential class (WRAP), and consequently the winter runoff potential, of a catchment area in relation to soil and site properties. Using the technique developed by Thomasson, in conjunction with the soil and slope properties existing within the Pilot Pool catchment area, a WRAP and runoff class of 5 was generated.

Farquharson (1978) presented an equation that can be used to estimate the average percentage of runoff volume (PERC), derived from the literature and data from National Environmental Research Council (1975). The equation was;

$$\mathbf{PERC} = 21.0\,\mathbf{S_1} + 40.0\,\mathbf{S_2} + 51.0\,\mathbf{S_3} + 54.0\,\mathbf{S_4} + 58.0\,\mathbf{S_5} - 7.5 \qquad (3.7)$$

where; **PERC** = % runoff volume,
$\mathbf{S_{1\,...5}}$ = WRAP Classes 1 to 5.

A runoff volume (%) applicable to the Pilot Pool catchment can be calculated from Equation 3.7 as 50.5 %, producing a runoff coefficient of 0.505, representative of the majority of clay catchments within the UK. This runoff coefficient (β) is used within Equation 3.9, being applied to the calculated figure for monthly net precipitation [P-ET(Grass)], when soil conditions of field capacity have been satisfied (Farquharson, 1978). When the value of monthly net precipitation is equal or less than zero the negative runoff volume is set to zero, i.e. not deducted from the water budget.

ΔV can be calculated with respect to the change in surface water level (Δ**H**), and the mean surface water area ($\overline{A}$) over the time step under consideration, using the equation;

$$\Delta V = \Delta H \times \overline{A} \tag{3.8}$$

where;
- ΔV = the change in water storage (m^3),
- ΔH = the change in surface water level (m),
- $\overline{A}$ = mean surface water area (m^2).

Thus, a more detailed water budget equation can be presented for the calculation of ΔV for the Pilot Pool over a given time period as;

$$\Delta H(\overline{A}_w + A_R) = (P - Eo)(\overline{A}_w) + (P - ET_{(Reed)})A_R + \beta(P - ET_G)(A_G - \frac{\Delta Aw)}{2} \tag{3.9}$$

when;

$$\overline{A}_w = (A_{W1} + \frac{\Delta A_w}{2}) \tag{3.10}$$

where;
- A_{W1} = starting area of open water, and
- $\frac{\Delta Aw}{2}$ = change in open water surface area over a given time.
- ΔH = the change in surface water level (m),
- P = precipitation (m),
- A_R = area of reedbed (m^2),
- A_G = area of grassland (m^2),
- β = runoff coefficient,
- ET_G = grassland evapotranspiration (m),
- $ET(Reed)$ = reedbed evapotranspiration (m),
- Eo = open water evaporation (m).

A set of assumptions are inherent within the application of Equation 3.9, including:

1) A_R does not vary, and is permanently 'wet', existing within A_W;

2) the area of reedstems contained within the A_R is negligible relative to the water area, and is ignored;

3) if $\beta(\mathbf{P} - \mathbf{ET}_G)(\mathbf{A}_{GI} - \frac{\Delta\mathbf{Aw}}{2})$ is < or = to 0 then set to 0, or

if $\beta(\mathbf{P} - \mathbf{ET}_G)(\mathbf{A}_{GI} - \frac{\Delta\mathbf{Aw}}{2})$ is > 0 then $\beta = 0.505$

Additional site-specific assumptions related to the direct use of Equation 3.9 within the Pilot Pool catchment are presented in Section 10.4.4.1.

As part of the fulfilment of Objective 4 it is necessary to verify the presented water budget model (see Section 10.4).

3.8 DISCUSSION.

Work to formulate the conceptual model of surface water fed reedbed ecosystems has identified a prescription of hydrometeorological parameters that require more detailed understanding on a site specific basis. The water budgets presented identify the need to ascertain an accurate estimate or measurement of the various inherent parameters.

Rainfall input can be monitored using well established techniques, and the techniques for the estimation of ET(Grass) and Eo are readily available (e.g. Penman, 1948). However, the estimation of ET(Reed) requires additional study.

Duever (1988) stated that:

> "Evapotranspiration is a major route by which water leaves natural ecosystems, and it frequently accounts for virtually all losses in wetlands because of their slow rates of flow and high surface area-to depth ratios".

Ingram (1981) identifies evapotranspiration as one of a list of six basic processes involving water transfer in wetland ecosystems, which are sufficiently different to be worth separate study. Thus an investigation was necessary to determine ET(Reed). A literature review was undertaken to see whether an estimate of ET(Reed) could be identified.

Chapter 4. LITERATURE REVIEW OF WETLAND EVAPOTRANSPIRATION.

4.1 INTRODUCTION.

> "Evapotranspiration represents the most important aspect of water loss in the hydrological cycle, accounting for the disposal of nearly 100% of the annual precipitation in arid regions and about 75% in humid areas" (Harrold, 1969).

Section 3.8 highlights the need for a detailed understanding of ET(Reed) if a realistic water budget calculation is to be produced for any wetland environment containing *Phragmites australis*. Both calculated estimates and direct measurements of the volume of water that will be required to replete the losses from wetland ecosystems due to evapotranspiration (ET) have been attempted by various researchers.

The water loss by transpiration from wetland flora was studied by Otis (1914). He found that water loss from areas covered by normal densities of emergent vegetation is several times greater than the evaporation loss from the same area of open water (Eo). Kuznecov (cited by Bernatowicz et al, 1976) stated that ET(Reed) (measured from a lysimeter located on land) is 1.5-2.5 times higher than Eo. This was confirmed by Uryvaev (1953) (cited by Krowlikowska, 1971) who found that ET(Reed) was up to 3 times higher than Eo. Kiend (cited by Bernatowicz et al, 1976) stated that the average loss as a result of emergent ET is 2-3 times higher than the amount of precipitation. Bernatowicz et al (1976) concluded their brief literature review with the remarks that;

> "helophytes rob the water from water bodies".

However, Bernatowicz et al also cited the works of Novikova (1963) who found that the evapotranspiration of *Phragmites australis* and *Typha angustiflora* was approximately 72% of Eo. Novikova explained this as a result of very low biomass of aerial shoots. ET losses differ depending upon habitat and this must be reflected in any water budget calculation. The measurement of site specific ET is very difficult and reliable values of ET from emergent vegetation, and particularly from a reedbed [ET(Reed)] have not yet been achieved. The literature search for references relating to ET from wetland ecosystems has identified only a very limited number of directly pertinent sources of information. An extensive review of case studies relating to ET(Wetland) is included in Section 4.5, with research works specific to ET(Reed) detailed in Section 4.6.

ET has an important role within the hydrological cycle, and ET estimates or measurements form an essential part of any practical problem in hydrology, agriculture and forestry. This is reflected in the multiplicity of techniques purporting to estimate ET, and the many previous attempts to improve its accuracy. For most applications, however, direct measurement of ET is not feasible for practical, theoretical or financial reasons. The lack of direct measurements can be overcome using two strategies:

1) ET can be estimated using formulae based on meteorological and hydroecological parameters, or,

2) evaporation from a pan (Epan) can be measured. (see Section 4.4.4)

'Estimation equations' are commonly used as a means of avoiding direct ET measurement, by replacing it with simpler, related measurements. Since the mid 1940's numerous formulae (e.g. Penman, 1948) have been proposed for estimating ET. Shuttleworth (1979) believed these studies may prove counter productive by diverting resources and attention away from direct ET measurements.

Accuracy of an estimation equation increases as it becomes closer to a physical description of the ET process, and many formulae require complex parameter inputs. The data necessary for such estimates also increases leading to implementation difficulties in estimating ET. Other equations (e.g. Thornthwaite, 1948) only require routinely available climatic data but in deriving these formulae many assumptions have had to be made and inherent inaccuracy follows. A summary of the techniques and formulae for the determination of ET is included in Sections 4.2.3, and Section 4.3 provides a background to the calculation of crop evapotranspiration [ET(Crop)].

The meteorological factors which affect ET have been well documented. Detailed reviews of these factors are presented in many standard texts including works by Ward (1975), Shuttleworth (1979) and Shaw (1983), and so no formal presentation is undertaken in this thesis. A brief discussion of ET is included in Section 4.2.

4.2. EVAPOTRANSPIRATION.

4.2.1 INTRODUCTION.

Much research has been undertaken to compare assessments of measured and calculated Eo and ET. Discrepancies are often large with many of the studies based on short periods of data collection. Such discrepancies may indicate that some if not all of the methods for determining ET are in error (Ward, 1975).

Included within ET is the rainfall intercepted by vegetation and returned to the atmosphere by direct evaporation. Shaw (1983) states that it is much more difficult to quantify ET than Eo since transpiration rates can vary considerably over an area, and the source of water from the ground for the plants requires careful definition.

4.2.2 POTENTIAL EVAPOTRANSPIRATION.

Eo is dependent only on meteorological factors: the ET rate is not only dependent on the atmosphere, but also on crop related factors and the amount of moisture in the soil (Eisenlohr, 1966). For many years workers believed that the type and form of vegetation cover had little effect on the ET rate, providing that the availability of surface water was not limited. To reduce complexities 'standard' rates were created e.g. Potential Evapotranspiration (PE) and Reference Crop Evapotranspiration (ETo). These provide a measure of the meteorological control on the ET process of a particular site. Some techniques determine one or more of these conceptual parameters rather than actual ET, with the final estimates presented as an equivalent depth of water lost over time (e.g. mm/day).

Thus, Potential Evapotranspiration (PE) was conceived (Thornthwaite, 1948). PE was defined by Gangopadhyaya et al (1966), who highlighted the function of a continuous supply of moisture, as;

> "the maximum quantity of water being lost as water vapour, in a given climate by a continuous, extensive stretch of vegetation covering the whole ground, when the soil is kept saturated".

PE is a climatic parameter which will not be affected by plant behaviour or type in so far as these affect colour (albedo) and stomatal closure (Ward, 1975). It can be seen as a 'scale' to be adjusted using appropriate coefficients, to provide an index of the ET from the relevant surface.

PE is controlled essentially by meteorological factors, whereas actual evapotransiration (AE) is also considerably affected by plant and soil factors. AE was defined by Rijtema (1965) as;

> "the loss of water in vapour state from a cropped soil to the atmosphere including vaporisation from the upper soil layers (evaporation) and vaporisation of water taken from the soil by plants (transpiration)" .

In reedbed ecosystems, water is rarely a limiting factor and thus the additional factors which affect AE (SMD etc.) are not discussed here.

4.2.3 EVAPOTRANSPIRATION FORMULAE.

Several formulae have been developed for use in the estimation of ET, and results vary widely (Shaw, 1983).

Penman (1948) initially developed a formula (see Appendix 3) for estimating Eo based on fundamental physical principles, using standard meteorological observations. Penman stated with respect to the great importance given to the study of Eo that it provides a "reproducible surface of known properties". This allows approaches to be developed for the study of ET(Crop) based upon studies of the dependence of Eo on weather conditions. He combined two classical approaches to the estimation of evaporation: the energy budget and the aerodynamic, producing an equation consisting of two principal terms;

1) energy (radiation) and,
2) aerodynamic (wind and humidity)

Penman (1956) found that for most of Europe the 'energy' portion of the equation is four or five times more significant than the 'aerodynamic' term. Virta (1966) also highlighted the importance of radiation in ET estimates, concluding that the accuracy of ET estimates were very sensitive to errors in the radiation measured.

Shaw (1983) states that the Penman formula is one of the 'most soundly based' methods of calculating Eo using readily available meteorological data, and is especially useful for practising engineers to understand question of water loss. The Penman formulae produces a smaller range of variation of Eo, than observed evaporation. This is because it is likely that a body of water exposed to the atmosphere would be more sensitive to changes in evaporation opportunity than computed estimates, which only reflect the interaction of selected meteorological factors. The accuracy of the Penman equation estimates varies depending on the season. In general, measured values are equal to or in excess of Penman estimates between September and January, and below Penman estimates for the remainder of the year. The closest estimation to reality occurs during March and April (Shaw, 1983).

Penman's method of calculating PE takes no account of the type and form of vegetation cover, and is least valid for the winter part of the year when the vegetation is dormant (Ward, 1975). Tanner (1967) concluded that it was necessary to include the effect of vegetation type if the ET figure was to have greater relevance locally.

Ward (1975) cites the formula published by Turc which estimates mean annual ET using air temperature and precipitation data. His formula (see Appendix 3) was developed from works in 254 drainage basins located worldwide, and he demonstrated that the formula could be applied in humid and arid climates, either hot or cold.

Montieth (1965) realised the necessity of incorporating a reference for vegetation within an equation which strived to produce figures of actual evapotranspiration. He augmented the Penman equation to produce a more complex and physically realistic model (the 'Penman-Montieth equation').

Although the Penman-Montieth equation (see Appendix 3) has greater accuracy in predicting AE from a specific local meteorological site, it may not be as extensively used as the original Penman equation. More complex data input bring constraints to its use, with the additional input of a coarse measurement of the canopy structure to provide a sub model of surface resistance.

The comparative relationship between Eo and ET(Crop), under the same conditions, can be used to develop crop coefficients based upon Eo. Rijtema (1965) stated that Eo data is often used in the calculation of PE from crops, with Eo;

> "multiplied by an experimentally determined factor for a certain crop in order to calculate the evapotranspiration".

Penman (1948) established an empirically derived seasonal crop factor, which could be applied as a crop coefficient (**f**) to calculated Eo values, to calculate PE (see Table 4.1).

Month	**Crop Factor (f)**
November - February	0.6
March, April, September, October	0.7
May - August	0.8

Table 4.1 Penman (1948) Seasonal Crop Factors.

A detailed presentation of additional estimation method used in the calculation of ETo is undertaken in Section 4.4.

4.3. CROP EVAPOTRANSPIRATION.

Crop Evapotranspiration [ET(Crop)] is the sum of the transpiration by the crop and evaporation from the soil (Esoil). ET(Crop) is used throughout the world in the calculation of crop water requirements, informing irrigation volumes and timing. In the case of ET(Reed), Esoil is replaced by evaporation from the underlying water surface, which during the early stages of the crop growing season forms a significant part of ET(Reed).

Doorenbos and Pruitt, (1977) defined ET(Crop) as,

> "the rate of evapotranspiration of a disease-free crop growing in a large field under optimal soil conditions, including sufficient water and fertiliser and achieving full production potential of that crop under the given growing environment."

Doorenbos and Pruitt developed the concept of the crop coefficient (Kc), providing numerous examples applicable under various meteorological conditions. Shuttleworth (1979) presents the concept of 'potential crop coefficient' (Kco), applicable where it is;

> "necessary to supply adequate water, but not excessive, so that the soil surface is not wet".

Shuttleworth's 'Kco' is equivalent to Kc under the conditions experienced in reedbed habitats, and as such Kco is not further discussed in this thesis.

Section 4.3.1 presents a summary of the Food and Agriculture Organisation (FAO) document entitled 'Crop Water Requirements, Irrigation and Drainage Paper 24' (Doorenbos and Pruitt, 1977), whilst Section 4.3.2 outlines the use of lysimeters in the measurement of ET(Crop).

4.3.1 FAO 'CROP WATER REQUIREMENTS'.

Doorenbos and Pruitt (1977) produced a methodology for the prediction of crop water requirements, detailed in FAO Irrigation and Drainage Paper No.24. This methodology has become an international standard and is commonly applied. It is endorsed by the major financing and development agencies as the recommended method for calculating crop water requirements (Smith, 1990).

FAO Paper No.24 is divided into two sections, the first is concerned with the calculation of ET(Crop), whilst the second discusses the application of ET(Crop) and crop water requirements to irrigation project planning, design and operation. It is the former which forms the subject of this section. For the calculation of ET(Crop) Doorenbos and Pruitt (1977) recommended a three stage procedure, outlined below.

Stage 1 The Effect of Climate on Crop Water Requirements.

This involves the determination of the Reference Crop Evapotranspiration, defined as;

> "the rate of evapotranspiration from an extensive surface of 8-15cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water".

Doorenbos and Pruitt state that the idea that PE represents a maximum rate might be because many of the original studies took place using short crops which maximises the control exerted by the atmosphere on PE (e.g. Penman, 1948, referred to 80 - 150 mm tall green grass). Thus, a new concept incorporating a surface independent parameter was created to provide a better defined standard evaporation rate; the Reference Crop Evapotranspiration (ETo). The use of ETo avoids the problem of vegetation control and advection, thus increasing the universality of locally derived empirical equations (Shuttleworth, 1979). Various methods used in the calculation of ETo are presented in Section 4.4.

Stage 2 The Effect of Crop Characteristics on Crop Water Requirements.

To adjust the calculated ETo figure with respect to the effect of crop type and crop characteristics, a crop coefficient (Kc) is applied to produce ET(Crop). Thus;

$$\mathbf{ET(Crop) = Kc \times ETo} \qquad (4.1)$$

Doorenbos and Pruitt (1977) identified the factors affecting the value of the crop coefficient (Kc) as: the crop characteristics; crop planting or sowing date; rate of crop development; length of growing season; and climatic conditions. The crop coefficients presented by Doorenbos and Pruitt were derived from field works, primarily using experimental lysimeters (see Section 4.3.2). They found soil water to be an important factor influencing many crop plants, however, this concept is not discussed further as reedbed soil water conditions are generally saturated.

Doorenbos and Pruitt divided the crop growing season into four stages (see Table 4.2) and provided Kc values for each stage of development of a range of crops. They stressed the need to collect local data on growing season and rate of development. They also stated that plant densities have limited effect on ET(Crop), although high densities may mean that full ground cover (crop development stage 3) is achieved earlier in the season.

Doorenbos and Pruitt provided guidelines for the production of a graphical representation of the Kc value for the different crop development stages. They stated that;

> "for simplification the values of Kc for the different periods within the growing season are represented as straight lines".

Figure 4.1 provides an example of a crop coefficient curve derived using these guidelines. The guidelines have been adapted for use within studies of Kc(Reed) (see Table 4.3).

Stage No.	Stage Name	Criteria
1	**Initial Stage**	Germination and early growth, when the soil surface is not or is hardly covered by the crop, (groundcover <10%).
2	**Crop Development Stage**	From end of Stage 1, to attainment of effective full groundcover, (groundcover = 70-80%)#.
3	**Mid Season**	From attainment of effective full groundcover to start of maturing as indicated by discolouring of leaves.
4	**Late Season**	From end of Stage 3, until full maturity or harvest.

 # Start of mid-season can be recognised in the field when crop has attained 70 to 80% groundcover which, however, does not mean that the crop has reached its mature height. Effective full groundcover refers to cover when Kc is approaching a maximum.

Table 4.2 Crop Development Stages (Doorenbos and Pruitt, 1977).

Stage 3 The Effect of Local Micro-climatic Conditions.

Local micro-climatic effects may also produce variations in ET(Crop). The 'clothesline' effect is quoted by many researchers (e.g. Shuttleworth, 1977) as affecting the upwind edge of their study areas, being particularly apparent when warm, dry winds, pass across the study areas producing appreciably higher ET(Crop) results. Dolan et al (1984) assert that;

> "evapotranspiration of wetland vegetation along the edge of a lake can be enhanced by the low humidity and elevated temperatures of an oncoming wind".

Thus, caution should be used when extrapolating results achieved under such conditions for application elsewhere.

Figure 4.1 Example of a Crop Coefficient Curve (Doorenbos and Pruitt, 1977).

Step No.	Activity	Graphical Representation
1	Establish start of growing season. (1st April).	na
2	Determine length of crop development stages using Table 4.2.	na
3	Initial Stage - determine mean Kc(Reed) for period.	Kc(Reed) constant - 'straight line'.
4	Crop Development Stage - determine mean Kc(Reed) for period.	Kc(Reed) - 'straight line' between end of Initial Stage Kc(Reed) and start of Mid-season Stage Kc(Reed).
5	Mid-season Stage - determine mean Kc(Reed) for period.	Kc(Reed) - 'straight line' between end of Crop Development Stage and start of Late Stage.
6	Late-season Stage - determine mean Kc(Reed) for period.	Kc(Reed) constant - 'straight line' between end of Mid season Stage Kc(Reed) and start of Dormant Stage Kc(Reed).
7	Dormant Stage - determine mean Kc(Reed) for period. (Late November - 31st March).	Kc(Reed) constant - 'straight line'.

Table 4.3 Guidelines in the Presentation of the Crop Coefficient Curve for *Phragmites australis* [Kc(Reed)].

4.3.2 LYSIMETERS.

Lysimeters, defined by Harrold (1969) as small units of soil on which water balance values can be determined, have been extensively used as hydrological instruments for many years. Generally, the aim is to reproduce the natural soil profile within a watertight container, to reproduce a typical vegetation cover with a representative root system, and to expose this sample surface to the same meteorological conditions as those experienced by the area being investigated (Ward, 1975). The ET losses from the lysimeter can be established by a change in mass of the lysimeter and contents. However, for studies of emergent vegetation the ET(Crop) can be established by measuring the water volume changes occurring within the lysimeter. These volumes are then adjusted for rainfall inputs.

Opinions vary as to the value of lysimeters. Linacre (1976) criticised their use in ET studies, based largely on the disturbance to the soil structure and soil desaturation. Dolan et al (1984) were also critical of the use of lysimeters in ET(Crop) studies, primarily because lysimeter methods involve the physical isolation of plants possibly subjecting them to unrealistic micro-climatic conditions. Ingram (1981) outlined the common faults occurring from the use of lysimeters, concluding that airflow and radiation disturbance are prevalent, and the interruption of lateral water movement may interfere with aeration or mineral nutrition. Virta (1960) showed that lowering the water level in a planted container by 13 mm caused a reduction in ET of approximately 16%. Virta (1966) recommended the use of data from containers with similar water depths to those occurring across the majority of the natural habitat studied. Ingram (1981) concurred with these recommendations, stating that where lysimeter water levels are adjusted experimentally, ET estimates may suffer from the "oasis effect", particularly if the areas involved are small, and the adjusted water levels are atypical of their surroundings.

Shuttleworth (1979) is very supportive, reporting that;

> "a well designed and maintained lysimeter can be of considerable use in providing measurements of evapotranspiration".

Many of the problems associated with the use of lysimeters are only relevant to measurements of losses from terrestrial crop plants. For example, within wetland emergent studies there should be no soil desaturation as the soil is constantly flooded. Many of the limitations have minimal effect in the use of lysimeters in the study of ET(Reed), particularly if the lysimeters are located within the reedstand.

4.3.3 DISCUSSION.

Doorenbos and Pruitt (1977) found that mean climatic data is often used for determining mean ET(Crop). They state that annual ET(Crop) will vary up to 25% for mid continental climates, monthly ET(Crop) can vary from one year to the next by 50% or more, and that daily values vary dramatically. All of these variations are obviously obscured when using mean climatic data. All data analysis should therefore be undertaken on the data from separate monthly periods prior to the calculation of mean monthly averages.
Doorenbos and Pruitt provide details of Kc from emergent vegetation types such as Papyrus and Cattails (see Table 4.4), which they state appear to have Kc values <1.0, resulting primarily from the plant characteristics affecting ET. They conclude that these Kc values should only be used to indicate annual not monthly/daily values. It can be deduced from their works that under non-flooding conditions and in drying soils ET from emergent vegetation can be expected to be reduced. They also state that ET of aquatic weeds is frequently compared to Eo, reporting that studies carried out under natural conditions show that when a water surface is covered by aquatic weeds ET is lower than Eo. This is primarily due of the sheltering of the water surface by the weeds. The same effect might be expected to occur within ET(Reed) during early season growth.

	Growing Conditions	Humid Light/Medium Wind	Humid Strong Wind
Reed Swamp - Papyrus and Cattail	Growing in Standing Water	0.85	0.85
	Growing in Moist Soil	0.65	0.65
Open Water (Eo)		1.10	1.15

Table 4.4 Kc Values for Aquatic Weeds and Coefficients for Open Water (Doorenbos and Pruitt, 1977).

4.4 METHODS OF CALCULATING ETo.

4.4.1 TEMPERATURE METHOD.

Many empirical formulae exist relating ETo to temperature. Doorenbos and Pruitt (1977) realised that many potential users of FAO-No.24 would only have access to temperature data, and thus included the 'FAO Temperature Method' (see Equation 4.2) based upon the Blaney-Criddle (Blaney and Criddle, 1950) equation.

$$\mathbf{ETo} = \mathbf{c}[\mathbf{p}(0.46\mathbf{T} + 8)] \qquad (4.2)$$

where; **ETo** is calculated for the month under consideration (mm/day).

T = mean daily temperature (^{o}C).

p = mean daily % of total annual daytime hours.

c = adjustment factor for minimum relative humidity, % sunshine hours, and daytime wind estimate.

Rijtema (1965) quotes from the works of Van Wijk (1953), who stated that

> "no method based on monthly temperatures alone can be expected to give reliable results for climatologically different regions."

Thus, the Temperature Method should only be employed where no other meteorological parameters are available. In addition, ETo calculations based on this method should not be made for periods less than one month, with ETo calculations undertaken for each calendar month for each year of record, rather than using mean temperatures based on several years records (Doorenbos and Pruitt, 1977).

4.4.2 RADIATION METHOD.

The Makkink (1957) formula was adapted by Doorenbos and Pruitt for areas where available climatic data includes air temperature, sunshine, cloudiness or radiation, but not measured wind and humidity. The radiation, when converted into heat, can be related to the energy required to evaporate water:

$$\mathbf{ETo} = \mathbf{c}(\mathbf{w} \times \mathbf{Rs}) \qquad (4.3)$$

where; **ETo** is calculated for the month under consideration (mm/day).
Rs = solar radiation in equivalent evaporation (mm/day).
w = weighting factor dependant on temperature/altitude.
c = adjustment factor, mean humidity and daytime wind.

w reflects the effect of temperature and altitude on the relationship between Rs and ETo, whilst, **c** accounts for the relationship between radiation and ETo (Doorenbos and Pruitt, 1977). Smith (1990) states that the radiation method has proven valid, in particular under humid conditions.

4.4.3 COMBINATION METHODS.

4.4.3.1 Penman Potential Evapotranspiration.

Many respect Penman as an authority in this field. Rijtema (1965) stated that the works of Penman;

> "generally speaking gives better results than methods based on a correlation with mean monthly temperatures".

However, he also criticised the works of Penman by stating the neglect of the heat storage below the evaporating surface limits the applicability in calculating ET(Crop), and points out that the difference in reflection (albedo) of a crop and a free water surface is also not taken into account.

Doorenbos and Pruitt (1977) state that the reduction factor presented by Penman (1948) greatly enhances the accuracy of the Penman equation. They concluded that figures calculated using the Penman equation, combined with a Kc of 0.8 closely predict ETo, particularly in calm conditions. Shuttleworth (1979) recommended the use of the Penman equation as the best available method of estimating ETo, and that it should be employed as the primary means of obtaining this standard rate whenever the relevant data are available.

From an analysis of a range of lysimeter data, Doorenbos and Pruitt proposed the 'FAO Modified Penman method', which has found worldwide application in irrigation development and management projects. The form of the equation used in FAO Paper No.24 is shown below;

$$\mathbf{ETo} = \mathbf{c}[\mathbf{w} \times \mathbf{Rn} + (1-\mathbf{w}) \times \mathbf{f}(\mathbf{u}) \times (\mathbf{ea} - \mathbf{ed})] \qquad (4.4)$$

where;

	w	= temperature related weighting factor.
	Rn	= net radiation in equivalent evaporation (mm/day).
	f(u)	= wind related function.
	(ea-ed)	= difference between saturated vapour pressure at mean air temperature and the mean actual vapour pressure of the air (mbar)
	c	= an adjustment factor to compensate for the effect of day

Doorenbos and Pruitt commented that this procedure for calculating ETo may seem rather complicated due to the fact that the formula contains components which need to be derived from measured related climatic data when no direct measurements of the variables are available. They present computational techniques and tables to facilitate the necessary calculations, and describe the accuracy of their Penman Method as +/- 10% during the summer. However, Smith (1990) concludes that this method is somewhat over predictive under non-advective conditions.

4.4.3.2 Penman-Montieth Potential Evapotranspiration.

Smith (1990) provides a detailed adaptation to the Penman-Montieth equation stating that;

> "Unanimous agreement was reached in the consultation to recommend the Penman-Montieth Approach as the presently best-performing combination equation".

However, it was noted that the Penman-Montieth Method requires very accurate radiation data, and this accuracy is of crucial importance. Although the adoption of the Penman-Montieth Method would eliminate the use of crop coefficients, there is still insufficient consolidated information on crop resistance available, and for this reason the use of crop coefficients was still recommended by Smith. Smith concluded that it is necessary to provide all potential users of an ETo formula with easier, less technically demanding methods of ETo calculation.

4.4.3.3 CROPWAT

CROPWAT is a computer program designed to calculate crop water requirements and irrigation schedules from climatic and crop data, using any IBM-PC type computer (360Kb). The procedures for calculation of the crop water requirements are mainly based on methodologies presented by Doorenbos and Pruitt (1977). CROPWAT version 5.6 is an update of earlier versions and includes a revised method for estimating ETo, adopting the approach of Penman-Montieth as recommended by Smith (1990).

CROPWAT requires;

1) basic information on the climatic station: country name, station name, altitude, latitude and longitude.

2) monthly climatic data on temperature, relative humidity, daily sunshine and windspeed.

Its outputs are the calculated ETo results, together with the climatic data in tabular form.

4.4.3.4 Meteorological Office Rainfall & Evaporation Calculating System (MORECS).

In the early 1970's the UK Meteorological Office produced a comprehensive computer package, MORECS, designed to provide estimates of weekly and monthly Eo, ET, and soil moisture deficits (SMD) in the form of averages for 190 grid squares (40 km x 40 km) over Great Britain (see Figure 4.2), using daily synoptic weather data as inputs (Hough et al, 1996). Northern Ireland is presently being included in the MORECS 2 coverage (Hough et al, 1996). MORECS is used by the Meteorological Office to calculate ETo for the Reference Crop grass.

Initially the basis of the MORECS system was the Penman Method of calculating ETo, used until 1977, when the Penman-Montieth Method was adopted. MORECS underwent an extensive revision in the winter of 1980/81. MORECS had been fully operational for 20 years, with the system being thoroughly tested through comparison with empirical field based studies. An upgrade in 1995 was introduced as MORECS 2, to reflect changes in crop types and cropping patterns since 1981 and the availability of new soils databases (Hough et al, 1996). However, Hough et al state that "much of the basic science remains unaltered". A single-site MORECS version is also available using measurements from a single weather station with the option to input site specific rainfall measurements.

The main components of the MORECS system are presented in Table 4.5 and are discussed below. The calculation of AE, soil water balance, and effective precipitation are only outlined briefly as these components are irrelevant in a study of wet reedbed habitats.

No.	Operation
1	Data collection, interpolation and averaging.
2	Analysis to obtain evaporative demand over each Square.
3	Calculation of AE using a soil moisture extraction model.
4	Calculation of water balance and effective precipitation.
5	Data output.

Table 4.5 Main Components of the MORECS System (Hough et al, 1996)

Aston University

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Figure 4.2 MORECS Squares

1) Daily Meteorological data is extracted from the Meteorological Office Synoptic Data Bank. The variables extracted for input into MORECS 2 are based upon the Penman-Montieth Method, and include:

Ta = mean air temperature
ed = average vapour pressure
n = duration of bright sunshine
U_2 = wind speed at 2 m

MORECS 2 also requires rainfall data input from gauges distributed throughout each grid-square. In 1995, there were approximately 300 'real-time' raingauges available for data input to MORECS 2 (Davies, 1995). Where available, radiation figures calculated from sunshine hours are input to MORECS 2. Coastal resorts regularly measure sunshine hours producing more accurate MORECS outputs in coastal areas (Davies, 1995).

Interpolation to obtain grid-square values is carried out using data from the nine nearest stations to the centre of each square, up to a maximum of 100 km from the centre. If less than three stations are found then an inverse distance squared method of interpolation is used. No data averaging is performed with single site MORECS (Hough et al, 1996).

2) Then daily PE is calculated for each grid-square for a range of surface covers from bare soil to forest, using a modified form of the Penman-Montieth equation (Hough et al, 1996).

3) In the third part of MORECS the PE estimates are converted to estimates of AE, by adjusting the bulk surface (or canopy) resistance, progressively reducing the rate of water loss from the potential value to zero as the available soil moisture decreases.

4) MORECS 2 calculates the daily water balance under the various types of cropped surfaces, producing a SMD. SMD outputs from MORECS 2 are closely correlated with areal values, measured in field experiments. In addition, MORECS 2 is also more realistic across a variety of soil types (Davies, 1995).

5) Data output from MORECS 2 is produced as both maps and tables, showing the grid-square weekly averages of the Penman variables, and also PE, AE, SMD, Stress (AE/PE), and effective precipitation ('excess rain') (Hough et al, 1996).

Hough (1997) states that the MORECS 2 output Eo provides an estimate of open water evaporation, and is calculated from the monthly MORECS Grass PE data by the application of a monthly conversion factor (see Table 4.6). He asserts that these conversion factors are standardised for use throughout the UK. He concludes that their is a close approximation (+/- 10%) between MORECS Eo, empirical Eo data from shallow waterbodies (< 2.00 m), and Epan measurements. He also asserts that MORECS 2 is consistently slightly lower than Epan data in the Summer, primarily due to the higher water temperatures recorded in shallow pans during this period.

Two forms of ETo based on MORECS data are adopted in this project: ETo MORECS Grass; and ETo MORECS Eo. MORECS provides an ETo in areas where site specific measurements may not be available. Crop coefficients available from the Meteorological Office can be applied to MORECS to output ET(Crop) directly for specific crops. However, Kc values related to *Phragmites australis* [Kc(Reed)] are not available, and there are no plans to incorporate any wetland emergents into MORECS 2 (Davies, 1995).

Month	Conversion Factor
Jan	0.6
Feb	1.1
Mar	1.1
Apr	1.3
May	1.3
Jun	1.3
Jul	1.3
Aug	1.3
Sep	1.2
Oct	0.9
Nov	0.6
Dec	0.4

Table 4.6 MORECS Monthly Conversion Factors Applied to MORECS Grass to Calculate MORECS Eo (Hough, 1997)

4.4.4 PAN EVAPORATION (Epan).

The use of a single measurement to estimate ETo seems attractive (Smith, 1990). The simplest and most widespread method of obtaining a direct measurement of the evaporation from a free water surface is to measure the loss from an evaporation pan (Epan). Evaporation pans have been widely used as a measurement technique giving a strictly local value of evaporation.

Gangapadhyaya et al (1966) list some 27 different examples of pan design, quoting various inter-calibrations between them. Doorenbos and Pruitt (1977) state that the most commonly accepted form of evaporation pan worldwide is the US Weather Bureau Class A Pan, which is exposed above the ground. However, pan types are of secondary importance relative to the issue of whether Epan does or does not provide a value which is both accurate and used readily.

Simplicity of design and construction and ease of operation has led to the worldwide measurement of Epan. Many researchers have applied pan coefficients (Kp) to the measured Epan data to provide a more realistic prediction of Eo and ETo. Ward (1975) reported that lake evaporation can be crudely estimated by applying a Kp of 0.7 to Epan, whilst Linacre et al (1970) quote the 'commonly employed Kp of 0.7' derived by Harbeck, with the caveat that it is not useful for daily periods, or less.

Rijtema (1965) cites the works of Wartena, who made a study of the energy balance of the US Class A Pan, and concludes that pans can be used only as simple indicators for determining the amount of water required for an irrigation area, and that it is not possible to give pan factors for evapotranspiring crops to satisfy all conditions. Rijtema highlighted the difficulties which arise when one tries to transfer pan factors from one area to another with significant differences in climate. However, both Stanhill (1961) and Talsma (1963) suggested a reasonable relationship appears to exist between Epan and ET(Crop) for mean monthly values.

Doorenbos and Pruitt (1977) found that the level at which the water is maintained within the pan is very important. Errors of up to 15% occur when water levels in Class A pans fall 100 mm below the accepted level of between 50 and 75 mm below the rim. Ingram (1981) states, regarding the use of US Class A

Pan data to compute evaporation, that "theoretically this device is highly unsound", for a variety of intrinsic factors e.g. low thermal capacity. However, Ingram defends the use of pan data on the grounds of cost, ease of use and practicality.

Despite the differences of opinion of various researchers, the practical value of the Epan method has been well recognised. Doorenbos and Pruitt (1977) concluded that;

> "Evaporation pans provide a measurement of the integrated effect of radiation, wind, temperature and humidity on evaporation from a specific open water surface",

suggesting that the use of properly sited pans to predict crop water requirements is warranted.

Values for ETo derived from Epan measurements adjusted using an appropriate Kp (see Table 4.7) may be useful in determining Eo. Doorenbos and Pruitt presented the relationship;

$$\mathbf{ETo} = \mathbf{Kp} \times \mathbf{Epan} \qquad (4.5)$$

where; **ETo** is calculated in mm/day.
Epan = pan evaporation (mm/day).
Kp = pan coefficient.

Doorenbos and Pruitt provided various climatic scenarios where Kp values must be changed to provide an accurate ETo. However, they state that little or no reduction in Kp is needed in humid, cool conditions. They suggest that the use of Epan methods to calculate ETo produces a possible error of up to 15%, dependant on pan location.

Smith (1990) states that the use of the Epan method for estimating ETo should only be recommended if instrumentation and the site are properly calibrated and managed. The energy storage of deep pans may be greater than that of a reference crop, providing lower daytime temperatures when ET is highest, whilst elevated pans have additional radiation exchange at the sides. Although a plant's response to the same climatic variables differs only slightly, these differences may be sufficient to produce a difference in water loss. In addition, most plants only transpire during the day whilst heat storage within a pan may produce night-time evaporation levels similar to those recorded during the day.

Wind km/day	Windward side distance of green crop (m)	Mean R.H. Low <40%	Mean R.H. Med. 40-70%	Mean R.H. High >70%
Light <175	1	0.55	0.65	0.75
	10	0.65	0.75	0.85
	100	0.70	0.80	0.85
	1000	0.75	0.85	0.85
Moderate 175-425	1	0.50	0.60	0.65
	10	0.60	0.70	0.75
	100	0.65	0.75	0.80
	1000	0.70	0.80	0.80
Strong 425-700	1	0.45	0.50	0.60
	10	0.55	0.60	0.65
	100	0.60	0.65	0.70
	1000	0.65	0.70	0.75
V. Strong >700	1	0.40	0.45	0.50
	10	0.45	0.55	0.60
	100	0.50	0.60	0.65
	1000	0.55	0.60	0.65

Table 4.7 Pan Coefficients (Kp) for Class A Pans (Doorenbos and Pruitt, 1977).

4.4.5 DISCUSSION.

The hydrologist has alternative strategies available for the estimation of ET from a particular area. Either ET can be estimated using formulae based on meteorological parameters, or Epan can be measured directly to provide an index of the ET from the surface of interest. The choice will not only depend on the predictive accuracy of the varying techniques but also on the resources available for the study. It will also depend on the type of climatic data available for the location, and the crop type/ecosystem studied. For areas of low vegetation, which are rarely subject to significant SMD (e.g. flooded and wet grasslands), ETo determined using the Penman Method may provide a useful estimate of AE. In areas of low rainfall where low growing vegetation is subjected to moisture stress, equation derived values for ETo can be used as an index and upper limit of AE. For areas where SMD may affect tall (> 1m) vegetation, values given by the Penman-Montieth equation will have the greatest relevance (e.g. carr woodland) (Smith, 1990).

The widespread availability of existing pan data means many estimation applications will continue to use Epan as a primary source. Pans should be located as closely as possible to the meteorological site if the figures are to be compared with those calculated using the Penman and/or Penman-Montieth Method. Ingram (1981) summarised the comparison between ET(Penman), Epan and Eo (see Table 4.8). These 'close comparisons' between Eo, Epan and ET data generated using estimation equations also suggest that the use of Epan within the calculation of crop water requirements is warranted.

Shuttleworth (1979) recommended that Epan data be used in preference to the Blaney-Criddle Method, and recommended using the Penman equation as the best available method of estimating ETo. Lafleur (1990) concluded that the Penman's formula is both theoretically sound and its use is widespread, making it attractive to calculate ETo.

The timescales over which data is collected may determine which method of ETo calculation is chosen. Smith (1990) notes that the project restrictions will clearly influence this. Time constraints placed on the data collection undertaken in this project were due to both the distance of the primary study sites from the research base, and the author's contractual commitments to his employer during the data collection period.

Period	Comparison
Complete Year	Penman ET = Eo
Growing Season	Penman ET = 1.1 Eo
Complete Year	Penman ET = 0.7 Epan
Growing Season	Penman ET = 0.8 Epan

Table 4.8 Comparison Between ET(Penman), Epan, and Eo (Ingram, 1981).

Many researchers (e.g. Jarvinen, 1978) have concluded that it is preferable to undertake several methods of determining ETo in parallel to increase the reliability of the results. The various methods used for calculating ETo within this project are detailed in Chapter Seven.

4.5 STUDIES OF WETLAND EVAPOTRANSPIRATION.

4.5.1 INTRODUCTION.

Those concerned with the steadily decreasing resources of surface water and the increasing demand for it, have undertaken research in an attempt to estimate the potential impact of the ET(Wetland) component within a water budget. The literature review identified a paucity of research studies undertaken with respect to ET(Wetland). Ingram (1981) noted that one reason for this lack of research is that works must be undertaken in:

> "an environment accessible only with difficulty, remote from power supplies and laboratory facilities, and rendered hostile by its exposure, its humidity, its insect fauna and its rough, wet and unstable ground surface".

Researchers have adopted various methods of measuring and or calculating ET(Wetland), their experimental techniques and associated findings form the basis for this Section.

4.5.2 LYSIMETER STUDIES.

One of the first investigation into ET(Wetland) using a lysimeter was undertaken by Blaney and Ewing (1946) using a tank 2 m x 2 m x 2 m set within swamp vegetation in California. Three years of measurements produced an annual ET(Wetland) of 1500 mm/yr, against an estimated Eo of 1210 mm/yr. Eo was calculated using the Blaney formula combined with Epan measurements.

Penman (1963) cited the works of Migahid who undertook ET measurements from Papyrus using lysimeters located within a swamp, in Egypt. A mean annual ET rate of 6.0 mm/day was recorded, with ET(Wetland) equivalent to Eo calculated using the Penman equation. Rijks (1969) also undertook ET studies of Papyrus swamps using lysimeters, concluding that ET was equal to Eo x 0.60.

Brezny et al (1973) used lysimeters during their ET study of aquatic weeds. Various floating and emergent vegetation were planted in cubical cement tanks (0.6 m x 0.6 m), filled with 250 mm of soil and 250 mm of water. Control tanks were just filled with 500 mm of water. The water levels in both planted and control tanks were topped up when levels fell by 100 mm. Brezny et al observed that ET from water chestnut, water lettuce, and swamp morning-glory were similar to that of Eo, whilst the ET from water hyacinth, narrowleaf cattail, and purple nutsedge were 35%, 65% and 140% higher than Eo, respectively.

The data from all planted cubicles (6 no. species) were pooled together to provide a coefficient relating ET with Eo. They found that the ratio between the ET of a particular species and Eo had a highly significant correlation and was relatively constant, and suggested the possibility of using Eo data to estimate ET(Wetland). Brezny et al also quoted the results of Seybold where Eo was higher than losses from a surface covered by common duckweed (*Lemna minor L.*)

The most comprehensive study of ET(Wetland) was undertaken by Kadlec (1988), who studied sedge planted lysimeters in both temperate and arid climates. For comparison an 'evaporation station' was established, located within a sedge dominated wetland at Carson City (USA), which consisted of a Class A pan, thermometers, a rain gauge, and an anemometer. All data was also compared with Eo results produced using the Penman equation. Epan (6 mm/day) consistently exceeded measured ET(Wetland) (4.5 mm/day) particularly during late June and early July. Results of the Penman equation (2.8 mm/day) were considerably lower than the measured ET with the exception of figures recorded during early June, when Penman Eo was greater or equal to ET(Wetland). Their results found Epan was not a direct measure of ET(Wetland), but was a good correlator of the meteorological driving forces, with ET(Wetland) equivalent to Epan x 0.8, and that the Penman equation underpredicted ET(Wetland). In addition, they stated that;

> "wetlands which are normally saturated are capable of realising their full evaporation potential".

4.5.3 WATER BUDGET AND CATCHMENT STUDIES.

Eisenlohr (1966) undertook research into the water loss from Prairie potholes through transpiration by hydrophytes. He suggested that transpiration has as its source, water absorbed by the roots, and that water reaches the root zone only as outflow seepage. This means that what is transpired is only really an abstraction by the roots from outflow seepage. However, he clarified this by stating that deep seepage (relative to the root zone) is relatively unaffected. He tentatively suggested that in some cases transpiration would occur using water from 'partly sealed' seepage, in which case transpiration would be at the expense of deep seepage and the total water loss from the pond would be reduced.

Eisenlohr found Eo to be greater than ET(Wetland) early in the season (up to mid/late June). However, ET(Wetland) was almost double Eo during late July and August. He concluded that Eo from an open Prairie hole is generally greater than the ET from an emergent covered pool. However, in certain circumstances (e.g. high plant densities) Eo was equal or less than ET, particularly in areas with longer growing seasons. He also commented that the evaporation coefficient within emergent stand should reach a maximum just before new growth begins, stating that emerged hydrophytes can reduce the windspeed at water surface to practically zero, and also reduce evaporation by shading the water surface. Neither of these process is confined to live plants.

Eisenlohr also reported that the rate at which hydrophytes transpire water is related to the amount of live plant material that has emerged from the water, choosing the emerged height of live vegetation as the most convenient measure of the vegetation to relate to transpiration rate. However, he noted that the decline in transpiration at the end of the growing season bears no relation to the height of vegetation, or to any other easily measured variable. As emergent vegetation extends as much as 2 m above the water surface, he believed it can hardly be called a 'short green crop', thus restricting the theoretical basis for the use of the Penman equation in studies of ET(Wetland).

Shjeflo (1968) also undertook work on potholes in North Dakota, USA, concluding that Eo from a clear pothole was about 11% greater than ET from vegetated ones (ET = Eo x 0.9) for the year as a whole. However, Shjeflo found at one site that the ET/Eo ratio changed throughout the growing season with ET/Eo in May equal to between 0.7 and 0.8, whilst in mid summer ET/Eo was about unity before declining towards 0.5 in October in accordance with a steep fall in ET. The autumnal decline in the ratio was believed to be a function of the onset of senescence and death.

Dolan et al (1984) monitored diurnal water table fluctuations within a freshwater wetland, suggesting this technique requires relatively simple instrumentation, and provides long-term measurements of ET for an entire plant community. On an annual basis the measured ET losses were comparable with calculated Penman ET and Epan data. They found that marsh ET>Eo during the growing season (June-November) with Eo>ET (December-May). They suggested that plant biomass represents the time-integrated effects of solar energy, and that peak plant biomass can lag significantly behind the period of maximum solar radiation. This time lag suggests that ET, although ultimately a function of solar radiation, might be more simply modelled by including biomass, not radiation.

Shuttleworth (1979) noted with respect to the accuracy of ET(Wetland) calculated using a water budget equation that;

> "the error in the evapotranspiration.... is an accumulation of the error in the other measured variables, and a worthwhile result requires that these variables should be known with fairly high accuracy."

4.5.4 ALBEDO STUDIES.

Linacre et al (1970) undertook an investigation to ascertain if emergents growing in a shallow irrigation lagoon reduced the amount of water available to farmers. This involved the use of albedo to assess the effective transfer coefficient for water vapour from a swamp in Australia. Water (albedo 5%) should absorb more radiation energy than green swamp vegetation (albedo 25%), and thus Eo should be greater than ET(Wetland). They also calculated ET(Wetland) using wind travel, dry/wet bulb temperature, and water surface temperature. The various ET and Eo results were compared by Linacre et al, who concluded that, except immediately after rain, ET(Wetland) was less than Eo, with an overall ratio calculated as ET = Eo x 0.6. They suggested that this was due to: the higher albedo of green vegetation; the shelter given by emergents in the swamp to the water surface; and the internal resistance to water movement within the vegetation.

4.5.5 BOWEN RATIO.

Lafleur (1990) undertook a study of sedge swamps in sub-arctic Canada using the Bowen ratio. He found that Penman's Eo seemed to be a good predictor of ET(Wetland), with ET(Wetland) < Eo x 0.83.

Gilman (1997) undertook an assessment of ET(Wetland) at the RSPB wetland nature reserve at Hams Wall, Somerset. Works began on planting the site, primarily with pot-grown *Phragmites australis,* in Spring 1995. Although seedling establishment was good, much of the study area (16ha) became dominated by other emergent species (e.g. *Typha spp.*), with a large proportion of the site existing as open water. Thus, the ET data was more representative of a ET(Wetland) than ET(Reed) (Gilman, 1997). ET studies began in 1995, with the measurement of PE using the Penman-Montieth Method, complemented during 1996 by an assessment of the Bowen ratio from the wetland area. Gilman found that the Bowen ratio was less than 1.0 during May, rising to a peak of approximately 1.25 during August. Minimal crop characteristic data was available to inform the influence of crop phenology on the ET rates and the developed Bowen ratios. In addition, no lysimeter experiments were undertaken to complement the works, although Gilman asserts that lysimeter data would greatly enhance the further applicability of the ET data within other projects.

4.5.6 DISCUSSION.

Many researchers have attempted to provide empirically derived coefficients for various wetland habitats [Kc(Wetland)]. One of the earliest attempts at producing a coefficient applicable to wetland ecosystems was undertaken by Blaney and Morin (1942), who compared ET(Wetland) losses to measured Epan (Class A) data [Kc(Wetland) Pan = 0.95]. Other workers have presented Kc(Wetland) values, and many more can be derived from the data presented in this Section. Table 4.9 presents a summary of the available data relating to ET(Wetland) and Kc(Wetland).

The work of Eisenlohr (1966) identified a correlation between the phenology of emergent vegetation and ET(Wetland), a topic referred to by Lafleur (1990), who states that the conflicting results of studies comparing ET/Eo ratios might be explained by the vegetation differences both physical and physiological encountered in each study.

These findings imply that there is a need to study plant phenology within ET works. This was undertaken as part of this research project and is discussed in Section 8.4.

4.6 EVAPOTRANSPIRATION FROM PHRAGMITES AUSTRALIS.

4.6.1 INTRODUCTION.

Of the research projects which have studied ET(Wetland) there have only been a handful of works undertaken specifically focusing on ET(Reed). Researchers have pursued four techniques to measure or calculate ET(Reed) including: lysimeter studies within Polish lakes to determine the influence of ET(Reed) on the water balance under varying climatic conditions (Bernatowicz et al, 1976) ; ET(Reed) derived from mass water balance (Burgoon et al, 1997); Bowen ratio calculations (Smid, 1975); and the use of cut leaves and stems to assess the influence of leaf panicle and inflorescence formation on transpiration (Krolikowska, 1971). A summary of the available data relating to ET(Reed) and Kc(Reed) is presented in Table 4.10.

Researcher	Study Site	Technique	ET(Wetland)	Kc(Wetland)
Blaney and Morin (1942)	na	na	na	Kc(Wetland) Pan 0.95
Blaney and Ewing (1946)	Swamp, California.	Lysimeter within swamp	1500 mm/yr	Kc(Wetland) Eo 1.24
Migahid cited by Penman (1963)	Papyrus swamp, Egypt	Lysimeter within swamp	6.0 mm/day (annual)	Kc(Wetland) Eo 1.00
Novikova (1963) **cited by Bernatowicz et al (1976)**	Kengir Reservoir	na	na	Kc(Reed) Eo 0.71 - 0.73
Eisenlohr (1966)	Prairie Pothole USA	Water Budget Calculation	na	Kc(Wetland) Eo <1.00 (to mid June) Kc(Wetland) Eo 2.00 (July/August)
Shjeflo (1968)	Prairie Pothole North Dakota, USA	na	na	Kc(Wetland) Eo 0.90 (annual) Kc(Wetland) Eo 0.75 (May) Kc(Wetland) Eo 1.00 (mid Summer) Kc(Wetland) Eo 0.50 (October)
Rijks (1969)	Papyrus Swamp	Lysimeters	na	Kc(Wetland) Eo 0.60
Linacre et al (1970)		Albedo assessment of transfer coefficient	na	Kc(Wetland) Eo <1.00
Linacre et al (1970)	Swamp, Australia		na	Kc(Wetland) Eo 0.6

Table 4.9 Summary of the Findings of the Literature Review - ET(Wetland) & Kc(Wetland).

Researcher	Study Site	Technique	ET(Wetland)	Kc(Wetland)
Brezny et al (1973)	Irrigation Canals, India	Lysimeters	na	Kc(Wetland) Eo > or = 1.00
Doorenbos and Pruitt (1977)	Papyrus/cattail swamp		na	Kc(Wetland) 0.85
Ingram (1981)	Literature Review		na	Kc(Wetland) Penman 1.40
Dolan et al (1984)	Freshwater wetlands USA	Diurnal water table fluctuations	na	Kc(Wetland) Penman 1.00 Kc(Wetland) Pan 1.00 Kc(Wetland) Eo >1.00 (Jun-Nov) Kc(Wetland) Eo <1.00 (Dec-May)
Kadlec (1988)	Sedge swamp Carson City, USA	Lysimeters	na	Kc(Wetland) Pan 0.80
Lafleur (1990)	Sedge Swamp, sub-arctic, Canada.	Bowen Ratio	na	Kc(Wetland) Eo <0.83
Gilman (1997)	Phragmites/Typha Somerset, UK.	Bowen Ratio	na	Kc(Wetland) <1.00 (May) Kc(Wetland) 1.25 (August)

Table 4.9 (cont.) Summary of the Findings of the Literature Review - ET(Wetland) & Kc(Wetland).

Researcher	Study Site	Technique	ET(Reed)	Kc(Reed)
Kuzenecov (1949) **cited by Bernatowicz et al (1976)**	na	Lysimeter located on land.	na	Kc(Reed) Pan 1.5 - 2.5
Uryvaev (1953) **cited by Krowlikowska (1971)**	na	na	na	Kc(Reed) Eo up to 3.0
Gel'bukh (1964)	Russian Reedbed	Lysimeter within-stand	na	Kc(Reed) Eo 0.8 - 2.5
Rudescu et al (1965) **cited by Krowlikowska (1971)**	Reedbelt, R. Danube Stem density $30/m^2$ Stem Height 4500 mm	Cut-stem weight changes	5 mm/day Annual 33 - 50 mm shoots/yr	na
Tuschl (1970) **cited by Smid (1975)**	Reedbed, Austria.	Cut-stem weight changes	13 mm/day (July)	na
Krolikowska (1971)	Reedbed, Mikolajskie Lake Stem density $54/m^2$ Stem height = 2700 mm	Cut-stem weight changes	2.23 mm/day (does not include Eo from within stand)	na
Gavenciak (1972) **cited by Smid (1975)**	Southern Slovakia	Lysimeter located within lawn.	17.9 to 27.8 mm/day	na

Table 4.10 Summary of the Findings of the Literature Review - ET(Reed) & Kc(Reed).

Researcher	Study Site	Technique	ET(Reed)	Kc(Reed)
Kvet (1973) cited by Smid (1975)	Reedbed, Czechoslovakia	Cut-stem weight changes	7.8 mm/day (July)	na
Kvet and Rejmankova (unpubl.) cited by Smid (1975)	Reedbed, Czechoslovakia	Lysimeter located within lawn, Typha angustifolia	10 to 12 mm/day (summer)	na
Smid (1975)	Reedbed Czechoslovakia Stem density 50-120/m^2	Bowen Ratio	6.9 mm/day (July)	Kc(Reed) Eo >1.0
Bernatowicz et al (1976)	Reedbed, Poland	Lysimeter within reedbed	na	Kc(Reed) Eo 0.92 - 1.27
Gilman and Newson (1983) cited by Crundwell (1986)	Reedbed, UK.	Lysimeter within reedbed	na	Kc(Reed) Eo 1.2 - 2.0
Burgoon et al (1997)	Reedbed, USA	Mass Water Balance Calculation	6.4 mm/day (May/June)	Kc(Reed) Grass 1.0

Table 4.10 (cont.) Summary of the Findings of the Literature Review - ET(Reed) & Kc(Reed).

4.6.2 LYSIMETER STUDIES.

The majority of the lysimeter studies of *Phragmites australis* were undertaken during the 1970's. However, prior to this period, Gel'bukh (1964) reported Russian measurements of ET(Reed), recorded from plants growing in 'special evaporation pans', which when compared to Eo provided a Kc(Reed) varying from 0.8 to 2.5.

Gavenciak (1972), quoted by Smid (1975), measured ET(Reed) from plants grown in a tank situated within a lawn, with maximum daily values of 17.9 mm and 27.8 mm for the two sites. Smid stated that the effect of advection on the ET(Reed) recorded from the small tanks placed in the lawn was considerable. In such cases, the reed clusters evapotranspirate as three-dimensional bodies. The method used by Gavenciak yields information useful for the estimation of evaporative losses from narrow channels overgrown with *Phragmites australis*, and can be used to compare values of ET(Reed) produced from lysimeters planted outside of a reedbed (see Section 6.3.3).

The most detailed lysimeter studies undertaken to date with respect to ET(Reed) were conducted by Bernatowicz et al (1976), who took measurements over a 3 year period of ET(Reed) and ET from other wetland emergents (e.g. *Typha latifolia*), calculating a form of biomass transpiration coefficient (i.e. mass of water transpired to produce a mass of dry crop). Plants were cultivated in metal phytometers (lysimeters) 0.3 m^2 in surface area, which once planted were three-quarters submerged in water. Unplanted phytometers were also installed. All phytometers were filled with lake mud and this was covered by a water layer 180 mm deep. ET(Reed) losses were replaced daily, with phenological characteristics accurately noted. They conclude that their results for phytometers located within a reedbed show a value of Kc(Reed) Eo between 0.92 and 1.27.

Bernatowicz et al also undertook parallel micro-climatic observations both within and outside the reedbed. They found diurnal temperatures within a reedbed to be less extreme than on land, with relative humidity higher in the reedbed by up to 9.4%. However, the greatest micro-climatic effect of the reedbed was on the wind speed, with the wind speed at 2 m above the surface (reed height 2.2 m) of the reedbed 1.4 m/sec lower than at the same height above bare ground. Wind speeds at the reedbed water surface were recorded as 0.0 m/sec until the windspeed above the reedbed was greater than 4 m/sec. They concluded that the micro-climatic conditions on an open area of land differ 'diametrically' with those noted within a reedbed. They noted that for emergents located on land (isolated phytometers) there is a free flow of air, lower humidity, optimum solar irradiance and greater temperature fluctuations. All this considerably increases the ET(Reed) of phytometers located on land compared to those within a reedbed.

Gilman and Newson (1983) (cited by Crundwell, 1986) used 'measuring cylinders' and 'bucket tanks' to measure ET(Reed) from a wetland community containing *Phragmites australis* and *Cladium mariscus*, in Anglesey, UK. They reported that Kc(Reed) Eo varied between 1.2 and 2.0.

4.6.3 MASS WATER BALANCE CALCULATIONS.

Burgoon et al (1997) are investigating the use of *Phragmites australis* for dewatering biosolids in the arid North-western USA, where Epan is 1,385 mm/annum. ET(Reed) was estimated by metering all water applied to the reedbeds and all filtrate water pumped back to the treatment plant, with storage volumes assumed to remain constant. An ET(Reed) rate of 6.4 mm/day was calculated for May to June 1996. They state that during the same period, the rate which might be expected from nearby hay crops is similar, thus producing a Kc(Reed) Grass of approximately 1.0.

4.6.4 BOWEN RATIO.

Smid (1975) stated the importance of ET(Reed) studies to hydrologists and plant physiologists. He calculated ET(Reed) from meteorological instruments located within a reedbed stand, using the Bowen ratio, producing a predicted value of 6.9 mm/day in July 1973. He estimated an accuracy of +/- 20% as a result of the methods used. He also compared his results with measured data from a 3 m^2 evaporation pan anchored in open water, stating that on summer days with sunny weather ET(Reed) > Eo. He concluded that his results refer to vigorously growing dense reed stands (50-129 shoots/m^2), and that "poorly growing and/or sparse reed stands may behave differently".

4.6.5 CUT LEAF WORKS.

During the 1960's both Beydeman (1960) and Rudescu et al (1965) (both cited by Krolikowska, 1971), undertook laboratory tests to determine the mass of water transpired by a reed stem. Tuschl (1970), cited by Smid (1975) undertook similar works studying weight loss of water from stems, leaves and whole shoots. Smid (1975) quotes the works in Czechoslovakia of Kvet (1973) and Rychnowska and Smid (1973) of single day measurements from cut shoots of *Phragmites australis*.

Krolikowska (1971) studied the transpiration rates of *Phragmites australis* from cut stems as dependant on: the time of day; 'month of the vegetation'; and the presence or lack of an inflorescence. She used cut reed shoots, 1.1 m long, with and without an inflorescence, cut from healthy green plants. The shoots were weighed immediately after cutting and then again after five minutes, with the difference in the weights equal to the weight of water transpired in five minutes. She calculated that reedbeds with a shoot density of 54 shoots/m^2 could transpire 2.23 kg/m^2/day of water, with the highest transpiration intensity found between 11 am and 1 pm, and transpiration peaking in late July/early August. She found that the leaves of reeds without an inflorescence transpire about 50% more than the leaves of flowering reed. Krowlikowska asserted that this data was not significantly different from the value estimated by Rudescu et al (cited by Smid, 1975) at 5 kg/m^2/day, concluding that reeds transpire;

> "at a rate which can significantly influence the water level in a lake".

Note that all of these experiments have only measured the transpiration rates of cut shoots, leaves etc. and make no attempt to measure ET(Reed).

4.6.6 DISCUSSION.

Literature reviews pertaining to ET(Wetland) were undertaken by Linacre (1976), Ingram (1981), and Crundwell (1986). Linacre's review of ET from reed swamp communities found that tall emergents reduce overall lake evaporation losses. However, Ingram concluded that the ETo(Wetland) /ET(Penman) coefficient for fens is about 1.4 or a little less. Crundwell identified a greater number of studies where ET(Wetland) was higher than ETo, with only a few examples where ETo was greater than ET(Wetland). Crundwell concluded that the majority of experimental works had been poorly designed and undertaken for only short periods.

In summary, ET(Reed) is a significant volume within the water budget of a reedbed. Previous work has produced techniques for the estimation of Eo, ET and ETo which provide 'standards' against which measured ET(Reed) can be compared, allowing the development of Kc(Reed) values. A very limited number of experiments have been undertaken to directly ascertain ET(Reed) and derive Kc(Reed), and the data presented by experienced researchers is sometimes contradictory. The importance of meteorological conditions and reed phenology to ET(Reed) is well recognised.

The measurement of ET(Reed) and the development of monthly Kc(Reed) values will form the overall 'contribution to knowledge' made by this research project, with an assessment made of the importance of phenological characteristics and meteorological conditions on the presented values.

Chapter 5. STUDY SITES.

5.1 INTRODUCTION.

Initially the ET(Reed) studies were undertaken as an extension of the comprehensive hydrometeorological monitoring programme undertaken by EHC on behalf of the Teesside Development Corporation (TDC). The monitoring programme was designed to inform the feasibility of establishing a major wetland nature reserve at the site in Teesside; the Teesside International Nature Reserve (TINR). A similar monitoring programme was established in South Wales on behalf of the Cardiff Bay Development Corporation (CBDC) to inform the proposals to create a compensation wetland at Redwick, Gwent.

Due to financial restrictions, ET(Reed) measurements were only available for the TINR and Redwick sites on a monthly, and fortnightly basis respectively. In order to greatly enhance the works on ET(Reed) and develop a crop coefficient applicable to *Phragmites australis* reedbed ecosystems [Kc(Reed)], a third site was required which could be monitored by the author on a more regular basis. In February 1995, a reedbed site at Himley Sewage Treatment Works, West Midlands was identified which fulfilled the necessary criteria, with experimental apparatus installed in March 1995. Thus the research data is available for three locations in England and Wales (see Figure 5.1).

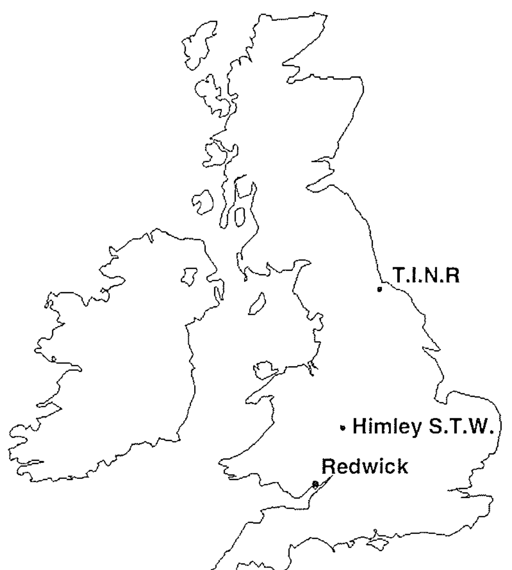


Figure 5.1 Location of Experimental Sites

Brief descriptions of the research sites are outlined below, including a synthesis of each sites: physical location; environmental context; habitat design proposals; and current status.

5.2 TEESSIDE INTERNATIONAL NATURE RESERVE (TINR).

5.2.1 INTRODUCTION.

The Teesmouth Estuary has been largely reclaimed from the sea to become one of the biggest industrial conurbation's in Western Europe. However, the area has retained a substantial natural character, and contains a large number of nature reserves and important conservation sites. Sites of Special Scientific Interest (SSSI's) include: Seal Sands; Cowpen Marsh; North Gare, Seaton Sands and South Gare. To the ornithologist in particular, the Tees Estuary has a major significance, with up to 5% of the UK's Shelduck population and attracting a host of other common and exotic bird species. The presence of such wildlife attractions provided the impetus for the philosophy behind the proposals for the TINR.

The TINR (NGR NZ 498228 - see Figure 5.2) is located in an area of major industrial development within the Teesside region, with much of the proposed nature reserve lying at or near sea level. In 1987, the TDC commissioned an assessment of the feasibility of establishing a major wildlife reserve in the Teesside region. The project brief was then defined to identify the target habitats as being:

> "200ha of wetland system including open water bodies, scrapes, reedbeds, alder and willow carr and intermediary and climax type woodlands" (Teesside International Nature Reserve, 1990).

5.2.2 HABITAT CREATION PROPOSALS.

The ultimate aim of the habitat creation proposals defined by the design team (including EHC), was to increase the diversity and abundance of wildlife which can be seen in Teesside. These proposals were carried out according to specific criteria necessary to retain, and where possible enhance, existing areas of wildlife interest, whilst creating an ecosystem of high ecological and conservation value that could be considered important on an 'international' scale. It was proposed to

DRY GRASSLAND

Figure 5.2

The Teesside International Nature Reserve

create a range of ecologically diverse habitats whose flora and fauna are complementary. The proposed ecotypes are typical of those found in Northern Britain, whilst the ecosystems contain species whose environmental tolerance ranges suit the prevailing conditions on Teesside.

Initial research identified an area suitable for the brief and elaborated upon the original concepts to produce a list of habitats that could potentially be created. These habitats included: open water; reedbed; other swamp habitats; carr woodland; scrub woodland; mixed deciduous woodland; and saltmarsh and brackish water communities.

As previously discussed in Section 2.4.5, reedbed represents the primary habitat for a number of specialist bird species that are increasingly rare in the UK. The large scale of reedbed creation on the TINR (c80 ha) should provide the essential conditions for such specialist species (TINR, 1990). It was envisaged that *Phragmites australis* reedbed would form the major vegetation type within the clay-based zone located in the north-western area of the TINR (see Figure 5.3). *Phragmites australis* would also be located along the entire length of the principal stream corridor, Holme Fleet, and fringing water bodies throughout the TINR. Much of the reedbed complex would be managed as a wet, mature reedbed with a network of small channels, dykes and open water bodies. These channels and dykes are attractive to bittern, and would also act to minimise visitor access enabling species which are prone to disturbance to breed on the TINR.

As *Phragmites australis* will not grow in water deeper than 1m and grows best in water shallower than 600 mm, it was proposed that gently sloping planting zones would be created around the lagoons and pools so that suitable growing conditions occur over large areas. These areas of created reedbed would be planted by transplantation of rhizome rich peat, with all areas 'ripped' to a depth of 150 mm to allow the rhizomes to penetrate the underlying clay substrates. Once planted the rhizomes would be flooded to a depth of 150 mm.

A range of other swamp types was also proposed including tussock sedge swamp, reedmace swamp, bur-reed swamp, reed sweet-grass swamp, and sea club-rush swamp. The inclusion of such habitats within the reedbed complex will add habitat diversity and thereby increase the ornithological interest to both reedbed specialists and a range of other bird species.

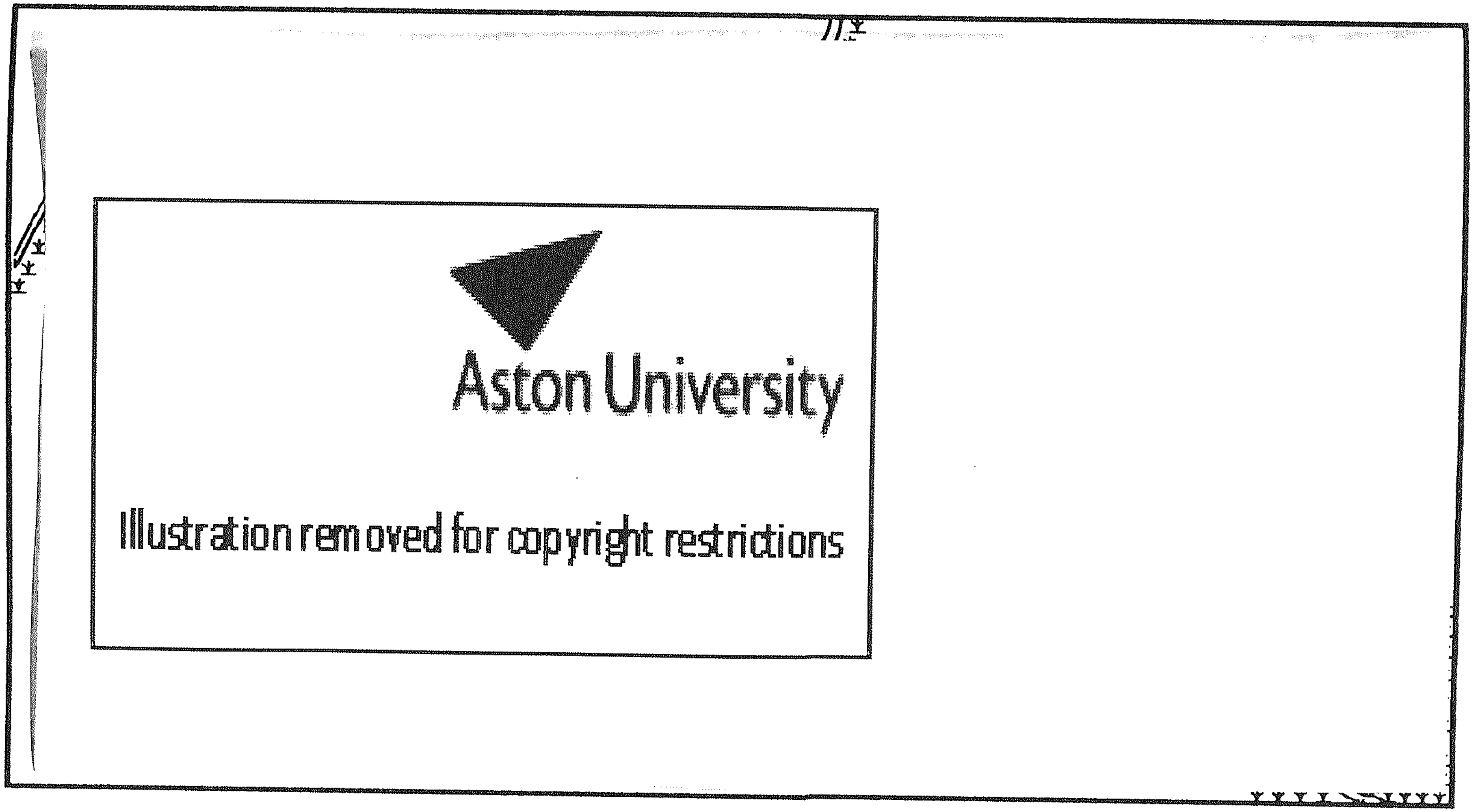
5.2.3 THE HAVERTON HOLE REEDBED COMPLEX.

The Haverton Hole Reedbed Complex is located in the north-western corner of the TINR (See Figure 5.3), covering an area of approximately 7 ha, with a ratio of reedbed to open water of 1.3 : 1. The reedbed complex appears to have formed in a depression within the Estuarine Warps and may result from subsidence due to a high density of solution salt extraction wells. Since brining ceased in the 1950's the rate of subsidence has steadily declined and today does not exceed 1-2 mm per year. The surface water input to Haverton Hole is from Belasis Beck, via Holme Fleet, with the channel entering from the north with a very small water surface gradient. Flanking Haverton Hole on the south side is a major spoil mound consisting of a range of spoil materials including furnace waste and slag.

In the period between the concept of developing a large reedbed complex on the TINR and the preparation of this thesis, two areas of reedbed habitat creation have been undertaken, extending the area of reedbed complex within the north-western corner of the TINR. The first of these operations was the creation of a reedbed pilot scheme, details of which are provided in Section 5.2.4. The second area of reedbed habitat creation, undertaken in September 1995, was constructed by British Gas PLC, with the TDC being responsible for design and supervision of the works. A total area of approximately 3 ha of open water and reedbed was created by the construction of two shallow pools located to the north and east of Haverton Hole. Immediately after construction, the areas surrounding the permanent open water of the southern pool, were covered by topsoil and planted with turves of *Phragmites australis* dug from the adjacent reedbed, under the supervision of the author. The northern pool was allowed to revegetate naturally.

5.2.4 THE HAVERTON HOLE REEDBED PILOT SCHEME.

The principal objective of the pilot scheme was to inform the feasibility of extending the Haverton Hole reedbed complex, and to create a naturally functioning wetland system. To the north-west of Haverton Hole two separate water bodies were created; the Pilot Pool, and the Peat Scrape. Construction works were undertaken in April 1988, with the TDC being responsible for design and supervision of the works.



KEY

A	The Pond	F	British Gas Water Body
B	Pilot Pool	G	Holme Fleet
C	Peat Scrape	H	Belasis Beck
D	Haverton Hole	J	Reedbed Trial Plots
E	British Gas Water Body	⚲	Reedbed

Scale 1:5,400 approx:

Figure 5.3
TINR - The Haverton Hole Reedbed Complex and Pilot Pool

The Pilot Pool was located (see Figure 5.3) in an area remote from peat substrates, within impermeable silty clays. During construction, the environs were sympathetically landscaped to increase rainfall capture. The pool was filled with water pumped from Haverton Hole, and once filled no additional pumping activities were undertaken. No input or output channels were included in the design as the associated water control structures would have required maintenance and management, not possible on an unmanned site. An area of approximately 3 ha of open water was created, fringed by a reedbed varying in stand width from 3 m to 20 m (see Figure 5.4).

Figure 5.4 The Pilot Pool (November 1996)

Following discussions with the Broads Authority and the Nature Conservancy Council it was agreed that the reed required to plant-up the Pilot Pool would be taken from Ward Marsh, Norfolk. The reed transplantation was carried out in April 1988, and involved the stripping of 120 tonnes of rhizome-rich surface peat from about 0.25 ha of Ward Marsh, transported to Teesside by road (George, 1992).

A shallow scrape was also excavated within peat dominated substrates to inform the establishment and development of a reedbed under differing soil types and varying hydrological regimes. The scrape is "bowl" shaped and water depths gently slope to a maximum depth of approximately 1.75 m. This area was allowed to revegetate naturally without planting. The water budget of the Peat Scrape is supplemented by throughflow from Haverton Hole moving within interconnecting peat strata. Overflow only occurs during the winter when water has been seen to outfall to Haverton Hole.

The isolation of the Pilot Pool catchment from the existing streamfed hydrology of the Haverton Hole Reedbed Complex, provided an ideal catchment for the study of a surface water fed reedbed system identified in Section 3.7. In addition to the absence of streamflow, the Pilot Pool catchment has no groundwater inputs and minimal migration of surface water into the underlying impermeable clay substrates, and provides a study area containing only the parameters identified in Equation 3.9.

5.2.5 REEDBED TRIAL PLOTS.

EHC approached the TDC during May 1993 with a design for two small reedbed trial plot areas to be constructed within the catchment of the Pilot Pool, TINR. The small plots, each measuring 240 m^2, were located along the south-eastern edge of the Pilot Pool (see Figure 5.3) within an area that had been topsoil stripped during the construction of the Pilot Pool in 1988. Each trial plot consisted of four reduce-level excavations connected to the Pilot Pool by a water supply trench. Each excavation measured 4 m x 15 m. In order to inform the success of various substrates as planting medium for reedbed development, the first trial plot was constructed within a stiff clay substrate, whilst the second trial plot was peat based.

EHC had been researching alternative methods of reedbed construction and establishment. This research had suggested that using small plantlets of *Phragmites australis,* grown in either a 90 mm pot or in 200 cc plugs, may be a more successful and cost effective way of producing large areas of mono-dominant species reedbeds than using rhizome infested material. Additionally the plantlets can be grown from seed in a short time period (4-6 months), and their use reduces the potential damage caused to the rhizome source areas. The trial plots would attempt to compare the success of reedbed establishment using both rhizome infested material and seed raised plantlets at various densities.

The planting strategy for the trial plots is presented in Figure 5.5. The trial plots were excavated using the backactor of a 3cx Site Master JCB, with the base of the plots 'ripped' using the backactor to facilitate more advantageous planting conditions within the clay substrate. The plantlets were planted manually, and firmly healed into the sediment for anchorage. Immediately after construction the young reed plantlets were inundated with water to a depth of 150 mm (see Figure 5.6).

All of the plantlets appeared to become fully established prior to the end of the 1993 growing season, with many of the stems measuring up to 0.6 m high. The measurements of reed establishment and development were programmed to begin in May 1994. However, immediately prior to the measurements commencing a family of Canada Geese became resident on the Pilot Pool. During the initial growing period of the trial reedbed plots (April - June 1994) the geese consumed all of the young green shoots over the entire experimental area. As a result of the denudation of the experimental plantlets, it was decided that monitoring of the development of the reedbed trial plots would no longer be undertaken as part of the on-going research studies.

5.2.6 CURRENT STATUS OF HABITAT CREATION WORKS.

At the end of 1996, limited additional habitat creation works had been undertaken on the TINR. A small clay-based waterbody had been recently created to the north-east of the proposed area of wet/flooded grassland (see Figure 5.2). The excavated material was used to create a 3 m high earthmound, designed to force flying birds to rise above the level of electricity powerlines.

In the autumn of 1996, the TDC prepared an application for funds to complete the construction of the TINR. The decision of the 'Lottery Fund Commission' is expected in Spring 1997.

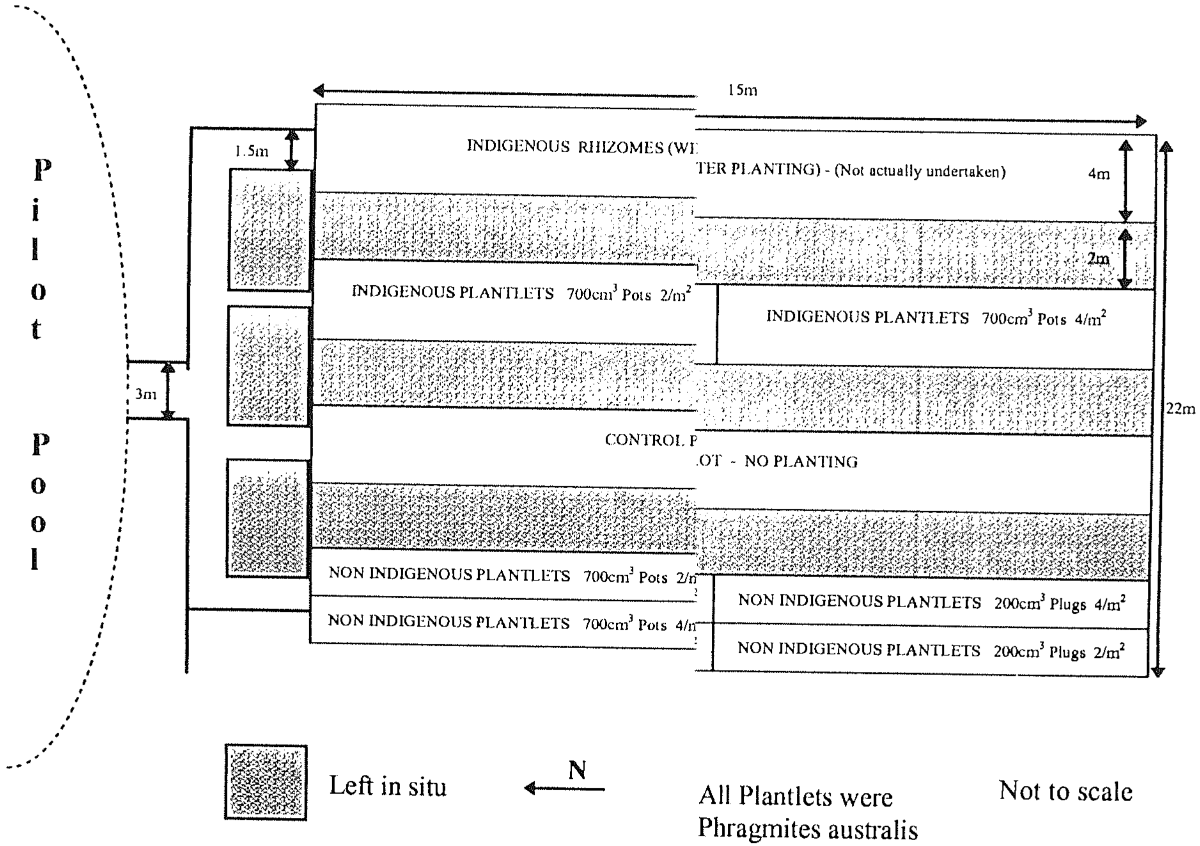


Figure 5.5 Reedbed Trial Plot - Planting Strategy

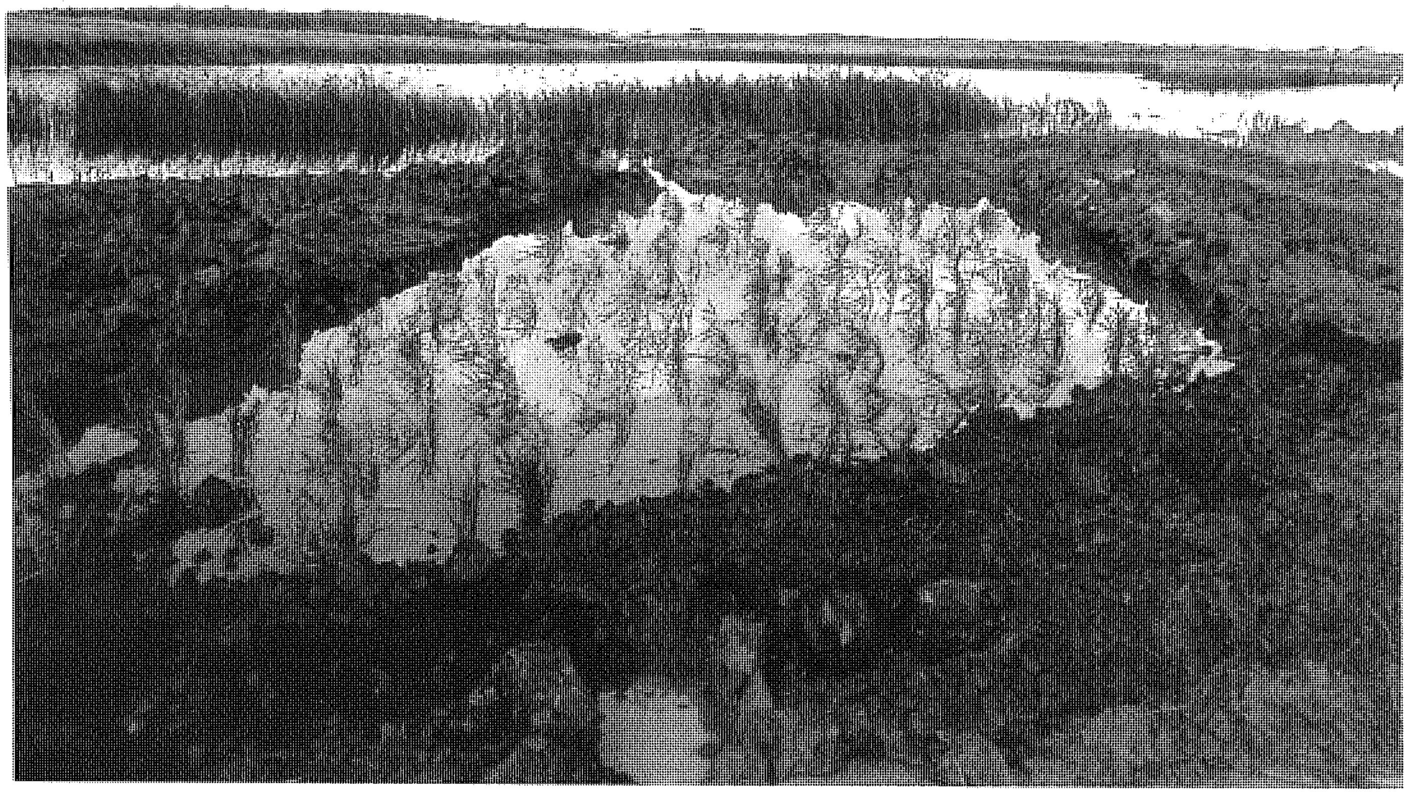


Figure 5.6 Inundated Reedbed Trial Plot

5.3 CARDIFF BAY BARRAGE COMPENSATION MEASURES - CREATION OF A WETLAND AT REDWICK, GWENT.

5.3.1 INTRODUCTION.

The Cardiff Bay Barrage Bill will allow the construction of a Barrage between Penarth Head and the entrance to the Queen Alexander Dock, enclosing the Taff Ely SSSI. The Cardiff Bay Development Corporation (CBDC) accepted the need to provide mitigation measures for the loss of the SSSI bird feeding grounds.

The proposal to create alternative feeding grounds by the development of an intertidal lagoon on the Wentlooge Levels was rejected on the grounds it was too experimental and not cost effective. A feasibility study of various mitigation measures was therefore commissioned by CBDC. The study set out to examine the practicalities of establishing a 'Wetland of Outstanding Value for Wintering and Breeding Waterfowl' and other rare or threatened bird species, resulting in a net increase in the numbers and diversity of bird species within the site boundaries. The existing nature conservation interests of the area concerned should not be prejudiced by its development. These existing nature conservation interests comprise the Gwent Levels Sites of Special Scientific Interest (SSSI's), and the adjacent Severn Estuary, which is an SSSI, a Wetland of International Importance (Ramsar Site), a Special Protection Area (SPA), and a proposed Special Area of Conservation (pSAC).

The first stage of the feasibility study was the assessment of alternative sites for their suitability to accommodate wetland habitat. The majority of the initial study areas were located on the Gwent Levels (Cardiff Bay Development Corporation Design Team, 1994a). The Gwent Levels comprise approximately 10,500 hectares of reclaimed estuarine land on the northern shore of the Severn Estuary, having a characteristic pattern of drainage, including natural water courses, main drainage channels or "reens", with associated field ditches and grips. The reens are distinctive of the landscape and are notable for their emergent and aquatic flora and fauna.

The reen system is controlled by the Environment Agency (EA) and the Caldicot and Wentlooge Internal Drainage Board (CWIDB). The EA are responsible for all main river reens, which remove flood waters off site, and the CWIDB control the bisecting reens, controlling flows through the system for agriculture, flood control and conservation interest. The EA also control and maintain the seawall defences and outfall culverts.

The site chosen for detailed study was a rectangular block of land (250ha) adjacent to the Severn Estuary, south and west of the village of Redwick (NGR ST 410 840 - see Figure 5.7). The Redwick site is bounded by Windmill Reen, Elver Pill Reen, and the seawall. There is little variation in the landscape character across the site, which retains the appearance of drained estuarine wetlands, criss-crossed by a network of hedgerows and reens. The surface sediments are dry and desiccated during the summer, and saturated in winter, with the present land use mainly mixed grazing of cattle and sheep combined with very small amounts of arable crops.

The Cardiff Bay Development Corporation Design Team (1994b) state that the Redwick site was:

> "considered the most acceptable for the creation of freshwater habitats by virtue of its size and shape, current ecological interest, low levels of disturbance from humans, the ease of which it could be isolated from the surrounding drainage systems, the open flat nature of the site, the lack of power lines, and suitability of surface and subsurface conditions for waterbody creation"

5.3.2. HABITAT CREATION PROPOSALS.

Following desk research, field survey works, and consultations with the Countryside Council for Wales (CCW), the Royal Society for the Protection of Birds (RSPB), the British Trust for Ornithology (BTO) and the Gwent Ornithological Society (GOS), the Cardiff Bay Development Corporation Design Team (1994c) concluded that the wetland habitat creation potential of the Redwick site should include: wet and flooded grassland; reedbed; and open water (see Table 5.1). It was intended that these habitats would form a complex of inter-relating freshwater wetland systems which can be managed in a flexible manner to create a wetland of outstanding value to birds, with the potential to attract bittern. The initial specifications for the structure and management of the reedbed and open water habitat type are presented in Tables 5.2 and 5.3 respectively.

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Figure 5.7
Creation of a Wetland at Redwick - Site Location

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HABITAT	AREA (ha)	RATIONALE
Phragmites Reedbed	60 ha (including 2-3 ha rootzone treatment area).	There are very few reedbeds left in Britain large enough to support breeding populations of birds which have a specific requirement for this habitat; these include the nationally rare species Bittern (15 breeding pairs in GB), Marsh Harrier, Garganey, Cetti's Warbler and Bearded Tit. The Reedbed at Redwick should provide sufficient habitat to support breeding pairs of the species mentioned above (minimum reedbed area 25 ha).
Wet/Flooded Grassland	70 ha	Damp pasture will provide suitable habitat for breeding waders (lapwing, redshank); winter flooding of grassland will provide feeding habitat for a variety of waterfowl.
Open Water	35 ha, divided between: 20 ha reedbed meres, 15 ha reservoirs.	Open water bodies will provide a wide variety of habitats for breeding and wintering wildfowl, and potential marginal habitats for wader. Islands will be provided for breeding terns and as refuges for breeding wildfowl.

Table 5.1 Redwick Habitat Specification - Wetland Habitat Types (Cardiff Bay Development Corporation Design Team, 1994c).

HABITAT FEATURES	DESCRIPTION
Vegetation Composition	Common reed (Phragmites australis) dominant.
Reedbed Types	85% of area to be wet reedbed; 15% of area to be dry reedbed.
Internal Structure	Wet reedbed to contain open water, with area 15% total reedbed; open water areas to be pools, and meres with sinuous margins; wet reedbed to have internal dyke network to maximise reed/water interface; c. 100m dyke per ha of reedbed, dyke width 2m.
Bed Profiles (depth below summer level)	Wet reedbed - 25% at 0.2 m depth, 75% at 0.5 m depth; dry reedbed - ground level; pools - depth to vary within and between pools, in range 0.05-0.5 m; dykes - depth to 1.5 m with shallower margins.
Reedbed Shape	Preferably square; inter-digitated with adjacent habitats (reservoirs, wet/flooded grasslands) to create maximum edge effect.
Water Level Management	Wet reedbed - water depth required at 0.1-0.5 m above ground level, with large area at 0.2 m or less during spring/early summer; dry reedbed - summer water level at/below ground level, possibly with periodic flooding regime.

Table 5.2 Redwick Habitat Specifications - Reedbed (Cardiff Bay Development Corporation Design Team, 1994c).

OPEN WATER FEATURES	DESCRIPTION
Waterbody Size	Reservoirs to cover 15 ha, probably in 2 x 6-8 ha blocks; smaller waterbodies possibly located in grassland habitats.
Shoreline Configuration	Extensive shallows to be created, slopes not to be steeper than 1:15; sinuous shoreline, to be modelled as series of spits and bays with dimensions of c. 10 m x 10 m.
Bed Profiles	Depths to vary within and between pools in range 0.3 m to 3.0 m, with majority of area at depths between 0.3 m - 1.5 m.
Islands	Islands to be located as far offshore as possible; for terns and smaller waders, to be sparsely vegetated, low in profile and topped by shingle/sand.
Water Level Management	For small waterbodies: high levels (1 m maximum) maintained in winter; progressive drawdown in spring.

Table 5.3 Redwick Habitat Specifications - Open Water (Cardiff Bay Development Corporation Design Team, 1994c).

5.3.3 CURRENT STATUS OF HABITAT CREATION WORKS.

The wetland habitat creation plans for the site at Redwick were abandoned in July 1994. Alternative sites within the Gwent Levels area (e.g. Uskmouth Power Station) were chosen by CBDC, and were the subject of a feasibility study undertaken during the summer of 1995. At the end of 1996, no habitat creation works had begun on any of the proposed sites, awaiting the decision of the 'Public Enquiry' scheduled for Spring 1997.

5.4 HIMLEY SEWAGE TREATMENT WORKS.

5.4.1 INTRODUCTION.

As previously discussed in the introduction to this Chapter, in order to greatly enhance the works on ET(Reed), a site was required which could be monitored by the author on a more regular basis, than had been possible for either of the other two experimental sites. It was anticipated that research undertaken at Himley would allow the development of a Kc(Reed), which might be applicable to root zone treatment (RZT) works. Research works at the Severn Trent Water Company Sewage Treatment Works at Himley began in April 1995.

Himley STW is located at NGR SO 877 912 (see Figure 5.8), approximately 0.5km south-west of the small town of Himley, situated on the western outskirts of the West Midlands conurbation. The Works lies immediately to the south of the Himley by-pass road (B 4176), and to the north of a disused railway embankment. The root zone treatment section of the works was installed in Summer 1991, in an attempt to reduce the ammonia and suspended solids content inherent within the final effluent (Green, 1995).

5.4.2 REEDBED CHARACTERISTICS.

The site consists of two gravity fed reedbed plots running in series (see Figure 6.5). Both reedbeds are constructed within a reduce level excavation (1.0 m - 1.85 m below existing ground level), partially backfilled with approximately 600 mm of fine gravel overlying an impermeable liner. Tertiary effluent is dispersed through the beds via a pipework system which allows water exiting from the rotating biological contactors to enter the upper reedbed. The upper reedbed measures 40 m by 13 m (520 m^2), with the surface of the gravel bed at approximately 0.4 m below the surrounding ground level. Water exits the upper reedbed into a small collection chamber prior to discharge into the lower reedbed. The gravel surface of the lower reedbed is set approximately 1.20 m below the surrounding ground level, with reedbed dimensions of 35 m by 12 m (420 m^2). The treated tertiary effluent outfalls from the lower reedbed into a small natural water course.

The Severn Trent Water Company were approached for information with respect to the reedbed planting and flow characteristics of the Himley site. Minimal information was provided, however, Green (1995) stated that the reedbeds had been planted during 1991, using pot-grown plantlets, at a density of 2 - 4 plantlets/m^2.

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Figure 5.8 Himley Sewage Treatment Works - Site Location

Chapter 6. EXPERIMENTAL DESIGN AND ET(Reed) RESULTS.

6.1 INTRODUCTION.

Section 4.3.2 undertakes a review of the use of lysimeters in studies of ET(crop). The use of lysimeters in the determination of ET(Wetland) was discussed in Section 4.5.2, whilst, Section 4.6.2 detailed the lysimeter studies undertaken by various researchers working with *Phragmites austalis* [ET(Reed)], with the most detailed of these studies undertaken by Bernatowicz et al (1976).

The experimental design used in this research programme is an adaptation of that developed by Bernatowicz et al (1976). The development of the phytometer principle is presented in Section 6.2, with the site specific details of the phytometer installation and monitoring programme contained in Section 6.3. A photographic record of various research activities was undertaken, including: plates of experimental installation activities; a month-by-month growth and development record of the establishment of *Phragmites australis* within the phytometers; and plates showing the environs in which the phytometers are located. A sample set of plates are displayed in Appendix 4.

The majority of researchers that have studied ET(Reed) undertook their experimentation during the growing season, when the vast majority of the annual ET(Reed) occurs. A similar monitoring period was adopted during this research programme with monitoring undertaken between the beginning of April and end of October. It was anticipated that these activities would allow the development of Kc(Reed) applicable for various stages of reed development.

Following a brief review of the ET(Reed) data and associated Kc(Reed) in 1996, a decision was taken to attempt to monitor the ET(Reed) during the dormant period of 1996/97. This data would complete a twelve month monitoring period, allowing the production of an annual ET(Reed) total, and the development of a Kc(Reed) for the dormant period. Consequently, ET(Reed) measurements were recorded during the period November 1996 to March 1997, on both the TINR, and at Himley.

It was anticipated that the recording of data during the dormant period would be complicated by the potential overtopping and drowning-out of the phytometers as a result of low ET(Reed) and relatively higher rainfall. These fears were realised to a degree within the experiments based on the TINR, however, the weekly monitoring visits to the 'managed' system at Himley produced uncorrupted ET(Reed) measurements.

Growth characteristics and establishment details of the *Phragmites australis* growing within phytometers are briefly described for the various sites in Sections 6.3. Detailed growth characteristic data are presented and discussed in Section 8.4. The ET(Reed) data for both the growing season and dormant period for each of the experimental sites are presented in Section 6.4.

6.2 DEVELOPMENT OF THE PHYTOMETER PRINCIPLE.

6.2.1 THE PHYTOMETER.

The plants used (*Phragmites australis*) were planted in rigid plastic barrels (phytometers) approximately 0.25 m^2 in surface area, as shown in Figures 6.1 and 6.2. The phytometers are filled with local sediment and are either planted-up to allow measurements of ET(Reed), or are left unplanted to provide an indication of the evaporation rate which might be expected from within a reedbed stand [E(Phyto)].

The sediment within the phytometers is covered with a controlled water layer 180 mm deep. It was anticipated that this water level would provide sufficient water to allow *Phragmites australis* to transpire at a 'Potential' rate between readings. To accommodate high rainfall inputs and avoid overtopping the water level is set 80 mm below the rim of the phytometer using a permanently sited hook gauge (see Appendix 4). Evaporation and evapotranspiration losses were replaced during each monitoring visit, with the water level within each phytometer returned to the specified reset level, using a suitable water source.

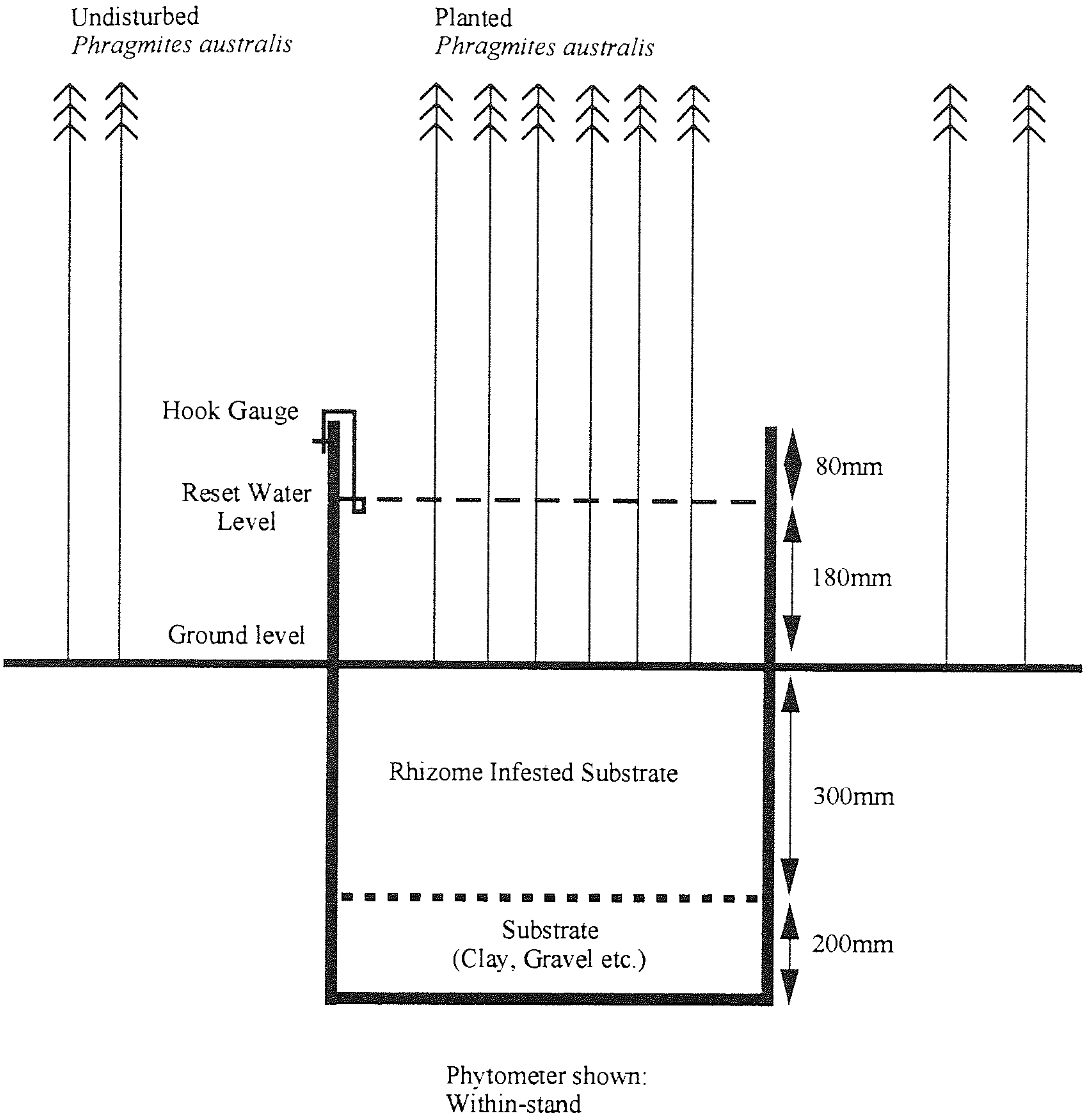

Figure 6.1 The Phytometer - Diagrammatic.

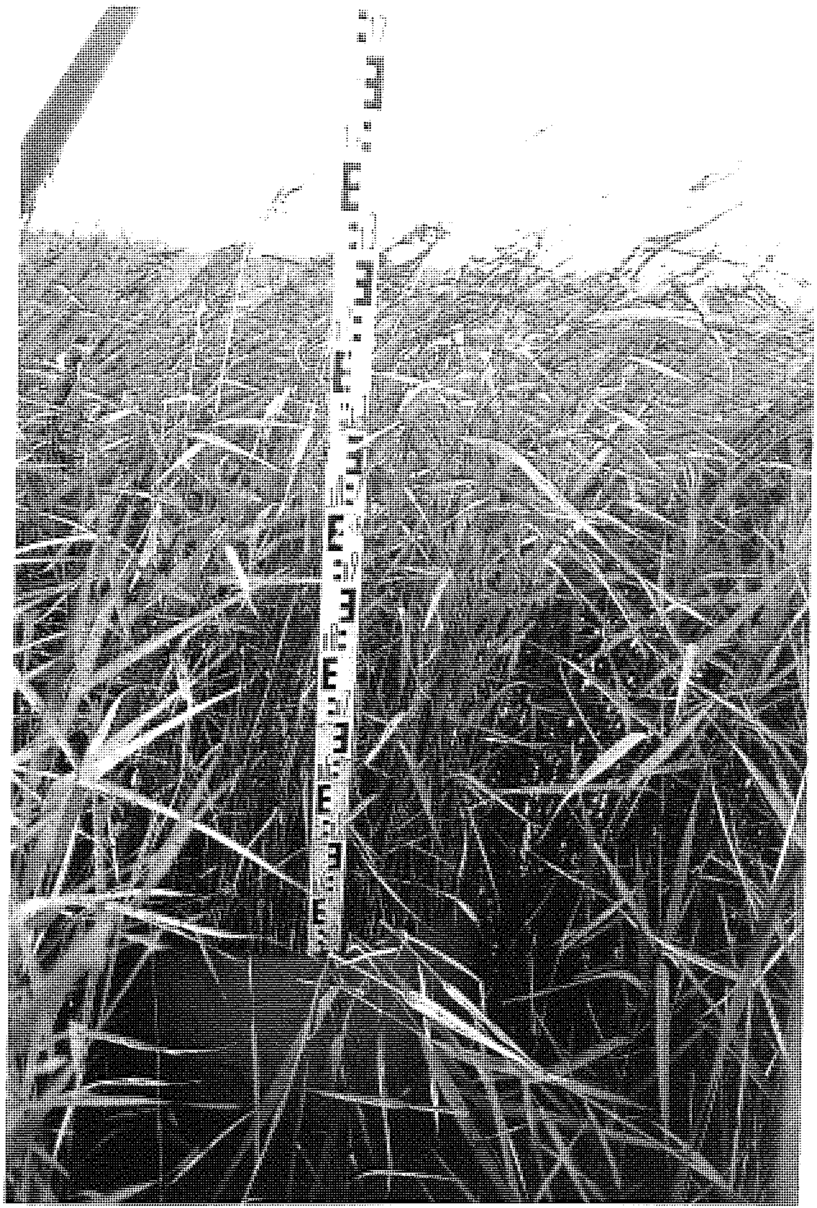

Figure 6.2 The Phytometer - Photographic.

In 1993, the changes in the level of the water surface within the phytometers were recorded to the nearest mm using a standard ruler. This linear measurement was converted to a volume by multiplying by the surface area of each phytometer. However, it became apparent toward the end of the growing season that the planted phytometers had reed stems occupying a significant proportion of the volume of the phytometer near to the sediment water interface. A decision was taken to directly measure the change in water volume occurring in each phytometer, and this was undertaken for all phytometers from the beginning of the 1994 growing season. Water volume adjustments undertaken to restore the water level within the phytometers to the 'reset' level were measured using a 1 litre measuring cylinder, calibrated in 10 ml gradations, thus giving an accuracy for each reading of +/- 0.5%.

All of the barrels used within the research experiments were pre-washed to ensure that no residual contamination, that might affect the growth and establishment of *Phragmites australis*, remained within them.

6.2.2 SITING THE PHYTOMETER.

The majority of the phytometers used within this research programme were sited within stands of wet reedbed, allowing the measurement of ET(Reed) from within-stand. However, it was apparent that a suitable reedbed stand might not be available within design schemes focusing on the creation of virgin reedbed habitat (see Section 6.3.3). Thus, a proportion of the phytometers located on the TINR were sited outside of a reedbed stand (not within-stand), within a predominantly terrestrial environment (four-fifths sunk into the ground). The siting of the phytometers on the TINR allowed the measurement of ET(Reed) from both within-stand and not within-stand, and hence the development of a correction factor, which was applied to the ET(Reed) recorded from not within-stand phytometers located at Redwick (see Section 8.3.3).

6.3 PHYTOMETER INSTALLATION AND MONITORING PROGRAMME.

6.3.1 INTRODUCTION.

A small trial of ten phytometers was undertaken on the TINR beginning in March 1993, this trial was extended by the addition of a further twenty experimental stations installed in March 1994. Ten phytometers were installed both at Redwick in September 1994, and at Himley in March 1995. Table 6.1 presents a detailed summary of the monitoring periods, number of phytometers, phytometer locations, and planting details, for each of the three study sites. The phytometer planting scheme and numbering schedule for the TINR, Redwick, and Himley are displayed in Figures 6.3 to 6.5 respectively. A detailed discussion of the installation activities and associated techniques for each site is presented in Sections 6.3.2 to 6.3.4.

6.3.2 TINR.

6.3.2.1 Pilot Study.

To facilitate both within-stand and not within-stand ET(Reed) measurements required a moderately large area of established *Phragmites australis* growing within a significant water feature. Two such areas were identified on the TINR: The Haverton Hole Reedbed, and the Haverton Hole Reedbed Pilot Scheme (see Figure 5.3). During 1992, EHC had monitored water levels within Haverton Hole, the Pilot Pool and the Peat Scrape, recording a greater variation in the water level in Haverton Hole and the Peat Scrape than in the Pilot Pool. This high variation in water level may have resulted in any phytometers located within the Haverton Hole Reedbed being inundated during the spring and early summer monitoring periods. As a consequence the Pilot Pool was the preferred site. In March 1993, the TDC approved the installation of six phytometers within the catchment areas of the Pilot Pool and the Peat Scrape (see Figure 6.3 - Phytometers nos. 1 to 6).

SITE	Year	Monitoring Frequency	Monitoring Periods		Phytometers		Planting Details		Located Within-stand	
			Apr-Oct	Nov-Mar	Planted no.	Unplanted no.	Rhizomes	Pots	Planted	Unplanted
TINR £	1993	MONTHLY	Yes		4 (2)**	2 (2)**	4	2	2 (0)**	1 (0)**
	1994		Yes		16	14	14	2	10	9
	1995		Yes		16	14	14	2	10	9
	1996		Yes		16	14	14	2	10	9
	1996-97			Yes	16	14	14	2	10	9
REDWICK $	1994	10 DAYS	Yes		5	5	0	5	0	
	1995		Yes*		5	5	0	5	0	
HIMLEY	1995	WEEKLY	Yes		5	5	5	0	5	5
	1996		Yes		5	5	5	0	5	5
	1996-97			Yes	5	5	5	0	5	5

£ - Installation activities funded by TDC
$ - Installation activities funded by CBDC
* - Monitoring commenced June 1995
** - Additional Phytometers installed July 1993

Table 6.1 Phytometer Planting Details and Monitoring Periods

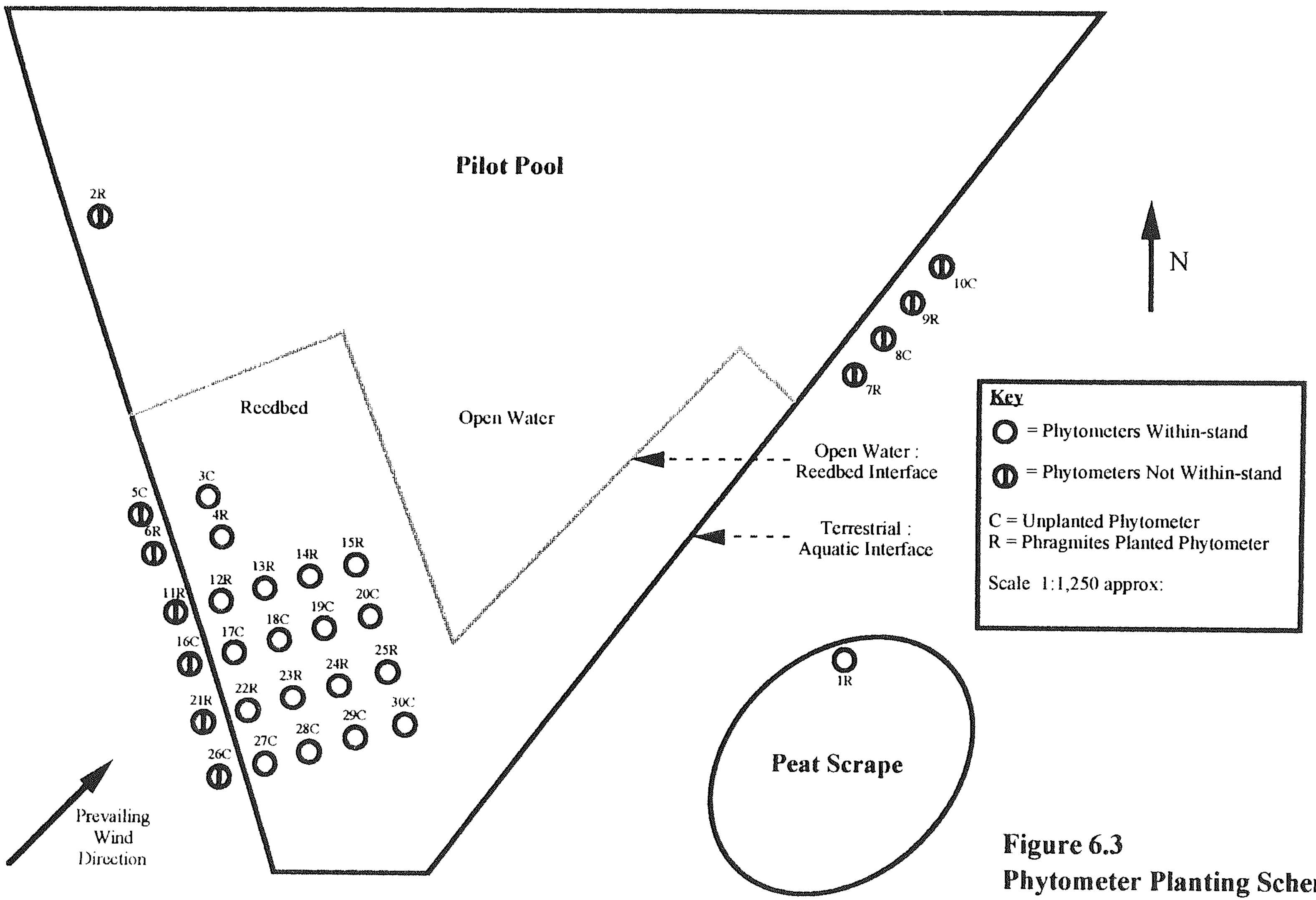

Figure 6.3
Phytometer Planting Scheme -TINR

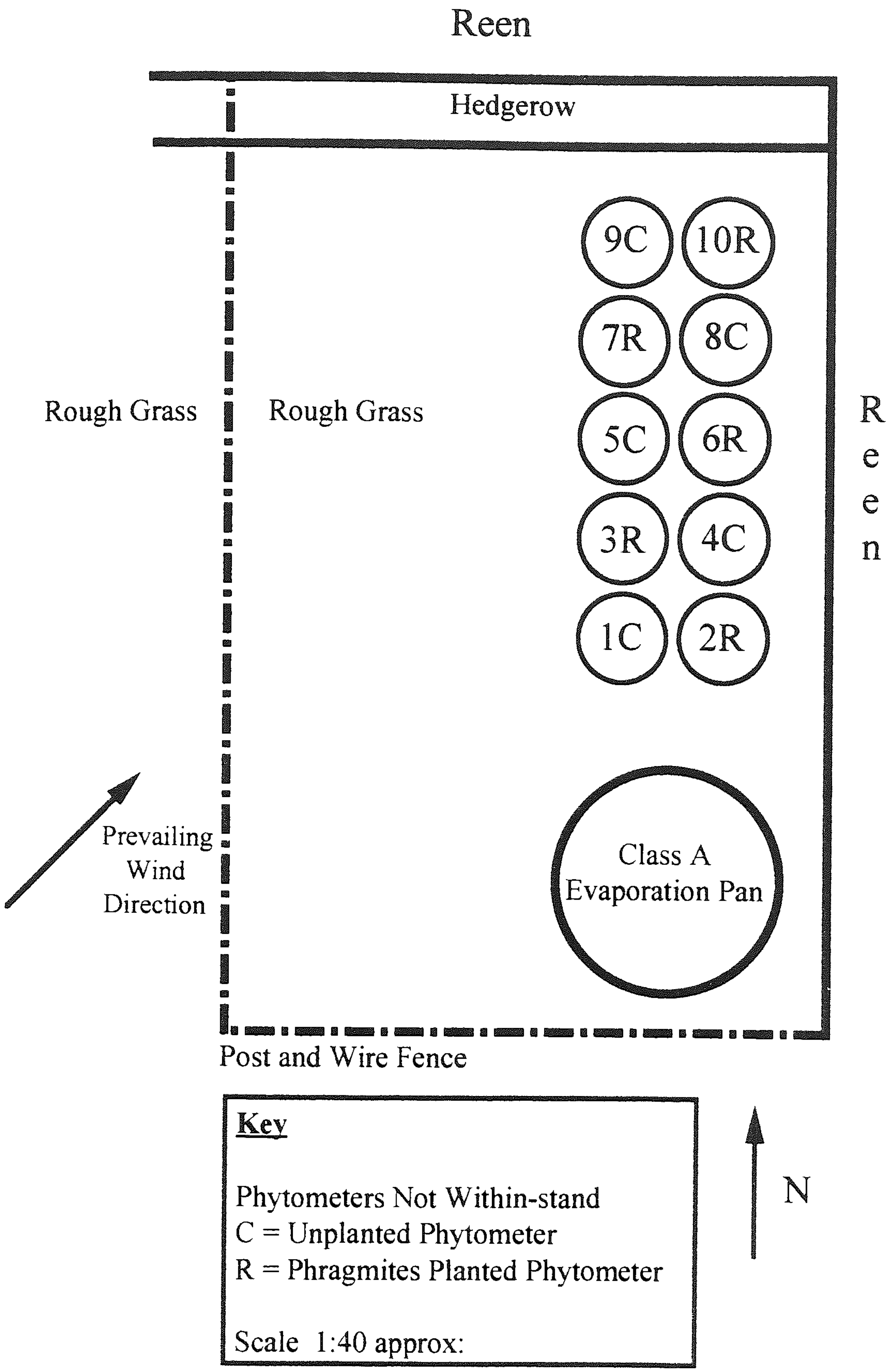

Figure 6.4 Phytometer Planting Scheme - Redwick.

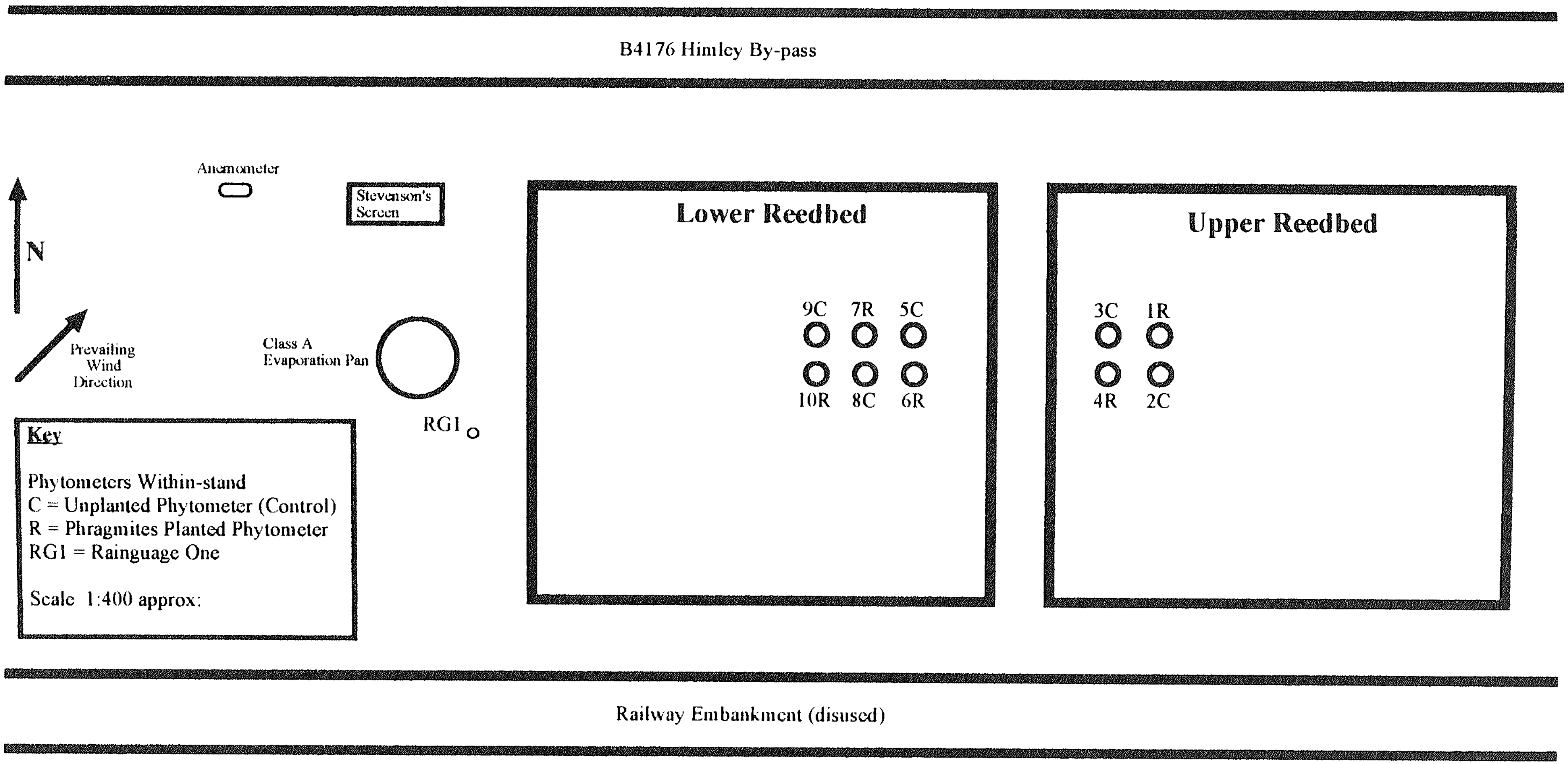

Figure 6.5 Phytometer Planting Scheme - Himley.

The phytometers were installed using the backactor of a 3cx - JCB style excavator, fitted with a 600 mm bucket. This allowed sensitive manipulation of the phytometers, and the excavation of a planting hole similar in diameter to that of the phytometer. During the reduce level excavation activities, the 'first dig' was excavated to a depth of 350 mm. This depth ensured that the horizontal rhizomes contained within the surface 300 mm suffered minimal damage. This rhizome-rich excavate was temporarily placed on dryland adjacent to the reedbed. The phytometer was positioned and filled with enough water to make it sink into position. At this stage it was necessary to ensure that the rim of the phytometer was parallel with the water surface to reduce the risk of overtopping/inundation. Rhizome-rich sediment was then placed in the phytometer by the bucket of the machine, whilst ensuring the rhizome-rich sediment /water interface was at the level specified in the experimental design. This procedure was carried out in the same manner for the unplanted phytometers, however, additional lake sediments were used instead of the rhizome-rich excavate. The sediment/water interface was set at the same level as in the planted phytometers. Finally, the phytometers were filled with water from the reedbed, taking care to ensure that no air pockets remained. The phytometers remained untouched for approximately two weeks prior to experimental works commencing.

The initial development of the freshly transplanted reed rhizomes was somewhat slower than the surrounding, established reedbed. This trend continued throughout much of the 1993 growing season, and was probably a result of rhizome disturbance. Four additional phytometers were installed within the 'Reedbed Trial Plots' in July 1993 (see Figure 6.3 - Phytometer nos. 7 to 10). Two of these phytometers were planted using pot grown *Phragmites australis,* the other two were left unplanted. Due to the subsequent poor establishment of the trial reedbed plots (see Section 5.2.5), these four phytometers are included within the data for ET(Reed) from phytometers located not within-stand.

The ET(Reed) measurements (within-stand) recorded in the 1993 growing season were derived from the data from only two phytometers, as the other phytometers were either; located not within-stand, or were unplanted. The measurements were also undertaken using a less accurate technique (e.g. linear water level change) than that developed, and used subsequently for the remainder of the experimental period (e.g. volumetric changes). In addition, the reed growth and establishment within the phytometers was poor in the 1993 growing season. As such, the presented ET(Reed) for 1993 should be viewed with these limitations in mind, and is not further discussed. However, the monthly ET(Reed) rates and trends are comparable to those recorded in subsequent years.

6.3.2.2 Full Study.

In order to improve the statistical significance of the experimental data from the Teesside area, it was necessary to install additional phytometers on the TINR. In addition, it was important to increase the number of experimental stations located within a reedbed stand as the data derived from these phytometers would provide a measurement of ET(Reed) from within-stand, which is representative of the ET(Reed) which might be expected from a large reedbed area. In March 1994, an additional twenty phytometers were installed within the large reedbed located in the southwest corner of the Pilot Pool (see Figure 6.3 - Phytometer nos. 11 - 30). One half of the phytometers were planted with rhizomes (as detailed above) whilst the remainder were left unplanted [E(Phyto)].

By the end of March 1994, a total of thirty phytometers had been installed on the TINR. Nineteen were located within a reedbed stand, with ten planted and nine left unplanted. Of the remaining eleven located not within-stand, six were planted and five were left unplanted (see Table 6.1). The establishment and subsequent development of the planted phytometers throughout the period of monitoring between 1994 and 1997 was good, with the height of the reeds within the experimental stations matching that of the surrounding reedbed.

In April 1994, high water levels within the Pilot Pool inundated the majority of the phytometers, and no data was recorded for this month. Data was available throughout the remainder of the growing season. However, data collection was not undertaken in October 1994 due to the commitment of the author to EHC contractual obligations.

An extreme rainfall event associated with the passage of a thunderstorm across the TINR in late August 1996, caused five of the unplanted phytometers to overtop. This overtopping of the water within the phytometer was evident from a line of very small debris fragments noted on the sides of the phytometers at the lowest point around the rim.

Monitoring was undertaken of the ET(Reed) during the dormant period between November 1996 and March 1997. ET(Reed) data was recorded from the majority of the phytometers throughout this period, with the relatively low rainfall producing minimal overtopping/inundation of the phytometers. Senescence occurred during late November, with the reed stems gradually reducing in number and height throughout the dormant period to a low, recorded at the end of March. Inflorescence were apparent throughout the dormant period with a marked decline recorded during February and March.

6.3.3 REDWICK.

No large areas of reedbed are located within the Redwick site boundaries, however, *Phragmites australis* was noted growing within the reen system controlled by the CWIDB, who were approached with respect to the installation of phytometers within a reen section. However, CWIDB felt that this was inappropriate as it might affect the inherent flow characteristics. Thus, installation of experimental equipment within a reedbed environment was not possible.

After consultation with a local landowner, permission was given to install ten phytometers (see Figure 6.4) in the corner of a 'set-aside' field located within the central, southern part of the Redwick site, adjacent to Mead Lane Reen. The phytometers were located in a terrestrial site approximately 1.5 m away from the reen edge. Although the siting of the phytometers limits the application of the experimental results, these works parallel the research works undertaken by Gavenciak (1972) (cited by Smid, 1975) and Kuzenecov (cited by Bernatowicz et al, 1976) (see Section 4.6.2).

Installation of the ten phytometers was undertaken in September 1993. A reduce level excavation was undertaken to a depth of 0.80 m below ground level, over an area approximately 3.5 m long and 1.5 m wide, using a JCB backactor. The phytometers were placed within the excavation, and backfilled with approximately 500 mm of brown clay rich subsoil (excavate), and a surface layer of 300 mm of topsoil (excavate). In order to reduce the risk of rain splash and surface runoff distorting the experimental results, approximately 200 mm of the phytometer extended above finished ground level. The area surrounding the phytometers was carefully backfilled to ensure stability and the phytometers filled with water from the adjacent reen.

No *Phragmites australis* rhizomes could be identified for use within the phytometers, however, Yarningdale Nurseries, kindly offered to supply pot grown *Phragmites australis* for research purposes. White (1993) recommended that planting activities were not undertaken until Spring 1994, as the newly established young plantlets might perish during a severe winter period. In March 1994, five of the phytometers were planted, with seven, 700 cm^3 planted-pots, used in each phytometer. The remaining five phytometers were left unplanted. The experimental area had been fenced to ensure stock animals could not damage the growing *Phragmites australis*.

Establishment of the pot grown *Phragmites australis* was good, with growth evident almost immediately. By the end of October 1994, the mean stem height was in excess of 1.00 m. Despite carefully backfilling the reduce level excavation area, Phytometer no.1 (unplanted) subsided and it became apparent that the volume of water held within the phytometer was being supplemented by surface runoff from the adjacent area. The measurements taken from Phytometer no.1 have not been used in the analysis of results.

During 1994, monitoring of the Redwick phytometers had been undertaken as part of the EHC contract with CBDC. This contract was not renewed until the end of June 1995. Thus there is no data available for the spring and early summer period of 1995.

6.3.4 HIMLEY STW.

The Severn Trent Water Company (STWC) were approached with a proposal to install ten experimental phytometers within the reedbed plots, located at Himley. Initial discussions (Green, 1995) identified two concerns associated with the installation and monitoring of phytometers located within a RTZ reedbed. The first was the impact on the area between the reedbed edge and the more centrally placed phytometers. This disturbance area was approximately 28 m^2 in the lower reedbed, and 14 m^2 in the upper reedbed. STWC agreed that this impact was acceptable in a reedbed with a total area of over 900 m^2. The second concern was that installation activities should not compromise the reedbed liner. The thickness of gravel substrate within the reedbed is only 600 mm, thus the use of a JCB-style machine for installation purposes was unacceptable, producing a requirement for the installation to be undertaken by hand. STWC granted permission to install phytometers within the Himley reedbeds (see Figure 6.5), providing a 200 mm thick substrate buffer was left below the base of each phytometer to prevent liner damage. Prior to installation, a small trial hole was carefully dug in the gravel substrate to ascertain the exact thickness of substrate. Each phytometer was sunk approximately 400 mm into the gravel substrate.

A special 'installation ring' was required to facilitate the reduce level excavation within a non-cohesive gravel substrate. Without this ring it would have required the over excavation of a considerably larger surface area of gravel substrate, resulting in damage to the reeds surrounding the phytometers and greatly increased labour costs. The diameter of the installation ring was 100 mm greater than the diameter of the phytometers. It was forced into the substrate to a depth of 400 mm, the gravel held within the ring was excavated by hand, and any rhizomatous material encountered placed to one side. The phytometer was placed within the excavation and backfilled with sufficient gravel to stabilise it. The ring was removed, and the phytometer filled to the specified level (260 mm below rim) with either: rhizome-rich, or rhizome-free, gravel substrate. Five phytometers were planted with rhizomatous material, whilst five were left unplanted. The rim of the phytometers protruded above the existing ground level by c400 mm to reduce the risk of inundation. The rim level was set with respect to the invert level on the reedbed outfall pipes. Each phytometer was filled with water to 80 mm below the rim.

Monitoring was undertaken during the growing season of 1995 (April - October), and throughout the annual period between April 1996 - March 1997. During the 1995 growing season the newly planted rhizomes developed slowly when compared to the surrounding, established (in-situ) reeds. This slow development became most apparent during July 1995, when the reeds within the experimental stations had achieved a mean stem length of only 0.85 m, whilst many of the established reeds had stem lengths in excess of 2.00 m. This resulted in the reeds within the phytometers being heavily shaded by the adjacent, taller reed growth, with a corresponding reduction in ET(Reed). Consequently, the ET(Reed) recorded at Himley in 1995 is not further used within this project. Reed growth and establishment was good during 1996, with the majority of the reed stems growing to similar heights to those growing within the adjacent reedbed.

ET(Reed) measurements were recorded during the dormant period between November 1996 and March 1997. From mid-October onwards the reeds progressed towards senescence, with stems turning to a yellowish-brown colour and leaf-fall occurring. Senescence was complete by the 21st November 1996, possibly hastened by a period of cold weather with associated snowfall occurring on the 19th November 1996. A significant standing crop remained throughout the dormant period. A short period of inundation affected the phytometers located within the Upper reedbed during mid-December. No data was recorded from Phytometer no.10 after the beginning of December 1996 due to a leak developing within the barrel, possibly caused by the expansion of ice within the phytometer in late November. In April 1997, all equipment was removed, and the site restored to the satisfaction of the Severn Trent Water Company.

6.4 ET(Reed) RESULTS.

For each of the experimental sites, ET(Reed) data for all phytometers sited within similar stand characteristics are averaged to provide mean monthly ET(Reed) values (mm/day). Phytometers which were subjected to overtopping/inundation are not included in the calculations. Mean monthly ET(Reed) for the TINR is separately calculated from both within-stand and not within-stand phytometer measurements. Redwick ET(Reed) data is representative of not within-stand phytometers, whilst the Himley phytometer's provide within-stand ET(Reed) data. The monthly ET(Reed) for each of the experimental sites is presented in Table 6.2. Table 6.3 provides a summary of the mean monthly ET(Reed) calculated for each experimental site, whilst Table 6.4 presents the mean monthly E(Phyto) values recorded on the TINR. The data from Table 6.3 is displayed graphically in Figure 6.6. The monthly ET(Reed) and E(Phyto) data recorded from each of the phytometers, from all three sites, is presented in conjunction with calculated standard deviations, standard error and confidence limits in Appendix 5.

Site	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
TINR	1993	na	na	na	Over	2.74	2.97	2.34	3.89	2.27	0.91	na	na
(Within-stand)	1994	na	na	na	Over	2.37	4.29	2.92	3.65	2.43	na	na	na
	1995	na	na	na	1.95	2.12	3.92	5.16	5.73	4.74	3.44	na	na
	1996	na	na	na	1.57	2.25	4.44	4.29	3.68	2.55	2.06	0.90	0.81
	1997	0.29	1.36	1.34	na	na	na	na	na	na	na	na	na
TINR	1993	na	na	na	Over	2.16	2.79	2.83	4.07	3.20	1.35	na	na
(Not Within-stand)	1994	na	na	na	Over	2.38	4.43	4.28	5.46	2.75	na	na	na
	1995	na	na	na	1.74	2.20	4.08	5.74	6.72	5.35	3.84	na	na
	1996	na	na	na	1.80	2.24	4.99	5.53	4.86	4.35	3.55	0.44	0.64
	1997	0.16	1.03	1.58	na	na	na	na	na	na	na	na	na
Redwick	1994	na	na	na	2.70	2.96	4.00	7.35	6.46	3.69	na	na	na
(Not Within-stand)	1995	na	na	na	na	na	na	9.58	13.39	9.90	4.81	na	na
Himley	1995	na	na	na	2.38	2.26	3.09	3.52	3.26	1.97	1.10	na	na
(Within-stand)	1996	na	na	na	1.38	2.41	3.84	4.99	6.19	6.30	2.96	0.90	0.21
	1997	0.18	0.82	0.73	na	na	na	na	na	na	na	na	na

Table 6.2 Monthly ET(Reed) for Each Experimental Site (mm/day).

Site	Period	Parameter	Jan (mm/day)	Feb (mm/day)	Mar (mm/day)	Apr (mm/day)	May (mm/day)	Jun (mm/day)	Jul (mm/day)	Aug (mm/day)	Sep (mm/day)	Oct (mm/day)	Nov (mm/day)	Dec (mm/day)
TINR	1994-97	Within Stand - Mean	0.29*	1.36*	1.34*	1.76	2.25	4.22	4.12	4.35	3.24	2.75	0.90*	0.81*
		Within Stand - Stan. Dev.	0.22*	0.42*	0.28*	0.42	0.53	0.62	1.24	1.38	1.25	1.09	0.51	0.41
		Within Stand - 99% Conf. Limits	0.22*	0.42*	0.28*	0.30	0.29	0.34	0.68	0.76	0.69	0.73	0.62	0.46
TINR	1994-97	Not Within-stand - Mean	0.16*	1.03*	1.58*	1.77	2.27	4.50	5.18	5.68	4.15	3.70	0.44*	0.64*
		Not Within-stand - Stan. Dev.	0.14*	0.66*	0.25*	0.34	0.65	1.18	1.34	1.46	1.36	1.12	0.25	0.34
		Not Within-stand - 99% Conf. Limits	0.14*	0.66*	0.11*	0.32	0.47	0.83	0.95	1.03	0.96	0.97	0.25	0.34
Redwick	1994-95	Not Within-stand - Mean	na	na	na	2.70	2.96	4.00	8.47	9.93	6.80	4.81	na	na
		Not Within-stand - Stan. Dev.	na	na	na	0.63	0.21	0.27	2.26	3.64	4.55	0.74	na	na
		Not Within-stand - 99% Conf. Limits	na	na	na	0.85	0.28	0.36	2.14	3.45	4.32	1.00	na	na
Himley	1996-97	Within Stand - Mean	0.18*	0.82*	0.73*	1.38*	2.41*	3.84*	4.99*	6.19*	6.30*	2.96*	0.90*	0.21*
		Within Stand - Stan. Dev.	0.13*	0.07*	0.13*	0.44*	0.74*	1.90*	2.73*	3.45*	4.81*	1.70*	0.18*	0.14*
		Within Stand - 99% Conf. Limits	0.19*	0.11*	0.20*	0.22*	0.38*	0.98*	1.41*	1.78*	2.48*	0.88*	0.27*	0.21*

* Based on 1996-97 data only

Table 6.3 Mean Monthly ET(Reed) for the Experimental Sites.

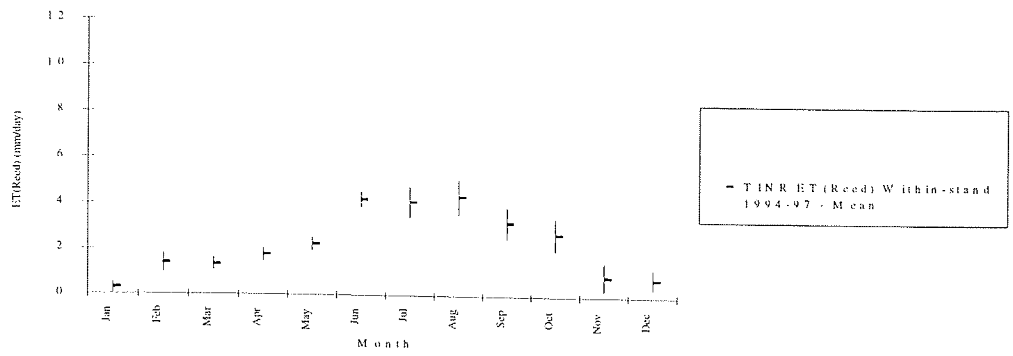

Figure 6.6a Mean Monthly ET(Reed) Within-stand - TINR 1994-97, Including 99% Confidence Limits.

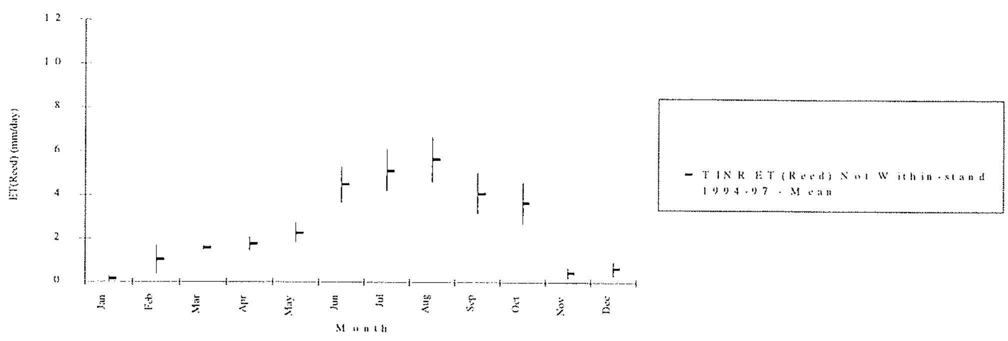

Figure 6.6b Mean Monthly ET(Reed) Not Within-stand - TINR 1994-97, Including 99% Confidence Limits.

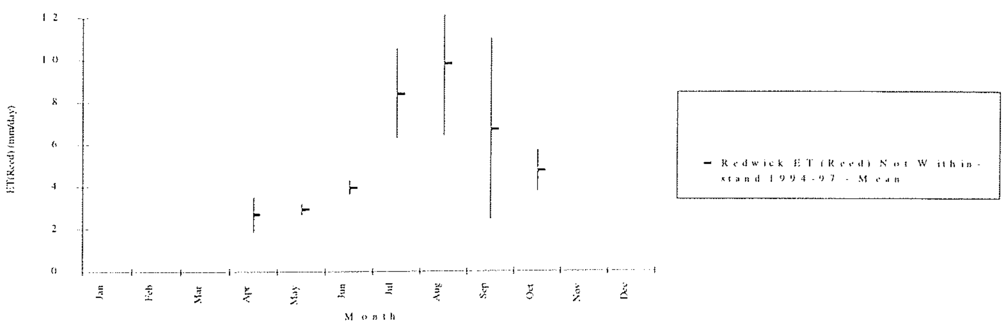

Figure 6.6c Mean Monthly ET(Reed) Not Within-stand - Redwick 1994-95, Including 99% Confidence Limits.

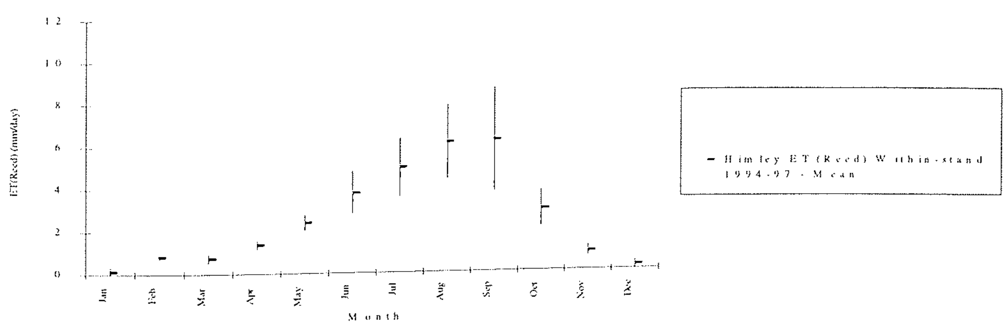

Figure 6.6d Mean Monthly ET(Reed) Within-stand - Himley 1996-97, Including 99% Confidence Limits.

E(Phyto) Within-stand	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1993	na	na	na	na	1.42	3.17	1.03	3.13	3.17	1.71	na	na
1994	na	na	na	na	2.67	3.39	2.30	2.58	2.19	na	na	na
1995	na	na	na	2.33	1.98	2.94	2.63	2.18	2.67	1.46	na	na
1996	na	na	na	1.79	2.61	2.91	1.97	2.39	1.03	1.09	0.87	0.59
1997	0.23	1.37	1.20	na	na	na	na	na	na	na	na	na
E(Phyto) Not Within-stand	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1993	na	na	na	na	2.52	3.27	1.84	3.37	2.58	0.54	na	na
1994	na	na	na	na	3.03	3.75	3.17	4.88	1.83	na	na	na
1995	na	na	na	2.22	2.88	3.40	3.92	3.41	3.59	1.80	na	na
1996	na	na	na	1.86	2.69	3.82	3.49	3.05	1.91	1.07	0.66	0.84
1997	0.17	1.17	1.50	na	na	na	na	na	na	na	na	na

Table 6.4 Monthly E(Phyto) Rates Recorded on the TINR (mm/day).

Chapter 7. REFERENCE CROP EVAPOTRANSPIRATION.

7.1 INTRODUCTION.

Section 4.4 presents a description of various methods of calculating Reference Crop Evapotranspiration (ETo), all of which require the measurement of meteorological data from a representative meteorological station. The choice of method used to calculate ETo is often dependant on the type of climatic data available. In the UK, several institutes and agencies keep climatic records (e.g. the Meteorological Office and the Environment Agency). Outside the UK, climatic records may be available from a range of national and local agencies: e.g. irrigation departments or agricultural research stations (Smith, 1990).

Section 7.2 presents the meteorological data available for each of the experimental sites, which is used in the calculation of the various forms of ETo (see Section 7.3). In Section 7.4 a statistical analysis of the variation between each of the developed ETo's is undertaken, with the inter-site variation in ETo considered in Section 7.5. Section 7.6 discusses the ETo rates calculated for 1995 with respect to other monitoring data years, with the work summarised in Section 7.7.

7.2 METEOROLOGICAL DATA.

7.2.1 INTRODUCTION.

Every opportunity was taken to collect accurate meteorological data for each of the experimental sites within the constraints of the research project: e.g. limited financial budgets. The meteorological parameters that were available from the TINR, Redwick and Himley are detailed below, and summarised in Tables 7.1 to 7.3. The meteorological data used by the Meteorological Office in the calculation of MORECS Grass for each of the relevant Squares (see Section 7.3.1) was also purchased, and is presented in Tables 7.4 to 7.6.

7.2.2 TINR

Meteorological data for the TINR is obtained from a Didcot Automatic Weather Station, located at NGR NZ 5080 2338, approximately 200 m East of the site boundary, with a US Class A Evaporation Pan installed adjacent to the weather station in November 1992. The weather station data is produced in the form of an hourly report which is compiled into a daily report. The output includes direct measurement of: solar radiation, net solar radiation, air/wet temperature, wind speed, wind direction, sunshine hours, rainfall, precipitation, and calculation of relative humidity and Penman and Penman-Montieth PE. A discussion of each meteorological variable is included in EHC (1991).

The values of Penman and Penman-Montieth PE calculated by the Didcot Station were extremely sensitive to the loss/inaccuracies of any of the meteorological parameters and were consistently very low when compared to Eo and Epan measurements. Isaard (1993) stated that the Didcot Station calculated PE using an adaptation of the Penman-Montieth equation developed for use by the Forestry Commission and was not applicable outside of coniferous plantations. Thus, the Didcot Station PE data is not used in this research project.

7.2.3 REDWICK.

Minimal meteorological data was available from the site at Redwick, primarily because a suitable, secure area could not be identified within the environs of the site for establishing a local meteorological station. Daily rainfall totals are logged at Redwick village. A US Class A pan was installed adjacent to the phytometers in October 1993, with data available from April to September 1994.

7.2.4 HIMLEY STW.

In March 1995, a raingauge and a US Class A pan were installed within a vegetated flat landscaped area at Himley STW. A Stevenson Screen was added in June 1995, facilitating the measurement of maximum and minimum temperature, and air/wet temperature. In 1996, attempts were made to supplement the collection of meteorological data with measurements of relative humidity and windspeed, however, these efforts were unsuccessful due to equipment failure and the limited financial resources available.

Due to the paucity of meteorological data recorded at Himley an alternative source was required. Data was made available by Wolverhampton University (Besenyei, 1996) from their meteorological station located at Compton (NGR 8884 9890), approximately 8 km to the north of the site at Himley.

Table 7.3 contains rainfall and evaporation data recorded at Himley STW, with the remaining parameters recorded at Compton.

7.2.5 COMPARISON BETWEEN SITE SPECIFIC AND MORECS SQUARE METEOROLOGICAL DATA.

Direct comparison of the annual variation between site specific and MORECS meteorological data is possible for the TINR (MORECS Square no. 80) between 1995 and 1997, and for Himley for 1996/97 (MORECS Square no. 125) (see Table 7.7).

The site specific data recorded on the TINR exhibits very similar temperatures to those published by MORECS, with a variation in annual mean of 0.2 °C. Annual mean values for sunshine hours are approximately 1.1 hrs/day higher from the site specific records than from MORECS, with mean annual wind speed logged approximately 45% higher within the MORECS Square than on the TINR. These variations between the site specific and MORECS data are a reflection of the inclusion of higher altitude, non-coastal areas located within Square no. 80, from which the MORECS data is averaged. This produces lower sunshine hours, and higher wind speeds than those recorded at the TINR which is located on the estuarine floodplain of the River Tees. Hough (1997) stated that it is probable that a site specific MORECS calculation for the TINR would have produced a slightly higher value for ETo MORECS than was calculated for Square no. 80

TINR 1993	Units	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann.
Temp.	°C	5.0	5.3	6.3	8.1	9.9	13.4	14.7	13.7	11.9	7.7	4.1	4.4	**8.7**
R.H.	%	85.3	86.7	70.0	75.2	75.2	74.9	70.8	72.7	76.4	76.2	74.2	72.9	**75.9**
Wind Speed	km/day	492	311	346	311	320	233	268	225	268	190	199	346	**292**
Sun Hours	hrs/day	0.67	1.62	5.25	5.79	7.79	9.80	9.00	8.40	5.50	2.80	0.90	0.30	**4.82**
Rainfall	mm/day	1.08	0.00	0.79	2.95	2.74	1.22	1.35	2.87	3.15	2.13	2.32	1.61	**1.85**
Epan	mm/day	0.77	0.39	1.52	2.07	2.71	2.93	2.61	2.71	2.10	0.68	0.40	0.00	**1.57**
TINR 1994	**Units**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Ann.**
Temp.	°C	4.9	2.6	7.0	7.8	9.3	14.1	16.6	14.8	11.8	9.3	9.1	5.7	**9.4**
R.H.	%	72.0	75.9	68.0	78.0	82.0	70.0	80.6	85.5	****	****	****	****	********
Wind Speed	km/day	393	273	475	363	311	294	188	245	285	276	268	354	**310**
Sun Hours	hrs/day	0.92	2.13	5.60	8.00	9.10	10.30	9.90	7.71	5.00	2.83	0.96	0.13	**5.22**
Rainfall	mm/day	2.10	1.61	0.68	1.40	1.16	0.75	0.53	1.33	2.37	2.26	2.00	2.60	**1.57**
Epan	mm/day	0.16	0.82	1.71	2.27	3.19	4.13	2.65	3.06	2.37	1.00	0.57	0.40	**1.86**
TINR 1995	**Units**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Ann.**
Temp.	°C	3.9	6.0	4.9	7.9	10.7	12.1	16.9	16.7	12.6	12.5	7.6	2.5	**9.5**
R.H.	%	****	****	****	****	****	****	****	****	****	****	****	****	********
Wind Speed	km/day	389	380	311	337	268	264	229	233	302	259	251	251	**290**
Sun Hours	hrs/day	0.37	2.44	5.48	7.80	9.55	9.24	10.00	8.04	5.59	4.14	1.29	0.13	**5.34**
Rainfall	mm/day	1.94	0.79	0.71	1.03	0.74	0.43	0.90	0.39	3.53	0.71	2.90	1.71	**1.32**
Epan	mm/day	0.65	0.07	1.39	2.36	2.30	3.02	2.91	2.48	2.02	1.04	0.8	0.23	**1.61**

Table 7.1 Local Meteorological Data - TINR 1993-97.

TINR 1996	Units	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann.
Temp.	°C	4.5	2.5	3.7	8.2	8.8	13.2	15.5	15.9	12.5	11.0	4.1	3.3	**8.6**
R.H.	%	****	****	****	****	****	****	****	****	****	****	****	****	****
Wind Speed	km/day	351	301	175	272	272	251	199	143	???	???	???	242	****
Sun Hours	hrs/day	0.32	2.34	2.29	7.05	8.82	9.76	9.41	8.77	5.08	3.67	1.15	0.14	**4.90**
Rainfall	mm/day	0.71	1.32	0.65	0.73	1.45	1.43	0.58	4.06	0.40	0.84	2.06	1.58	**1.32**
Epan	mm/day	0.29	0.14	0.84	1.68	2.68	3.75	3.07	3.29	1.89	0.72	0.11	0.26	**1.56**
TINR 1997	**Units**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Ann.**
Temp.	°C	2.6	7.3	7.9	na	na	na	na	na	na	na	na	na	****
R.H.	%	****	****	****	na	na	na	na	na	na	na	na	na	****
Wind Speed	km/day	166	580	285	na	na	na	na	na	na	na	na	na	****
Sun Hours	hrs/day	0.82	2.81	6.05	na	na	na	na	na	na	na	na	na	****
Rainfall	mm/day	1.14	2.55	0.37	na	na	na	na	na	na	na	na	na	****
Epan	mm/day	0.18	1.09	1.44	na	na	na	na	na	na	na	na	na	****

Table 7.1 (cont.) Local Meteorological Data - TINR 1993-97.

Redwick 1994	Units	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann.
Rainfall	mm/day	na	na	na	1.79	2.79	1.10	1.19	2.62	3.02	2.77	3.23	4.87	****
Epan	mm/day	na	na	na	3.03	2.81	2.80	2.60	2.86	1.54	na	na	na	****

Table 7.2 Local Meteorological Data - Redwick 1994.

Himley 1995	Units	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann.
Temp.	°C	4.1	5.9	6.1	9.4	12.0	14.5	19.0	19.5	13.7	12.5	7.5	2.5	**10.6**
R.H.	%	65.0	66.0	67.0	64.0	59.0	56.0	64.0	57.0	72.0	75.0	83.0	78.0	**61.2**
Wind Speed	km/day	97	135	112	92	80	78	96	103	285	77	55	103	**109**
Sun Hours	hrs/day	1.50	2.90	4.10	6.50	6.40	7.00	8.10	8.90	6.00	3.60	2.10	1.40	**4.88**
Rainfall	mm/day	na	na	na	0.57	1.09	0.54	0.73	0.25	2.18	1.16	na	na	****
Epan	mm/day	na	na	na	2.33	2.84	3.50	4.57	4.68	1.47	0.68	na	na	****
Himley 1996	**Units**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Ann.**
Temp.	°C	4.3	2.3	4.3	8.6	9.5	14.9	16.9	17.2	19.5	11.4	5.6	4.1	**9.9**
R.H.	%	80.3	75.8	70.9	61.2	57.6	58.7	59.7	59.3	62.7	75.4	73.1	80.1	**67.9**
Wind Speed	km/day	217	94	166	83	109	48	41	35	96	61	65	115	**94**
Sun Hours	hrs/day	0.51	2.42	1.44	3.86	5.81	8.37	7.90	6.05	3.62	2.90	2.93	0.64	**3.87**
Rainfall	mm/day	na	na	na	1.73	1.53	1.32	0.83	2.18	0.47	2.10	2.59	1.48	****
Epan	mm/day	na	na	na	1.55	2.41	3.42	3.39	2.51	1.99	1.01	0.2	-0.1	****
Himley 1997	**Units**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Ann.**
Temp.	°C	1.4	5.9	7.6	na	na	na	na	na	na	na	na	na	****
R.H.	%	81.4	76.2	69.1	na	na	na	na	na	na	na	na	na	****
Wind Speed	km/day	101	302	139	na	na	na	na	na	na	na	na	na	****
Sun Hours	hrs/day	1.03	2.90	4.10	na	na	na	na	na	na	na	na	na	****
Rainfall	mm/day	0.42	2.4	0.64	na	na	na	na	na	na	na	na	na	****
Epan	mm/day	0.05	0.29	0.88	na	na	na	na	na	na	na	na	na	****

Table 7.3 Local Meteorological Data - Himley 1995-97.

TINR 1994	Units	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann.
Temp.	°C	na	na	na	na	8.7	13.4	16.2	14.5	11.6	9.3	9.1	5.6	****
V.P.	MB	na	na	na	na	8.6	10.9	13.9	12.4	11.0	9.6	10.1	7.6	****
Wind Speed	km/day	na	na	na	na	450	396	240	332	387	347	354	418	****
Sun Hours	hrs/day	na	na	na	na	5.64	7.57	6.50	5.39	3.60	3.32	1.93	1.91	****
Rainfall	mm/day	na	na	na	na	0.83	0.85	1.19	1.87	2.18	1.68	2.17	2.16	****
TINR 1995	**Units**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Ann.**
Temp.	°C	3.7	5.9	4.6	7.5	10.3	11.9	16.2	16.5	12.6	12.4	7.6	2.7	**9.3**
V.P.	MB	6.6	7.1	6.3	7.8	9.1	10.6	14.1	13.9	12.1	11.3	9.2	6.4	**9.5**
Wind Speed	km/day	493	504	437	442	339	435	318	320	358	413	398	453	**409**
Sun Hours	hrs/day	2.06	3.58	4.56	4.84	6.28	5.74	6.40	8.53	4.17	3.99	1.47	0.94	**4.38**
Rainfall	mm/day	2.57	1.67	1.25	1.11	1.30	1.00	0.69	0.28	3.37	0.69	3.35	2.45	**1.64**

Table 7.4 MORECS Meteorological Data for Square 80 - TINR.

TINR 1996	Units	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann.
Temp.	°C	4.3	2.9	4.0	7.7	8.2	13.1	14.9	15.2	12.6	10.7	5.1	3.1	**8.5**
V.P.	MB	7.5	6.1	6.7	7.9	7.8	10.6	12.2	13.1	11.0	10.2	7.3	6.4	**8.9**
Wind Speed	km/day	573	491	493	333	392	288	282	285	322	378	400	346	**382**
Sun Hours	hrs/day	0.35	2.88	0.98	3.73	6.14	7.22	5.87	6.86	3.53	3.54	2.57	0.98	**3.72**
Rainfall	mm/day	0.84	2.28	0.78	1.27	1.26	1.08	0.91	2.07	0.61	1.38	2.50	2.34	**1.44**
TINR 1997	**Units**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Ann.**
Temp.	°C	3.0	6.1	7.4	na	na	na	na	na	na	na	na	na	****
V.P.	MB	6.5	7.2	7.8	na	na	na	na	na	na	na	na	na	****
Wind Speed	km/day	251	536	395	na	na	na	na	na	na	na	na	na	****
Sun Hours	hrs/day	1.75	3.45	4.99	na	na	na	na	na	na	na	na	na	****
Rainfall	mm/day	0.46	2.03	0.52	na	na	na	na	na	na	na	na	na	****

Table 7.4 (cont.) MORECS Meteorological Data for Square 80 - TINR.

Redwick 1994	Units	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann.
Temp.	°C	na	na	na	8.3	11.4	14.6	18.3	16.3	13.1	10.9	na	na	****
V.P.	MB	na	na	na	8.0	9.6	11.7	14.3	13.3	11.9	10.4	na	na	****
Wind Speed	km/day	na	na	na	403	283	368	251	283	284	251	na	na	****
Sun Hours	hrs/day	na	na	na	5.55	4.26	8.00	7.73	5.49	3.72	4.83	na	na	****
Rainfall	mm/day	na	na	na	2.09	2.56	0.87	1.22	2.36	3.36	3.34	na	na	****
Redwick 1995	**Units**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Ann.**
Temp.	°C	na	na	na	na	na	na	18.7	20.6	13.9	13.7	na	na	****
V.P.	MB	na	na	na	na	na	na	15.6	13.9	12.3	12.4	na	na	****
Wind Speed	km/day	na	na	na	na	na	na	302	221	248	272	na	na	****
Sun Hours	hrs/day	na	na	na	na	na	na	7.34	9.58	4.75	3.61	na	na	****
Rainfall	mm/day	na	na	na	na	na	na	0.48	0.23	4.17	2.44	na	na	****

Table 7.5 MORECS Meteorological Data for Square 157 - Redwick.

Himley 1995	Units	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann.
Temp.	°C	na	na	na	8.6	11.3	13.9	18.3	18.7	12.9	12.1	na	na	****
V.P.	MB	na	na	na	8.0	9.1	10.5	14.0	13.2	11.8	11.7	na	na	****
Wind Speed	km/day	na	na	na	355	315	318	304	266	286	331	na	na	****
Sun Hours	hrs/day	na	na	na	6.19	6.36	7.13	7.88	8.84	4.14	4.44	na	na	****
Rainfall	mm/day	na	na	na	0.50	1.44	0.41	1.01	0.34	2.80	1.27	na	na	****
Himley 1996	**Units**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Ann.**
Temp.	°C	na	na	na	7.9	8.7	14.0	16.2	16.1	13.2	5.2	5.2	5.2	****
V.P.	MB	na	na	na	8.1	8.1	11.0	12.7	13.2	11.0	7.7	7.7	7.7	****
Wind Speed	km/day	na	na	na	294	363	254	270	285	315	352	352	352	****
Sun Hours	hrs/day	na	na	na	3.98	5.47	8.77	7.43	5.92	4.41	2.73	2.73	1.58	****
Rainfall	mm/day	na	na	na	1.65	1.39	1.15	1.03	1.90	0.42	1.97	2.47	1.38	****
Himley 1996	**Units**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Ann.**
Temp.	°C	1.8	6.5	8.1	na	na	na	na	na	na	na	na	na	****
V.P.	MB	6.2	7.6	8.3	na	na	na	na	na	na	na	na	na	****
Wind Speed	km/day	197	526	360	na	na	na	na	na	na	na	na	na	****
Sun Hours	hrs/day	1.05	2.68	4.49	na	na	na	na	na	na	na	na	na	****
Rainfall	mm/day	0.40	2.00	0.64	na	na	na	na	na	na	na	na	na	****

Table 7.6 MORECS Meteorological Data for Square 125 - Himley.

Site	Period	Parameter	Units	Data Source	
				Local	MORECS
TINR	1995-96	Temp. Sun Hours Wind Speed	°C hrs/day km/day	9.1 5.12 271	8.9 4.05 400
Himley	1996-97	Temp. Sun Hours Wind Speed	°C hrs/day km/day	10.2 4.18 100	9.0 4.27 327

Table 7.7 Comparison Between Mean Annual Meteorological Data from both Local and MORECS Sources.

Comparison between the mean monthly meteorological data available for Himley with the MORECS data for Square no. 125, again produces variations. Himley has a mean monthly temperature approximately 1.2 °C higher than that averaged for MORECS, however, there was minimal variation in the recorded sunshine hours. The major variation was exhibited between the recorded wind speeds, with that logged for the MORECS Square three times higher than that recorded for Himley.

As previously stated there is no site specific meteorological data available for Redwick to allow comparison with the MORECS data.

A sensitivity analysis was undertaken using the data presented in Table 7.7 within the CROPWAT program. This analysis (see Appendix 6) shows only minimal variation in ETo is produced by the interchange of the majority of the meteorological parameters between Local and MORECS sources. However, the ETo value was sensitive to the large variation in wind speeds recorded from Local and MORECS sources, with a variation of up to -15.2% noted when substituting the Local (Compton) wind speed data within the MORECS Square data for Himley. Wind speed experiences the greatest spatial variation, and of all the recorded parameters it was the one most subject to erroneous measurement and equipment failure.

The comparisons between local and MORECS meteorological data have highlighted the importance of site specific measurements, particularly in areas where the MORECS Square is not representative of the creation site. However, MORECS data may be useful in identifying erroneous local data, and may provide an adequate substitute in these circumstances. MORECS data may be used within a feasibility study to provide initial meteorological data, which may be more representative if 'site-specific' MORECS data is purchased.

7.3 DEVELOPED FORMS OF ETo.

7.3.1 INTRODUCTION.

The meteorological data presented in Section 7.2 was used in the calculation of ETo Pan and ETo CROPWAT. ETo Pan data was available for the sites at TINR and Himley throughout the experimental period, however, ETo Pan was only available for Redwick between April and September 1994. ETo CROPWAT for the TINR was calculated using data from the weather station, whilst at Himley the ETo CROPWAT was calculated using data from the Compton Meteorological Station. No ETo CROPWAT was calculated for Redwick due to the lack of site specific meteorological data.

The development of ETo MORECS has previously been discussed in Section 4.4.3.4. ETo MORECS (Eo and PE Grass) data was purchased from the Meteorological Office, for Cleveland/Durham (Square no.80), South Staffordshire/West Midlands (Square no.157), and South-east Wales/Avon (Square no.125) (see Figure 4.2), to provide representative ETo MORECS values for the experimental sites at TINR, Redwick, and Himley respectively.

The availability of the various forms of ETo for each of the experimental sites is presented in Table 7.8, with monthly values of ETo presented for each of the experimental sites in Tables 7.9 to 7.11.

Site	Year	ETo Pan	ETo CROPWAT	ETo MORECS
TINR	1993	Yes	Yes	No
	1994	Yes	Yes	Yes
	1995	Yes	Yes	Yes
	1996	Yes	Yes	Yes
	1997	Yes	Yes	Yes
Redwick	1994	Yes	No	Yes
	1995	No	No	Yes
Himley	1995	Yes	Yes#	Yes
	1996	Yes	Yes#	Yes
	1997	Yes	Yes#	Yes

 # = Calculated using Compton Meteorological Data.

Table 7.8 ETo Availability for each Experimental Site

Year	ETo	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1993	ETo Pan	0.62	0.31	1.22	1.66	2.17	2.34	2.09	2.17	1.68	0.54	0.32	0.00
	ETo CROPWAT	0.60	0.60	1.50	1.90	2.50	3.20	3.10	2.80	1.80	1.00	0.70	0.80
	ETo MORECS Grass	na	na	na	na	na	na	na	na	na	na	na	na
	ETo MORECS Eo	na	na	na	na	na	na	na	na	na	na	na	na
1994	ETo Pan	0.13	0.66	1.37	1.82	2.55	3.30	2.12	2.45	1.90	0.80	0.46	0.32
	ETo CROPWAT	1.00	0.80	1.80	1.90	2.30	3.60	3.30	2.40	1.30	0.70	0.40	0.80
	ETo MORECS Grass	0.54	0.54	1.70	2.05	2.44	3.26	2.87	2.47	1.67	1.03	0.60	0.55
	ETo MORECS Eo	0.32	0.59	1.87	2.66	3.17	4.24	3.73	3.21	2.00	0.93	0.36	0.22
1995	ETo Pan	0.52	0.06	1.11	1.89	1.84	2.42	2.33	1.98	1.62	0.83	0.64	0.18
	ETo CROPWAT	0.80	0.80	1.50	1.90	2.60	3.20	3.60	3.00	2.00	1.20	0.90	0.80
	ETo MORECS Grass	0.56	0.97	1.47	1.88	2.95	2.74	3.13	3.15	1.82	1.81	0.66	0.57
	ETo MORECS Eo	0.34	1.05	1.62	2.44	3.83	3.56	4.07	4.09	2.18	1.63	0.40	0.23
1996	ETo Pan	0.23	0.11	0.67	1.34	2.14	3.00	2.46	2.63	1.51	0.58	0.09	0.21
	ETo CROPWAT	0.70	0.60	1.10	1.80	2.40	3.30	3.40	2.80	1.90	1.30	0.90	0.80
	ETo MORECS Grass	0.48	0.72	0.86	1.74	2.81	3.16	2.99	2.73	1.82	1.38	0.86	0.51
	ETo MORECS Eo	0.29	0.79	0.95	2.26	3.65	4.11	3.89	3.55	2.18	1.24	0.52	0.20
1997	ETo Pan	0.14	0.87	1.15	na	na	na	na	na	na	na	na	na
	ETo CROPWAT	0.40	1.00	1.60	na	na	na	na	na	na	na	na	na
	ETo MORECS Grass	0.31	1.07	1.50	na	na	na	na	na	na	na	na	na
	ETo MORECS Eo	0.19	1.18	1.65	na	na	na	na	na	na	na	na	na

Table 7.9 TINR - Calculated ETo 1993-97 (mm/day)

Year	ETo	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1994	ETo Pan	na	na	na	2.42	2.25	2.24	2.08	2.29	1.23	na	na	na
	ETo CROPWAT	na	na	na	na	na	na	na	na	na	na	na	na
	ETo MORECS Grass	0.67	0.66	1.51	2.20	2.52	3.38	3.56	2.63	1.80	1.08	0.67	0.62
	ETo MORECS Eo	0.40	0.73	1.66	2.86	3.15	4.40	4.63	3.41	2.16	0.98	0.40	0.25
1995	ETo Pan	na	na	na	na	na	na	na	na	na	na	na	na
	ETo CROPWAT	na	na	na	na	na	na	na	na	na	na	na	na
	ETo MORECS Grass	0.67	0.85	1.64	1.99	3.02	3.44	3.56	3.97	1.96	1.60	na	na
	ETo MORECS Eo	0.40	0.93	1.80	2.59	3.78	4.48	4.63	5.16	2.36	1.44	na	na

Table 7.10 Redwick - Calculated ETo 1994-95 (mm/day)

Year	ETo	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1995	ETo Pan	na	na	na	1.86	2.27	2.80	3.66	3.74	1.18	0.54	na	na
	ETo CROPWAT	0.40	0.70	1.10	1.90	2.60	3.10	3.50	3.30	2.30	0.80	0.30	0.30
	ETo MORECS Grass	na	na	na	2.07	3.14	3.39	3.90	3.85	1.89	1.54	0.57	0.28
	ETo MORECS Eo	na	na	na	2.69	3.92	4.41	5.07	5.01	2.27	1.39	0.34	0.11
1996	ETo Pan	na	na	na	1.24	1.93	2.74	2.71	2.01	1.59	0.81	0.16	-0.06
	ETo CROPWAT	0.50	0.50	1.00	1.60	2.50	3.10	3.10	2.40	1.90	0.90	0.30	0.30
	ETo MORECS Grass	0.40	0.69	0.86	1.81	2.69	3.32	3.38	2.98	2.00	1.29	0.71	0.35
	ETo MORECS Eo	0.24	0.75	0.94	2.35	3.37	4.32	4.39	3.87	2.40	1.16	0.43	0.14
1997	ETo Pan	0.05	0.23	0.70	na	na	na	na	na	na	na	na	na
	ETo CROPWAT	0.20	0.80	1.20	na	na	na	na	na	na	na	na	na
	ETo MORECS Grass	0.27	1.09	1.45	na	na	na	na	na	na	na	na	na
	ETo MORECS Eo	0.16	1.20	1.59	na	na	na	na	na	na	na	na	na

Table 7.11 Himley - Calculated ETo 1995-97 (mm/day)

7.3.2 ETo DATA ANOMALIES.

The ETo Pan data recorded on the TINR in July and August 1995 is somewhat anomalous, being appreciably lower than the equivalent months in 1996. The accidental use of slightly saline water to replace evaporative losses from the pan in late June may have reduced the value of ETo Pan recorded in July and August 1995. The pan water was changed in early September 1995.

The negative value of ETo Pan calculated for Himley during December 1996 was possibly due to sublimation of water onto the almost permanently frozen pan water. Alternatively, the negative ETo Pan may be a result of a higher proportion of the monthly precipitation entering the pan than was recorded by the raingauge.

The ETo Pan data from the TINR and Redwick sites in 1994 is displayed in Figure 7.1. The ETo Pan recorded on the TINR gradually rises from a low point in April to reach a peak value of 3.30 mm/day in June, gradually reducing through the remainder of the summer period, whilst, the ETo Pan data recorded at Redwick exhibits a peak rate of 2.42 mm/day in April, and subsequently varies only slightly throughout the summer. The ETo Pan data recorded in Redwick appears somewhat anomalous, particularly when compared to the ETo MORECS Eo data determined for the same period (see Table 7.10). It is possible that the ETo Pan data recorded at Redwick was reduced by the 'sheltering effect' of the crop growth (0.6 m high) in the field immediately adjacent the pan.

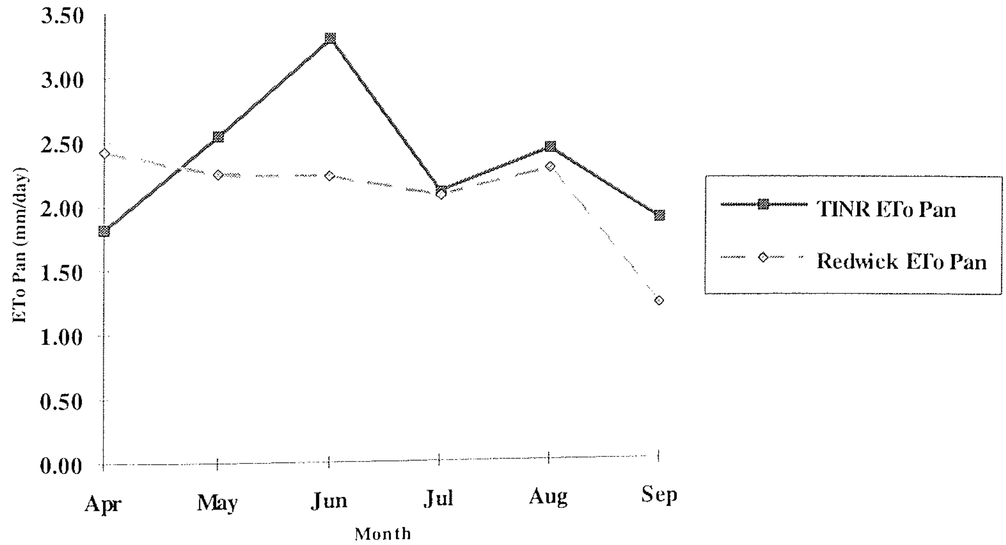

Figure 7.1 ETo Pan Data - TINR and Redwick Growing Season 1994

7.4 RELATIONSHIP BETWEEN THE VARIOUS FORMS OF ETo.

Any analysis of a relationship between the various forms of ETo requires the availability of a large data set, preferably with continuous data available through a period of years. A complete data set of all forms of ETo is available for the TINR for 1994-96 (see Table 7.9), whilst, at Himley (see Table 7.11), all of the various forms of ETo are available for only one complete annual cycle (1996-97). At Redwick, the calculated ETo data is incomplete, and what data there are is only available for one year (see Table 7.10). The result of the relative paucity of ETo data available for the experimental sites at Redwick and to a lesser extent Himley, is that the majority of data analysis that is undertaken within this research is focused on the experimental site at the TINR.

Tables 7.12 and 7.13 respectively present the annual and growing season (April to October inclusive) rates of the various forms of ETo on the TINR (1994-96). Both rates show a distinct ranking trend, with ETo Pan the lowest, followed in increasing rate order by ETo MORECS Grass, ETo CROPWAT, and ETo MORECS Eo.

	ETo Pan (mm/day)	ETo CROPWAT (mm/day)	ETo MORECS Grass (mm/day)	ETo MORECS Eo (mm/day)
TINR 94	1.49	1.69	1.64	1.94
TINR 95	1.28	1.86	1.81	2.12
TINR 96	1.25	1.75	1.67	1.79

Table 7.12 Mean Annual Rate for Various ETo on the TINR.

	ETo Pan (mm/day)	ETo CROPWAT (mm/day)	ETo MORECS Grass (mm/day)	ETo MORECS Eo (mm/day)
TINR 94	2.13	2.21	2.26	2.85
TINR 95	1.84	2.50	2.50	3.11
TINR 96	1.95	2.41	2.38	2.98

Table 7.13 Mean Growing Season Rate for Various ETo on the TINR.

Figure 7.2 presents the mean monthly ETo values calculated for the TINR. The various ETo rates show similar trends throughout the year, peaking during June and July, and at their lowest between December and February, reflecting the overriding importance of solar radiation and temperature to the calculated values.

Figure 7.2 also displays the relationship between the various forms of ETo. An assessment of this relationship can be undertaken using the coefficient of correlation. There are different measures of correlation but the most generally used is the Pearson product-moment coefficient of correlation, commonly symbolised as r (Harper, 1977). The Coefficient of Determination (r^2) developed between ETo Pan and ETo CROPWAT (e.g. TINR, 1993, $r^2 = 0.86$), is a measure of the proportion of total variation that can be explained by the regression equation (Owen and Jones, 1983). When $r^2 = 0.86$, we can conclude that 86% of the variation between ETo Pan and ETo CROPWAT can be explained by the regression equation, leaving only 14% to be explained by other factors (e.g. impact on CROPWAT calculation of crop factors).

Table 7.14 presents values for r and r^2 developed between each of the forms of ETo available for each experimental site for: the annual period; the growing season (Apr-Oct); and dormant period (Nov-Mar). For the majority of individual site years the r and r^2 values exhibit a strong positive correlation between all forms of ETo in both the annual period and growing season. The positive correlation's presented for the dormant period are slightly weaker than for the annual/growing period reflecting the greater influence of distortion factors inherent particularly within the measurement of ETo Pan. The relatively weak positive correlation presented for Redwick (ETo Pan: ETo MORECS Eo) is a reflection of the anomalous pan data previously discussed in Section 7.3.2.

The very strong positive correlation between ETo CROPWAT and ETo MORECS Eo for all sites is to be expected, as both forms of ETo have the Penman-Montieth equation as the basis for their calculation. The strong positive correlation evident between the various forms of ETo allows the meaningful computation of regression equations, permitting the calculation of the various forms of ETo from a single ETo. The general equation for any straight line on a graph is:

$$y = a + bx \qquad (7.1)$$

where a (intercept) and b (slope) are constants. Table 7.14 also presents the slope and intercept values calculated with respect to the various ETo regression equations.

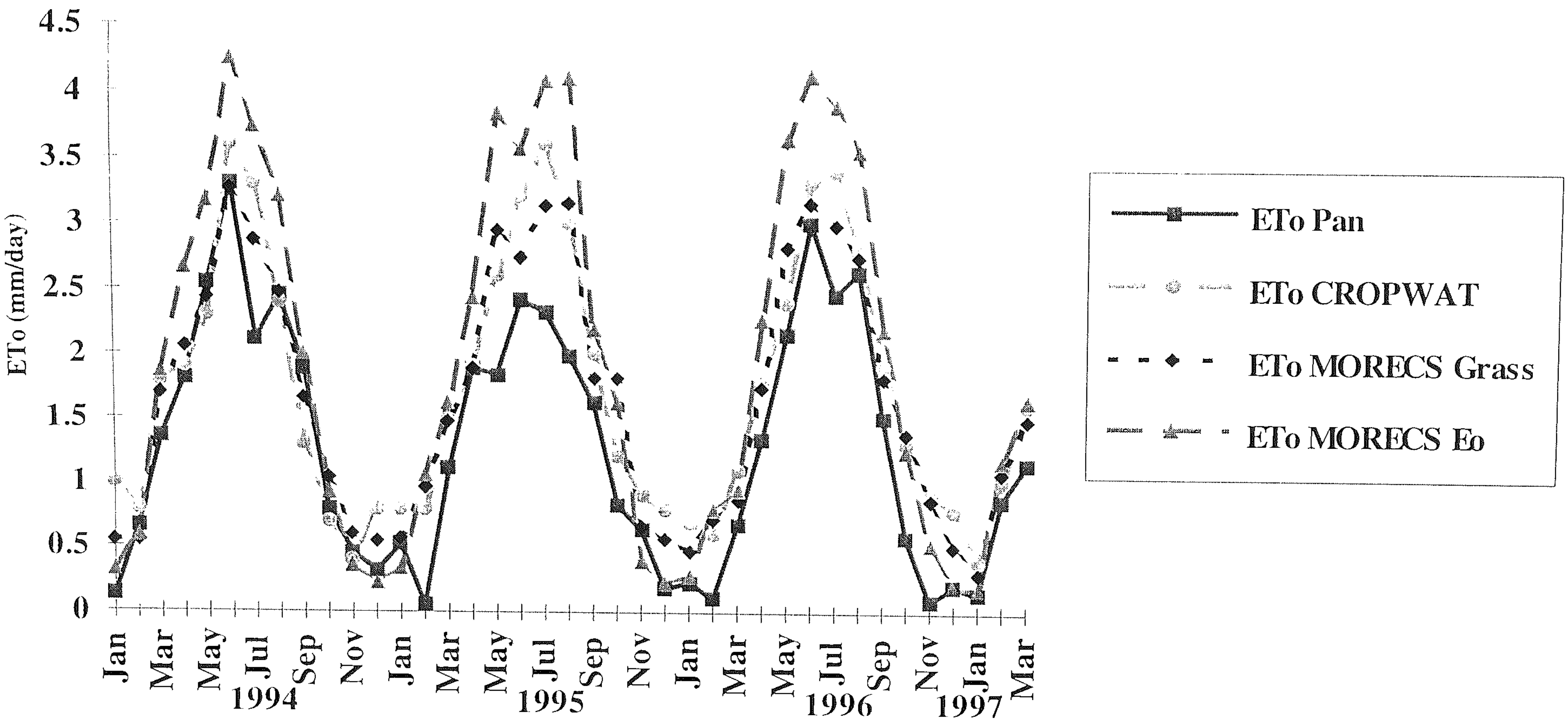

Figure 7.2 Monthly ETo Values - TINR 1994-97

Site	Correlation Parameters	Growing Season					Dormant Period					Annual				
		Year	Pearson Coeff.		Regression Eq.		Year	Pearson Coeff.		Regression Eq.		Year	Pearson Coeff.		Regression Eq.	
			r	r^2	Inter	Slope		r	r^2	Inter	Slope		r	r^2	Inter	Slope
TINR	EToPan:EToCROPWAT	**1993**	0.93	0.86	0.15	0.71	**1993/94**	0.83	0.69	-0.54	1.01	**1993**	0.95	0.91	-0.15	0.82
	EToPan:EToCROPWAT	**1994**	0.84	0.72	0.73	0.63	**1994/95**	0.72	0.52	-0.12	0.71	**1994**	0.89	0.79	0.02	0.87
	EToPan:EToCROPWAT	**1995**	0.90	0.82	0.43	0.56	**1995/96**	0.89	0.80	-0.65	1.24	**1995**	0.95	0.90	-0.14	0.77
	EToPan:EToCROPWAT	**1996**	0.94	0.89	-0.48	0.94	**1996/97**	0.83	0.70	-0.39	0.94	**1996**	0.98	0.96	-0.57	1.04
	EToPan:EToCROPWAT	**1993-96**	0.84	0.71	0.31	0.69	**1993-97**	0.75	0.57	-0.28	0.83	**1994-97**	0.92	0.85	-0.21	0.88
Himley	EToPan:EToCROPWAT	**1995**	0.92	0.85	-0.67	1.18	**1995/96**	na	na	na	na	**1995**	na	na	na	na
	EToPan:EToCROPWAT	**1996**	0.99	0.98	-0.09	0.88	**1996/97**	0.92	0.84	-0.14	0.63	**1996**	na	na	na	na
	EToPan:EToCROPWAT	**1995-96**	0.93	0.87	-0.44	1.07	**1995-97**	0.92	0.84	-0.14	0.63	**1996-97**	0.99	0.98	-0.25	0.94
TINR	EToPan:EToMORECS (Eo)	**1993**	na	na	na	na	**1993/94**	na	na	na	na	**1993**	na	na	na	na
	EToPan:EToMORECS (Eo)	**1994**	0.91	0.83	0.33	0.63	**1994/95**	0.54	0.29	0.24	0.35	**1994**	0.97	0.94	0.16	0.68
	EToPan:EToMORECS (Eo)	**1995**	0.80	0.64	0.55	0.42	**1995/96**	0.33	0.11	0.22	0.28	**1995**	0.91	0.84	0.20	0.51
	EToPan:EToMORECS (Eo)	**1996**	0.97	0.94	-0.30	0.76	**1996/97**	0.96	0.92	-0.05	0.73	**1996**	0.98	0.96	-0.14	0.71
	EToPan:EToMORECS (Eo)	**1994-96**	0.86	0.74	0.21	0.59	**1994-97**	0.74	0.54	0.12	0.48	**1994-97**	0.94	0.89	0.07	0.63

NB. Growing Season (1st April - 31st October), Dormant Period (1st November - 31st March)

Table 7.14 Pearson Correlation Coefficients Developed Between Forms of ETo

Site	Correlation Parameters	Growing Season					Dormant Period					Annual				
		Year	Pearson Coeff.		Regression Eq.		Year	Pearson Coeff.		Regression Eq.		Year	Pearson Coeff.		Regression Eq.	
			r	r^2	Inter	Slope		r	r^2	Inter	Slope		r	r^2	Inter	Slope
Himley	EToPan:EToMORECS (Eo)	1995	0.98	0.97	-0.62	0.82	1995/96	na	na	na	na	1995	na	na	na	na
	EToPan:EToMORECS (Eo)	1996	0.97	0.94	0.05	0.58	1996/97	0.91	0.83	-0.07	0.40	1996	na	na	na	na
	EToPan:EToMORECS (Eo)	1995-96	0.96	0.93	-0.36	0.73	1996-97	0.91	0.83	-0.07	0.40	1996-97	0.98	0.96	-0.16	0.63
Redwick	EToPan:EToMORECS (Eo)	1994	0.49	0.24	1.31	0.22	1994/95	na	na	na	na	1994	na	na	na	na
TINR	EToCROPWAT:EToMORECS (Eo)	1993	na	na	na	na	1993/94	na	na	na	na	1993	na	na	na	na
	EToCROPWAT:EToMORECS (Eo)	1994	0.98	0.96	-0.38	0.91	1994/95	0.81	0.66	0.47	0.54	1994	0.96	0.92	0.35	0.69
	EToCROPWAT:EToMORECS (Eo)	1995	0.93	0.86	0.09	0.77	1995/96	0.34	0.12	0.71	0.21	1995	0.96	0.92	0.45	0.66
	EToCROPWAT:EToMORECS (Eo)	1996	0.95	0.90	0.35	0.69	1996/97	0.90	0.81	0.49	0.61	1996	0.97	0.95	0.45	0.66
	EToCROPWAT:EToMORECS (Eo)	1993-96	0.95	0.90	0.00	0.80	1994-97	0.82	0.67	0.53	0.51	1994-97	0.96	0.93	0.40	0.68
Himley	EToCROPWAT:EToMORECS (Eo)	1995	0.95	0.90	0.30	0.62	1995/96	0.82	0.67	0.20	0.66	1995	na	na	na	na
	EToCROPWAT:EToMORECS (Eo)	1996	0.98	0.96	0.16	0.66	1996/97	0.98	0.96	0.11	0.64	1996	0.99	0.98	0.19	0.65
	EToCROPWAT:EToMORECS (Eo)	1995-96	0.96	0.93	0.23	0.64	1995-97	0.92	0.85	0.17	0.62	1996-97	0.99	0.98	0.10	0.67

NB. Growing Season (1st April - 31st October), Dormant Period (1st November - 31st March)

Table 7.14 (cont.) Pearson Correlation Coefficients Developed Between Forms of ETo

7.5 INTER-SITE VARIATION IN ETo.

A selection of inter-site comparisons between ETo's was undertaken, and are discussed below. There is only one period in which a single form of ETo data (ETo MORECS) is available for all three experimental locations. Other comparisons are undertaken but do not include all sites.

ETo MORECS Grass and ETo MORECS Eo data exhibit similar trends for all three experimental sites for the 1995 growing season, with the mean ETo MORECS Grass rate recorded for the TINR Square being 13% lower than that recorded for the Himley and Redwick Squares.

ETo MORECS Eo and ETo Pan are both available for direct comparison between the TINR and Redwick during the 1994 growing season. However, as previously discussed in Section 7.3.3 the ETo Pan data recorded at Redwick in 1994 was anomalous and as such is not discussed. The ETo MORECS Grass and Eo rates recorded for Redwick and the TINR in 1994 show similar trends. The mean growing season rate recorded for Redwick is approximately 8% higher than that calculated for the TINR.

Table 7.15 contains the mean ETo rates calculated for TINR and Himley between April 1996 - March 1997, for the growing season, the dormant period, and the annual period, facilitating an inter-site comparison between the various forms of ETo calculated for these periods. The ranking between each form of ETo for the annual and growing season on the TINR is the same as previously identified in Section 7.4. However, the Himley ETo data for the same periods shows a slight variation, with ETo CROPWAT calculated as less than ETo MORECS Grass. This feature may be a result of the use of inaccurate wind speed data recorded for Himley (see Section 7.2.2) within the ETo CROPWAT calculation, producing low values for ETo CROPWAT. ETo Pan rates recorded on the TINR are higher than those noted at Himley, particularly during the dormant period, however, the ETo MORECS Grass and ETo MORECS Eo rates are lower on the TINR than at Himley, with the greatest variation evident during the growing season. This may be a function of the MORECS data for Square no. 80 not being wholly representative of the TINR site, or anomalies in the recorded pan data (see Section 7.2.2).

SITE	ETo	Annual (Apr-Mar)	Growing Season (Apr-Oct)	Dormant Period (Nov-Mar)
TINR	ETo Pan	1.33	1.95	0.49
	ETo CROPWAT	1.73	2.41	0.94
	ETo MORECS Grass	1.74	2.37	0.85
	ETo MORECS Eo	2.05	2.98	0.75
Himley	ETo Pan	1.17	1.86	0.22
	ETo CROPWAT	1.51	2.23	0.56
	ETo MORECS Grass	1.76	2.50	0.77
	ETo MORECS Eo	2.10	3.12	0.70

Table 7.15 Mean ETo Rates for the TINR And Himley (mm/day) (April 1996-March 1997).

7.6 ETo 1995 - AN EXTREME YEAR ?

The majority of the ETo forms calculated for each of the experimental sites exhibit mean monthly rates higher during the growing season of 1995 than in other years. At Himley, the mean ETo Pan data recorded for the growing season of 1995 (2.29 mm/day) is considerably higher than that recorded in 1996 (1.88 mm/day). The mean ETo MORECS Grass and ETo MORECS Eo rates recorded for the 1995 growing season for Square no. 80 (TINR) were 2.50 mm/day and 3.11 mm/day respectively, approximately 11% higher than the mean values for the 1994 and 1996 growing season. Similar higher mean 1995 growing season rates for ETo MORECS Grass and ETo MORECS Eo were recorded for Square no. 125 (Himley), 13% higher, and Square no. 157 (Redwick), 14% higher.

The higher mean growing season rates of ETo recorded in 1995, were predominantly a function of a very high ETo rate recorded during August. The ETo MORECS Grass values calculated in August 1995 for the TINR, Himley, and Redwick Squares were respectively 27%, 29% and 51% higher than the values recorded for the same month during other years of the monitoring period.

A detailed analysis of the possible extreme nature of the ETo values calculated during the 1995 growing season, and specifically August 1995, would require access to long-term (30 year) continuous monthly climatic data for each of the sites' respective MORECS Squares. Financial restrictions prohibited the purchase of this data, however, it would appear that the ETo rates calculated for the 1995 growing season are higher than the norm and that August 1995 was quite extreme, with the variation from the mean ETo values greatest at Redwick and smallest on the TINR.

7.7 DISCUSSION AND SUMMARY.

Smith (1990) recommended that where possible the ETo should be calculated using the Penman-Montieth equation. However, he recognised the need for continued use of evaporation pan data, stating that pans provide a low technology alternative to estimation techniques such as that developed by Penman (1948). During this project access to accurate, site specific/local meteorological data was available at the TINR and at Himley. This allowed the calculation of an ETo rate based upon the Penman-Montieth equation (ETo CROPWAT) and upon evaporation pan data (ETo Pan) for these experimental sites. The availability within the UK of MORECS data allowed ETo values based upon the Penman-Montieth equation to be purchased for the Squares containing each of the experimental sites. The MORECS data provided an ETo for the Redwick site where the recording of only minimal site specific meteorological data precluded the calculation of an ETo by any other method.

The monthly ETo rates displayed in Figure 7.2 show that the ETo Pan data is consistently slightly lower than the majority of the other forms of ETo. This could be interpreted to be a function of the use of an inappropriate pan coefficient. Indeed, if the mean annual rates of ETo Pan displayed in Table 7.12 had not been adjusted by the application of a factor of 0.8 they would have very similar values to those of ETo CROPWAT and ETo MORECS Grass. However, the use of the highest pan coefficient presented by Doorenbos and Pruitt (1977) (Kp = 0.85 - see Table 4.6) would still produce ETo Pan values lower than those provided by all other forms of ETo. It is more likely that the lower rate of ETo Pan is a function of the anomalies identified in Section 7.3.2 and the fact that measurements and adjustments were undertaken on a monthly basis.

Initially the Meteorological Office erroneously supplied MORECS data for Square no.87 which is adjacent to the Southeast corner of Square no. 80 (TINR). Comparison of these data sets produced a mean value of ETo MORECS Grass 8% higher for Square no.80, primarily due to the higher proportion of high ground in Square no.87. This demonstrates the importance of ensuring representative meteorological data is used in the calculation of ETo. Any Kc(Reed) values developed using MORECS data are only as accurate as the variation between the mean Square data and site specific data allows.

The various forms of ETo showed a variation between the calculated mean annual rates of up to 46%, thus, the chosen form of ETo will greatly affect the value of the developed Kc(Reed). Analysis showed that the majority of the various forms of ETo were strongly positively correlated with respect to each other, allowing the development of regression equations. The ETo rates were generally higher at Redwick than at either the TINR or Himley, with the ETo data calculated for August 1995 somewhat extreme, particularly at Redwick.

In summary;

1) Evaporation pan data provides a low technology, site specific form of ETo, with the advantage that any developed Kc(Reed) will be applicable in any areas where pan data is available, potentially worldwide. However, during this project ETo Pan data was subject to distortions produced by various characteristics: pan siting; use of inappropriate pan water; monitoring frequency etc. This may limit the accuracy of any Kc(Reed) developed using the ETo Pan data presented in this thesis.

2) CROPWAT provides a method for the calculation of a site specific ETo rates based upon the Penman-Montieth equation. In common with all estimation techniques, the calculated ETo CROPWAT is dependent on the availability and accuracy of the input meteorological data.

3) MORECS provides a 'tried and tested' calculation method based on the Penman-Montieth equation which can provide an ETo where no other form of ETo can be calculated. However, ETo MORECS data is only valid if the chosen Square is representative of the identified design area. In addition, any Kc(Reed) developed from ETo MORECS is precluded from precise application in areas where MORECS data is unavailable (e.g. outside of the UK). However, Kc(Reed) values developed using ETo MORECS may be applied to ETo data generated using slight variations on the Penman-Montieth equation to provide a moderately accurate prediction of ET(Reed).

All forms of ETo are included throughout the remainder of this thesis as the use of a single ETo in the development of Kc(Reed) would limit its future application.

Chapter 8. ANALYSIS OF ET(Reed) RESULTS.

8.1 INTRODUCTION.

This chapter reports the analysis and subsequent discussion of the ET(Reed) results displayed in Table 6.2. The presentation of this chapter is similar to that of the previous chapter, with some of the sections mirroring the analysis and form of discussion undertaken with respect to the development of an ETo. This will allow the reader to appreciate the parallel development of ETo and ET(Reed) which will be used to calculate the Kc(Reed) values presented in Chapter Nine.

Table 8.1 presents a summary of ET(Reed), ETo MORECS Grass, and rainfall for the period between April 1996 to March 1997. It is apparent that the annual totals of ET(Reed) are considerably higher than the annual ETo values, and that rainfall was insufficient to balance the measured ET(Reed). Table 8.1 provides additional confirmation of the importance of ET(Reed) within reedbed water budgets.

Site	ET(Reed) (mm)	ETo MORECS Grass (mm)	Rainfall (mm)
TINR	777	635	523
Himley	932	649	538

Table 8.1 ET(Reed), ETo MORECS Grass, and Rainfall Data from TINR and Himley (April 1996 - March 1997).

Section 8.2 provides a general overview and discussion of the seasonal variations experienced in the ET(Reed) results recorded during this research project. A general evaluation and discussion of the various factors which affect ET(Reed) is undertaken in Sections 8.3 (climate) and 8.4 (crop characteristics). In Section 8.5, the ET(Reed) results obtained during this research project are discussed with respect to the findings of other researchers working on *Phragmites australis*, with a summary included in Section 8.6.

8.2 SEASONAL VARIATION IN ET(Reed).

The majority of the ET(Reed) data which is available for analysis has been recorded from the experimental site at the TINR. As a result, the TINR data is used as the primary source for analysis and discussion of ET(Reed).

Figure 8.1 displays the monthly ET(Reed) recorded from within-stand phytometers located on the TINR between 1993 and 1997. The ET(Reed) shows a marked rise between the rates recorded in May and June, with peak ET(Reed) measured between June and August. Following the peak, the ET(Reed) rate declines slowly through the autumn period. When compared with the ETo data presented in Figure 7.2, it is apparent that the resultant shape of the displayed data are similar, however, the ET(Reed) peaks later in the season, and declines more slowly during the autumn. This feature is most apparent in the ET(Reed) data recorded at Himley during 1996/97 (see Figure 8.2), when the peak rate was recorded during August/September. The variation between the ET(Reed) and ETo rates impacts greatly on the developed Kc(Reed) values (see Chapter Nine).

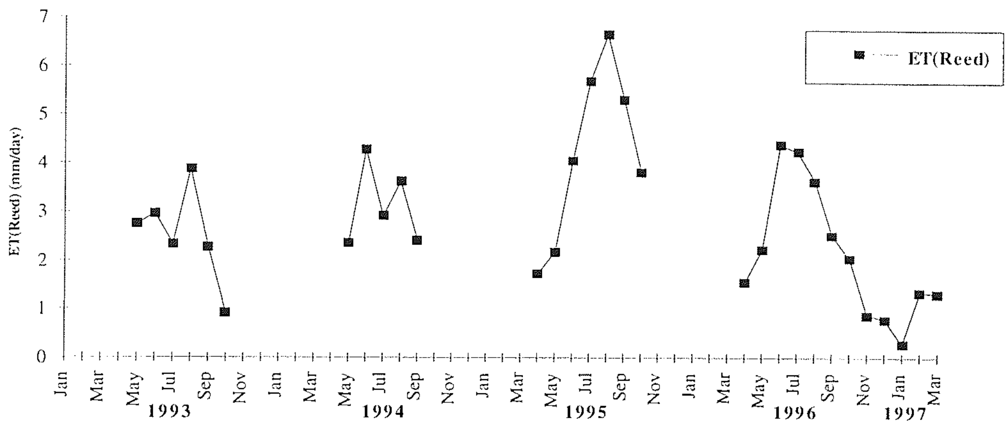

Figure 8.1 Monthly ET(Reed) Recorded on the TINR, 1993-97.

During the TINR site visits in July and August 1995, and July 1996, many of the phytometers located both within-stand and not within-stand had little or no surface water remaining within them. The rhizomatous sediment was observed to be partially desiccated at the surface, with the sediment saturated at a depth of 200 mm. It was not possible to assess the time period over which these conditions had existed, although it was unlikely to be greater than 2 to 3 days. The lack of a surface water component within the phytometer will effectively replace the evaporation from the crop-covered water surface with evaporation from a crop-covered soil surface. As the soil surface becomes partially desiccated the water losses from the phytometer, which are embodied within the ET(Reed) rates displayed in Table 6.2, are likely to exist at a level slightly below the 'potential' rate. During the mid-summer period, when the reed crop is fully developed, the divergence from the 'potential' rate is probably minimal as evaporation from the water surface is low compared to the transpiration component of a 'fully-supplied' crop. However, it is possible that the ET(Reed) rates recorded from the phytometers on the TINR during these three months are slightly lower than the actual ET(Reed) which was experienced by the 'wet' reedbed. As the divergence from the 'potential' rate was likely to be minimal, and existed for a very short time period, the results from these phytometers were included within the calculation of mean monthly ET(Reed).

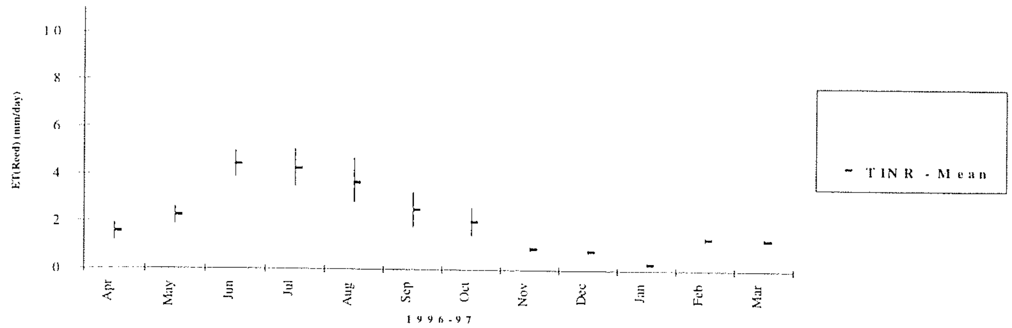

Figure 8.2a ET(Reed) Within-stand Recorded at TINR, 1996-97, Including 99% Confidence Limits.

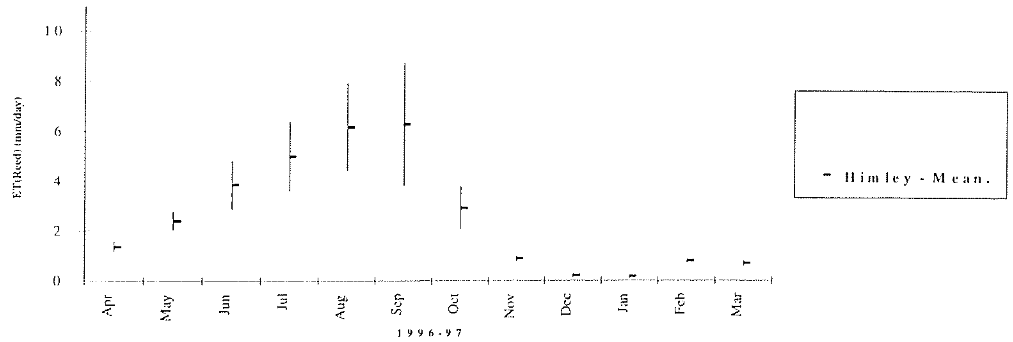

Figure 8.2b ET(Reed) Within-stand Recorded at Himley, 1996-97, Including 99% Confidence Limits.

8.3 CLIMATIC INFLUENCE ON ET(Reed).

8.3.1 INTRODUCTION.

Section 8.2 briefly outlined the seasonal variations which occurred in the recorded ET(Reed) data. Section 8.3 undertakes a detailed analysis of the influence of climate on ET(Reed), examining both inter-site and intra-site variations, and the somewhat extreme data recorded during 1995.

8.3.2 INTER-SITE VARIATION IN ET(Reed).

In the development of a Kc(Reed) it is necessary to undertake measurement of ET(Reed) and the calculation of ETo for the same periods. As such this section mirrors the presentation and analysis undertaken in Section 7.5. However, because of the smaller data set of ET(Reed) results, this section primarily discusses the inter-site variation in the recorded ET(Reed) rates during two periods when data is available for two of the experimental sites.

The ET(Reed) data recorded from within-stand phytometers located at the TINR and Himley provides a meaningful inter-site comparison, particularly as the phytometers at each site have similar mean crop characteristics (see Section 8.4.3). Only the data recorded at these sites during 1996-97 is used, thus removing any distortions which might otherwise be produced from the poor establishment of reeds at Himley in 1995. The monthly ET(Reed) rates recorded at the TINR and at Himley between April 1996 and March 1997 are displayed in Figure 8.2. In general, the rates recorded at Himley show a far greater seasonal variation than those recorded at the TINR. There is minimal difference in the ET(Reed) recorded at the two sites in Spring and early Summer, however, during July, August and particularly September the ET(Reed) rate recorded at Himley is considerably higher. In contrast, during the dormant period, lower ET(Reed) rates were recorded at Himley than on the TINR. This was particularly apparent between December and February. The mean annual ET(Reed) rate recorded between April 1996 and March 1997 at Himley (2.55 mm/day) was almost 20% higher than that recorded for the same period on the TINR (2.13 mm/day).

Figure 8.3 shows that the not within-stand ET(Reed) rate recorded from Redwick is much higher than that recorded on the TINR. In 1994, the ET(Reed) at Redwick was 27% higher than that for the TINR, with the rate recorded in the four month period between July and October 1995, approximately 74% higher at Redwick.

The inter-site variation in ET(Reed) is primarily influenced by: climatological variations; crop characteristics; and phytometer location. These factors are discussed in the remainder of this chapter and also in Chapter Nine, to explain the ET(Reed) variations noted above.

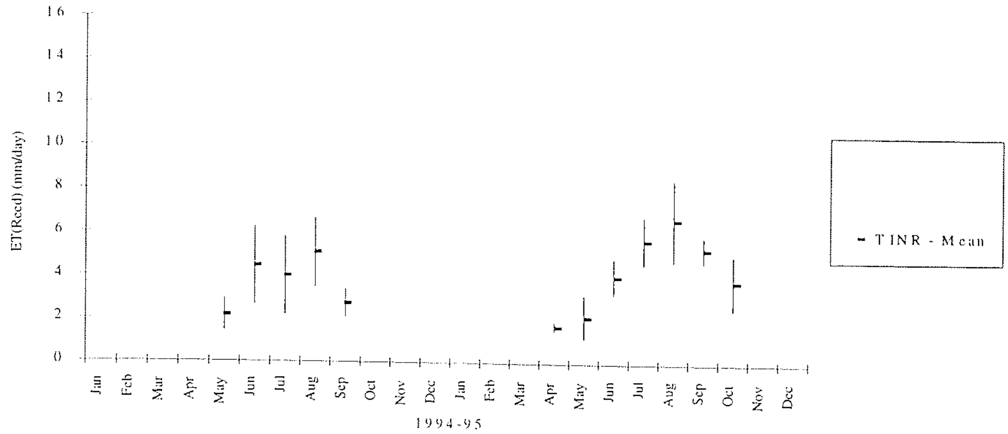

Figure 8.3a ET(Reed) Not Within-stand, TINR, 1994-95, Including 99% Confidence Limits.

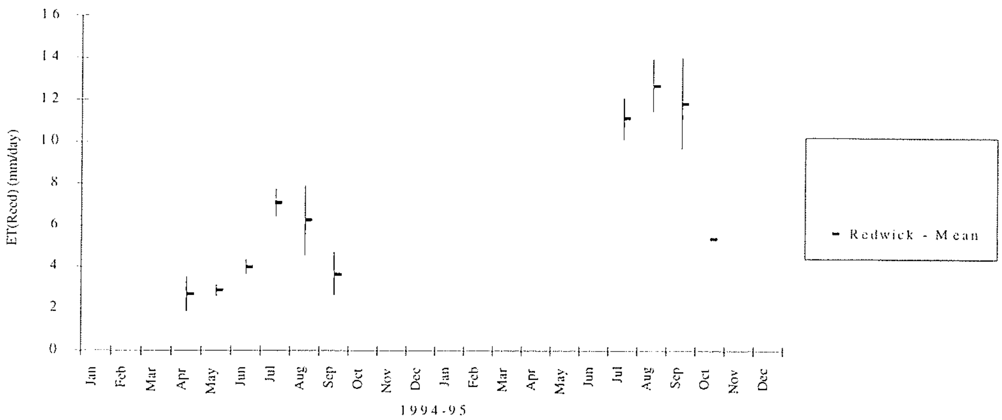

Figure 8.3b ET(Reed) Not Within-stand, Redwick, 1994-95, Including 99% Confidence Limits.

8.3.3 INTRA-SITE VARIATION IN ET(Reed).

The location of phytometers both within-stand and not within-stand has allowed the development of a theme presented by other researchers (e.g. Bernatowicz et al, 1976), that the ET(Reed) rates are dependant on the location of the experimental apparatus. The ET(Reed) rates recorded reflect the variation in micro-climatic conditions experienced within a reedbed stand. Bernatowicz et al (1976) summarised the variation in the micro-climatic conditions which exist within a reedbed stand when compared to not within-stand as: lower wind velocities (reducing air exchange); higher air humidity; lower air temperatures; and weaker solar irradiance. All of these variations contribute to a lower ET(Reed) rate recorded from within-stand.

Figure 8.4 displays the ET(Reed) recorded for both within-stand and not within-stand phytometers on the TINR. An analysis of the variation shown in Figure 8.4 has been undertaken to ascertain the influence of phytometer siting (micro-climate) on ET(Reed). Both the ET(Reed) from within-stand and not within-stand are very similar in April and May, however, during June a divergence is apparent with the higher ET(Reed) rate recorded from not within-stand. This divergence increases through the summer to a maximum in October. Between November and February the ET(Reed) rate is greater from within-stand.

The measurement of ET(Reed) from both within-stand and not within-stand has allowed the development of a set of monthly linear coefficients which are applicable to mean monthly ET(Reed) rates calculated from not within-stand phytometers (see Table 8.2). This enables an adjusted within-stand figure for ET(Reed) to be determined from not within-stand data. The mean monthly coefficient developed for Spring and early Summer is approximately 1.00, whilst the coefficient applicable to not within-stand data for the remainder of the summer and early autumn is approximately 0.77. The mean coefficient value for the dormant period is 1.46. The development of mean monthly coefficients applicable to not within-stand ET(Reed) rates may be useful if, like at Redwick, no reedbed stand is available for the siting of a set of phytometers to aid the design of a reedbed. This adjusted value may be particularly useful in areas where limited ETo data is available.

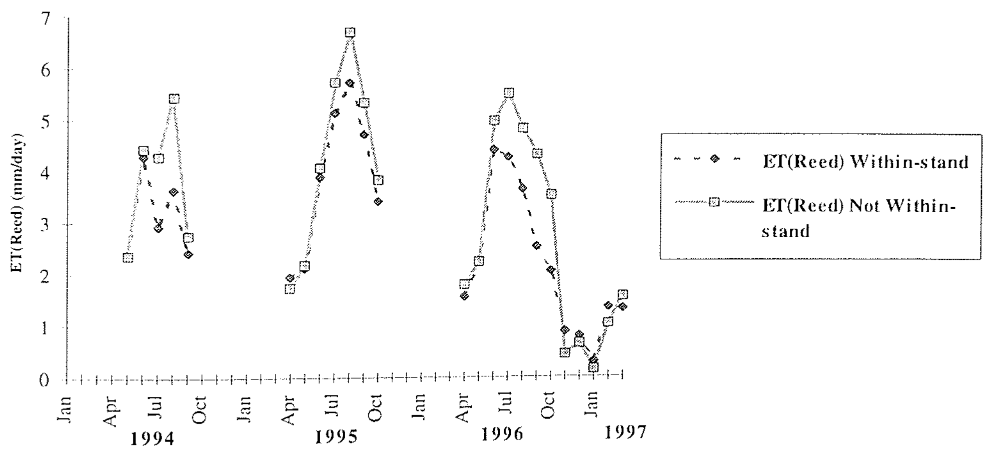

Figure 8.4 Monthly ET(Reed) Recorded from both Within-stand and Not Within-stand Phytometers, TINR, 1994-97.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1994	na	na	na	na	1.00	0.97	0.68	0.67	0.88	na	na	na
1995	na	na	na	1.12	0.96	0.96	0.90	0.85	0.89	0.90	na	na
1996	na	na	na	0.87	1.01	0.89	0.78	0.76	0.59	0.58	2.06	1.27
1997	1.81	1.32	0.85	na	na	na	na	na	na	na	na	na
Mean	1.81	1.32	0.85	0.99	0.99	0.94	0.79	0.76	0.79	0.74	2.06	1.27

Table 8.2 Coefficient Developed for Application to ET(Reed) Not Within-stand, to Convert to ET(Reed) Within-stand (Using TINR 1994-97 data).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1994	na	na	na	2.67	2.93	3.76	5.81	4.91	2.92	na	na	na
1995	na	na	na	na	na	na	7.57	10.21	7.82	3.56	na	na

Table 8.3 Redwick - Calculated ET(Reed) Within-stand Data (mm/day) (using coefficients presented in Table 8.2).

The greater ET(Reed) recorded from not within-stand phytometers during the summer months is a response of the standing crop being more exposed to the parameters which drive ET(Reed) e.g. higher irradiance, and wind speeds, producing a 'clothes-line' effect. The majority of not within-stand phytometers were also located within a terrestrial environment, and act as an 'oasis', experiencing low ambient humidity, again increasing ET(Reed). The not within-stand phytometers also develop a greater standing crop further increasing the ET(Reed) recorded during the growing season (see Section 8.4.3).

The higher ET(Reed) rates recorded from within-stand during the dormant period is probably a function of the dominance of Eo within the ET(Reed) values recorded. Eo from the within-stand phytometers may be increased above the rate recorded from not within-stand as a result of the storage of latent heat in the waterbody encompassing the reedbed stand. The long grass growing immediately adjacent to many of the not within-stand phytometers may also reduce Eo significantly during the dormant period, with the grass having a greater 'sheltering effect' on the phytometer water surface than the decaying reed stems of the reedbed stand.

The application of the mean monthly coefficients presented in Table 8.2 to the not within-stand data recorded in Redwick provides an indication of the ET(Reed) which might be anticipated from phytometers located within-stand at Redwick. The adjusted values for Redwick ET(Reed) within-stand are presented in Table 8.3. The adjusted monthly ET(Reed) values for 1994 remain slightly higher than the equivalent values recorded on the TINR in 1994, whilst the 1995 values are significantly higher than those recorded during the same period on the TINR. The implications of the adjusted ET(Reed) values on the Kc(Reed) are discussed in Section 9.3.6.

An inspection of the total ET(Reed) recorded from individual phytometers at Redwick during 1995 (see Appendix 5), shows that a higher ET(Reed) rate was noted throughout the growing season for Phytometer numbers 2 and 3 (see Figure 6.4). These phytometers are located at the southern end of the experimental area and are exposed to greater irradiance, whilst acting to partially shelter the other planted phytometers from the prevailing wind. Although the Redwick Phytometer numbers 6 and 7 are apparently both exposed to similar micro-climatic conditions, the mean ET(Reed) rate recorded from Phytometer 7 is 17% higher than that recorded from Phytometer 6. It is possible that this is a function of micro-climatic conditions, however, the variation in ET(Reed) is more likely to be a result of a variation in crop characteristics within these phytometers (see Section 8.4).

8.3.4 ET(Reed) 1995 - AN EXTREME YEAR ?

Section 7.5 states that the ETo values developed during the growing season of 1995, and specifically during August 1995 are somewhat extreme. It might be expected that the ET(Reed) data recorded during the same period might also be extreme. The ET(Reed) data from Himley was distorted by poor reed establishment, whilst that recorded at Redwick was from not within-stand phytometers which had very high standing crop values (see Section 8.4). However, the data recorded at the TINR was not subject to any such limitations. The ET(Reed) data recorded on the TINR in 1995 and 1996 (see Table 6.2) are compared to ascertain the impact of the somewhat extreme meteorological conditions experienced.

The mean growing season ET(Reed) recorded on the TINR in 1995 was 3.87 mm/day, compared to 2.98 mm/day recorded in 1996. Only slight variation in the ET(Reed) rate was experienced between the Spring and early Summer values recorded for 1995 and 1996. However, the mean ET(Reed) rate recorded for the period July to October in 1995 was 4.77 mm/day, almost 27% higher than that recorded for the same period in 1996 (3.77 mm/day). The ET(Reed) recorded during August 1995 (5.73 mm/day) showed the greatest variation from the 1996 value (4.29 mm/day), almost 34% higher.

The marked variation in the ET(Reed) rate recorded during 1995 is greater than the variation experienced within the various forms of ETo, and is probably a function of crop characteristics. This phenomena will be reflected in higher Kc(Reed) calculated for 1995.

8.4 INFLUENCE OF CROP CHARACTERISTICS ON ET(Reed).

Many researchers (e.g. Doorenbos and Pruitt, 1977) have attempted to evaluate the effect crop characteristics have on the overall water loss from a given area, indeed this is the basic premise of this research project. An attempt is made in this section to analyse the impact of various growth characteristics of *Phragmites australis* on the recorded rates of ET(Reed).

The crop phenological characteristics which were recorded include crop height (stem length), stem density, number of flowering shoots (inflorescence), and occurrence of other emergent species e.g. *Typha, Juncus* etc. Crop characteristics were recorded during each site visit undertaken between 1995-1997.

Commitments to EHC contractual obligations prevented crop measurements being undertaken in April 1995. A complete crop development record is available for the period between April 1996-March 1997. Crop characteristics were only recorded sporadically during 1994 and are not presented within this thesis. Crop characteristics for the TINR are separately presented for the phytometers located both within-stand and not within-stand. No attempts were made to measure stem diameter or to calculate leaf area index.

Prior to any analysis of the impact of crop phenological characteristics on the measured ET(Reed) a brief description of the recorded crop parameters is presented in each section. Crop height and stem density are presented in Sections 8.4.1 and 8.4.2 respectively. Standing crop data is calculated and discussed in Section 8.4.3, and is used to identify the crop development stages previously discussed in Section 4.3.1. Section 8.4.4 assesses the effect of the occurrence of inflorescence on ET(Reed), whilst Sections 8.4.5 discusses the impact of other emergent species on the recorded evapotranspiration. An assessment of the correlation between crop characteristics and ET(Reed) rates is undertaken in each of the respective sections outlined below.

8.4.1 CROP HEIGHT.

Crop height was measured from the estimated lowest point where the vertical stem protruded above the sediment surface within the phytometer (thus part of the stem that was measured was underwater), to the estimated highest point where the stem terminated at the break of the youngest leaf. Table 8.4 contains the recorded crop height data for the experimental phytometers.

There is a rapid increase in stem length during May, June and early July, with maximum crop height recorded at Himley and TINR during August 1995 (Redwick maximum - October 1995). Crop height decreases only slightly between August and late October, followed by a progressive decrease experienced throughout the dormant period. The mean stem heights recorded within the phytometers on the TINR between 1994 and 1997, and at Himley in 1996 were similar to those of their respective in-situ reedbed.

The mean stem heights were shorter on the TINR than at Himley or Redwick, with heights at Himley during 1996 approximately 30% higher than those recorded from the within-stand phytometers located on the TINR. Mean stem height recorded at Redwick during 1995 was also significantly higher than that recorded on the TINR (not within-stand). It is apparent from the TINR data, that the reeds growing in phytometers located within-stand are taller than those growing not within-stand.

Site	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
TINR (Within-Stand)	1995	na	na	na	na	0.56	0.85	1.07	1.11	1.01	1.01	na	na
TINR (Within-Stand)	1996	na	na	na	0.07	0.40	0.84	0.96	1.09	1.00	1.00	0.87	0.82
TINR (Within-Stand)	1997	0.68	0.64	0.55	na	na	na	na	na	na	na	na	na
TINR (Not Within-Stand)	1995	na	na	na	na	0.50	0.71	1.03	1.05	0.94	0.90	na	na
TINR (Not Within-Stand)	1996	na	na	na	0.08	0.36	0.64	0.84	0.91	0.91	0.88	0.76	0.73
TINR (Not Within-Stand)	1997	0.69	0.59	0.60	na	na	na	na	na	na	na	na	na
Himley (Within-Stand)	1995	na	na	na	na	0.45	0.88	0.99	0.95	1.28	0.89	na	na
Himley (Within-Stand)	1996	na	na	na	0.22	0.44	1.12	1.24	1.40	1.36	1.30	1.18	1.18
Himley (Within-Stand)	1997	0.91	0.78	0.45	na	na	na	na	na	na	na	na	na
Redwick (Not Within-Stand)	1995	na	na	na	na	na	na	1.10	1.16	1.43	1.44	na	na

Table 8.4 Crop Height (m).

	ET:Density (r)	ET:Height (r)	ET:Crop (r)	ET:Inflo. (r)
All Sites (Within-stand)	0.68	0.77	0.85	-0.17
All Sites (Not Within-stand)	0.93	0.93	0.97	0.07
All Sites (All Phytometers)	0.87	0.56	0.93	0.23

Table 8.5 Pearson Product Correlation Coefficients Developed Between Crop Phenological Characteristics : ET(Reed) for August.

Crop height recorded during the 1996 growing season from both within, and not within-stand on the TINR, shows a substantial reduction in height when compared with the equivalent data for 1995. The mean height reduction experienced in 1996 is apparent throughout the growing season, with the greatest reduction experienced from phytometers located not within-stand, in early and mid season. This reduction in overall height may have been a result of the preceding cold winter and spring period.

Table 8.5 shows a weak positive correlation between ET(Reed) : crop height (r = 0.56) when all phytometers from all of the sites are used (see Figure 8.5).

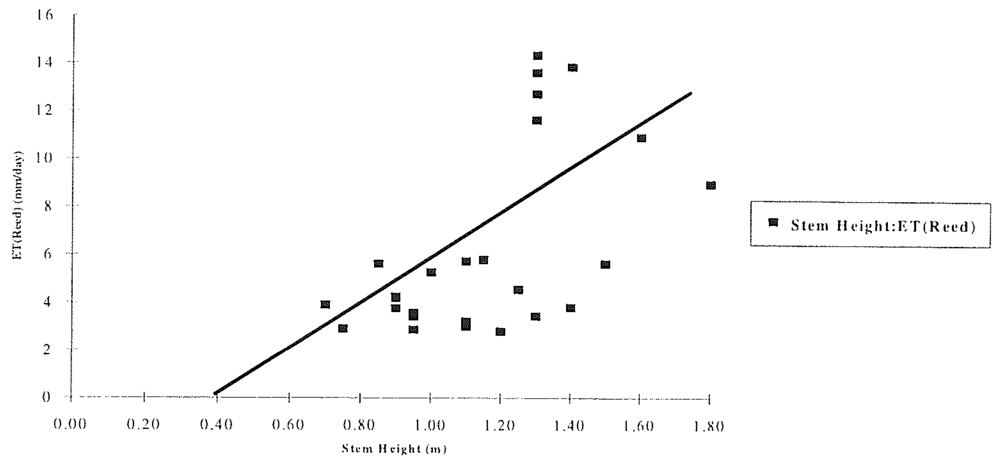

Figure 8.5 ET(Reed) : Stem Height, All Phytometers (August values).

8.4.2 STEM DENSITY.

Stem density is measured directly as the number of individual stems occurring within each planted phytometer. All stems are counted, including the few that remain from previous seasons'. Reed 'stubble' shorter than 250 mm is not included. The stem number recorded is adjusted for the area of each phytometer to provide a crop density (stems/m^2).

The stem density data for all sites (see Table 8.6) exhibits similar seasonal trends to the crop height data, peaking at Himley and TINR in late July/August, following a period of density increase particularly evident during June. Stem density gradually declines between September and March.

Site	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
TINR (Within-Stand)	1995	na	na	na	na	209	370	396	459	451	451	na	na
TINR (Within-Stand)	1996	na	na	na	316	316	420	481	475	445	420	421	431
TINR (Within-Stand)	1997	379	319	226	na	na	na	na	na	na	na	na	na
TINR (Not Within-Stand)	1995	na	na	na	na	399	578	609	663	660	648	na	na
TINR (Not Within-Stand)	1996	na	na	na	514	514	651	743	708	647	619	609	576
TINR (Not Within-Stand)	1997	499	415	329	na	na	na	na	na	na	na	na	na
Himley (Within-Stand)	1995	na	na	na	na	288	379	455	455	455	447	na	na
Himley (Within-Stand)	1996	na	na	na	272	345	418	485	514	480	456	389	353
Himley (Within-Stand)	1997	346	333	283	na	na	na	na	na	na	na	na	na
Redwick (Not Within-Stand)	1995	na	na	na	na	na	na	798	1024	1228	1228	na	na

Table 8.6 Stem Density (stems/m²)

Mean stem densities within phytometers located within-stand on the TINR in 1996 are very similar to the densities recorded at Himley in the same year, with the inter-site variation for the growing season being less than 4%. Therefore any inter-site variation in the ET(Reed) results is unlikely to be a direct function of crop density. At Redwick, the mean stem density was very high, rising from 798 stems/m^2 in July to 1,228 stems/m^2 in September 1995. The mean stem density recorded at Redwick was approximately 2.4 times higher than the mean stem density recorded at both TINR (within-stand) and Himley.

The increase in stem density recorded on the TINR in 1996 may have been a function of the preceding cold winter and spring period, possibly causing damage to the colt shoots, resulting in a greater density of shorter stems.

It is apparent from the TINR data that the phytometers located not within-stand have a greater stem density than those located within-stand. Bernatowicz et al (1976) stated from their research findings that the diurnal temperature fluctuations recorded from within-stand are less extreme than those recorded from an adjacent terrestrial situation. It is possible that the increased stem density recorded from the not within-stand phytometers is a result of lower temperatures damaging the colt stems producing greater stem density and shorter stems.

Figure 8.6 shows a moderately strong positive correlation between ET(Reed) rates and crop density when the data from all phytometers from all sites is used (***r*** = 0.87). The coefficient produced for not within-stand phytometers has a very strong positive correlation (***r*** = 0.93).

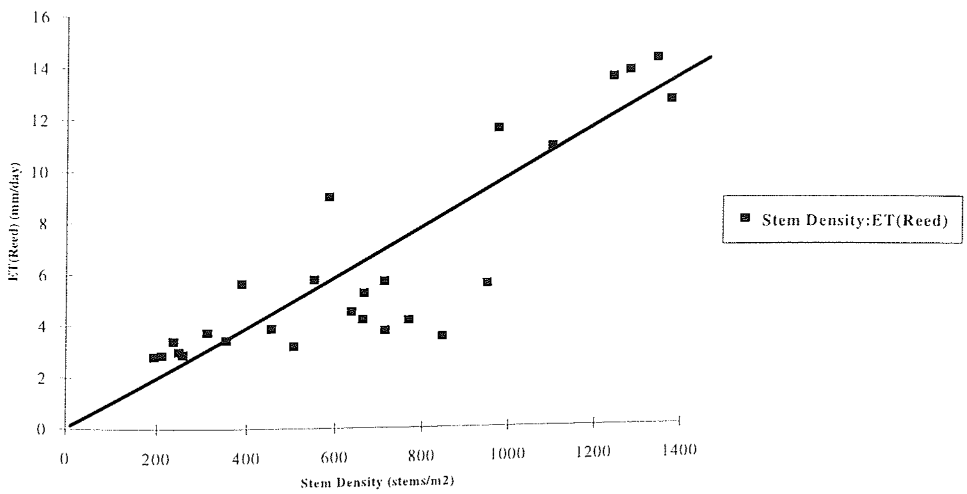

Figure 8.6 ET(Reed) : Stem Density, All Phytometers (August values).

8.4.3 STANDING CROP.

Crop height and density data can be combined as shown in Equation 8.1, to produce a measure of 'Standing Crop' (see Table 8.7).

$$\underset{\text{(height (m) . stems/m}^2\text{)}}{\textbf{Standing Crop}} = \underset{\text{(m)}}{\textbf{Mean Crop Height}} \times \underset{\text{(stem/m}^2\text{)}}{\textbf{Mean Stem Density}} \qquad (8.1)$$

Standing crop data can be used to identify the length of the four stages of crop development presented in Table 4.2. If the highest value of mean standing crop is equivalent to the attainment of maximum standing crop (100%), then this value can be used to calculate the end of crop development stage 1 (when standing crop is > 10% of maximum standing crop) and also the beginning of stage 3 (when standing crop is 75% of maximum standing crop). Crop development stage 2 is the period between the end of stage 1 and the beginning of stage 3, whilst the length of stage 4 is estimated from field observations of the yellowing of leaves (start) and the onset of senescence (end).

Figure 8.7 presents the mean monthly standing crop calculated for within-stand phytometers on the TINR (1995-97) and Himley (1996-97), with the mean standing crop reaching a peak at the end of August. The data for Himley 1995 is ignored for the reasons previously discussed in Section 6.3.4. No early season (April - June) data was recorded for Redwick and thus crop development stages could not be ascertained.

The approximate length of each crop development stage is presented in Table 8.8 and noted on Figure 8.5, including the dormant period measured from senescence to the first appearance of shoots above water level, observed on the TINR and Himley between mid November 1996 and the end of March 1997. The crop development stages identified on Figure 8.7 are further discussed in conjunction with the derived Kc(Reed) values in Section 9.3.

Site	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
TINR (Within-Stand)	1995	na	na	na	na	117	315	424	510	455	455	na	na
TINR (Within-Stand)	1996	na	na	na	22	126	353	462	518	445	420	366	353
TINR (Within-Stand)	1997	258	204	124	na	na	na	na	na	na	na	na	na
TINR (Not Within-Stand)	1995	na	na	na	na	200	410	627	696	620	583	na	na
TINR (Not Within-Stand)	1996	na	na	na	39	185	416	624	644	589	545	463	421
TINR (Not Within-Stand)	1997	344	245	197	na	na	na	na	na	na	na	na	na
Himley (Within-Stand)	1995	na	na	na	na	130	333	450	432	582	398	na	na
Himley (Within-Stand)	1996	na	na	na	60	152	468	601	720	652	593	459	417
Himley (Within-Stand)	1997	315	259	127	na	na	na	na	na	na	na	na	na
Redwick (Not Within-Stand)	1995	na	na	na	na	na	na	878	1188	1757	1769	na	na

Table 8.7 Calculated Standing Crop (Height (m) . stems/m^2)

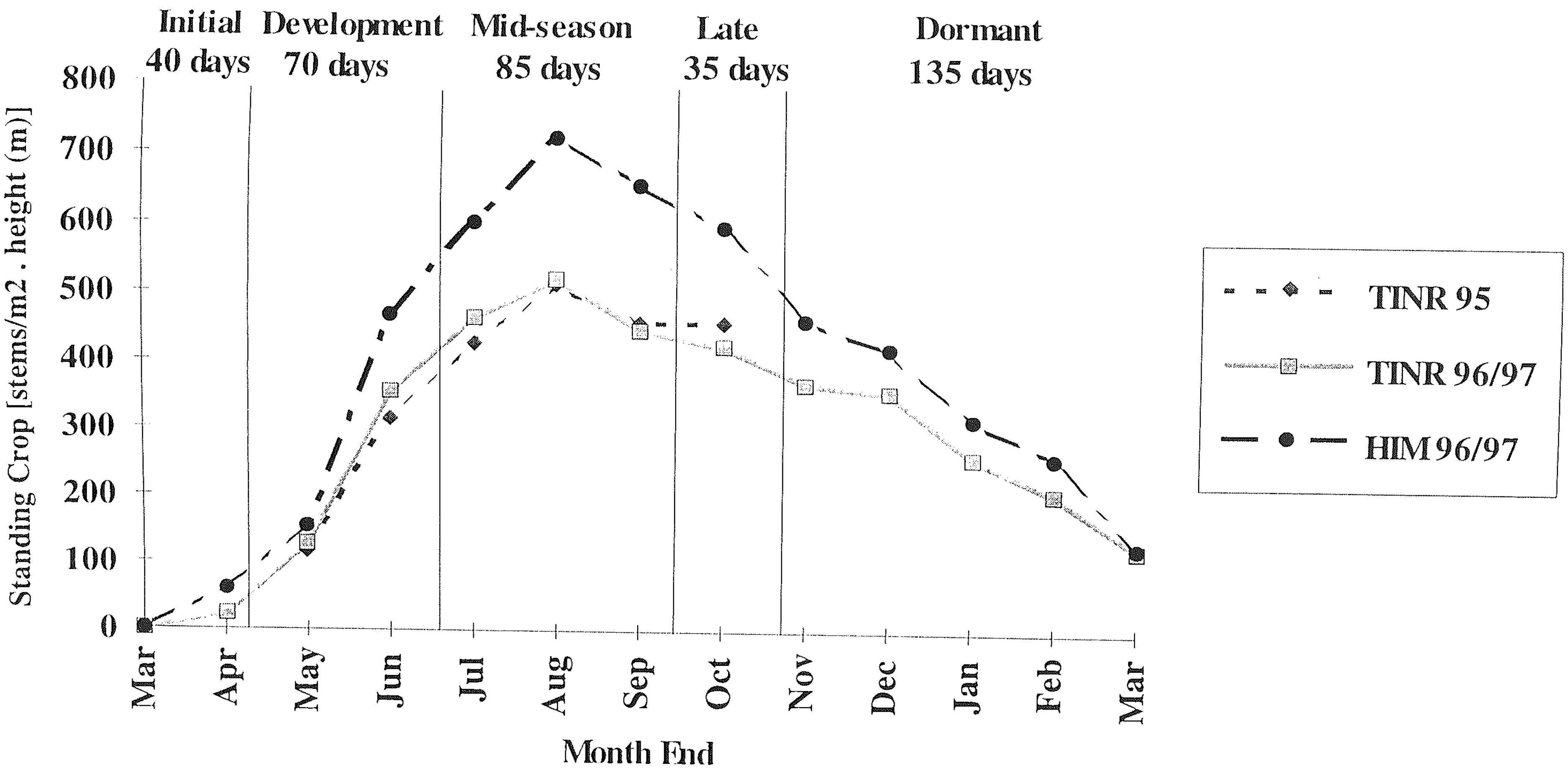

Figure 8.7 Mean Standing Crop Within-stand [stems/m² . height (m)].

Crop Development Stage	Stage Length (Days)	Standing Crop (Height (m) . stems/m^2)		
		TINR 1995	TINR 1996	Himley 1996
1) **Initial Stage** (Standing Crop <10% maximum)	40	< 51	< 52	< 72
2) **Crop Development** (Standing Crop >10% but <75% maximum)	70	51 to 383	52 to 389	72 to 540
3) **Mid-Season Stage** (Standing Crop >75% maximum)	85	> 383	> 389	> 540
4) **Late Season Stage** (Yellowing of leaves to Senescence)	35	na	na	na
5) **Dormant Period** (Senescence to signs of growth)	135	na	na	na

Table 8.8 Crop Development Stages Produced Using Mean Standing Crop Data From Within-stand Phytometers.

Eisenlohr (1966) concluded that ET from emergent vegetation was strongly correlated with the standing crop during mid to late summer when the crop existed as a three-dimensional unit. The only period when a strong correlation between ET(Reed) and standing crop was calculated in this project was during August. Table 8.5 presents the correlation coefficients developed during August. The correlation calculated for all sites from all phytometers ($r = 0.93$) produces a strong positive correlation between standing crop and ET(Reed). The regression equations for both within-stand and not within-stand phytometers are presented as Equation 8.2 and 8.3 respectively, allowing the adjustment of ET(Reed) rates with respect to standing crop. These equations are for use only with; peak standing crop data recorded during mid-late summer, within the UK and other similar climatic regions.

$$\text{ET(Reed)}_{\text{Within-stand}} \text{ [mm/day]} = 1.8 + 0.005[\text{Standing Crop (height (m) .stems/m}^2)] \quad [r = 0.85] \tag{8.2}$$

$$\text{ET(Reed)}_{\text{Not Within-stand}} \text{ [mm/day]} = 0.0 + 0.008[\text{Standing Crop (height (m) .stems/m}^2)] \quad [r = 0.95] \tag{8.3}$$

The intercept value (see Figure 8.8) calculated in Equation 8.2 (1.76 mm/day) is not dissimilar to that measured for within-stand E(Phyto) in August 1996, at 2.39 mm/day (see Table 6.4). Equation 8.2 may therefore be used to estimate ET(Reed) from a given standing crop value for a natural or constructed wastewater wetland during mid-late summer.

Equation 8.3 was produced from not within-stand data (see Figure 8.9), and although the Pearson coefficient was strongly positive the equation appears to be unrealistic of 'real-life' situations. The effectively zero value for the intercept is not representative of situations where standing crop is very low, as ET(Reed) would possess a significant value representative of Eo. It would appear that the regression equation has been distorted by the large number of data points recorded at Redwick which are representative of high values of standing crop and ET(Reed).

Table 8.9 presents a forecast of ET(Reed) rates for various situations where standing crop data is available, both from the sites studied in this research and from other researchers (e.g. Krolikowska, 1971), and includes the actual ET(Reed) rates recorded. The data presented has been calculated using Equations 8.2 and 8.3. The values calculated for the study sites provide accurate predictions of ET(Reed), this is to be expected as the equations used were developed from the data from these sites. The ET(Reed) value calculated for Redwick for August 1995 using Equation 8.2 (7.39 mm/day) may be indicative of the rate which might have been anticipated had the phytometers been located within-stand, and appears more realistic than the rate of 10.18 mm/day presented in Table 8.3.

Using a standing crop of 600 stems/m^2/m^{-1} in Equation 8.3 can provide an estimate of the ET(Reed) rate which might have been recorded at Redwick (not within-stand) in August 1995 (4.76 mm/day) if the standing crop had been similar to that recorded on the TINR and Himley. If this value is then adjusted using the mean monthly coefficient for August presented in Table 8.2 (0.76) an estimate can be made of the ET(Reed) which might be expected from a within-stand phytometer at Redwick which had a similar standing crop value as that of the TINR and Himley [ET(Reed) = 3.62 mm/day]. This estimate is considerably lower than the equivalent rate (5.73 mm/day) recorded on the TINR, suggesting that the relationship between ET(Reed) and standing crop is not linear, particularly when standing crop values are high. This is to be expected as increasing the standing crop will reduce evaporation from the water surface, and each individual stem will act to shelter other stems, reducing irradiance and turbulence, and raising relative humidity, acting as a negative feedback.

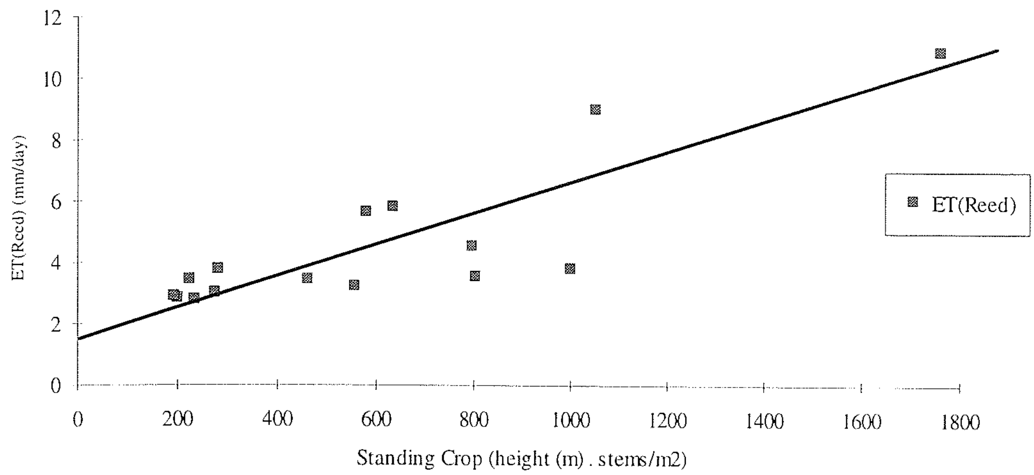

Figure 8.8 ET(Reed) : Standing Crop, Within-stand, TINR and Himley, August 1995 (showing Equation 8.2).

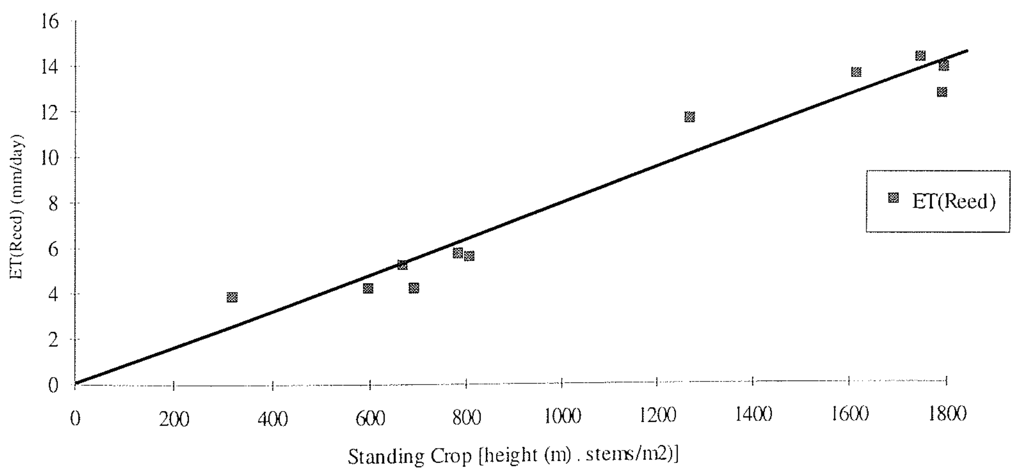

Figure 8.9 ET(Reed) : Standing Crop, Not Within-stand, TINR and Redwick, August 1995 (showing Equation 8.3).

The value of 2.94 mm/day for an average UK reedbed was calculated using standing crop data developed from Hawke and José (1996), and may be indicative of a mean ET(Reed) for mid-late summer, this could be verified from further study, possibly allowing the validation of Equation 8.2 (see Section 11.2).

Table 8.9 shows ET(Reed) values calculated from standing crop data provided by other researchers. The calculated ET(Reed) values are generally lower than the ET(Reed) rates recorded by these researchers. The ET(Reed) calculated from Krowlikowska (1971) standing crop data appears similar to her measured value, however, her values are for transpiration only and are not directly comparable. Thus, Equation 8.2 is not validated by other research data, limiting its application outside of this thesis. The unrealistic nature of Equation 8.3 may cast doubts over the accuracy and applicability of Equation 8.2, which was developed using the same methodology. However, Equation 8.2 may be of use in design situations where known high values of standing crop are anticipated and minimal ETo data is available for the development of ET(Reed) using the developed Kc(Reed) values presented in Chapter Nine.

Eliminating standing crop from Equations 8.2 and 8.3 gives:

$$\mathbf{ET(Reed)}_{\text{Within-stand}} = \mathbf{0.6\ ET(Reed)}_{\text{Not Within-stand}} + \mathbf{1.8} \qquad [8.4]$$

If the $ET(Reed)_{\text{Not Within-stand}}$ rate recorded at Redwick in August 1995 is used within Equation 8.4, the calculated $ET(Reed)_{\text{Within-stand}}$ rate is 9.73 mm/day. This rate remains considerably higher than the rate recorded on the TINR. Equation 8.4 should only be applied in areas; with similar climates to the UK, using $ET(Reed)_{\text{Not Within-stand}}$ data recorded only during mid-late summer, where reedbeds are to be created but experimental phytometers cannot be located within-stand, and limited ETo data is available. However, any rates calculated using Equation 8.4 must be seen as 'ball-park' estimates of ET(Reed) which might be expected during mid-late summer, being for use only within feasibility studies.

	TINR & Himley	Redwick	Hawke and José (1996)	Krolikowska (1971)	Rudescu et al (cited by Krowlikowska, 1971)	Smid (1975)	Smid (1975)
Density & Height	**500 x 1.20**	**1024 x 1.16**	**200 x 1.25**	**54 x 2.7**	**30 x 4.5**	**50 x 3.25**	**120 x 3.25**
Standing Crop	**600**	**1188**	**250**	**145.8**	**135**	**162.5**	**390**
Within-stand -Eq 8.2	4.60 (4.57)	7.39 (na)	2.94 (na)	2.45 (2.23)	2.40 (5.00)	2.53 (6.9)	3.61 (6.9)
Not Within-stand - Eq 8.3	4.76 (4.86)	9.44 (13.39)	na	na	na	na	na

(Actual ET(Reed) shown in brackets).

Table 8.9 Calculation of ET(Reed) from Standing Crop Data (Using Equations 8.2 and 8.3)

8.4.4 INFLORESCENCE DATA.

The recorded inflorescence data for the experimental phytometers is presented in Table 8.10. No attempt was made to distinguish between inflorescence of varying sizes. Initial signs of inflorescence were generally apparent during late July, with the first count undertaken during late August. Inflorescence numbers peak during August-September, decreasing primarily after senescence has occurred, with only the largest inflorescence remaining throughout the dormant period. Those inflorescence which remain after the dormant period have usually developed on larger diameter, taller stems.

The highest density of inflorescence was recorded at Redwick. On the TINR, inflorescence densities were higher within the phytometers located not within-stand. The density was very low at Himley, with two of the phytometers failing to produce a single inflorescence in either the 1995 or 1996 growing season.

Figure 8.10 shows there is little correlation between the density of inflorescence and ET(Reed) rates. No further analysis of the inflorescence data is undertaken within this thesis.

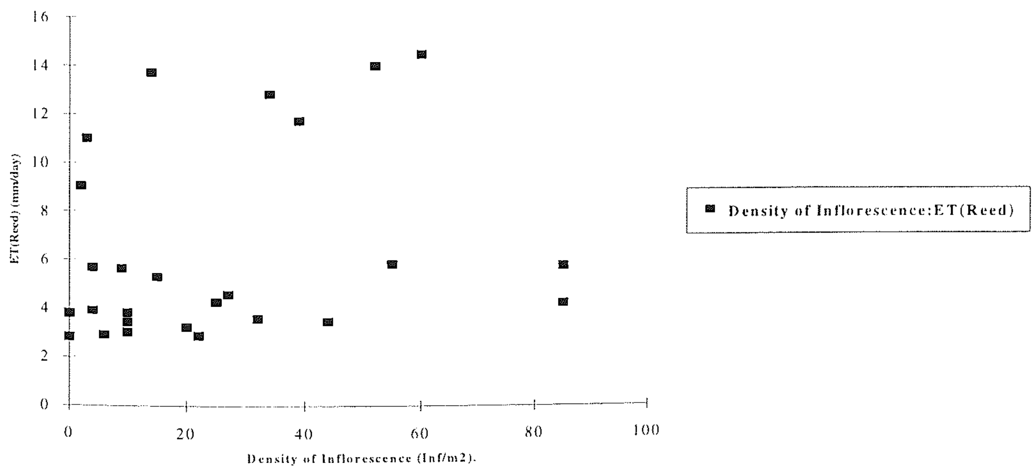

Figure 8.10 ET(Reed) : Density of Inflorescence, All Phytometers (August).

Site	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
TINR (Within-Stand)	1995	na	na	na	na	0	0	0	80	83	81	na	na
TINR (Within-Stand)	1996	na	na	na	0	0	0	0	90	93	90	53	47
TINR (Within-Stand)	1997	41	35	22	na	na	na	na	na	na	na	na	na
TINR (Not Within-Stand)	1995	na	na	na	na	0	0	0	128	132	124	na	na
TINR (Not Within-Stand)	1996	na	na	na	0	0	0	0	152	147	125	116	108
TINR (Not Within-Stand)	1997	85	69	40	na	na	na	na	na	na	na	na	na
Himley (Within-Stand)	1995	na	na	na	na	0	0	0	2	2	2	na	na
Himley (Within-Stand)	1996	na	na	na	0	0	0	0	7	9	5	3	3
Himley (Within-Stand)	1997	3	2	2	na	na	na	na	na	na	na	na	na
Redwick (Not Within-Stand)	1995	na	na	na	na	na	na	na	173	171	167	na	na

Table 8.10 Inflorescence (Inf/m^2)

8.4.5 SPECIES VARIABILITY.

The phytometers located within-stand on the TINR were planted with rhizome infested substrate material inherent to the experimental site. A result of this planting procedure was the introduction of non-*Phragmites* species into the planted phytometers. These included *Typha spp.* and *Juncus spp.* Minimal numbers of non-*Phragmites* species were identified within the phytometers located not within-stand. With hindsight, it would have been preferable to establish single species phytometers by the removal of non-*Phragmites* species, thus, eliminating any influence of other emergent species on the recorded ET.

If the mean ET(Reed) recorded from phytometers containing only *Phragmites australis* (4.42mm/day) is compared to the rate recorded from phytometers which also contain some non-*Phragmites* species (3.19 mm/day), it appears that the occurrence of other emergents reduces the ET(Reed) recorded. *Typha spp.* were found within some of the phytometers that have a lower ET(Reed) rate. However, on closer examination it became apparent that the phytometers in which *Typha spp.* are present also have an overall low value of standing crop. Thus, although it would initially appear that *Typha spp.* reduces ET(Reed), this reduction is probably due to overall lower standing crop values.

In addition to studying *Phragmites australis*, Bernatowicz et al (1976) undertook lysimeter experiments using *Typha angustifolia* and *Typha latifolia*, the direct ET(Typha) measurements are reproduced in Figure 8.11 and 8.12. It is apparent that these emergent species have a higher ET rate than *Phragmites australis*, both within and not within-stand. This higher ET rate may have implications for the water balance of reedbeds which contain *Typha spp.*, as this species may act to "dry-out" such habitats and facilitate the hydroseral succession to carr woodland. It may be thus necessary to remove *Typha spp.* from reedbeds which are subject to drought conditions to reduce the ET losses. In water deficit areas it may also be advisable to create new reedbeds using potted plant or stem cuttings of *Phragmites australis* rather than rhizome infested substrates, which may introduce *Typha spp.*.

ET rates of various emergent species applicable in the UK could be ascertained from a series of experimental studies similar to those undertaken by Bernatowicz et al (1976) (see Section 11.2).

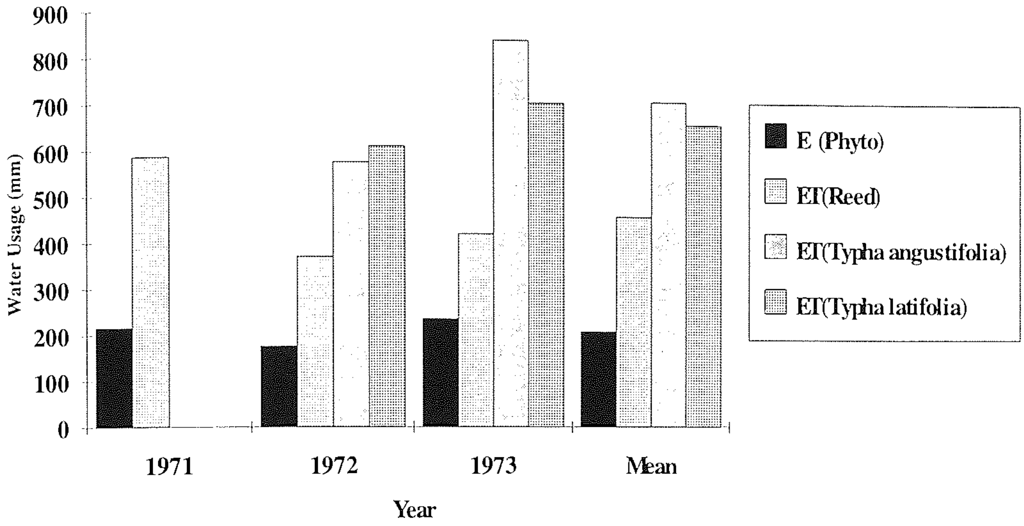

Figure 8.11 Water Usage Data Presented by Bernatowicz et al (1976), Poland - Within-stand Phytometers (May - September).

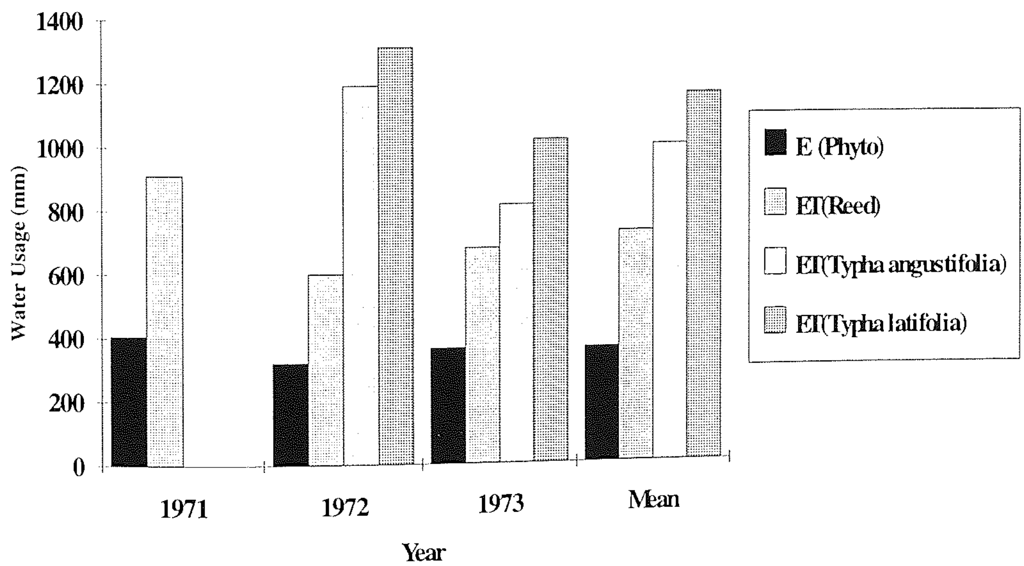

Figure 8.12 Water Usage Data Presented by Bernatowicz et al (1976), Poland - Not Within-stand Phytometers (May - September).

8.4.6 DISCUSSION.

Eisenlohr (1966) believed that the observed dependence of ET(Wetland) on the emergent height of vegetation was associated with the change in the total volume of vegetation transpiring during the growing season. When a crop is fully developed, completely covering the water surface it is expected that crop phenological characteristics (e.g. standing crop) will greatly influence the ET(Reed) rate recorded. This phenomena is likely to have a stronger positive correlation with not within-stand phytometers than from within-stand phytometers, as in the former the standing crop is functioning as a three-dimensional unit with a greater surface area exposed to the processes which encourage ET(Reed).

8.5 ET(Reed) - COMPARISON WITH OTHER RESEARCH.

Table 4.9 displays the findings of the ET(Reed) experiments undertaken by various researchers. Appropriate ET(Reed) data from Table 4.9 is presented in Table 8.11 in conjunction with the ET(Reed) recorded during this research project thus allowing a direct comparison.

The majority of the within-stand ET(Reed) rates noted in Table 8.11 are similar to those recorded during the same periods in this research, particularly those values determined from the ET(Reed) data presented by Bernatowicz et al (1976) (see Figures 8.11 and 8.12). Table 8.11 also includes the ET(Reed) rate recorded by Gavenciak (cited by Smid, 1975) from lysimeters located not within-stand. These rates are considerably higher than those recorded during this project, however, they are within the same order of magnitude.

The ET(Reed) measurements presented by the authors in Table 8.11 were recorded during short periods of anticipated peak ET(Reed) rate, and from reedbeds exposed to continental climates. The values presented by Burgoon et al (1997) are almost double those recorded in the UK, and can be seen as a potential maximum ET(Reed) rate for the early summer, undertaken in meteorological conditions encouraging greater ET(Reed) than those which occur in more temperate maritime conditions in the UK.

Researcher	Form of ET(Reed)	Period	ET(Reed) (mm/day)
Gavenciak (Smid, 1975)	Not Within-stand	Not defined	17.9 to 27.8
Aston University - TINR		August	up to 5.7
Aston University - Redwick		August	up to 13.4
Smid (1975)	Within-stand	June-October	1.4 to 6.9
Aston University - TINR		June-October	0.9 to 5.7
Aston University - Himley		June-October	3.0 to 6.3
Bernatowicz et al (1976) *	Within-stand	May-September	3.0
Aston University - TINR		May-September	3.6
Aston University - Himley		May-September	4.8
Bernatowicz et al (1976) *	Not Within-stand	May-September	4.8
Aston University - TINR		May-September	4.4
Aston University - Redwick		May-September	6.4
Burgoon et al (1997)	Within-stand	May/June	6.4
Aston University - TINR		May/June	3.1
Aston University - Himley		May/June	3.1

* Calculated from Figures 8.11 and 8.12.

Table 8.11 Comparison of ET(Reed) Developed By Various Researchers.

8.6 SUMMARY.

In this chapter the ET(Reed) data recorded during this research project has been analysed and discussed. An assessment has been made of both the inter-site, and intra-site variations in recorded data, leading to the tentative development of a set of monthly coefficients applicable to the not within-stand data recorded at Redwick, allowing the calculation of a possible within-stand figure for ET(Reed). Analysis found that the variation in ET(Reed) rates experienced between individual phytometers may be a function of the value of standing crop, and an attempt was made to develop a regression equation which could adjust ET(Reed) data recorded from phytometers with varying standing crop (Equation 8.2 and 8.3). Equation 8.4 may be of use in the estimation of ET(Reed) from a created reedbed where no ETo data is available and phytometers can only be sited not within-stand. This is further discussed in Section 9.3.3.

The ET(Reed) data recorded during the 1995 growing season and in particular during August 1995 was significantly higher than during other data years. The increase in ET(Reed) recorded was proportionally higher than the increase in ETo, which will be reflected in the developed Kc(Reed) for 1995.

The ET(Reed) rates reported in this study compare favourably with the literature values presented by Bernatowicz et al (1976), both for within-stand and not within-stand phytometers. The ET(Reed) values reported by other researchers were significantly higher than those recorded during this research. However, absolute comparisons of these ET(Reed) rates is complicated by the differences in methodologies and sampling frequencies, with the highest reported rates measured from reedbeds located in continental Europe, whereas this study was undertaken within the maritime climate of the UK.

The development of Kc(Reed) will allow a more informed assessment of the link between crop characteristics and ET(Reed) as much of the underlying meteorological influences will be removed. The development of a Kc(Reed) for each of the various crop development stages is discussed in Section 9.4.

Chapter 9. DEVELOPMENT AND APPLICATION OF Kc(Reed).

9.1 INTRODUCTION.

Section 4.3 discussed crop evapotranspiration [ET(Crop)] and presented the procedure developed by Doorenbos and Pruitt (1977) used in the calculation of ET(Crop). Equation 4.1 can be rearranged to give,

$$\mathbf{Kc} = \frac{\mathbf{ET(Crop)}}{\mathbf{ETo}} \qquad (9.1)$$

where **Kc** = Crop Coefficient
ET(Crop) = Crop Evapotranspiration
ETo = Reference Crop Evapotranspiration.

The calculation of ETo was undertaken in Chapter Seven, with the crop evapotranspiration [ET(Reed)] measurements recorded during this research presented in Section 6.4 and discussed in Chapter Eight. Given the form of Equation 9.1, it is apparent that any variation between the ET(Reed) and ETo rates, impacts directly on the developed reedbed crop coefficient [Kc(Reed)].

Section 9.2 includes the monthly Kc(Reed) values developed in this research. Section 9.3 provides a general overview and discussion of the seasonal variations in the value of Kc(Reed), and an evaluation of the various factors which affect Kc(Reed). Section 9.4 presents values for Kc(Reed) with respect to crop development stages. The Kc(Reed) values developed during this research project are compared with the findings of other researchers working on *Phragmites australis* in Section 9.5. A comparison between Kc(Reed) and Kc(Rice) is undertaken in Section 9.6. Section 9.7 discusses the use of the Kc(Reed) developed using MORECS Grass PE data in the development of a simple reedbed water balance applicable across the UK. Section 9.8 provides a reedbed water budget calculation for the proposed habitat creation area on the TINR, with an overall discussion in Section 9.9.

9.2 MONTHLY Kc(Reed).

The calculated values of Kc(Reed) developed from the four forms of ETo discussed in Chapter Seven are presented in Tables 9.1 to 9.4. These tables contain monthly Kc(Reed) values developed from the ET(Reed) data recorded at all sites, and in addition, Kc(Reed) values developed for Redwick for within-stand phytometers using the adjusted ET(Reed) data presented in Table 8.3. The readers' attention is directed to the limitations previously highlighted with respect to the use of the Redwick data (e.g. small data set, not within-stand, and extremely high value of standing crop).

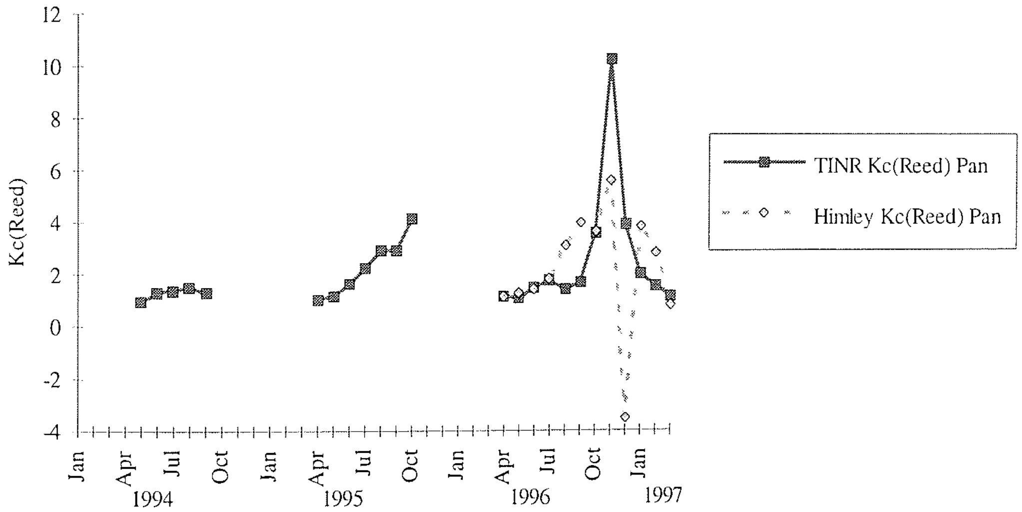

Figure 9.1 Kc(Reed) Pan Values for TINR, 1994-97 and Himley, 1996-97.

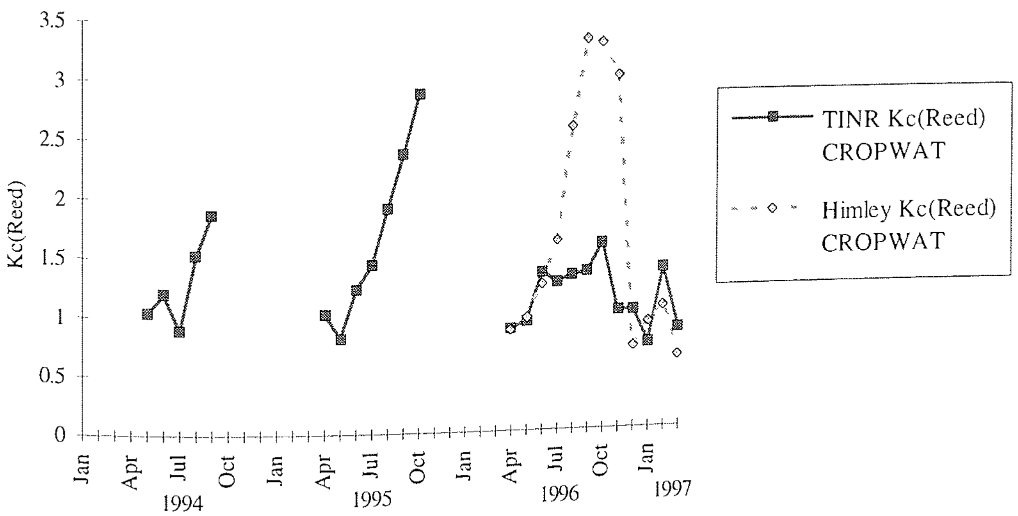

Figure 9.2 Kc(Reed) CROPWAT Values for TINR, 1994-97 and Himley, 1996-97.

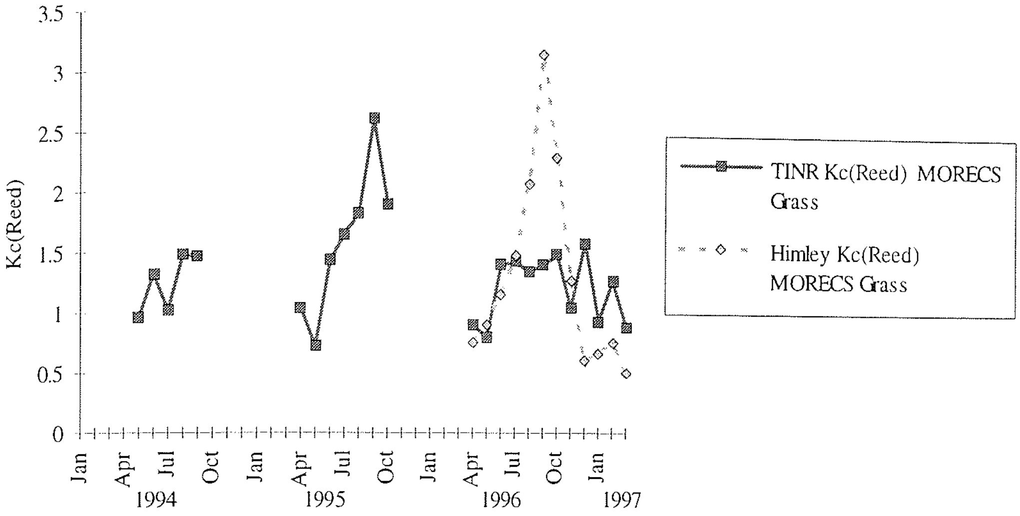

Figure 9.3 Kc(Reed) MORECS Grass Values for TINR, 1994-97 and Himley, 1996-97.

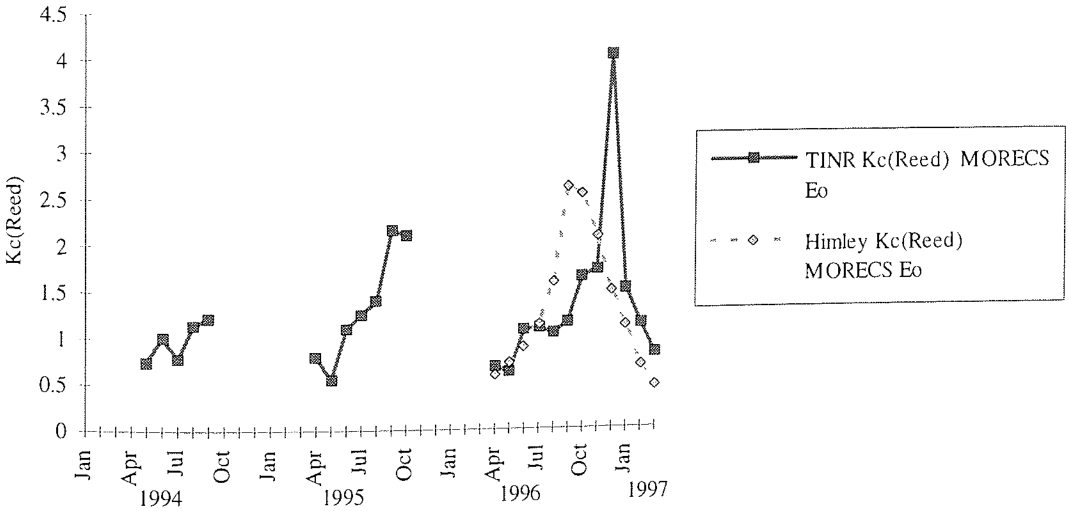

Figure 9.4 Kc(Reed) MORECS Eo Values for TINR, 1994-97 and Himley, 1996-97.

Site	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
TINR - (Within-stand)	1993	na	na	na	Over	1.26	1.27	1.12	1.79	1.35	1.67	na	na
	1994	na	na	na	Over	0.93	1.30	1.38	1.49	1.28	na	na	na
	1995	na	na	na	1.03	1.15	1.62	2.22	2.89	2.93	4.13	na	na
	1996	na	na	na	1.17	1.05	1.48	1.75	1.40	1.69	3.58	10.26	3.89
	1997	2.01	1.56	1.16	na	na	na	na	na	na	na	na	na
TINR - (Not Within-stand)	1993	na	na	na	Over	1.00	1.19	1.35	1.88	1.90	2.50	na	na
	1994	na	na	na	Over	0.93	1.34	2.02	2.23	1.45	na	na	na
	1995	na	na	na	0.92	1.20	1.69	2.46	3.39	3.30	4.63	na	na
	1996	na	na	na	1.34	1.05	1.66	2.25	1.85	2.88	6.12	4.89	3.05
	1997	1.14	1.18	1.36	na	na	na	na	na	na	na	na	na
Redwick - (Not Within-stand)	1994	na	na	na	1.11	1.32	1.79	3.53	2.82	3.00	na	na	na
	1995	na	na	na	na	na	na	na	na	na	na	na	na
Redwick - (Within-stand)*	1994	na	na	na	1.1	1.3	1.7	2.8	2.1	2.4	na	na	na
	1995	na	na	na	na	na	na	na	na	na	na	na	na
Himley - (Within-stand)	1995	na	na	na	1.28	0.99	1.10	0.96	0.87	1.68	2.02	na	na
	1996	na	na	na	1.11	1.25	1.40	1.84	3.08	3.96	3.66	5.63	-3.50
	1997	3.87	2.83	0.83	na	na	na	na	na	na	na	na	na

* Calculated using coefficients presented in Table 8.2.

Table 9.1 Monthly Kc(Reed) Pan for Each Experimental Site (Based on ETo Pan).

Site	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
TINR -	1993	na	na	na	Over	1.10	0.93	0.75	1.39	1.26	0.91	na	na
(Within-stand)	1994	na	na	na	Over	1.03	1.19	0.88	1.52	1.87	na	na	na
	1995	na	na	na	1.03	0.82	1.23	1.43	1.91	2.37	2.87	na	na
	1996	na	na	na	0.87	0.94	1.35	1.26	1.31	1.34	1.59	1.00	1.01
	1997	0.73	1.36	0.84	na	na	na	na	na	na	na	na	na
TINR -	1993	na	na	na	Over	0.86	0.87	0.91	1.45	1.78	1.35	na	na
(Not Within-stand)	1994	na	na	na	Over	0.93	1.23	1.30	2.28	2.12	na	na	na
	1995	na	na	na	0.92	1.19	1.28	1.59	2.24	2.68	3.20	na	na
	1996	na	na	na	1.00	0.93	1.51	1.63	1.74	2.29	2.73	0.49	0.80
	1997	0.40	1.03	0.99	na	na	na	na	na	na	na	na	na
Redwick -	1994	na	na	na	na	na	na	na	na	na	na	na	na
(Not Within-stand)	1995	na	na	na	na	na	na	na	na	na	na	na	na
Redwick -	1994	na	na	na	na	na	na	na	na	na	na	na	na
(Within-stand)*	1995	na	na	na	na	na	na	na	na	na	na	na	na
Himley -	1995	na	na	na	1.25	0.87	1.00	1.01	0.99	0.86	1.38	na	na
(Within-stand)	1996	na	na	na	0.86	0.96	1.24	1.61	2.58	3.32	3.29	3.00	0.70
	1997	0.90	1.03	0.61	na	na	na	na	na	na	na	na	na

* Calculated using coefficients presented in Table 8.2.

Table 9.2 Monthly Kc(Reed) CROPWAT for Each Experimental Site (Based on ETo CROPWAT).

Site	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
TINR -	**1993**	na	na	na	na	na	na	na	na	na	na	na	na
(Within-Stand)	**1994**	na	na	na	Over	0.96	1.32	1.02	1.48	1.46	na	na	na
	1995	na	na	na	1.04	0.72	1.43	1.65	1.82	2.60	1.90	na	na
	1996	na	na	na	0.90	0.80	1.40	1.43	1.35	1.40	1.49	1.05	1.59
	1997	0.94	1.27	0.89	na	na	na	na	na	na	na	na	na
TINR -	**1993**	na	na	na	na	na	na	na	na	na	na	na	na
(Not Within-Stand)	**1994**	na	na	na	Over	0.96	1.36	1.49	2.21	1.65	na	na	na
	1995	na	na	na	0.93	0.75	1.49	1.83	2.13	2.94	2.12	na	na
	1996	na	na	na	1.03	0.80	1.58	1.85	1.78	2.39	2.57	0.51	1.12
	1997	0.52	0.96	1.05	na	na	na	na	na	na	na	na	na
Redwick -	**1994**	na	na	na	1.23	1.17	1.18	2.06	2.46	2.05	na	na	na
(Not Within-Stand)	**1995**	na	na	na	na	na	na	2.69	3.37	5.05	3.01	na	na
Redwick -	**1994**	na	na	na	1.21	1.16	1.11	1.63	1.87	1.62	na	na	na
(Within-Stand)*	**1995**	na	na	na	na	na	na	2.18	2.56	3.99	2.23	na	na
Himley -	**1995**	na	na	na	1.15	0.72	0.91	0.90	0.85	1.04	0.71	na	na
(Within-Stand)	**1996**	na	na	na	0.76	0.90	1.16	1.48	2.08	3.15	2.29	1.27	0.60
	1997	0.67	0.75	0.50	na	na	na	na	na	na	na	na	na

*** Calculated using coefficients presented in Table 8.2.**

Table 9.3 Monthly Kc(Reed) MORECS Grass for Each Experimental Site (Based on ETo MORECS Grass).

Site	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
TINR -	1993	na	na	na	na	na	na	na	na	na	na	na	na
(Within-stand)	1994	na	na	na	Over	0.75	1.01	0.78	1.14	1.22	na	na	na
	1995	na	na	na	0.80	0.60	1.10	1.30	1.40	2.20	2.10	na	na
	1996	na	na	na	0.69	0.62	1.08	1.10	1.04	1.17	1.66	1.73	4.05
	1997	1.53	1.15	0.81	na	na	na	na	na	na	na	na	na
TINR -	1993	na	na	na	na	na	na	na	na	na	na	na	na
(Not Within-stand)	1994	na	na	na	Over	0.75	1.04	1.15	1.70	1.38	na	na	na
	1995	na	na	na	0.71	0.57	1.15	1.41	1.64	2.45	2.36	na	na
	1996	na	na	na	0.80	0.61	1.21	1.42	1.37	2.00	2.86	0.85	3.20
	1997	0.84	0.87	0.96	na	na	na	na	na	na	na	na	na
Redwick -	1994	na	na	na	0.94	0.94	0.91	1.59	1.89	1.71	na	na	na
(Not Within-stand)	1995	na	na	na	na	na	na	2.07	2.59	4.19	3.34	na	na
Redwick -	1994	na	na	na	0.93	0.90	0.90	1.30	1.40	1.40	na	na	na
(Within-stand)*	1995	na	na	na	na	na	na	1.60	2.00	3.30	2.50	na	na
Himley -	1995	na	na	na	0.88	0.58	0.70	0.69	0.65	0.87	0.79	na	na
(Within-stand)	1996	na	na	na	0.59	0.72	0.89	1.14	1.60	2.63	2.55	2.09	1.50
	1997	1.13	0.68	0.46	na	na	na	na	na	na	na	na	na

* Calculated using coefficients presented in Table 8.2.

Table 9.4 Monthly Kc(Reed) MORECS Eo for Each Experimental Site (Based on ETo MORECS Eo).

9.3 SEASONAL VARIATION IN Kc(Reed).

9.3.1 INTRODUCTION.

As previously stated in Section 7.4 and 8.2, the majority of the data which is available for the development of Kc(Reed) has been recorded from the experimental site at the TINR. The Kc(Reed) values developed for the TINR (1994-97) and Himley (1996-97) experimental sites, using the various forms of ETo, and within-stand ET(Reed) measurements are presented in Figures 9.1 to 9.4. The data displayed in these figures forms the primary focus of the analysis and discussion of Kc(Reed).

In general, all of the various forms of Kc(Reed) exhibit a similar trend through the majority of the growing season. The closest similarity is experienced between the values displayed in Figures 9.2 to 9.4. This is to be expected as these Kc(Reed) values are determined from ETo data which are all calculated using a form of the Penman-Montieth equation (see Section 7.4).

The peak rate for ET(Reed) (July/August) was recorded later in the growing season than the peak rate for ETo (June), with the ET(Reed) rate declining more slowly through the autumn (see Section 8.2). This has a significant impact on the shape of the Kc(Reed) graphs presented. In general, the Kc(Reed) values recorded during April are approximately 1.0. This is a function of the importance of evaporation early in the growing season when crop development is minimal. During May there is a slight reduction in the majority of the Kc(Reed) values. This may be a reflection of the 'sheltering effect' of the new reed growth reducing the evaporation from the water surface within the phytometer, with the reed transpiration not sufficiently high enough to compensate for the reduced evaporation. All forms of Kc(Reed) exhibit a gradual rise from the May value, reaching a peak in late summer/early autumn.

The Kc(Reed) Pan values show a distinct increase between May and July, for all site years, however, the August and September values show varying trends dependant on which site year is under discussion. The peak Kc(Reed) Pan values are recorded during October and November, showing a gradual reduction through the dormant period. The Kc(Reed) Pan from the TINR ranged from 0.93 in May 1994 to 10.26 in November 1996, however, some of these values may have been influenced by anomalous ETo Pan values (see Section 7.3.2).

The Kc(Reed) CROPWAT values exist at, or slightly below 1.0 in April and May, from which point they rise rapidly, with the exception of the low value recorded in July 1994, to a peak rate in October. During the dormant period the Kc(Reed) CROPWAT value falls markedly to a low in December/January (0.70). In February 1997, the Kc(Reed) CROPWAT value was higher than in either January or March, a function of the relatively high ET(Reed) recorded during February 1997, possibly resulting from above average wind speed. The Kc(Reed) CROPWAT values for the TINR varied from a low of 0.73 in January 1997 to a high of 2.87 in October 1995.

As previously stated, the Kc(Reed) MORECS Grass and Kc(Reed) MORECS Eo values show very similar trends to the Kc(Reed) CROPWAT. During the dormant period, the Kc(Reed) MORECS Grass exhibits far less month-to-month variation, producing a smoother trend line than that given by either Kc(Reed) CROPWAT or Kc(Reed) MORECS Eo. This 'smoothing effect', combined with a mean dormant period Kc(Reed) MORECS Grass of approximately 1.0 suggests that the ET(Reed) data recorded during the dormant period may be driven by similar meteorological forces as ETo MORECS Grass.

The Kc(Reed) MORECS Grass values for the TINR varied from 0.72 in May 1995 to 2.60 in September 1995, with the Kc(Reed) MORECS Eo varying between 0.55 in May 1995 and 4.05 in December 1996.

At first appearance the very high Kc(Reed) Pan and Kc(Reed) MORECS Eo values calculated for December 1996 would appear to have a significant influence on the overall calculation of ET(Reed) which might be expected during the winter months. However, the very high Kc(Reed) values are a result of very low ETo values rather than particularly high ET(Reed). The actual ET(Reed) recorded in December is low and its impact on annual reedbed water budgets is probably not significant, except in areas where the annual deficit is high.

ET(Reed) rates recorded on the TINR during a small proportion of the monitoring period may have been slightly lowered by the short-term absence of surface water within the phytometers (see Section 8.2). This may result in the developed values of Kc(Reed) for these months being slightly lower than might otherwise have been calculated, however, the variation is unlikely to be significant.

9.3.2 INTER-SITE VARIATION IN Kc(Reed).

Section 8.3.2 presents two periods during which inter-site variations in ET(Reed) are discussed. These same periods are used in this section with respect to the inter-site variation in Kc(Reed).

The Kc(Reed) within-stand data calculated for both the TINR and Himley between April 1996 and March 1997 are based on similar standing crop characteristics (see Section 8.4.3). The mean annual Kc(Reed) calculated for Himley is higher than that recorded at the TINR, with the most significant monthly variation noted between July and October. However, during the dormant period Kc(Reed) values are higher on the TINR.

The reason Kc(Reed) values are higher at Himley than those calculated for the TINR may be a direct reflection of variations within the reedbeds used to site the phytometers. On the TINR the phytometers are located in a 'wet-reedbed', with surface water present around the phytometers throughout the year, whilst at Himley, the reedbed has mean water levels below ground level. The 'dry' nature of the reedbed at Himley is particularly apparent during the summer/autumn period, creating an environment which might increase ET(Reed) above that which would be recorded in a 'wet' reedbed, potentially producing the higher Kc(Reed) values.

It could be argued that the higher Kc(Reed) values experienced on the TINR during December and January are the result of the location of the phytometers within a large waterbody which acts as a heat source during the dormant period, producing a 'warming' influence on its environs, potentially increasing Kc(Reed). However, it might also be expected that the treated effluent which enters the Himley reedbed would raise temperatures within the phytometers in the dormant period. In the absence of temperature measurements from the phytometers and their environs, it may be possible to identify the occurrence of this phenomena by observation of ice thicknesses occurring on the phytometers, and on water features located outside the influence of the treated effluent e.g. the evaporation pan. At Himley, during the period from late November 1996 to mid-January 1997, ice thicknesses recorded within the phytometers were less than 35 mm, and often no ice was present. Ice thicknesses of up to 130 mm were regularly noted within the evaporation pan.

A comparison between the Kc(Reed) values calculated for not within-stand phytometers located at the TINR and at Redwick shows that during the 1994 growing season the Kc(Reed) values were generally similar at both sites. However, during the short period of 1995 (July-October) in which data is available from both sites, the values at Redwick are appreciable higher than those calculated at the TINR. This is primarily a result of the extremely high standing crop value recorded at Redwick distorting the Kc(Reed) (see Section 9.3.4).

9.3.3 INTRA-SITE VARIATION IN Kc(Reed).

Section 8.3.3 discusses the intra-site variation in ET(Reed) recorded on the TINR. As the intra-site variation in Kc(Reed) is a direct function of the variation in the recorded ET(Reed) no further discussion is necessary. The Kc(Reed) values developed for both within-stand and not within-stand phytometers on the TINR (1996/7) are displayed in Figure 9.5.

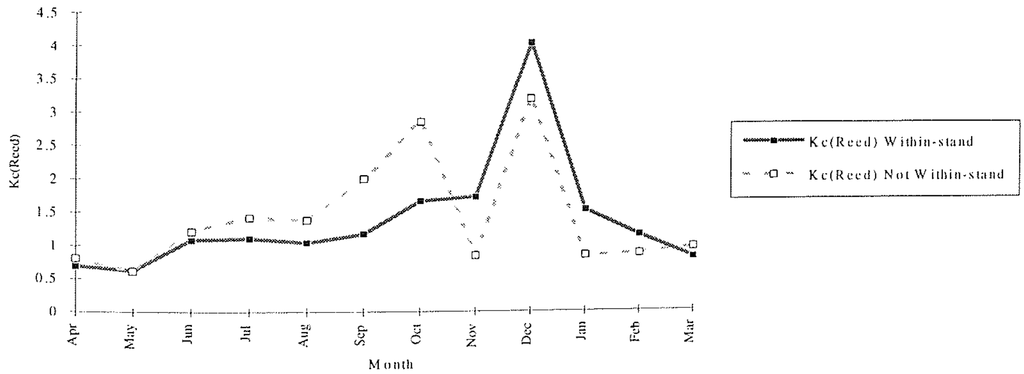

Figure 9.5 Kc(Reed) MORECS Eo for both Within-stand and Not Within-stand Phytometers, TINR, 1996-97.

In Section 8.4.3, Equation 8.4 was developed for application to ET(Reed) rates recorded from not within-stand phytometers during periods of high standing crop (August), producing an estimate of ET(Reed) within-stand. The ET(Reed) rate calculated (using Equation 8.4) for within-stand phytometers at Redwick in August 1995 can be used to give a Kc(Reed) MORECS Grass of 2.45 and Kc(Reed) MORECS Eo of 1.89. These Kc(Reed) values are higher than those developed for August 1995 on the TINR [Kc(Reed) MORECS Grass = 1.82 and Kc(Reed) MORECS Eo = 1.40] and at Himley in August 1996 [Kc(Reed) MORECS Grass = 2.08 and Kc(Reed) MORECS Eo = 1.60], however, they are not markedly dissimilar. This suggests that Equation 8.4 may be justified for the calculation of ET(Reed) from a created reedbed using a phytometer located not within-stand. The higher than average Kc(Reed) values developed may indicate that ET(Reed) obtained from Equation 8.4 may be an over estimation. This over estimation may be appropriate within feasibility studies and initial design, ensuring adequate water supplies are available.

9.3.4 EFFECT OF STANDING CROP ON Kc(Reed).

The role of standing crop in controlling the ET(Reed) rate was discussed in Section 8.4.3. The development of Kc(Reed) allows for the underlying influence of the ETo rates on measured ET(Reed) to be removed, therefore allowing a more direct assessment of the influence of standing crop.

For within-stand data from both the TINR and Himley, a moderate positive correlation exists between Kc(Reed) MORECS Grass and standing crop for the annual period between April 1996 - March 1997 (**r** = 0.72). There is a strong positive correlation for the period between April and August (**r** = 0.88), and minimal correlation during the dormant period (**r** = 0.32).

In general, Kc(Reed) values were very high during months which exhibited relatively high standing crop. Although standing crop reduces slightly during September and October, it still strongly influences the Kc(Reed). During this period the most marked change in the crop characteristics is the appearance of inflorescence. However, Section 8.4.4 states that no correlation was evident between the number of inflorescence and ET(Reed). In addition, Krowlikowska (1971) suggested that the development of inflorescence actually reduces ET(Reed) and as a consequence, Kc(Reed). The link between the development of inflorescence and Kc(Reed) values is not discussed further. During this late summer period it is possible that the increase in the Kc(Reed) value experienced is a function of crop activities occurring within the rhizomes e.g. bud growth (see Table 2.6).

ET(Reed) is highest after a period of peak ETo, and peak Kc(Reed) occurs immediately after a period of peak ET(Reed). This 'lag' is primarily a function of the crop taking time to respond to the environmental factors to which it has been exposed.

9.3.5 Kc(Reed) 1995 - AN EXTREME YEAR ?

Section 8.3.4 discussed the variation in the ET(Reed) rates recorded during the summer of 1995 at the TINR and to a lesser extent at Redwick. The Kc(Reed) MORECS Eo values (within-stand) developed during the growing season on the TINR (1994-96) are displayed in Figure 9.6. All of the Kc(Reed) MORECS Eo values are similar during the period between April and June, however, the values developed for the period between August and October 1995 are significantly higher than those experienced in other years. The greatest variation in the intra-year data occurs during September, when the Kc(Reed) MORECS Eo value for the TINR in 1995 is approximately 81% higher than during either 1994 or 1996. A similar peak in the intra-year values was seen during September 1995, at Redwick.

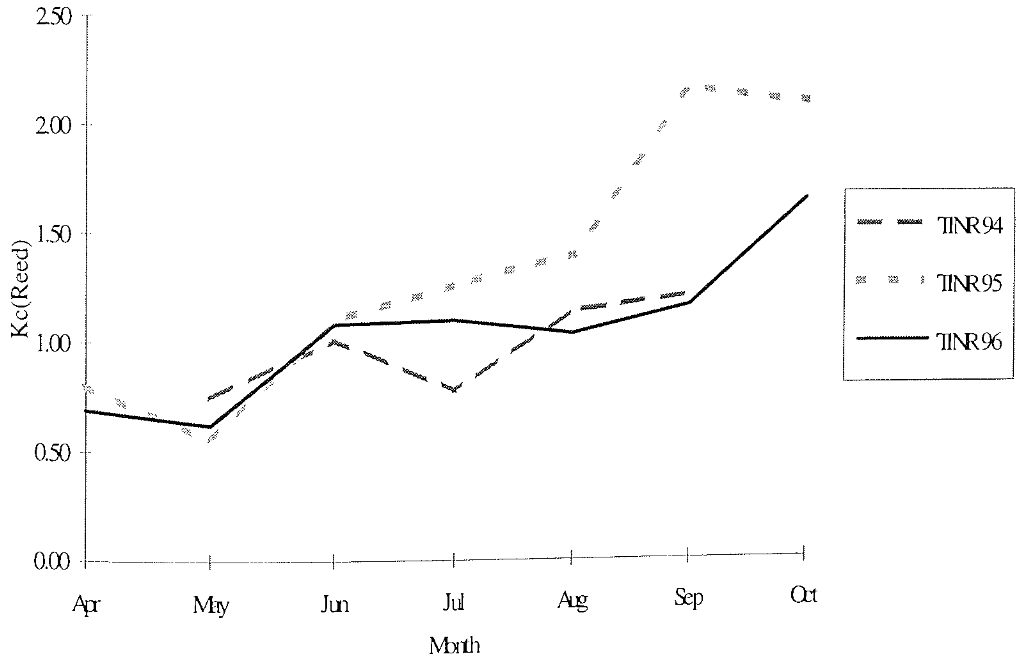

Figure 9.6 Kc(Reed) MORECS Eo Within-stand, Growing Season, TINR, 1994-96.

The incorporation of the somewhat extreme monthly Kc(Reed) values calculated in 1995, within a mean monthly Kc(Reed) applicable in the UK, will produce an over estimation of ET(Reed) in average years. This over estimation may be appropriate within feasibility studies (see Section 9.3.3). The ET(Reed) data recorded in 1995 will be used in the calculation of a mean monthly Kc(Reed) value applicable in the UK (see Section 9.3.6).

9.3.6 MONTHLY Kc(Reed) APPLICABLE WITHIN THE UK.

The development of a monthly value for Kc(Reed) applicable within the UK, requires the selection and use of the most appropriate data sets. The use of certain data from the various experimental sites has been previously discounted (see Sections 6.3.3 and 6.3.4). Monthly Kc(Reed) values applicable in the UK have been developed using the data from the TINR in 1994, 1995, and 1996-7, and the period between April 1996 to March 1997 at Himley, and are presented for each of the various forms of ETo in Table 9.5, and displayed in Figure 9.7. The Kc(Reed) Pan data calculated between November and February appears anomalous (see Section 7.3.2) and it is recommended that the mean value calculated for this period for Kc(Reed) Pan is used when calculating ET(Reed) (see Table 9.5). Limited statistical analysis of the Kc(Reed) values presented in Table 9.5 has been undertaken due to the small size of the sample data set.

It is possible to compare the actual ET(Reed) recorded, with the ET(Reed) predicted using the Kc(Reed) values presented in Table 9.5. Any difference between these values will be directly proportional to the variation between the actual monthly Kc(Reed) (see Tables 9.1 - 9.4) and the mean monthly Kc(Reed) applicable in the UK (see Table 9.5).

Although the Kc(Reed) values calculated during the summer from Himley are higher than those developed for the TINR (see Section 9.3.2), they have been included within the development of a monthly coefficient for the UK. In the development of a set of mean monthly Kc(Reed) values applicable in the UK, the ratio of data used from the sites at the TINR and Himley is 3 : 1 in the growing season, and 1 : 1 in the dormant season. Thus, the values presented in Table 9.5 incorporate more data calculated from the 'natural' flooded reedbeds, and less from constructed, 'dry' reedbeds. This effectively raises the mean summer Kc(Reed) values applicable in the UK, to marginally lower than those developed for the TINR during the summer of 1995. This provides a set of monthly Kc(Reed) values which may produce slight over predictions of mean ET(Reed) from 'wet' reedbeds. The possibility that a minority of the Kc(Reed) values developed for the TINR were reduced by the ET(Reed) occurring below the 'potential' rate (see Section 9.3.1) also suggests that the use of the Himley data is appropriate. Over predictions of water usage within any equation developed to calculate the feasibility of reedbed development are preferable to ensure sufficient water will be available to sustain the created habitats.

Form of Kc(Reed)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Kc(Reed) Pan - Mean	2.55*	2.55*	1.00	1.11	1.10	1.45	1.79	2.21	2.46	3.79	2.55*	2.55*
Kc(Reed) Pan - Standard Deviation	3.14*	3.14*	0.26	0.28	0.30	0.33	0.69	1.01	1.54	1.36	3.14*	3.14*
Kc(Reed) Pan - 99% Confidence Limits	2.77*	2.77*	0.22	0.18	0.15	0.17	0.35	0.51	0.79	0.81	2.77*	2.77*
Kc(Reed) CROPWAT - Mean	0.82	1.20	0.73	0.92	0.94	1.25	1.30	1.83	2.22	2.58	2.00	0.86
Kc(Reed) CROPWAT - Standard Deviation	0.56	0.38	0.19	0.23	0.30	0.40	0.47	0.77	1.24	1.21	1.17	0.50
Kc(Reed) CROPWAT - 99% Confidence Limits	0.46	0.32	0.16	0.14	0.15	0.20	0.24	0.39	0.64	0.72	1.11	0.45
Kc(Reed) MORECS Grass - Mean	0.81	1.01	0.70	0.90	0.85	1.33	1.40	1.68	2.15	1.89	1.16	1.10
Kc(Reed) MORECS Grass - Standard Deviation	0.64	0.41	0.25	0.24	0.29	0.34	0.47	0.59	1.22	0.75	0.48	0.83
Kc(Reed) MORECS Grass - 99% Confidence Limits	0.53	0.34	0.21	0.16	0.15	0.17	0.24	0.30	0.63	0.45	0.45	0.75
Kc(Reed) MORECS Eo - Mean	1.33	0.92	0.64	0.69	0.66	1.02	1.07	1.30	1.80	2.11	1.91	2.78
Kc(Reed) MORECS Eo - Standard Deviation	1.05	0.37	0.22	0.18	0.22	0.27	0.37	0.45	1.03	0.84	0.79	2.13
Kc(Reed) MORECS Eo - 99% Confidence Limits	0.87	0.31	0.19	0.11	0.11	0.13	0.19	0.23	0.53	0.50	0.75	1.93

* See Section 9.3.6.

Table 9.5 Mean Monthly Kc(Reed) Developed from Within-stand Phytometers, UK.

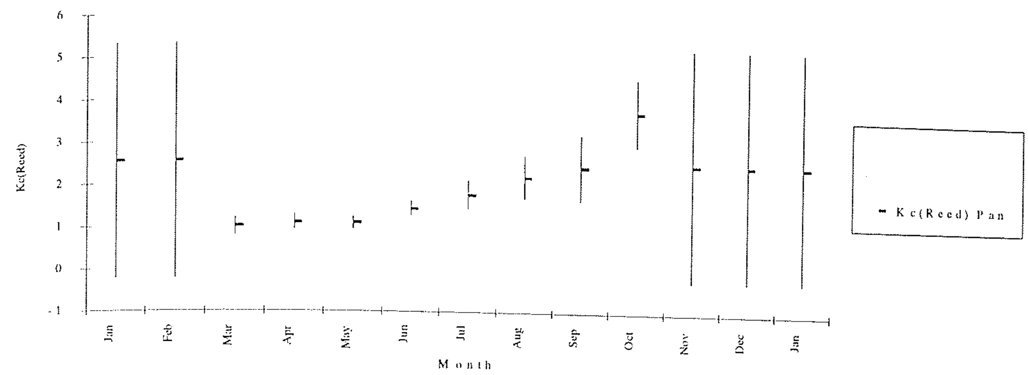

Figure 9.7a Mean Monthly Kc(Reed) Pan, Within-stand, UK.

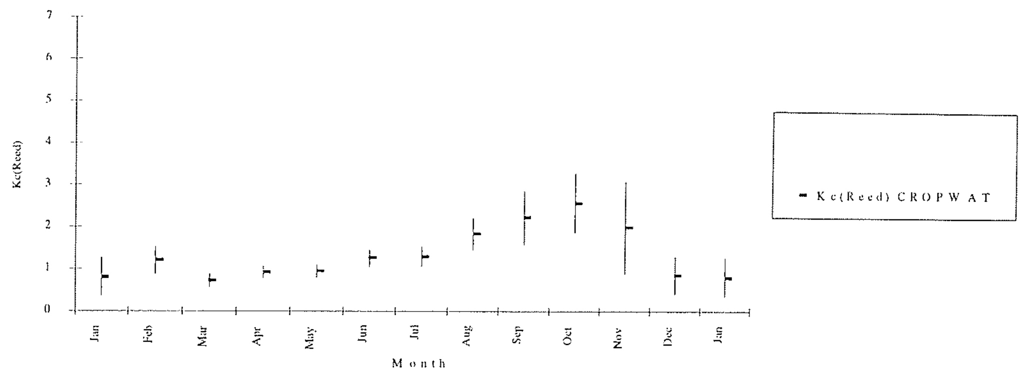

Figure 9.7b Mean Monthly Kc(Reed) CROPWAT, Within-stand, UK.

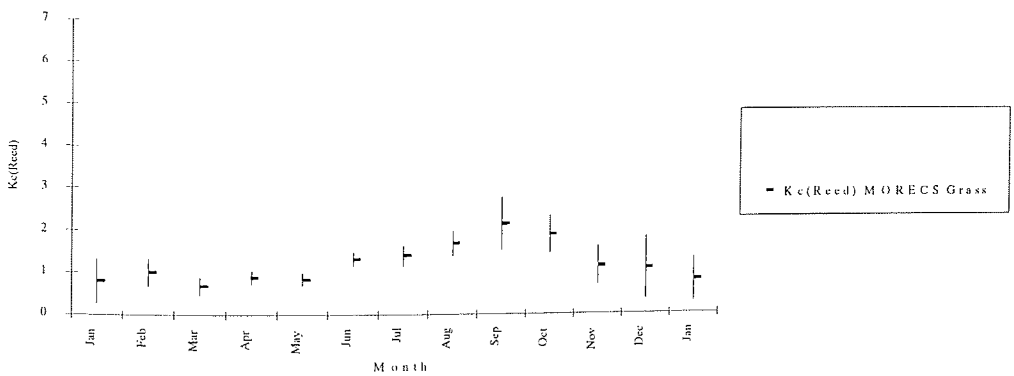

Figure 9.7c Mean Monthly Kc(Reed) MORECS Grass, Within-stand, UK.

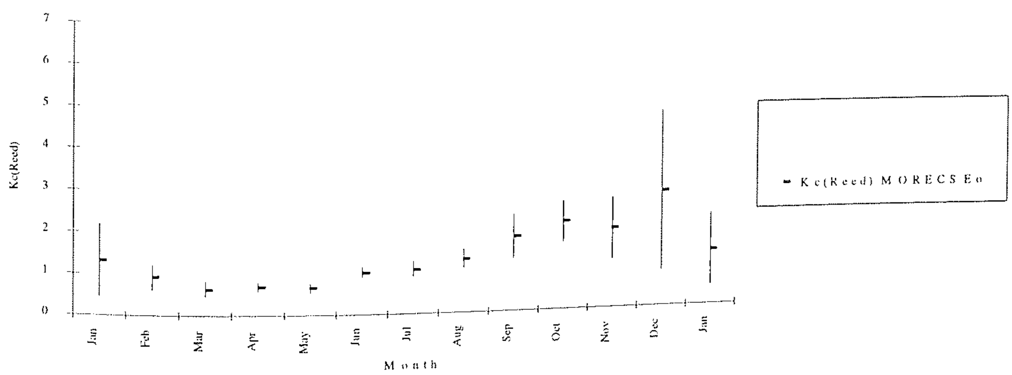

Figure 9.7d Mean Monthly Kc(Reed) MORECS Eo, Within-stand, UK.

The monthly Kc(Reed) MORECS Grass values presented in Table 9.5 will be used in combination with additional ETo MORECS data in Section 9.5, in the development of a UK reedbed water balance, based upon the MORECS Squares. The adoption of the monthly values shown in Table 9.5 may be particularly appropriate if the 'much discussed predictions' of climatic change are experienced within the UK (see Section 11.3). If the predictions of warmer, drier summers do not materialise, any slight excess calculated within the reedbed water budget by the adoption of the values displayed in Table 9.5 will allow enhanced water level management.

9.4 Kc(Reed) - RELATED TO CROP STAGES

Table 8.8 presents the calculated time period for each of the crop development stages identified by Doorenbos and Pruitt (1977) (see Section 4.3.1). It is possible to develop a Kc(Reed) value for each of these development stages for the annual period between April 1996 and March 1997 at the TINR and Himley. This period was chosen as it provides Kc(Reed) and detailed standing crop data for a complete year, including the dormant period. The dormant period Kc(Reed) carries the analysis beyond the crop development stages presented by Doorenbos and Pruitt. However, it is a useful parameter, which is appropriate for presentation here, as reeds have a significant standing crop throughout the dormant period, which may influence ET(Reed).

The Kc(Reed) values for all forms of ETo are calculated with respect to the varying crop development stages for the experimental sites at the TINR and Himley, and are presented in Tables 9.6 and 9.7 respectively. Table 9.8 presents a set of Kc(Reed) values for each of the various crop development stages derived using ET(Reed) and ETo data from the TINR in 1994, 1995, and 1996-97, and the period between April 1996 to March 1997 at Himley. The same data was used in the calculation of the mean monthly Kc(Reed) values presented for the UK in Table 9.5. The crop development stages were assumed to be the same for each data year and for each site.

The Kc(Reed) MORECS Grass values applicable to the various crop development stages, are displayed in conjunction with the monthly Kc(Reed) for the same period, for the TINR, Himley, and the UK in Figures 9.8, 9.9 and 9.10 respectively. Figures 9.8 to 9.10 have been prepared using the guidelines presented by Doorenbos and Pruitt (1977) (see Table 4.3). The disadvantage of using the guidelines presented in Table 4.3 is that the actual calculated Kc(Reed) value for both crop development stages 2 and 4 are not used in the presentation of Figures 9.8 to 9.10. In accordance with the guidelines detailed by Doorenbos and Pruitt, the Kc(Reed) for these periods are represented by a line which joins the previous and the subsequent Kc(Reed) value. This line is not representative of the actual Kc(Reed) value calculated for that period. Thus, the graphical representation cannot be used to determine the Kc(Reed) values for crop development stages 2 and 4.

The Kc(Reed) values for Redwick are not presented for the various crop development stages as no standing crop data is available for stages 1 and 2.

The development of Kc(Reed) values representative of the various crop development stages, allows an enhanced discussion of the effect of standing crop on Kc(Reed). During crop development stage 1, Kc(Reed) MORECS Grass is less than 1.0. This might be expected, as although during this period the reed growth resembles that of a Penman short crop (grass), the crop is not "fully covering the surface". Thus, there will inevitably be a loss of water from the phytometer as evaporation, but this, combined with the reed transpiration, is not as high as the ET from a Penman short crop, producing a Kc(Reed) Grass which is less than 1.0.

Kc(Reed) rises above 1.00 during crop development stage 2, and rises significantly above 1.0 at the start of crop development stage 3 when crop growth reaches 75% of its maximum development. During stage 3, *Phragmites australis* no longer exists as a Penman short crop, extending to a height greater than the "80 to 150 mm" presented by Doorenbos and Pruitt (1977) for a Reference Crop. Thus, a Kc(Reed) greater than 1.0 is perhaps expected, reflecting the overall influence of the standing crop on Kc(Reed). The peak value for Kc(Reed) MORECS Grass occurs during crop development stage 3 at both the TINR (1.40) and Himley (2.32), the calculated mean UK value is 1.59. All forms of Kc(Reed) display values significantly greater than 1.0 during crop development stages 3 and 4.

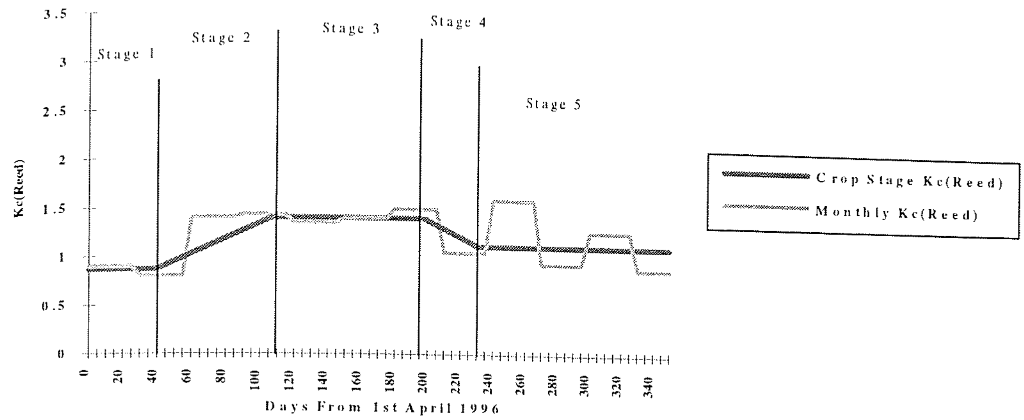

Figure 9.8 Kc(Reed) MORECS Grass - Using Monthly, and Crop Development Stage Values, TINR, April 1996 - March 1997.

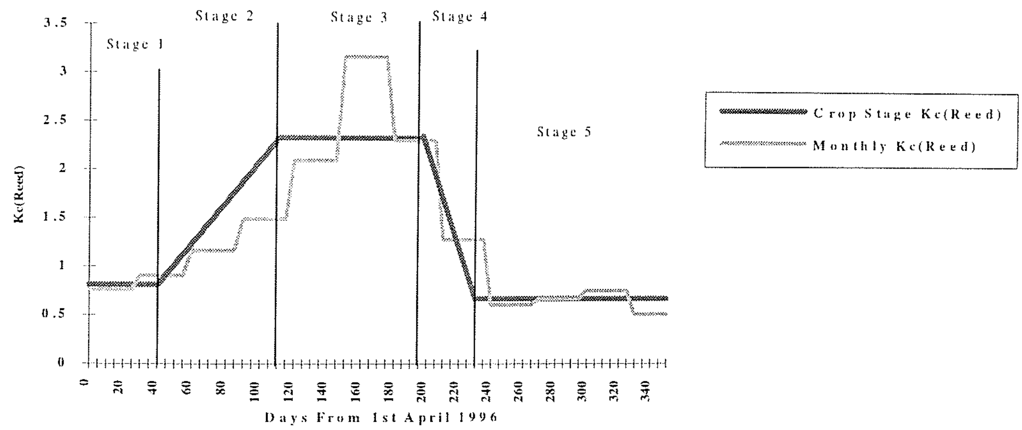

Figure 9.9 Kc(Reed) MORECS Grass - Using Monthly, and Crop Development Stage Values, Himley, April 1996 - March 1997.

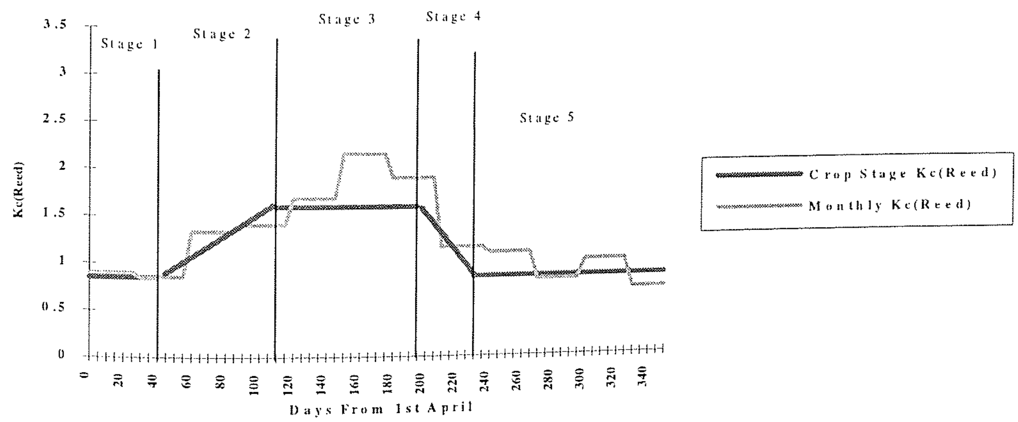

Figure 9.10 Kc(Reed) MORECS Grass - Using Monthly, and Crop Development Stage Values, UK.

Crop Development Stage	Period (Days from 1st April)	ET (Reed) (Mean) mm/day	Kc(Reed) Using ETo Pan	Kc(Reed) Using ETo CROPWAT	Kc(Reed) Using ETo MORECS Grass	Kc(Reed) Using ETo MORECS Eo
1	1 to 40	1.74	1.13	0.89	0.87	0.67
2	40 to 110	3.77	1.45	1.23	1.25	0.96
3	110 to 195	3.07	1.66	1.34	1.40	1.14
4	195 to 230	1.40	3.50	1.31	1.30	1.69
5	230 to 365	0.95	1.73	1.00	1.12	1.22
Growing Season Mean	1 to 230	2.80	1.44	1.16	1.25	1.11
Annual Mean	1 to 365	2.12	1.58	1.18	1.22	1.04

NB. Crop Development Stage 5 = Dormant Period.

Table 9.6 Kc(Reed) Developed For Various Crop Development Stages - TINR 1996-97.

Crop Development Stage	Period (Days from 1st April)	ET (Reed) (Mean) mm/day	Kc(Reed) Using ETo Pan	Kc(Reed) Using ETo CROPWAT	Kc(Reed) Using ETo MORECS Grass	Kc(Reed) Using ETo MORECS Eo
1	1 to 40	1.64	1.16	0.90	0.81	0.63
2	40 to 110	3.76	1.50	1.28	1.03	0.92
3	110 to 195	5.52	3.19	2.71	2.32	1.88
4	195 to 230	1.78	3.50	3.18	1.85	2.41
5	230 to 365	0.52	2.36	0.87	0.67	0.69
Growing Season Mean	1 to 230	4.01	2.16	1.81	1.60	1.29
Annual Mean	1 to 365	2.58	2.19	2.03	1.45	1.27

NB. Crop Development Stage 5 = Dormant Period.

Table 9.7 Kc(Reed) Developed for Various Crop Development Stages - Himley 1996-97.

Crop Development Stage	Period (Days from 1st April)	ET (Reed) (Mean) mm/day	Kc(Reed) Using ETo Pan	Kc(Reed) Using ETo CROPWAT	Kc(Reed) Using ETo MORECS Grass	Kc(Reed) Using ETo MORECS Eo
1	1 to 40	1.80	1.05	0.72	0.85	0.80
2	40 to 110	3.66	1.45	1.19	1.22	0.94
3	110 to 195	3.57	1.98	1.37	1.59	1.29
4	195 to 230	1.72	3.50	2.21	1.40	2.15
5	230 to 365	0.70	1.84	0.91	0.85	0.93
Growing Season Mean	1 to 230	3.01	1.66	1.23	1.31	1.11
Annual Mean	1 to 365	2.15	1.89	1.17	1.23	1.08

NB Crop Development Stage 5 = Dormant Period

NB Data derived in accordance with the methodology detailed by Doorenbos and Pruitt (1977) - the range of variability within this data cannot be evaluated.

Table 9.8 Kc(Reed) Developed for Various Crop Development Stages - Developed for the UK.

During crop development stage 4, the Kc(Reed) Pan and Kc(Reed) Eo values show an increase when compared to stage 3, reflecting the declining rate of evaporation which constitutes the underlying ETo forms. However, the Kc(Reed) MORECS Grass exhibits a slight reduction during stage 4, with the resultant shape of the data (see Figures 9.8 to 9.10) being similar to that displayed in Figure 4.1. This reduction in Kc(Reed) MORECS Grass is a result of the overall decline in ET(Reed) which occurs as the reeds prepare for the onset of senescence. Senescence is complete by the start of crop development stage 5, with an accompanying reduction in Kc(Reed) values developed for the dormant period. In general, the dormant period values for Kc(Reed) are approximately 1.0.

If the relevant data is available to ascertain the various crop development stages, the Kc(Reed) values displayed in Table 9.8 can be used in the calculation of ET(Reed). However, the crop development stages used in Table 9.8 were developed from only a limited amount of data, for a period of only one year. As such, it is recommended that the monthly values of Kc(Reed) presented in Table 9.5 are used wherever possible in preference to the Kc(Reed) values presented in Table 9.8. In areas where reedbed creation projects are primarily an extension to an existing habitat it may be possible to determine crop development stages from the existing reedbed stands. If these stages can be determined, ET(Reed) should be calculated using both the values for each development stage (see Table 9.8) and the mean monthly values (see Table 9.5). The highest ET(Reed) value calculated using these two techniques should be used for design purposes to ensure adequate water volumes are available for reedbed creation.

9.5 Kc(Reed) - COMPARISON WITH OTHER RESEARCH

Tables 4.9 and 4.10 provide a list of Kc(Wetland) and Kc(Reed) computed by other researchers. Although the values of Kc(Wetland) may not be directly comparable to the values of Kc(Reed) developed in this research project, they provide a useful reference data set, allowing a broader discussion than is possible from the limited number of Kc(Reed) values which are available.

Eisenlohr (1966), and Dolan et al (1984), produced similar trends in the value of Kc(Wetland) Eo to the Kc(Reed) MORECS Eo trends presented in this thesis, with Kc(Wetland) Eo being <1.0 early in the growing season (April-mid June), and >1.0 during the summer and autumn period. Blaney and Ewing (1946) provided a Kc(Wetland) Eo value of 1.24, whilst, Ingram (1981) presented a Kc(Wetland) Penman value of 1.4. These are both similar to the mean values calculated in this research for the equivalent parameters: e.g. mean annual Kc(Reed) MORECS Grass = 1.33. The values provided by Dolan et al (1984) [with Kc(Wetland) Pan = 1.0 and Kc(Wetland) Penman = 1.0] and Migahid, cited by Penman (1963), [Kc(Wetland) Eo = 1.0] suggest Kc(Wetland) values of approximately 1.0. The remaining values presented in Table 4.9 have values which are lower than the equivalent mean values calculated during this research, however, the vast majority occur within the low range of the monthly variation found.

The Kc(Wetland) Eo calculated by Novikova (cited by Bernatowicz et al 1976) is considerably lower than the majority of Kc(Reed) MORECS Eo values calculated from either the TINR or Himley. Although no time period can be ascertained with respect to the Kc(Wetland) Eo values, Novikova's values of between 0.71 and 0.73 are similar to those Kc(Reed) Eo values determined in this research during April and May. Novikova developed the Kc(Wetland) Eo values from reedstands which contained *Phragmites australis* and *Typha angustifolia,* and as such the developed coefficients are not directly comparable to this research. The data presented by Bernatowicz et al (1976) (see Section 8.5) would suggest that ET(Typha*)* was considerably higher than ET(Reed), and therefore the coefficient developed by Novikova may have even been increased by the occurrence of *Typha angustifolia* within the studied reedstands.

Gilman (1997) produced a form of Kc(Wetland) which was developed using the Bowen ratio. He found that AE recorded during May was less than the value of PE [Kc(Reed) < 1.0]. However, during August AE was approximately 25% higher than PE [Kc(Reed) = 1.25]. September values of AE were also higher than PE. No annual values could be developed, as equipment failure occurred during periods of low solar radiation (after mid-October). The Kc(Reed) values developed from the work undertaken by Gilman appear to exhibit very similar trends to the Kc(Reed) Eo values presented in Table 9.5. However, a direct comparison is difficult without access to the complete data recorded by Gilman.

From Shjeflo's (1968) studies of prairie potholes in North Dakota, USA, values for Kc(Wetland) Eo can be calculated as 0.75 for May, and 1.0 for mid-summer.

These values are slightly lower than the Kc(Reed) MORECS Eo shown in Table 9.5, with the greatest variation occurring during October, when the Kc(Wetland) Eo value is 0.5 - considerably lower than the Kc(Reed) MORECS Eo (2.11). This significant variation for October is probably a function of the differences in: the crop type; the technique used to measure either the ET(Crop) or the rate of ETo; the location of the study sites; and in the date of senescence.

In order to place the values of Kc(Reed) developed during this research project in context, it is necessary to compare them with those produced from the research of other authors using *Phragmites australis* (see Table 4.10). A summary of the various Kc(Reed) values presented by other researchers, and the equivalent Kc(Reed) values calculated within this research project, for similar periods, are presented in Table 9.9.

Uryvaev (cited by Krowlikowska, 1971), Gel'bukh (1964), Bernatowicz et al (1976), and Gilman and Newson (cited by Crundwell, 1986) all developed Kc(Reed) values for use with Eo, - the latter three authors used within-stand phytometers. Uryvaev stated that the value of Kc(Reed) Eo may reach as high as 3, this compares with the highest value for Kc(Reed) MORECS Eo in this research (within-stand) at 2.63, calculated for Himley in September 1996. Gel'bukh (1964) found a Kc(Reed) Eo for Russian reedbeds varying between 0.8 to 2.5, and all of the mean Kc(Reed) MORECS Eo values calculated in this research fall within this broad range. Bernatowicz et al (1976) presented a Kc(Reed) Eo of 0.92 to 1.27 from reedbed data from Poland. The equivalent mean value [Kc(Reed) MORECS Eo = 1.12] determined from this research for the May to September period, once again lies within these margins. Gilman and Newson discovered that the value of Kc(Reed) Eo varied between 1.2 and 2.0. These Kc(Reed) Eo values are slightly higher than the mean annual Kc(Reed) MORECS Eo calculated in this study at 1.13. However, the values of Kc(Reed) MORECS Eo calculated during August (1.30) and September (1.80) (see Table 9.5) lie within the range found by Gilman and Newson.

Hawke and José (1996) present an annual Kc(Reed) Transpiration of 1.4 applicable in the UK, which was not derived from experimental data but chosen following a literature search (José, 1997). This value was chosen for use with transpiration data available in MAFF (1976). However, the MAFF transpiration figures are equivalent to AE from grassland. This form of ETo is obviously not compatible within a 'wet' reedbed situation where ET occurs at the 'potential' rate.

However, although the value of Kc(Reed) presented by Hawke and José is not directly compatible with that derived in this project, it is remarkably close in magnitude.

Kc(Reed) Pan values can be determined from the work undertaken by Smid (1975) (see Table 9.10), who estimated the value of ET(Reed) using the Bowen ratio. The Kc(Reed) Pan values calculated from Smid's data are only representative of the conditions prevailing on the four days on which measurements were taken. However, with the exception of the value calculated for October, they are not dissimilar to the equivalent values provided in Table 9.5, with the seasonal mean value (June-October) for Kc(Reed) Pan calculated as 1.65, compared to 2.01 calculated in this project.

Section 8.4.5 discusses the ET(Reed) rates presented by Bernatowicz et al (1976). Values representative of ETo Pan can be estimated from the evaporation recorded from the unplanted, control phytometers (not within-stand) by the application of a pan coefficient (Kpan = 0.8), and hence a set of Kc(Reed) values can be directly determined using Equation 9.1. The ETo Pan values, ET(Reed) rates, and the calculated Kc(Reed) values are presented in Table 9.11. The Kc(Reed) values produced are representative of the mean value between May and September, when Kc(Reed) Pan was calculated for within-stand phytometers in Poland, at 1.58. This value is also very similar to the mean Kc(Reed) Pan of 1.66 from the Aston research (see Table 9.9).

From the data presented by Burgoon et al (1997) a Kc(Reed) Grass of 1.0 can be calculated for May to June from arid areas of the USA. This value is similar to the Kc(Reed) MORECS Grass (1.09) calculated from this research for the same period.

Researcher	Country	Form of Kc(Reed)	Period	Mean Value Kc(Reed)
Uryvaev (Krowlikowska, 1971)	Not defined	Kc(Reed) Eo	Not defined	Up to 3.0
Aston University	UK	Kc(Reed) MORECS Eo	Apr 96 - Mar 97	1.13
Gel'buhk (1964)	Russia	Kc(Reed) Eo	Not defined	0.8 to 2.5
Aston University	UK	Kc(Reed) MORECS Eo	Apr 96 - Mar 97	1.13
Bernatowicz et al (1976)	Poland	Kc(Reed) Eo	May - September	0.92 to 1.27
Aston University	UK	Kc(Reed) MORECS Eo	May - September	1.12
Gilman and Newson (Crundwell, 1986)	UK	Kc(Reed) Eo	Not defined	1.20 to 2.00
Aston University	UK	Kc(Reed) MORECS Eo	Apr 96 - Mar 97	1.13
Bernatowicz et al (1976) #	Poland	Kc(Reed) Pan	May - September	1.58
Aston University	UK	Kc(Reed) Pan	May - September	1.66
Smid (1975)	Czechoslovakia	Kc(Reed) Pan	June - October	1.65
Aston University	UK	Kc(Reed) Pan	June - October	2.01
Hawke and José (1996)	Czechoslovakia	Kc(Reed) Pan	June - October	1.65
Aston University	UK	Kc(Reed) Pan	June - October	2.01
Burgoon et al (1997)	USA	Kc(Reed) Grass	May/June	1.00
Aston University	UK	Kc(Reed) MORECS Grass	May/June	1.09

Value not presented by Bernatowicz et al but calculated from their data.

Table 9.9 Comparison of Kc(Reed) Developed by Various Researchers.

Date	ET(Reed) (mm/day)	Epan (mm/day)	ETo Pan (mm/day)	Kc(Reed) Pan
1st June	5.6	5.4	4.32	1.30
27th July	6.9	3.7	2.96	2.33
11th August	5.5	4.0	3.20	1.72
5th October	1.4	1.6	1.28	1.09
Season Mean	4.85	3.68	2.94	1.65

NB. ETo Pan = Epan x 0.8.
Season Mean based on data from June to October.

Table 9.10 ET(Reed) and Epan Data Presented by Smid (1975), and Calculated ETo Pan and Kc(Reed) Pan.

Kuzenecov (cited by Bernatowicz et al, 1976) undertook ET(Reed) measurements in lysimeters located on land, outside of a reedbed, from which a Kc(Reed) Pan was developed which varied between 1.5 to 2.5. The not within-stand data developed using the Bernatowicz et al (1976) results produces a mean value for Kc(Reed) Pan of 2.51 (see Table 9.11). An equivalent figure for the Kc(Reed) Pan derived from the TINR not within-stand data (1994-96) provides a mean value of 1.98. This value lies within the range identified by Kuzenecov and is once again not dissimilar to that calculated from the Polish based research undertaken by Bernatowicz et al. Thus, the Kc(Reed) values developed in this research project from the not within-stand phytometer record may be appropriate in the calculation of the ET(Reed) which might be expected from narrow reedbeds which often fringe water bodies, or from narrow channels/ditches in which *Phragmites australis* dominate (e.g. the Caldicot Levels).

The reedbed stands within which the majority of the ET(Reed) measurement were undertaken in this project did not exist as large (> 2 ha) continuous blocks, but as linear perimeter features surrounding waterbodies or as relatively small areas greatly exposed to advective conditions. It is anticipated that the Kc(Reed) values derived from previous research (see Table 9.6) were calculated from ET(Reed) measurements recorded in similar 'advection influenced' reed stands. However, this could not be confirmed as limited experimental design criteria could be discerned from the references. Thus, the Kc(Reed) values displayed in Table 9.5 should be applied where similar situations exist. These Kc(Reed) values are appropriate for use in reedbeds designed as bittern habitat as such systems often exist as semi-linear features which have a high proportion of reed : water interface within them, which increases air turbulence and thus increases ET(Reed).

The mean Kc(Reed) values produced from the works of other researchers are generally very similar to the Kc(Reed) values calculated in this project. This similarity would suggest that the Kc(Reed) values presented in Table 9.5 can be applied in the calculation of ET(Reed) across both the UK and continental Europe. In addition, the similarity between the Kc(Reed) values calculated for arid areas of the USA (Burgoon et al, 1997) may indicate that the Kc(Reed) values presented in Table 9.5 are applicable in arid areas, possibly in other continents. However, the value presented in Table 9.5 for October and November may not be applicable in continental climates where earlier senescence may require the use of the dormant period Kc(Reed) presented in Table 9.8.

The Kc(Reed) values presented in Table 9.5 allows the use of varying types of climatic data to determine ET(Reed). The presentation of a set of monthly Kc(Reed) values based upon ETo MORECS and ETo CROPWAT fulfils the recommendation set out by Smith (1990), that any Kc should be applicable to an ETo calculated using a form of the Penman-Montieth equation.

Within-stand Phytometers	**1971**	**1972**	**1973**	**Mean**
ETo Pan	2.12	1.67	1.91	1.90
ET(Reed)	3.82	2.42	2.75	2.99
Kc(Reed) Pan	1.80	1.45	1.44	1.58
Not Within-stand Phytometers	**1971**	**1972**	**1973**	**Mean**
ETo Pan	2.12	1.67	1.91	1.90
ET(Reed)	5.95	3.92	4.44	4.77
Kc(Reed) Pan	2.81	2.35	2.33	2.51

NB ETo and ET(Reed) values represent mean ET rates recorded between May and September (mm/day). Kc(Reed) values have no units.

Table 9.11 Calculated ET(Reed), ETo Pan, and Kc(Reed) - from Water Usage Data Presented by Bernatowicz et al (1976).

9.6 COMPARISON OF Kc(Reed) WITH Kc(Rice).

Of the crop coefficients [Kc(Crop)] presented by Doorenbos and Pruitt (1977), the crop which is most similar to reed in its characteristics, phenology and growing environment, is rice. Doorenbos and Pruitt present Kc(Rice) values for different: geographical locations; seasons; and meteorological conditions (see Table 9.12). The values of Kc(Rice) exhibit only very small variation between each of the different continental areas. The greatest variation in Kc(Rice) is experienced between intra-continental climates, with values presented for both 'wet' and 'dry' seasons. No intra-continental climatic variation in Kc(Rice) is shown during the first and second month after planting. The greatest variation is experienced between the values for 'Humid Asia', where, during the dry season, the Kc(Rice) applicable during the mid-season growth period is up to 23% higher than during the wet season. However, this is the maximum intra-continental climatic variation experienced, with the variation falling to 5% or less during the last four weeks prior to harvest.

The Kc(Rice) values presented for Europe (dry season), vary within the growing season (May-October) from between 0.95 to 1.30, dependant on growth stage and wind speed (see Table 9.12). No Kc(Rice) values are presented in Table 9.12 which are applicable to areas in Europe where relative humidities are greater than 70%. The Kc(Reed) values calculated during this research project have been developed within climates where relative humidity is greater than 70%, and therefore the values of Kc(Rice) for Europe are not directly comparable as they do not have the same intra-continental climate.

The Kc(Rice) values show only small inter-continental variations exist throughout much of the world. If a similar phenomena exists for Kc(Reed), the values developed in this research could be applicable worldwide. The similarity between the Kc(Reed) developed during this project and that calculated by other researchers working within different climates, may support the worldwide application of the Kc(Reed) values presented in Table 9.5. However, this hypothesis requires rigorous experimental testing prior to its adoption.

The effect of strong wind speed on the value of Kc(Rice) is quantified in Table 9.12. Strong wind speed raises the Kc(Rice) primarily during mid-season growth from 1.20 (light to moderate wind) to 1.30 (strong wind). It might be expected that this effect would be mirrored in Kc(Reed). Inaccuracies within the windspeed data for Himley, and the lack of short-term (daily) Kc(Reed) data from the TINR, preclude the further analysis and discussion of this point with respect to data recorded during this research project. However, if greater wind speed did have a similar effect on the developed Kc(Reed) as on Kc(Rice), this might have a significant impact on the Kc(Reed) applicable in areas with high mean wind speeds. It is possible that Kc(Reed) values applicable in coastal regions, particularly areas exposed to the prevailing wind direction, may experience greater ET(Reed) losses than might be calculated by the application of the

Kc(Reed) values presented in Table 9.5. The existence of this phenomena may have already been accounted for, as the presented Kc(Reed) values include a large proportion of data recorded from the flat, coastal site at the TINR, although the location of the site on the east coast of the UK, limits the exposure to high wind speeds during mid-season development.

	Planting Date	**Harvest Date**	**First & Second Month Kc(Rice)**	**Mid-Season Kc(Rice)**	**Last 4 weeks Kc(Rice)**
Hunid Asia					
Wet season (monsoon)	June-July	Nov-Dec			
light to mod. wind			1.1	1.05	0.95
strong wind			1.15	1.1	1
Dry season ##	Dec-Jan	mid May			
light to mod. wind			1.1	1.25	1
strong wind			1.15	1.35	1.05
North Australia					
Wet season	Dec-Jan	Apr-May			
light to mod. wind			1.1	1.05	0.95
strong wind			1.15	1.1	1
South Australia					
Dry summer	Oct	March			
light to mod. wind			1.1	1.25	1
strong wind			1.15	1.35	1.05
Humid S. America					
Wet season	Nov-Dec	Apr-May			
light to mod. wind			1.1	1.2	0.95
strong wind			1.15	1.3	1
Europe (Spain, S. France, and Italy)					
Dry season	May-Jun	Sep-Oct			
light to mod. wind			1.1	1.2	0.95
strong wind			1.15	1.3	1
USA					
Wet summer (south)	May	Sep-Oct			
light to mod. wind			1.1	1.2	0.95
strong wind			1.15	1.3	1
Dry summer (Calif.)	Early May	Early Oct			
light to mod. wind			1.1	1.25	1
strong wind			1.15	1.35	1.05

When RH(min)>70%, Kc values for wet season are to be used.

Table 9.12 Kc(Rice) Values Presented by Doorenbos and Pruitt (1977).

9.7 USE OF Kc(Reed) IN THE DEVELOPMENT OF A REEDBED WATER BUDGET APPLICABLE IN THE UK.

9.7.1 INTRODUCTION.

The use of a simple water budget equation to inform the hydrological feasibility of a reedbed development was described in Chapter Three. Equation 3.7 can be used in the calculation of a water budget applicable to reedbeds created within an impermeable clay catchment, and can be further simplified to:

$$\Delta V_{reedbed} = R - ET(Reed) \qquad (9.2)$$

where $\Delta V_{reedbed}$ = change in volume of water storage within a reedbed (m^3/ha)
R = rainfall input (m^3/ha)
ET(Reed) = reedbed evapotranspiration (m^3/ha)

A water budget calculation, based on Equation 9.2, is undertaken for the proposed reedbed creation area on the TINR in Section 9.8.

9.7.2 UK REEDBED WATER BUDGET BASED UPON MORECS DATA.

Mean monthly precipitation data and ETo MORECS Grass PE data were purchased from the Meteorological Office for each of the 190 MORECS Squares, for the period between 1961-1990, giving 12 values of P and PE for each Square. Limited financial resources precluded the purchase of data for each individual year. Mean monthly ET(Reed) totals were calculated from the ETo MORECS Grass data by the application of the monthly Kc(Reed) values presented in Table 9.5. ETo MORECS Grass data was chosen as the ETo as it is an accurate data source (Hough, 1997), available across the UK, for which a Kc(Reed) MORECS Grass had been developed. ETo MORECS Grass data does not provide a site specific calculation, however, it may be useful in the development of a UK reedbed water budget strategy. The 30 year mean monthly rainfall and ET(Reed) values were used within Equation 9.2 to calculate the monthly value of $\Delta V_{reedbed}$, for each of the MORECS Squares. A specimen of the calculated water budget spreadsheet is provided in Table 9.13.

If it is assumed that the winter water budget surplus is stored within the reedbed ecosystem, the monthly totals of $\Delta V_{reedbed}$ presented in Table 9.13, can be accumulated to produce an annual reedbed water budget volume. A negative water budget volume implies a net deficit, which would require the provision of an additional water source, should a reedbed habitat be created within the MORECS Square under consideration. Figure 9.11 displays the annual reedbed water budget total (m^3/ha) for each of the MORECS Squares and provides an indication of the areas of the UK where the development of a surface water fed reedbed habitat requires a water input in addition to that provided by rainfall.

In reedbed habitat developments where the storage of the winter surplus volumes is not possible (e.g. where no reservoir or pumping is available), it may be more appropriate to ignore the calculated winter surplus values (set to zero). The accumulation of mean monthly water budget deficits, with all surpluses ignored, provides a water budget deficit based on no winter surplus ($\Delta V_{reedbed\ nws}$). Figure 9.12 displays annual $\Delta V_{reedbed\ nws}$ for each of the MORECS Squares.

The water budget deficits presented in Figures 9.11 to 9.12 can be converted to L/sec per ha to provide an indication of the rate of additional water supply needed to sustain the water level within the reedbed habitat. This value can be used to inform the volumes for abstraction licenses and pumping rates, allowing the calculation of an annual cost of sustaining the water volumes within the reedbed ecosystem. The required flow rate varied between a maximum of 0.25 L /sec per ha for Square no. 163, to no flow rate required for approximately 20 Squares e.g. Square no. 112.

Recent research undertaken by the RSPB has suggested that within the majority of reedbed ecosystems, additional water volumes are required to facilitate a positive flow through the reedbed stand, particularly in highly eutrophic water bodies. Although the need for this positive flow has been identified, the flow rates have not yet been quantified (José, 1997). Equation 9.2 does not account for this additional volume. The impact of this additional requirement on the calculated water budget deficits displayed in Figure 9.11 and 9.12, would be to increase the number of MORECS Squares where both an annual $\Delta V_{reedbed}$ and annual $\Delta V_{reedbed\ nws}$ deficits occur. This in turn would increase the area of the UK in which additional water volumes would be required, in addition to rainfall, to adequately sustain the reedbed water budgets.

Square No. 80	Units	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann.
Rainfall (MORECS)	m^3/ha	555	398	499	447	523	539	529	642	528	534	649	578	**6421**
ETo MORECS Grass	m^3/ha	151	176	352	487	726	763	791	695	517	323	197	144	**5322**
Kc(Reed) MORECS Grass	none	0.81	1.01	0.70	0.90	0.85	1.33	1.40	1.68	2.15	1.89	1.16	1.10	**na**
ET(Reed)	m^3/ha	122	178	246	438	617	1015	1107	1168	1112	610	229	158	**7001**
ΔV reedbed nws	m^3/ha	0	0	0	0	-94	-476	-578	-526	-584	-76	0	0	**-2334**
ΔV reedbed	m^3/ha	433	220	253	9	-94	-476	-578	-526	-584	-76	420	420	**-580**

Table 9.13 An Example of a Reedbed Water Budget Calculation Based Upon MORECS 30 Year Average Data (1961-1990).

TINR 1994	Units	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann. Tot.
Rainfall Volumes	m^3/ha	650	450	210	420	360	225	165	410	710	700	600	805	**5705**
ET(Reed) Volumes	m^3/ha	155	168	471	576	735	1287	905	1132	729	577	237	288	**7260**
ΔV reedbed	m^3/ha	495	282	-261	-156	-375	-1062	-740	-722	-19	123	363	517	**-1555**
ΔV reedbed nws	m^3/ha	0	0	-261	-417	-792	-1854	-2594	-3316	-3335	0	0	0	**-3335**
TINR 1995	**Units**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Ann. Tot.**
Rainfall Volumes	m^3/ha	600	220	220	310	230	130	280	120	1060	220	870	530	**4790**
ET(Reed) Volumes	m^3/ha	161	204	431	585	657	1176	1600	1776	1422	1066	246	233	**9557**
ΔV reedbed	m^3/ha	439	16	-211	-275	-427	-1046	-1320	-1656	-362	-846	624	297	**-4767**
ΔV reedbed nws	m^3/ha	0	0	-211	-486	-913	-1959	-3279	-4935	-5297	-6143	0	0	**-6143**
TINR 1996	**Units**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Ann. Tot.**
Rainfall Volumes	m^3/ha	220	370	200	220	450	430	165	1260	120	260	620	490	**4805**
ET(Reed) Volumes	m^3/ha	84	202	248	471	698	1332	1330	1141	765	639	270	251	**7431**
ΔV reedbed	m^3/ha	136	168	-48	-251	-248	-902	-1165	119	-645	-379	350	239	**-2626**
ΔV reedbed nws	m^3/ha	0	0	-48	-299	-547	-1449	-2614	-2495	-3140	-3519	0	0	**-3519**

Table 9.14 Calculated Reedbed Water Budgets, TINR 1994-96.

TINR	Units	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann. Tot.
ΔV reedbed	m^3	75,180	119,220	31,110	12,960	20,730	15,540	10,380	5,190	22,050	38,880	75,180	75,180	**501,600**
ΔV reedbed nws	m^3	0	0	31,110	12,960	20,730	15,540	10,380	5,190	22,050	38,880	0	0	**156,840**

Table 9.15 Streamflow Estimates From Belasis Beck/Holme Fleet Catchment, TINR.

Square No. 91	Bittern LIFE Reserve	Units	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Rainfall (MORECS)	Leighton Moss (RSPB)	m^3/ha	1282	802	1008	766	756	836	853	1133	1224	1378	1365	1311	12714
ETo MORECS Grass		m^3/ha	95	129	289	475	766	778	786	700	481	296	151	85	5031
Kc(Reed) MORECS Grass			0.81	1.01	0.70	0.90	0.85	1.33	1.40	1.68	2.15	1.89	1.16	1.10	
ET(Reed)		m^3/ha	77	130	202	428	651	1035	1100	1176	1034	559	175	94	6662
ΔV reedbed nws		m^3/ha	0	0	0	0	0	-199	-247	-43	0	0	0	0	-489
ΔV reedbed		m^3/ha	1205	672	806	339	105	-199	-247	-43	190	819	1190	1218	6052
Square No. 120	**Bittern LIFE Reserve**	**Units**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
Rainfall (MORECS)	Walberswick (NNR) Minsmere (RSPB)	m^3/ha	572	410	494	481	486	533	573	599	530	594	696	622	6590
ETo MORECS Grass		m^3/ha	137	166	367	537	833	845	903	804	589	356	194	128	5859
Kc(Reed) MORECS Grass			0.81	1.01	0.70	0.90	0.85	1.33	1.40	1.68	2.15	1.89	1.16	1.10	
ET(Reed)		m^3/ha	111	168	257	483	708	1124	1264	1351	1266	673	225	141	7771
ΔV reedbed nws		m^3/ha	0	0	0	-2	-222	-591	-691	-752	-736	-79	0	0	-3073
ΔV reedbed		m^3/ha	461	242	237	-2	-222	-591	-691	-752	-736	-79	471	481	-1181
Square No. 142	**Bittern LIFE Reserve**	**Units**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
Rainfall (MORECS)	Cley Marshes (NWT) Titchwell (RSPB)	m^3/ha	502	354	434	437	435	468	484	492	505	539	610	531	5791
ETo MORECS Grass		m^3/ha	136	163	360	545	863	873	926	832	586	352	187	125	5948
Kc(Reed) MORECS Grass			0.81	1.01	0.70	0.90	0.85	1.33	1.40	1.68	2.15	1.89	1.16	1.10	
ET(Reed)		m^3/ha	110	165	252	491	734	1161	1296	1398	1260	665	217	138	7886
ΔV reedbed nws		m^3/ha	0	0	0	-54	-299	-693	-812	-906	-755	-126	0	0	-3644
ΔV reedbed		m^3/ha	392	189	182	-54	-299	-693	-812	-906	-755	-126	393	394	-2095

Table 9.16 Calculated Reedbed Water Budgets for MORECS Squares Containing Areas for Proposed Reedbed Development Under the Bittern LIFE Project. (Based Upon MORECS 30 Year Average Data, 1961-90).

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Figure 9.11 Annual Reedbed Water Budget for the MORECS Squares (m^3/ha).

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Figure 9.12 Annual Reedbed Water Budget for the MORECS Squares Assuming No Winter Storage (m^3/ha).

9.7.3 'WORST CASE SCENARIOS'.

Figures 9.11 to 9.12 were created using mean monthly long-term (30 year) data, providing an average value for reedbed water budget deficit. It would be appropriate to undertake a similar water budget calculation which used data recorded during a dry period, when rainfall was very low and calculated ET(Reed) was higher than normal to estimate the 'worst case scenario'. Meteorological data for the drought period of 1976-77 might be used in such an evaluation. However, limited financial resources prevented the purchase of the monthly MORECS data for this period.

The development of a worst case scenario water budget deficit could be used in the calculation of: the water budget recovery time (period to restore equilibrium within the mean water balance flux); a maximum abstraction consent; or maximum pumping volumes/costs. Although worst case scenario deficits may have a limited significance within an established reedbed ecosystem, the occurrence of such an extreme event during the planting and establishment period of a reedbed may be detrimental, if not, fatal to the success of the project. Therefore it may be necessary to provide a 'safety net' water volume which can be used, if necessary, during the first few seasons after planting. A form of worst case scenario water budget calculation, based on 1995 data is undertaken for the proposed reedbed creation area on the TINR in Section 9.8.

9.8 A REEDBED WATER BUDGET FOR THE TINR

Site specific monthly rainfall and ET(Reed) data recorded on the TINR between 1994-96, has been used to calculate a reedbed water budget based upon Equation 9.2. The monthly and annual values of $\Delta V_{reedbed}$ and $\Delta V_{reedbed\ nws}$ are presented in Table 9.14. The annual $\Delta V_{reedbed}$ varies between -1,555 m^3/ha and -4,767 m^3/ha.

Initial habitat proposals for the TINR identified an area for reedbed development of 40ha. Based upon the calculated values for 1994 and 1996 this habitat block would produce an annual $\Delta V_{reedbed}$ of approximately -83,600 m^3. During 1995 the annual $\Delta V_{reedbed}$ would have been approximately -190,700 m^3. Therefore, without additional water volume inputs the reedbed is not sustainable.

Catchment runoff calculations and monthly stream flow measurements have been used to estimate the annual streamflow volumes entering the site from the Belasis Beck /Holme Fleet catchment area. The monthly streamflow estimates are shown in Table 9.15, producing an annual total streamflow input of approximately 500,000 m^3. Thus, the mean annual streamflow input to the reedbed site is sufficient to compensate for the calculated annual $\Delta V_{reedbed}$ even during 1995.

If no storage is available in the reedbed, $\Delta V_{reedbed\ nws}$ deficits for the proposed reedbed begin to accumulate in March and continue to increase through the summer, reaching a maximum in early-mid autumn. The accumulated $\Delta V_{reedbed\ nws}$ for the proposed habitat block during 1994 and 1996 was approximately -137,000 m^3, whilst during 1995, this volume was approximately -245,700 m^3.

If no storage is available, streamflow inputs are only available during periods when monthly $\Delta V_{reedbed\ nws}$ is negative. The streamflow input from the Belasis Beck/Holme Fleet catchments occurring between March and October is approximately 157,000 m^3. This streamflow input is sufficient to compensate for annual $\Delta V_{reedbed\ nws}$ in 1994 and 1996. However, during 1995, even with streamflow inputs to compensate for the annual $\Delta V_{reedbed\ nws}$, an overall annual deficit of approximately -88,800 m^3 might still be expected if the 40 ha reedbed were in situ. This deficit is equivalent to a fall in water level of -220 mm (reedstem volume assumed insignificant) over the reedbed area of 40 ha. Thus, even with streamflow inputs, the majority of the reedbed would have become 'dry' in 1995. In addition, the streamflow was calculated using mean meteorological data, and the significantly lower streamflow which might be expected during an extreme year, would increase the water level/volume reduction estimates.

This discussion might lead to the rejection of reedbed creation on the TINR due to insufficient water input to the system. However, it must be stated that the period these calculations represent were considerably drier than the mean, with ET also slightly elevated, particularly in 1995. Without many years of meteorological data to compare against, it is difficult to ascertain a return period applicable to the data presented above. These conditions may constitute a rare event, with a return period of say 1 : 100 years, which might be acceptable as a basis for design. Thus, it is necessary to clarify the return period for the 'dry' reedbed which was predicted for 1995 prior to the rejection of reedbed creation on the TINR.

9.9 DISCUSSION.

It is essential that any proposals for the development of a reedbed habitat (e.g. Bittern LIFE Project) includes the accurate calculation of water availability within the creation area and its catchment. Water must be available to compensate for the annual water budget deficit, and sufficient supplies should exist to sustain the reedbed during periods of high summer deficit. The Bittern LIFE Project identified thirteen existing areas for the creation/restoration of large reedbed habitat units (see Section 2.5.3.3), with all but two occurring near to the Norfolk and Suffolk coastline (see Figure 2.2). The majority of the reedbed areas identified by the Bittern LIFE Project lie within MORECS Squares nos. 91, 120, and 142. A water budget calculation based upon Equation 9.2, and using 30 year mean MORECS data, was undertaken for each of these three Squares (see Table 9.16).

Square no. 91 contains the RSPB reedbed-dominated reserve at Leighton Moss. The water budget presented for this Square shows a moderately large (approximately 6,050 m^3/ha) annual water surplus, with only a very small $\Delta V_{reedbed\ nws}$ deficit (June to August) of less than -500 m^3/ha. The large reedbed areas at Walberswick Marshes (NNR) and Minsmere (RSPB) are located within Square no. 142. An annual $\Delta V_{reedbed}$ deficit of -2,095 m^3/ha was calculated for this area, with a $\Delta V_{reedbed\ nws}$ of almost -3,700 m^3/ha. A smaller annual $\Delta V_{reedbed}$ deficit (-1,181 m^3/ha) was calculated for the large reedbed areas at Cley Marshes (Norfolk Wildlife Trust) and Titchwell (RSPB), located in Square no. 120, with a slightly lower value for $\Delta V_{reedbed\ nws}$ deficit of almost -3,100 m^3/ha. The $\Delta V_{reedbed\ nws}$ deficits for Square nos. 120 and 142 occurred mainly between May and October, with a minimal deficit calculated for Square no. 142 during April.

From the above analysis it is clear that almost all of the sites identified within the Bittern LIFE Project, occur within areas where the water budget calculation based upon Equation 9.2, produces a marked annual $\Delta V_{reedbed}$ deficit, and a large $\Delta V_{reedbed\ nws}$ deficit. Similar deficits were calculated for the TINR, where, it would appear necessary to provide an additional water source which was available to supplement rainfall and streamflow supplies during periods of deficit.

The $\Delta V_{reedbed\ nws}$ deficits calculated for Square no. 142 would produce a reduction in mean water level within the reedbed of nearly -400 mm. If the bed cross-section were similar to those defined in Table 5.2, this would result in a large proportion of the habitat area existing as 'dry' reedbed with permanent standing water restricted primarily to open ditches and meres. A water level reduction within the proposed reedbed of -400 mm, may be detrimental to the ecosystem as a whole and extremely damaging to the target bird species (e.g. bittern), limiting food availability and feeding areas, possibly resulting in the migration/death of the bittern.

The creation of large, additional reedbed areas at the sites identified by the Bittern LIFE Project, may produce extra pressures on available water resources within areas where supply is already limited. This might not only incur economic costs, but could possibly result in the detriment of the water environment as a whole. One scenario might be that the additional reedbed areas created for the bittern, may, during a dry summer period, reduce the water level across the area as a whole to a greater extent than would have been experienced if no additional areas had been created. Within the Bittern LIFE Project the assessment of integrated water resources would allow an informed decision to be taken with respect to the sustainability of the existing reedbed reserves and any additional areas which might be created.

A natural hydrologically sustainable surface water fed system is one where hydrological inputs from precipitation (P) and surface water inflow (Si) are appropriately balanced both temporally and spatially with the hydrological outputs from the system (ET, Eo and So), such that the water level regime/hydroperiod of the designated habitat and identified target species are completely satisfied, and require no hydrological management.

The replacement of the annual $\Delta V_{reedbed}$ and/or $\Delta V_{reedbed\ nws}$ deficits could represent a significant economic cost in the management of a large reedbed area, requiring the possible abstraction of water from available adjacent resources. The period of lowest reedbed water levels will generally coincide with the lowest water levels/flows within adjacent streams, rivers and boreholes, and also the period of limited surface water runoff. Thus, reedbeds created within surface water fed clay catchments may have limited additional water supply resources available to compensate for the high summer ET(Reed) losses. In appropriate areas, the additional water source required during the summer could take the form of retained winter surpluses within an 'off-line' pumped storage reservoir.

Even on sites where the annual streamflow inputs are sufficient to compensate for $\Delta V_{reedbed}$ (e.g. the TINR), it is unrealistic to expect all of the streamflow volume to be available to fully compensate for the $\Delta V_{reedbed}$ deficit. Such a regime would reduce the availability of streamflow volume inputs into other aquatic/wetland habitats; e.g. wet /flooded grasslands, and to maintain the aquatic ecosystems of the stream itself.

Figure 9.11 shows areas in the UK where a reedbed acts as a 'net consumer' of water producing an annual $\Delta V_{reedbed}$ deficit. In a natural hydrologically sustained system, to compensate for this deficit a 'net producer' of water is required to balance the water budget e.g. sympathetically contoured grassland. If a reedbed habitat is to be created within a surface water fed clay catchment located within an area where direct rainfall input is insufficient to compensate for ET(Reed) losses (see Section 9.7), and no additional water is available from either streamflow or pumped sources, it is essential to calculate the area of hydrologically sustainable reedbed prior to construction.

In the majority of the areas in the UK where a large annual $\Delta V_{reedbed}$ deficit was calculated, Eo losses will also be greater than direct rainfall input. For example, taking MORECS Square no.142 the calculated value for annual open water deficit is -1,284 m^3/ha, with an accumulated summer deficit of -3,118 m^3/ha. Thus, any meres and ditches associated with a reedbed development may also contribute to the overall water deficit. The design and construction of a suitably large catchment area (usually grassland) surrounding the reedbed is necessary to supplement the reedbed water budget with surface water runoff volumes. If a surface water fed, clay catchment reedbed ecosystem were to be created within Square no.142, the surrounding grassland area necessary to sustain it can be calculated using a modified version of Equation 3.9:

$$\mathbf{Ag} = \frac{[\mathbf{P(Aw + Ar)}] - [\mathbf{ET(Reed)\ Ar + Eo\ Aw}]}{-\beta\,[\mathbf{Pnet}]} \qquad (9.3)$$

Assuming a total reedbed ecosystem of 100ha, with 15% open water and 85% reed (see Table 5.2), then the net annual deficit can be calculated for Square no.142 as -197 575 m^3. If the runoff coefficient (0.505) calculated using Equation 3.7 is applied to the winter surplus rainfall, an annual grassland runoff volume is calculated at 832 m^3/ha. Thus the area surrounding the reedbed ecosystem would need to be in excess of 240 ha to provide sufficient runoff to compensate for the annual losses. A ratio of reedbed ecosystem to surrounding catchment of 1 : 2.4 can be calculated using Equation 9.3, and could provide a guide to land requirements within Square no. 142, with the area of reed (85 ha) occupying a quarter of the total land area (340 ha). A reedbed ecosystem sustained in this way will experience a relatively large annual variation in surface water level which may be incompatible with other requirements (e.g. suitability for bittern).

From the water budget calculations undertaken in this Chapter it is possible to produce a tentative list of hydrologically-based criteria which should be considered during the feasibility study for a surface water fed reedbed ecosystem within a clay catchment. These criteria are listed in Table 9.17. The values of $\Delta V_{reedbed}$ and $\Delta V_{reedbed\ nws}$ used in Table 9.17 have been chosen to relate to those presented in Figure 9.11 and 9.12.

It might be more appropriate to target reedbed development 'moneys' within areas where calculated water budgets indicate an annual surplus, or at least only a small deficit. This may become more important as the need for additional volumes required to produce a flow through the reedbed becomes clear and is quantified by further research. Any additional water requirements would increase the area of the UK shown in Figures 9.11 and 9.12 where the annual water budget was not sustained by direct rainfall inputs, possibly to encompass all of England.

From the calculations in Section 9.7, the areas of the UK where the ET(Reed) losses are compensated for by direct rainfall input are primarily located in the west of England, Wales and Scotland. Reedbed establishment within these areas is unlikely to be hindered by any of the phenological restrictions discussed in Section 2.4.4 (Self, 1997). Self et al (1996) suggest that reedbeds should be created within areas presently colonised by the bittern. However, bittern has historically colonised reedbeds outside the existing hinterlands of Norfolk and Suffolk and there is a strong possibility that as a species it could do so again (Self, 1997).

Scenario Number	ΔV reedbed (m^3/ha)	ΔV reedbed nws (m^3/ha)	Reedbed Habitat Area (m^2)	Grassland Catchment Area (m^2)	Comments
1	> +1000	> or = 0	increase	decrease	Ensure reedbed will not 'drown out' by providing surface outflow channel.
2	> 0 but <+1000	> or = 0	no change	no change	Minimal water level adjustments may be required following 'extreme' periods.
3	> or = 0	<0 but > -2000	no change	no change	Ensure all winter surplus is retained.
4	> or = 0	< -2000	no change/dec.	no change/inc.	Ensure all winter surplus is retained, possibly pumped to 'off-line' reservoir. for application in Summer.
5	< 0 but >-1000	< 0 but >-2000	decrease	increase	Ensure no water is lost via streamflow etc. Provide additional supply - low annual volumes/costs.
6	< 0	< -2000	decrease	increase	Ensure water level changes are appropriate for target species. Provide additional supply - moderate annual volumes/costs.
7	< -2000	< -3000	decrease	increase	Possibly unsustainable without large additional water supply high annual volumes/costs. Possible impact on/by other water users and water environment.

Table 9.17 Criteria for Assessing the Feasibility of Reedbed Habitat Creation Within a Surface Water Fed Clay Catchment, based on Water Budget Calculations.

From a commercial viewpoint, the west of England contains a greater number of thatched properties than any other area (George, 1992). At present, most of these properties use imported thatching materials (see Section 2.4.6) and the advent of additional, local supplies might produce an 'economically viable' land-use, with the cost of pumping during 'drawdown' operations being offset by the income from the sale of reed bundles. In the longer term, money from commercial harvesting could be used to fund the development of larger reedbed areas.

In conclusion, for successful reedbed creation and the establishment of breeding target species, additional water supplies may be required within areas where $\Delta V_{reedbed}$ or $\Delta V_{reedbed\ nws}$ deficits occur. Even if sufficient catchment area is provided to produce a sustainable annual reedbed water budget, natural 'drawdown' caused by $\Delta V_{reedbed\ nws}$ deficits may mean additional supplies will be necessary to maintain optimum reedbed conditions. Additional supplies may also be required to compensate for possible 'losses' associated with water level 'drawdown' undertaken to allow management operations (e.g. reed harvesting), or to compensate for unforeseen circumstances, e.g. vandalism of retaining structures etc. Newly created reedbeds also require the influx of large capital water volumes during the habitat development phase, to produce optimum establishment conditions. However, it may be possible to reduce the necessity for an additional source during the construction period if the reedbed is developed in phases. For example, on the TINR, a phased development of the reedbed habitat would allow the capital volumes to be sourced from accumulated annual streamflow surpluses.

Chapter 10. THE HYDROLOGICAL DESIGN OF CREATED SURFACE WATER FED REEDBEDS.

10.1 INTRODUCTION.

Figures 3.2 to 3.4 present a set of conceptual models which have been developed for various wetland hydrological regimes. From these models, water budget equations applicable to the hydrological assessment of the feasibility and design of created wetlands were presented. These focused primarily on surface water fed reedbeds. The water budget models emphasised the need for a detailed study of ET(Reed) which, together with the calculation of Kc(Reed) has been the focus of this research project.

In fulfilment of Objective 4 (see Section 1.2) it is necessary to create a hydrological design methodology applicable to surface water fed reedbed creation (see Section 10.2). Techniques suitable for the assessment of each of the parameters contained within the water budget equations presented in Chapter Three are discussed in Section 10.3. These techniques are summarised in Table 10.1 with respect to their use within feasibility, design, and the establishment stage. In Section 10.4, data from the catchment area of the Pilot Pool, TINR (see Section 5.2.4) is used in the verification of the water budget model (see Figure 3.4).

Many of the theoretical and technical ideas presented in Section 10.3 are not discussed in detail, and the reader is referred to standard hydrological textbooks such as those by Shaw (1983) and Ward (1975).

10.2 A HYDROLOGICAL DESIGN METHODOLOGY APPLICABLE TO SURFACE WATER FED REEDBED CREATION.

The methodology presented in Figure 10.1 outlines a sequence of actions necessary to achieve the hydrological design of a created surface water fed reedbed, both with and without a streamflow input using the water budget models presented in Figure 3.3 and 3.4 respectively. The vast majority of scenarios are included within the methodology, which lead to four possible outcomes. These outcomes include: a hydrologically sustainable system; a pumped storage

/additional water system; a system which requires post construction modification; a scenario where wetland creation is not possible.

Initially, it is essential to ascertain the design criteria which are generally identified by a design team. It is necessary for the wetland hydrologist to form part of this team, which commonly includes members from other disciplines e.g. ecologists, landscape architects, civil engineers etc. In general, the wetland ecologists will supply a prescription of seasonal water depths for the habitat to be created and the habitat areas for the identified target species. The design team should also identify within the creation site existing areas where habitat creation is subject to constraints e.g. neighbouring SSSI's. Opportunities should also be assessed e.g. extension or integration of existing wetland habitats.

The collection of relevant hydrometeorological data forms an important part of the methodology. Hydrometeorological monitoring should be undertaken where possible to provide data at a site specific level (see Section 10.3). The hydrometeorological data is used within the appropriate water budget model to initially ascertain whether the water budget is appropriate for the development of the proposed design, and if sufficient water volumes exist to fulfil the overall habitat requirements.

Should the water budget be unsustainable it is necessary to identify additional water sources which are suitable for supply purposes. If the water budget calculations identify that there are sufficient volumes on an annual basis, but seasonal distribution produces deficits, it may be possible to compensate for these deficits by the incorporation of water storage areas within the design. If no additional supplies can be identified, it may be pertinent to redefine the design criteria to determine the area of wetland habitat which is sustainable within the site's water budget constraints (see Section 9.7). The new habitat areas/specifications are used within the water budget model to confirm that the new budgets are sustainable. Even if the water budget confirms that these areas are hydrologically sustainable, the scheme may be rejected by the design team if the overall habitat specifications are outside the initial design constraints e.g. if the habitat area is insufficient to support breeding bitterns. The establishment of habitat areas which do not fulfil the initial specifications should only be undertaken if this is acceptable to all parties concerned. Hydrologically unsustainable reedbeds will require the design and implementation of a management programme which will necessitate an on-going financial input.

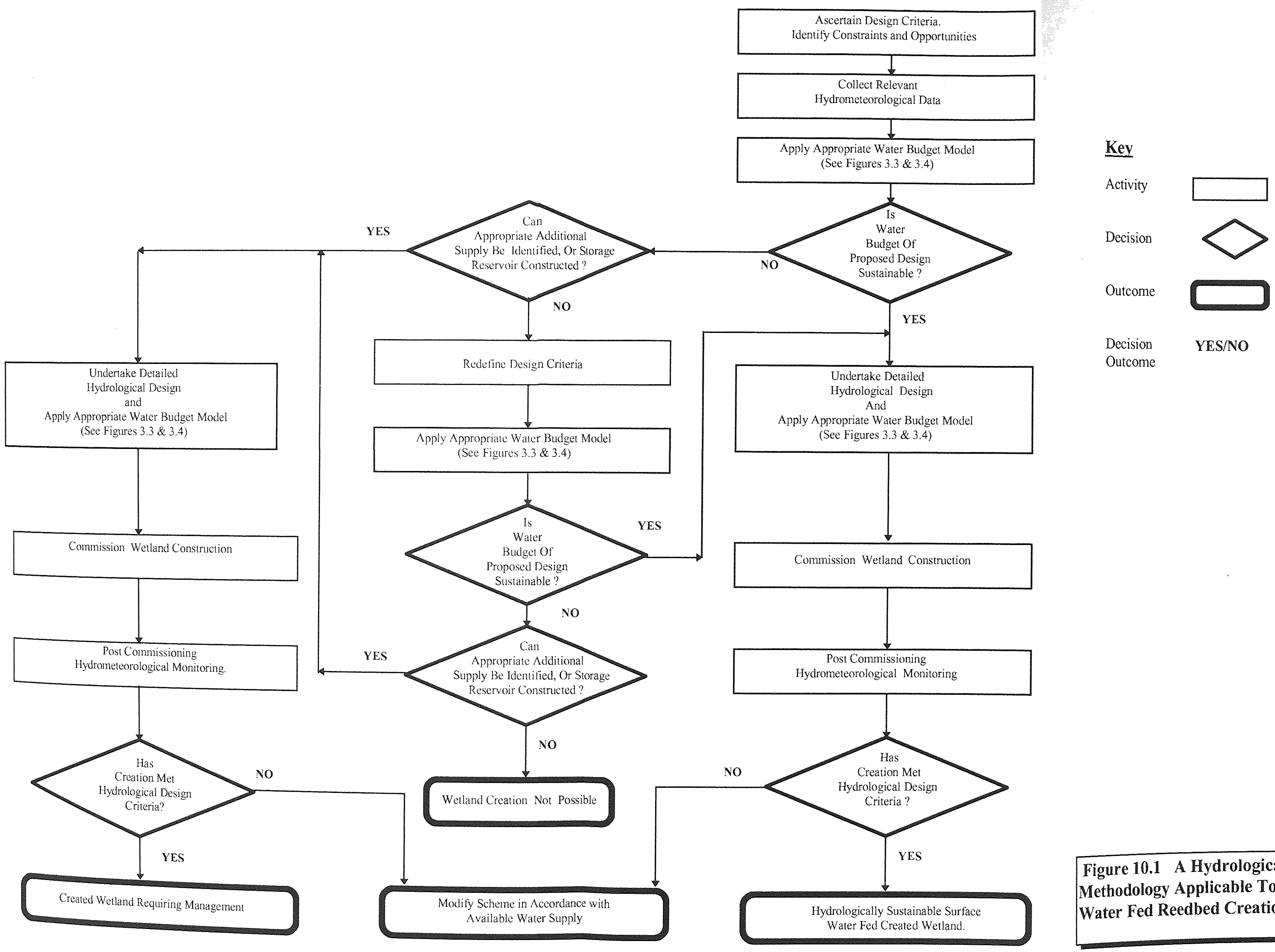

Figure 10.1 A Hydrological Design Methodology Applicable To Surface Water Fed Reedbed Creation.

Wetland habitat should not be created if the water budget model identifies insufficient water volumes and no additional supply is available.

If through the application of the water budget model it can be shown that the hydrological design specifications can be fulfilled, a detailed design should be undertaken prior to the commissioning of the wetland construction, to inform the need for reprofiling activities and the location of retaining structures etc. Detailed design should also address further issues, e.g. identify flood alleviation opportunities. It may also be possible to reduce the overall maintenance and management of the habitat areas if additional facilities are incorporated within the hydrological design. For example, the division of habitat into hydrologically separate areas may allow rotational management and harvesting in *Phragmites australis* reedbeds which may reduce the accumulation of reed litter, thus minimising the need for costly reprofiling.

Post commissioning hydrometeorological monitoring should be undertaken to identify the success of the creation scheme in fulfilling the initial project design criteria. This monitoring data should be used in conjunction with the appropriate water budget model to ascertain the impact of actual site conditions on the water budget of the created ecosystem. If the design criteria have not been met it will be necessary to modify the scheme in accordance with the actual available water supply.

10.3 ASSESSMENT OF WATER BUDGET PARAMETERS.

10.3.1 TIDAL INFLOW/OUTFLOW.

One parameter which is not obviously apparent from Figure 3.2, but is presented by Mitsch and Gosselink (1993), is the tidal influence (see Equation 3.3). With many existing, and proposed reedbed habitats located within coastal locations (see Figure 2.1) the hydrological impact of tidal volumes is potentially of great significance. An assessment should be made of the periodicity and volume of tidal water onto any reedbed creation area. This may be achieved from the study of historical sea-flood information available from the Environment Agency (EA). For design, it is advisable to assess the impact of sea-level rise on proposals.

After establishment, the encroachment of tidal volumes via poorly operating non-return valves fitted to outfall culverts can be detected using a salinity/temperature probe installed within the outfall watercourse. George (1992) identifies other hydrologically related design methodologies associated with the impact of tidal waters.

10.3.2 GROUNDWATER.

The inclusion of groundwater would not seem appropriate within a project remit for the hydrological design of surface water fed reedbed systems. However, before a methodology for such a system can be applied it is necessary to assess whether a creation site has a groundwater component.

At an initial feasibility stage it may be possible to inform the likelihood of a groundwater flux by study of an appropriately scaled geological map. This may be supplemented by additional information with respect to soil and subsurface conditions available from the Soil Survey of England and Wales (1983). More detailed information (borehole records etc.) may be available from the British Geological Survey, and a list of wells and abstraction boreholes within 2km of the creation site can be purchased from the EA. A survey of aerial photographs and maps will identify any spring/seepage lines which occur on site or adjacent the site boundaries. These features can be confirmed during a 'walkover' survey.

For design, it is advisable to install on site a set of piezometers and dipwells to provide information on the depth of the water table, and the likelihood of horizontal groundwater flux. These monitoring points must be carefully installed to limit the occurrence of anomalous 'local' readings, particularly within clay sediments. Any sediments encountered should be logged in accordance with BS 5930 (1981). The monitoring points should be located in a series of transects across the proposed creation area to inform the homogeneity of the underlying sediments and the direction of any lateral groundwater flow. Monitoring points should also be included on areas adjacent to proposed creation site to assess the changes in groundwater flux after establishment.

Water Budget Parameter	Assessment Technique		
	Feasibility Stage	**Design Stage**	**Establishment Stage**
Tidal	Contact EA Flood/Coastal Defence Officer.	Land Drainage Consent - EA Assess Impact of Sea Level Rise (Brown, 1994).	Ensure coastal defences are competent.
Groundwater	Geological Maps - BGS. EA Groundwater Section.	Assess on-site hydraulic conductivity Install monitoring positions - dipwells etc. Pumping test if appropriate.	Monitor dipwells etc. on adjacent land to assess impact of creation on environs.
Streamflow	Contact EA Catchment Officer, IDB engineer Estimate flows using catchment area equations.	Seek abstraction/discharge consents and Land Drainage Consent if appropriate (EA) Gauge flows using area-velocity technique.	Ensure inlet/retaining structures/pumps are maintained/operated appropriately.
Surface Inflow	Establish runoff coefficient. (Thomasson, 1978, and Farquarson, 1978) Assess size and topography of catchment.	Assess runoff coefficient using measured infiltration rates and rainfall intensity data.	Runoff coefficient may be increased by removal of vegetation and soil compaction. Measure actual runoff volumes as a function of water level rise - direct precipitation
Surface Outflow	Soil Survey Maps.	Install access tubes to allow soil moisture to be assessed using neutron probe.	Reduce excess surface outflow by construction of small, engineered bunds.
Precipitation	MORECS data (Met. Office) or nearest station (EA) - Worst case scenario data.	Site specific measurements Correlation with feasibility data.	Continual measurement will inform additional volume requirements.

Table 10.1 Data Acquisition for the Hydrological Design of Surface Water Fed Reedbed Systems.

Water Budget Parameter	Assessment Technique		
	Feasibility Stage	**Design Stage**	**Establishment Stage**
Open Water Evaporation	MORECS - Worst case scenario data. Eo calculated from ET(Grass) PE using coefficients (see Table 7.7).	Site specific MORECS Eo Epan measurements adapted using coefficients (see Table 4.3).	Continual measurement will inform additional volume requirements.
ET(Grass)	MORECS Grass PE and AE Worst case scenario data.	Site specific MORECS Grass PE and AE CROPWAT if appropriate site specific met. data is available.	Continual measurement will inform additional volume requirements.
ET(Reed)	Kc(Reed) MORECS Grass applied to Worst case scenario data for MORECS Grass PE.	Measurement of ET(Reed) using within-stand phytometers.	Continual measurement will inform additional volume requirements.
Habitat Areas	Area defined by target species requirements.	Water budget calculation informs sustainability of areas. Adjust if appropriate or provide additional supply or storage.	Actual fluxes in water budget will influence actual habitat areas.
Water Storage	Calculate storage volumes from initial habitat area and specifications.	Assess existing capital volumes. Provision to store winter surplus volumes.	Assess changes in storage volume resulting from siltation etc.

Table 10.1 (cont.) Data Acquisition for the Hydrological Design of Surface Water Fed Reedbed Systems.

If a potential groundwater supply is identified at depth, below an impermeable horizon (aquiclude) it may be possible to use this water to adjust any seasonal deficits calculated in the surface water budget. The potential yield from such a source can be calculated using Darcy's equation (Ward, 1975), which expresses the relationship between percolation velocity, permeability of water-yielding materials, and the hydraulic gradient. Actual yields may be assessed via a pumping test. An abstraction license must be obtained from the EA prior to the onset of pumping. Falling-head tests may also be undertaken within dipwells/boreholes to inform the hydraulic conductivity of the near-surface sediments to ascertain the likely seepage losses from any created habitat. The hydraulic conductivity may also be used to assess the impact of any lateral migration of water away from the created habitat on neighbouring land-use activities. A low hydraulic conductivity for both horizontal and lateral movement precludes significant seepage losses or gains.

10.3.3 STREAMFLOW.

Wetlands designed within floodplains are likely to have a significant streamflow. Baseline flow volumes and characteristics are available for most rivers and large streams from the EA and/or the relevant Internal Drainage Board.

Abstraction and discharge consents may be necessary if streamflow volumes are to be utilised within the created area. Consents are provided by the EA, however, they may not be available for abstraction during the summer period when the water inputs are needed to compensate for ET(Reed) losses. Thus, the proximity of the created system to the floodplain may not be advantageous in water budget terms, unless storage is available. Construction of wetlands within floodplain areas will also require land drainage consent from the EA to ensure that the wetland will not increase the flooding risk.

During a feasibility study it may be necessary to estimate streamflow using theoretical models of the upstream catchment area, particularly in 'non-adopted' streams. For design, it may be appropriate to monitor streamflow which should be undertaken both upstream (input) and downstream (output) of the wetland creation site, to inform the potential impact of additional habitat establishment on the water balance of the stream. It may be possible to install a weir which can be monitored using a depth probe connected to a data-logging device which can be downloaded via a telemetry link or during the site monitoring visits. If this is not possible, regular site visits will be necessary to monitor flows with a velocity meter.

Created wetlands located on floodplains will commonly exist within highly permeable alluvial zones where the water balance may be supplemented by groundwater inflows during periods of low streamflow inputs. Thus, these wetlands are not entirely surface water fed and are outside the remit of this research. In areas of impermeable substrates within floodplains the creation of surface water fed wetlands may be possible as streamflow volumes contribute to overall water budgets over and above rainfall inputs, supplementing for ET losses. This supplementary volume may be in the form of controlled water inputs to wetlands via a control structure or pumping.

The creation of wetland areas within floodplains which are isolated from streamflow fluxes may allow more precise control of the water level management regime, as the stochastic variability of streamflow is eliminated, possibly to the benefit of target species (Hawke and José, 1996). Much of the fenland areas of Lincolnshire and East Anglia, where a large proportions of the rivers are contained within embankments, with little hydraulic continuity with their floodplain, have the potential for construction of off-line wetlands.

10.3.4 SURFACE INFLOW.

Eisenlohr et al (1972) state that the infiltration capacity of the soil controls the amount of surface runoff. However, they conclude that even in clay dominated catchments the amount of surface runoff is very unpredictable and is dependant on antecedent conditions, asserting that:

> "even on an annual basis, there seems to be no correlation between precipitation and basin inflow".

During a feasibility study it may be necessary to estimate the infiltration capacity, to assess accurately a value for surface runoff, and develop a site specific runoff coefficient (β) (see Section 3.7.3). For design, the actual infiltration capacity of the created wetland catchment area can be measured using a dual-ring infiltrometer. If this activity is undertaken on a monthly basis a runoff coefficient can be developed in conjunction with rainfall intensities for use within water budget equations.

Surface runoff only occurs when precipitation rate exceeds infiltration capacity of the soil. Low intensity rainfall events will tend to infiltrate the soil surface, whilst during high intensity events surface runoff will occur, particularly in soils with low permeability which are saturated or where surface capping has occurred encouraging runoff. Rainfall intensity measurement is discussed in Section 10.3.6.

Surface runoff volumes are also dependent on the size and configuration of the catchment area of the created wetland area. Slope gradients can be estimated from topographical data. However, the actual runoff from large catchment areas into the wetland system may be lower than predicted as a proportion of the catchment area may be non-contributing except during periods of high runoff (Eisenlohr et al, 1972). In such circumstances consideration may be given to regrading to maximise the surface inflow.

A water level recorder could be installed within a pilot study area. The water level data can be used to assess the relationship between rainfall intensity and duration, the catchment area, and the changes in water level and volumes experienced within the wetland ecosystem.

10.3.5 SURFACE OUTFLOW.

Surface outflow takes the form of overland or throughflow. Within surface water fed reedbed systems which are not integrated into a drainage network, and have no streamflow component, surface outflow forms the principal non-atmospheric loss from the system. Outflows occur primarily during periods of high water level within the wetland system, with the volume losses recorded as gains within the surrounding terrestrial area. Surface outflows within impermeable sediments can be reduced by the construction of small bunds.

The occurrence of surface outflow can be assessed with reference to the hydraulic conductivity of the near surface sediment and soil horizons, combined with the designed topography of the created wetland and its environs. Actual surface outflow is very difficult to measure (Eisenlohr et al 1972).

It may be possible to quantify overland flow if a representative area is bunded, and the flow directed into a channel, thus enabling monitoring (see Section 10.3.3).

Estimates of throughflow may be possible using a Wallingford Neutron Probe (Bell, 1976). During the design stage it is advantageous to undertake a pilot study in a location which has the same hydrological characteristics as the final created wetland. A set of access tubes are then installed in a transect line beginning at the edge of the trial area and moving away from the trial site perpendicular to the edge. The soil moisture levels recorded from the access tubes installed adjacent to the trial area are compared to those located further away to provide a quantitative assessment of the effect of the change in water levels within the trial area on soil moisture in the adjacent environs. Thus, allowing a volume of throughflow to be estimated.

Neutron probe studies of soil moisture at Redwick were undertaken by EHC on behalf of CBDC as part of the wetland creation feasibility studies. These works showed that the movement of water from within a waterbody to the surrounding environs was minimal within the clay sediments which occur on the site. Surface outflow only occurred if water levels were high enough to provide sufficient head to produce overland flow.

In areas where surface outflow does exist a greater length of shoreline per unit area of reedbed ecosystem may increase the amount of surface interchange with the surrounding area (Millar, 1971). This could possibly increase the inflow into the reedbed in the winter and increase the outflow during the summer, resulting in greater water level fluctuations, which may be disadvantageous to target species.

Surface outflow may enter topographical low areas within the environs of the designed wetland habitat, creating ponded surface water and saturated sediment areas which may be attractive to wading birds e.g. snipe.

10.3.6 PRECIPITATION.

Within surface water fed reedbed systems with no streamflow inputs and limited surface runoff, precipitation is the principal input to the water budget, and characteristically exhibits both spatial and temporal variability. For a feasibility study it may be appropriate to use data recorded from the nearest rainfall recording stations, available from the Meteorological Office or from the Regional Water Company Plc., or MORECS data from the relevant Square. Long-term (30 year) mean annual or preferably mean monthly rainfall data forms an essential part of any hydrologically based design methodology. 'Worst case scenario' calculations should be undertaken using data recorded during a drought period e.g. 1976-77. If MORECS rainfall data is to be used the relevant Square must be representative of the creation area.

During design, the installation of a raingauge on the wetland creation site will allow the development of a correlation between the site-specific rainfall and that estimated from neighbouring stations. Rainfall intensity can be recorded using a tipping bucket raingauge connected to a data-logging system. After establishment, the continued measurement of rainfall will allow an estimation of additional volume requirements.

10.3.7 OPEN WATER EVAPORATION.

For a feasibility study, the most appropriate source of Eo data within the UK is MORECS, which can be purchased from the Meteorological Office for various time periods (e.g. monthly, weekly etc.). MORECS Eo data can be calculated from MORECS Grass by the application of the coefficients presented in Table 4.6. MORECS Eo estimates have shown a strong correlation with actual Eo (Hough, 1997), and the use of 30 year mean monthly data and worst case scenario data is recommended.

For design, the use of single-site MORECS Eo data (see Section 4.4.3.4) is recommended as this should minimise the inaccuracies inherent in the use of mean data representative of the standard 40 km by 40 km squares. The use of US Class A Evaporation Pan measurements in conjunction with the pan coefficients presented in Table 4.7 can also provide an indication of Eo at a site specific level, however, the data produced may be subject to anomalies (see Section 7.3.2).

In the UK evaporation pan measurements have shown a strong correlation with MORECS Eo data which has resulted in the measurement of Epan being superseded by MORECS (Hough, 1997). However, Epan data may be the only Eo equivalent measurements available in certain countries (Smith, 1990).

10.3.8 EVAPOTRANSPIRATION.

Potential ET(Grass) can be calculated using well established estimation equations (see Section 4.2), however, these equations generally require the use of a large number of input parameters which may not be available for the site of the wetland creation area. Within the UK, MORECS ET Grass AE and PE data (based upon the Penman-Montieth equation) are available as a mean Square value, and as site-specific MORECS. MORECS ET(Grass) data is strongly correlated with field observations (Hough et al, 1995) and is recommended for use within UK feasibility studies. AE Grass data is used in conjunction with rainfall data to calculate runoff volumes using a runoff coefficient (see Section 3.7.3).

For design, site specific MORECS data may be appropriate for use, however, a site specific value of ETo [comparable to ET(Grass) PE] based upon the Penman-Montieth equation can be calculated using CROPWAT (Smith, 1992). This requires access to meteorological measurements of sunshine hours, temperature, relative humidity and windspeed, which can be obtained by the installation of the appropriate equipment. This method requires the purchase and maintenance of relatively expensive equipment which must be regularly monitored either by a datalogger or during regular site visits, and has proven in the case of the TINR to be vulnerable to equipment failure.

ET(Reed) can be estimated using the Kc(Reed) values presented in Table 9.5 with the appropriate ETo measurements. Where possible the ETo should be based upon the Penman-Montieth equation. Within the UK, the use of ETo MORECS Grass is recommended in conjunction with the monthly Kc(Reed) MORECS Grass. To estimate the ET(Reed) which might be expected from a 'dry' reedbed with mean water levels below the ground surface (e.g. root-zone treatment works), the use of the Kc(Reed) values developed from Himley STW during 1996/97 is recommended (see Tables 9.1 to 9.4).

If a reedbed already exists within the area designated for creation, ET(Reed) can be directly measured using within-stand phytometers after an establishment period which should be a minimum of 1 year in duration. If there is no existing reedbed, and no ETo data which could be used to calculate ET(Reed), phytometers can be located not within-stand, with the data adjusted using the coefficients presented in Table 8.2. If standing crop data is also recorded an estimate of ET(Reed) within-stand can be calculated (August only) using Equation 8.4. Site specific rainfall measurements are essential if ET(Reed) is to be measured accurately.

Doorenbos and Pruitt (1977) present Kc values for a wide range of crops and vegetation types which can be used to estimate ET(Crop) (see Section 4.3). Within the UK, ET(Crop) estimates (e.g. barley, deciduous trees etc.) are directly available from the Meteorological Office, based upon the MORECS system.

10.3.9 HABITAT AREAS.

The area of each wetland habitat to be created may be dictated by the requirements of the target species. An initial water budget based upon these areas will inform the hydrological sustainability of the created area and identify the need for additional water supplies. If these water budgets produce a marked annual water budget deficit, and no appropriate additional water supply can be found then it will be necessary to change the ratio of habitat areas to provide more 'net producers' and less 'net consumers' of water (see Section 9.9). A calculation undertaken in Section 9.9 produced a ratio of catchment area (net producing) to reedbed areas (net consuming) of 3 : 1. Although this calculation was specific to MORECS Square no. 142, the ratio may be tentatively applied within clay catchments across much of the south-east of England, particularly East Anglia. After establishment the actual fluxes in the water budget will influence the actual area of each habitat.

10.3.10 WETLAND STORAGE.

Equation 3.1 shows that the fluxes in the water budget produce corresponding fluxes in wetland storage. The calculation of changes in storage within a created reedbed ecosystem are detailed in Section 10.4. During feasibility, water storage volumes can be calculated from the habitat areas, using knowledge of their hydrological specifications and the topography. Wetland water storage may be provided through sympathetic site grading and/or the installation of retaining structures to raise water levels. Site grading may be essential if the existing topography is not compatible with the final habitat specifications. It is advisable to incorporate flexibility within the maximum storage volumes to allow for siltation etc. After establishment, the impact of siltation and reed-litter build up on storage volumes should be assessed to inform dredging periodicity etc.

To allow accurate water level management, it may be necessary to provide 'off line' storage areas within reedbed creation schemes. These storage areas are essential in areas where water budget deficits occur regularly, allowing additional water to be introduced as necessary. Storage of winter water budget surpluses may be essential to successful reedbed establishment.

10.4 VERIFICATION OF THE WATER BUDGET MODEL.

10.4.1. INTRODUCTION.

Section 3.7 asserted the need to verify the developed conceptual models and the derived water budget equations (Equations 3.2 and 3.9). These equations are used to calculate an estimate of the monthly volume changes ($\Delta\mathbf{V}$) which occur within the Pilot Pool waterbody, TINR. The data necessary for input into these equations has been previously presented above. The assumptions inherent within these equations were detailed in Section 3.7, with additional site specific assumptions highlighted in Section 10.4.4.1.

Verification of the clay catchment water budget model can be undertaken using water storage data from the Pilot Pool. $\Delta\mathbf{V}$ can be determined using Equation 3.8. Waterbodies located within a wetland area, with associated low slope gradients may exhibit relatively large changes in mean water surface area ($\overline{\mathbf{A}}$) associated with relatively small changes in surface water level ($\Delta\mathbf{H}$). Thus, any study undertaken to verify a water budget model using $\Delta\mathbf{V}$ requires accurate measurement of the catchment characteristics which affect $\Delta\mathbf{V}$, primarily $\Delta\mathbf{H}$ and $\overline{\mathbf{A}}$. The topographical data required in the calculation of $\Delta\mathbf{V}$ is discussed in Section 10.4.2. Section 10.4.3 outlines the use of a Digital Elevation Model (DEM) of the Pilot Pool catchment area in the calculation of $\Delta\mathbf{V}$. The DEM was created using a Geographical Information System (see Appendix 7).

The measurement of water level (**H**) and hence $\Delta\mathbf{H}$ within the Pilot Pool was facilitated by the installation of a permanent standard metric gauge board, with monthly values recorded to an accuracy of 0.01m. The maximum and minimum recorded water levels (**H**) during the period January 1994 to December 1996 were 2.08 mAOD and 1.54 mAOD respectively.

10.4.2 PILOT POOL CATCHMENT AREA - TOPOGRAPHICAL DATA.

The calculation of an accurate figure for monthly $\overline{\mathbf{A}}$,requires the provision of high resolution topographical data for the areas of the waterbody subject to non-permanent inundation: the pool perimeter, and island fringes. A topographical survey of the Pilot Pool catchment area had been undertaken by the TDC during 1993, however very few spot heights were recorded within the waterbody fringes. The majority of those that were recorded, are located within a small section of the northwestern corner of the waterbody. The paucity of spot heights and their clustered nature would distort any digital mapping data interpolated from their use (Elgy, 1997).

The Pilot Pool and associated catchment area were constructed from a design drawing detailing contours between 0.0 mAOD and 6.00 mAOD at 0.5 m intervals. The finished ground levels and bank gradients/profiles were verified in 1993 (TDC, 1993). Minor siltation had occurred in certain areas within the waterbody, however, the majority of the deposition areas were located at profile levels below the minimum recorded water level, resulting in a reduction in the capital storage volumes, but not affecting the storage fluxes. A copy of the design drawing (not presented here due to poor quality of reproduction) was used to establish the topographical characteristics of the Pilot Pool catchment area. However, it is important to recognise that the level of accuracy and detail of any digital data can only be as good as that of the original documentation.

10.4.3 DIGITAL ELEVATION MODEL (DEM).

The digitised contour data was input into a GIS (IDRISI). The elevation of the area between each contour is interpolated within IDRISI to produce a Digital Elevation Model (DEM) (see Figure 10.2). The upper right hand corner of Figure 10.2 is outside the catchment area boundary line, and is not representative of the site itself. The "visual step" in the image seen in this part of Figure 10.2 is produced by "noise" from the DEM creation process (Elgy, 1997). Manipulation of the DEM within IDRISI allows the total area of a given height within the range 1 to 300 cm (0.01 mAOD to 3.00 mAOD) to be calculated. The HISTO module of IDRISI was used to output data as an attribute values file. The computed area data (number of pixels) representative of a respective integer value (height) were exported into an EXCEL spreadsheet package for analysis. The output surface contour data facilitates the calculation of $\overline{\mathbf{A}}$ at various water levels (**H**). Monthly fluxes within the water budgets are calculated, with the corresponding volumetric changes within the waterbody calculated using the data output from the DEM.

10.4.4 MODEL VERIFICATION - A COMPARISON BETWEEN ACTUAL AND CALCULATED VALUES OF H AND ΔH.

Two water budget calculations were undertaken. Firstly, a simple water budget using Equation 3.2 was calculated, to inform the dynamics of a reedbed ecosystem only with no catchment runoff inputs. Secondly, a whole catchment water balance study was attempted based upon Equation 3.9. A comparison between the actual and calculated values of **H** and Δ**H** was undertaken to verify the water budget model.

10.4.4.1 Input Data And Inherent Assumptions.

The water budgets have been calculated using ETo MORECS Eo and ETo MORECS Grass values for open water evaporation and grassland evapotranspiration respectively. ET(Reed) values were generated from within-stand phytometer measurements from the experimental site, with the dormant period data being calculated by the application of Kc(Reed) MORECS Eo to the respective ETo. Site specific rainfall data was logged by the TINR automatic weather station. The runoff coefficient (0.505) was calculated using Equation 3.7.

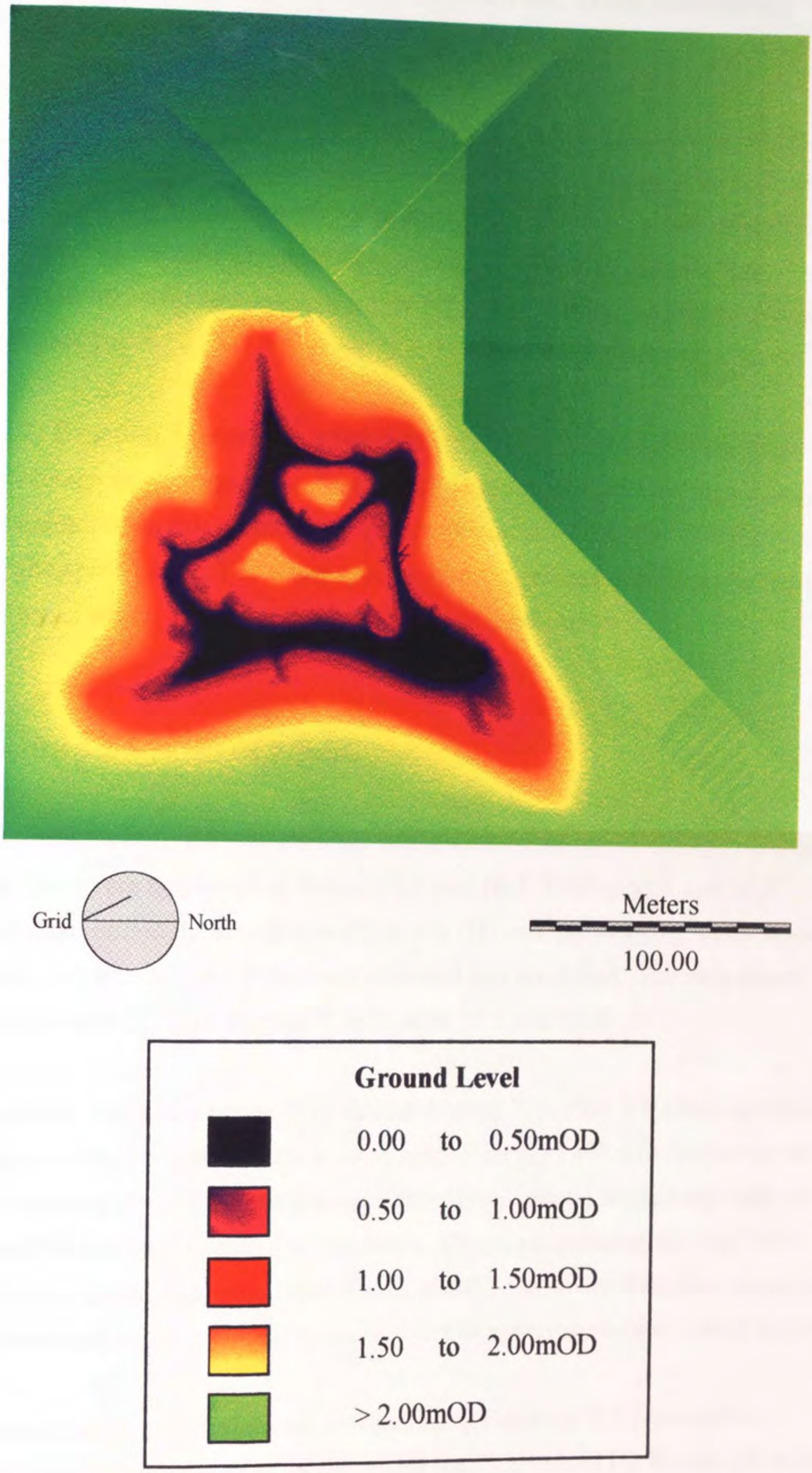

Figure 10.2 Pilot Pool Catchment Area - Digital Elevation Model.

Addition assumptions inherent within Equation 3.9 have been applied within the water budget calculation undertaken for the Pilot Pool. These assumptions include;

1) the water level within the Pilot Pool reaches a maximum level of 2.08 mAOD, at which point water outfalls to the Haverton Hole Reedbed Complex. Thus, any predicted water level greater than 2.08 mAOD is reset to 2.08 mAOD, simulating actual conditions. If this was not undertaken further calculations of $\Delta\mathbf{H}$ would be distorted by an erroneous value for $\overline{\mathbf{A}}$.

2) Equation 3.9 contains a function for the calculation of intra-month change in water/grassland area ($\Delta\mathbf{A}$). Within the Pilot Pool water budget calculations this would produce a feedback loop/circular reference within the spreadsheet. The water volume flux was calculated using the habitat areas which existed at the end of the previous month.

10.4.4.2 Analysis Of Results.

The data used within the water budget calculations, and the calculated monthly volume fluxes are displayed in Tables 10.2 and 10.3. Tables 10.4 and 10.5 respectively contain the monthly water levels (**H**) and the monthly water level changes ($\Delta\mathbf{H}$) for the Pilot Pool, both recorded and modelled. The data from Tables 10.4 and 10.5 are displayed in Figures 10.3 and 10.4.

The monthly water level data (**H**) calculated using Equation 3.2 shows a moderate correlation with the actual water level recorded during 1994 and the spring of 1995. However, during the summer of 1995 the calculated water level falls to a point well below that of the recorded value. This is exacerbated during 1996, when in August the calculated water level was 0.55 m lower than that recorded. This divergence reflects the cumulative effect of ignoring surface runoff inflows.

The water budget calculations undertaken using Equation 3.9 produced a reasonably accurate prediction of the actual monthly values for **H** and $\Delta\mathbf{H}$ within the Pilot Pool (see Figures 10.3 and 10.4) with a minimal annual bias. The largest error within the calculated data appears to be the over-estimation of the fall in water level during July and August. This over estimation shows a small negative bias and may highlight possible measurement errors or indicate that a surface runoff component enters the waterbody during this period.

It is possible that the ET(Reed) measurements recorded from the within-stand phytometers are not representative of the actual ET(Reed). However, the reedbed area (0.3 ha) is small when compared with the waterbody (approx. 1.4 ha), and the whole catchment area (3.0 ha). Thus the impact of an error in ET(Reed) is perhaps less significant than within a waterbody/catchment area where the proportion of reedbed was greater. An over-estimation of the ETo MORECS Eo value during this period would have a greater significance to the accuracy of the water budget of the Pilot Pool, although this is unlikely to have occurred (see Section 7.3.2), although the total Eo might have been distorted by errors in the measurement of waterbody area. However, the most probable reason for the over-prediction of falls in summer water level is produced by the assumption that no runoff enters the waterbody during the summer. In reality much of the northern catchment area is poorly vegetated, heavily compacted clay (topsoil removed), and during the summer months a significant proportion of the rainfall is recorded as high intensity, short duration events (EHC, 1993), probably producing a significant quantity of runoff volume. Attempts were made to assess the impact of runoff within the Pilot Pool by the installation of a permanent chart water level recorder. However, works were thwarted by equipment failure and vandalism. Summer runoff has been visually noted during walkover surveys undertaken during the monitoring visits.

During August and September 1996 the calculated water level changes show a large discrepancy when compared to the recorded data. In August 1996, the calculated water level change ($\Delta \mathbf{H}$) (using Equation 3.9) was +0.05 m, compared to a recorded rise of +0.11 m. The higher than predicted water level rise was a result of extremely high intensity rainfall, producing a high proportion of surface runoff which is not included within the calculated value. In September 1996, the water budget equation predicted a change in water level of -0.05 m, which contrasts with the recorded fall of -0.23 m. This large variation was the result of pumping activities associated with the construction of a new pipeline within the catchment area of the Pilot Pool. If this period is removed from the overall assessment of the correlation between actual and calculated changes in $\Delta \mathbf{H}$ (based on Equation 3.9), the Pearson Product coefficient becomes strongly positive with $r = 0.94$.

TINR 1994	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
RAIN (mm)	65	45	21	42	36	23	16	41	71	70	60	81
ETo MORECS Eo (mm)	10	16	58	75	98	127	116	100	60	29	11	7
ETo MORECS Grass (mm)	13	11	46	57	71	94	89	72	46	28	15	13
ET(Reed) (mm)	15	17	47	60	74	128	90	113	73	58	24	29
WATER BUDGETS (mm)												
R-Eo (Water) (mm)	55	29	-37	-33	-62	-105	-100	-59	11	41	49	74
R-ET (Grass) (mm)	52	34	-25	-15	-35	-72	-72	-31	26	42	46	68
R-ET (Reed) (mm)	50	28	-26	-18	-38	-106	-74	-72	-2	12	36	52
HABITAT AREAS (m^2)												
Water Area (m^2)	14321	14321	13981	13883	13219	12410	11808	11273	11369	11563	11915	12410
Grass Area (m^2)	12736	12736	13076	13174	13838	14647	15249	15784	15688	15494	15142	14647
Reed Area (m^2)	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000
VOLUME FLUXES (m^3)												
Water Area (m^3)	789	416	-529	-461	-861	-1381	-1236	-694	125	467	567	877
Si (m^3)	na	na	na	na	na	na	na	na	na	na	na	na
Reed Area (m^3)	149	85	-77	-53	-114	-317	-221	-216	-6	36	109	155
PILOT POOL FLUX (m^3)												
ΔV (m^3)	938	502	-606	-514	-975	-1699	-1457	-910	119	503	675	1032
ΔH (m)	over	over	-0.04	-0.02	-0.04	-0.11	-0.09	-0.07	0.01	0.03	0.05	0.07
Water Level (mAOD)	2.08	2.08	2.04	2.02	1.96	1.85	1.76	1.69	1.70	1.73	1.78	1.85

Table 10.2 Calculated Water Budgets for the Pilot Pool Catchment, TINR, 1994-96 - No Runoff Included.

TINR 1995	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
RAIN (mm)	60	22	22	31	23	13	28	12	106	22	87	53
ETo MORECS Eo (mm)	10	30	50	73	119	107	126	127	66	50	12	7
ETo MORECS Grass (mm)	14	14	42	55	94	77	97	95	50	47	15	10
ET(Reed) (mm)	16	21	43	59	66	117	160	178	142	107	24	24
WATER BUDGETS (mm)												
R-Eo (Water) (mm)	50	-8	-28	-42	-96	-94	-98	-115	40	-28	75	46
R-ET (Grass) (mm)	46	8	-20	-24	-71	-64	-70	-83	56	-25	72	43
R-ET (Reed) (mm)	44	1	-21	-28	-43	-105	-132	-166	-36	-85	63	29
HABITAT AREAS (m^2)												
Water Area (m^2)	12809	12710	12503	12226	11575	10953	10111	8281	8710	7901	9056	9605
Grass Area (m^2)	14248	14347	14554	14831	15482	16104	16946	18776	18347	19156	18001	17452
Reed Area (m^2)	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000
VOLUME FLUXES (m^3)												
Water Area (m^3)	622	-101	-356	-526	-1174	-1089	-1074	-1162	330	-244	593	417
Si (m^3)	na	na	na	na	na	na	na	na	na	na	na	na
Reed Area (m^3)	132	4	-63	-84	-128	-314	-395	-497	-109	-254	188	88
PILOT POOL FLUX (m^3)												
ΔV (m^3)	755	-97	-419	-610	-1302	-1403	-1469	-1659	222	-498	781	504
ΔH (m)	0.05	-0.01	-0.03	-0.04	-0.08	-0.10	-0.11	-0.14	0.03	-0.05	0.07	0.04
Water Level (mAOD)	1.90	1.89	1.86	1.82	1.74	1.64	1.53	1.39	1.42	1.37	1.44	1.48

Table 10.2 (cont.) Calculated Water Budgets for the Pilot Pool Catchment, TINR, 1994-96 - No Runoff Included.

TINR 1996	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
RAIN (mm)	22	37	20	22	45	43	18	126	12	26	62	68
ETo MORECS Eo (mm)	9	22	29	68	113	123	120	110	65	39	15	4
ETo MORECS Grass (mm)	7	14	21	50	81	88	92	79	49	34	17	11
ET(Reed) (mm)	9	20	21	47	70	133	133	115	76	64	27	24
WATER BUDGETS (mm)												
R-Eo (Water) (mm)	13	15	-9	-46	-68	-80	-102	16	-53	-13	47	64
R-ET (Grass) (mm)	15	23	0	-28	-36	-45	-74	47	-37	-8	45	58
R-ET (Reed) (mm)	14	17	-1	-25	-25	-90	-115	11	-64	-38	35	44
HABITAT AREAS (m^2)												
Water Area (m^2)	9629	9923	9880	9461	8553	7085	5354	5681	4500	4206	4836	4826
Grass Area (m^2)	17428	17134	17177	17596	18504	19972	21703	21376	22557	22851	22221	15056
Reed Area (m^2)	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000
VOLUME FLUXES (m^3)												
Water Area (m^3)	125	144	-88	-455	-644	-685	-723	85	-301	-58	197	310
Si (m^3)	na	na	na	na	na	na	na	na	na	na	na	na
Reed Area (m^3)	41	50	-3	-74	-74	-271	-346	33	-193	-113	104	131
PILOT POOL FLUX (m^3)												
ΔV (m^3)	165	194	-91	-530	-718	-956	-1069	118	-494	-171	300	441
ΔH (m)	0.01	0.02	0.00	-0.04	-0.06	-0.10	-0.10	0.01	-0.07	-0.02	0.04	0.05
Water Level (mAOD)	1.49	1.51	1.51	1.47	1.41	1.31	1.21	1.22	1.15	1.13	1.17	1.22

Table 10.2 (cont.) Calculated Water Budgets for the Pilot Pool Catchment, TINR, 1994-96 - No Runoff Included.

TINR 1994	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
RAIN (mm)	65	45	21	42	36	23	16	41	71	70	60	81
ETo MORECS Eo (mm)	10	16	58	75	98	127	116	100	60	29	11	7
ETo MORECS Grass (mm)	13	11	46	57	71	94	89	72	46	28	15	13
ET(Reed) (mm)	15	17	47	60	74	128	90	113	73	58	24	29
WATER BUDGETS (mm)												
R-Eo (Water) (mm)	55	29	-37	-33	-62	-105	-100	-59	11	41	49	74
R-ET (Grass) (mm)	52	34	-25	-15	-35	-72	-72	-31	26	42	46	68
R-ET (Reed) (mm)	50	28	-26	-18	-38	-106	-74	-72	-2	12	36	52
HABITAT AREAS (m^2)												
Water Area (m^2)	14321	14321	13046	13883	13219	12410	11808	11273	11505	11866	12363	13102
Grass Area (m^2)	12736	12736	14011	13174	13838	14647	15249	15784	15552	15191	14694	13955
Reed Area (m^2)	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000
VOLUME FLUXES (m^3)												
Water Area (m^3)	789	416	-529	-431	-861	-1381	-1236	-694	125	472	581	910
Si (m^3)	333	218	0	0	0	0	0	0	204	330	349	505
Reed Area (m^3)	149	85	-77	-53	-114	-317	-221	-216	-6	36	109	155
PILOT POOL FLUX (m^3)												
ΔV (m^3)	1271	720	-606	-484	-975	-1699	-1457	-910	323	839	1039	1569
ΔH (m)	over	over	-0.03	-0.03	-0.06	-0.11	-0.09	-0.07	0.03	0.05	0.07	0.10
Water Level (mAOD)	2.08	2.08	2.05	2.02	1.96	1.85	1.76	1.69	1.72	1.77	1.84	1.94

Table 10.3 Calculated Water Budgets for the Pilot Pool Catchment, TINR, 1994-96 - Runoff Included.

TINR 1995	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
RAIN (mm)	60	22	22	31	23	13	28	12	106	22	87	53
ETo MORECS Eo (mm)	10	30	50	73	119	107	126	127	66	50	12	7
ETo MORECS Grass (mm)	14	14	42	55	94	77	97	95	50	47	15	10
ET(Reed) (mm)	16	21	43	59	66	117	160	178	142	107	24	24
WATER BUDGETS (mm)												
R-Eo (Water) (mm)	50	-8	-28	-42	-96	-94	-98	-115	40	-28	75	46
R-ET (Grass) (mm)	46	8	-20	-24	-71	-64	-70	-83	56	-25	72	43
R-ET (Reed) (mm)	44	1	-21	-28	-43	-105	-132	-166	-36	-85	63	29
HABITAT AREAS (m^2)												
Water Area (m^2)	13865	13852	13247	13102	12410	11794	10953	9923	10409	10111	11002	11454
Grass Area (m^2)	13192	13205	13810	13955	14647	15263	16104	17134	16648	16946	16055	15603
Reed Area (m^2)	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000
VOLUME FLUXES (m^3)												
Water Area (m^3)	657	-109	-388	-558	-1259	-1168	-1157	-1259	396	-291	758	506
Si (m^3)	327	55	0	0	0	0	0	0	480	0	617	346
Reed Area (m^3)	132	4	-63	-84	-128	-314	-395	-497	-109	-254	188	88
PILOT POOL FLUX (m^3)												
ΔV (m^3)	1116	-50	-451	-642	-1387	-1481	-1552	-1755	767	-546	1563	940
ΔH (m)	0.07	-0.01	-0.04	-0.03	-0.09	-0.10	-0.11	-0.13	0.06	-0.04	0.12	0.06
Water Level (mAOD)	2.01	2.00	1.97	1.94	1.85	1.75	1.64	1.51	1.57	1.53	1.65	1.71

Table 10.3 (cont.) Calculated Water Budgets for the Pilot Pool Catchment, TINR, 1994-96 - Runoff Included.

TINR 1996	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
RAIN (mm)	22	37	20	22	45	43	18	126	12	26	62	68
ETo MORECS Eo (mm)	9	22	29	68	113	123	120	110	65	39	15	4
ETo MORECS Grass (mm)	7	14	21	50	81	88	92	79	49	34	17	11
ET(Reed) (mm)	9	20	21	47	70	133	133	115	76	64	27	24
WATER BUDGETS (mm)												
R-Eo (Water) (mm)	13	15	-9	-46	-68	-80	-102	16	-53	-13	47	64
R-ET (Grass) (mm)	15	23	0	-28	-36	-45	-74	47	-37	-8	45	58
R-ET (Reed) (mm)	14	17	-1	-25	-25	-90	-115	11	-64	-38	35	44
HABITAT AREAS (m^2)												
Water Area (m^2)	11563	11808	11794	11454	11002	10409	9345	9923	9206	8861	9776	10645
Grass Area (m^2)	15494	15249	15263	15603	16055	16648	17712	17134	17851	18196	17281	16412
Reed Area (m^2)	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000
VOLUME FLUXES (m^3)												
Water Area (m^3)	149	173	-105	-544	-779	-881	-1062	148	-526	-119	415	626
Si (m^3)	115	183	0	0	0	0	0	421	0	0	414	502
Reed Area (m^3)	41	50	-3	-74	-74	-271	-346	33	-193	-113	104	131
PILOT POOL FLUX (m^3)												
ΔV (m^3)	305	405	-107	-618	-854	-1152	-1408	603	-719	-232	933	1259
ΔH (m)	0.02	0.03	-0.01	-0.04	-0.06	-0.08	-0.11	0.05	-0.06	-0.03	0.07	0.10
Water Level (mAOD)	1.73	1.76	1.75	1.71	1.65	1.57	1.46	1.51	1.45	1.43	1.50	1.60

Table 10.3 (cont.) Calculated Water Budgets for the Pilot Pool Catchment, TINR, 1994-96 - Runoff Included.

1994	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Recorded	2.08	2.08	2.01	1.98	1.92	1.81	1.76	1.72	1.74	1.82	1.87	1.96
Calc. (no runoff)	2.08	2.08	2.04	2.02	1.96	1.85	1.76	1.69	1.70	1.73	1.78	1.85
Calc. (runoff inc.)	2.08	2.08	2.05	2.02	1.96	1.85	1.76	1.69	1.72	1.77	1.84	1.94
1995	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Recorded	2.03	2.00	1.97	1.94	1.86	1.78	1.70	1.61	1.67	1.64	1.73	1.84
Calc. (no runoff)	1.90	1.89	1.86	1.82	1.74	1.64	1.53	1.39	1.42	1.37	1.44	1.48
Calc. (runoff inc.)	2.01	2.00	1.97	1.94	1.85	1.75	1.64	1.51	1.57	1.53	1.65	1.71
1996	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Recorded	1.85	1.91	1.89	1.86	1.83	1.74	1.66	1.77	1.54	1.57	1.63	1.79
Calc. (no runoff)	1.49	1.51	1.51	1.47	1.41	1.31	1.21	1.22	1.15	1.13	1.17	1.22
Calc. (runoff inc.)	1.73	1.76	1.75	1.71	1.65	1.57	1.46	1.51	1.45	1.43	1.50	1.60

Table 10.4 **Pilot Pool Monthly Water Levels (mAOD), Recorded, Calculated (no runoff), Calculated (runoff included), TINR, 1994-96.**

1994	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Recorded	0.02	0.00	-0.07	-0.03	-0.06	-0.11	-0.05	-0.04	0.02	0.08	0.05	0.09
Calc. (no runoff)	0.00	0.00	-0.04	-0.02	-0.04	-0.11	-0.09	-0.07	0.01	0.03	0.05	0.07
Calc. (runoff inc.)	0.00	0.00	-0.03	-0.03	-0.06	-0.11	-0.09	-0.07	0.03	0.05	0.07	0.10
1995	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Recorded	0.07	-0.03	-0.03	-0.03	-0.08	-0.08	-0.08	-0.09	0.06	-0.03	0.09	0.11
Calc. (no runoff)	0.04	0.01	-0.02	-0.05	-0.08	-0.09	-0.11	-0.13	0.03	-0.03	0.07	0.04
Calc. (runoff inc.)	0.07	-0.01	-0.03	-0.03	-0.09	-0.10	-0.11	-0.13	0.06	-0.04	0.12	0.06
1996	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Recorded	0.01	0.06	-0.02	-0.03	-0.03	-0.09	-0.08	0.11	-0.23	0.03	0.06	0.16
Calc. (no runoff)	0.02	0.02	0.00	-0.05	-0.05	-0.08	-0.12	0.02	-0.05	-0.01	0.04	0.06
Calc. (runoff inc.)	0.02	0.03	-0.01	-0.04	-0.06	-0.08	-0.11	0.05	-0.06	-0.02	0.07	0.10

Table 10.5 Pilot Pool Monthly Water Level Changes (m), Recorded, Calculated (no runoff), Calculated (runoff included), TINR, 1994-96.

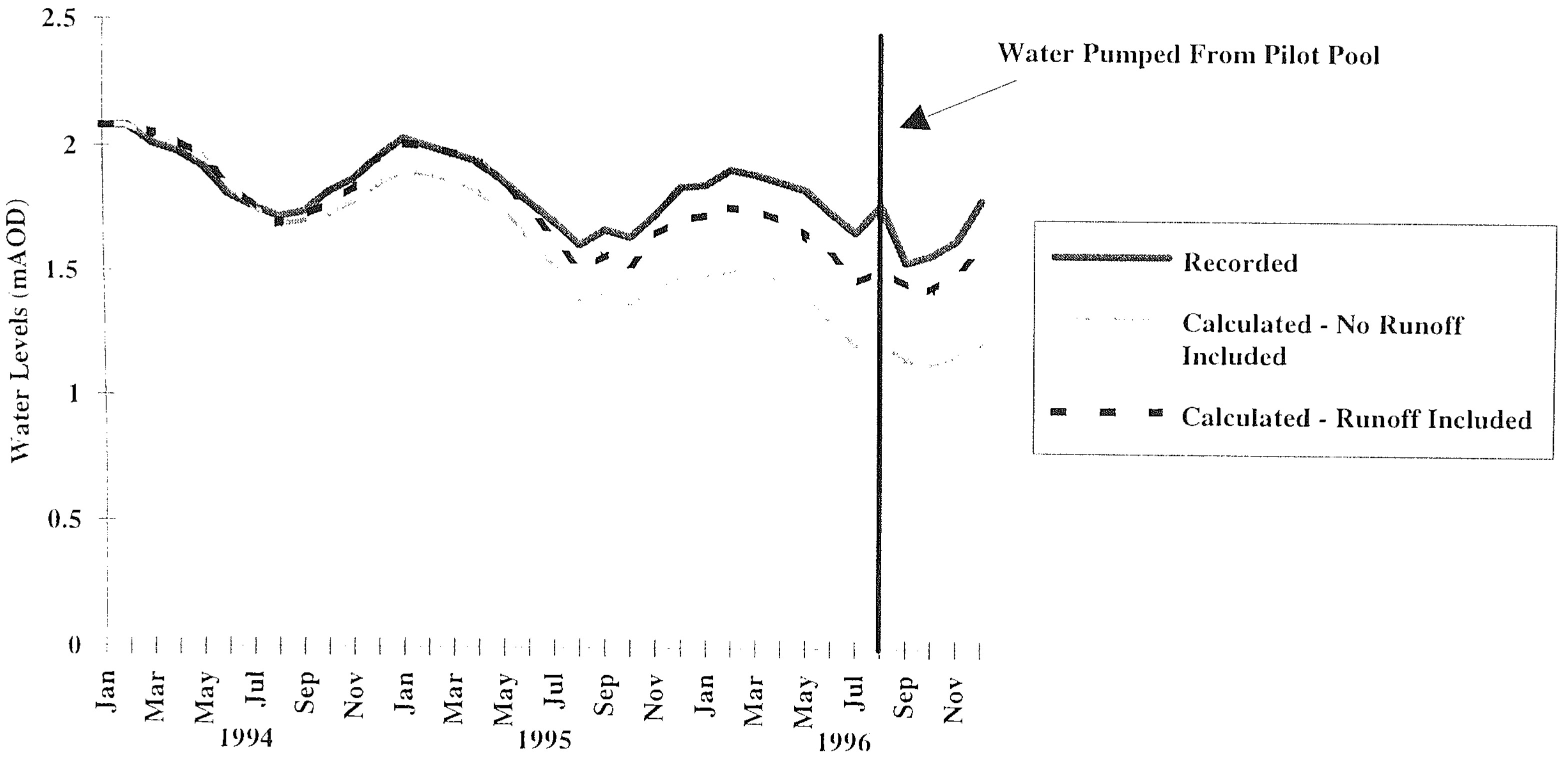

Figure 10.3 Pilot Pool Monthly Water Levels, Recorded, Calculated (no runoff), Calulated (runoff included), TINR, 1994-96.

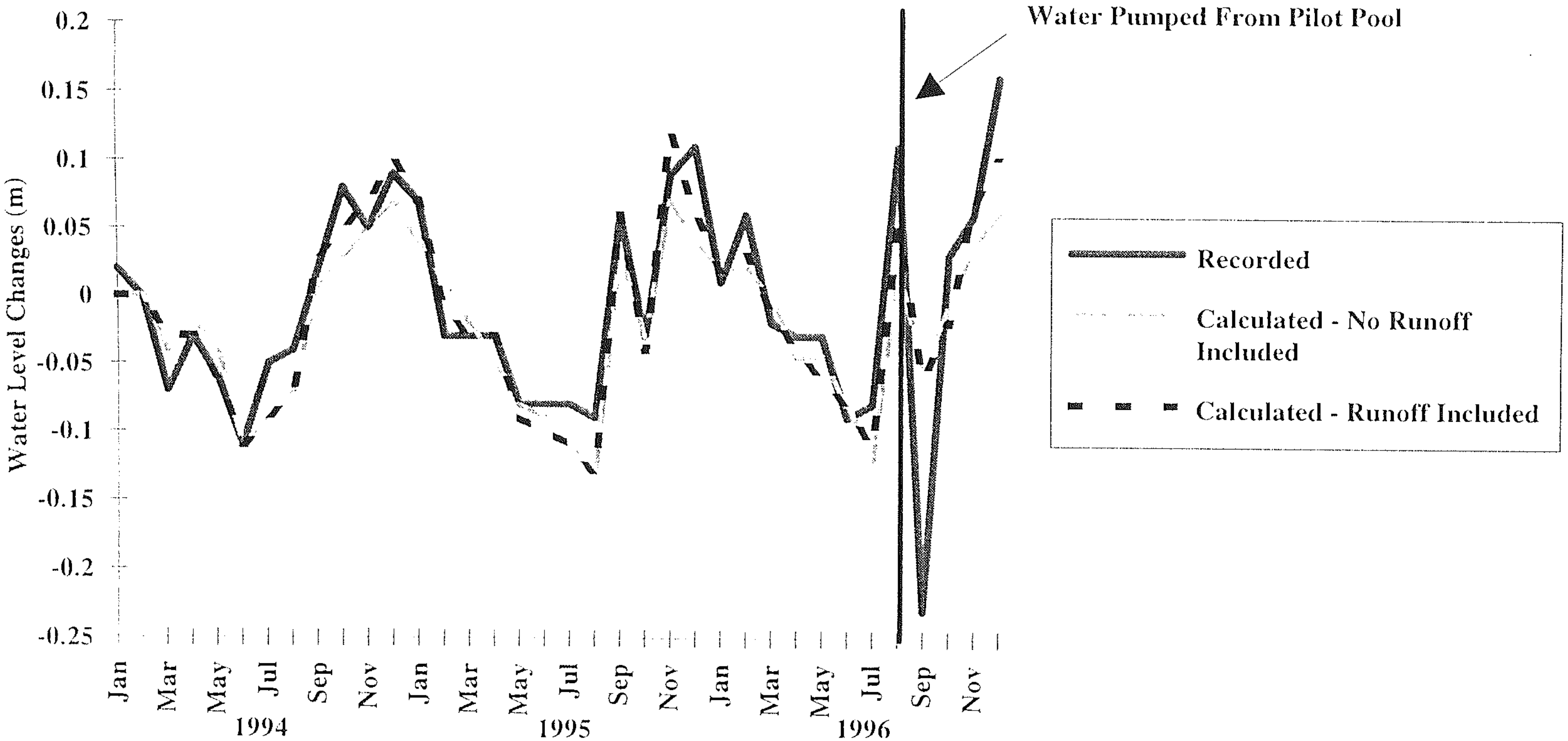

Figure 10.4 Pilot Pool Monthly Water Level Changes, Recorded, Calculated (no runoff), Calulated (runoff included), TINR, 1994-96.

10.5 DISCUSSION.

Equation 3.9, appears to provide an accurate technique for the prediction of ΔV, which when combined with the data output from the DEM produces an estimated value for H which agrees well with the actual monthly water level. The further validation of Equation 3.9 would require the use of data recorded from different catchment areas, which were similar to that of the Pilot Pool (surface water fed, no streamflow inputs). The RSPB were approached in the hope that their wetland nature reserves may contain a suitable catchment for validation purposes, however, no suitable site was identified (José, 1997).

The absence of vegetation from large areas of the Pilot Pool catchment may have produced additional surface runoff inflows which are not accounted for in Equation 3.9. Thus, in order to estimate the surface runoff from a catchment it is important to determine the vegetation cover.

The large reduction in water level calculated using Equation 3.2 was far in excess of that which actually occurred. This demonstrates the importance of surface runoff volumes in sustaining water levels within a reedbed/open water complex. This feature was highlighted by Eisenlohr (1966) and should not be overlooked in the apportioning of land in wetland habitat creation schemes (see Section 9.9). In reality, had such a large reduction in the water level occurred within the Pilot Pool system, the reedbed area would have become 'dry'. This would have reduced the value of ET(Reed), with the exposed pool margins producing a high percentage of surface runoff during rainfall events. These features would have reduced the fall in the estimated water level.

In conclusion, the inclusion of surface runoff volumes developed using an appropriate runoff coefficient produced a more accurate prediction of ΔH than that calculated using Equation 3.2, although it still under predicted the actual storage held within the waterbody. If Equation 3.9 had been used to calculate the volume of water required from an alternative/additional water supply it would have produced an over prediction of the volume requirements, particularly during the months of July and August. However, over prediction is more appropriate at feasibility stage than any under prediction of water requirements, ensuring sufficient supplies to sustain any habitat development proposals. Thus, Equation 3.9 is recommended for use in determining the feasibility of surface water fed reedbed creation.

Chapter 11. PROJECT EVALUATION AND IDENTIFICATION OF FUTURE RESEARCH NEEDS

The consideration of various aspects of this research project have been discussed throughout this thesis whenever the need arose. The discussion presented in this chapter will, therefore, be more general in nature and directed to the identification of future research needs.

11.1 THE PROJECT

In general, undertaking a research project on a primarily part-time basis means that the work extends over several years. This project has been no exception, and from initial involvement with EHC design projects and associated monitoring schemes, to completion of this thesis, has spanned the period between 1992 - 1997. During this period there has been advancements in the understanding of wetland hydrology, with the hydrological requirements of reedbed ecosystems and their inherent target species now well understood. Recent reedbed creation schemes have been cited throughout this thesis and the reader is guided to the work of Hawke and José (1996) for details of additional projects. In the majority of these schemes the water budget has been given limited attention and the concept of natural hydrological sustainability has often only been given 'lip service' (José, 1997).

It became clear from reviewing the available literature relating to wetland habitat design, that inadequate attention had been given to the determination of ET(Reed). This research project has provided monthly Kc(Reed) values which can be used in conjunction with various forms of ETo for the calculation of ET(Reed).

11.2 THE FIELD EXPERIMENTATION AND DEVELOPMENT OF Kc(Reed)

This project demonstrated the application of a well-established experimental technique, lysimetry, in the determination of ET(Reed). This technique is particularly successful during the growing season, and where regular monitoring visits are possible. In addition, the reedbed water levels should be sufficiently stable to minimise the risk of phytometer inundation.

During the dormant period the potential loss of measurements due to inundation may limit the use of phytometers in many reedbeds, however, total data loss may be avoided if additional phytometers are established at higher topographical levels. The establishment of phytometers at a variety of topographical levels throughout the reedbed may also be advantageous if the annual water level variation is sufficient to cause many of the experimental positions to exist with a large proportion of the sides of the phytometer exposed above the water level, possibly within a 'dry' reedstand. This is likely to increase the ET(Reed) rate recorded from the exposed phytometer (see Section 9.3.2), and more representative data might be forthcoming from phytometers installed at lower topographical levels. The influence of the variation of water levels external to the phytometer on the recorded ET(Reed) is recommended for further study.

Section 8.4.3 discusses the relationship between standing crop and ET(Reed). The Kc(Reed) values presented in this thesis were developed from phytometers with a standing crop which was higher than that present across much of the UK (Hawke and José, 1996). ET(Reed) measurements from standing crop values equivalent to those which are likely to occur within created ecosystems would allow the development of a set of Kc(Reed) values from which the most appropriate could be selected for use in water budget calculations. It would therefore be advantageous to monitor phytometers planted at different densities within any newly created reedbed. If the phytometers were planted during the creation process the variation in Kc(Reed) throughout the development and establishment stages could be assessed, thus enhancing the water budget calculations for further schemes.

No specific quantitative research was identified in the literature with respect to ET(Reed) or Kc(Reed) during the dormant period, and therefore no comparison could be drawn with other experimental data. The dormant season ET(Reed) recorded on the TINR was over 140 mm, constituting approximately 18% of the annual atmospheric losses. This experimental data has identified the potential of significant ET(Reed) losses from the dormant period water budget which could be confirmed by additional research, allowing the developed dormant Kc(Reed) values to be refined.

The overall similarity between the Kc(Reed) values developed in this research project with those of other researchers has allowed a broad validation of the data presented. Field measurements of water level (**H**) and habitat areas (**A**) within a reedbed dominated catchment could be used to validate the application of the various Kc(Reed) developed. This may be possible in the near future if on-going reedbed creation schemes produce appropriate study areas.

Section 7.7 discusses the use of various ETo forms in the development of Kc(Reed). This is further developed in Section 10.5, which asserts that the ETo data required by wetland hydrologists to calculate ET(Reed) is often limited by what data is available, and that the ETo form used may change according to what stage of the reedbed creation project has been reached. During this project various ETo forms were developed, each had its own advantages both from a viewpoint of accuracy and ease of generation. These features have been discussed throughout this thesis producing an overall conclusion that site specific ETo data, generated using a form of the Penman-Montieth equation is recommended. However, such data may be difficult to generate and expensive to purchase. Indeed, within the UK small conservation organisations may be unable to afford the purchase cost of long-term MORECS data to accurately predict ET(Reed), and thus inform the feasibility of virgin reedbed creation or extension to existing reserves. However, such organisations may have man-power available to monitor an evaporation pan, the data from which can subsequently be used in conjunction with Kc(Reed) Pan and raingauge values to calculate ET(Reed).

11.3 QUANTIFICATION OF PARAMETERS WITHIN THE MODEL OF SURFACE WATER FED REEDBED ECOSYSTEMS.

Extensive reedbed areas are planned for creation in the South and East of the UK (see Sections 2.5.3 and 5.2). If these areas are to be surface water fed then research works pertaining to the ET(Reed) are of obvious significance. This research project has established a technique for the calculation of monthly ET(Reed) using available ETo data. However, it may be appropriate to undertake further research in addition to that discussed in Section 11.2 with respect to ET(Reed) specifically and ET(Wetland) in general. Some of these research needs are discussed here.

Although mono-dominant stands of *Phragmites australis* are the focus ecosystem of much of the habitat development discussed in this project, this ecosystem needs to be seen as part of an overall "patchwork" with various associated wetland habitats. From a hydrological viewpoint the establishment of accurate ET(Reed) estimates is only one part of a water budget from such a patchwork of ecosystems. Section 8.4.5 discusses the use of the developed experimental technique in the measurement of ET from other wetland species. The review of the ET works undertaken by Bernatowicz et al (1976) identifies the significantly higher ET rates recorded from other emergent species, e.g. *Typha* spp. Establishment of crop coefficients for all of the major wetland emergents would allow the water budgets developed to be applied to other wetland ecosystems to accurately calculate deficit volumes. The creation of ecosystems dominated by species with low ET rates and positive water budgets may provide the additional water necessary to supply adjacent reedbeds.

Towards the end of this research programme the author became aware of suggestions (José, 1997) that the water budget model (see Figure 3.4) developed for surface water fed ecosystems was possibly inadequate for application within reedbeds which were constructed for the bittern. The need for a throughflow component within the reedbed system may mean that the water budgets developed using Equation 3.9 are inappropriate unless a recirculation system is proven to be sufficient in creating the required "flow". If however, the "flow" needs to come in the form of additional inputs and outputs to the system the use of the hydological model presented in Figure 3.3 will be more appropriate. As previously stated, the effect of throughflow requirements on the sustainable establishment of reedbeds would be to greatly increase the proportion of the UK where water budget deficits were inherent in surface water fed systems. The need to fully evaluate the impact on the water budget of throughflow requirements in reedbed ecosystems is apparent.

It may be advantageous to focus research efforts on minimising ET(Reed), thus reducing the overall budget deficit. Such research could attempt to assess the impact of both changes in the micro-climatic conditions and phenotypical characteristics on ET(Reed).

Section 9.6 discussed the possible role of wind speed on Kc(Reed). The reduction of wind ventilation can be affected if the long-section of the reedbed is aligned parallel with the prevailing wind direction (Bernatowicz et al, 1976). Such a reedbed may have a lower ET(Reed). This design criteria may be subject to restrictions, however, it might be suitable for adoption in sites where water was a limiting factor to reedbed development. In addition, it may be possible to reduce ET(Reed) by the provision of shelterbelts, which might take the form of appropriately designed fencing which could be aesthetically sympathetic to the habitat it is adjacent to. It may also be possible to use a biological windbreak through the provision of carr woodland, however, an understanding of water use within the carr, and an assessment of the ET from such a system on the overall water budget would be essential prior to implementation.

Within created reedbeds which are planted-up rather than allowed to develop their own sub-climax community, it is theoretically possible to dictate the overall phenotypical characteristics of the species within the resultant ecosystem. The use of *Phragmites australis* which have adaptations resulting in a lower ET(Reed) rate would be advantageous in the deficit areas shown in Figures 9.11 and 9.12. The use of seed from reeds which are adapted to be drought tolerant may result in a lowering of ET(Reed) (Self, 1997), however, this requires verification with experimental evidence.

In a world where biotechnology and genetic engineering are commonplace, it may be possible to 'create' a reed phenotype which has a low Kc(Reed). Such a 'mutation' would need to be rigorously tested in large field trials to allow an assessment of any detrimental effects associated with its use.

The fact that the annual value of Kc(Reed) MORECS Grass is greater than 1.0 would imply that reedbed creation in areas of former grassland will increase the water budget outputs from these areas. This idea that reedbeds are "net consumers" of water was discussed briefly in Section 9.9. However, it is necessary to place this phenomena in context as part of an overall water resources strategy. Section 9.9 recommends that the creation of surface water fed reedbeds should be focused in areas where the water budget was sustainable, primarily outside the South and East of England. From a water resources viewpoint the creation of reedbeds within areas of budget deficit is insupportable, indeed, the creation of additional reedbeds adjacent to similar existing ecosystems in deficit areas may affect the sustainability of the established areas, many of which are already suffering from water shortages (José, 1997) and the majority of which are protected and heralded for their conservation value. It is somewhat ironic that many pro-wetland conservation organisations are demanding that water resource strategies are focused on the protection of water budgets within wetland areas, whilst the same bodies are involved in attempts to create large areas of "net water consumption". Although the water budget deficit from such schemes are small compared to the demands of industry, agriculture, and domestic uses, they may become significant if large wetland habitat creation schemes become prevalent.

It could be suggested that wetlands would probably be hydrologically sustainable if they were "restored" within a hydrological system which included streamflow and groundwater within the water budget. This approach will not decrease the total losses from the system by ET(Reed), however, it is probable that the wetland can be designed to have a positive 'impact' on the overall water environment (e.g. increased storage, flood attenuation etc.) which could compensate for the water lost through ET(Reed).

Even if water budget calculations suggest that created wetlands are hydrologically sustainable based upon long term meteorological data, the implications of the now established "global warming" on climate may affect the water budget significantly both of proposed and existing wetland areas. Brown (1992) suggests that there could be a rise in sea-level around the UK coasts of 200 mm by the year 2030. This would result in the major incursion of salt water into many coastal reedbed sites. Gilbert et al (1996) state that almost 37% of the total reedbeds recorded in England and Wales are coastal, concluding that tidal incursion could have a

> "widespread impact on the flora and fauna of coastal reedbeds, prejudicial to their current wildlife. Bitterns do not breed in tidal reedbeds."

During the majority of the period that this thesis was being prepared, numerous reports were being presented on recent climatic anomalies and changes within the UK. The possibility of changes in rainfall quantities and distribution are reported in the popular media almost on a daily basis. A variety of evidence has been presented that suggests that mean monthly rainfall recorded during 1995, 1996 and part of 1997 was appreciably lower than previous averages, with the drought being the "most severe since 1740-43" (Eden, 1997). Furthermore, rainfall appears to be becoming focused during the winter period, accompanied by drier, warmer summers (Duckworth and Lyster, 1997). Duckworth and Lyster state that;

> "climate change predictions suggest that the once-in-250-years drought of the 1990s could be occurring one year in three by 2050".

If these climatic trends continue in the longer term, the implication to annual water budget deficit and, perhaps more significantly, summer accumulated deficits may have severe effects on our established wetland habitats and possibly devastating consequences to created surface water fed systems. Under these circumstances the planned increase in target species numbers and their distribution is unlikely to occur.

If naturally sustainable wetland hydrology is not feasible at creation sites additional water supplies are required. The form these supplies take may vary dependant on the size of the deficit. However, the use of treated effluent particularly within reedbed ecosystems established primarily for nature conservation is currently the topic of widespread research (Gilman, 1997). It would appear that the reedbeds and associated habitats created as part of the Cardiff Bay Barrage Compensation Measures will rely on treated effluent as a significant input to their water budgets. One of the initial concerns raised with respect to the use of treated effluent within areas created for nature conservation was the impact of turbidity on bittern populations. Bitterns feed by the use of sight and high turbidity levels could result in bittern migration (José, 1997). Eutrophication, in the form of high phosphate loading within open water bodies is also of concern particularly if this increases the occurrence of toxic blue-green algae. In addition, the possibility of eco-concentrated toxicity of various substances found in treated effluent may also limit its use.

Water quality considerations are generally outside the remit of this research project, however, the creation of reedbeds in areas of net annual water budget deficit must only be undertaken if the quality of non-precipitation input is appropriate. All of the hydrological inputs to the water budget contain dissolved solids and salts, the majority of which will only be removed from the ecosystem by surface outflow. The processes of evaporation and evapotranspiration only act to concentrate such dissolved salts. If the water balance and the topography combine to produce a reedbed which does not overflow, these salts will potentially become concentrated within the ecosystem, and result in the system becoming brackish.

If the non-detrimental use of treated effluent within reedbeds created for nature conservation can be established through a detailed research programme, large areas of multi-purpose reedbed could be created. These reedbeds could provide tertiary effluent treatment and valuable nature conservation areas particularly for target species, whilst also providing areas where humans can interact (properly supervised/administered) with one of our previously diminishing wetland resources. Perhaps we all could be "drawn to a sanctuary, wet and priceless" (Mitchell, 1990).

In conclusion, the calculation of the annual and accumulated summer water losses due to ET(Reed) should be seen as part of an overall water resources strategy which involves the assessment of all the fluxes within the water budget including determination of sediment types, and their impact on seepage losses, runoff etc. There may be a need to develop additional supplies or storage volumes which are available during periods of highest ET(Reed) to compensate for falling water levels. Treated effluent may be suitable for introduction into reedbed ecosystems managed primarily for nature conservation. The establishment of large, high conservation quality reedbeds may be achievable if the 'natural' hydrological regime of restored reedbed is reinstated, or if water resource management is targeted on 'created' habitats in areas where the anthropogenic water requirements are compatible.

11.4 FUTURE RESEARCH NEEDS

The previous discussion identified a selection of research requirements which are summarised below with respect to both broad and specific research needs.

11.4.1 BROAD RESEARCH NEEDS

The broad research needs which have been identified from this project are:

1) A comparison between the water budget requirements of wetland habitats and the water budgets of the existing systems (e.g. agriculture) which wetland creation/restoration may replace.

2) An assessment of the impact of climate change on the water budgets of both existing wetlands and creation projects, focusing on: sea level rise; and increasing annual/summer water budget deficits.

3) The calculation of the change in water budgets associated with the impact of "flow" requirements within reedbeds developed for target species.

11.4.2 SPECIFIC RESEARCH NEEDS

The development of a greater understanding of the role of standing crop and the influence of the variation of water levels external to the phytometer on measured ET(Reed) is recommended for further study.

With respect to wetland crop coefficients the following research is suggested:

1) the provision of a set of monthly Kc(Reed) values applicable to various stages of reedbed establishment.

2) confirmation through additional research, of the developed dormant Kc(Reed) values.

3) validation of the presented Kc(Reed) values by field based water budget studies of a reedbed dominated catchment.

4) the development of crop coefficients for all dominant wetland species.

Investigation into techniques for the minimisation of ET(Reed) through the manipulation of:

1) micro-climate - the effect of shelterbelts;

2) phenotypic characteristics - development of phenotypes with lower ET(Reed).

Chapter 12. CONCLUSIONS.

12.1 ET(Reed).

The key to the development of a surface water fed reedbed water budget is the calculation of ET(Reed), which within an impermeable clay catchment forms the principal water loss from the system, whilst the measurement of rainfall (principal input) and the calculation of surface runoff can be assessed using established techniques. The literature search undertaken as part of the initial design works for the TINR identified a dearth of references with respect to ET(Reed). The need for research into the hydrology of reedbeds, the measurement of ET(Reed), and the development of a Kc(Reed) was identified, and at this point the aims and objectives of this research were defined.

12.2 AIM.

The aims and objectives of the research have remained constant since the project's formulation with the exception of those changes stated in Section 1.2. In satisfying each objective it has been necessary to achieve particular goals, and these will be discussed in Section 12.3.

The overall aim of the project,

> *"To develop a methodology for the hydrological design of surface water fed reedbed habitats",*

has been accomplished.

A hydrological design methodology has been developed (see Section 10.2) which enables areas to be identified within which reedbed creation is either: hydrologically sustainable; cannot be supported without supplementary water inputs; is not possible. If the habitat creation areas are known, then the impact of each of these areas on the water budget can be evaluated using crop coefficients in conjunction with ETo based upon well established estimation methods. Using the experiences gained throughout the research programme, criteria have been presented which enable an assessment of the hydrological feasibility and sustainability of reedbed habitats to be undertaken based upon wetland water budgets.

12.3 OBJECTIVES.

In order to fulfil the aim of the research four distinct objectives were established. The degree of success the project has had in achieving each objective will now be evaluated.

1) *To undertake a comprehensive review of published literature, focused on the hydrological functioning of wetland systems, with an emphasis on reedbeds.*

A detailed literature review was undertaken with additional references sourced throughout the research period. A wetland classification primarily based on hydrological criteria was identified (Ramsar Convention, 1971), and reedbed ecosystems were comprehensively described. Chapter Three was dedicated to the hydrological functioning of wetland systems with key terms identified and discussed including: water balance; hydroperiod; hydrological processes; and hydrological management, with reedbed hydrology emphasised throughout. The hydrological characteristics of reedbeds were discussed with respect to the needs of species targeted by conservation initiatives.

The literature review identified the important role that ET played within the overall water budget of wetland systems. However, extensive searching identified a paucity of references with respect to ET(Reed), providing limited relevant information, with the data and conclusions of the published research often conflicting. A technique was identified for the measurement of ET(Reed).

2) *To formulate a conceptual hydrological model of surface water fed reedbed systems.*

Conceptual hydrological models of wetland systems have been previously presented by other researchers (e.g. Duever, 1988) with each model illustrating major system components and their relationship with each other. These models are applicable to the majority of wetland systems which occur where the groundwater fluxes are a large component of the water budget, and strongly influence the hydroperiod.

The study sites identified for wetland habitat creation in this project are however located in areas where there is minimal groundwater flux. A conceptual hydrological model of surface water fed reedbed systems was developed from which the monitoring programme necessary to inform the hydrological design of reedbed systems was identified. The conceptual hydrological model is presented for application within similar reedbed systems.

3) *To design and undertake a monitoring programme to enable the components of the conceptual model to be quantified and hence facilitate design.*

The need to quantify the various components of the water budget model/equation produced a requirement for the design and implementation of a site specific monitoring programme necessary to inform the feasibility and sustainability primarily of reedbed habitats. For the TINR (1990), lateral migration and groundwater fluxes were assumed to be insignificant as the hydraulic conductivity of the underlying substrate was very low. Various aspects of the monitoring programme have been identified and discussed throughout this thesis, with the measurement of ET(Reed) forming the focus of the research studies.

The components of the conceptual model of the Pilot Pool, TINR, which were monitored were the principal input (rainfall) and the principal output [ET(Reed)] from a reedbed water budget. Eo and ET(Grass) were calculated using well established estimation techniques. An established technique (Farquharson, 1978) was used to provide a runoff coefficient applicable to the value of net precipitation [P - ET(Grass)]. This coefficient was used to calculate runoff volumes and hence assess their contribution to the overall reedbed water budget. Potential streamflow volumes were estimated using both catchment size based calculations, and by the gauging of flows during the monthly site visits.

From monitoring ET(Reed) over a long period, Kc(Reed) values were established which enable ET(Reed) to be determined for reedbeds subject to significant advective influences, using an appropriate ETo. The phytometers used in the development of Kc(Reed) were located within-stand and were monitored with a frequency of at least once a month. Once installed, a period of establishment was necessary to allow the phenological characteristics of the transplanted rhizomes to regain equilibrium with the in-situ reeds. The use of phytometers was simple, non-destructive, scientifically established, and repeated in a variety of situations, with varying substrates.

4) To create a hydrological design methodology applicable to surface water fed reedbed creation.

A hydrological design methodology was determined in Section 10.2. When assessing a site for reedbed creation, priority should be given to those locations where the annual water budget deficit ($\Delta V_{reedbed}$) is minimal, and the accumulated summer deficit ($\Delta V_{reedbed\ nws}$) does not exceed the criteria set for the target species. It will also be advantageous if storage facilities and supplementary water sources are available.

The calculation of water budgets based upon MORECS data identified a large proportion of the UK where the creation of hydrologically sustainable reedbeds would require the inclusion of 'net water producer' habitats within the catchment area. It was recognised that this is not always possible and that additional water supplies may be necessary. The creation of hydrologically sustainable reedbed systems within the South and East of England may not be possible without a streamflow or groundwater input. Similar conclusions were reached with respect to the sites identified within the Bittern LIFE Project.

The need for supplementary water sources may be particularly apparent if reedbeds are created in areas where no former wetlands have existed. Additional supplies may form part of an integrated catchment approach, designed to minimise the effect of, or to, other users and the water environment as a whole. The use of treated effluent as an alternative supply was also suggested where water quality problems do not exist, particularly adjacent to estuarine discharge points.

The methodology identifies the need to apply the developed water budget model (see Figure 10.1) to evaluate the various components of the water budget. The water budget model was applied to the Pilot Pool catchment of the TINR. It was apparent that surface runoff (Si) formed an essential component of this water budget and that ET(Reed) and Eo are the principal outputs from the system. ET(Reed) would produce a significant annual water budget deficit if a large area of reedbed (40 ha) was created on the TINR. An additional water source would be required to meet the hydrological requirements of the target species - bittern.

12.4 Kc (Reed).

As recommended by Smith (1990) for estimating crop water requirements, a series of monthly Kc(Reed) values are presented in this thesis which have been developed to enable ET(Reed) within reedbeds subject to significant advective influences to be calculated, from an appropriate form of ETo based upon the Penman-Montieth equation. The Kc(Reed) values have been compared with those developed by, and from, the works of other researchers based mainly in continental Europe. The validity of the Kc(Reed) values presented has been established within Europe and may be applicable worldwide. Kc(Reed) MORECS Grass is recommended for use within the UK, whilst Kc(Reed) Pan may have application in areas where no other ETo form is available.

12.5 SUMMATION.

The overall aim of this project has been achieved. However, Chapter Eleven identifies a number of recommendations for further research, which if undertaken could allow the complete integration of wetland water budgets within overall catchment based water requirements. The reedbed water budget model could be employed to calculate the sustainable percentage of various habitat areas which can be created, based upon standard meteorological data. It is believed that this tool will be applicable to reedbed habitat creation programmes across Europe. The water budget model can be adapted for use within other wetland ecosystems.

In conclusion, this thesis presents the Kc(Reed) values and the methodology for the hydrological design of surface water fed reedbed habitats as a small contribution to the global efforts to restore and re-create our lost wetland heritage.

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APPENDICES.

APPENDIX 1.

WETLAND LANDSCAPES IDENTIFIED BY DUGAN (1990).

ESTUARIES

Estuaries are bodies of water where a river mouth widens into a marine ecosystem, where the salinity is intermediate between salt and freshwater, and where tidal action is an important bio-physical regulator. Each estuary can support a range of different wetland habitats. In most temperate estuaries intertidal mud and sand flats, salt marshes, and scattered rocky outcrops are common features. Tropical and sub-tropical estuaries are dominated by mangrove swamps with nipa palm growing in higher areas (Dugan, 1990). Mangrove swamps cover 14 million hectares worldwide and approximately 80 species of plant are recognised as being mangroves (Dugan, 1993). Mangroves establish a network of horizontal or 'cable' roots, which anchor the tree to the soft mud, trapping more sediment, enabling mangrove 'pioneers' to move progressively seaward at rates of up to 100 m/annum (Maltby, 1986). Approximately two thousand species of fish are dependant upon mangrove swamps for survival.

OPEN COASTS

Open Coasts are those not subject to the influence of river water and lagoon ecosystems, with ecosystems varying from mudflats to mangroves (Dugan, 1990).

FLOODPLAINS

Floodplains are the periodically flooded land between river channels and valley sides. Permanent or semi-permanent areas of standing water may be left after the recession of flood waters in the form of oxbows and other depressions. These waters are often dry season refuges for fish and are a key resource for many subsistence farming communities in Africa, Asia and South America. In the USA, these areas supported the bottomland hardwood forests which once covered vast areas of the floodplain of the south-eastern USA. This wetland type still covers

23.5 million hectares in the USA (Maltby, 1986). In Europe, the Hainburg Forest, near Vienna is regularly flooded by snowmelt waters. It is one of the largest areas of riverine forests left in Europe and supports three-quarters of Europe's tree species.

Many of the world's larger rivers spread out over floodplains, many of them covering vast areas that include grassy marshes, flooded forest, oxbow lakes and other depressions. Some of the most important floodplains, such as the Inner Niger Delta in Mali, are in arid areas where their exceptional productivity is not only vital to the local economy, but also supports spectacular concentrations of waterbirds and other wildlife (Dugan, 1993).

FRESHWATER MARSH

Marshes occur where the mineral based soil is water logged but where the summer level, while close to the surface, is seldom above it. Marshes vary greatly, are dominated by herbaceous plants, which are adapted to fluctuating water and nutrient levels, and sustained by water sources other than direct rainfall. In the UK, marshes once covered vast areas of boulder clay around lowland glacial lakes and river valleys on alluvial gravels, sands and silts. However, most of the UK's large marshes have been lost.

Maltby (1986) describes three major groups of marsh:

1) Tidal Saltmarsh - typical of temperate shorelines between high and low tidal extremes;

2) Tidal Freshwater Marshes - found further inland at the head of tides but not exposed to salt water stress;

3) Freshwater Marshes - dominated by grasses and sedges and accounting for 90% of the wetland area of the USA. They occur on mineral soils and do not accumulate peat.

Marsh vegetation is extremely varied. The dominant plants are reeds, rushes, grasses and sedges which are commonly referred to as emergents since they grow with their stems partly in and partly out of the water (Maltby, 1992). Some marshes may be locally dominated by Juncus spp. or dicotyledonous herbs such as *Epilobium hirsutum. Carex spp.* are often important where the soil has a very high organic content. Grazing often encourages coarse, tussock forming grasses such as *Deschampsia caespitosa.* Lowland marshes in the UK are usually invaded by such trees as Grey Willow (*Salix atrocinerea*) and Common Alder (*Alnus glutinosa*), with Bog Myrtle (*Myrica gale*) dominating early tree succession in acid and peaty conditions (BTCV, 1976).

Although few marshes can compare in size to the 10,000 km^2 of the Florida Everglades (Maltby, 1986), the vast number of small marshes makes this type of wetland among the most widespread and important worldwide. Large areas of southern Africa are dotted with "dambos", small freshwater marshes which provide essential grazing and agricultural land for many rural communities. The North American Prairie Pothole region includes several million freshwater marshes. In the USA, some of the larger marshes dominated by *Phragmites spp., Typha spp.* and *Cyperus papyrus* which have standing water throughout the year, are normally referred to as swamps (Dugan, 1993).

Swamps may contain water tolerant woody plants which require up to 20 years for development.

LAKES

Lakes and ponds develop through several processes, with many of the largest formed by folding and faulting associated with movement of the Earth's crust, e.g. Lake Tanganyika, Africa. Glacial action has also been a major process in lake formation (Dugan, 1990).

PEATLANDS

Peatlands exist on all continents at all latitudes, and with a total area of 4 million km^2, storing 20% of the global soil carbon pool. Oxidation of this carbon pool either by burning or via drainage may greatly increase the levels of carbon dioxide, a known "greenhouse" gas (Maltby, 1992). There are a great diversity of peatlands worldwide, the pattern being governed by acidity, climate and hydrology. Peat formation generally occurs under conditions of low temperature, high acidity, low nutrient supply, waterlogging and oxygen deficiency; conditions which slow the decomposition of dead plant matter. Some peatlands, namely bogs, are highly acidic and nutrient deficient whilst others, such as fens, are neutral and nutrient rich (Dugan, 1993). Mires are areas of permanently wet peat (>400 mm thick) caused by a water table very near the surface (siligenous mires) or high rainfall which saturates the peat even though it is above ground level (ombrogenous mires). They exist as both "bog" and "fen" depending on whether their vegetation is adapted to acid or alkaline conditions.

Basin Mires develop from small, deep ponds which lack an outlet. Vegetation forms a mat over the water's surface which eventually becomes so thick that plants are raised on a layer of soggy peat above the water, which becomes anaerobic and acid dominated by *Sphagnum spp.*. The UK's best developed basin mires are found in Cheshire and Staffordshire.

Valley Mires develop where water flows through shallow valleys but where the drainage is impeded. Peat formation dominates but the vegetation may exist as a bog or a fen depending on the mineral content of the surrounding/underlying rocks.

Raised Mires develop from Valley Mires where the annual rainfall exceeds 1010 mm (BTCV, 1976). Peat builds up until it is above the groundwater table. Rainfall leaches out minerals from raised areas which generally exist as a dome dominated by *Sphagnum spp.*.

Blanket Mires develop where the annual rainfall exceeds 1395 mm. Here, all flat ground and gentle slopes remain permanently waterlogged, peat builds up and large areas become uniformly blanketed. Numerous examples of blanket mires occur in the UK predominantly in the north and west (BTCV, 1976).

SWAMP FOREST

Swamp Forests develop in still water areas, around lake margins and in parts of floodplains. Their character and species diversity varies according to geographical location and environment, often covering vast areas. In Africa, the forested floodplains cover hundreds of thousands of square kilometres (Dugan, 1993). These areas in the southern states of the USA are characterised by Cypress Swamps (Maltby, 1986).

APPENDIX 2.

THE BITTERN LIFE PROJECT.

APPENDIX 3.

ESTIMATION EQUATIONS.

Penman Equation (1948):

$$E = (h\Delta' + E_a\gamma')/(\Delta' + \gamma')$$

Where;	E	= Evaporation in mm/day
	h	= Net radiation energy available at surface
	Δ'	= de_a/dT_a
	Ea	= Value of Eo obtained by putting $e_s = e_a$ in sink strength formula
	γ'	= Constant of wet and dry bulb hygrometer equation; in ^OF and mm. Hg, $\gamma = 0.27$

Turc Formula (see Ward, 1975):

$$ET' = \frac{P'}{(0.9 + (P/L)^2)^{1/2}}$$

where;	ET'	= mean annual potential evapotranspiration (mm)
	P'	= mean annual precipitation (mm)
	L	= $300 + 25T + 0.05T^3$
	T	= mean air temp(^OC).

Penman-Montieth Equation (Montieth, 1965):

$$\lambda E' = \frac{\Delta (R_n - G) + \rho Cp(es - e)/ra}{\Delta + \gamma(1 + rs / ra)}$$

Where;

E'	= rate of water loss (kg m^{-2} s^{-1})
Δ	= rate of change of saturated vapour pressure with temperature (mb $^oC^{-1}$)
R_n	= net radiation (W m^{-2})
G	= soil heat flux (W m^{-2})
ρ	= air density (kg m^{-3})
Cp	= specific heat of air at constant pressure (1005 J kg^{-1})
es	= saturation vapour pressure at screen temperature (mb)
e	= screen vapour pressure (mb)
λ	= latent heat of vaporisation (=2465000 J kg^{-1})
γ	= psychometric constant (= 0.66 for temperature in ^oC and vapour pressure in mb)
rs	= bulk surface (canopy) resistance (s m^{-1})
ra	= bulk aerodynamic resistance (s m^{-1})

APPENDIX 4.

PHYTOMETERS - A PHOTOGRAPH RECORD.

A Phytometer Located Within-stand, Pilot Pool, TINR, August 1996

A Phytometer Located Not Within-stand, Pilot Pool, TINR, August 1996

An Unplanted Phytometer Located Within-stand, Pilot Pool, TINR, August 1996

A Hook Gauge

Rhizome Rich Substrate Used To Establish Phytometers, Pilot Pool, TINR, March 1993

APPENDIX 5.

MONTHLY ET(Reed) AND E(Phyto) DATA

Phyto. No.	Location	Measurement	Apr (mm/day)	May (mm/day)	Jun (mm/day)	Jul (mm/day)	Aug (mm/day)	Sep (mm/day)	Oct (mm/day)
1	Within	ET(Reed)	over	over	over	over	3.52	2.10	0.81
4	Within	ET(Reed)	0.20	2.83	2.97	2.35	4.26	2.43	1.00
3	Within	E(Phyto)	1.13	1.47	3.17	1.03	3.13	3.17	1.71
2	Not within	ET(Reed)	1.83	2.17	4.10	3.42	4.94	3.30	1.29
6	Not within	ET(Reed)	0.90	1.87	2.73	1.81	2.87	2.17	0.58
7	Not within	ET(Reed)	na	na	na	na	6.35	4.20	2.65
9	Not within	ET(Reed)	na	na	na	na	3.65	2.57	0.65
5	Not within	E(Phyto)	1.13	2.47	3.27	2.03	2.77	2.47	0.94
8	Not within	E(Phyto)	na	na	na	na	3.68	3.03	0.84
10	Not within	E(Phyto)	na	na	na	na	3.23	2.27	0.81

EXPERIMENTAL RECORDS TINR 1993 - All Phytometers.

Phyto. No.	Location	Measurement	Apr (mm/day)	May (mm/day)	Jun (mm/day)	Jul (mm/day)	Aug (mm/day)	Sep (mm/day)	Oct (mm/day)
1	Within	ET(Reed)	over	2.30	4.56	3.58	4.61	3.44	na
4	Within	ET(Reed)	over	2.34	5.47	4.22	4.99	1.50	na
12	Within	ET(Reed)	over	3.35	4.67	3.26	3.71	2.83	na
13	Within	ET(Reed)	over	1.28	4.09	2.93	4.28	2.70	na
14	Within	ET(Reed)	over	2.64	4.25	3.16	2.72	2.07	na
15	Within	ET(Reed)	over	1.65	3.53	2.04	2.72	2.07	na
22	Within	ET(Reed)	over	3.50	5.12	2.58	3.21	2.50	na
23	Within	ET(Reed)	over	2.42	3.66	2.98	4.01	2.66	na
24	Within	ET(Reed)	over	2.24	3.74	2.31	3.03	2.10	na
25	Within	ET(Reed)	over	1.99	3.85	2.12	3.15	2.40	na
Mean	Within	ET(Reed)	over	2.37	4.29	2.92	3.65	2.43	na
Stan. Dev.	Within	ET(Reed)	na	0.68	0.65	0.68	0.80	0.53	na
Stan. Err.	Within	ET(Reed)	na	0.22	0.21	0.22	0.25	0.17	na
95% Conf.	Within	ET(Reed)	na	0.43	0.41	0.43	0.51	0.34	na
99% Conf.	Within	ET(Reed)	na	0.65	0.62	0.65	0.76	0.50	na

EXPERIMENTAL RECORDS TINR 1994 - ET(Reed) Within-stand.

Phyto. No.	Location	Measurement	Apr (mm/day)	May (mm/day)	Jun (mm/day)	Jul (mm/day)	Aug (mm/day)	Sep (mm/day)	Oct (mm/day)
3	Within	E(Phyto)	over	1.16	2.37	0.87	2.45	3.14	na
17	Within	E(Phyto)	over	3.58	4.40	3.74	4.58	2.03	na
18	Within	E(Phyto)	over	2.64	2.93	1.32	2.10	1.83	na
19	Within	E(Phyto)	over	2.93	3.43	1.97	2.42	1.90	na
20	Within	E(Phyto)	over	2.33	3.36	1.80	2.38	1.93	na
27	Within	E(Phyto)	over	2.93	4.30	3.62	2.80	2.33	na
28	Within	E(Phyto)	over	2.90	3.60	4.39	2.42	2.30	na
29	Within	E(Phyto)	over	2.65	3.21	1.97	2.10	2.03	na
30	Within	E(Phyto)	over	2.90	2.90	1.04	1.94	2.17	na
Mean	Within	E(Phyto)	over	2.67	3.39	2.30	2.58	2.19	na
Stan. Dev.	Within	E(Phyto)	na	0.66	0.66	1.29	0.79	0.40	na
Stan. Err.	Within	E(Phyto)	na	0.22	0.22	0.43	0.26	0.13	na
95% Conf.	Within	E(Phyto)	na	0.44	0.44	0.86	0.53	0.26	na
99% Conf.	Within	E(Phyto)	na	0.66	0.66	1.29	0.79	0.40	na

EXPERIMENTAL RECORDS TINR 1994 - E(Phyto) Within-stand.

Phyto. No.	Location	Measurement	Apr (mm/day)	May (mm/day)	Jun (mm/day)	Jul (mm/day)	Aug (mm/day)	Sep (mm/day)	Oct (mm/day)
2	Not within	ET(Reed)	over	1.58	4.30	4.60	4.36	3.07	na
6	Not within	ET(Reed)	over	1.83	3.51	3.17	5.52	2.10	na
7	Not within	ET(Reed)	over	3.04	7.26	6.18	6.84	3.48	na
9	Not within	ET(Reed)	over	over	4.68	4.93	6.10	2.97	na
11	Not within	ET(Reed)	over	2.30	3.71	2.93	4.55	2.77	na
21	Not within	ET(Reed)	over	2.08	3.19	2.15	3.20	2.13	na
Mean	Not within	ET(Reed)	over	2.17	4.44	3.99	5.09	2.75	na
Stan. Dev.	Not within	ET(Reed)	na	0.56	1.48	1.50	1.32	0.55	na
Stan. Err.	Not within	ET(Reed)	na	0.25	0.61	0.61	0.54	0.22	na
95% Conf.	Not within	ET(Reed)	na	0.50	1.21	1.22	1.07	0.45	na
99% Conf.	Not within	ET(Reed)	na	0.75	1.82	1.83	1.61	0.67	na

EXPERIMENTAL RECORDS TINR 1994 - ET(Reed) Not Within-stand.

Phyto. No.	Location	Measurement	Apr (mm/day)	May (mm/day)	Jun (mm/day)	Jul (mm/day)	Aug (mm/day)	Sep (mm/day)	Oct (mm/day)
5	Not within	E(Phyto)	over	2.71	3.38	1.68	1.84	3.16	na
8	Not within	E(Phyto)	over	3.41	4.82	5.19	5.96	2.61	na
10	Not within	E(Phyto)	over	over	3.90	4.10	7.45	2.61	na
16	Not within	E(Phyto)	over	2.32	3.07	1.77	2.84	1.66	na
26	Not within	E(Phyto)	over	2.71	3.57	1.86	4.84	1.93	na
Mean	Not within	E(Phyto)	over	2.79	3.75	2.92	4.59	2.39	na
Stan. Dev.	Not within	E(Phyto)	na	0.45	0.67	1.62	2.28	0.60	na
Stan. Err.	Not within	E(Phyto)	na	0.23	0.30	0.73	1.02	0.27	na
95% Conf.	Not within	E(Phyto)	na	0.45	0.60	1.45	2.04	0.53	na
99% Conf.	Not within	E(Phyto)	na	0.68	0.90	2.18	3.05	0.80	na

EXPERIMENTAL RECORDS TINR 1994 - E(Phyto) Not Within-stand.

Phyto. No.	Location	Measurement	Apr (mm/day)	May (mm/day)	Jun (mm/day)	Jul (mm/day)	Aug (mm/day)	Sep (mm/day)	Oct (mm/day)
1	Within	ET(Reed)	1.22	1.84	4.10	5.85	6.49	4.91	3.95
4	Within	ET(Reed)	over	1.07	3.88	4.16	5.87	5.86	3.46
12	Within	ET(Reed)	2.05	2.38	3.57	4.38	4.44	4.91	2.88
13	Within	ET(Reed)	over	2.96	4.59	4.81	4.65	4.78	2.60
14	Within	ET(Reed)	2.02	1.99	3.90	5.80	5.74	4.05	2.28
15	Within	ET(Reed)	over	1.77	2.85	4.17	4.88	4.18	4.66
22	Within	ET(Reed)	2.31	2.42	3.69	5.16	5.84	4.09	2.98
23	Within	ET(Reed)	1.85	2.20	4.49	7.04	7.95	5.45	4.68
24	Within	ET(Reed)	2.07	2.22	3.65	4.23	4.27	4.22	2.13
25	Within	ET(Reed)	2.13	2.29	4.43	5.85	7.20	4.86	4.81
Mean	Within	ET(Reed)	1.95	2.11	3.91	5.15	5.73	4.73	3.44
Stan. Dev.	Within	ET(Reed)	0.35	0.50	0.52	0.97	1.22	0.61	1.03
Stan. Err.	Within	ET(Reed)	0.13	0.16	0.16	0.31	0.39	0.19	0.32
95% Conf.	Within	ET(Reed)	0.26	0.31	0.33	0.61	0.77	0.38	0.65
99% Conf.	Within	ET(Reed)	0.40	0.47	0.49	0.92	1.16	0.58	0.97

EXPERIMENTAL RECORDS TINR 1995 - ET(Reed) Within-stand.

Phyto. No.	Location	Measurement	Apr (mm/day)	May (mm/day)	Jun (mm/day)	Jul (mm/day)	Aug (mm/day)	Sep (mm/day)	Oct (mm/day)
3	Within	E(Phyto)	over	2.04	2.42	1.45	1.49	2.58	0.88
17	Within	E(Phyto)	2.31	1.99	2.96	2.61	2.19	3.72	1.82
18	Within	E(Phyto)	2.23	2.00	2.35	1.84	1.66	3.09	1.42
19	Within	E(Phyto)	2.31	1.96	2.93	2.84	2.21	2.70	1.45
20	Within	E(Phyto)	over	1.90	3.40	3.05	2.30	2.57	1.48
27	Within	E(Phyto)	2.45	2.36	3.13	3.33	2.80	1.95	1.97
28	Within	E(Phyto)	2.27	1.94	3.45	3.40	2.68	2.64	1.48
29	Within	E(Phyo)	2.27	1.77	2.96	2.49	2.01	2.47	1.33
30	Within	E(Phyto)	2.45	1.90	2.90	2.65	2.30	2.28	1.31
Mean	Within	E(Phyto)	2.07	2.02	2.98	2.70	2.27	2.71	1.53
Stan. Dev.	Within	E(Phyto)	0.09	0.16	0.38	0.65	0.42	0.50	0.31
Stan. Err.	Within	E(Phyto)	0.03	0.05	0.13	0.22	0.14	0.17	0.10
95% Conf.	Within	E(Phyto)	0.07	0.11	0.25	0.43	0.28	0.33	0.21
99% Conf.	Within	E(Phyto)	0.10	0.16	0.38	0.65	0.42	0.50	0.31

EXPERIMENTAL RECORDS TINR 1995 - E(Phyto) Within-stand.

Phyto. No.	Location	Measurement	Apr (mm/day)	May (mm/day)	Jun (mm/day)	Jul (mm/day)	Aug (mm/day)	Sep (mm/day)	Oct (mm/day)
2	Not within	ET(Reed)	over	1.89	4.42	6.17	6.29	5.86	4.82
6	Not within	ET(Reed)	1.53	1.20	3.14	4.30	4.75	4.79	2.98
7	Not within	ET(Reed)	1.73	2.41	4.11	6.75	8.03	5.37	4.71
9	Not within	ET(Reed)	over	3.70	5.14	5.39	6.03	5.84	2.83
11	Not within	ET(Reed)	1.78	2.22	4.16	6.58	9.08	4.76	2.86
21	Not within	ET(Reed)	1.87	1.77	3.60	5.46	6.09	5.64	4.85
Mean	Not within	ET(Reed)	1.73	2.20	4.10	5.78	6.71	5.38	3.84
Stan. Dev.	Not within	ET(Reed)	0.14	0.85	0.68	0.91	1.56	0.50	1.04
Stan. Err.	Not within	ET(Reed)	0.07	0.34	0.28	0.37	0.64	0.20	0.43
95% Conf.	Not within	ET(Reed)	0.14	0.69	0.56	0.75	1.28	0.41	0.85
99% Conf.	Not within	ET(Reed)	0.22	1.03	0.84	1.12	1.92	0.61	1.28

EXPERIMENTAL RECORDS TINR 1995 - ET(Reed) Not Within-stand.

Phyto. No.	Location	Measurement	Apr (mm/day)	May (mm/day)	Jun (mm/day)	Jul (mm/day)	Aug (mm/day)	Sep (mm/day)	Oct (mm/day)
5	Not within	E(Phyto)	1.97	1.49	2.52	2.62	2.09	2.53	1.07
8	Not within	E(Phyto)	2.92	4.00	4.36	4.92	4.86	4.23	2.58
10	Not within	E(Phyto)	over	2.78	4.16	5.68	5.10	4.88	3.12
16	Not within	E(Phyto)	1.91	1.72	2.86	3.21	2.23	3.02	0.92
26	Not within	E(Phyto)	2.09	1.77	2.85	3.21	2.84	3.30	1.24
Mean	Not within	E(Phyto)	2.22	2.35	3.35	3.93	3.42	3.59	1.78
Stan. Dev.	Not within	E(Phyto)	0.47	1.04	0.85	1.30	1.45	0.95	1.00
Stan. Err.	Not within	E(Phyto)	0.24	0.47	0.38	0.58	0.65	0.42	0.45
95% Conf.	Not within	E(Phyto)	0.47	0.93	0.76	1.17	1.29	0.85	0.89
99% Conf.	Not within	E(Phyto)	0.71	1.40	1.14	1.75	1.94	1.27	1.34

EXPERIMENTAL RECORDS TINR 1995 - E(Phyto) Not Within-stand.

Phyto. No.	Location	Measurement	Apr (mm/day)	May (mm/day)	Jun (mm/day)	Jul (mm/day)	Aug (mm/day)	Sep (mm/day)	Oct (mm/day)	Nov (mm/day)	Dec (mm/day)	Jan (mm/day)	Feb (mm/day)	Mar (mm/day)
1	Within	ET(Reed)	0.92	2.31	5.07	4.97	3.83	over	1.79	over	over	over	over	over
4	Within	ET(Reed)	1.52	2.18	4.57	3.73	3.47	2.97	3.16	1.74	1.40	0.60	2.01	1.25
12	Within	ET(Reed)	1.86	2.43	3.93	3.52	2.89	2.07	1.97	over	over	0.28	1.56	1.57
13	Within	ET(Reed)	1.24	1.67	3.51	3.22	3.02	2.06	1.58	1.29	0.98	0.28	1.24	1.00
14	Within	ET(Reed)	1.37	1.97	3.92	4.13	3.59	2.27	1.51	0.69	over	0.46	1.40	1.32
15	Within	ET(Reed)	1.40	2.08	4.52	4.89	5.83	2.53	2.12	0.72	0.49	0.13	0.94	1.10
22	Within	ET(Reed)	2.44	3.17	5.53	4.25	3.44	1.85	2.09	over	0.78	0.55	1.95	1.95
23	Within	ET(Reed)	1.61	2.05	4.82	5.88	3.24	4.22	3.13	0.37	0.48	0.05	1.05	1.41
24	Within	ET(Reed)	1.75	2.42	4.05	3.44	2.92	2.03	1.27	over	1.23	0.29	1.28	1.25
25	Within	ET(Reed)	1.61	2.22	4.49	4.83	4.58	2.97	2.01	0.60	0.31	-0.03	0.79	1.21
Mean	Within	ET(Reed)	1.57	2.25	4.44	4.29	3.68	2.55	2.06	0.90	0.81	0.29	1.36	1.34
Stan. Dev.	Within	ET(Reed)	0.41	0.39	0.61	0.85	0.91	0.75	0.63	0.51	0.41	0.22	0.42	0.28
Stan. Err.	Within	ET(Reed)	0.13	0.12	0.19	0.27	0.29	0.25	0.20	0.21	0.15	0.07	0.14	0.09
95% Conf.	Within	ET(Reed)	0.26	0.25	0.38	0.54	0.57	0.50	0.40	0.42	0.31	0.15	0.28	0.19
99% Conf.	Within	ET(Reed)	0.38	0.37	0.57	0.80	0.86	0.75	0.60	0.62	0.46	0.22	0.42	0.28

EXPERIMENTAL RECORDS TINR 1996/97 - ET(Reed) Within-stand.

Phyto. No.	Location	Measurement	Apr (mm/day)	May (mm/day)	Jun (mm/day)	Jul (mm/day)	Aug (mm/day)	Sep (mm/day)	Oct (mm/day)	Nov (mm/day)	Dec (mm/day)	Jan (mm/day)	Feb (mm/day)	Mar (mm/day)
3	Within	E(Phyto)	1.41	2.15	2.40	1.31	2.97	0.76	0.74	1.35	1.07	0.30	1.68	1.07
17	Within	E(Phyto)	1.74	2.42	2.61	1.99	over	1.02	1.00	over	over	0.30	1.06	1.07
18	Within	E(Phyto)	1.60	2.31	2.46	1.66	over	0.88	1.03	0.84	over	0.27	1.62	1.14
19	Within	E(Phyto)	1.82	2.63	2.99	1.95	2.02	1.14	0.84	0.63	0.47	0.21	1.45	1.22
20	Within	E(Phyto)	1.89	3.01	3.51	2.39	over	1.11	0.89	0.73	over	0.17	1.18	1.22
27	Within	E(Phyto)	2.10	2.62	3.25	2.31	2.64	1.19	1.23	0.62	0.33	0.32	1.16	1.52
28	Within	E(Phyto)	1.80	2.80	3.13	2.44	1.93	1.01	0.93	0.81	0.46	0.13	1.03	1.17
29	Within	E(Phyto)	1.76	2.74	2.90	1.77	over	0.96	0.89	0.90	0.48	0.11	1.78	1.17
30	Within	E(Phyto)	2.01	2.80	2.95	1.88	over	1.16	2.26	1.10	0.71	0.22	1.40	1.18
Mean	Within	E(Phyto)	1.79	2.61	2.91	1.97	2.39	1.03	1.09	0.87	0.59	0.23	1.37	1.20
Stan. Dev.	Within	E(Phyto)	0.21	0.27	0.37	0.37	0.50	1.06	0.46	0.25	0.27	0.08	0.28	0.13
Stan. Err.	Within	E(Phyto)	0.07	0.09	0.12	0.12	0.25	0.35	0.15	0.09	0.11	0.03	0.09	0.04
95% Conf.	Within	E(Phyto)	0.14	0.18	0.25	0.25	0.50	0.70	0.31	0.17	0.22	0.05	0.19	0.09
99% Conf.	Within	E(Phyto)	0.21	0.27	0.37	0.37	0.75	1.06	0.46	0.26	0.33	0.08	0.28	0.13

EXPERIMENTAL RECORDS TINR 1996/97 - E(Phyto) Within-stand.

Phyto. No.	Location	Measurement	Apr (mm/day)	May (mm/day)	Jun (mm/day)	Jul (mm/day)	Aug (mm/day)	Sep (mm/day)	Oct (mm/day)	Nov (mm/day)	Dec (mm/day)	Jan (mm/day)	Feb (mm/day)	Mar (mm/day)
2	Not within	ET(Reed)	1.86	2.35	5.45	5.30	4.23	3.59	3.48	over	1.03	0.17	over	1.62
6	Not within	ET(Reed)	1.35	1.71	3.41	4.65	4.27	3.56	2.40	0.28	0.39	0.23	0.29	1.35
7	Not within	ET(Reed)	2.07	2.62	6.67	6.83	5.65	6.17	4.89	0.42	0.29	0.04	1.38	1.82
9	Not within	ET(Reed)	2.49	3.25	5.84	5.76	3.92	3.36	2.05	over	1.00	0.12	1.32	2.01
11	Not within	ET(Reed)	1.67	1.60	3.75	4.49	5.30	3.74	2.79	0.77	0.64	0.43	1.86	1.55
21	Not within	ET(Reed)	1.36	1.88	4.83	6.13	5.76	5.66	4.99	0.29	0.46	-0.03	0.32	1.12
Mean	Not within	ET(Reed)	1.80	2.24	4.99	5.53	4.86	4.35	3.43	0.44	0.64	0.16	1.03	1.58
Stan. Dev.	Not within	ET(Reed)	0.43	0.68	1.40	0.94	0.75	1.17	1.12	0.25	0.34	0.14	0.66	0.25
Stan. Err.	Not within	ET(Reed)	0.17	0.28	0.57	0.39	0.31	0.48	0.46	0.13	0.14	0.06	0.30	0.10
95% Conf.	Not within	ET(Reed)	0.35	0.56	1.14	0.77	0.62	0.96	0.91	0.25	0.28	0.12	0.59	0.21
99% Conf.	Not within	ET(Reed)	0.52	0.83	1.71	1.16	0.92	1.44	1.37	0.38	0.42	0.18	0.89	0.31

EXPERIMENTAL RECORDS TINR 1996/97 - ET(Reed) Not Within-stand.

Phyto. No.	Location	Measurement	Apr (mm/day)	May (mm/day)	Jun (mm/day)	Jul (mm/day)	Aug (mm/day)	Sep (mm/day)	Oct (mm/day)	Nov (mm/day)	Dec (mm/day)	Jan (mm/day)	Feb (mm/day)	Mar (mm/day)
5	Not within	E(Phyto)	1.60	1.96	2.85	1.52	2.68	2.16	1.01	0.69	0.70	0.16	1.13	1.37
8	Not within	E(Phyto)	2.50	3.35	5.26	5.06	3.55	2.60	1.53	over	0.92	0.11	1.47	2.10
10	Not within	E(Phyto)	2.30	3.28	5.17	4.70	3.94	2.28	1.51	over	1.26	0.26	1.60	2.09
16	Not within	E(Phyto)	1.29	2.31	2.77	2.94	2.44	1.12	0.67	0.46	0.48	0.18	0.86	0.84
26	Not within	E(Phyto)	1.61	2.56	3.03	3.25	2.64	1.38	0.63	0.83	over	0.15	0.78	1.08
Mean	Not within	E(Phyto)	1.86	2.69	3.82	3.49	3.05	1.91	1.07	0.66	0.84	0.17	1.17	1.50
Stan. Dev.	Not within	E(Phyto)	0.51	0.61	1.28	1.43	0.66	0.63	0.44	0.18	0.33	0.06	0.36	0.58
Stan. Err.	Not within	E(Phyto)	0.23	0.27	0.57	0.64	0.29	0.28	0.20	0.11	0.17	0.02	0.16	0.26
95% Conf.	Not within	E(Phyto)	0.46	0.54	1.15	1.28	0.59	0.56	0.39	0.21	0.33	0.05	0.33	0.52
99% Conf.	Not within	E(Phyto)	0.69	0.82	1.72	1.92	0.88	0.84	0.59	0.32	0.50	0.07	0.49	0.77

EXPERIMENTAL RECORDS TINR 1996/97 - E(Phyto) Not Within-stand.

Phyto. No.	Location	Measurement	Apr (mm/day)	May (mm/day)	Jun (mm/day)	Jul (mm/day)	Aug (mm/day)	Sep (mm/day)	Oct (mm/day)
2	Not within	ET(Reed)	1.75	2.65	3.68	6.66	7.00	3.99	na
3	Not within	ET(Reed)	3.48	2.89	3.92	7.43	4.29	4.35	na
6	Not within	ET(Reed)	2.87	2.78	3.93	6.57	5.77	2.31	na
7	Not within	ET(Reed)	2.85	3.20	4.42	7.65	7.45	4.00	na
10	Not within	ET(Reed)	2.55	2.81	4.05	7.24	6.76	3.81	na
Mean	Not within	ET(Reed)	2.70	2.87	4.00	7.11	6.26	3.69	na
Stan. Dev.	Not within	ET(Reed)	0.63	0.21	0.27	0.47	1.26	0.80	na
Stan. Err.	Not within	ET(Reed)	0.28	0.09	0.12	0.21	0.56	0.36	na
95% Conf.	Not within	ET(Reed)	0.57	0.18	0.24	0.42	1.12	0.71	na
99% Conf.	Not within	ET(Reed)	0.85	0.28	0.36	0.64	1.69	1.07	na

EXPERIMENTAL RECORDS Redwick 1994 - ET(Reed) Not Within-stand.

Phyto. No.	Location	Measurement	Apr (mm/day)	May (mm/day)	Jun (mm/day)	Jul (mm/day)	Aug (mm/day)	Sep (mm/day)	Oct (mm/day)
1	Not within	E(Phyto)	over	over	over	over	over	over	na
4	Not within	E(Phyto)	2.19	1.99	1.92	2.59	1.96	1.77	na
5	Not within	E(Phyto)	3.01	1.87	2.32	3.19	2.41	1.34	na
8	Not within	E(Phyto)	1.72	1.95	2.37	2.91	2.29	2.04	na
9	Not within	E(Phyto)	3.51	2.25	2.35	2.99	2.50	1.39	na
Mean	Not within	E(Phyto)	2.61	2.01	2.24	2.92	2.29	1.64	na
Stan. Dev.	Not within	E(Phyto)	0.80	0.16	0.21	0.25	0.24	0.33	na
Stan. Err.	Not within	E(Phyto)	0.40	0.08	0.11	0.12	0.12	0.17	na
95% Conf.	Not within	E(Phyto)	0.80	0.16	0.21	0.25	0.24	0.33	na
99% Conf.	Not within	E(Phyto)	1.20	0.24	0.32	0.37	0.35	0.50	na

EXPERIMENTAL RECORDS Redwick 1994 - E(Phyto) Not Within-stand.

Phyto. No.	Location	Measurement	Apr (mm/day)	May (mm/day)	Jun (mm/day)	Jul (mm/day)	Aug (mm/day)	Sep (mm/day)	Oct (mm/day)
2	Not within	ET(Reed)	na	na	na	11.81	13.51	12.50	5.86
3	Not within	ET(Reed)	na	na	na	12.13	13.65	14.62	6.55
6	Not within	ET(Reed)	na	na	na	10.23	11.33	10.67	4.95
7	Not within	ET(Reed)	na	na	na	11.25	12.56	11.59	4.87
10	Not within	ET(Reed)	na	na	na	10.81	13.27	10.65	4.96
Mean	Not within	ET(Reed)	na	na	na	11.25	12.86	12.01	5.44
Stan. Dev.	Not within	ET(Reed)	na	na	na	0.76	0.96	1.65	0.74
Stan. Err.	Not within	ET(Reed)	na	na	na	0.34	0.43	0.74	0.33
95% Conf.	Not within	ET(Reed)	na	na	na	0.68	0.86	1.48	0.15
99% Conf.	Not within	ET(Reed)	na	na	na	1.02	1.28	2.21	0.07

EXPERIMENTAL RECORDS Redwick 1995 - ET(Reed) Not Within-stand.

Phyto. No.	Location	Measurement	Apr (mm/day)	May (mm/day)	Jun (mm/day)	Jul (mm/day)	Aug (mm/day)	Sep (mm/day)	Oct (mm/day)
1	Not within	E(Phyto)	na	na	na	over	over	over	over
4	Not within	E(Phyto)	na	na	na	2.43	2.44	3.34	2.92
5	Not within	E(Phyto)	na	na	na	3.02	3.04	3.95	1.39
8	Not within	E(Phyto)	na	na	na	2.83	2.89	2.95	2.46
9	Not within	E(Phyto)	na	na	na	2.74	2.79	3.33	1.43
Mean	Not within	E(Phyto)	na	na	na	2.75	2.79	3.39	2.05
Stan. Dev.	Not within	E(Phyto)	na	na	na	0.25	0.26	0.41	0.76
Stan. Err.	Not within	E(Phyto)	na	na	na	0.12	0.13	0.21	0.38
95% Conf.	Not within	E(Phyto)	na	na	na	0.25	0.26	0.41	0.17
99% Conf.	Not within	E(Phyto)	na	na	na	0.37	0.39	0.62	0.08

EXPERIMENTAL RECORDS Redwick 1995 - E(Phyto) Not Within-stand.

Phyto. No.	Location	Measurement	Apr (mm/day)	May (mm/day)	Jun (mm/day)	Jul (mm/day)	Aug (mm/day)	Sep (mm/day)	Oct (mm/day)
1	Within	ET(Reed)	1.98	2.11	1.68	1.77	2.02	1.96	0.84
4	Within	ET(Reed)	2.00	2.89	4.27	6.82	4.47	2.70	1.00
6	Within	ET(Reed)	1.40	2.34	2.37	2.76	2.48	1.85	0.90
7	Within	ET(Reed)	1.71	2.68	4.14	5.10	3.72	3.08	1.64
10	Within	ET(Reed)	2.43	2.36	1.94	2.28	2.56	1.96	0.99
Mean	Within	ET(Reed)	1.90	2.48	2.88	3.75	3.05	2.31	1.07
Stan. Dev.	Within	ET(Reed)	0.38	0.31	1.23	2.14	1.01	0.55	0.32
Stan. Err.	Within	ET(Reed)	0.17	0.14	0.55	0.96	0.45	0.25	0.14
95% Conf.	Within	ET(Reed)	0.34	0.27	1.10	1.91	0.90	0.49	0.06
99% Conf.	Within	ET(Reed)	0.51	0.41	1.66	2.87	1.35	0.74	0.03

EXPERIMENTAL RECORDS Himley 1995 - ET(Reed) Within-stand.

Phyto. No.	Location	Measurement	Apr (mm/day)	May (mm/day)	Jun (mm/day)	Jul (mm/day)	Aug (mm/day)	Sep (mm/day)	Oct (mm/day)
2	Within	E(Phyto)	1.70	2.68	1.67	1.07	0.85	0.69	0.72
3	Within	E(Phyto)	1.64	2.35	1.33	1.15	1.01	1.33	0.46
5	Within	E(Phyto)	1.44	2.24	1.30	0.90	0.91	1.06	0.71
8	Within	E(Phyto)	1.23	2.40	1.38	0.90	0.77	0.90	0.48
9	Within	E(Phyto)	1.38	2.50	1.52	1.18	0.87	1.47	1.05
Mean	Within	E(Phyto)	1.48	2.43	1.44	1.04	0.88	1.09	0.68
Stan. Dev.	Within	E(Phyto)	0.19	0.16	0.15	0.13	0.09	0.31	0.24
Stan. Err.	Within	E(Phyto)	0.09	0.07	0.07	0.06	0.04	0.14	0.11
95% Conf.	Within	E(Phyto)	0.17	0.15	0.14	0.12	0.08	0.28	0.05
99% Conf.	Within	E(Phyto)	0.26	0.22	0.20	0.18	0.12	0.42	0.02

EXPERIMENTAL RECORDS Himley 1995 - E(Phyto) Within-stand.

Phyto. No.	Location	Measurement	Apr (mm/day)	May (mm/day)	Jun (mm/day)	Jul (mm/day)	Aug (mm/day)	Sep (mm/day)	Oct (mm/day)	Nov (mm/day)	Dec (mm/day)	Jan (mm/day)	Feb (mm/day)	Mar (mm/day)
1	Within	ET(Reed)	0.98	1.63	2.68	2.83	2.73	1.85	0.87	0.87	0.01	-0.01	0.77	0.57
4	Within	ET(Reed)	1.30	2.62	6.16	7.93	8.76	8.91	4.09	1.11	0.28	0.25	0.91	0.83
6	Within	ET(Reed)	1.35	2.21	2.80	4.43	5.51	5.31	2.48	0.67	0.21	0.16	0.75	0.66
7	Within	ET(Reed)	2.12	3.56	5.60	7.71	10.67	13.23	5.06	0.95	0.32	0.28	0.85	0.85
10	Within	ET(Reed)	1.17	2.03	1.96	2.03	3.27	2.19	1.83	over	over	over	over	over
Mean	Within	ET(Reed)	1.38	2.41	3.84	4.99	6.19	6.30	2.87	0.90	0.20	0.17	0.82	0.73
Stan. Dev.	Within	ET(Reed)	0.44	0.74	1.90	2.73	3.45	4.81	1.70	0.18	0.14	0.13	0.07	0.13
Stan. Err.	Within	ET(Reed)	0.19	0.33	0.85	1.22	1.54	2.15	0.76	0.09	0.07	0.06	0.04	0.07
95% Conf.	Within	ET(Reed)	0.39	0.66	1.70	2.44	3.09	4.30	1.52	0.18	0.14	0.13	0.07	0.13
99% Conf.	Within	ET(Reed)	0.58	0.99	2.55	3.66	4.63	6.45	2.28	0.27	0.21	0.19	0.11	0.20

EXPERIMENTAL RECORDS Himley 1996/97 - ET(Reed) Within-stand.

Phyto. No.	Location	Measurement	Apr (mm/day)	May (mm/day)	Jun (mm/day)	Jul (mm/day)	Aug (mm/day)	Sep (mm/day)	Oct (mm/day)	Nov (mm/day)	Dec (mm/day)	Jan (mm/day)	Feb (mm/day)	Mar (mm/day)
2	Within	E(Phyto)	1.51	1.67	1.02	0.80	1.64	0.75	0.75	1.31	0.20	0.12	0.73	0.67
3	Within	E(Phyto)	1.32	1.85	1.58	0.76	0.63	0.72	0.39	0.65	0.06	0.05	0.34	0.68
5	Within	E(Phyto)	1.42	1.95	1.42	0.76	1.03	0.50	1.07	0.57	0.30	0.17	0.71	0.60
8	Within	E(Phyto)	1.10	1.37	1.11	0.94	1.08	0.50	0.30	0.23	0.14	0.14	0.36	0.51
9	Within	E(Phyto)	1.43	2.01	2.20	1.03	1.27	0.55	0.24	0.42	0.18	0.01	0.45	0.78
Mean	Within	E(Phyto)	1.36	1.77	1.46	0.86	1.13	0.60	0.55	0.69	0.18	0.12	0.54	0.62
Stan. Dev.	Within	E(Phyto)	0.16	0.26	0.47	0.12	0.37	0.12	0.35	0.41	0.09	0.06	0.19	0.10
Stan. Err.	Within	E(Phyto)	0.07	0.11	0.21	0.05	0.17	0.06	0.16	0.21	0.04	0.03	0.09	0.05
95% Conf.	Within	E(Phyto)	0.14	0.23	0.42	0.11	0.33	0.11	0.31	0.41	0.09	0.06	0.19	0.10
99% Conf.	Within	E(Phyto)	0.21	0.34	0.63	0.16	0.50	0.17	0.47	0.62	0.13	0.10	0.28	0.15

EXPERIMENTAL RECORDS Himley 1996/97 - E(Phyto) Within-stand.

APPENDIX 6.

ETo SENSITIVITY ANALYSIS USING LOCAL AND MORECS DATA.

Meteorological Data Used to Calculate ETo.	ETo (mm/day) No Meteorological Parameter Variation	ETo (mm/day) Single Meteorological Parameter Varied	Variation (mm/day)	Variation %
TINR - Local Data	1.90	na	na	na
TINR - MORECS Data	1.92	na	na	na
TINR - Local Data with MORECS Temp.	1.90	1.88	-0.02	-1.06
TINR - Local Data with MORECS Sun Hours	1.90	1.83	-0.07	-3.83
TINR - Local Data with MORECS Wind Speed	1.90	1.99	0.09	4.52
TINR - MORECS Data with Local Temp.	1.92	1.94	0.02	1.03
TINR - MORECS Data with Local Sun Hours	1.92	1.98	0.06	3.03
TINR - MORECS Data with Local Wind Speed	1.92	1.82	-0.10	-5.49
Himley - Local Data	1.71	na	na	na
Himley - MORECS Data	1.89	na	na	na
Himley - Local Data with MORECS Temp.	1.71	1.64	-0.07	-4.27
Himley - Local Data with MORECS Sun Hours	1.71	1.71	0.00	0.00
Himley - Local Data with MORECS Wind Speed	1.71	1.98	0.27	13.64
Himley - MORECS Data with Local Temp.	1.89	1.99	0.10	5.03
Himley - MORECS Data with Local Sun Hours	1.89	1.89	0.00	0.00
Himley - MORECS Data with Local Wind Speed	1.89	1.64	-0.25	-15.24

APPENDIX 7.

GEOGRAPHICAL INFORMATION SYSTEMS.

A Geographic Information System (GIS) is a computer assisted system for the acquisition, storage, analysis and display of geographic data. A GIS software, is typically made up of different components, however, central to the system is the database, a collection of maps and associated information in digital form. The database is concerned with earth surface features, and can be comprised of two elements of data that are found on a map. Firstly, a spatial database describing the geography (shape and position) of surface features, and secondly, an attribute database describing the characteristics and qualities of these features. Not all GISs use the same logic for achieving this. However, the majority use one or a combination of both of the fundamental map representation techniques: Vector and Raster (Eastman, 1993).

With vector representation, the boundaries of the features are defined by a series of points encoded with a pair of numbers giving the X and Y co-ordinates. When joined with straight lines, these points form the graphic representation of that feature. The attributes of features are then stored within a traditional database management software programme.

With raster systems, the graphic representation of features and their attributes are merged into unified data files, with the study area typically subdivided into a fine mesh of grid cells in which the condition or attribute of the earth's surface at that point is recorded. Each cell is given a numeric value, which may than represent either a feature identifier, a qualitative code or a quantitative attribute value (Elgy, 1997). Raster systems are typically data intensive, and have substantially more analytical power than their vector counterparts particularly in the analysis of data that are continuously changing over space such a terrain, vegetation biomass, rainfall etc. In the raster system, the data directly controls the visible form we see.

Raster and vector systems each have their special strengths. As a result, most GISs incorporate elements from both representational techniques, and allow the conversion of data between raster and vector formats. Data must often be generated through digitising, which producing vector files, which must be converted if the subsequent analysis is to be done in raster format.

This section has only provided a brief overview of the components and application of GISs. Curran (1985), and Barrett and Curtis (1992), provide a detailed discussion of GISs highlighting the exhaustive applications.

IDRISI for WINDOWS (1.0)

IDRISI for Windows allows for highly interactive and flexible on screen cartographic composition, which may be saved for later display, printed to windows-compatible devices, and exported in a variety of common desktop publishing formats. IDRISI for Windows consists of a main interface programme and a collection of over one hundred programme modules that provide facilities for the input, display and analysis of geographic data of different types. A detailed description of all of the programme modules available in IDRISI for Windows is provided by Eastman (1995).

Map Digitising Systems

A Map Digitising System can be used to convert existing paper maps into digital form, thus developing a database. In the most common method of digitising, the paper map is attached to a digitising tablet or board (e.g. Calcomp Drawing Board II), and the features traced with a stylus or puck in accordance with the procedures required by the digitising software. Many Map Digitising Systems also allow for some editing of the digitised area. Map Digitising and editing in IDRISI for Windows is provided by the software package TOSCA. TOSCA is one of a number of independent digitising software packages that support the IDRISI data format.

From the Pilot Pool design drawing all of the contours between and including 0.00 mAOD and 2.50 mAOD were digitised to provide the data necessary for interpolation. The catchment boundary was delineated, and once digitised was allocated a contour height of 3.00 mAOD (estimated mean).

Image Processing

Following the digitising, the vector contours were converted to raster format (with the use of INITIAL and LINERAS programme modules) with all of the pixels intersected by a vector line assigned the identifier of that vector line. Raster cells were representative of an area of 0.25 m^2. The INTERCON module of IDRISI was then run on the rasterized file to produce the interpolated DEM of the catchment area at a resolution of 0.01 mAOD.

APPENDIX 8.

GLOSSARY.

ACTUAL EVAPOTRANSPIRATION (AE) - the amount of water which is removed from the (crop + soil) combination into the air in an unirrigated crop. It is equal to or less than the Potential Evapotranspiration (mm/day).

ALBEDO - the ratio of the amount of solar radiation reflected by a body to the amount incident upon it.

BOWEN RATIO - the ratio between the sensible heat flux density and the latent heat flux density. In wetland studies, where the Bowen ratio is > 1.0, ET(Crop) is greater than ETo (Gilman, 1997).

CLOTHESLINE EFFECT - horizontal heat transfer (advection) from warm and dry upwind area to a relatively cooler crop field resulting in increased ET(Crop); particularly refers to the field border effect or to patchwork of small interspersed fields.

CROP COEFFICIENT (Kc) - ratio between crop evapotranspiration of a disease-free crop, and reference crop evapotranspiration (ETo) when crop is grown in large fields under optimum growing conditions, or ET(Crop) = Kc. ETo.

CROP EVAPOTRANSPIRATION [ET(Crop)] - rate of evapotranspiration of a disease free crop growing in a large field (one or more ha) under optimal soil conditions, including sufficient water and fertiliser and achieving full production potential of that crop under the given growing environment; includes water loss through transpiration through vegetation, and evaporation from the soil surface and wet leaves (mm/day).

CROP HEIGHT - measured from the estimated lowest point where the vertical stem protrudes above the sediment surface within the phytometer (thus part of the stem that was measured was underwater), to the estimated highest point where the stem terminates at the break of the youngest leaf (m).

CROP WATER REQUIREMENTS - depth of water required by a crop or a diversified pattern of crops for evapotranspiration [ET(Crop)] during a given period (mm/day as average for given period).

DESCRIPTIVE AND PREDICTIVE MODELS - Descriptive, refers to models that describe an existing structure or known behaviour of a system, whilst Predictive refers to models that are used to extrapolate the structure or behaviour of a system outside the existing data boundaries. Most mathematical models combine both functions, since prediction is usually accomplished by mathematical manipulating the descriptive model. Another way of thinking of the relationship is that descriptive models are mathematical tools available to model builders for interpolation, while prediction requires extrapolation beyond the existing data (Costanza and Sklar, 1985).

DEVELOPMENT STAGE - for a given crop the period between end of initial stage and full ground cover or when ground cover is between 10 and 75% (days).

DIGITAL ELEVATION MODEL (DEM) - is a term used to refer to an image which stores data that can be envisioned as 'heights on a surface', interpolating estimates of elevation data in locations where the height is unknown, based on the known heights of nearby 'control' points.

DORMANT PERIOD - period between the beginning of November and the end of March.

EFFECTIVE FULL GROUNDCOVER - Percentage of groundcover by the crop when ET(Crop) is approaching maximum - generally 70 to 80% of surface area (%).

OPEN WATER EVAPORATION (Eo) - rate of water loss from liquid to vapour phase from an open waterbody by physical processes (mm/day).

EVAPOTRANSPIRATION - rate of water loss through transpiration from vegetation plus evaporation from the soil or water surface (mm/day).

FULL GROUND COVER - soil covered by crops approaching 100% when looking downwards.

GROUND COVER - percentage of soil surface shaded by crop if the sun were directly overhead (%).

GROWING SEASON - period between the beginning of April and the end of October.

HELOPHYTES - plants of wet habitats with at least 1m of aerial growth.

HYDROPHYTES - plants of wet habitats.

INITIAL DEVELOPMENT STAGE - for a given crop the period during germination or early growth when ground cover is less than 10% (days).

INFLORESCENCE - the entire group of flowers on a single stem (mononcot.).

MID-SEASON STAGE - for a given crop for the period between effective full ground cover and the onset of maturity (i.e. leaves start to discolour or fall off) (days).

MORECS (Meteorological Office Rainfall and Evaporation Calculation System) - a comprehensive computer package designed to provide estimates of weekly and monthly Eo, ET, and soil moisture deficits (SMD) in the form of averages for 190 grid squares (40 km x 40 km) over Great Britain, using daily synoptic weather data as inputs.

OASIS EFFECT - effect of dry fallow surrounds on the micro-climate of a relatively small acreage of land where an air mass moving into an irrigated area will give up sensible heat. For small fields this may result in a higher ET crop using climatic data collected inside the irrigated area; conversely ET crop predictions based on weather data collected outside the irrigated fields may over predict actual evapotranspiration losses.

PAN COEFFICIENT (Kp) - ratio between reference evapotranspiration ETo and water loss by evaporation from an open water surface of a pan or ETo = kp x Epan.

PAN EVAPORATION (Epan) - rate of water loss by evaporation from an open water surface of a pan (mm/day).

PHENOLOGICAL - the study of plant characteristics as affected by climate, especially dates of seasonal phenomena, as opening of flowers.

POTENTIAL CROP COEFFICIENT (Kco) - presented by Shuttleworth (1979), applicable where it is necessary to supply adequate water, but not excessive, so that the soil surface is not wet.

POTENTIAL EVAPOTRANSPIRATION (PE) - the loss of water from a crop or surface where the water supply is such that unhindered evaporation occurs. This evaporation rate is governed by the weather and by the crop height. In the UK in general the loss of water from crops is at the potential rate until the available water capacity has been reduced to about 20 - 40% of the maximum amount (mm/day).

PRECIPITATION - total amount of precipitation (rain, drizzle, snow, hail, fog, condensation, hoar frost and rime) expressed in depth of water which would cover a horizontal plane if there is no runoff, infiltration or evapotranspiration (mm/day).

REFERENCE CROP EVAPOTRANSPIRATION (ETo) - rate of evapotranspiration from an extended surface of 80 to 150 mm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water (mm/day).

SENESCENCE - period when plants cease the majority of metabolic activities, prior to becoming dormant.

SOIL MOISTURE DEFICIT (SMD) - the amount by which the soil moisture content is below the field capacity state. It can also be defined as the amount of water which would have to be added to the soil in order to bring it back to field capacity (mm).

STANDING CROP - crop height (m) and stem density (stem/m^2) data are combined by multiplication to produce a measure of Standing Crop (height (m).stems/m^2). Standing crop data can be used to identify the length of the crop development stages.

STEM DENSITY - measured directly as the number of individual stems occurring within each planted phytometer. All stems are counted, including the few that remain from previous seasons'. Reed 'stubble' shorter than 250 mm is not included. The stem number recorded is adjusted for the area of each phytometer to provide a density (stems/m^2).

SUNSHINE HOURS (n) - number of hours of bright sunshine per day, also sometimes defined as the duration of traces or burns made on a chart by Campbell Stokes recorder; hours.

TRANSPIRATION - rate of water loss through the plant which is regulated by physical and physiological processes (mm/day).

WETLAND CREATION - the construction of a wetland in an area which was not a wetland in the recent past, and typically involves the removal of upland soils to elevations which will support growth of wetland species (Weller, 1990).

WINDSPEED (U_2) - speed of air movement at 2 m above ground surface in unobstructed surroundings; mean in m/sec over the period considered, or total wind run in km/day.