Water Regime Requirements of the Native Flora

with particular reference to ESAs

Silsoe College

May 1997

Silsoe College, School of Agriculture, Food and the Environment

MAFF Commissioned Project BD0209

Final Report to the Ministry of Agriculture, Fisheries and Food

WATER REGIME REQUIREMENTS OF THE NATIVE FLORA

- WITH PARTICULAR REFERENCE TO ESAs

Dr DJG Gowing, JC Gilbert, Prof EG Youngs and Prof G Spoor

May 1997

Silsoe College
Cranfield University
Silsoe
Bedford MK45 4DT

Executive Summary

1. If water levels in Environmentally Sensitive Areas (ESAs) are to be managed effectively for nature conservation objectives, then quantitative information relating to the water-regime tolerances of vegetation is required. In order to provide this information, the relationship between species distribution and the long-term prevailing water regime needs to be understood with considerable precision. The information must also be in a form which is transferable between sites.

2. To identify the water-regime tolerances of species, data were gathered from areas of species-rich lowland wet grassland throughout England. A total of 2,393 microsites were sampled, each consisting of a 1 m^2 quadrat of grassland, and treated as independent observations. At each, the species complement was recorded and the water regime during the previous 10-20 years was modelled.

3. Water-regime determination required the estimation of weekly water-table positions at each of the microsites. This involved the use of dedicated hydrological models and the principles on which these were developed are described. Historic data sets were used for meteorological variables and boundary conditions, whilst soil parameters and microtopography were recorded on site. Using this information, each of the microsites was modelled separately.

4. A microsite's water regime could potentially impose two stresses on the plant species growing there; drought stress when water tables are low and aeration stress when they are high. Each individual regime was characterised by use of a peak-over-threshold method to derive parameters capable of explaining species distributions. The analysis treats the two potential stresses separately and thus defines water regime tolerances on a surface rather than a linear scale. The two axes of the surface

represent the degree of potential stress imposed by drought and by aeration and each microsite sampled represents an individual point on this surface.

5. Seven separate sites were successfully modelled and these reflect the full range of water regimes experienced by wet grassland, extending from “transition to fen” at one extreme to “dry grassland” at the other. A “favoured” water regime zone within this range was derived for a number of species. The derivation was based on the presence or absence of a particular species at each of the 2,393 sampled microsites. This favoured water-regime zone was deemed to be the area within which the relative frequency of occurrence for a species was significantly higher than it would have been were that species randomly distributed across the whole water-regime range.

6. Of 170 species recorded during field sampling, 67 occurred sufficiently often, and over a sufficient number of sites for a valid statistical analysis to be made. A plot of favoured water regime is presented for each of these 67 species. Information on the tolerance ranges of the other 100 species can be obtained from the data base, but the information would not be so precise or so transferable as for the 67 presented.

7. The information generated by the project has already been applied to assist in an ESA review and in the formulation of Water Level Management Plans. Its future use in these areas and more generally in terms of habitat restoration could be enhanced if the raw data were analysed at a plant-community rather than a plant-species level.

Contents

Page

List of Figures

List of Tables

1 Background to the project

1.1 Introduction

Ecologists have long recognised the close association between a site's water regime and its vegetation (e.g. Tansley, 1939). The most comprehensive description of this relationship to date has been the work of the German Botanist, Ellenberg (1963; 1988), whilst in the British context, Grime *et al*. (1988) and Wheeler and Shaw (1995) have also provided descriptions of species tolerances. Most of this existing work, however, is qualitative rather than quantitative and, in the case of Ellenberg, is entirely subjective. On sites with natural hydrological systems, this may be the appropriate type of information for considering the ecological development and structure of vegetation. It is less directly applicable, however, to the hydrological management of sites where water regimes are controlled. When the objective is to maintain a water regime for a specific vegetation type, as is the case in those Environmentally Sensitive Areas with wetland interest, then quantified information is required to guide managers and engineers.

Such quantitative data have not been readily available. Work in the Netherlands on wet meadows and dune systems (Grootjans and Ten Klooster, 1980; van der Laan, 1979) has produced numerical information relating to the water regime tolerances of herbaceous vegetation. These data, and those of Wheeler and Shaw (1995), are expressed as water-table depths, which do not allow derived tolerance ranges to be transferred readily between sites. There is, therefore, a clear gap in our knowledge relating to the quantitative requirements of semi-natural vegetation with respect to water regime. Transferable information is essential for the rational management and restoration of wet grassland with conservation interest.

1.2 Project FD0502

Silsoe College embarked on the quantification of native plant water-regime requirements nine years ago, when they undertook a project jointly with the Institute of Hydrology and the Institute of Terrestrial Ecology. The project was commissioned by the MAFF Flood and Coastal Defence Division to quantify the water-regime requirements of grassland plants, in order to provide information which may be used by water managers and engineers. The management of water levels in rivers and ditches has a major impact on the soil-water regimes of adjacent fields and the project provided a model which enabled the risk of hydrological change, following a river engineering operation, to be assessed in terms of the potential impoverishment of wet grassland plant assemblages on adjacent land (Gowing *et al*., 1994).

At that time, the only comprehensive sources of information on plant species water requirements or preferences were largely qualitative. Although of interest to the ecologist, this information could not be used directly by river engineers to predict the impact and the extent of a projected change in stage-level management. There was then an impediment to communication between conservationists and water engineers, due to a lack of quantifying terms which could be used by both groups in common to describe the water-regime requirements of wildlife habitats. This gap in knowledge was filled in part by the project, which was completed in 1994. The end product was a computer model which allowed proposed changes in the stage-level management of water courses to be assessed directly in terms of the likely impacts on wet grassland species. This program is referred to as the Silsoe College Hydrology And Flora Risk Identification Model (SCHAFRIM). Within the constraints of that project, the model could only be fully validated for one soil type in one climatic region of the country, although the project team did begin to compile data sets from other wet grassland sites of conservation value, with a view to broadening the applicability of SCHAFRIM.

Initial work in controlled environments using plants in lysimeters demonstrated that the physiological tolerances of wetland species in terms of water-regime were very wide, and did not reflect the true ecological tolerance. Literature survey also emphasised this point (Ellenberg, 1952). It was therefore recognised that useful information on plant water requirements was most appropriately gathered from the field. This was necessary to allow for the full effects of inter-specific competition. The approach developed in project FD0502 was based on modelling water tables beneath individual 1 m^2 quadrats, on sites where plant distributions were approaching an equilibrium with the prevailing water regime. The natural distribution of a species on a site was then correlated to the variation in water regime on a very local scale. A groundwater model was developed (Youngs *et al.*, 1989), which was capable of analysing water table movements at any point in the rectangular ditch-bounded fields found on the sampled sites.

Data were gathered initially from Tadham Moor SSSI in Somerset, for the following reasons:

i) it contained a rich and diverse wet-grassland flora;

ii) the management, both of hydrology and of vegetation had been constant for many years and hence the distribution of plants was probably close to an equilibrium situation;

iii) there was already a detailed botanical survey programme in progress (Mountford *et al.*, 1993), and

iv) the soil type (peat) and site layout were readily incorporated into the hydrological model of Youngs.

By 1993, approximately 600 individual 1 m^2 quadrat locations had been surveyed botanically and the water-table depths modelled retrospectively over a 15-year period. Statistical analysis of these data allowed the water-regime requirements of some 70 species to be defined.

1.3 Project BD0209

The current project, which began in June 1994, aimed to continue the work started in FD0502. The specific objectives for this phase of the project are set out in Chapter 2. It is funded by MAFF Environmentally Sensitive Area (ESA) Division and has the overall aim of improving the water management of wetland ESAs through an improved understanding of the requirements and tolerances of wet grassland vegetation in terms of water regime.

Lowland ESAs with wetland interest all have highly regulated hydrology. In order to fulfil the objectives of the ESA scheme, the desired water regimes for such areas of conservation interest must be clearly specified. This is currently done by means of prescriptions, which set quantified limits for levels and depths in water-courses. The main benefit of this method is the relative ease of monitoring compared to prescribing limits for in-field regimes.

When the scheme was implemented, there were no quantified estimates for the water regime tolerances of grassland plants were not available, therefore there was no method for predictively assessing the effect of the prescribed water regime. This lack of knowledge hampered the formulation of optimal guidelines. The research conducted by Silsoe College in collaboration with others over the past nine years together with the results of the current project has provided the missing-link to a large extent. The information obtained so far formed a useful tool during the 1996 review of ESA prescriptions, particularly with relevance to the Somerset Levels and Moors, where there was concern that the highest water level prescription was not the ideal one for its stated purpose (Gowing, 1996).

The combination of a comprehensive data set of wet grassland plant requirements together with the modelling capabilities of SCHAFRIM allows newly proposed stage level regimes to be assessed prior to implementation, thereby allowing any risks in terms of conservation interest to be identified.

1.4 Relationship to other MAFF-sponsored research

This project (BD0209) forms part of a suite of research funded by the Ministry under the title of “Wetland restoration”, co-ordinated by the Institute of Terrestrial Ecology at Monkswood Research Station (Project BD0213). The various projects within the programme have been interactive, with data being collected from common sites and interim results being shared. Four of the twelve field sites studied in this project have been considered by one or more other projects within the programme as a whole. The results presented here (Appendix C) will be utilised in the interpretation phase of project BD0208, which aims to assess the impact of the different tiers of management agreement available under ESA schemes on wet grassland ecology.

2 Objectives

The project had the following objectives;

1 To expand the current database, held by Silsoe College, to produce a more comprehensive listing of plant species.

2 To develop the database for use on different soil types and in different climatic zones.

3 To estimate the critical periods of the year when plants are most sensitive to stresses induced by drought or flooding and to quantify their tolerances.

4 To design and develop water-regime prescriptions which may best suit conservation and farming requirements in ESAs.

5 To develop a methodology for assessing the range of possible habitats on a given site, to allow planning for biodiversity.

3 Approach and methodology

3.1 Rationale

The overall aim is to provide quantitative information on the water-regime tolerances of native plants in a format which is accessible to those responsible for the hydrological management of sites with conservation interest. It has been shown in an earlier phase of the work that trying to employ the type of controlled-environment technique, routinely used in agricultural research, is unproductive due to the difficulty of faithfully reproducing the natural competitive milieu in an artificial system. The current project therefore sets out to collect data directly from the field and to interpret the natural distribution of plant species in such a way as to reveal their tolerance of differing water regimes.

The spatial distribution of grassland species is highly dynamic, but if a sufficiently large sample is taken then relationships between species' requirements and environmental conditions can be derived. An underlying assumption of this type of approach is that the species are in some form of quasi-equilibrium with the prevailing water regime at the particular microsite at which it was recorded. A microsite in this context is a one metre square area of grassland which was used as the fundamental survey unit for both botanical survey and hydrological modelling in this project. The sites selected for study, therefore, needed to have had stable hydrological conditions over a long period (>15 years) in order that the near equilibrium condition could reasonably be assumed. Water regime may vary widely from year to year in response to shifts in meteorological variables. An assumption made here is that a species' distribution pattern only changes gradually in response to such variation and inertia in the system avoids wholesale change in species assemblage in reaction to a single extreme year. It is acknowledged nevertheless that some species are more dynamic than others and may show large variation in distribution between years. To address this weakness, the data used in this analysis were collected in six different field seasons, so the effect of any one abnormal year will be limited. Furthermore all the data considered are in the form of presence or absence of a species at a particular microsite. Although estimates of abundance were recorded in the field they have not been employed in this initial analysis because measures of species cover are so variable between seasons and no correction was made for the varying phenological stage of the vegetation at the time of recording.

The relative distribution of plant species in the field is not exclusively a function of soil water regime. Other environmental factors such as nutrient availability in the soil and surface management regime in terms of mowing or grazing intensity are also factors strongly influencing the competitive ability of plant species. These factors cannot be eliminated when using field data, but site selection aimed to minimise their variation by only including sites which were unfertilised, of near neutral soil reaction and which were managed in a manner similar to traditional hay-making with aftermath grazing practices. It is acknowledged that the nutrient availability of soils will vary even in the absence of artificial inputs. In wet grassland situations, however, the availability is likely to be a function of the water regime itself due both to the restriction of the rooting zone and depression of mineralisation rates by high water tables and the reduced uptake ability of roots in dry soil. Nutrient regime could therefore be viewed as one of the mechanisms by which water regime influences plant competition in mesotrophic soils. In more nutrient-limited situations where the lateral transport of soluble nutrients by seepage water is an important factor in plant nutrition, the interaction of water regime and nutrient availability is much more complex, but such situations are not addressed here. The results of the current work are intended for application to neutral, mesotrophic, lowland wet grasslands and their extrapolation to other habitat types should be made with care.

A total of 2,393 microsites are considered in the analysis presented here. Each is treated as an independent observation for statistical purposes and only results for those species which were observed sufficiently frequently for meaningful confidence limits to be placed on their response to water regime are presented. The presence or absence of a species at a site is not purely a function of the prevailing environmental factors but may be influenced by historical factors and proximity to a source of propagules. Therefore some false patterns could arise if a species were present at just one or two sites because of a very local range, and therefore absent from other sites which may have been hydrologically suitable, but beyond its normal geographical range. To address this point, the tolerances presented in Appendix C are only for those species which occurred at more than half the sites studied and therefore can be considered as having a broad geographical range.

3.2 Hydrological modelling

As discussed above, the working assumption is that the distribution of a species with respect to water regime is a product of a long timescale and that seasonal variations play a relatively minor role. On this basis therefore, the monitoring of hydrological regime at a site over one, two or even three seasons would not provide sufficient information to comment on a species distribution as the estimates of soil water contents may be unduly influenced by one or two years with abnormal rainfall patterns. Hence it was not possible to collect all the necessary data by direct observation within the timescale of a three year project. In addition, to produce reliable estimates of water regime at over 2,000 separate locations by direct observation would have required a very large budget. These limitations were overcome by the use of a number of hydrological models which were capable of simulating hydrological conditions retrospectively using historic meteorological data and site records of boundary conditions such as ditch water levels. All the sites selected for study either had pre-existing instrumentation for the observation and recording of water-table behaviour or they were instrumented to obtain such information during the project. These observations were then used to validate the models which were based on the principles of soil physics and relied on estimates of soil parameters being made on each of the sites.

3.3 Data analysis

The aim of the analysis is to determine the effect of water regime on species' distributions. Other environmental variables are not considered independently. They can either be viewed as contributing to the determination of the water regime such as elevation, slope and soil structure; or themselves partially being functions of the prevailing water regime, such as nutrient availability, soil temperature or intensity of grazing (see below) and thus be included in the analysis; or to be entirely independent of water regime such as the species of animal used for grazing, in which case their effects will appear as noise in the data.

The concept of water regime is a complex one. Its effects on plant distribution are not limited to the direct effect of water supply to the root system. The soil moisture status determines a range of other important criteria for plant growth, which are briefly outlined below;

- *the air-filled porosity of the soil and therefore the ability of oxygen gas to diffuse from the atmosphere into the root zone.* A waterlogged soil can rapidly become anoxic producing a very hostile environment to plants which are not specifically adapted to it.
- *the specific heat capacity and thermal diffusivity of soil is determined largely by its moisture content.* The rate of soil warming in spring is an important determinant of interspecific competition and is dependent on water regime.
- *the intensity of grazing can be affected by soil moisture status.* Wet soils have a lower bearing capacity than dry ones and grazing animals will sink into the soil. These animals such as cattle, but especially sheep, will graze drier areas of a field in preference to such wet ones. In areas affected by rabbit grazing, lower grazing pressure on wet soils is even more marked.
- *the rate of nutrient mineralisation from organic detritus.* The low oxygen status of wet soils restricts the metabolic activity of bacteria which mediate the transformation of organically bound nutrients such as nitrogen and phosphorus into soluble forms which are more readily available to the plant.
- *the volume of rooting zone in which plants can extract nutrients from the soil.* Plant roots are less capable of actively taking up nutrients from anoxic soil due to lack of metabolic energy and therefore the water table can form a lower boundary to the zone of nutrient extraction. Nutrients need to be in a soluble form and to diffuse via a water film toward a plant root. In dry soils these requirements are not met and thus nutrient uptake is impeded.

This wide spectrum of effects can be condensed onto two axes of variation. Firstly the soil moisture tension, which reflects the dryness of the soil. High values of this variable indicate a range of potential stresses on the plant; a reduced water supply, a reduced nutrient supply and an increased susceptibility to grazing. The combination of these effects has been termed **"drought stress"** in the current analysis (Gowing and Spoor, 1997). The second axis of variation reflects the air-filled porosity and hence the oxygen status and redox potential of the soil. This is measured in terms of water-table height with high values reflecting a high water table and hence poor soil aeration. High values on this axis reflect a second, distinct set of potential stresses to which the plant is exposed; a reduced oxygen supply for root respiration and hence an impaired root performance, a reduced nutrient availability due to reduced mineralisation and reduced rooting volume and finally reduced soil temperatures in spring, retarding early growth. The combination of these effects has been termed **“aeration stress”**.

These two sources of potential stress tend to show an inverse correlation. If a microsite has a high “drought stress” value then it is likely to have a correspondingly low “aeration stress”. It is important to note that this relationship is not a strict one however. It is possible for a microsite to have high values on both axes either due to large seasonal fluctuations in seasonal water tables which might render it very wet in spring but very dry in summer or due to low soil porosity which results in the same site experiencing both stresses because its air filled porosity remains low even when drained. Conversely a microsite with high porosity soil and a relatively stable water table may not experience either type of stress. As a consequence it is not possible to measure precisely a species’ tolerance to water regime on a single linear axis. Variation along both the axes described above needs to be considered. The subjective rankings of Ellenberg’s Feuchtezahl categorise species into broad bands with the vast majority of wet grassland species falling into just three groups (F-values of 6, 7 or 8). This is perhaps as precise a ranking as one can achieve on a single axis. The descriptions of Grime *et al*. (1988) are similarly restricted. Although both are used very successfully in ecological interpretation of vegetation, the extent to which such broad classifications can be applied to the fine regulation of soil water status to meet ecological objectives is limited. The analysis used here will treat drought stress and aeration stress separately and quantify the tolerance range of a species as an area on a continuous planar surface rather than as a point or band on a linear scale.

4 Site selection and descriptions

4.1 Site selection

The first phase of the project was the location of suitable study sites from which to gather base data. Following application for access, site visits and collation of available historic data, the sites in Table 4.1 were selected for on-going study within the terms of this project.

Table 4.1 List of selected sites together with their ESA scheme if applicable or else the grassland type of which they are typical. The existence of data inherited from project FD0502 is also noted.

Site Name	ESA (or grassland type)	Previous data
Baysbrown Pool	Lake District	No
Belaugh	The Broads	No
Blackthorn	Upper Thames Tributaries	No
Broad Dale	(Northern floodplain)	No
Cricklade North Meadow	(Typical flood meadow)	Yes
Dancing Gate Farm	Lake District	No
Nethercote Farm	Upper Thames Tributaries	No
Southlake Moor	Somerset Moors	No
Strumpshaw Fen	The Broads	No
Tadham Moor	Somerset Moors	Yes
Upwood Meadows	(Typical ridge and furrow)	Yes
West Sedgemoor	Somerset Moors	Yes

These sites were selected using the following criteria;

i) presence of a stable species-rich flora

ii) presence of a hydrological system which could lend itself to being modelled

iii) availability of historic data in terms of water-level behaviour in adjacent water courses

iv) providing a spread in terms of soil type, hydrology and climatic region in order to give a representative sample of wet hay meadows within ESAs

v) making best use of pre-existing information from previous projects

vi) falling within designated ESAs wherever possible, but to use sites outside their boundaries when necessary to fulfil the other criteria.

A map showing the locations of the sites is presented in Figure 4.1 and further information about them is presented in Table 4.2.

Table 4.2 Additional information on chosen sites. Soil type identifies the predominant class of topsoil together with subsoil if significantly different. The soil moisture deficit indicates the maximum value attained during the summer of an average year (Smith and Trafford, 1976).

Site Name	Landowner/tenant	Soil type	Soil moisture deficit
Baysbrown Pool	Mr K Rowand	Organic soils over silty clay	10 mm
Belaugh	Mr D Rose	Fen peat	108 mm
Blackthorn	Mr PB Hart	Clay	97 mm
Broad Dale	Mr W Marrs	Clay & sandy loams	39 mm
Cricklade North Meadow	English Nature *et al*	Clay loam over sand	78 mm
Dancing Gate Farm	Mr JC Hartley	Silty clay over gravel	10 mm
Nethercote Farm	Mr B Chanin	Clay loam over gravel	82 mm
Southlake Moor	English Nature	Humose clay over peat	85 mm
Strumpshaw Fen	RSPB	Shallow peats and silty clays	108 mm
Tadham Moor	English Nature	Deep peat	85 mm
Upwood Meadows	Cambs Wildlife Trust	Clay	106 mm
West Sedgemoor	RSPB	Deep peat	85 mm

The sites listed in Table 4.3 were also investigated, including a field visit, but were not pursued further as they failed to meet the desired criteria, either due to a gap in available information, lack of species-richness or the complexity of hydrological modelling that would be involved. As can be seen from Table 4.1, the final selection includes representatives from a range of ESAs; 3 from the Somerset Levels and Moors, 2 from the Norfolk Broads, 2 from the Lake District and 2 from the Upper

Thames Tributaries. Three which fall close to but beyond ESA boundaries are included since they are typical examples of species-diverse hay meadows.

Table 4.3 List of sites which were visited to assess their suitability for inclusion within the project but rejected.

Site Name	ESA (or grassland type)	Data from previous project
Chapel Bridge Meadows	Lake District	No
Elmlea meadows	(Typical flood meadow)	Yes
Great Blencow	(Northern floodplain)	No
Heigham Holmes	The Broads	No
Kettlewell meadows	Pennine Dales	No
Sizewell Belts	Suffolk River Valleys	No
Upper Wharfedale	Pennine Dales	No

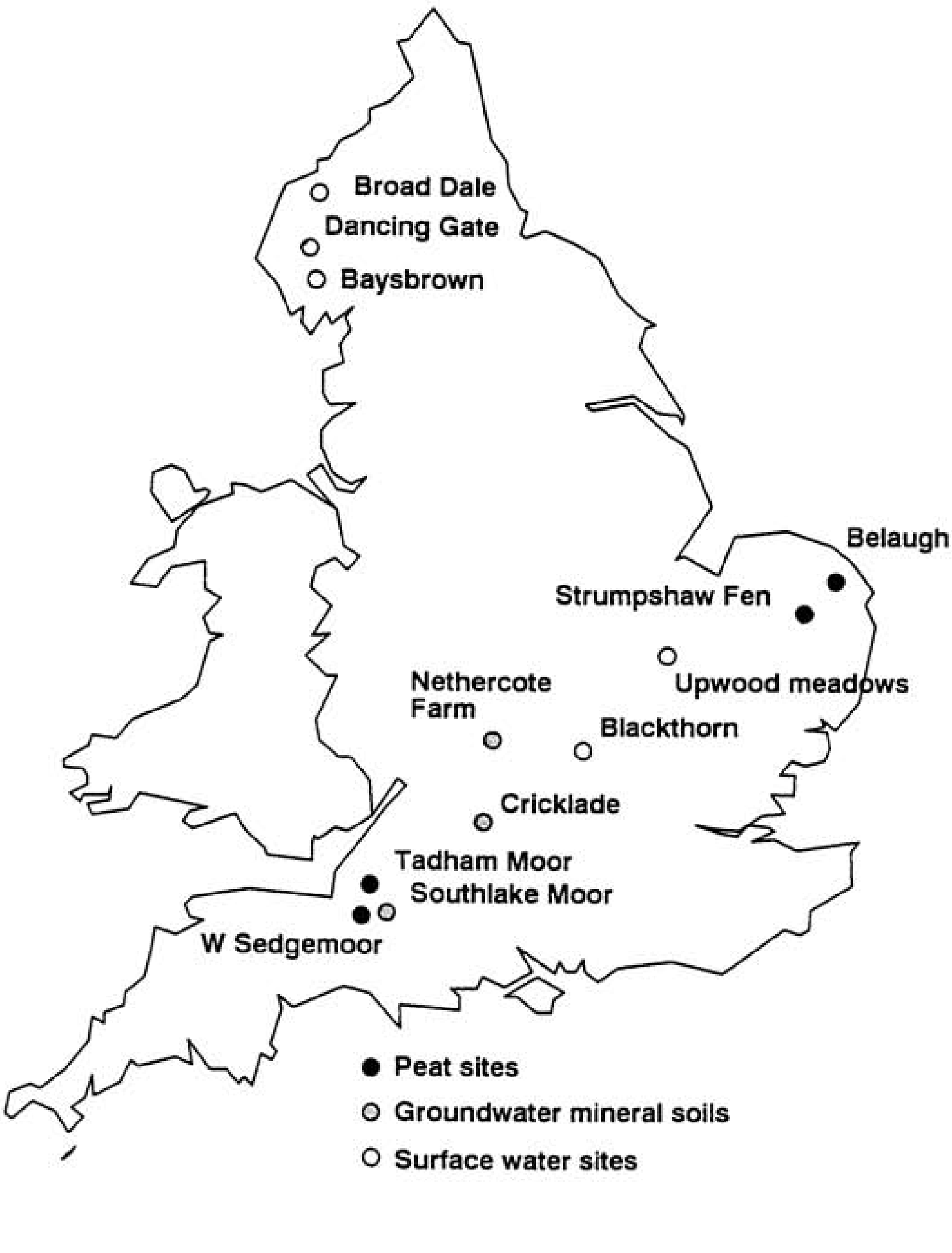


Figure 4.1 Geographical locations of the sites.

4.2 Site descriptions

This section gives a brief summary for each site in terms of its soils, vegetation and management. Outline maps are presented for the seven modelled sites in Appendix A, including the dipwell layout and an Ordnance Survey Grid Reference point. Vegetation communities referred to in the description are labelled in accordance with the National Vegetation Classification (NVC; Rodwell, 1992 et seq.).

4.2.1 Baysbrown Pool, Langdale, Cumbria. NGR NY314 054

This is a valley bottom site with alluvial and organic soils, lying between Great Langdale Beck and a smaller stream, known as Baysbrown Pool. The particular field sampled was of particular interest, as it apparently showed a transition from an MG3 (upland hay meadow) type community to an MG8 (flood meadow) stand, and included the genus Euphrasia, which had not been encountered elsewhere. It is a privately owned site with no statutory nature conservation designation, but is under a management agreement with the National Park Authority. The site is grazed, mainly by sheep, throughout late summer and winter and then shut up for hay in April. The particular interest of this site is that it is climatically one of the wettest hay meadows in England, being situated in a valley of the Cumbrian mountains and experiencing around 1500 mm rainfall per year.

4.2.2 Belaugh Old Farm, Wrexham, Norfolk. NGR TG 292 177

The site comprises three fields surrounded by ditches and lying adjacent to the River Bure. The water levels within the ditch system are in open connection with the river and are therefore controlled by the stage-level management of the river. Information on river levels was available from the gauging station at Horstead, a few kilometres upstream. The site's vegetation consists of a range of swamp communities (S24, S6) interspersed with fen meadow (M22) and flood meadow (MG8) and therefore represents the wettest extreme of the range of sites sampled. It is privately owned and under a Broads ESA Tier 3 agreement and its grazing regime is as for a hay meadow, although the vegetation is not actually cut.

4.2.3 Blackthorn Meadow IV, Nr Bicester, Oxfordshire. NGR SP 632 190

The meadow lies in the floodplain of the River Ray just to the east of the village of Blackthorn. It has marked ridge and furrow topography and lies above the regular flooding zone of the river, so complete inundation is extremely rare. The vegetation shows great variety between the ridges and the furrows which make up the field. The higher areas support typical hay-meadow vegetation (MG4 and MG5), whilst the lower strips contain rush-pasture (MG10) and inundation grassland (MG13). It is privately owned and entered into the Upper Thames Tributaries ESA. It is left shut up in spring and early summer then grazed by cattle until winter. Hay making is no longer practised due to the difficulties with mechanisation on such undulating topography.

4.2.4 Broad Dale SSSI, Gamelsby, Cumbria. NGR NY 255 525

The site lies on the wide floodplain of the River Whampool, whose bed has now been lowered to the extent that overtopping is an uncommon event. The soils are relatively impermeable clays and parts of the site show distinct ridge and furrow topography. The vegetation is similar to the other Cumbrian sites, showing a mixture of hay meadow (MG4) and rush-pasture (MG10) communities. The site has a complex ownership pattern and lies outside the northern limit of the Lakes ESA, but is largely under a management agreement with English Nature to support the continued practice of traditional hay-making with aftermath grazing.

4.2.5 North Meadow NNR, Cricklade, Wiltshire. NGR SU 096 958

Perhaps the best surviving example of a flood meadow in England, this 50 ha site is bounded both by the River Thames and a distributary of the River Churn. It has a complex hydrology with a thin (< 1 m) layer of alluvium overlying a superficial sand aquifer. The vegetation is that of a classic flood meadow (MG4), with the drier hay-meadow (MG5) and the inundation grassland (MG13) both well represented. The majority of the site is owned by English Nature, but there is a complex system of hay and grazing rights for local residents. Management is by hay cut in July followed by aftermath grazing, largely by horses, until the winter floods.

4.2.6 Dancing Gate Farm, Bassenthwaite, Cumbria. NGR NY 240 260

The field under study is 0.5 km south of Bassenthwaite Lake in the floodplain of the River Derwent. It is composed of slowly permeable alluvial deposits overlying gravels and having an undulating topography. The community type present at this site consists of a mosaic of damp hay-meadow (categorised as MG3 or MG4 hay-meadows by the NVC) together with wetter rush-pasture (MG10) and inundation grassland (MG13). The site is privately owned, entered into a Lakes ESA agreement and managed as a traditional hay meadow with aftermath grazing by sheep.

4.2.7 Nethercote Farm (Lower Sainthill Field), Bourton-on-the-Water, Gloucestershire. NGR SP 175 190

The field represents the vestiges of a once extensive flood meadow / water meadow system on the floodplain of the River Windrush to the south of the town of Bourton-on-the-Water. It consists of river alluvium overlying gravel and has a ridge and furrow topography with organic soils in the furrows. The vegetation was found to be very species rich and an intimate mixture (as a result of ridge and furrow) of dry meadow (MG5) and flood meadow (MG8), verging toward fen-meadow (M22) in the wettest areas. The site is privately owned, has no statutory designation for its nature conservation interest, but is entered under the Upper Thames Tributaries ESA scheme. It is managed as a hay meadow with aftermath grazing by cattle.

4.2.8 Southlake Moor SSSI, Burrowbridge, Somerset. NGR ST 364 301

The Moor has soils of the Middelney series, alluvial clay overlying sedge peat. It has a very flat topography and three of the more species-rich meadows near the centre of the Moor were selected for study. The water levels in the dense ditch network are tightly controlled by two sluices. Much of the moor is now a raised water level area, but the records used in this report were collected prior to its implementation. The vegetation is allied to that of flood meadows (MG8) and the privately owned land is traditionally managed for hay with cattle grazing the aftermath. The area is entered into the Somerset Levels and Moors ESA scheme.

4.2.9 Strumpshaw Fen Reserve, Brundall, Norfolk. NGR TG 342 060

The site is a set of three fields forming part of an RSPB Reserve. The soils are mainly organic and are pump-drained, lying below the level of the adjacent embanked River Yare, which is tidal. The vegetation of this site was at the wet end of our range, being composed largely of fen-meadow (M22). The area is entered into the Broads ESA scheme and grazed by cattle through late summer and autumn. Hay has not been regularly cut, but the management amounts to a traditional hay meadow regime.

4.2.10 Tadham Moor SSSI, Wedmore, Somerset. NGR ST 416 455

Tadham Moor comprises of a collection of ditch-bounded meadows totalling an area of 23 ha on deep peat soils in the Brue Valley. Water levels in the ditch system are regulated by the arterial drainage channel called the North Drain. The vegetation grades between flood meadow (MG8) and drier hay meadow (MG5). The land is owned by English Nature and managed as an experimental site by the Institute of Grassland and Environmental Research. The site has been used for a series of research projects relating to the management of lowland wet grassland and wetland restoration (Mountford *et al.*, 1993). Parts of the site have been artificially fertilised as part of a nitrogen application trial and recently some areas have had water levels raised. All the points sampled for this project were prior to such treatments and thus unaffected by them.

4.2.11 Upwood Meadows NNR, Upwood, Cambridgeshire. NGR TL 251 825

One field, Bentley Meadow, was surveyed at this site. It has pronounced ridge and furrow topography on poorly-draining clay soil. A significant amount of water can pond on the site over winter. The vegetation is largely of the old hay meadow type (MG5) and species-rich. The site is managed by the local Wildlife Trust, grazing with cattle from July until October. Hay is not regularly cut.

4.2.12 West Sedgemoor SSSI, Somerset. NGR ST 352 257

Two ditch bounded fields were selected from near the centre of the Moor. Water levels in the ditches are controlled by the Moor’s own pumping station and the deep permeable peat soils produce stable water table conditions. The vegetation was at the wetter end of the hay-meadow continuum, consisting of flood meadow (MG8) and rush-pasture (MG10 and M23) communities. The fields form part of the RSPB’s reserve and are farmed by them using traditional hay-meadow management. They are entered into the Somerset Levels and Moors ESA scheme.

5 Data collection

This section details, site by site, the botanical and hydrological data gathered in the field, either during the lifetime of this project or inherited from previous work.

At each of the microsites referred to, a $1m^2$ quadrat was used to compile a complete species list of all vascular plants and mosses present, together with an indication of their abundance.

All references to dipwells relate to plastic tubewells 4 cm in diameter, perforated for most of their length (except for the top 30 cm) with the holes protected by a woven nylon sock. These were installed to either 1.0 or 1.5 m depth, depending on soil type, using a 5 cm Dutch auger. Water table depths were read at either fortnightly or monthly intervals, using a graduated staff fitted with an electrical-contact on the end. Historic meteorological data relating to each of the sites were purchased from the Meteorological Office.

5.1 Baysbrown Pool.

Botanical. Sixteen quadrats were recorded in the summer of 1995 in two blocks having contrasting water-regimes within a single field. A further 24 quadrats, in the same field, were recorded in 1996.

Hydrological. Two dipwells were installed in July 1995 and marked by steel caps - these were to be regularly recorded by a local farmer. Unfortunately, during hay-making, the steel caps were dislodged from the wells, making them impossible to relocate. New dipwells were re-installed in the autumn of 1995 and were recorded successfully. Soil samples were taken for laboratory analysis of hydraulic conductivity and moisture release at various suctions. The soil profile of the site was described.

5.2 Belaugh Old Farm.

Botanical. Preliminary quadrat recording was undertaken by ITE Monkswood in July 1995 which established that the vegetation was sufficiently diverse for the purposes of this project. A survey of 75 quadrats was carried out by ITE Monkswood in July 1996 with the topographic elevation of each quadrat being recorded by Silsoe staff.

Hydrological. The site was instrumented by ADAS (Soil and Water Research Centre) with 12 dipwells and 3 autorecorders (two measuring water table elevation and one measuring ditch water level). Regular recording was conducted by ADAS (Norwich). ADAS also undertook the task of retrieving historic stage-level data for the River Bure at Horstead and measuring the soil parameters of the site as part of project BD02010.

5.3 Blackthorn Meadow IV.

Botanical. 200 quadrats were recorded during June 1995.

Hydrological. All 200 quadrats were mapped and levelled using a “Total Station” surveying device to give maximum accuracy in this topographically complex field. Seven dipwells were installed along two transects in January 1995, which are now being monitored by ADAS (Cambridge) as part of a wider study in the area. The site is of interest being a surface water gley with pronounced ridge and furrow in an area occasionally inundated by the neighbouring River Ray. Auger hole tests of soil conductivity were conducted during dipwell installation in January. Soil samples were taken for laboratory analysis of hydraulic conductivity and moisture release at various suctions. The soil profile of the site was also described.

5.4 Broad Dale.

Botanical. 40 microsite locations were recorded in summer 1995 followed by a further 109 quadrats in summer 1996. Of the 149 quadrats, 60 were located on a sand ridge which runs across the site parallel to the River Whampool. The remaining 89 were collected from the clay floodplain.

Hydrological. This is the northernmost site, but less wet climatically than the others in Cumbria. Three dipwells were installed and are being read by the landowner. Soil samples were taken from both the clay area and the sand ridge for laboratory analysis of hydraulic conductivity and moisture release at various suctions. Soil profiles have been described for a range of points. The site shows considerable microtopographic variability. Information on the neighbouring River Whampool does not exist close enough to the study site to be relevant, but river stage levels are no longer thought to be a significant factor in the field water-regime, which is now dominated by climatic inputs.

5.5 Cricklade North Meadow.

Botanical. 57 quadrats were recorded in 1992 and a further 72 in 1993. The major survey, amounting to 452 microsites was undertaken in 1994. A further 189 quadrats were sampled in 1996. The locations of the latter were targeted to cover areas that were undersampled in previous surveys.

Hydrological. English Nature wardens continued to monitor dipwells which were installed in 1989. Soil coring was undertaken to establish the nature of the profile. Auger-hole tests and undisturbed cores for a falling head permeameter were used to estimate hydraulic conductance of the alluvium. Detailed records of water levels in both adjacent rivers, the Thames and the Churn, have been provided by the Environment Agency (EA).

5.6 Dancing Gate Farm.

Botanical. Forty-five quadrats were recorded at this site in July 1995.

Hydrological. Each quadrat surveyed was mapped and levelled in. Soil cores were taken to describe the profile, which is a heavy clay alluvium overlying a coarser gritty deposit. The interest in this site stems from its interesting topography which creates a variety of humps and hollows, occupied by contrasting vegetation types. Six dipwells were installed forming a crucifix of two transects running across the site. The National Park's ranger of the adjoining Bassenthwaite Lake Reserve undertook to record the wells at regular intervals.

5.7 Nethercote Farm.

Botanical. A regular grid of 60 microsites were surveyed in June 1995. The total unimproved area of the site was small (no more than 1 ha in extent), therefore, although the flora was novel and diverse, a larger number of samples could not be justified.

Hydrological. Six dipwells were installed in April 1995. These were recorded by the landowner, who also monitored the rainfall. Elevations of wells and of quadrats were taken in June. Measurements of soil conductivity were taken by the auger-hole method during dipwell installation and undisturbed cores were taken for falling-head permeameter analysis and calculation of soil moisture release at various suctions in the laboratory at Silsoe. The soil profile was described at a number of points in the field. Stage level data for the nearby River Windrush have been supplied from the local EA.

5.8 Southlake Moor.

Botanical. 200 quadrats were recorded in 1994 in conjunction with ITE staff under project BD0208.

Hydrological. Four dipwell transects and their associated gauge boards were read by staff from ADAS, who were also responsible for recording soil parameters at this site as part of project BD0210.

5.9 Strumpshaw Fen.

Botanical. A botanical survey was undertaken in July 1995, with 150 quadrats recorded.

Hydrological. 12 dipwells were installed in March 1995 and have been read by the staff of the RSPB reserve. The caps of two dipwells were lost during summer 1995 and these dipwells could no longer be located. A record of stage levels at the adjacent pumping station has also been kept. Soil conductivity was assessed by the auger-hole method in March, when soil cores to study the profile were taken. Elevations of both the wells and the quadrat locations were recorded in July.

5.10 Tadham Moor.

Botanical. A total of 952 microsites have been recorded at Tadham for use in this project. The surveys took place in 1986, 1989, 1990, 1991, 1993 and 1994, before raised water levels were introduced to the site. A further 108 microsites were recorded in 1995 from fields that had not been affected by the raised water levels. Botanical information was recorded by ITE staff as part of project BD0204 with Silsoe staff measuring the topographic elevation of each quadrat.

Hydrological. All positions were mapped and levelled in, those recorded in 1995 were done with the aid of “Total Station” surveying equipment. The dipwells and gauge boards on the site have been monitored by ADAS under project BD0205. For the purposes of this project, only microsites in the “control” fields of the ITE experiment (BD0204) are included as the water-regime in the other plots will not fulfil the stability criteria.

5.11 Upwood Meadows.

Botanical. 161 quadrats have been recorded from this site, 49 in 1992 and 32 in 1993 under a previous project and 80 in 1996 as part of this project.

Hydrological. 5 dipwells were installed and dipwell data continue to be collected by one of the site's managers. Hydraulic conductivity was measured both in the field using the auger hole method and in the laboratory by the falling head permeameter. A soil pit was dug to describe the soil profile, dry bulk density was measured and moisture content variability across the ridges and furrows was investigated.

5.12 West Sedgemoor.

Botanical. A number of microsites were recorded in the summers' of 1993, 1994 and 1995. Many of the fields at West Sedgemoor have had their water regimes altered over the past 5 years. Only 60 of the microsites recorded were located in fields where it is known that the water regime has not been altered.

Hydrological. Our previously installed dipwells and the RSPB gauge boards were monitored by RSPB staff on the site. All new sampling positions were mapped and levelled in and measurements were made of ditch depths. Soil parameters and conductivity estimates were measured on site as part of an earlier project.

6 Water Regime Characterisation

6.1 Hydrological models

Three separate hydrological models have been developed within this project to characterise water regimes at the various sites. The first is the ditch-bounded water-table model which has been applied to West Sedgemoor, Tadham Moor, Southlake Moor and Belaugh Old Farm. The second is the shallow aquifer-controlled water-table model which has been applied to Cricklade North Meadow and the third is the ridge and furrow water-balance model which has been applied to Upwood Meadows and Blackthorn Meadow IV. All have been used retrospectively with historic data sets from the Meteorological Office and some with stage level records from adjacent water courses supplied by the Environment Agency (formerly National Rivers Authority) or from the site manager's own records. Each has then been validated against water-table depth observations taken on-site. It has not been possible during the time span of this project to effectively validate the models for the sites at Baysbrown Pool, Dancing Gate Farm and Nethercote Farm, due to the exceptionally dry conditions providing biased data for model validation. The Strumpshaw Fen site is influenced by significant seepage from the adjoining river which, as yet, has not been quantified. (See section 6.2 for greater detail.)

The sections below describe the principles on which the models were developed with some details of their calibration and validation. Table 6.1 displays the measured values of the soil parameters that were used in the modelling of each site. A note setting out the physical basis of the models is attached to the end of this chapter (section 6.4) and a more complete set of validation graphs is presented in Appendix A.

Table 6.1 Measured values of the soil parameters used in the hydrological modelling

Site	Topsoil hydraulic conductivity ($m.d^{-1}$)	Subsoil hydraulic conductivity ($m.d^{-1}$)	Topsoil drainable porosity	Subsoil drainable porosity
Belaugh	3.0	3.0	0.35	0.35
Blackthorn	0.2	~0	0.06	not applicable
Cricklade	0.24	~10 to 100	0.12	0.20
Southlake	0.08	1.0	0.12	0.10
Tadham	2.5	1.75	0.15	0.15
Upwood	0.2	~0	0.06	not applicable
West Sedgemoor	1.5	0.75	0.27	0.27

6.1.1 The ditch-bounded water-table model

This model was originally developed for the West Sedgemoor situation (Youngs *et al*, 1989) and has been applied directly to Tadham Moor. The model has been extended to include cases where, due to lack of surface drainage to the ditch system, water ponds on the surface of fields(Youngs, 1994). This expanded version of the model has been applied to the Southlake Moor and Belaugh Old Farm sites.

The ditch-bounded water-table model has been developed for low-lying land with soils, of high permeability, intersected by a network of ditches. At the sites in question, each field is approximately rectangular in shape with ditches along each edge that have a common water level. During the winter the ditches generally drain the field. The water table falls from a peak in the field centre to the level of the top of the seepage surface at the ditch (close to ditch water level). Since the field is of finite length and surrounded by ditches, the resulting water-table shape is domed and can be described mathematically using the concept of shape factors to give the seepage potential of any point in the field (Figure 6.1). The water-table height at a specific point is the maximum water-table height midway between parallel drains modified by the shape factor. (See section 6.4 for full explanation.)

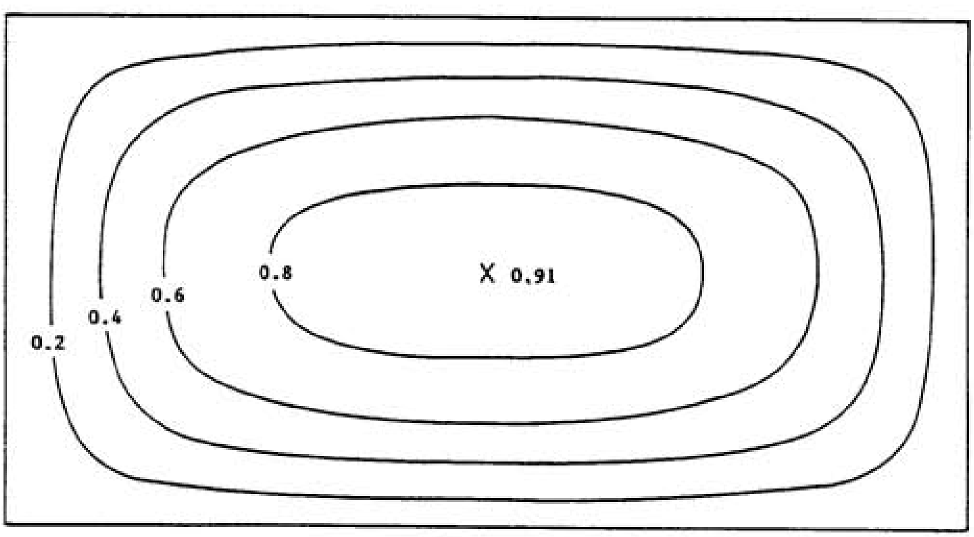


Figure 6.1 Contours of seepage potential (shape factors) for a rectangular field with one side twice the length of the other.

In the summer, the water level in the ditches is generally higher than the field water tables so sub-surface irrigation occurs. Evapotranspiration lowers the water table in the field and water seeps in from the surrounding ditches, creating a bowl shaped water table. When the water table falls below a critical depth, moisture tension in the root zone begins to rise more sharply and evapotranspiration is reduced. Figure 6.2 shows the shape of the water table in the winter and summer situations. The elevation or depression of the water table is dependent on the spacing between the ditches, the hydraulic conductivity of the soil, the depth of permeable soil and the rainfall or evapotranspiration rate.

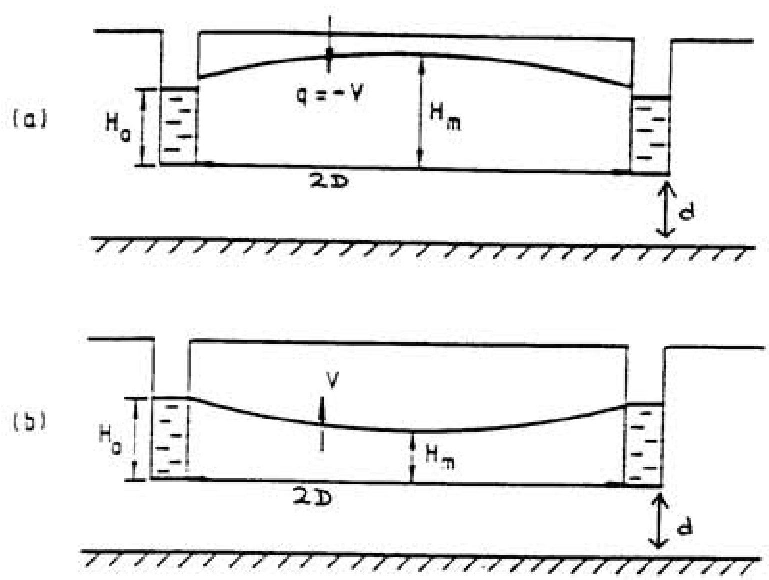


Figure 6.2 The water-table shape between water-filled ditches acting as drains (a) and as irrigation channels (b)

The model requires inputs of rainfall, evapotranspiration and the water level in the ditches on a weekly basis. As shown in section 6.4, this information is used to calculate the weekly water table height at each specified location within the field. An example of the three inputs and the resultant water table are shown in Figure 6.3.

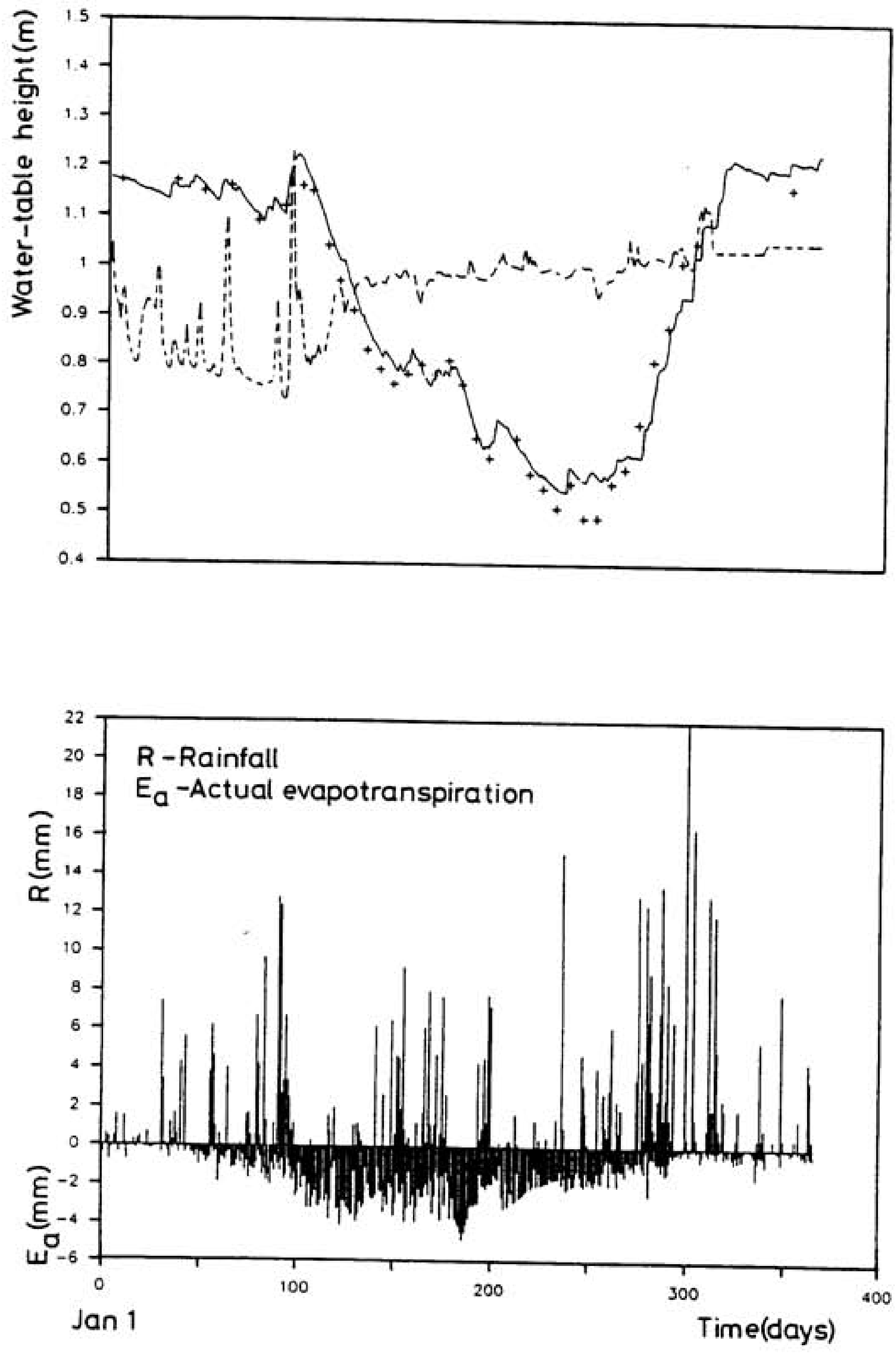


Figure 6.3 The three inputs required for the ditch-bounded water-table model, rainfall and evapotranspiration (lower graph) and ditch water level (broken line, upper graph) and the model prediction of the water table height (full line) compared with dipwell observations (symbols) for West Sedgemoor.

At West Sedgemoor and Tadham Moor shallow drainage grips enable surface water to drain into the surrounding ditches. Southlake Moor and Belaugh Old Farm tend not to have such surface drainage. As a result, when the water-table rises above the soil surface, water is able to pond on the field. A separate routine was introduced into the model to simulate the hydrology of the latter sites so that surface water was retained to a specified level above the mean field height. The water retention height was calculated from maps showing the extent of winter flood waters.

The model was run for the locations and elevations of the dipwells at each site using weekly rainfall and evapotranspiration data. This generated a weekly water table height for every dipwell. This data was used to validate the model against dipwell data measured in the field. Examples of the results of the validation are shown in Figures 6.4 - 6.7. Full validation results are given in Appendix A.

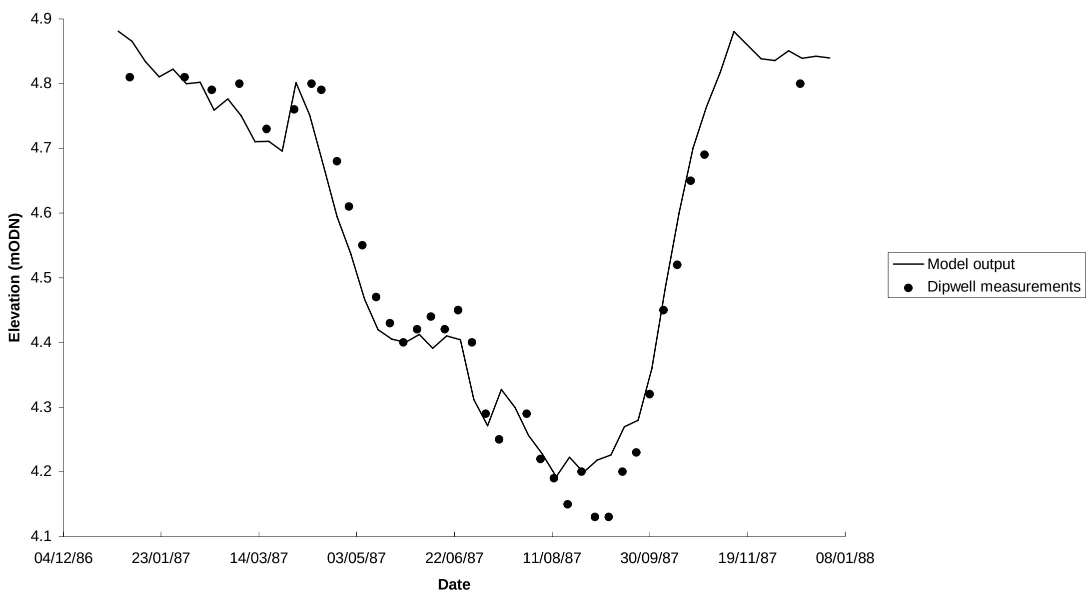


Figure 6.4 Model output shown against dipwell measurements for West Sedgemoor

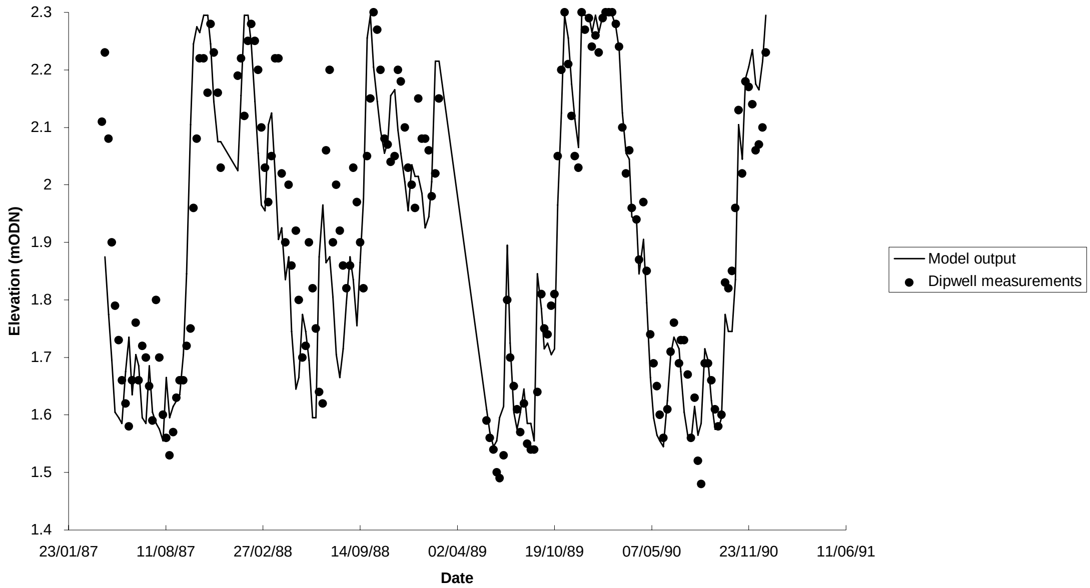


Figure 6.5 Model output shown against dipwell measurements for Tadham

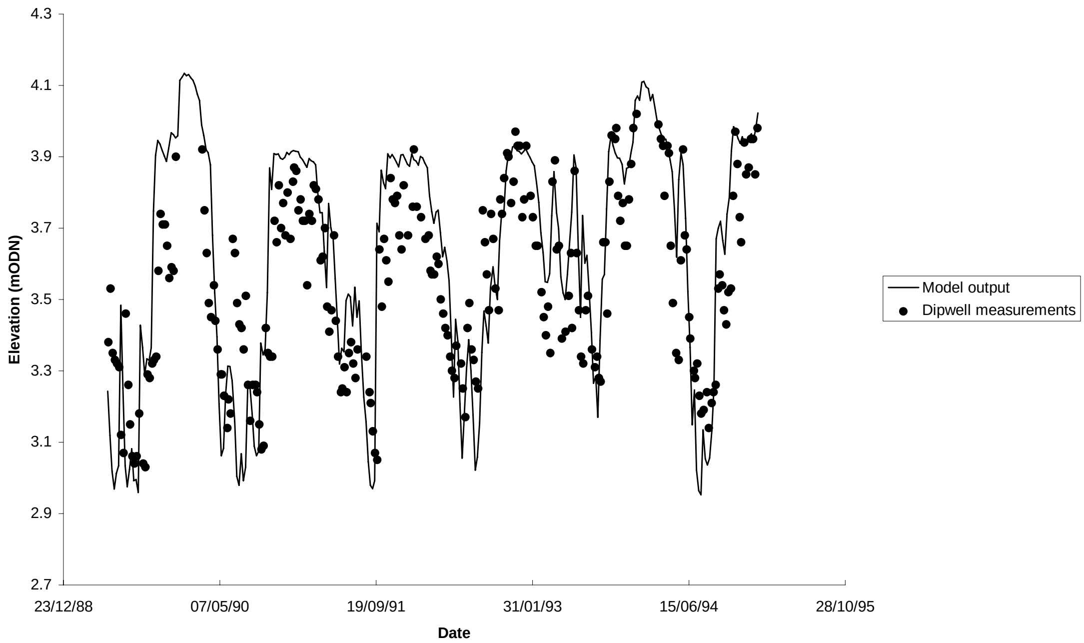


Figure 6.6 Model output shown against dipwell measurements for Southlake Moor

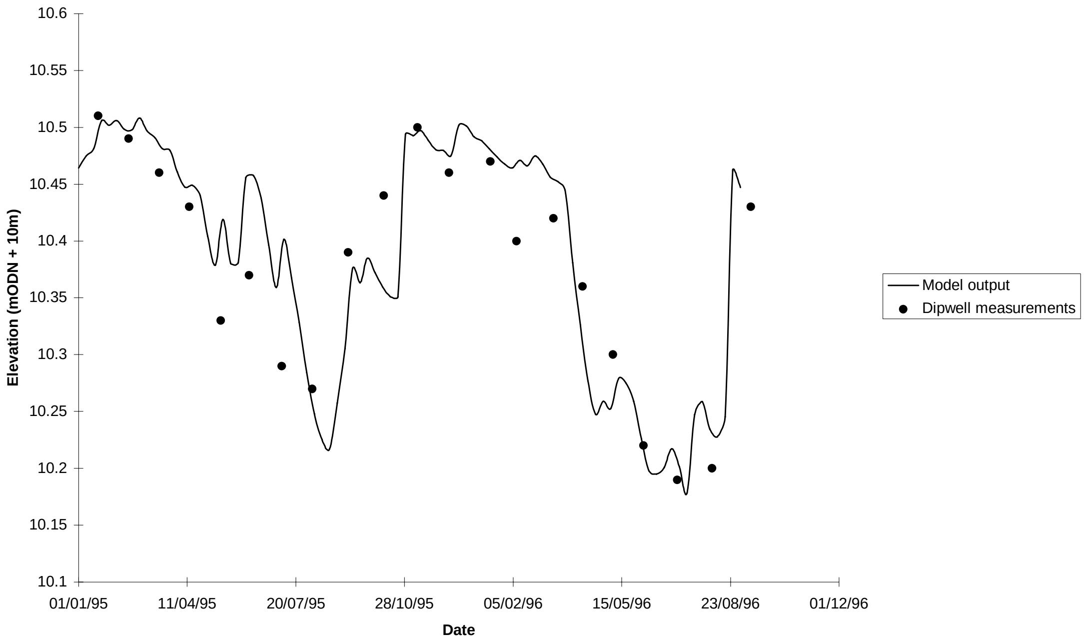


Figure 6.7 Model output shown against dipwell measurements for Belaugh Old Farm

6.1.2 The shallow aquifer-controlled water-table model

This model has been developed to describe the hydrological situation at Cricklade North Meadow where alluvial topsoils overlie a river-fed aquifer. Water can be supplied upwards from the bottom of the soil profile as well as downwards through the soil surface as rainfall.

The floodplain meadow at Cricklade is bounded by two rivers, the Thames and the Churn, whose stage level behaviour dominates the water regime. A profile of the soil and geology of the site is given in Figure 6.8. The bedrock beneath the meadow is oolitic limestone, the major aquifer in the Cotswolds. This is confined by the overlying Oxford clay which is of low permeability. Above the clay is a shallow aquifer of river-terrace deposits of mainly coarse sands which are very permeable and form a hydraulic connection between the two rivers. It is this layer which transmits the hydraulic head from the rivers across the whole site. The sand layer varies laterally in its composition causing the transmissivity of the shallow aquifer to vary between different compartments (shown in Figure 6.9) of the meadow. Finally, finer-textured alluvium overlying the sands gives rise to the soils of the Thames and Kelmscott series (Payne, 1987).

textured alluvium overlying the sands gives rise to the soils of the Thames and Kelmscott series (Payne, 1987).

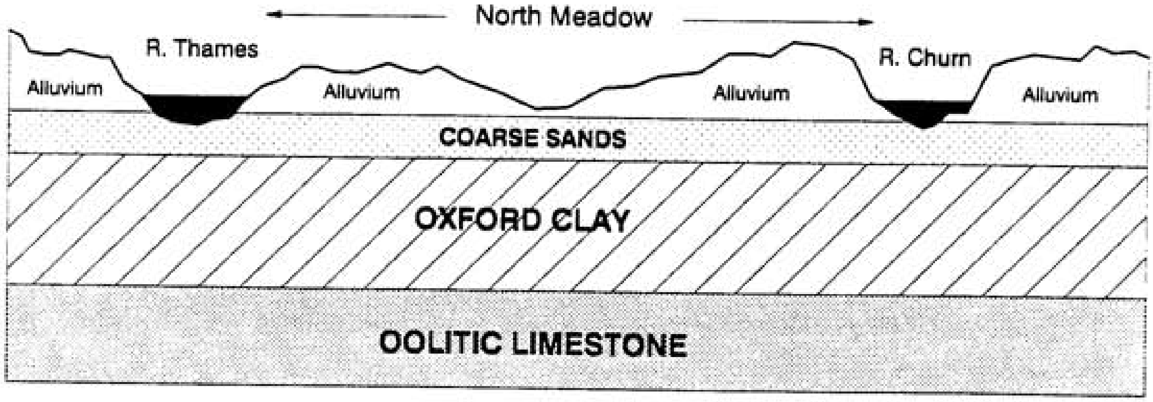


Figure 6.8 A simplified geological profile of Cricklade North Meadow

The variation in transmissivity of the sand layer could not be measured directly due to the disturbance that would have been caused to the National Nature Reserve. Instead, the value of transmissivity across the meadow was optimised from the dipwell records over a two-year period and validated against observations for a third year. Other soil parameters such as the saturated hydraulic conductivity of the alluvial topsoil and its drainable porosity were measured *in situ* or from undisturbed core samples collected for laboratory analysis.

A number of assumptions were made in order to model the site. These were that both the rivers were in good connection throughout the meadow with the shallow sand aquifer, that no loss of water occurs by deep seepage through the Oxford clay and that the net surface rainfall and evaporation is uniform across the site.

Three hydrological scenarios had to be considered in the model to describe the water behaviour throughout the year. First, the surface flooding case, which regularly occurs during winter and spring. Since the surface elevation varies across the meadow, to model the flood situation, the area had to be divided into nine compartments selected on a basis of a general topographic survey (Figure 6.9). For each compartment the river stage levels which would cause water to flow from one or both of the rivers into the compartment and the maximum ponded water level which would be reached before water escapes from the compartment were calculated. This information was used to calculate the depth of water stored on the field surface at any point in the meadow. High winter rainfall may also result in the occurrence of surface ponding. Water unable to exit a compartment via overland flow was assumed either to drain via the alluvium into the aquifer or to be evaporated into the atmosphere.

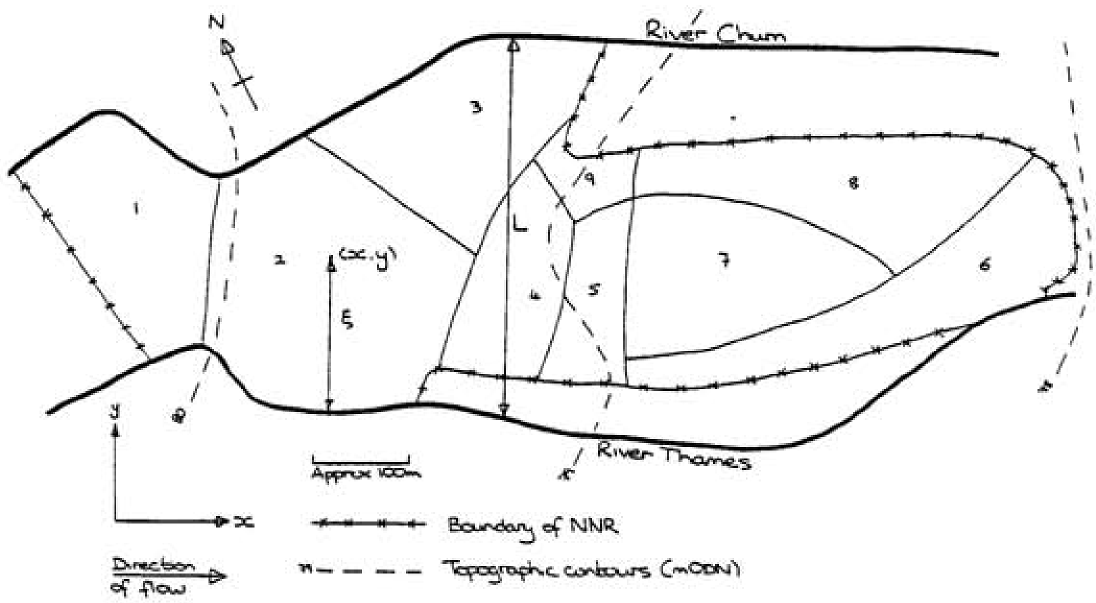


Figure 6.9 A sketch map of Cricklade North Meadow. Numbers refer to the compartments used in the treatment of surface flooding.

rise. In the model, the change in water-table height is calculated each week from the net water input / loss and the soil's drainable porosity as shown in section 6.4.

The third scenario occurs when the water table falls to within the sand layer. Water may enter this layer through the deep percolation of rainfall or by lateral seepage from the rivers. As the water table drops the transmissivity of the aquifer is also reduced in proportion to the depth of the layer which becomes unsaturated. The interface between the sand aquifer and its overlying alluvium appears, from augering studies, not to be a sharp one and hence some upward capillary rise can continue even when the water table falls below the interface.

The shallow aquifer-controlled water-table model was run in a similar way to the ditch-bounded water-table model to generate a weekly water table height for every dipwell. This output was validated against dipwell data measured in the field. An example of the results of the validation is shown in Figure 6.10. Full validation results are given in Appendix A.

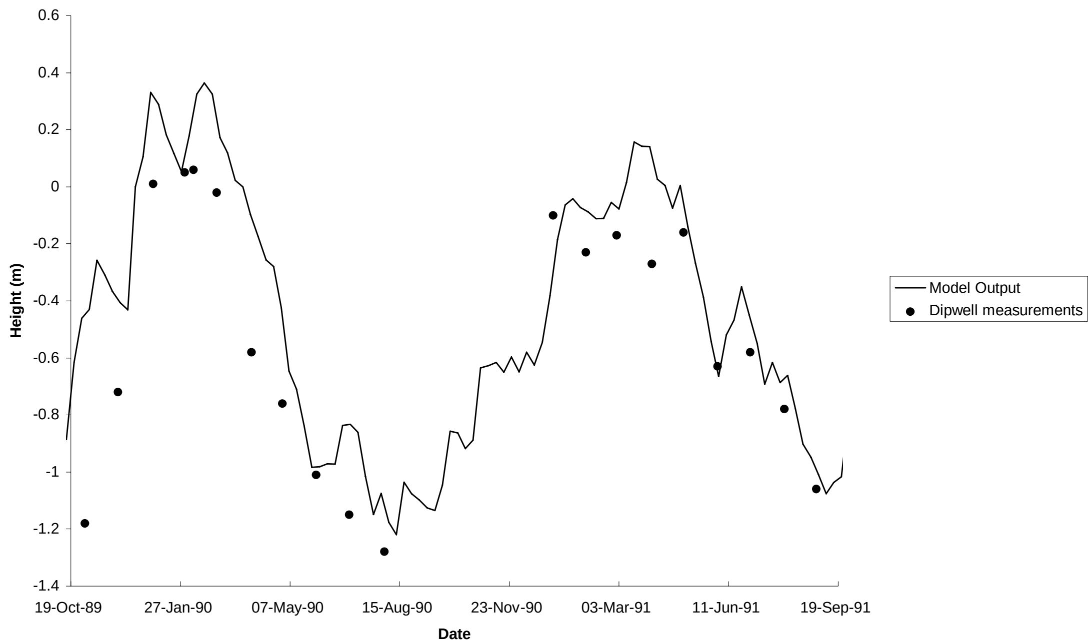


Figure 6.10 Model output shown against dipwell measurements for Cricklade North Meadow

6.1.3 The ridge and furrow water-balance model

The sites at Upwood Meadows in Cambridgeshire and Blackthorn Meadow IV in Oxfordshire both have ridge and furrow topography. A relatively permeable topsoil overlies as almost impermeable subsoil with water frequently flooding the furrows. Analysis of the microtopography, combined with a water-balance approach, have enabled the water-table behaviour to be simulated retrospectively and the resulting model has been calibrated against the long record of water-table depths available from Upwood Meadows courtesy of the local Wildlife Trust.

It has been assumed for geometric purposes that the ridges and furrows are triangular in cross-section. At both sites the modelled ridges and furrows slope with a constant gradient along the direction of the ridge crest. Raised areas at the lowest end of the fields prevent water from leaving the fields either as seepage or surface flow until the water level overtops at a specified level. A small amount of deep seepage does occur. It is assumed that water only enters the field as rainfall. It may leave the field by evapotranspiration, as floodwater during an overtopping event or as deep seepage.

The soil is effectively a two-layered system. The topsoil is of variable thickness depending on the elevation of the ridges and furrows and it is permeable, whereas the subsoil is relatively impermeable. The interface between topsoil and subsoil appears from hand augering studies to slope at a constant gradient and is unaffected by the ridge and furrow topography above.

Both Bentley Meadow at Upwood and Blackthorn Meadow IV are entirely enclosed by tall hedges and the grass is left ungrazed until late summer. The evapotranspiration from these sites will therefore not be as high as would be expected from the short-grass reference crop used as a standard by the Meteorological Office for evapotranspiration calculations. Calibration of the model for Upwood Meadows indicated that a value of 70% of the reference crop evapotranspiration should be used as potential evapotranspiration at this site. This figure was also used and validated for Blackthorn Meadow IV.

During periods of evapotranspiration, it is assumed water will be lost at the full potential rate when the water table is within 0.5 m of the mean elevation of the field surface. When the water table falls below this, evapotranspiration is assumed to decrease exponentially with increasing soil moisture tension

During the winter months, surface water stands in the bottom of the furrows at the lowest ends of the fields. The model considers the field as two separate regions separated by a movable boundary defined by the limit of surface water (see Figure 6.11). The first region comprises the area of the field below the limit of surface water in the furrows at any particular time. In this area the water table is flat and continuous with the water level in the furrow. The exception is during a period of excess rainfall when the water-table becomes domed within the ridge. Then it is assumed that half the rain that falls on the ridge drains into the furrow. The second region is the area above the surface water limit. In this area the water table is sloping towards the lowest end of the field and no allowance is made for water build-up in the ridges. The water table height is defined midway between ridge top and furrow bottom at the highest end of the field and it is assumed that the water table slopes at a constant gradient from this level to the level of the flat water table in the first system. All seepage and run-off from the latter region is added to the water level in the former region and the boundary between the two moves each time the water-balance is calculated.

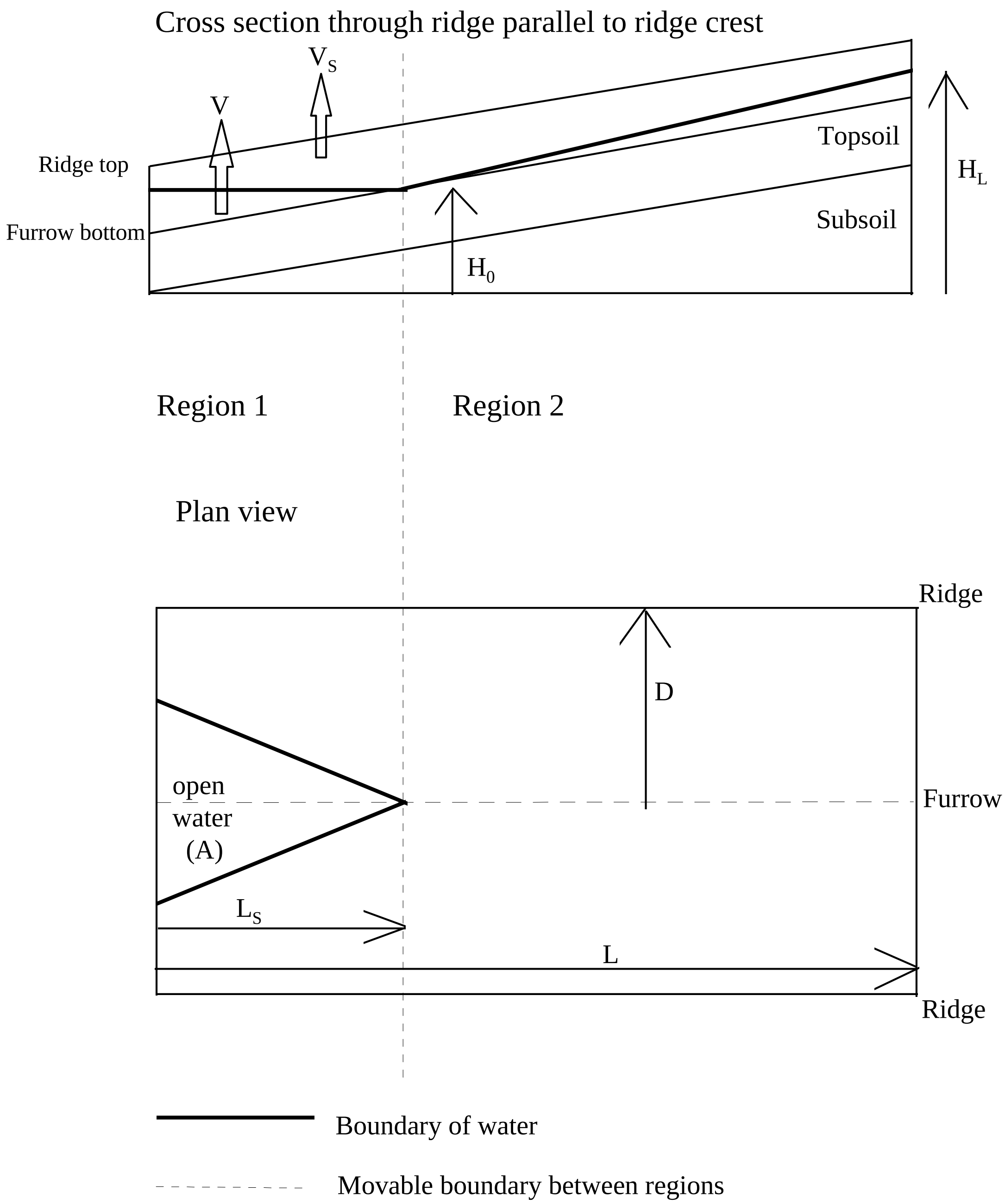


Figure 6.11 Diagram to show the boundaries used in the ridge and furrow water-balance model.
. (See text of section 6.4 for definition of labels)

During periods of no surface water, the water table may fall below the base of the topsoil even at the lowest end of the field. During such periods the water-balance is calculated purely in terms of water deficit in order that the date may be estimated when the water table reappears in the topsoil.

The model calculates water levels at weekly intervals using weekly rainfall and evapotranspiration estimates derived from local weather stations. As the water level fluctuates, the overall apparent drainable porosity of the field varies. It is a function both of the topsoil drainable porosity and the extent of open water, which can be regarded as having a drainable porosity of unity. A weighted average of these two values is taken each week. The weighting depends on the water table position and the area of open water at the start of each week.

The ridge and furrow water-balance model was run in a similar way to the ditch-bounded water-table model to generate a weekly water-table height for every dipwell. This data was used to validate the model against dipwell data measured in the field. Example of the results of the validation are shown in Figures 6.12 and 6.13. Full validation results are given in Appendix A.

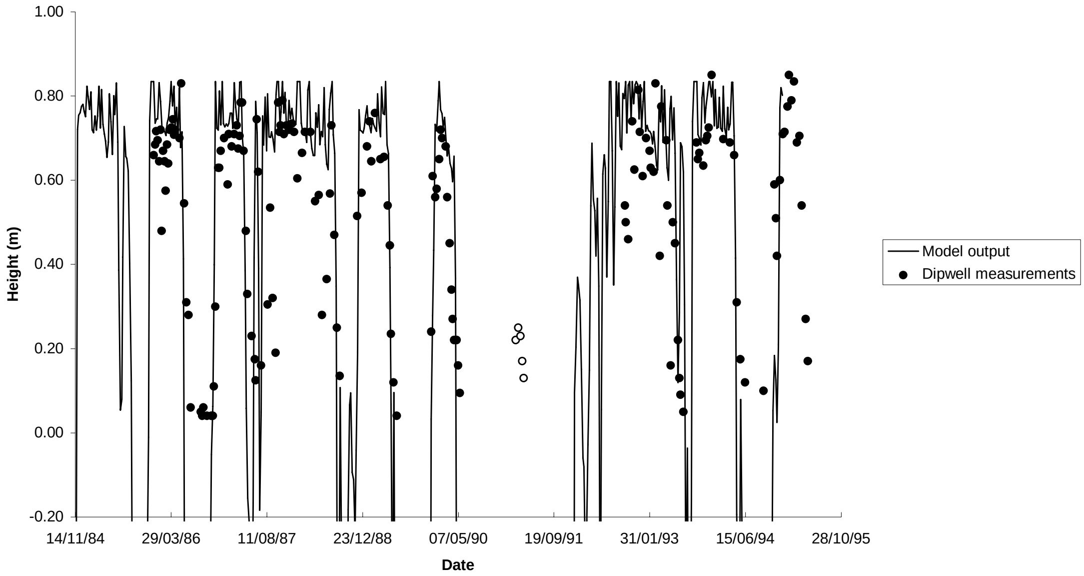


Figure 6.12 Model output shown against dipwell measurements for Upwood Meadows. Height relative to an arbitrary datum (The hollow circles represent water perched in the dipwell that was assumed to be unconnected to a true water table. This situation occurred following an exceptionally dry summer.)

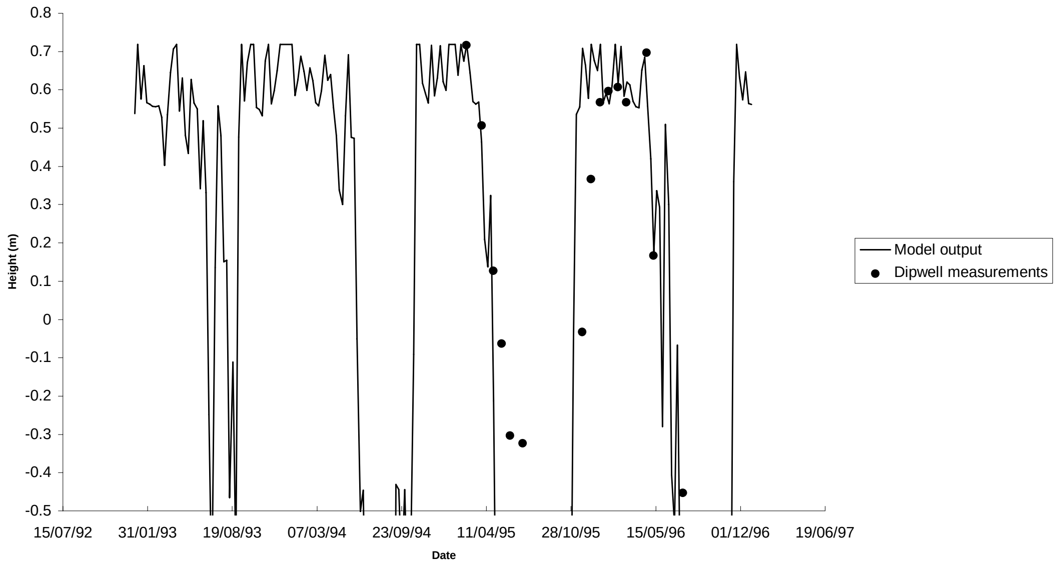


Figure 6.13 Model output shown against dipwell measurements for Blackthorn Meadow IV. Height relative to an arbitrary datum.

Following validation, the models were run for all the quadrat locations and elevations at every site to give weekly water-table heights for each quadrat. This information was used to calculate the drought and aeration SEV for each quadrat.

6.2 Hydrological modelling of remaining sites

The three models described above have been applied to seven of the twelve sites studied. The remaining five are yet to have a model fitted and validated, they are therefore omitted from all later analyses. The 2,393 microsites used to determine species' tolerance ranges are all from the seven sites which have had models validated. Data from the remaining sites will be incorporated at a later date. The reason for the delay in fitting models to these five sites is primarily the abnormal meteorological conditions which have prevailed during the lifetime of the project and hence constitute *force majeur*. The rainfall over the period April 1995 to April 1997 was the lowest total over a two-year period in England and Wales since records began (Meteorological Office, pers. comm.) and this unfortunately coincided with the period of hydrological instrumentation and data collection on sites. In several of the sites the water table failed to reach the topsoil layer even in winter, therefore the lateral seepage of water under these conditions could not be assessed and the resultant data set was insufficient for fitting a model. Data collection continues at the majority of these sites with the intention of adding their microsites into the model once a useful set of observations for validation have been attained for each. A brief hydrological description of the remaining sites is set out below.

6.2.1 Baysbrown Pool

This is a topographically flat site with shallow peat soils overlying mineral soil with impeded drainage. The field studied is surrounded by ditches but lateral seepage is considered minor and much of the drainage is overland flow. A version of ridge and furrow water-balance model may be appropriate here.

6.2.2 Broad Dale SSSI

Ridge and furrow topography on a river floodplain with impermeable clay soils typify this site. The river rarely floods but significant quantities of water are stored on the surface of the meadow in wet years. Data collection from dipwells continues and fitting of the ridge and furrow water-balance model should be straightforward once some high water-table observations have been recorded.

6.2.3 Dancing Gate Farm

The meadow has very varied topography with clay soils overlying more permeable gravels believed to be in hydraulic continuity with the neighbouring Bassenthwaite Lake. A version of the shallow aquifer-controlled water-table model may be applied here once a suitable data set has been achieved. Data collection continues.

6.2.4 Nethercote Farm

The field being studied is named Lower Sainthill Meadow. It has ridge and furrow topography overlying fluvial sands and gravels. It is thought that the site will be amenable to the shallow aquifer-controlled water-table model with the minor gravel aquifer being influenced by the neighbouring River Windrush. Data collection continues from five dipwells in the field.

6.2.5 Strumpshaw Fen Reserve

Dipwells have been monitored at this site which has deep peat soils over a two-year period and high water tables have been observed. It was expected that the ditch-bounded water-table model could be applied here because superficially all the conditions for fitting the model were in place. The site is bounded to the South by the River Yare but protected from it by a high clay bund, believed to isolate the site. Ditches within the reserve were regulated from a pump giving a record of boundary conditions for each of the sampled fields. Once the model had been applied and the output compared to field observations, discrepancies were uncovered. The conclusion was that river water seeps through the bund and supplies the site with water throughout the year. To be able to quantify this external supply, a much longer dataset will be required in order to calibrate an entirely new model.

6.3 Water-regime quantification

6.3.1 The concept of Sum Exceedence Values (SEVs)

In this analysis of water regime, when ‘drought stress’ is referred to, it means not only the direct effect of limited water supply, but also the influence a deep water table may have on nutrient supply and grazing pressure (see section 3.3). ‘Drought’ therefore is a convenient label rather than a mechanism. Likewise, ‘aeration stress’ is an amalgam of the direct effects of limited oxygen supply together with the likelihood of reduced nutrient availability and of lower soil temperatures in spring.

To describe the role of water table regime on plant competition one must first be able to quantify its effect.

i) Firstly, the aim was to understand the prevailing hydrology which has led to a particular set of species growing at a point location. Using past meteorological data, it was possible to model retrospectively the water table regime of a particular 1 m^2 microsite over a 10 to 20-year period, thereby giving a series of annual hydrographs which are used to derive the degree of stress to which plants at that site had actually been subjected.

ii) Secondly, a method of interpreting the hydrological data in a physiologically meaningful form was required, to allow comparisons between microsites and enable the hydrological tolerances of different species to be determined.

A useful technique for interpretation of water-regime effects is the Dutch concept of Sum Exceeded Values (SEVs). This involves setting a threshold depth for the onset of stress then summing the degree to which the water table exceeds or falls below this level during the growing season (Sieben, 1965). In this way the annual hydrographs can be interpreted to give two values; one for potential drought stress, the other to reflect potential aeration stress (Fig. 6.14). The absolute value will vary from year to year reflecting variations in rainfall patterns (Fig. 6.15), but when a mean value is reflect potential aeration stress (Fig. 6.14). The absolute value will vary from year to year reflecting variations in rainfall patterns (Fig. 6.15), but when a mean value is taken over 15 consecutive years, it is a reliable estimate of the water regime at a particular microsite (coefficient of variance <10%). The degree of stress as estimated by SEVs will vary significantly between microsites just a few metres apart in the field, reflecting changes in microtopography and seepage potential, therefore this approach is able to explain differences in plant community composition on a very fine scale.

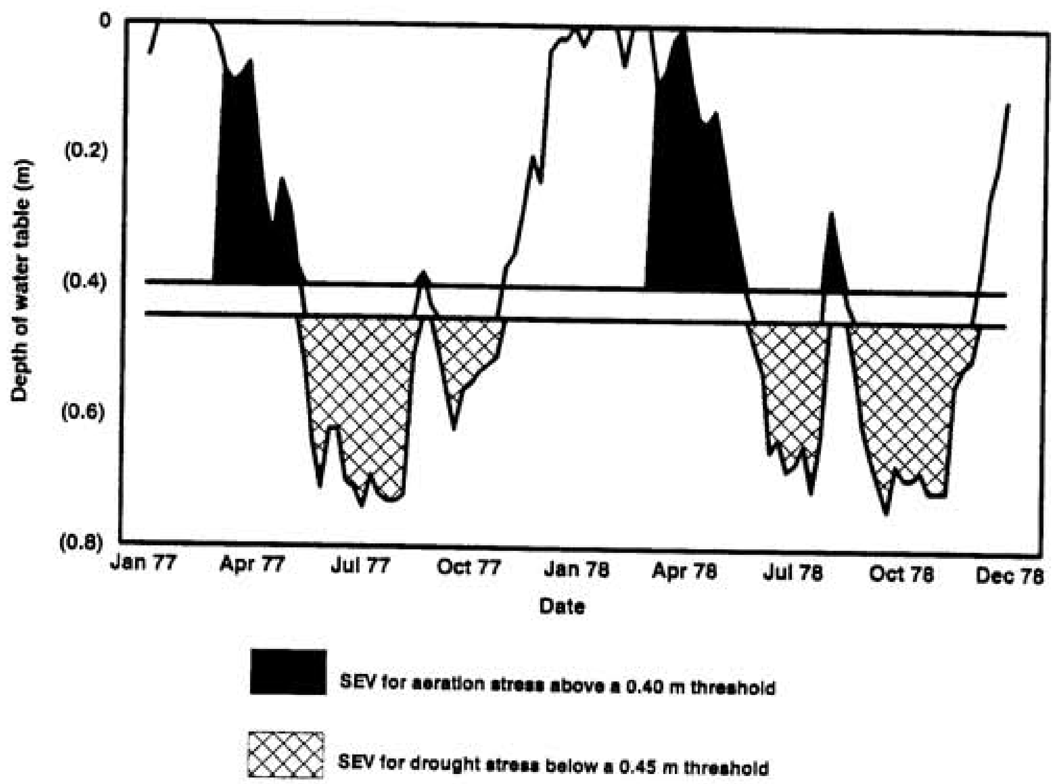


Figure 6.14 A hydrograph showing water-table depth variation over two annual cycles. The shading illustrates how Sum Exceedence Values are derived.

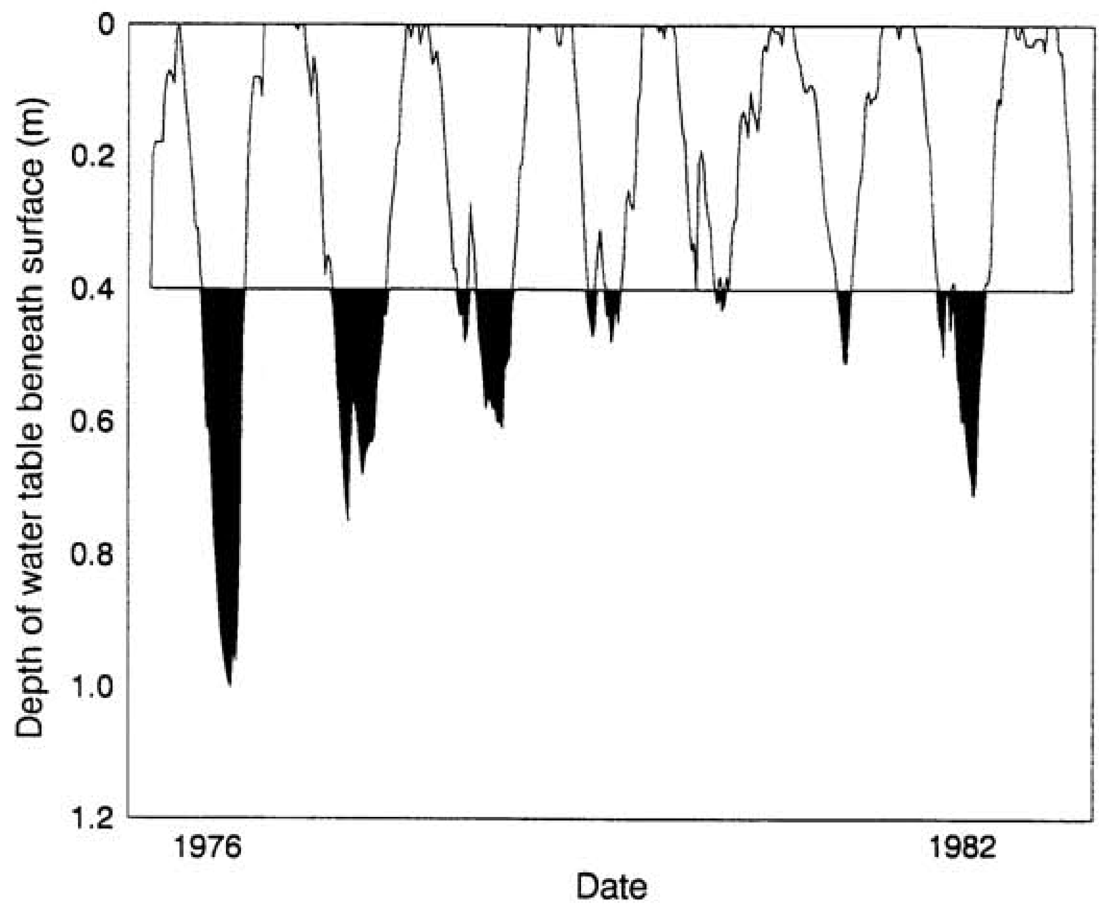


Figure 6.15 Hydrograph over a 7-year period demonstrating the between-year variation in SEVs due to fluctuation in rainfall amounts and patterns.

The threshold values are set using purely physical criteria - soil porosity, conductivity and evaporation demand. They are therefore not species specific. Factors relating to the plants' rooting depths and root volumes may influence its SEV tolerance range, but do not determine the threshold itself. The numerical values of the thresholds are calculated as follows;

Drought threshold. Physiological studies have shown that plants respond to soil moisture tensions in excess of 0.5 m (Ψ = 5 kPa) (Henson *et al.*, 1989). Drought-sensitive species may close their stomata, slow their growth rate and reduce nutrient uptake once the soil becomes drier than this. Therefore, this value was used as the critical surface moisture tension in the calculation of the drought-threshold depth, calculation was set equal to the long-term average potential evapotranspiration in June;

Aeration threshold. Field-drainage studies have indicated that soils require at least 10% air-filled porosity to allow oxygen diffusion to occur at a rate sufficient to supply the respiratory demands of the root during periods of rapid growth (Wesseling and van Wijk, 1957). On peat soils for example, this air-filled porosity corresponds to approximately 0.4 m tension in soil moisture (Campbell and Richards, 1950; Walker, 1995). Using the Richards equation and an average value for evapotranspiration during the growing season, the water-table threshold depth, above which the shallowness of the water-table may lead to anoxic conditions in the root zone can be calculated. This is taken to be when the air-filled porosity at 5 cm depth falls below 10%.

Using these thresholds, an SEV for drought and an SEV for aeration can be assigned to each of the sample points individually. In the aeration case, threshold exceedence is only considered if it occurs within the period March-September, the active growing season (Broad and Hough, 1993). Outside this season, the root oxygen demand is much smaller and the risk of potential stress less marked.

There are a number of other methods by which to characterise a water regime, many of them simpler than SEV calculation. To investigate whether one of the more straightforward parameters had equal explanatory power to SEVs, statistical tests were performed using the data from a single site (Tadham Moor). The alternative parameters tested were;

1. Annual mean water-table depth
2. Mean water table depth during the growing season (March-September inc.)
3. Simple duration of water tables exceeding one of the specified thresholds rather than a peak-over-threshold measure.

The statistical package MINITAB (Minitab Inc., State College, Pennsylvania) was used to fit response surfaces by logistic regression to a selection of species' distributions with respect to water regime as defined either by SEV or by one of the three alternatives previously listed. The quality of the fit was measured by the deviance of the logistic regression, which was then taken as a measure of the explanatory power of that parameter. The results indicate that all four parameters showed significant correlations with the distributions of most species (Table 6.2), but the only one to give a significant correlation with all species and which generated the best fit in the largest number of cases was the one using SEVs.

Table 6.2. Results of logistic regression tests on four models using different parameters of water regime. (**n.s**. = non significant correlation)

Species	**SEVs**	**Annual mean**	**Growing-season mean**	**Duration of exceedence**
Carex disticha	202	94	177	180
Carex hirta	28	18	5 **n.s.**	20
Carex nigra	104	50	79	106
Carex panicea	18	4 **n.s.**	9	20
Ranunculus acris	52	70	44	33
Ranunculus repens	41	43	32	42
Agrostis capillaris	13	4 **n.s.**	2 **n.s.**	4 **n.s.**
Agrostis stolonifera	45	21	37	35
Agrostis canina	84	40	59	54
Best fit	**5**	**2**	**0**	**2**

The above preliminary analysis was in agreement with a more comprehensive study of different water-regime parameters (Noest, 1994) which also concluded that degree of threshold exceedence had most explanatory power with respect to species' distributions. The Sum Exceedence concept was therefore adopted as the parameter for water-regime characterisation in all further analysis.

6.3.2 Soil moisture tensions

The modelling approach used in SCHAFRIM (Gowing *et al.*, 1994) relied on water-table depth as a measure of both drought and aeration stress, which was adequate to describe water regimes on sites with deep permeable soils. The introduction of sites with low-porosity mineral soils, however, required this method to be reappraised. On some of the newer sites, there is no meaningful water-table depth during the summer months, because all the free water in the top soil is lost by evapotranspiration. The quantification of drought stress by means of water-table depth below a threshold was therefore no longer feasible and an alternative measure was required. Once the water table has ceased to influence the root zone, water extracted from the unsaturated profile by plant roots is not replaced, its water content is therefore reduced and the moisture tension of the soil matrix increases. The moisture content of the root zone is calculated using a simple water-balance method and the tension derived from this figure using a soil-moisture release curve (e.g. Figure 6.16.)

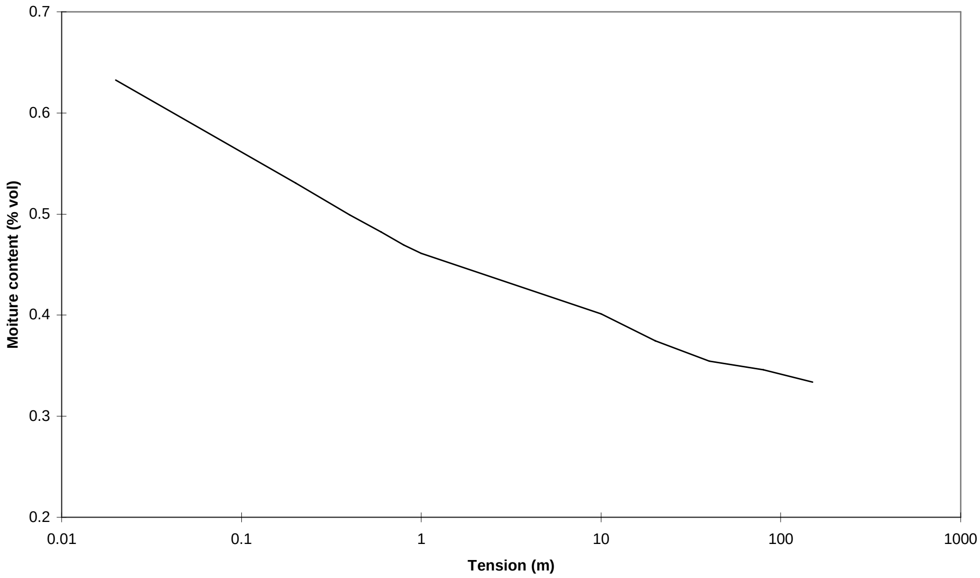


Figure 6.16 Soil moisture release curve for Blackthorn Meadow IV topsoil

In this way, each of the models produces a weekly estimate of soil moisture tension calculated in pF units,

$$pF = \log_{10}(\Psi)$$

where Ψ is either the moisture tension in the root zone expressed as a head of water in centimetres or the depth of the water table in centimetres when the full evaporative demand is being met by the water table.

The depth of the root zone was investigated at each site during hand augering. The bulk of the root mass was found in the top 100 or 150 mm of the profile at all sites in agreement with the findings of Dumortier (1991), though traces of root were found at 1 m depth. Root activity is not necessarily correlated with root mass and therefore the depth of the soil layer contributing to root uptake is difficult to assess. For the purposes of this study the "root-zone" is taken as the top 0.5 m of the profile.

pF values can then be interpreted by the same peak-over-threshold technique as was used to generate SEVs described above. The threshold value is taken to be 0.5 m tension as before, which equates to a pF value of ~ 1.7. This approach can unify all the study sites and allow all microsites to be plotted on the same graph (Figure 6.17). This figure shows the spread of water regimes sampled extends across the whole range of possibilities which could be encountered on wet grasslands. At the wet end of the scale (Belaugh Old Farm), some microsites are so wet throughout the year that they are very marginal for grassland management and are approaching fen vegetation. At the other extreme (Cricklade North Meadow), a few of the microsites are almost perfectly drained, almost uninfluenced by groundwater and approaching a chalk grassland sward in terms of species composition. The distribution of samples over the range is not an even one, being limited by the sites available for study, but it is considered that it represents an adequate spread to allow a meaningful interpolation over the full range.

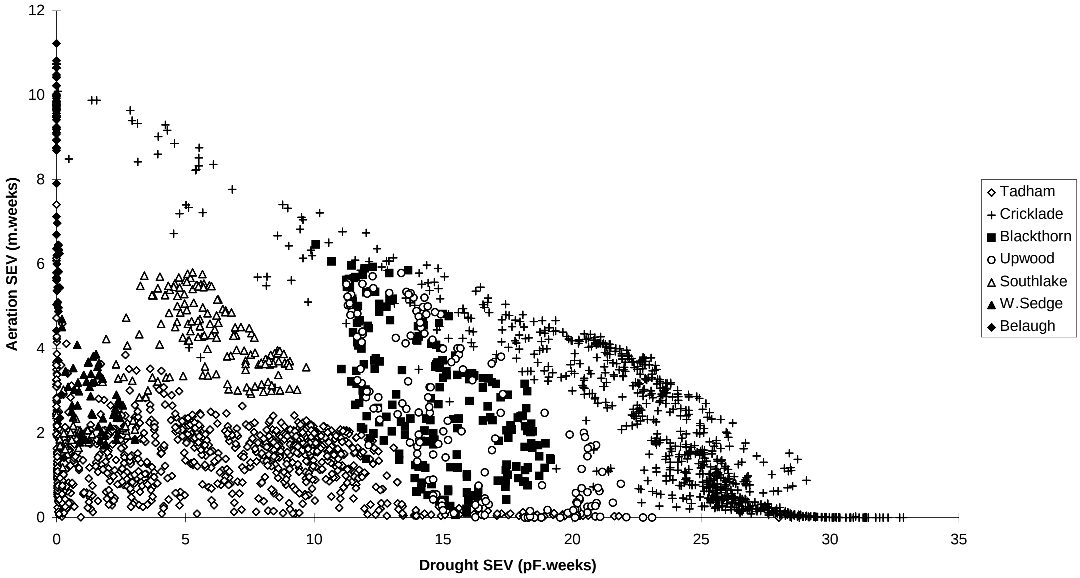


Figure 6.17 The distribution of SEVs over all seven of the modelled sites.

7 Species distribution with respect to water regime

The range of modelled water regimes, as shown in Fig. 6.17, provide a useful description of the total water-regime niche space which can be sub-divided to describe the favoured water regimes of particular species.

7.1 Botanical data interpretation

The objective of the vegetation recording was to build up a database of those plant species which occur in semi-natural wet grassland communities, managed for hay. Such communities form the target vegetation of many ESA schemes, as they combine high diversity, aesthetic and conservation value with tolerable agricultural productivity (project BD0208 describes the vegetation objectives for ESA schemes). Each of the 2,393 microsites sampled for this project was botanically surveyed and a complete species list recorded. All these data have been gathered using some form of random-placement sampling technique, aimed at representing a stand of vegetation as a whole, rather than targeting particular species or communities. The latter methodology could be used, however, to generate a data set for the rarer species, which are not sufficiently represented in the current database for firm conclusions to be drawn about their water regime requirements. Future work could employ such techniques to answer questions relating to species of particular conservation interest.

All microsites were defined as a $1m^2$ quadrat. On most sites there was at least 10 m between sampled points and they were treated as independent observations. All samples were at least 10m from boundary ditches, rivers or field margins in order to avoid edge effects. Some of the ridge and furrow sites, however, were sampled with more closely spaced quadrats to reflect the finer scale variation in vegetation type. Only presence/absence information is used in this analysis, although species abundance in the form of percentage cover values is also available in the database for all microsites. Considering all twelve sites which were surveyed, more than 230 species were recorded, which encompasses the vast majority of lowland wet grassland species native to Britain. A complete species list with the number of observations of each species at each of the modelled sites is presented in Appendix B, where the nomenclature of vascular plants follows that of Stace (1991). Those species with zero records are ones found at one or more of the five sites yet to be modelled. Many species have only been recorded in a small number of microsites and the information generated is insufficient to describe a clear range of favoured water regimes and as such have been excluded from the current analysis. As described in section 3.3, those species which occur in less than half the modelled sites albeit at high frequency, are also excluded from the current analysis, as their absence at other sites may be a result of historical accident rather than unsuitable water regime. Using these selection criteria the full list was filtered to give a subsidiary list of 67 species which were recorded at more than 100 microsites in total, which is sufficient to describe a favoured range with statistical confidence, and with a presence at more than half the modelled sites, which suggests it is a widely distributed species. It is this subgroup whose favoured water regime niches are presented in Appendix C.

It is expected that some of the further 160 species can be similarly defined once the remaining sites have been modelled. It would also be possible to derive the favoured regime of any species which occurs at a reasonable frequency but only in a limited number of sites. This information is not presented here, however, as care needs to be taken in extrapolating the species' tolerance into ranges over which the species had not been sampled.

7.2 One-dimensional analysis of species' relationship to water regime

Interpretation of data in a previous project (FD0502) had been based on a one-dimensional analysis of the relationship between the water regime as measured by SEVs and the distribution of a given plant species as measured by relative frequency (Figure 7.1). The plots represent a rolling average of the species' relative frequency within a subset of microsites, which are ranked from lowest potential stress to highest along the abscissa. The ordinate has relative frequency defined as;

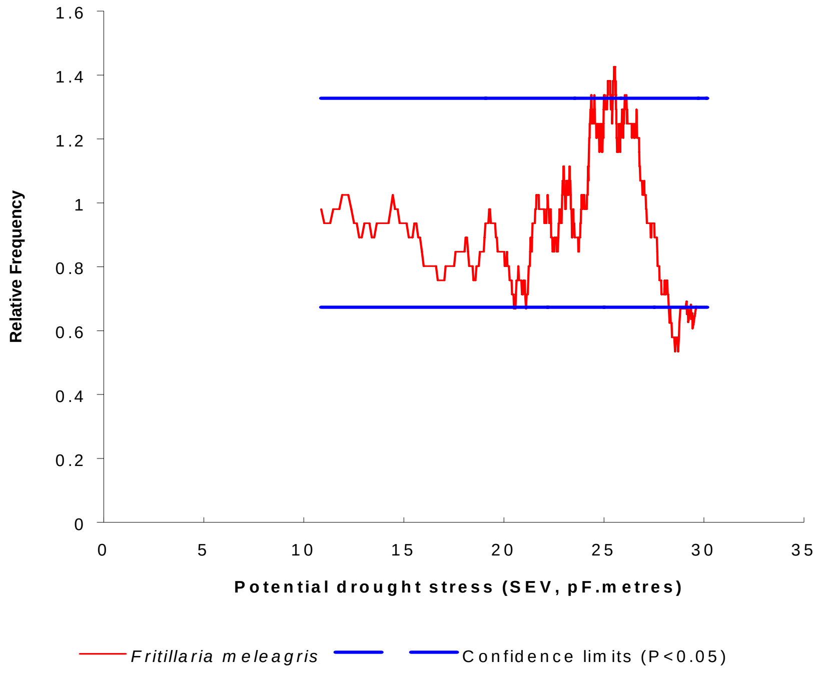
$$\text{Relative Frequency} = \frac{\text{Proportion of microsites in sample with the species present}}{\text{Proportion of total microsites with the species present}}$$

From such a figure, it was possible to define a water-regime tolerance range over which the plant occurred relatively frequently. This was a linear range either with respect to drought stress or aeration stress. This approach yields comparable information to the ecological rankings of Ellenberg (1988) (Figure 7.2) and indeed of Grime *et al.* (1988). The Silsoe approach, however, has the advantage of being quantitative, such that it can potentially be used in the management of habitats, and for making predictive estimates of species in danger of disappearance following a change in water management. This was the basis of SCHAFRIM (Gowing *et al.*, 1994).

The current project was able to extend this approach to compare tolerance ranges between distinct sites. In order to achieve this, the method for determining the cumulative amount of drought stress had to be adjusted to use values of soil moisture tension in the root zone rather than water-table depth (see section 6.3.2). This allowed true groundwater sites to be compared with sites which do not have a water table in summer (Figures 7.3 and 7.4).

7.3 Two-dimensional analysis of species' relationship to water regime

In the current project, the approach moved further, to consider the two stresses simultaneously and to produce two-dimensional frequency plots which describe a tolerance zone. This approach has the advantage of allowing any interaction between the two stresses to be accounted for. A preliminary example of this type of output is shown in Figure 7.5.



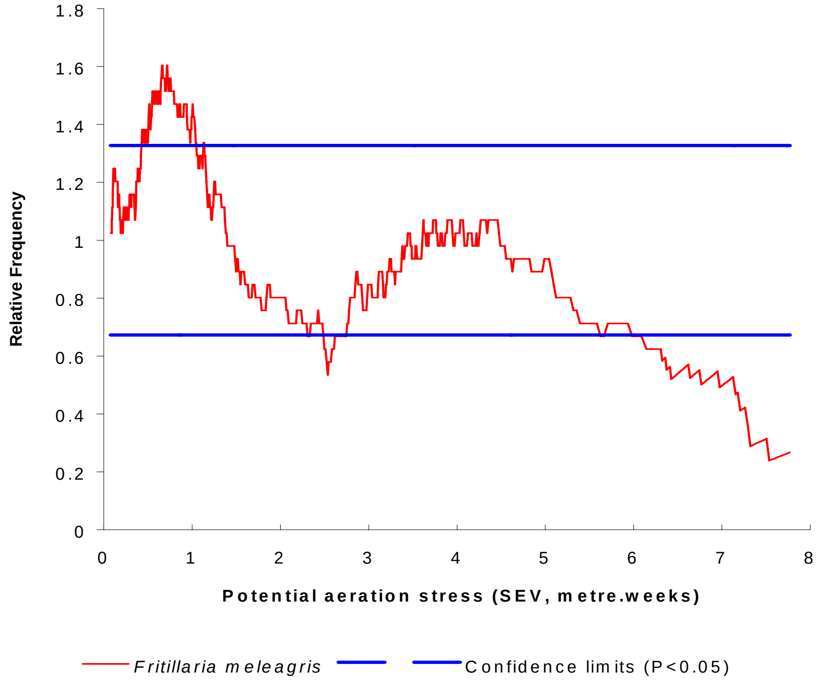


Figure 7.1 One-dimensional plots of the distribution of *Fritillaria meleagris* (Snakes-head Fritillary) with respect to potential stresses imposed by the water regime at Cricklade North Meadow, Wilts.

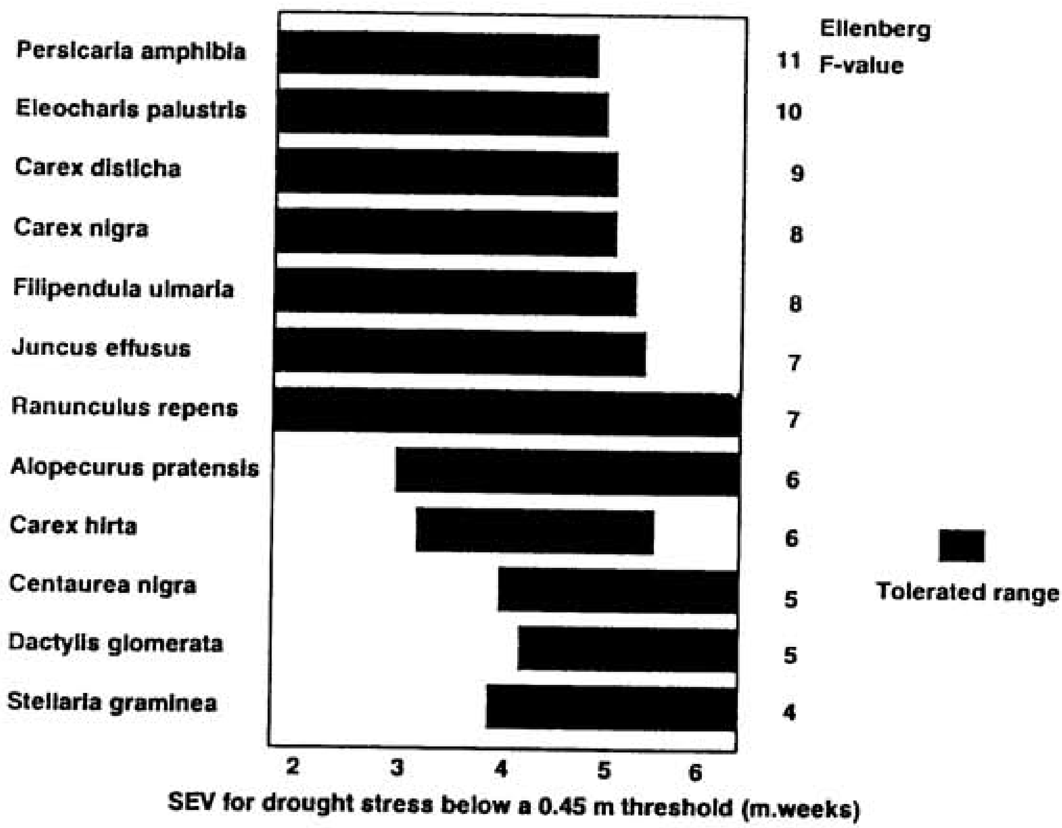


Figure 7.2 Tolerance ranges with respect to potential drought stress as characterised by SEV below a water-table depth. Ellenberg's F-values for each species are given to illustrate degree of agreement. (See box at end of chapter for explanation of Ellenberg's scale.)

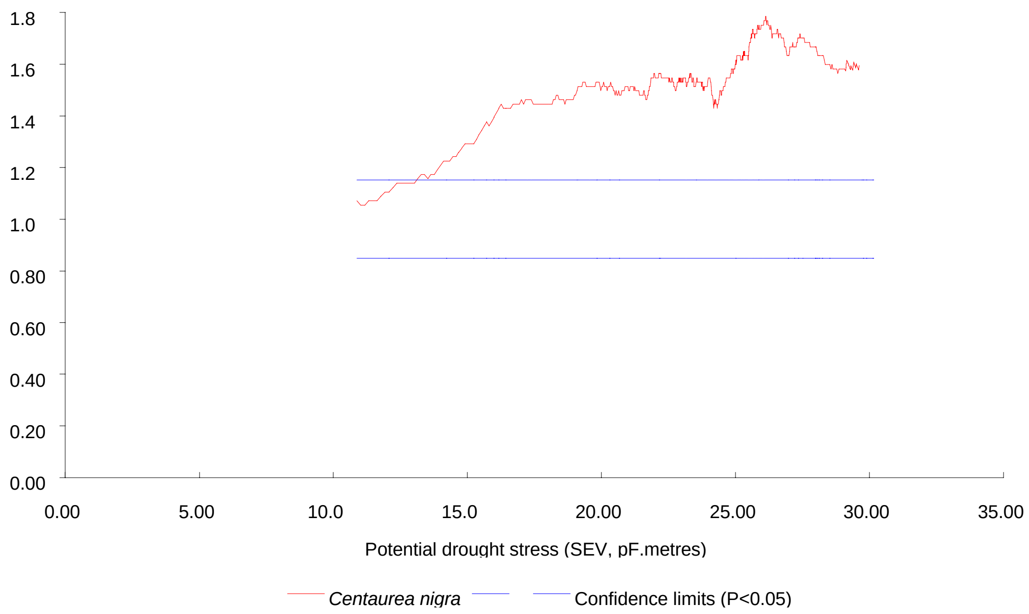


Figure 7.3 The distribution of *Centaurea nigra* with respect to potential drought stress on a mineral soil at Cricklade North Meadow. The confidence limits are those for the species' frequency across all seven sites.

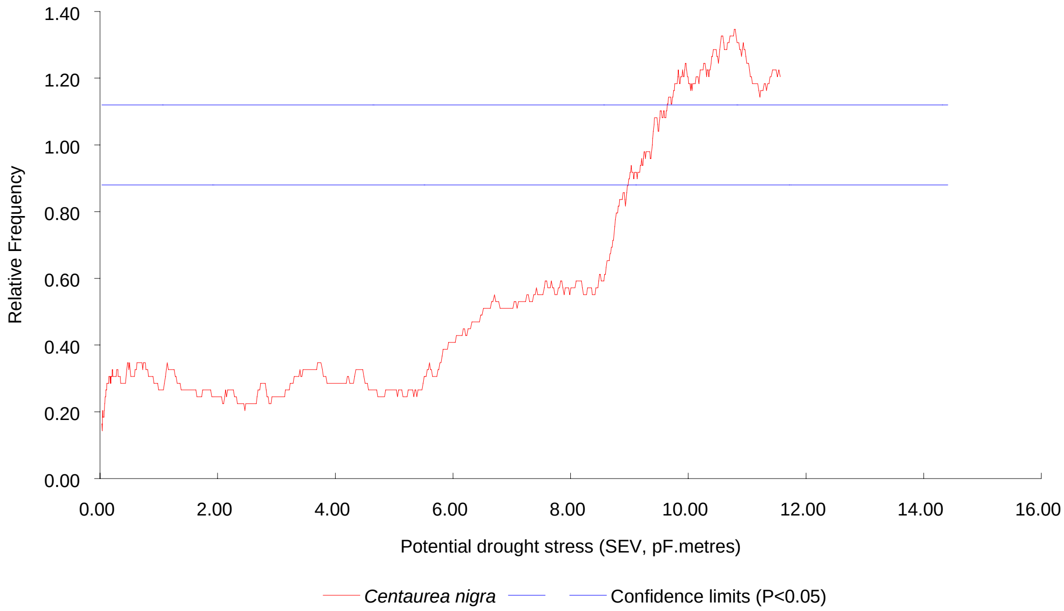
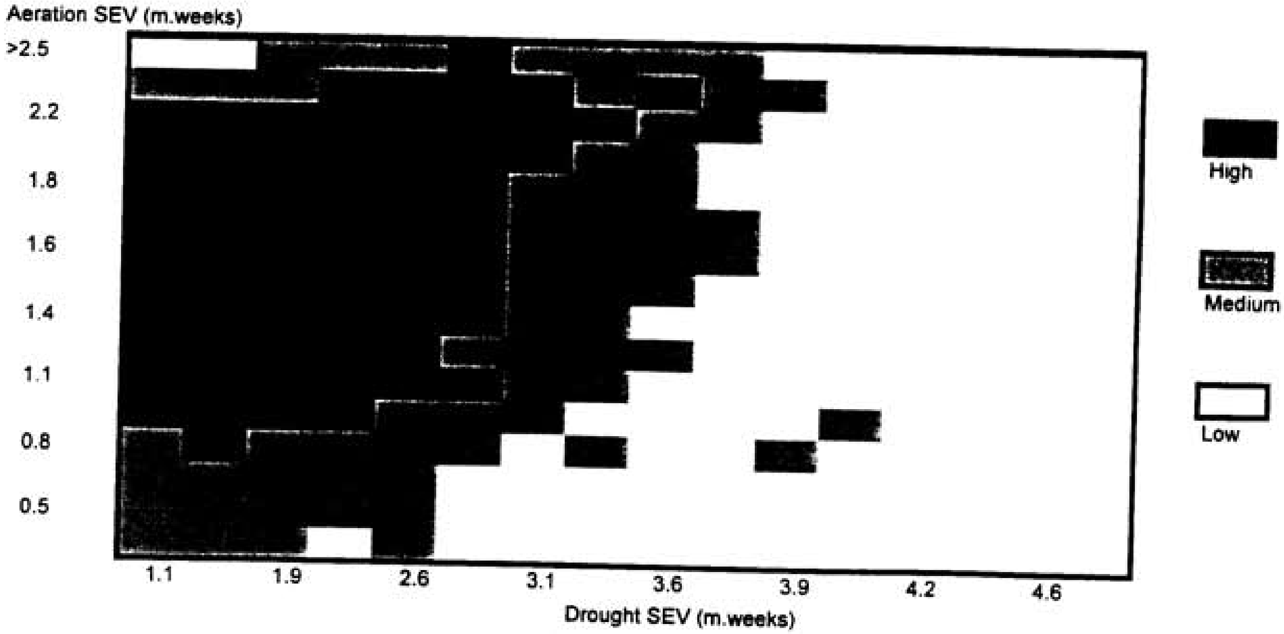


Figure 7.4 The distribution of *Centaurea nigra* with respect to potential drought stress on a peat soil at Tadham Moor for comparison with Fig. 7.3. The confidence limits are those for the species' frequency across all seven sites



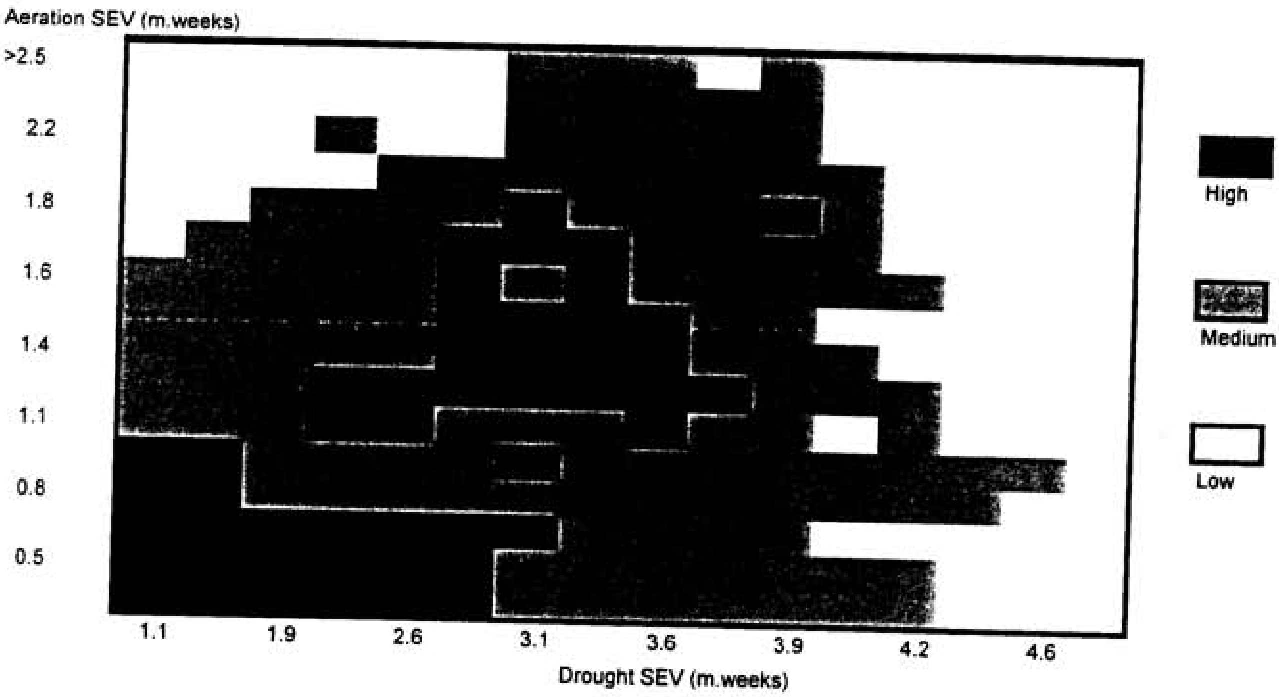


Figure 7.5 Distributions of Carex nigra (Common Sedge, above) and Carex hirta (Hairy Sedge, below) with respect to water regime on Tadham Moor. Shading density reflects relative frequency of the species within a sample of similar microsites. "High" refers to frequency above the upper 95% confidence limit. "Medium" refers to frequencies within the 95% confidence interval.

The method was then developed further to present the data as contour plots showing the probability of locating the plant at a given water regime. A technique for smoothing the presence/absence data was required and two previous studies were identified as offering possible solutions (Le Duc *et al.*, 1992; Trexler and Travis, 1993). The software package, “SURFER” (Keckler, 1995), was found to offer the capability to generate plots which depict the “favoured” water regime niche for a particular species. The method by which the plots were generated is set out in the box below. The program sampled the data to define the region within the total niche space in which a given species was significantly more frequent than in the remainder of the area. Figure 7.6 is an example of the output of the procedure. Plots for all the species which are sufficiently common and sufficiently widespread to meet the criteria set out in section 7.1, are presented in Appendix C at the end of this report.

Procedure for generating “favoured water-regime” plots using SURFER

The inputs to the program were the water regime information, as presented in Figure 6.17, and the species’ presence/absence data for each of the microsites. The program superimposes a 50 x 50 grid over the scatter-graph and estimates the likelihood of the species being present at any point by sampling the 120 observations which are closest to that grid node. The sampled points are drawn evenly from the four quadrants surrounding the node and an unweighted average of their values (present = 1, absent = 0) is taken.

The overall proportion (p) of microsites containing the species in question is calculated from all seven sites. An expected value of the mean number of microsites containing the species within a sample (μ) can be obtained. Only species with $p > 0.042$ have been used in the analysis, so with sample size = 120, μ will be >5 in all cases. This enables one to approximate the distribution of mean values to the normal distribution and to apply confidence limits to μ. The “favoured” water regime of a species is taken to be the range of niche space over which it occurs at a significantly ($P<0.05$) higher frequency than would occur by chance, were its distribution independent of water-regime.

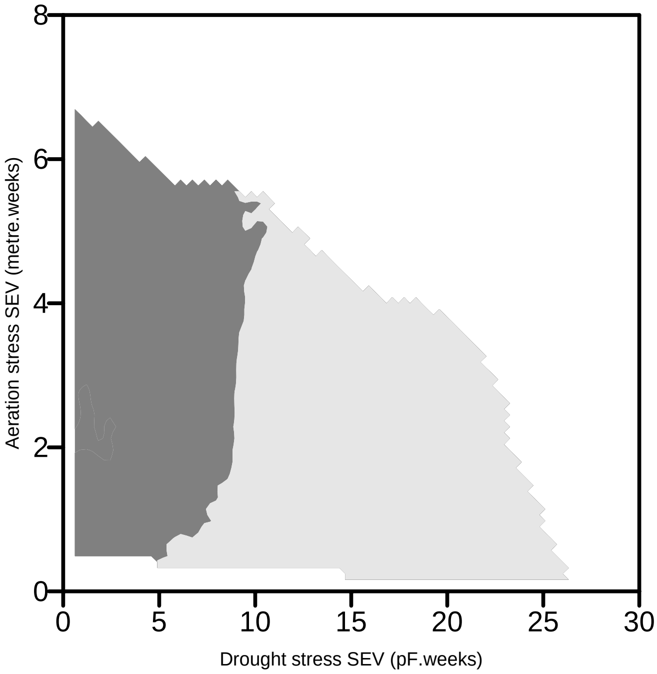


Figure 7.6 Distribution of Carex nigra (Common Sedge) frequencies with respect to water regime across all seven modelled sites. The shaded zone (both tones) represents the area over which sufficient data were available for analysis and the darker tone represents the region in which the species is significantly more frequent ($P<0.05$) than the overall mean.

7.4 Discussion of favoured water-regime plots

The diagrams presented in Appendix C provide an insight into the autecology of the species listed there, in addition to providing quantitative information for water-regime interpretation. It is possible to identify perhaps 10 distinct groupings, in terms of response to water regime, amongst the 67 species. These may relate to the different survival strategies exhibited by the various species.

The groupings are described below under the following headings;

a) the type of stress potentially being imposed by the water regime

b) a simple interpretation of the soil water status creating the condition

c) some examples of species falling into the category together with the Feuchtezahl (F-value or water value) ascribed to them by Ellenberg (see box at the end of the section for definitions of these.)

1	**a)**	**(type of stress imposed)** **Requiring aeration stress to compete, but avoiding drought stress.**	
	b)	(soil water status leading to the condition) Permanently wet soils	
	c)	*(species which exemplify the grouping*	*Ellenberg F-value))*
		Alopecurus geniculatus	*9*
		Caltha palustris	*8*
		Oenanthe fistulosa	*9*
		Senecio aquatica	*8*
2	**a)**	**Requiring aeration stress with or without some drought stress.**	
	b)	Soils wet in spring at least	
	c)	*Poa trivialis*	*7*
3	**a)**	**Requiring both stresses to compete most successfully**	
	b)	Soil wet in spring and dry in summer	
	c)	*Alopecurus pratensis*	*6*
		Deschampsia cespitosa	*7*
		Elytrigia repens	*5*
4	**a)**	**Requiring drought stress to compete, but avoiding aeration stress.**	
	b)	Soils always well drained or dry	
	c)	*Dactylis glomerata*	*5*
		Leontodon taraxacoides	*6*
		Trisetum flavescens	*
5	**a)**	**Requiring drought stress with or without some aeration stress.**	
	b)	Soils dry during summer at least	
	c)	*Carex flacca*	*6*
		Lathyrus pratensis	*6*
		Silaum silaus	*7*
6	**a)**	**Avoiding both stresses.**	
	b)	Soils with stable water tables, being permanently moist but not waterlogged	
	c)	*Festuca pratensis*	*6*
		Filipendula ulmaria	*8*
		Lotus pedunculatus	*8*
7	**a)**	**Avoiding drought stress, with or without some aeration stress**	
	b)	Soils at least moist throughout the year	
	c)	*Carex nigra*	*8*
		Juncus articulatus	*8*
		Ranunculus repens	*7*

8 a) Avoiding aeration stress, with or without some drought stress

b) Soils well drained throughout the year, may dry in summer

c)	*Agrostis capillaris*	*
	Carex hirta	*6*
	Cerastium fontanum	*5*

9 a) Species showing two quite separate domains on the plot

b) These could be species with a ruderal element to their strategy, allowing them to quickly colonise gaps whether created by high aeration or by high drought stress; <u>or</u> species composed of two distinct ecotypes <u>or</u> species adapted to low nutrient conditions which can compete successfully on soils where the effect of low nutrient availability is compounded by very wet or very dry soil.

c)	*Cynosurus cristatus*	*5*
	Leontodon hispidus	*4*

10 a) Species showing no clear pattern with respect to water regime

b) These could be species with very wide tolerance, <u>or</u> species composed of a large number of separate ecotypes <u>or</u> species whose distribution is dominated by a factor which is independent of water regime.

c)	*Brachythecium rutabulum*	
	Leontodon autumnalis	*5*
	Lolium perenne	*5*
	Rumex acetosa	*
	Taraxacum agg.	*5*
	Trifolium pratense	*
	Trifolium repens	*

It is important to note that this information reflects the species' behaviour under traditional hay-meadow management on soils with near neutral pH. The same species may show a quite different response on sites with a less intensive grassland management regime or with more extreme values of soil pH.

Definition of Ellenberg F-values (Ellenberg, 1988)

3	Dry site indicators, more often found on dry ground than moist places, not found on damp soil.
4	Between 3 & 5
5	Moist-soil indicators, mainly on soils of average dampness, absent from both wet ground and places which may dry out.
6	Between 5 & 7
7	Damp-site indicators, mainly on constantly damp, but not wet, soils.
8	Between 7 & 9
9	Wet-site indicators; often in water-saturated, badly aerated soils.
*	Indifferent behaviour, i.e. a wide amplitude or different behaviour in different parts of Europe.

8 Application of project results

8.1 Interpretation of water regimes in terms of plant habitat suitability

In terms of monitoring vegetational change in response to altered hydrology, the best information previously available was the subjective ranking of Ellenberg's moisture values (Ellenberg, 1988). This has a number of limitations. It is on rather a coarse scale which may mean subtle changes are overlooked and it attempts to describe the requirements of all species on a single linear scale (1-12). This project has demonstrated that a water regime may impose stress on plants from two sources; aeration and drought. The magnitude of one stress is not necessarily correlated with the magnitude of the other and therefore both considerations are required to describe a species' tolerance range. This study has produced a more detailed ranking than that given by Ellenberg (albeit for a more limited range of species) and in two dimensions such that the influence of the two potential stresses may be defined.

On sites where the water regime can be understood quantitatively, either by use of models such as those presented in this report or by direct monitoring, the project's results can interpret the regime in terms of plant habitat suitability. Information on soil structure would be essential to achieve this as the threshold for aeration stress and the rate of cumulation of drought stress are both functions of the soil's porosity. Once a regime has been characterised by SEVs then its position on the plane representing niche space can be defined and hence comparison to the plots in Appendix C will indicate which species are likely to be favoured by the regime and which may be less suited. The main application in practice is foreseen as being on sites where a change to the hydrological system needs to be assessed in terms of its impact on vegetation composition. Being able to specify both "before" and "after" positions on an SEV plot will allow one to list those species likely to decline as a result of the change. To predict those likely to benefit from the change is a much more complex ecological problem, but the information presented here is one tool to help in meeting the challenge, indicating where water-regime requirements would be met.

On sites where the hydrological system is more complex, the project's information may be difficult to apply directly, but may be used instead to interpret botanical data in terms of the water regime which supports the vegetation. In other words, to use plants as hydrological indicators. Using species in this way has been problematic in the past because currently available information relating to plant water-regime requirements has been site specific (Wheeler and Shaw, 1995). It is this obstacle that the project has addressed and to some considerable extent overcome.

8.2 Critique of ESA water level prescriptions

This and previous projects have built up a large database of plant water-regime requirements for sites in the Somerset Levels and Moors ESA. This information is now at a stage where it can contribute to the formulation of policy in terms of the water management within the ESA to promote conservation. As part of the project, a draft critique of water level prescriptions was compiled (Spoor *et al.*, 1996b) and subsequently a fuller examination made of the impacts of raised water levels on grassland swards (Gowing, 1996).

Results from sites in other ESAs, which are either presented here or will become available once the remaining five sites have been modelled, will inform the debate on management prescriptions in those areas too. The full range of water-regimes liable to be encountered in wet grassland have been modelled (Fig. 6.17), the majority of species likely to be found on such sites have been sampled (Appendix B) and the data on water-regime requirements of species appears to be transferable between sites (cf. Fig. 7.3 and Fig. 7.4), therefore an initial assessment of other schemes should be possible with the existing information.

The water-regime requirement information presented here enables estimates to be made of the extent to which the ESA scheme objectives can be met on a specific site. They could also identify any further in-field water-management measures which may be necessary on certain sites to maximise environmental benefits (Spoor *et al*, 1996a).

8.3 Planning for Biodiversity

In terms of the variation in species richness with water regime, the information collected can be interpreted to indicate which types of regime are more likely to result in higher levels of α-diversity (*sensu* Whittaker, 1975). A preliminary analysis is presented in Fig. 8.1. Two zones of high diversity are indicated. The one to the right of the plot corresponds to the very dry unflooded areas on Cricklade North Meadow, which have been deprived of nutrient inputs from either manure or silt for a long period and appear to have a very low productivity. These areas are approaching chalk grassland swards in their structure and can exhibit similar levels of species richness. They may be of great conservation value, but are not representative of wet hay-meadows in general, being at the extreme edge of the range. The gradient of more relevance is that labelled AB on the plot. It suggests stable water-table conditions in the growing season, resulting in low levels of either stress (point A) can result in high diversity swards (>22 spp/m^2). This may be a result of a small rooting volume limiting the nutrient availability to plants. Greater fluctuation will promote more mineralisation of organic matter, which may lead to more productive and less diverse swards. The zone of greatest fluctuation and hence highest level of combined potential stress (point B) indeed results in the lowest species richness observed (<18 spp/m^2). Therefore to encourage species richness within a hay meadow situation, stable water tables throughout the growing season are a desirable objective.

In terms of β-diversity (*sensu* Whittaker, 1975), that is the spatial segregation of different vegetation types within a defined area, the current data on species water requirements may not be the most appropriate type of information. It would be useful to look at the data on a community rather than a species level. Such information could then be used to assess water regimes across a site and indicate the degree of variation likely to be created in vegetation composition. Whether the aim of hydrological management would be to maximise the β-diversity within a site or to maintain the integrity of a particular vegetation stand would depend on the nature of the conservation interest of the existing vegetation. Planning for β-diversity may be most appropriate in habitat creation schemes.

the conservation interest of the existing vegetation. Planning for β-diversity may be most appropriate in habitat creation schemes.

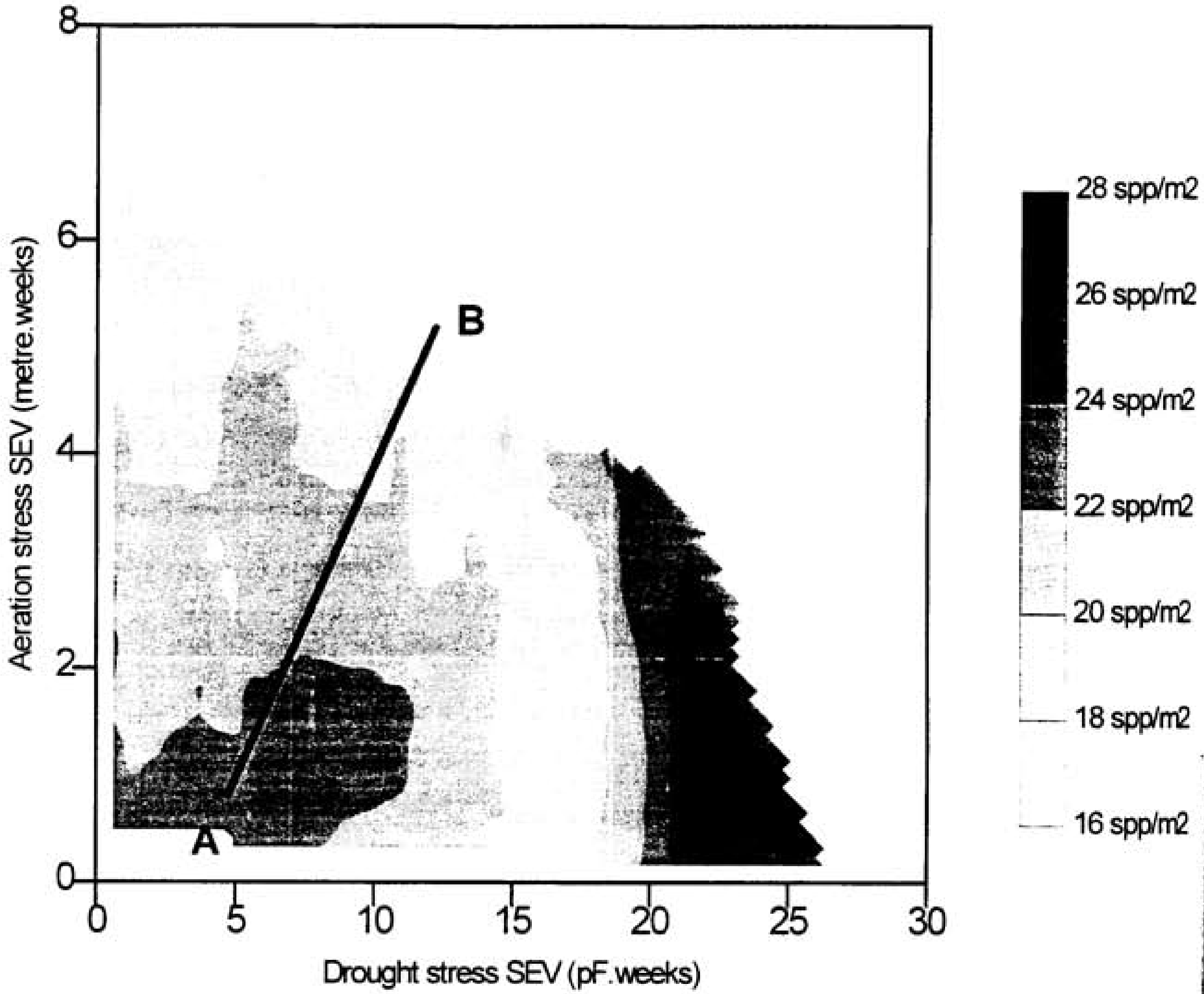


Figure 8.1. Species richness (α-diversity) with respect to water regime across all seven sites. See text for explanation of AB.

8.4 Water Level Management Plans

The Water Level Management Plans initiative (MAFF/WHO/AD/EN/NRA, 1994) has stimulated a great deal of interest in the relationships between water levels, soil water status and vegetation. The current project results will help to inform the debate surrounding these issues and to put plans on a more solid foundation by encouraging the quantification of water regimes which is an essential step if rational management is to be achieved. A major benefit of the current results is that they enable vegetation requirements to be expressed in quantitative terms, which can then be interpreted to allow the necessary engineering or management controls to be specified clearly.

The information, albeit in a draft form, has already been applied to real situations (Hann *et al*., 1996; Ward, 1996; Rebane *et al*., 1997) and has aided in the definition of the target water regime and the recognition of constraints which hinder its achievement. Water-regime-requirement information at a species level can only be fully used if the site manager or statutory conservation body is able to be precise in terms of the species composition of the target vegetation of a site. This level of precision has often been absent at the sites investigated to date. To bridge the current gap, either more time needs to be devoted to defining vegetation objectives or the water-regime information needs to be expressed in more general terms; at a plant community level for example.

9 Research outputs

Published papers and conference presentations emanating from this project are summarised within the following categories;

Articles published during the project;

Gilbert, J.C., Gowing, D.J.G., Spoor, G. and Mountford, J.O. (1996). Quantifying the hydrological requirements of plants as a tool for the water management of wet grassland. In: Problems of environmental development in rural areas. Vol. 10 Ecological aspects of environmental development. Warsaw Agricultural University.

Spoor, G. and Gowing, D.J.G. (1995). Defining conservation requirements for water level management plans. *ADA Gazette*, Autumn 1995, p 40.

Spoor, G. and Gowing, D.J.G. (1996). Reconciling water management needs for agriculture and wetland conservation. Proceedings of 6th Drainage Workshop (Ljubljana). International Committee for Irrigation and Drainage. pp 354-361.

Spoor, G., Gowing, D.J.G. and Gilbert, J.C. (1996). A quantitative approach to water level management planning for complex sites. In: Proceedings of the 31st MAFF Conference for River and Coastal Engineers. Ministry of Agriculture, Fisheries and Food, Flood Defence Division.

Youngs, E.G. (1995). Developments in the physics of infiltration. Soil Science Society of America Journal, 59, 307-313.

Youngs, E.G., Spoor, G. and Goodall, G.R. (1996). Infiltration from surface ponds into soils overlying a very permeable substratum. Journal of Hydrology, 186, 327-334.

Articles accepted for publication and currently in press;

Gowing, D.J.G. And Spoor, G. (1995). The effect of water table depth on the distribution of plant species in lowland wet grassland. At "UK Floodplains Symposium" - Linnean Society, London. October 1995.

Gowing, D.J.G. and Youngs, E.G. (1996). The effect of the hydrology of a Thames flood meadow on its vegetation pattern. At "Floodplain Rivers: hydrological processes and ecological significance” - Birmingham University, June 1996, British Hydrological Society.

Gowing, D.J.G., Spoor, G. and Mountford, J.O. (1994). The influence of minor variations in hydrological regime on the composition of wet-grassland plant communities. At "European Wet Grasslands" - Loughborough University, December, 1994, International Centre of Landscape Ecology.

Spoor G., Gowing, D.J.G., and Mountford, J.O. (1993). Quantification of water-regime requirements of ditch-bank and wet-grassland flora. "Conservation and management of drainage system habitat". Nottingham, September 1993. International Centre of Landscape Ecology.

Articles in preparation;

Gowing, D.J.G. and Mountford J.O. (1996). Spatial variation in long-term water regime allows *Agrostis capillaris* and *A. stolonifera* to co-exist within a wet-grassland sward. For submission to *Journal of Ecology*.

Mountford, J.O., Tallowin, J.R.B., Sparks, T.H., Gowing, D.J.G., Gilbert, J.C., Manchester, S.J., Rose, S.C., Treweek, J.R. and Armstrong, A.C. (1997). Experimental and monitoring studies of the use of raised water-levels for grassland rehabilitation. Submitted to British Grassland Society Conference, September 1997.

Other reports and presentations;

Gowing, D.J.G. (1996). Examination of the potential impacts of alternative management regimes in the Somerset Levels and Moors ESA. Report to Ministry of Agriculture, Fisheries and Food Environmentally Sensitive Areas Division, London.

Spoor, G., Gowing, D.J.G. and Gilbert, J.C. (1996). Hydrological Management for Conservation - A short course for the Environment Agency. Silsoe College, Cranfield University.

10. Future research needs

The results of the project indicate the following six areas as those requiring further investigation and study, in order to maximise the benefits from the research undertaken to date.

10.1 Modelling of remaining sites

As discussed in section 6.2, five of the twelve sites sampled during the project have not contributed to the final analysis of data because fully validated hydrological models could not be constructed within the time-frame of the project. In one case, Strumpshaw Fen, this was because the hydrological system was more complex than it had initially appeared, but in the other four cases, it was due to a lack of useful site observation data caused by exceptionally dry weather conditions which prevailed during the monitoring period. These four sites should be amenable to water-regime analysis once a data set has been compiled which reflects a more typical year in terms of rainfall. The addition of the Cumbrian sites in particular would enhance the data base and also demonstrate the transferability of species-tolerance information between different climatic zones.

10.2 Analysis of critical growth stage

One intention of the current project was to compare the distribution of species over two sites which differed in the seasonality of their water management. Information received prior to the project's start, suggested that Southlake Moor would provide a contrast to the other sites in Somerset as the farmers there operated a derogation to the ESA prescription whereby surface water was removed from the Moor at an earlier date. In practice, having modelled the hydrology of the site in liaison with ADAS, it is apparent that water regime does not in fact differ substantially on a seasonal basis. Therefore a new approach to this issue needs to be devised. The potential method, which currently shows most promise, is the analysis of water regime over different seasons to ascertain which shows the greatest explanatory power. This would enable the period where water tables are most critical to plant competition to be identified.

Ideally, in order to pursue the original methodology, a new site would have to be located, where the water management did impose a different seasonal hydrological regime. Areas of grassland which are managed according to traditional water-meadow practices, which includes summer flooding, would be the ideal sites from which to gather information. Furthermore, they would provide a good overlap between peat-soil and mineral-soil sites in terms of their water regime. Unfortunately, within the time frame and resources of the current project, the inclusion of extra sites was not feasible, but the study of such a site should be set as a future research goal. An active water meadow has been identified within the Avon Valley ESA and preliminary permission regarding access for research purposes has been obtained.

10.3 Dissemination of results

The underlying aim of this project was to demonstrate that the water-regime tolerances of grassland species can be quantified. In order to provide a rigorous argument and sound data, it has been necessary to consider soil water parameters such as SEV and soil water potential, which are not readily comprehensible to those practitioners who are actively managing the water regimes of important conservation sites. The limitation of the research in this respect has been recognised and methods for expressing the research output in a more accessible format are being explored. It is hoped that the requirements of each species in terms of its tolerance to drought, for example, can be expressed as a number of weeks per year for which it can tolerate a water table below a given threshold or a given soil moisture deficit. This type of information would be able to guide practical water management directly and be used in the formulation of ESA prescriptions, which is the main functional objective of the exercise.

10.4 Development of an optimal hydrological regime for conservation of biodiversity

Following the implementation of ESA schemes, a great deal of botanical and hydrological information has been gathered, particularly in Somerset. Much of the necessary data now exist to allow an optimal ditch-management regime to be identified, which in many areas could suit all interests, while in others could be tailored to meet specific objectives. Current research under various biodiversity initiative will allow nature conservation objectives to be defined with greater clarity. There will then be scope for translating these objectives into clearly defined water regimes and for recommending an appropriate means of implementation.

10.5 Predicting rates of change in wet-grassland ecosystems in response to altered hydrological regime

The ability to predict rates of change would allow the future benefits of ESA management to be quantified predictively and give guidance for the most appropriate and cost effective methods of monitoring success. It would require the interpretation of the relationship between water management control and the ecological status of wet grassland with a dynamic perspective. Again much of the field data required for this research is already available and further analysis and updating of what is currently held would give added value to previous MAFF-sponsored research. The most suitable format for this approach would be at a community rather than a species level.

10.6 Use of traditional water meadow management techniques to enhance the ecological interest of wet grassland in ESAs

Investment in water control infrastructure could maximise benefits to both agriculture and conservation interests. ESA schemes broadly attempt to re-establish the water levels which prevailed prior to agricultural intensification. Problems arise, however, where the traditional infrastructure for water control has been lost. Recent technological advances may allow for the necessary control mechanisms to be reinstated at relatively low cost. A pilot study to demonstrate this is advocated. In addition, a combined hydrological and botanical study of one of the very few remaining traditional water meadows would provide the necessary baseline data to guide the effective restoration or rehabilitation of former sites.

11 References

Broad, H.J. and Hough, M.N. (1993). The growing and grazing season in the United Kingdom. *Grass and Forage Science*, **48**, 26-37.

Campbell, R.B. and Richards, L.A. (1950). Some moisture and salinity relationships in peat soils. *Agronomy Journal*, **42**, 582-585.

Childs, E.C., and Youngs, E.G. 1961. A study of some three-dimensional field-drainage problems. *Soil Science*, **92**, 15-24.

Dougherty, E., Leeds-Harrison, P.B., Youngs, E.G., and Chamen, W.C.T. 1995. Hydrographs from mole-drained lands under different tillage treatments. *Soil Use and Management*, **11**, 177-182.

Dumortier, M. (1991). Below ground dynamics in a wet grassland ecosystem. In: *Plant root growth: an ecological perspective*. ed. D Atkinson. Blackwell, Oxford.

Ellenberg, H. (1952). Physiologisches und ökologisches verhalten derselben Pflanzenarten. *Berliner Deutsch Botanische Gestern*, **65**, 350-361.

Ellenberg, H. (1963). *Vegetation Mittleuropas mit den Alpen*. Verlag Eugen Ulmer, Stuttgart.

Ellenberg, H. (1988). *Vegetation Ecology of Central Europe*. 4th edition. Cambridge University Press. 731pp.

Gardner, W.R. 1958. Some steady-state solutions of the unsaturated moisture flow equation with application to evaporation from a water table. *Soil Science*, **85**, 228-232.

Gardner, W.R. and Fireman, M. (1958). Laboratory studies of evapotranspiration from soil columns in the presence of a water table. *Soil Science*, **85**, 244-249.

Gowing, D.J.G. (1996). *Examination of the potential impacts of alternative management regimes in the Somerset Levels and Moors ESA.* Report to Ministry of Agriculture, Fisheries and Food Environmentally Sensitive Areas Division, London.

Gowing, D.J.G. and Spoor, G. (1997). The effect of water table depth on the distribution of plant species in lowland wet grassland. In: *UK Floodplains* Linnean Society/RSPB, London.

Gowing, D.J.G. and Youngs, E.G. (1997). The effect of the hydrology of a Thames flood meadow on its vegetation pattern. In*: Floodplain Rivers: hydrological processes and ecological significance*. British Hydrological Society.

Gowing, D.J.G., Spoor, G., Mountford, J.O. and Youngs, E.G. (1994). *The Water-Regime Requirements of Lowland Wet Grassland Plants - a model to identify species at risk from hydrological changes.* Report to MAFF Flood and Coastal Defence Division. Silsoe College.

Grime, J.P., Hodgson, J.G. and Hunt, R. (1988). *Comparative Plant Physiology: a functional approach to common British species.* Unwin Hyman, London. 742pp.

Grootjans, A.P. and Ten Klooster, W.P. (1980). Changes of ground water regime in wet meadows. *Acta Botanica Neerlandica*, **29**, 541-554.

Hann, M.J., Gilbert, J.C., Spoor, G., Gowing, D.J.G. and Ward, D. (1996). *Easton Valley, Part of Benacre to Easton Bavents SSSI: Water Level Management Plan and Enhancement Proposals.* Report to the Environment Agency, Peterborough.

Henson, I.E., Jenson, C.R. and Turner, N.C. (1989). Leaf gas exchange and water relations of lupins and wheat. I. Shoot responses to soil water deficits. *Australian Journal of Plant Physiology*, **16**, 401-413.

Keckler, D. (1995). SURFER for Windows, version 6. Golden Software, Colorado.

Laan, D. van der (1979). Spatial and temporal variation in the vegetation of dune slacks in relation to the ground water regime. *Vegetatio*, **39**, 43-51.

Le Duc, M.G., Hill, M.O. and Sparks, T.H. (1992). A method for predicting the probability of species occurrence using data from systematic surveys. *Watsonia*, **19**, 97-105.

MAFF/WO/ADA/EN/NRA (1994). *Water level management plans: a procedural guide for operating authorities*. Ministry for Agriculture, Fisheries and Food, London.

Mountford, J.O., Lakhani, K.H. and Kirkham, F.W. (1993). Experimental assessment of the effects of nitrogen addition under hay-cutting and aftermath grazing on the vegetation of meadows on a Somerset peat moor. *Journal of Applied Ecology*, **30**, 321-332.

Noest, V. (1994). A hydrology-vegetation interaction model for predicting occurrence of plant species in dune slacks. *Journal of Environmental Management*, **40**, 119-128.

Payne, K.R. (1987). *Management plan for North Meadow National Nature Reserve*. Nature Conservancy Council, Newbury.

Rebane, M. and Gowing, D.J.G. (1997). Draft Water Level Management Plans for six nature conservation sites in the Central Area of the Environment Agency's Anglian Region. Ecoscope, Cambridge.

Rodwell, J.S. (1992 *et seq.*) *British Plant Communities.* Vols. 2-4. Cambridge University Press.

Sieben, W.H. (1965). Het verband tussen outwatering en obrengst bij de jonge zavelgranden in de Noordoostpolder. *Van Zee tot Land.,*. **40**, 1-117.

Smith, L.P. and Trafford, B.D. (1976). *Climate and Drainage*. MAFF Technical Bulletin No. **34**. HMSO, London.

Spoor, G., Gowing, D.J.G. and Gilbert, J.C. (1996a). A quantitative approach to water level management planning for complex sites. In*: Proceedings of the 31st MAFF Conference for River and Coastal Engineers*. Ministry of Agriculture, Fisheries and Food, Flood Defence Division.

Spoor, G., Youngs, E.G., Gowing, D.J.G. and Gilbert, J.C. (1996b). A draft critique of the water management prescriptions in the Somerset Levels and Moors ESA. In: Water-regime requirements of the native flora - Interim report. Silsoe College, Cranfield University.

Stace, C.A. (1991). *New flora of the British Isles*. Cambridge University Press.

Tansley, A.G. (1939). *The British Islands and their vegetation*. Cambridge University Press.

Trexler, J.C. and Travis, J. (1993). Non-traditional regression analyses. *Ecology*, **74**, 1629-1637.

Walker, L.M. (1995). *Water table management in wildlife habitats*. PhD thesis. Cranfield University.

Ward, D. (1996). *Water Level Management Plan for Cricklade North Meadow NNR*. Andrews Ward Associates / Environment Agency (Thames Region).

Wesseling, J. and van Wijk, W.R. (1957). Soil physical conditions in relation to drain depth. In *Drainage of Agricultural Lands*, ed. J.N. Luthin. American Society for Agronomy, Madison.

Wheeler, B.D. and Shaw, S. C. (1995). Plants as hydrologists? An assessment of the value of plants as indicators of water conditions in fens. In: *Hydrology and hydrochemistry of British Wetlands*. eds. JMR Hughes and AL Heathwaite. Wiley and Sons, Chichester.

Whittaker, R.H. (1975). *Communities and ecosystems*. Macmillan.

Youngs, E.G. 1980. The analysis of groundwater seepage in heterogeneous aquifers. *Hydrological Sciences Bulletin*, **25**, 155-165.

Youngs, E.G. 1985. A simple drainage equation for predicting water-table drawdowns. *Journal of Agricultural Engineering Research*, **31**, 321-328.

Youngs, E.G. 1991. A note on the power-law land-drainage equation for deep soils. *Journal of Agricultural Engineering Research*, **49**, 161-163.

Youngs, E.G. 1992. Patterns of steady groundwater movement in bounded unconfined aquifers. *Journal of Hydrology*, **131**, 239-253.109.

Youngs, E.G. (1994). Seepage to ditches from a ponded surface. *Journal of Hydrology*, **161**, 145-154.

Youngs, E.G., Chapman, J.M., Leeds-Harrison, P.B., and Spoor, G. 1991. The application of a soil physics model to the management of soil-water conditions in wildlife habitats. In: *Hydrological Basis of Ecologically Sound management of Soil and Groundwater* (Proceedings of the Vienna Symposium), IAHS Publication no. 202, 91-100.

Youngs, E.G., Leeds-Harrison, P.B. and Chapman, J.M. (1989). Modelling water-table movement in flat low-lying lands. *Hydrological Processes*, **3**, 301-315.

Acknowledgements

We are indebted to the following landowners for permission to survey sites on their land; Mr B Chanin, Mr PB Hart, Mr JC Hartley, Mr W Marrs, Mr K Rowand, Nuclear Electric, the National Trust, English Nature and the Royal Society for the Protection of Birds, and to Phil Taylor of the National Parks Authority and Roy Lamborn for locating and negotiating access to some of these. We are grateful to Mike Prosser and Hilary Wallace of Ecological Surveys, Bangor, for their efficiency and expertise in conducting botanical surveys and processing the data, to Owen Mountford and his colleagues at ITE Monkswood for access to their data records for Tadham Moor, and to Suzanne Boon, Tim Sparks (ITE) and Peter Higginbottom (Silsoe) for their aid in data processing and analysis.

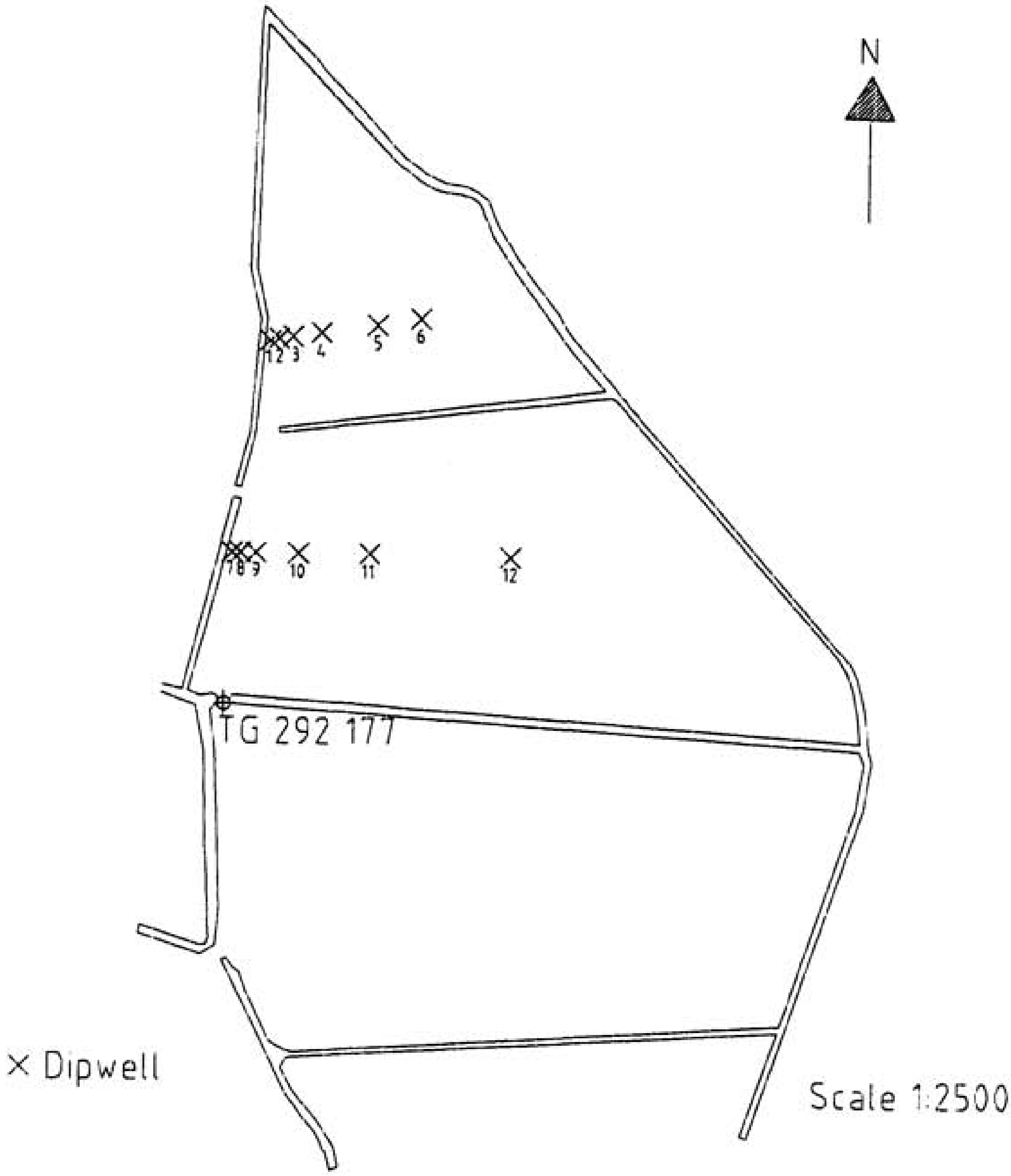
Our particular thanks go to Pete Barron, Dominic Ash, John Leece, David Rowand, Brad Robson, Mike Blackburn, Brian Chanin, Billy Marrs, Albert Knott, Julian Jones, Nicky Hobern and Terry Wells for the regular collection of dipwell data on sites which they either own or manage and to Steve Rose at ADAS for co-ordinating this work at other sites. We also thank Ian Sturdy, Olivia Mellors, Kathy Glenny, Mark Huband, Marie Bennet and Stuart Moody of the National Rivers Authority and Paul Harker of the Meteorological Office for supplying hydrological data. We are grateful to John Killick, Terry Wells, Patty Phillips, Mike Hann and Jean McCluskey for their assistance in the field.

We are also particularly indebted to David Hicks of Rycotewood College, Thame, for his assistance and expertise in using “Total Station” surveying techniques at several of our experimental sites and to Peter Leeds-Harrison for comments on hydrological models.

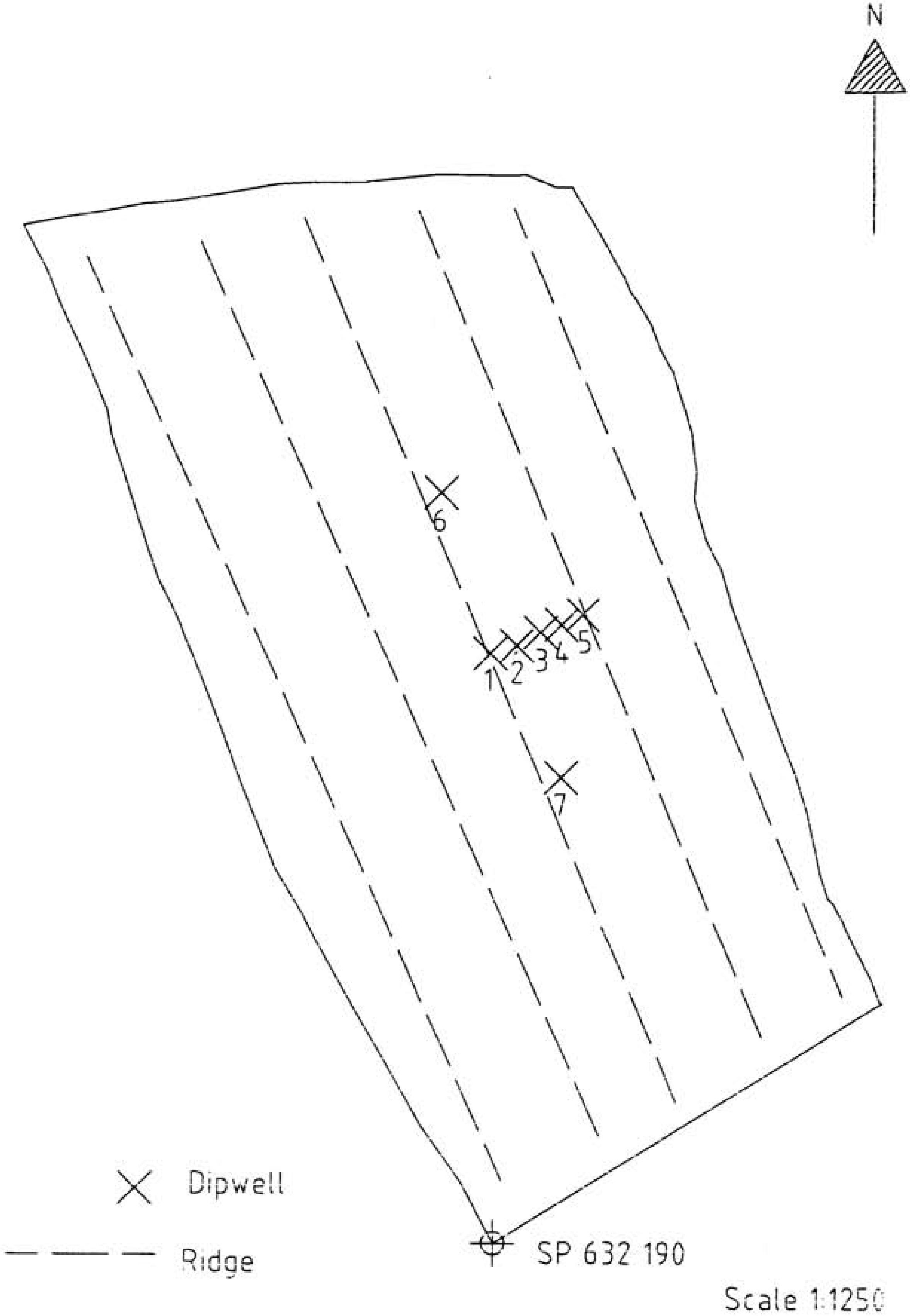
Appendix A

Maps and dipwell validation plots

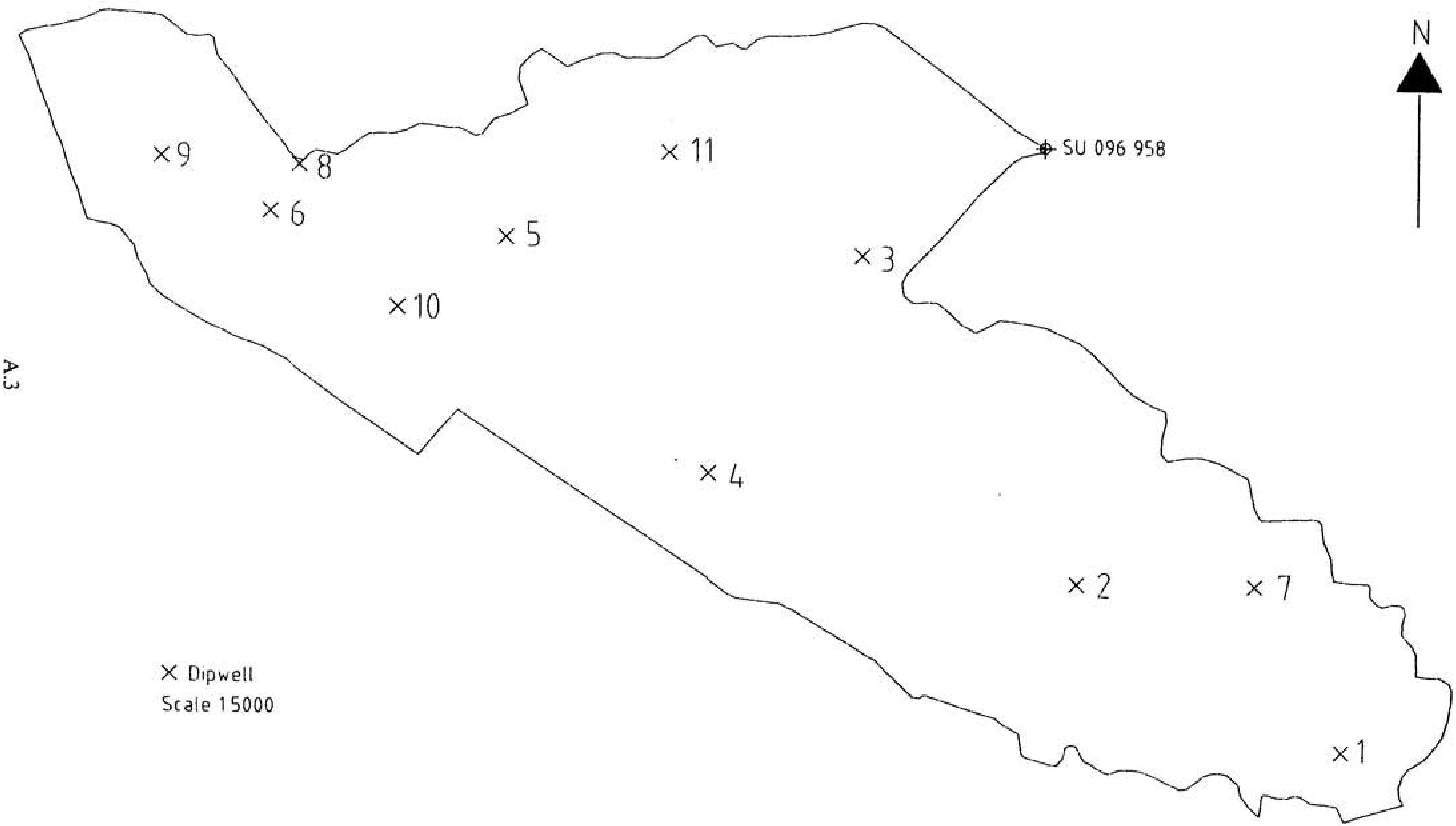
Belaugh Old Farm Dipwell Locations



Blackthorn Meadow IV Dipwell Locations

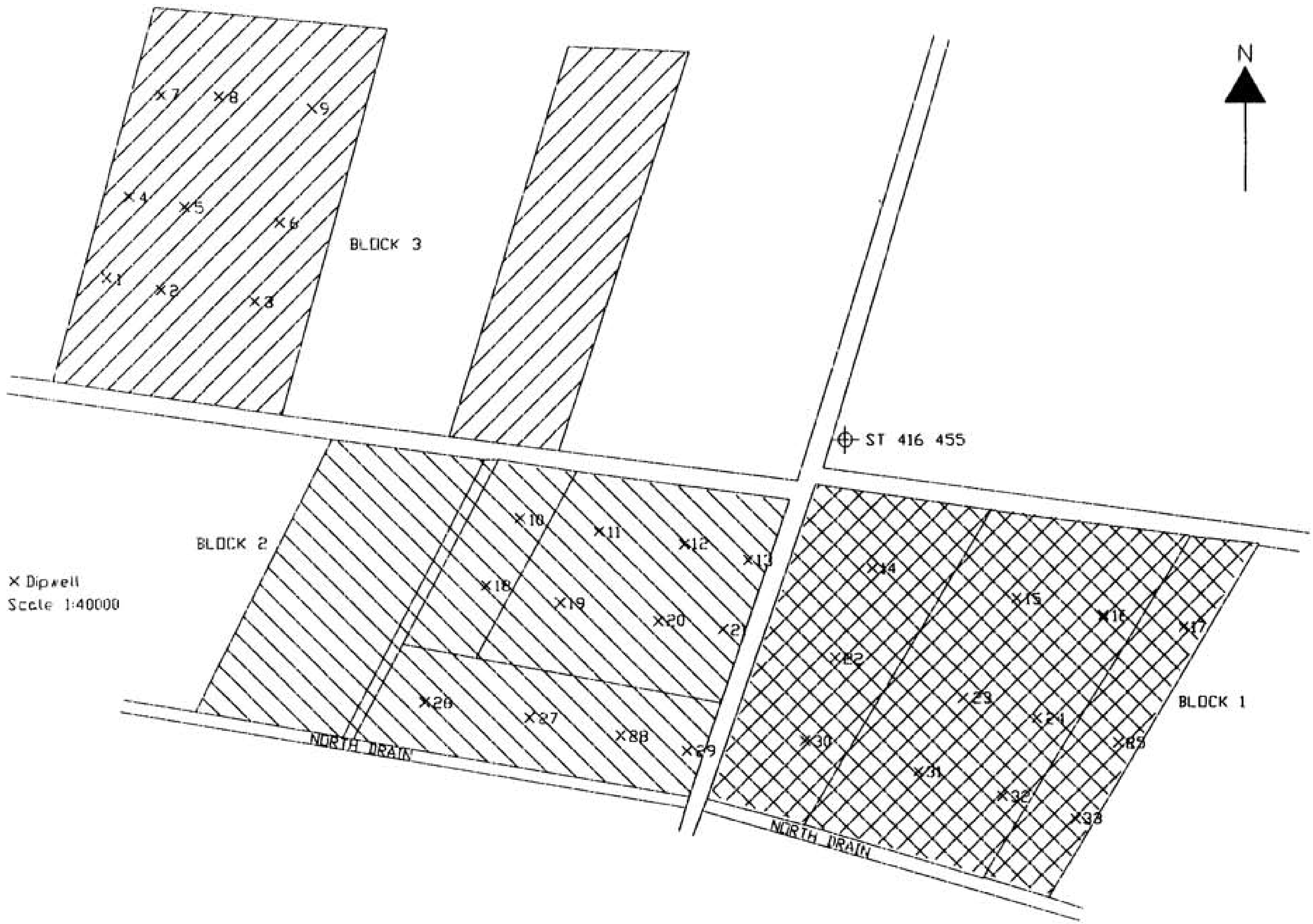


Cricklade North Meadow Dipwell Locations

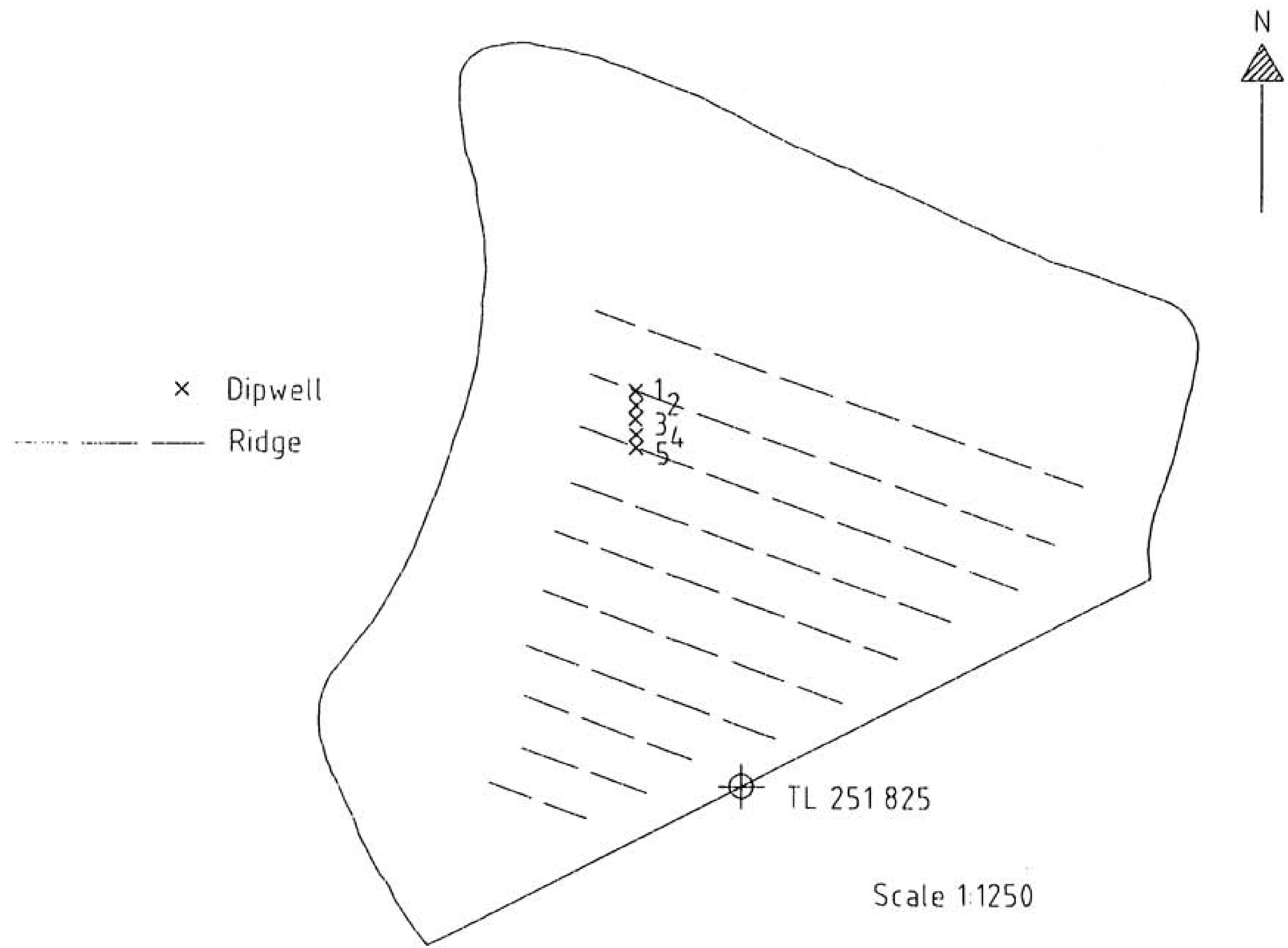


Southlake Moor Dipwell Locations

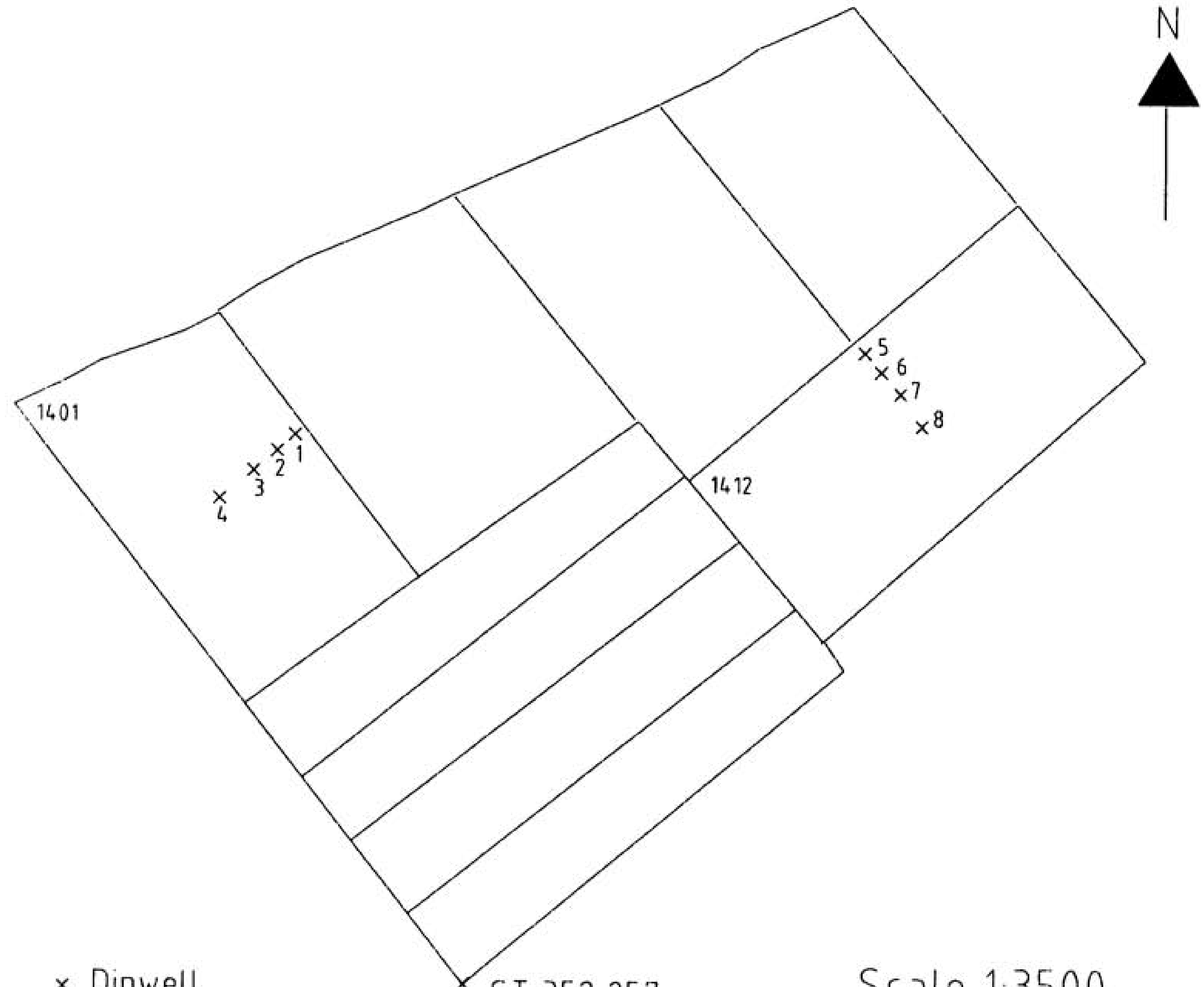
Taaham Moor Dipwell Locations



Upwood Meadow Dipwell Locations



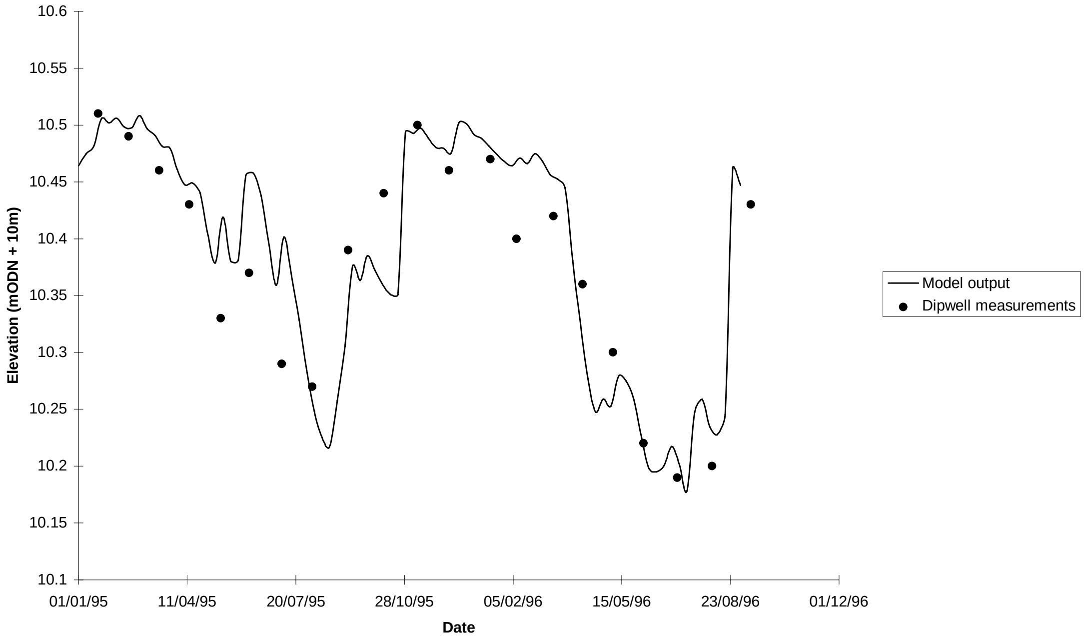
West Sedgemoor Dipwell Locations



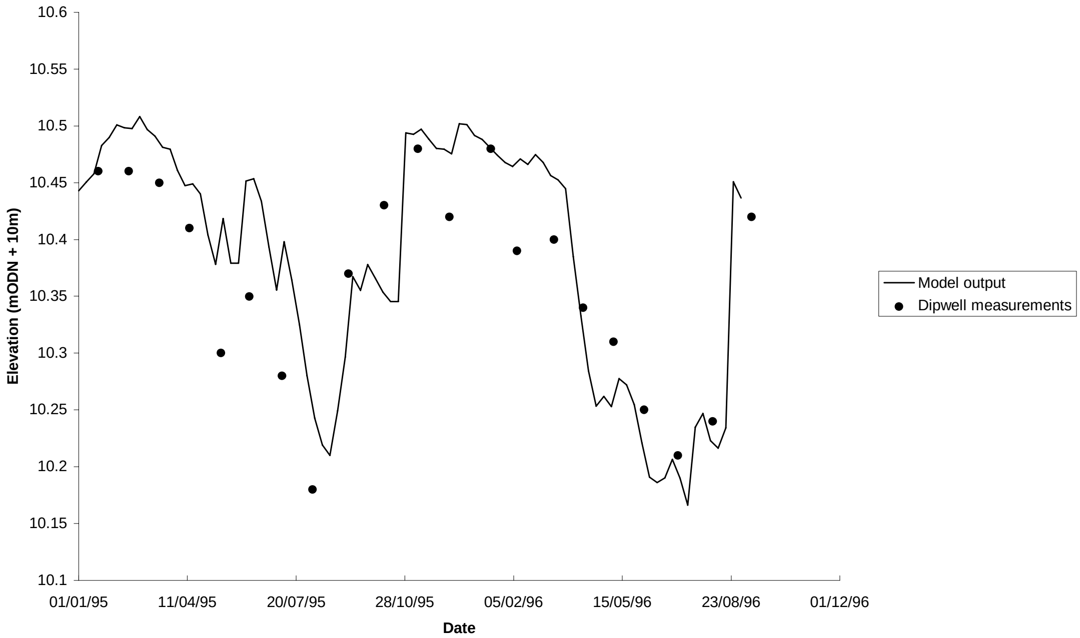
× Dipwell

Scale 1:3500

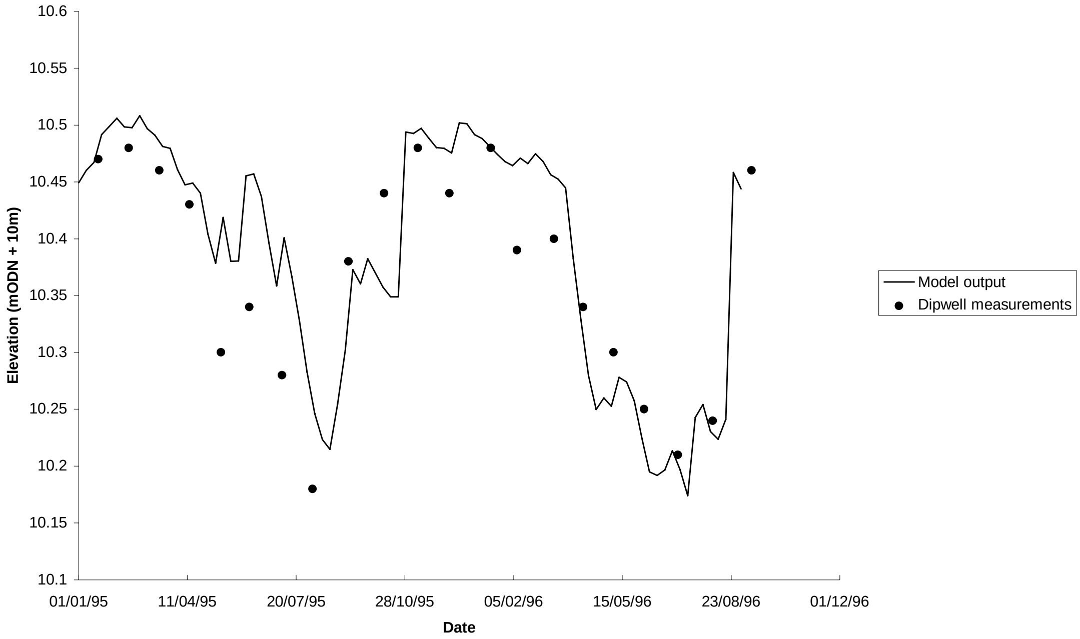
Belaugh Old Farm dipwell 4



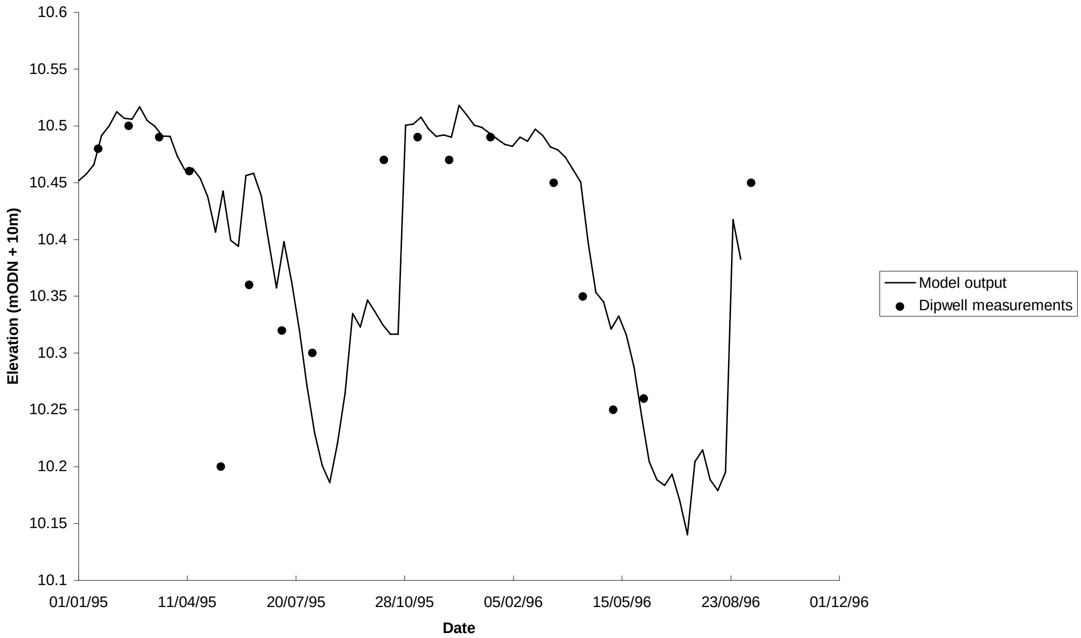
Belaugh Old Farm dipwell 5



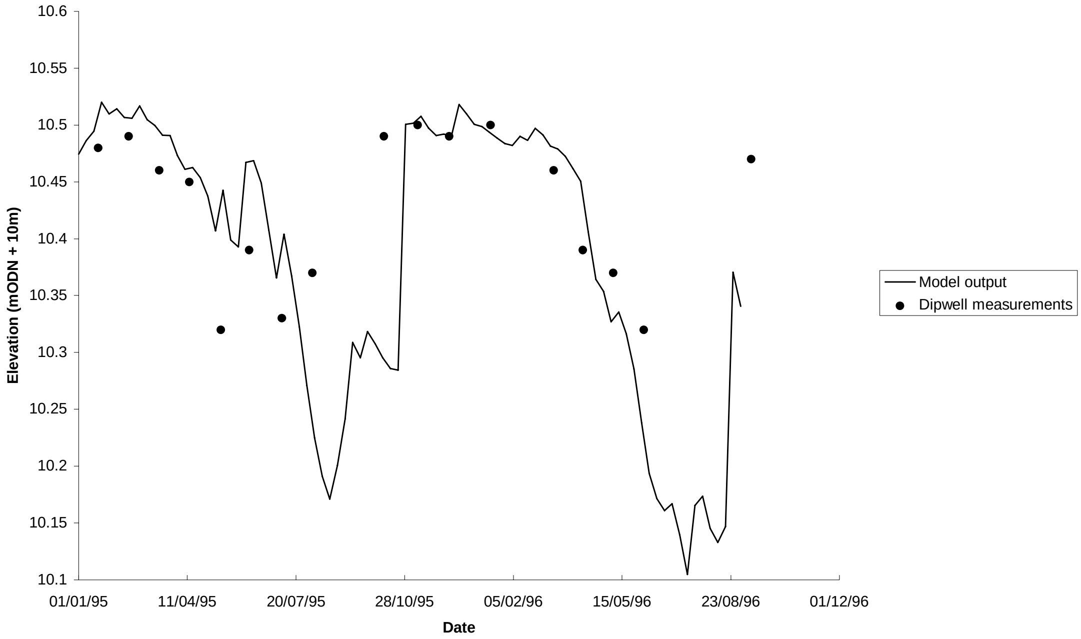
Belaugh Old Farm dipwell 6



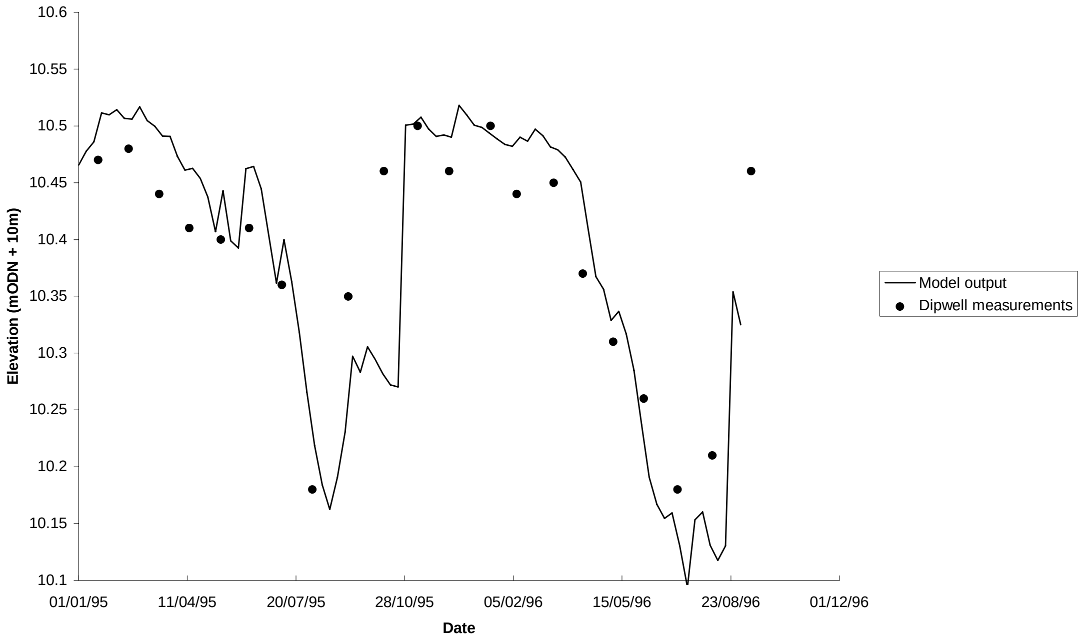
Belaugh Old Farm dipwell 10



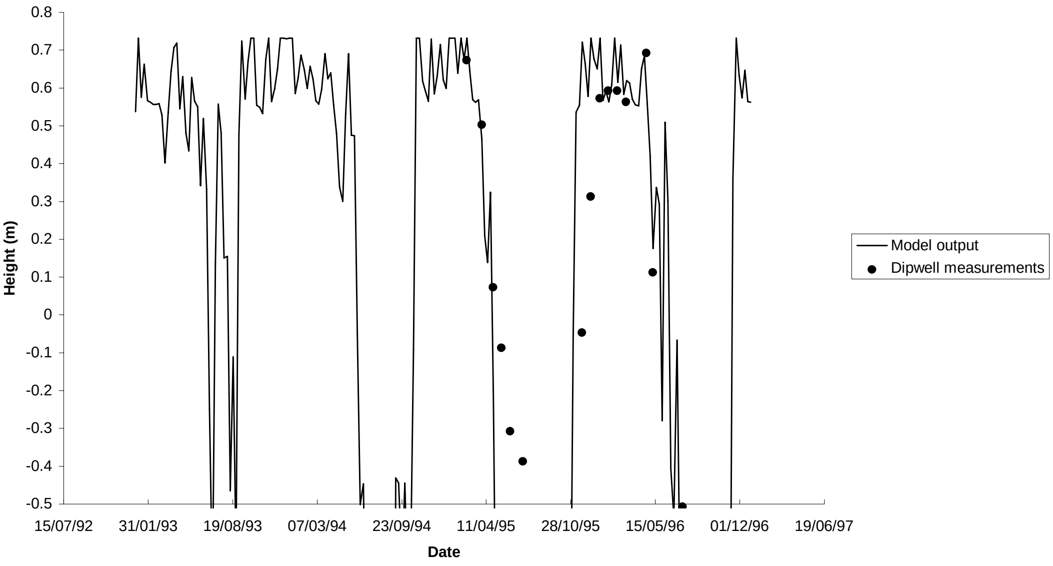
Belaugh Old Farm dipwell 11



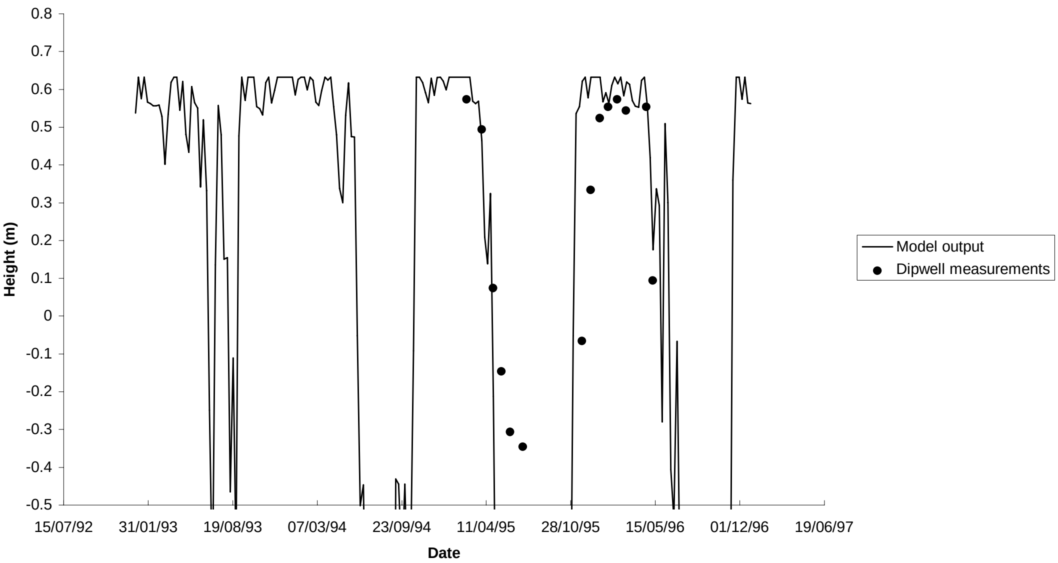
Belaugh Old Farm dipwell 12



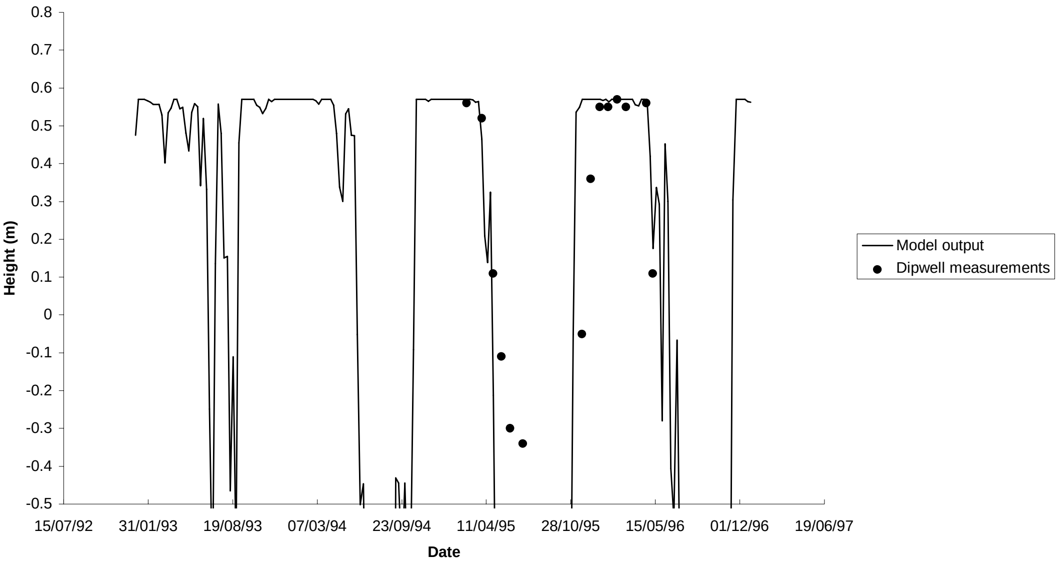
Blackthorn Meadow IV dipwell 1



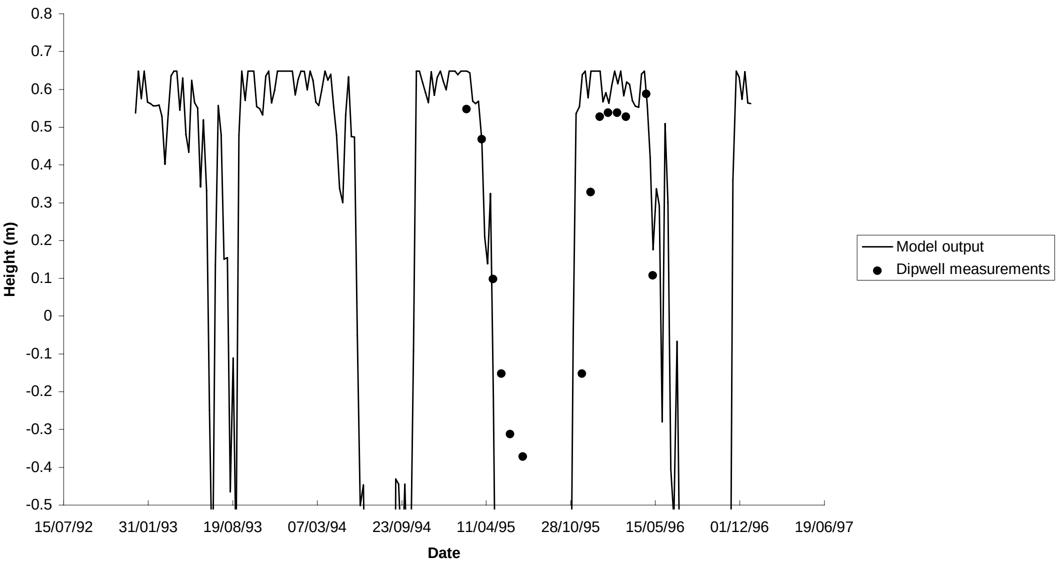
Blackthorn Meadow IV dipwell 2



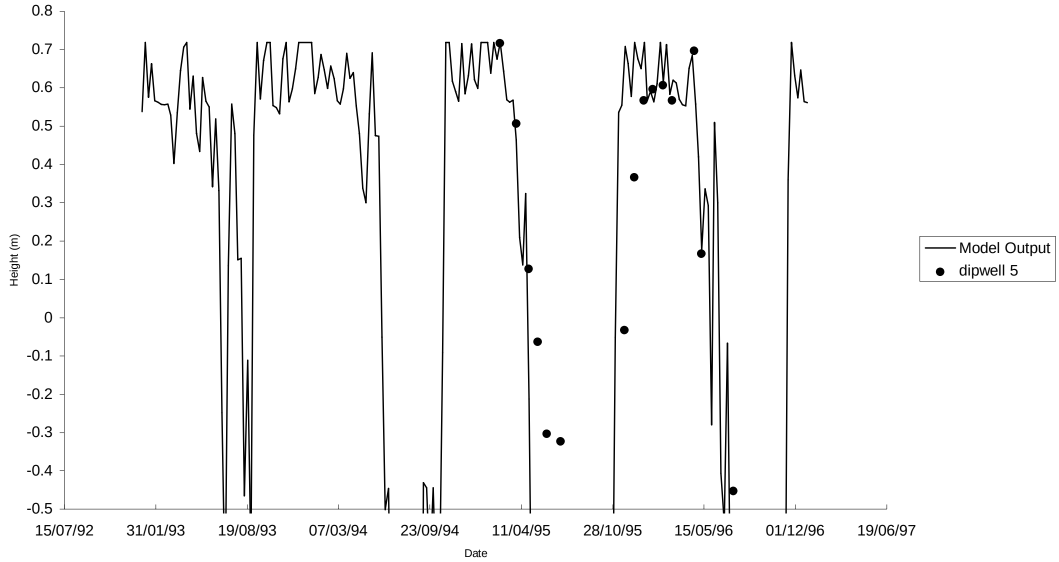
Blackthorn Meadow IV dipwell 3



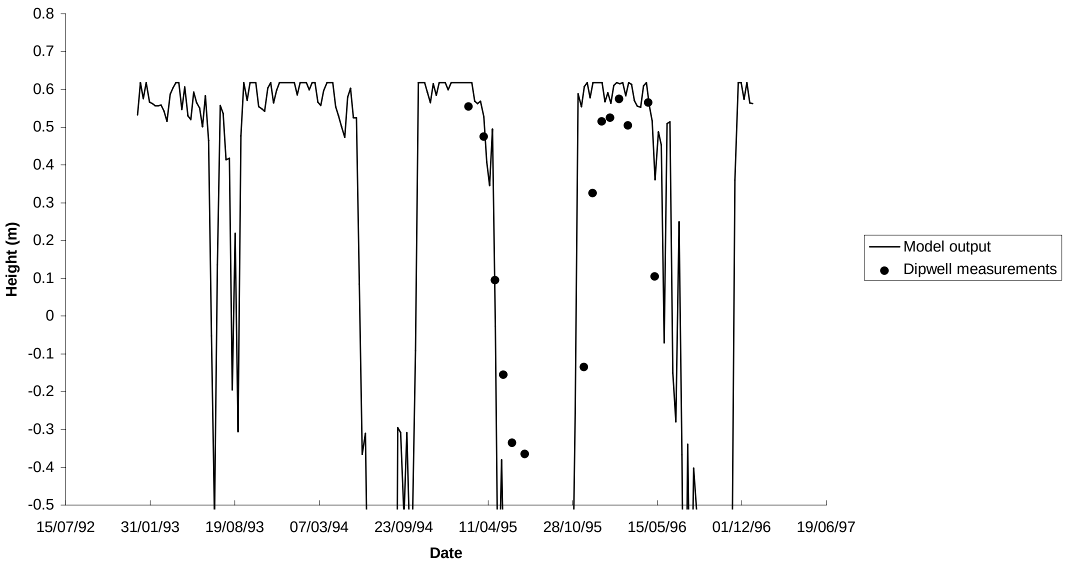
Blackthorn Meadow IV dipwell 4



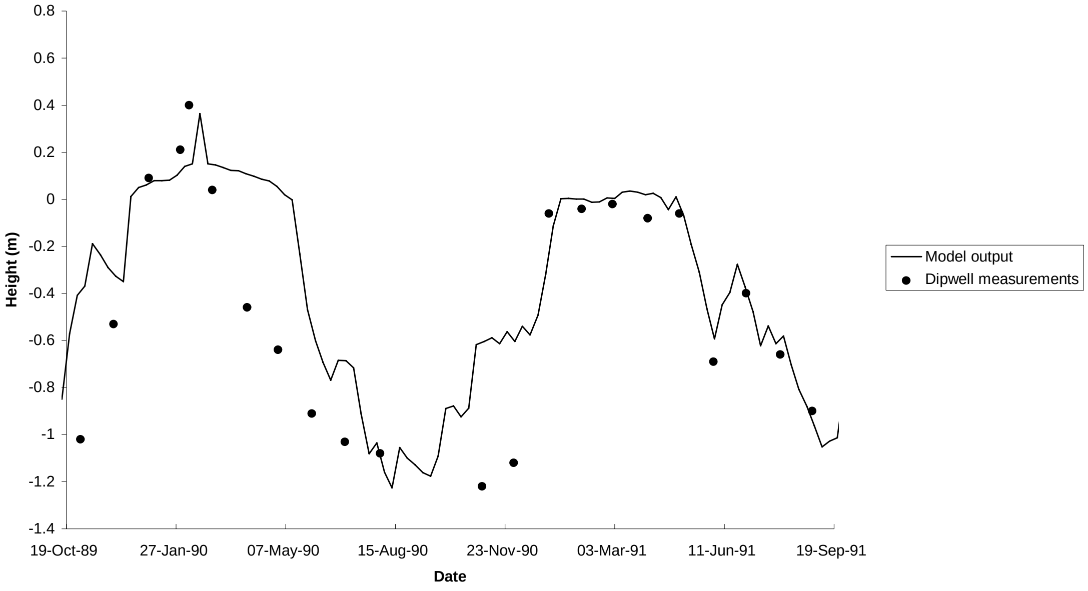
Blackthorn Meadow IV dipwell 5



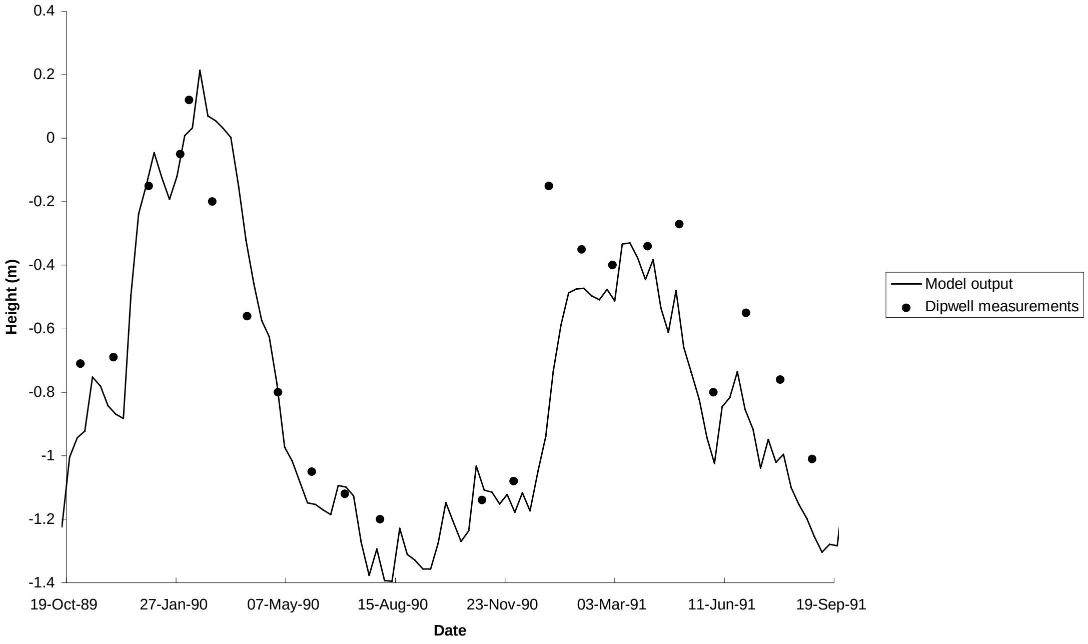
Blackthorn Meadow IV dipwell 6



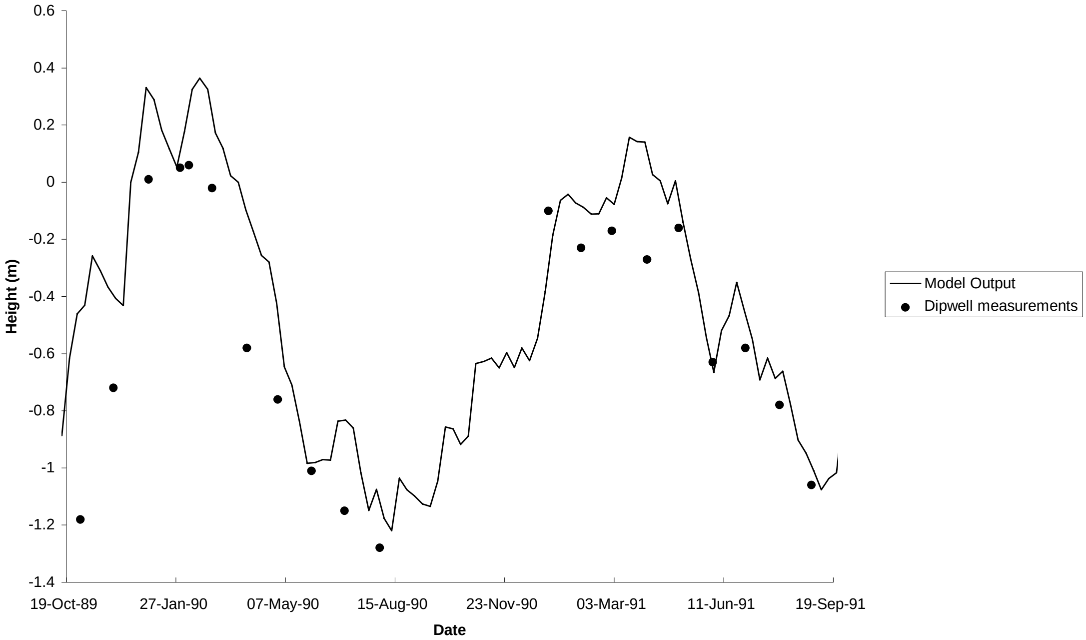
Cricklade North Meadow dipwell 2



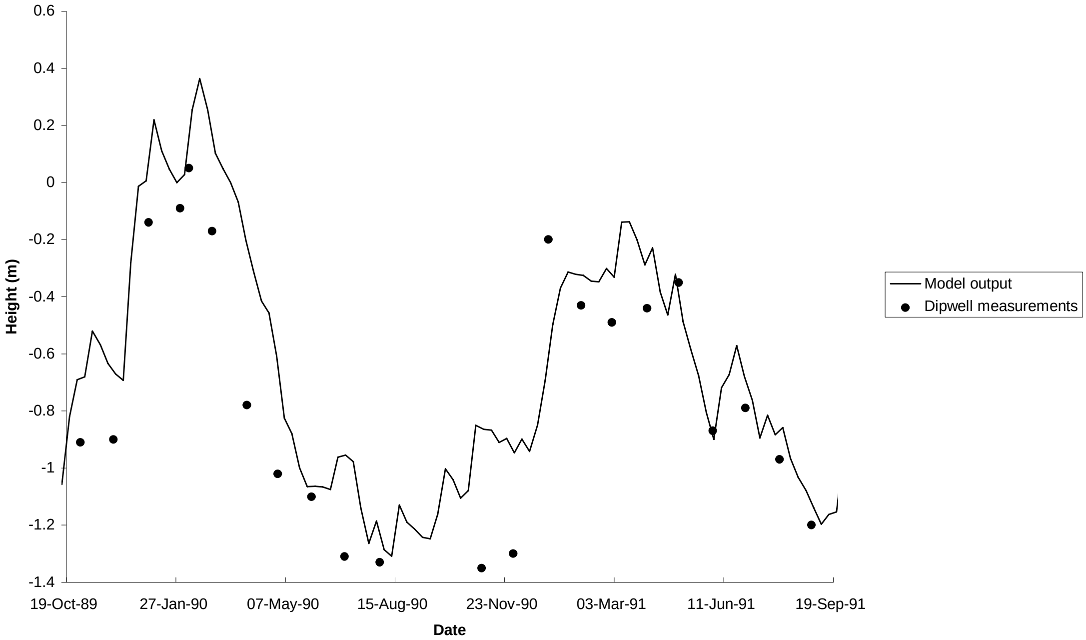
Cricklade North Meadow dipwell 3



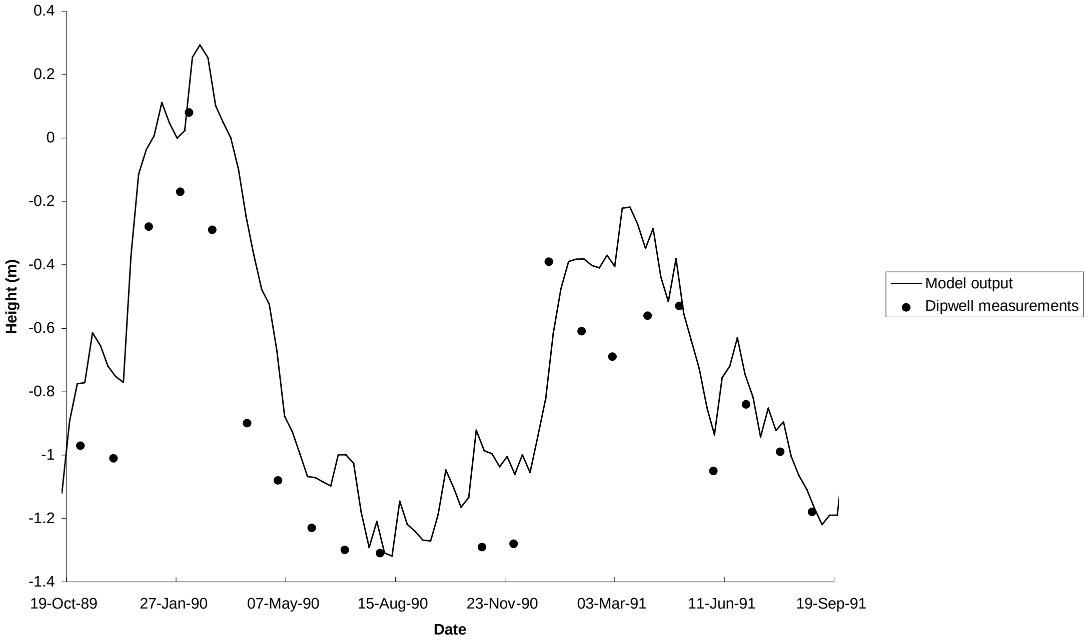
Cricklade North Meadow dipwell 4



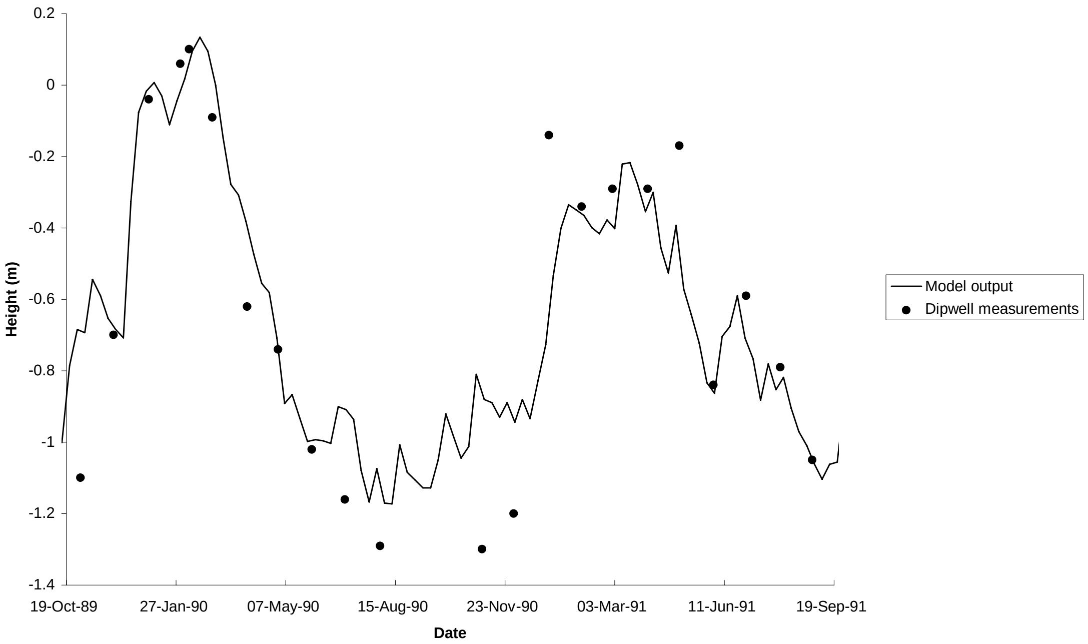
Cricklade North Meadow dipwell 5



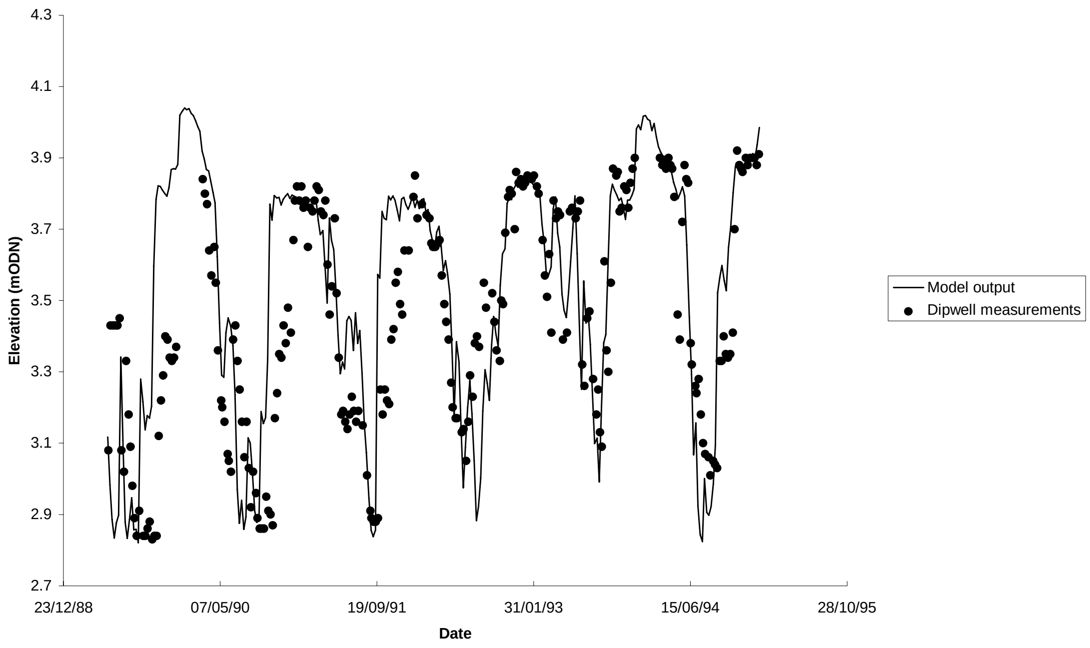
Cricklade North Meadow dipwell 6



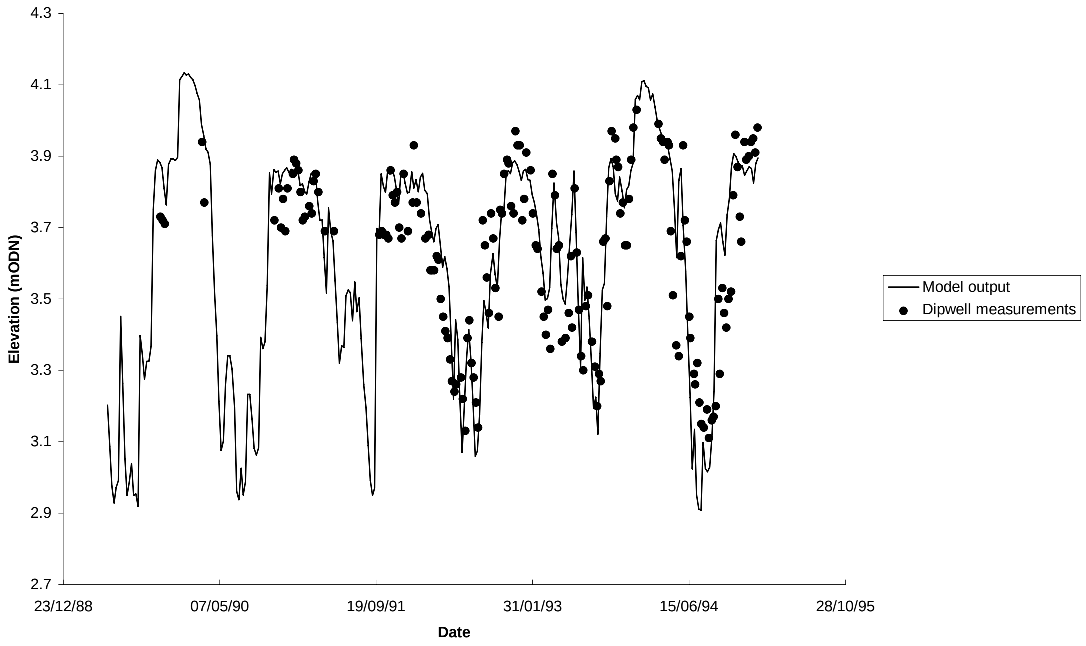
Cricklade North Meadow dipwell 7



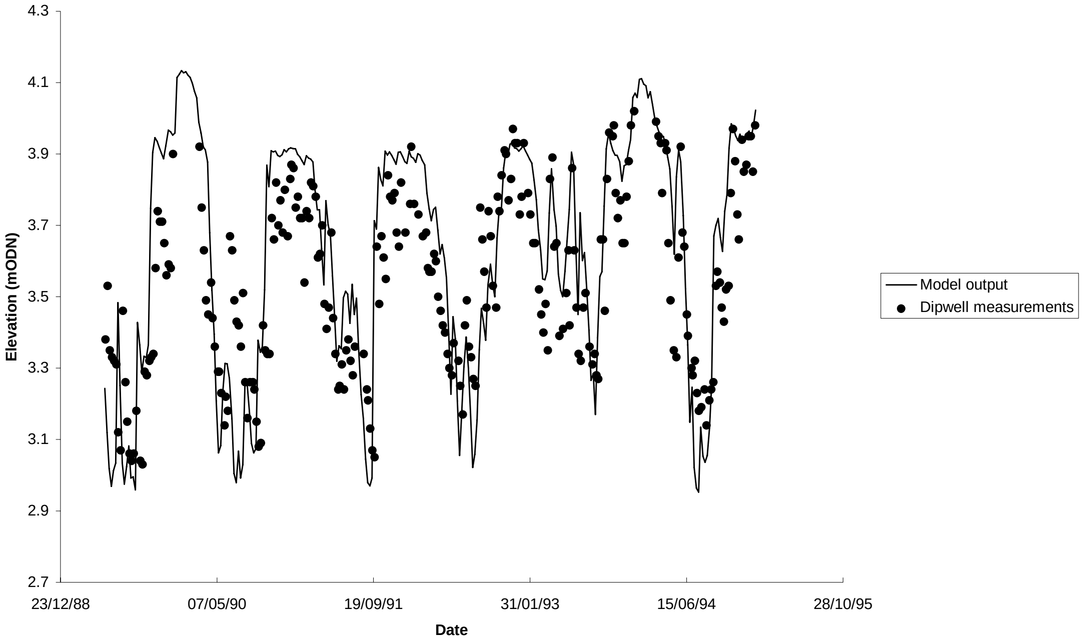
Southlake Moor dipwell 15



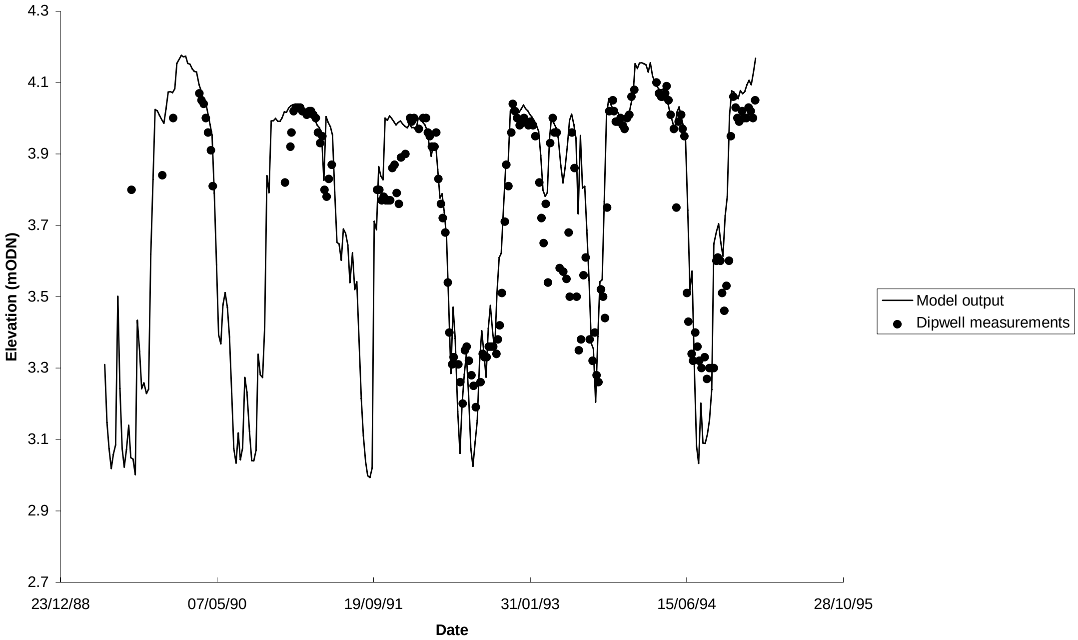
Southlake Moor dipwell 34



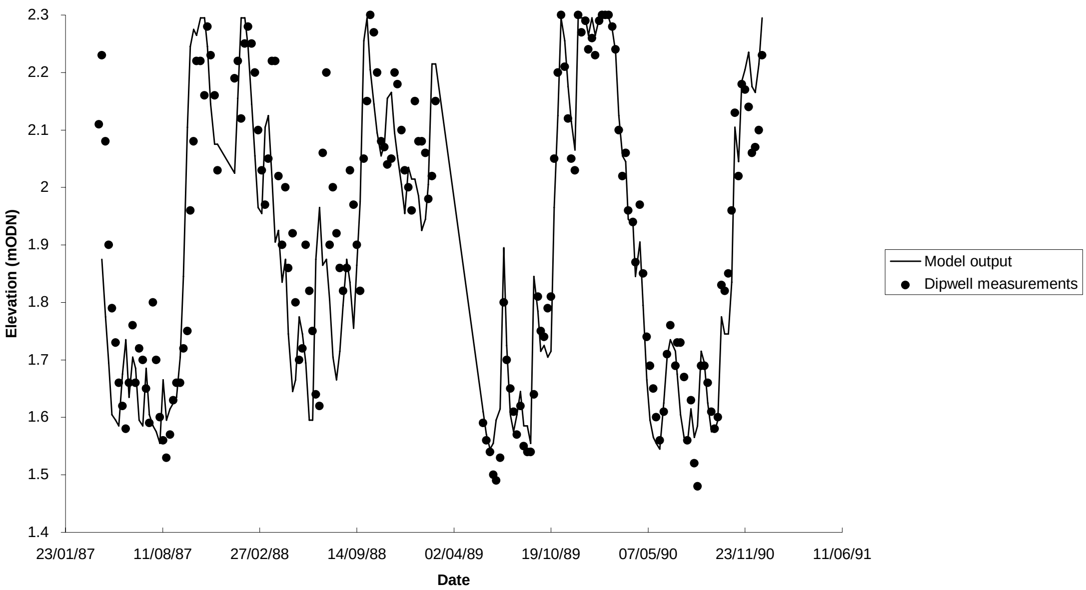
Southlake Moor dipwell 35



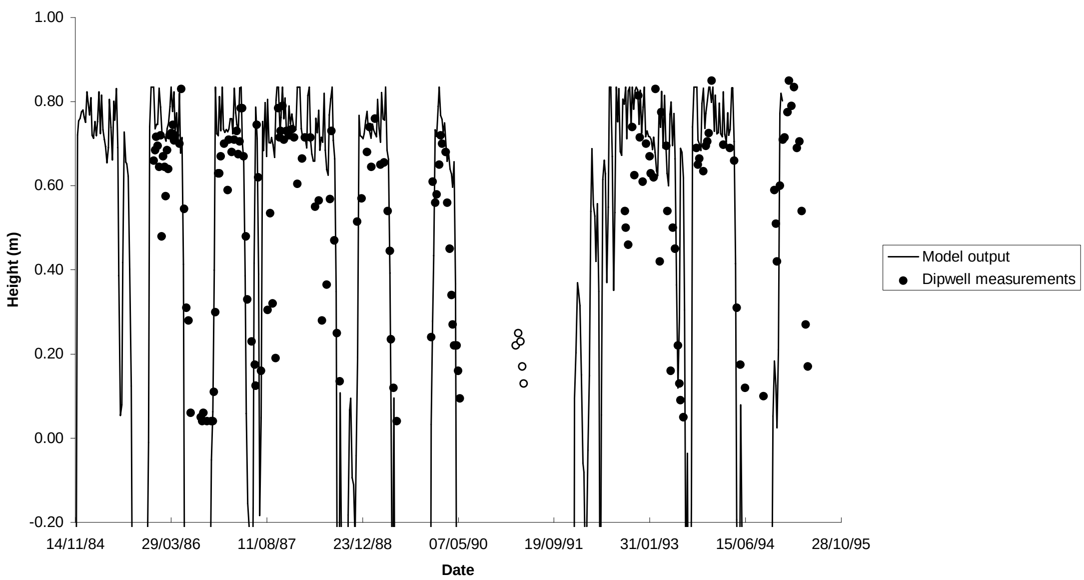
Southlake Moor dipwell 54



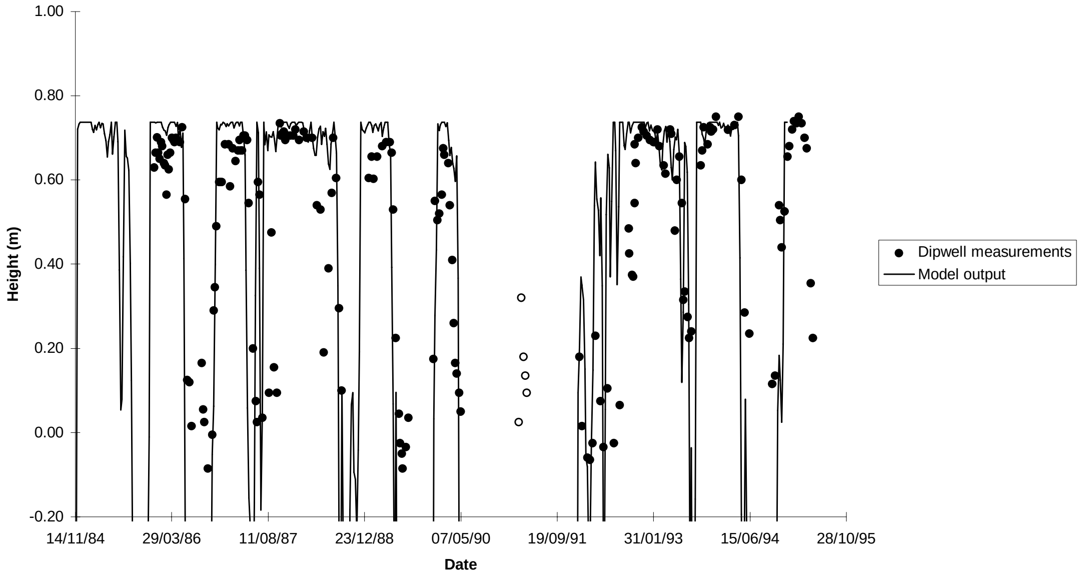
Tadham Moor dipwell 15



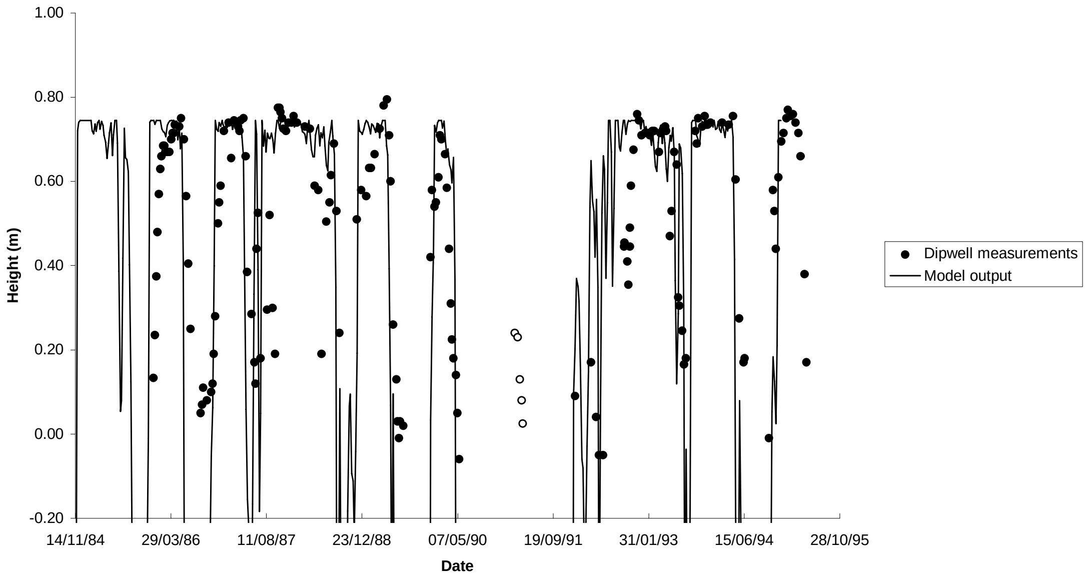
Upwood Meadows dipwell 1



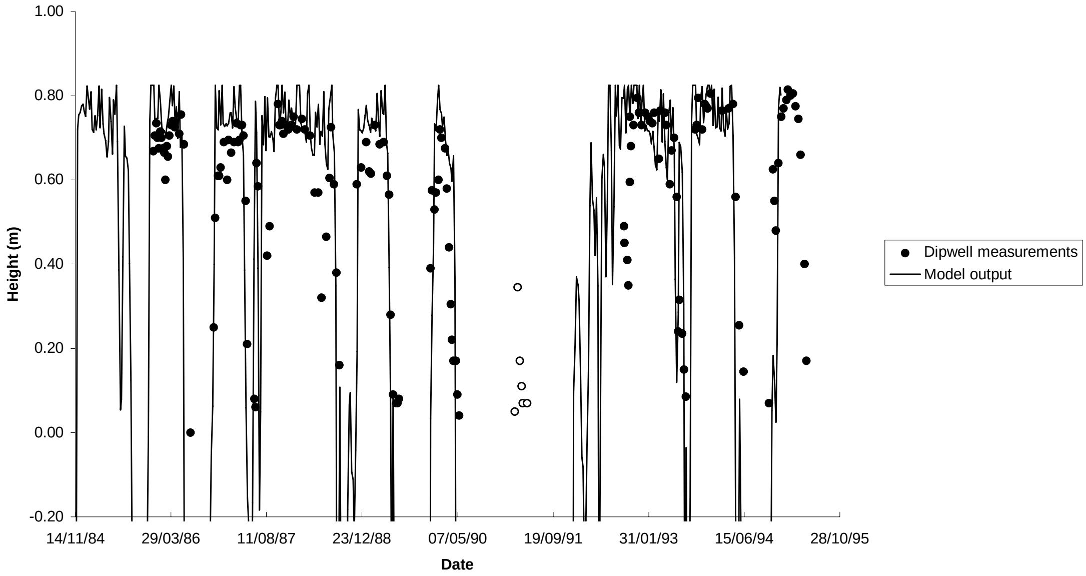
Upwood Meadows dipwell 2



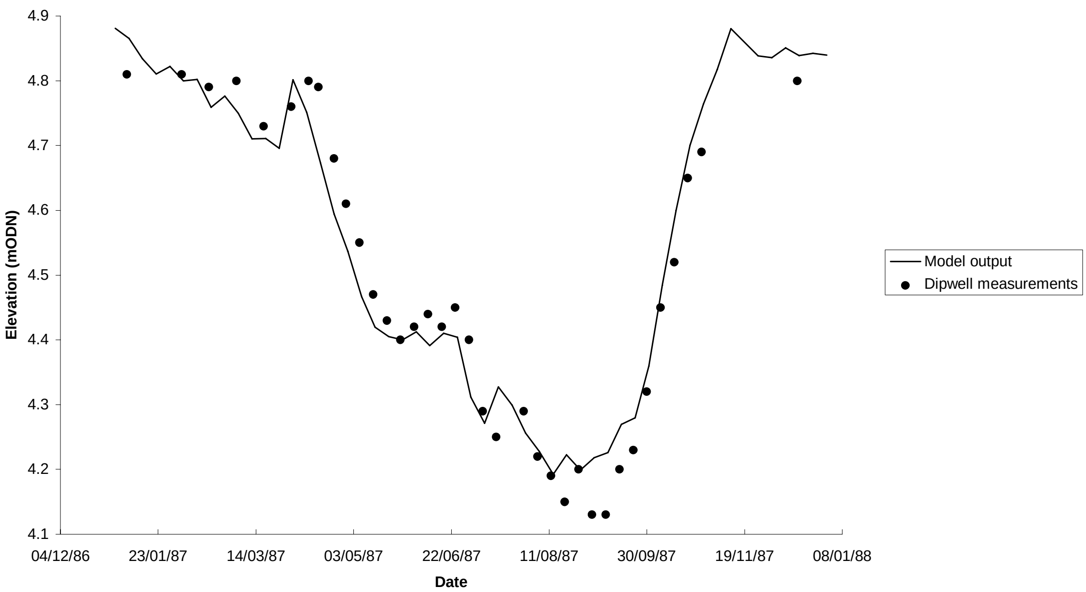
Upwood Meadows dipwell 4



Upwood Meadows dipwell 5



West Sedgemoor dipwell 1



Appendix B. Listing of all species recorded. The number of times a species occurred at each of the modelled sites and the total number of records for those sites are given.

<u>Site Coding</u>

BE	Belaugh Old Farm, Wroxham, Norfolk
BT	Blackthorn (Meadow IV), Oxfordshire
CR	Cricklade North Meadow NNR, Wiltshire
SL	Southlake Moor SSSI, Burrowbridge, Somerset
TA	Tadham Moor SSSI, Wedmore, Somerset
UP	Upwood Meadows NNR, Cambridgeshire
WS	West Sedgemoor SSSI, Somerset

Species	**BE**	**BT**	**CR**	**SL**	**TA**	**UP**	**WS**	**Total**
Quadrats recorded	***75***	***199***	***770***	***175***	***952***	***162***	***60***	***2393***
Achillea millefolium	0	36	5	0	20	57	0	**118**
Achillea ptarmica	0	1	0	0	0	1	0	**2**
Agrimonia eupatoria	0	0	0	0	0	4	0	**4**
Agrostis canina sens.lat.	0	0	37	42	279	2	57	**417**
Agrostis capillaris	0	72	204	134	608	103	0	**1121**
Agrostis stolonifera	54	105	241	155	437	58	22	**1072**
Ajuga reptans	0	0	1	0	32	0	0	**33**
Allium vineale	0	0	1	0	0	0	0	**1**
Alnus glutinosa	2	0	0	0	0	0	0	**2**
Alopecurus geniculatus	0	7	29	61	93	2	1	**193**
Alopecurus pratensis	1	197	435	151	226	105	0	**1115**
Angelica sylvestris	0	1	0	0	7	0	0	**8**
Anthoxanthum odoratum	0	129	516	161	873	79	59	**1817**
Anthriscus sylvestris	0	0	3	0	0	0	0	**3**
Arrhenatherum elatius	1	3	242	1	41	37	0	**325**
Avenula pubescens	0	5	17	0	0	61	0	**83**
Bellis perennis	0	0	123	40	69	17	0	**249**
Brachythecium rutabulum	23	49	211	78	194	71	0	**626**
Briza media	0	5	177	0	27	29	0	**238**
Bromopsis erecta	0	0	1	0	0	0	0	**1**
Bromus commutatus	0	0	176	0	0	0	44	**220**
Bromus hordeaceus sens.lat.	0	0	0	5	158	0	2	**165**
Bromus racemosus	0	46	385	102	217	0	0	**750**
Bryum bicolor	0	0	0	0	17	0	0	**17**
Calamagrostis canescens	36	0	0	0	0	0	0	**36**
Calamagrostis epigejos	0	0	0	0	0	0	0	**0**
Calliergon cuspidatum	28	7	35	81	545	8	0	**704**
Caltha palustris	6	0	22	0	81	0	36	**145**
Calystegia sepium	0	0	2	0	6	0	0	**8**
Cardamine hirsuta	0	0	0	0	24	0	0	**24**
Cardamine pratensis	37	73	168	146	781	21	54	**1280**
Carex acuta	0	0	1	0	0	0	0	**1**
Carex acutiformis	0	0	19	0	0	0	0	**19**
Carex distans	0	0	0	0	0	0	0	**0**
Carex disticha	31	35	33	69	395	0	0	**563**
Carex flacca	0	1	23	0	58	64	0	**146**
Carex hirta	0	5	109	0	121	10	1	**246**
Carex hostiana	0	0	0	0	7	0	0	**7**
Carex nigra	39	8	76	96	312	0	37	**568**
Carex otrubae	0	0	0	0	1	0	0	**1**
Carex panicea	14	0	19	3	170	0	47	**253**
Carex paniculata	6	0	0	0	0	0	0	**6**
Carex pseudocyperus	5	0	0	0	0	0	0	**5**

Species	BE	BT	CR	SL	TA	UP	WS	Total
Carex riparia	42	39	10	39	115	0	6	**251**
Carex rostrata	0	0	0	0	10	0	0	**10**
Carex spicata	0	1	0	0	0	1	0	**2**
Carex viridula subsp.oedocarpa	0	0	0	0	0	0	2	**2**
Centaurea nigra agg.	0	96	568	80	277	105	46	**1172**
Cerastium fontanum	7	53	338	3	646	78	2	**1127**
Ceratodon purpureus	0	0	0	0	10	0	0	**10**
Cirriphyllum piliferum	0	0	0	0	0	0	0	**0**
Cirsium arvense	10	45	10	9	112	44	0	**230**
Cirsium dissectum	0	0	0	0	41	0	48	**89**
Cirsium palustre	30	0	0	0	57	0	0	**87**
Cirsium vulgare	2	0	0	0	14	21	0	**37**
Climacium dendroides	0	0	0	0	5	0	0	**5**
Crataegus monogyna	0	0	5	0	5	2	0	**12**
Crepis capillaris	0	3	6	0	0	0	0	**9**
Cynosurus cristatus	0	55	637	41	582	105	58	**1478**
Dactylis glomerata	0	28	484	0	163	92	0	**767**
Dactylorhiza fuchsii	0	0	0	0	0	0	0	**0**
Dactylorhiza incarnata	7	0	0	0	0	0	0	**7**
Dactylorhiza praetermissa	1	0	3	0	4	0	1	**9**
Danthonia decumbens	0	0	0	0	6	2	2	**10**
Deschampsia cespitosa	0	63	108	57	150	54	2	**434**
Drepanocladus aduncus	0	0	0	5	2	0	0	**7**
Eleocharis palustris	0	0	14	5	110	0	0	**129**
Eleocharis uniglumis	0	0	0	0	0	0	0	**0**
Elytrigia repens	0	89	3	4	20	17	0	**133**
Epilobium hirsutum	0	0	0	0	1	0	0	**1**
Epilobium parviflorum	16	0	0	0	0	0	0	**16**
Epilobium roseum	2	0	0	0	0	0	0	**2**
Equisetum arvense	0	0	27	0	0	0	0	**27**
Equisetum fluviatile	18	0	13	0	17	0	0	**48**
Equisetum palustre	40	0	37	2	7	0	0	**86**
Eupatorium cannabinum	2	0	0	0	0	0	0	**2**
Eurhynchium praelongum	3	45	130	9	68	8	0	**263**
Festuca arundinacea	6	0	0	3	19	68	1	**97**
Festuca ovina agg.	0	0	0	0	5	0	0	**5**
Festuca pratensis	1	7	107	88	291	17	44	**555**
Festuca rubra agg.	1	127	668	1	809	145	3	**1754**
Filipendula ulmaria	33	24	391	30	767	4	49	**1298**
Filipendula vulgaris	0	67	0	0	0	18	0	**85**
Fissidens taxifolius	0	0	0	0	0	0	0	**0**
Fritillaria meleagris	0	0	144	0	0	0	0	**144**
Funaria hygrometrica	2	0	0	0	0	0	0	**2**
Galeopsis tetrahit	0	0	1	0	0	0	0	**1**
Galium aparine	0	4	1	0	16	2	0	**23**
Galium palustre sens.lat.	37	0	19	1	122	0	21	**200**
Galium uliginosum	27	0	0	0	0	0	0	**27**
Galium verum	0	40	7	0	0	46	0	**93**
Geranium dissectum	0	1	7	0	37	12	3	**60**
Geranium molle	0	0	0	0	0	3	0	**3**
Glechoma hederacea	0	0	0	5	55	1	0	**61**
Glyceria declinata	0	0	0	0	5	0	0	**5**
Glyceria fluitans	3	2	8	26	183	7	3	**232**
Glyceria maxima	4	0	2	0	109	0	0	**115**
Gnaphalium uliginosum	5	0	0	0	0	0	0	**5**
Hedera helix	0	0	0	0	1	0	0	**1**
Heracleum sphondylium	0	0	111	0	0	1	0	**112**
Holcus lanatus	23	162	567	16	842	140	57	**1807**
Hordeum secalinum	0	7	214	7	3	113	0	**344**

Species	BE	BT	CR	SL	TA	UP	WS	Total
Hydrocotyle vulgaris	38	0	0	0	12	0	8	**58**
Hypericum tetrapterum	2	0	0	0	1	0	0	**3**
Hypochoeris radicata	0	2	9	0	75	3	0	**89**
Iris pseudacorus	5	0	0	0	9	0	1	**15**
Juncus acutiflorus	0	2	6	10	18	0	0	**36**
Juncus articulatus	12	2	8	2	117	0	2	**143**
Juncus bufonius sens.lat.	7	0	1	0	0	0	0	**8**
Juncus conglomeratus	0	19	0	0	6	0	7	**32**
Juncus effusus	32	3	0	6	238	0	21	**300**
Juncus inflexus	15	5	0	0	72	0	0	**92**
Juncus subnodulosus	40	0	0	0	0	0	0	**40**
Lathyrus palustris	0	0	0	0	0	0	0	**0**
Lathyrus pratensis	6	108	325	0	49	111	0	**599**
Leontodon autumnalis	0	2	443	102	312	1	30	**890**
Leontodon hispidus	1	1	137	2	74	10	40	**265**
Leontodon taraxacoides	0	0	99	5	1	2	0	**107**
Lescurea patens	0	0	0	0	0	6	0	**6**
Leucanthemum vulgare	0	0	386	0	26	10	0	**422**
Linum catharticum	0	0	79	0	0	0	0	**79**
Lolium multiflorum	0	0	0	0	1	0	0	**1**
Lolium perenne	10	3	697	141	586	101	8	**1546**
Lotus corniculatus	7	41	285	0	45	72	0	**450**
Lotus uliginosus	24	0	24	2	141	0	0	**191**
Luzula campestris	1	61	10	0	99	71	0	**242**
Lychnis flos-cuculi	22	0	62	11	86	0	15	**196**
Lycopus europaeus	6	0	0	0	0	0	0	**6**
Lysimachia nemorum	0	0	0	0	0	0	0	**0**
Lysimachia nummularia	0	12	53	15	164	4	0	**248**
Lysimachia vulgaris	43	0	0	0	0	0	0	**43**
Lythrum salicaria	35	0	0	0	0	0	0	**35**
Medicago lupulina	0	0	63	0	0	7	0	**70**
Mentha aquatica	38	0	0	0	5	0	1	**44**
Mentha arvensis	0	0	0	0	4	0	0	**4**
Menyanthes trifoliata	6	0	0	0	0	0	0	**6**
Molinia caerulea	0	0	0	0	0	0	0	**0**
Myosotis discolor	0	0	0	0	136	0	0	**136**
Myosotis laxa	18	0	1	0	20	0	12	**51**
Myosotis scorpioides	1	0	11	0	14	0	0	**26**
Odontites verna	3	0	0	0	0	0	0	**3**
Oenanthe aquatica	0	1	0	0	0	0	0	**1**
Oenanthe fistulosa	2	0	39	50	33	0	0	**124**
Oenanthe silaifolia	0	8	0	0	0	0	0	**8**
Ophioglossum vulgatum	0	1	95	0	0	2	0	**98**
Orchis morio	0	0	0	0	0	3	0	**3**
Parnassia palustris	0	0	0	0	0	0	0	**0**
Pedicularis palustris	6	0	0	0	0	0	0	**6**
Persicaria amphibia	9	8	70	148	183	0	0	**418**
Persicaria maculosa	0	2	0	0	2	0	26	**30**
Peucedanum palustre	24	0	0	0	0	0	0	**24**
Phalaris arundinacea	0	35	10	3	9	0	2	**59**
Phleum pratense	10	7	387	75	546	45	22	**1092**
Phleum pratense subsp.bertolonii	0	0	0	0	0	52	0	**52**
Phragmites australis	47	0	2	0	0	0	0	**49**
Plagiomnium undulatum	0	0	0	0	0	5	0	**5**
Plantago lanceolata	0	10	582	99	664	27	53	**1435**
Plantago major	5	1	9	1	0	0	0	**16**
Plantago media	0	0	0	0	0	11	0	**11**
Poa annua	3	0	1	1	2	0	0	**7**

Species	BE	BT	CR	SL	TA	UP	WS	Total
Poa humilis	0	0	0	0	125	0	0	**125**
Poa pratensis sens.lat.	0	3	5	6	191	11	0	**216**
Poa trivialis	32	184	521	166	388	126	28	**1445**
Potentilla anglica	0	0	0	0	3	0	0	**3**
Potentilla anserina	2	3	0	0	138	0	0	**143**
Potentilla erecta	1	4	0	0	6	9	0	**20**
Potentilla palustris	9	0	0	0	0	0	0	**9**
Potentilla reptans	0	107	111	0	79	69	0	**366**
Potentilla sterilis	0	0	1	0	0	0	0	**1**
Primula veris	0	9	4	0	0	90	0	**103**
Prunella vulgaris	0	1	382	11	187	16	16	**613**
Prunus spinosa	0	1	0	0	0	0	0	**1**
Pseudoscleropodium purum	0	0	0	0	0	16	0	**16**
Pulicaria dysenterica	1	0	0	0	0	0	0	**1**
Ranunculus acris	2	173	661	149	831	104	50	**1970**
Ranunculus aquatilis sens.lat.	0	0	0	0	1	0	0	**1**
Ranunculus bulbosus	0	28	335	0	0	95	0	**458**
Ranunculus ficaria	0	0	0	0	9	0	0	**9**
Ranunculus flammula	31	0	1	16	14	0	45	**107**
Ranunculus repens	18	95	281	169	764	31	44	**1402**
Ranunculus sceleratus	8	0	0	1	0	0	0	**9**
Rhinanthus minor agg.	18	0	615	0	0	0	2	**635**
Rhizomnium punctatum	0	0	1	0	0	0	0	**1**
Rhynchostegium confertum	0	0	19	2	3	1	0	**25**
Rhytidiadelphus squarrosus	0	2	0	0	0	0	0	**2**
Rorippa nasturtium-aquaticum.	2	0	0	0	0	0	0	**2**
Rosa canina agg.	0	0	0	0	1	0	0	**1**
Rubus caesius	0	0	0	0	0	0	0	**0**
Rumex acetosa	2	152	613	128	845	87	16	**1843**
Rumex conglomeratus	20	0	4	0	0	1	0	**25**
Rumex crispus	0	0	58	0	46	0	0	**104**
Rumex hydrolapathum	1	0	0	0	2	0	0	**3**
Rumex obtusifolius	0	0	4	0	3	0	0	**7**
Rumex sanguineus	0	1	0	0	0	0	0	**1**
Sagina procumbens	2	0	0	0	0	0	0	**2**
Salix cinerea subsp.oleifolia	12	0	0	0	0	0	0	**12**
Salix fragilis	0	2	1	0	0	0	0	**3**
Samolus valerandi	0	0	0	0	0	0	0	**0**
Sanguisorba officinalis	0	162	360	0	0	23	0	**545**
Scrophularia auriculata	3	0	0	0	0	0	0	**3**
Scutellaria galericulata	19	0	0	0	0	0	0	**19**
Senecio aquaticus	6	0	0	119	78	0	55	**258**
Senecio erucifolius	0	1	0	0	0	0	0	**1**
Senecio jacobaea	0	0	0	0	0	7	0	**7**
Serratula tinctoria	0	0	0	0	0	3	0	**3**
Silaum silaus	0	76	417	13	13	98	0	**617**
Solanum dulcamara	1	0	0	0	0	0	0	**1**
Sonchus asper	6	0	0	0	2	2	0	**10**
Sonchus oleraceus	0	0	0	0	0	0	0	**0**
Stachys officinalis	0	0	0	0	0	11	0	**11**
Stachys palustris	0	0	0	0	0	0	0	**0**
Stellaria alsine	2	0	0	0	0	0	0	**2**
Stellaria graminea	0	21	0	0	398	3	0	**422**
Stellaria holostea	0	0	0	0	0	0	0	**0**
Stellaria media agg.	0	0	0	0	0	1	0	**1**
Stellaria palustris	1	0	0	0	7	0	0	**8**
Succisa pratensis	2	14	7	0	5	49	0	**77**
Symphytum officinale	0	0	2	0	0	0	0	**2**
Taraxacum sect.taraxacum	2	44	651	147	667	4	8	**1523**

Species	BE	BT	CR	SL	TA	UP	WS	Total
Thalictrum flavum	0	0	41	1	9	0	39	**90**
Thelypteris thelypteroides	38	0	0	0	0	0	0	**38**
Tragopogon pratensis	0	0	122	0	0	0	0	**122**
Trifolium dubium	0	0	11	1	40	3	0	**55**
Trifolium medium	0	0	0	8	0	1	0	**9**
Trifolium ochroleucon	0	0	0	0	0	7	0	**7**
Trifolium pratense	3	22	599	67	522	33	25	**1271**
Trifolium repens	3	14	632	153	522	58	34	**1416**
Triglochin palustris	0	0	0	0	7	0	0	**7**
Trisetum flavescens	0	32	335	1	5	87	0	**460**
Typha latifolia	1	0	0	0	0	0	0	**1**
Urtica dioica	0	0	0	0	8	0	0	**8**
Valeriana dioica	0	0	0	0	0	0	0	**0**
Valeriana officinalis	4	0	0	0	0	0	0	**4**
Veronica beccabunga	5	0	0	0	0	0	0	**5**
Veronica catenata	6	0	0	0	0	0	0	**6**
Veronica chamaedrys	0	0	0	0	0	7	0	**7**
Veronica scutellata	0	0	0	0	1	0	0	**1**
Veronica serpyllifolia	0	0	0	4	99	0	0	**103**
Vicia cracca	9	38	205	17	129	16	13	**427**
Vicia sativa subsp.nigra	0	0	1	0	0	1	0	**2**
x Festulolium loliaceum	1	0	22	0	2	2	0	**27**