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Methods for the prediction of the impact of groundwater abstraction on East Anglian wetlands

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Executive Summary

This is the final report of the Anglian Regional Operational Investigation 558 : "The Protection of East Anglian Wetlands". The objective of the project was the development of methodologies for evaluation of the likely impact of groundwater abstraction on wetland sites. The methodologies should be suitable for use at all wetland sites in East Anglia, regardless of the amount of data available for the site. A primary requirement of the methodologies is that they should indicate whether a wetland might be at risk from proposed abstractions.

In the Terms of Reference, the project objective was defined in relation to the groundwater catchments of wetland sites. The project was run in two phases, and in the course of the first phase the significance of groundwater catchments in the protection of wetlands from the effects of groundwater abstraction was examined. It was concluded that identification of the groundwater catchment was not required when assessing the possibility of the wetland being adversely affected by a specific groundwater abstraction. The emphasis of the project thus changed to a consideration of wetland behaviour in response to variations in water budget, and to the effect of groundwater pumping on that water budget.

The maintenance of wetlands in a low-rainfall region depends upon groundwater inputs, but groundwater is not the only important component of the water budget. In this report emphasis is placed on the construction of a simple but comprehensive water budget model, on a monthly timescale, that will predict the impact of changes in the groundwater supply on water levels in the wetland, most importantly during the summer months and in drought years. This MIROS model, which can be used for sites with *no* local data but can also be refined to take account of available data, has been developed in the form of a spreadsheet.

Prohibition of abstractions that would cause any fall whatsoever in water levels at wetland sites is not a practical solution. For a given wetland site, predicted changes in water level and flow, resulting from a proposed groundwater abstraction, should be evaluated by an objective procedure which must recognise the water needs of plant communities. As an improvement to the simple Theis method for predicting the propagation of impacts through the aquifer, a new well function has been developed to quantify the effect of pumping on an idealised wetland. The analytical model characterises a wetland by its size, expressed as an effective radius, and a parameter which is a measure of the resistance to flow between the underlying aquifer and the wetland.

Quantitative measures of the physical habitat needs of wetland plants are difficult to establish, but one approach based on field evaluation has confirmed the value of the Sum Exceedance Value (SEV) as a measure of the length and intensity of summer drought in wetland soils. The SEV can be calculated from measured or modelled water-level data on an annual or long term average basis. In this report, the combination of the MIROS model with the SEV method has been used as one means of estimating the maximum acceptable drawdown in the wetland.

The results lead to a suite of methodologies which allows an assessment of the susceptibility of a wetland to a specific proposed abstraction to be made, regardless of the amount of data available. These allow more data to be used, when available, to further quantify the wetland water budget.

1. Introduction

1.1 Background

There is an abundance of definitions of a wetland, but the for the purposes of this report a wetland is defined as "an area of land whose hydrology and ecology is determined by excess water, usually in the form of a high water table giving rise to saturation or high moisture content in the root zone, and whose natural vegetation communities are dominated by plants that are adapted to these soil conditions".

Wetlands in general constitute a dwindling habitat under considerable developmental pressure. They are often protected from the effects of development by Site of Special Scientific Interest (SSSI) notification, and the presence of SSSIs is taken into account by local authorities and the National Rivers Authority (NRA) as part of the planning and licensing process. For potential threats to the conservation value of a site to outweigh the value of development, it is necessary to prove the extent of the impact of the proposed development. Environmental statements, required for some capital schemes, are often weak in the area of evaluation and prediction of potential impacts on natural systems (Boon, 1991), and it may be difficult to provide necessary scientific evidence to support unequivocal assertions relating to environmental impact on a particular site. In particular, the relationships between surface water, shallow groundwater and deep groundwater are complex and difficult to quantify.

Wetlands, by their very nature, require an input of water for their survival. The amount, timing and quality of the water available control the type of wetland and the nature and diversity of the plants and animals which the wetland supports. In many cases, the need for the protection of the wetland is seen, in the first instance, as the need to protect the plant species which thrive in these environments providing a habitat for specialist animal communities, for instance wading birds, which have declined in the wider countryside.

In order to adequately protect wetlands it is necessary to understand the role they play in the regional water resource environment. A long term water balance would show groundwater-fed wetlands to be areas of groundwater discharge. However, in the short term wetlands may recharge the underlying aquifer, thus maintaining groundwater levels in times of drought.

In the past wetland areas in East Anglia were much more extensive than at present. Thus plant diversity could be maintained even in prolonged periods of low rainfall. Historical development, including land drainage and deepening of river channels, has reduced the wetland area present to an amount which needs careful management to ensure its conservation. The remaining areas of wetland are usually surrounded by land which has been developed, either for agricultural or urban use, and as such the wetlands are threatened by changes in agricultural and urban practices (e.g. deep drainage of fields, deepening of stream channels, diversion of runoff into storm sewers).

The occurrence of wetland sites in their present positions is the result of many factors. The most difficult effect to distinguish from visual surveys is the effect of the underlying geology. It is likely that most wetlands occur where they do because of a combination of topographic, hydrological and geological features, which have subsequently been impacted by man-made influences. A knowledge of the combination of features present at each site aids the understanding of the processes which are of importance for that site, and it is important that these features are correctly described.

Increasing demand for new groundwater abstraction (for a variety of reasons including, for example, regional increase in demand, nitrate pollution of existing sources, and interference effects from other licensed abstractions) provides additional potential stress on wetland environments. The habitat value of wetlands is almost invariably linked to a pattern of hydrology and hydrogeochemistry that has been stable in the long term, and short term disturbances to this pattern can have important consequences to the composition and diversity of the ecosystem. Wetland sites are often dependent on groundwater flows providing a sufficient quantity of water of the correct quality, or on the maintenance of a stable shallow groundwater body, for instance within peat, by a connection with the groundwater in an underlying major aquifer. In many cases the relationship between deep and shallow aquifers is poorly understood, being only hinted at by the interpretation of deep-well aquifer tests, e.g. as a 'leaky artesian' condition, or suggested by water quality considerations. It is difficult to state categorically how drawdown in a major aquifer will affect the seasonal and long-term behaviour of the wetland water table, or the quality of the waters in the shallow saturated zone.

Before it is possible to predict how a wetland will react to changes in the regional groundwater regime it is first necessary to develop an understanding of how the wetland interacts with the rest of the environment under present conditions. In order to properly understand the hydrodynamics of an individual wetland site, the various components which control the wetland behaviour must be quantified. These components include the geology, topography, hydrogeology, water balance and water requirements of the flora and fauna which are to be preserved. The scales (both temporal and spatial) on which these data are required are different from those of data which are routinely collected for other purposes. Thus it is unlikely that there will be sufficient data available on a specific wetland site to enable an in-depth understanding of its function to be gained without many years of new data collection.

1.2 Previous studies

In order that the protection of wetlands becomes a tractable problem it is necessary to develop a general approach which can be used until more site specific data can be collected. A previous study of East Anglian fens by Birmingham University (Lloyd *et al.*, 1993) suggested that wetlands should be categorised into one of eight classes depending on the source of water (surface, confined aquifer, unconfined aquifer). This classification scheme is shown in Figure 1.1. After wetlands have been classified in this scheme it is possible to qualitatively describe their vulnerability to activities such as groundwater abstraction, river abstraction and changes in agricultural practices. This is shown in Table 1.1. The classification of wetlands into these categories is based upon desk studies, and should not require any additional field measurements.

A further part of the Birmingham University study (Gilvear *et al.*, 1994) compared the results of extensive data collection exercises - including the creation of numerical models - with the results obtained from applying the classification scheme. They concluded that the desk studies generally led to a correct classification of the wetland. However, local anomalies in geology (e.g. holes in a clay covering) could be important, and would not be distinguished except by detailed field investigations. The classification scheme gives a guide to the likely effect of changes in the local water regime, but does not enable these effects to be quantified.

1.3 Present study

As a means of protecting wetland sites, the Anglian Region of the National Rivers Authority wanted to be able to:-

1. Define groundwater catchment areas to wetland environments.

2. Estimate the effects of groundwater abstraction on these catchment areas.

3. Estimate the total groundwater resource required by individual wetland environments.

Accordingly, terms of reference for Anglian Regional Operational Investigation: 558 were drawn up and tenders invited. The British Geological Survey in conjunction with the Institute of Hydrology were selected to carry out the required study.

The project was structured in two Phases. Phase 1 entailed devising a series of possible methodologies by consideration of 12 wetland sites. Phase 2 was to use these methodologies on a further 25 sites.

The project brief laid strong emphasis on the need for definition of wetland groundwater catchment areas, as a necessary step in estimating the impact of groundwater abstraction on the individual wetlands. Water balance calculations for the wetland sites were to be used to check that the delineated groundwater catchments were sufficient to provide the groundwater inputs required to maintain the wetlands.

As Phase 1 of the project progressed it became apparent that the accurate delineation of the wetland groundwater catchment was not possible with the available data. However, it was also suggested that the effect on a wetland of pumping from a well was not dependent on the position of the well with respect to the groundwater catchment area. Thus the report on Phase 1 of the Project (Adams *et al.*, 1994) concentrated on water balance studies. The approach adopted involved the consideration of the likely water requirements of the plant species present at wetland sites and introduced the concept of Sum Exceedance Values in a hydrological context. A spreadsheet model was developed to quantify the range of probable groundwater inputs to the wetland sites. These values were then associated with groundwater catchment areas. A methodology for assessing the likely impact of historical groundwater abstraction on the groundwater levels in the vicinity of the wetlands was used together with existing data on wetland dehydration to produce guidelines on acceptable water level changes.

The change in emphasis of the Project from that envisaged in the original tender documents led to review of the Phase 2 objectives and the production of a new proposal for the second stage of the work. The major target of the revised Phase 2 was to develop a better understanding of the hydraulics of wetland systems by simulation studies. This would involve both analytical and numerical work. Consideration of further wetland sites would also be used to confirm the validity of the water balance studies and to refine further the guidelines suggested in Phase 1. Some numerical modelling work would also be carried out to confirm the view that a knowledge of the position of the groundwater catchment area was not necessary for the protection of wetlands from the effects of groundwater abstraction.

Thus the purpose of this report is to describe a methodology that can be implemented by the NRA-Anglian Region to quantitatively assess the impact of current and proposed groundwater abstractions on wetlands. This methodology, or hierarchical suite of methodologies, should be suitable for use with all wetland sites in East Anglia, regardless of the amount of data available for the site. A primary requirement of the methodologies is that they should indicate whether a wetland might be at risk from proposed new abstractions. This would enable the NRA to require that further site specific investigations be carried out before an abstraction license could be granted. Thus the methodology should, in the first instance, over-protect the wetland, in case subsequent investigations show that the wetland is more susceptible than its initial classification would suggest.

This study also provides a methodology for assessing the overall groundwater requirement of wetland sites, based upon assumptions about the water requirements of wetland plant species. A quantification of this volume of water is required by the NRA to help in the allocation of total water resources within the Anglian region.

It is important to note that this report provides a detailed discussion of the methodologies and their development. It is not intended to be a manual on the application of the methodologies - this would require a somewhat different presentation.

The methodologies described in this report were initially developed by consideration of 12 wetland sites in Norfolk. This was carried out as Phase 1 of this project. Due to the paucity of data, assumptions needed to be made at various steps in order to provide a workable methodology. These assumptions, and indeed the methodologies, were then refined by consideration of a further 11 sites in Norfolk and Suffolk, about which far more data had been collected; this constituted Phase 2 of the project. The sites considered in this study are listed in Table 1.2. This report contains the conclusions of the combined Phase 1 and 2 of the project. Ideas that were tested but subsequently discarded in Phase 1 have been reported previously (Adams *et al.*, 1994) and will not be repeated here. The application of the methodologies to the 11 Phase 2 sites is reported in Appendix B of this Report.

In Phase 1 of this project, a great deal of emphasis was placed on the delineation of wetland groundwater catchment areas. During the course of Phase 1 the realisation grew that this was not entirely necessary for the protection of wetlands from the effects of water level changes. Thus this work is only mentioned in passing in this report, except in Appendix A3 which describes modelling work which was undertaken to help clarify the position.

To make this report accessible to the wide variety of specialists concerned with wetland conservation, a large part of the specialist *hydrogeological* background to the proposed methodologies is reported in Appendices A1 - A4.

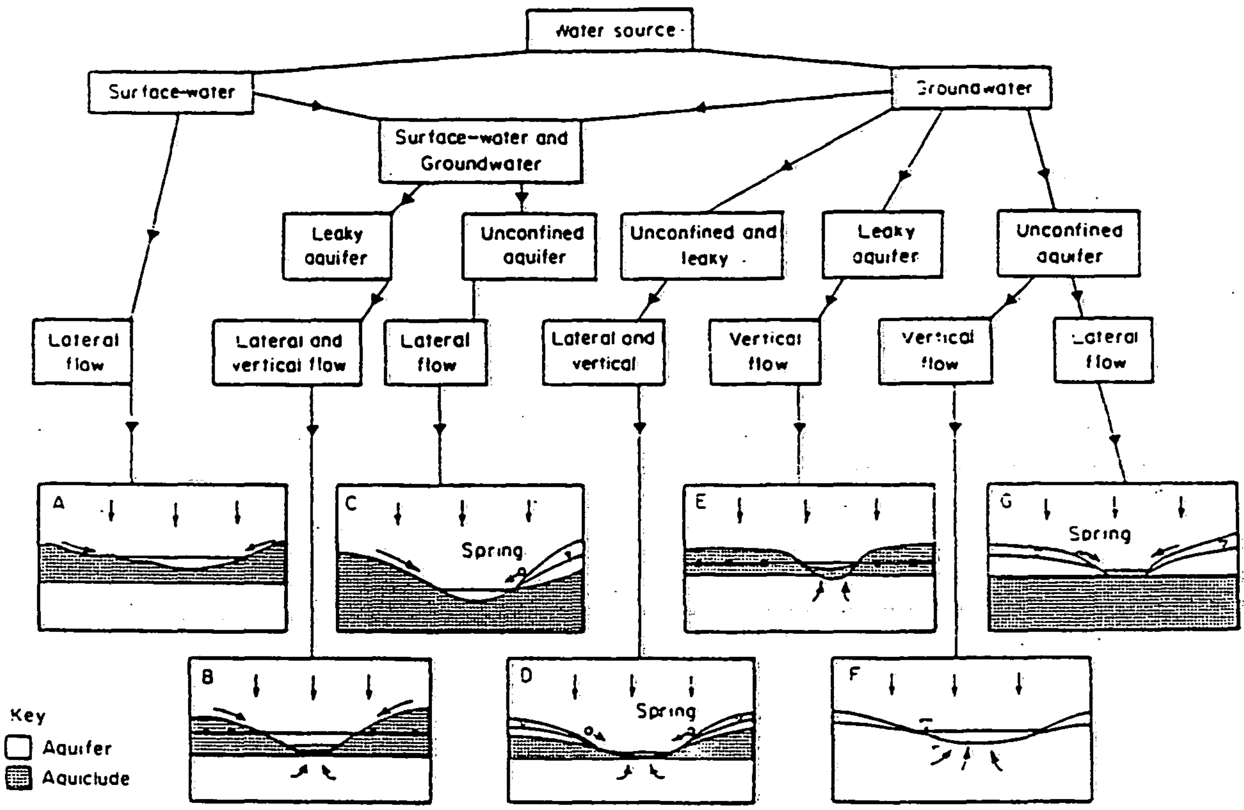

Figure 1.1 A proposed classification for East Anglian wetlands (from Lloyd *et al.*, 1993).

Table 1.1 **General hydrological vulnerabilities of the hydrogeological classes (after Lloyd *et al*, 1993)**

	Groundwater abstraction from main aquifer	River improvement	Deepening of drains related to agriculture	Surface-water abstraction
Class A	No effect	May increase drainage	May affect those parts of the site near the drains	May affect surface water inputs to the site
Class B	Lowering of piezometric surface may reduce spring flows	May increase drainage dependent on the control of river water levels on the sites. For some sites there may be no effect	Groundwater component not affected but water may drain away more quickly	There should be little effect unless abstraction is from within the wetlands or the water levels in the drains leaving the site are affected
Class C	No effect		May affect those parts of the site near the drains	
Class D	May decrease main aquifer contribution			
Class E	As for Class B	Enclosed basin (?) not applicable	Enclosed basin (?) not applicable	
Class F	May cause decrease in spring flow	May increase drainage dependent on the control of river water levels on the sites	May intercept some groundwater and decrease spring flows	
Class G	No effect		May affect those parts of the site near the drains	

Table 1.2 Wetland sites in Norfolk and Suffolk used in Phases 1 and 2 of this study

Phase 1 Sites	Phase 2 Sites
Badley Moor	Blo'Norton & Thelnetham Fens
Booton Common	Broad Fen
Dersingham Bog	Catfield Fen
Ducan's Marsh	Chippenham Fen
East Ruston Common	East Harling Fen
East Walton Common	Foulden Common
Forncett Meadows	Hopton Fen
Great Cressingham Fen	Kenninghall & Banham Fens & Quidenham Mere
Middle Harling Fen	Redgrave & Lopham Fens
Potter & Scarning Fens	Smallburgh Fen
Roydon Common	Weston Fen
Shotesham Common	

2. Wetlands and water use

Wetlands are distinguished from other habitats by their moist or saturated soils and by a range of specialised plants which can survive or even exploit the unusual physical and chemical conditions in wetland soils. Excess water is fundamental to the development and continued existence of wetlands, and the conservation of wetlands is inseparably linked to the preservation of this excess water, a difficult problem in these times of increasing demands for water in the driest parts of the year. Wetlands do not co-exist easily with modern agriculture, which on the one hand needs to irrigate in summer, while also seeking in the winter and spring to eliminate wetland conditions that are hostile to almost all commercial crops.

Wetland ecosystems consist of interdependent communities of both flora and fauna: while the fauna (for example wading birds, or the Great Raft Spider of Redgrave and Lopham Fens) are sometimes the high-profile elements of the ecosystem, the whole system is supported by the dominant species of the plant community, which have their own special requirements. Wetland soils, while they do not always remain saturated, do not experience the soil moisture deficits that build up in other soils, and plant roots must contend with low oxygen availability and associated chemical problems. Some wetland species, rarely faced with the need to inhibit transpiration in response to soil drought, have little defence against dehydration, and wetland plants that have evolved to thrive under specialised conditions are easily out-competed by invasive dryland species once the soil environment is changed by drainage or a reduction in the water supply. In particular the breakdown of peat under oxidised conditions provides a flush of nutrients that encourages a crop of fast-growing weeds and can also lead to eutrophication of open water bodies.

It is not easy to quantify the water needs of wetlands. One approach would be to calculate the evapotranspirational demand of the wetland plant community in response perhaps to the range of climatic conditions actually experienced at the site. However this takes no account of the essential flow through the system, that distributes nutrients, maintains water quality in open water bodies, and removes or disperses excess toxic products. In most wetlands, the point of outflow of this water is the hydraulic control that maintains a consistent regime of water levels.

An alternative approach, involving much more instrumentation and intensive survey, is to quantify the elements of the water balance, including groundwater flow, over a short period. This intensive hydrological approach, though scientifically rigorous, suffers from three main disadvantages:

1. The method is difficult to extrapolate to other sites that do not have the necessary instrument networks. It is common experience that, on the detailed level, all wetlands are different.

2. It evaluates the site as it is now, probably after some human interference has already taken place. Thus the water budget derived from the study may not reflect the long-term needs of the site.

3. The period of observation is arbitrarily chosen in climatic terms, and may not

represent fully the range of dry, wet and 'average' years that would be encountered over a longer period.

The methodology presented in this report could be regarded as a hybrid between the two. In view of the need to produce estimates of wetland water needs and to predict the impact of new licensed groundwater abstractions at short notice, the method must be simple and must require no new field instrumentation at the site, while it must also be capable of taking account of the year-to-year variation in water needs and the effects of the dramatic climatic droughts that afflict East Anglia from time to time.

2.1 Wetland types

There has long been a demand for wetland classification systems, not least from those with operational responsibilities, faced with a bewildering range of wetland sites, each unique in some way. An appropriate classification system, the argument goes, could reduce that range to a manageable list of types, each with a well-defined set of features and operating rules that would work for all wetlands of that type. The need for classification has been just as obvious to wetland scientists, who must have some means of categorising their research sites and extrapolating some or all of the results from one site to all the sites of that type.

Unfortunately, there are complications of three main types:

1. A given wetland site can contain sub-areas of several distinct wetland types, e.g. at East Ruston Common, wet and dry heath drain towards poor fen, fed by a mixture of seepage flow from superficial sands and Crag groundwater.

2. The classification may be based on criteria that are not appropriate for the purpose in hand.

3. Not all wetlands of a certain type will behave in the same way, and the differences between sites of the same type may be greater than the differences between sites of distinct types. There may be quantitative factors, for instance small sites will generally be more susceptible than larger sites, or other criteria not considered in the classification, for instance the increased susceptibility brought about by damage in the past.

At this point it is useful to introduce a broad wetland classification that has both hydrological and ecological relevance. Because of the special physical and chemical conditions in wetland soils, which delay decomposition processes, some wetlands have a tendency to store up organic matter as peat. Peatlands or *mires* are wetlands with a significant peat horizon forming the substrate for the plant community. Mires are further divided on the basis of their water supply, into *bogs* which derive most or all of their water and nutrient input from the atmosphere in rainfall and snow and *fens* whose inputs of water and nutrients come from adjacent land, as surface runoff, soil drainage or groundwater. The vegetation communities of bogs and fens are determined largely by the chemistry of the water: bogs are acidic and low in nutrients, while fens tend to be better supplied with nutrients and bases. *Poor fens* are fed by land that is itself poor in nutrients, and carry intermediate communities related to bogs, while fens develop into fen woodland or *carr* when subject to dehydration or lack of cutting or grazing management. When a wetland is well-supplied with mineral sediment, and/or the decomposition processes are sufficiently rapid to prevent the build-up of peat, it develops a mineral soil and usually a community dominated by grassy species, and is known as a *marsh*. *Wet meadow* usually develops from marsh or fen through grazing and drainage.

The division of wetlands into bogs, fens and marshes does not help greatly in the assessment of the water budget or vulnerability to impacts, and the Birmingham University classification was an attempt to categorise East Anglian wetlands (a sample of 60) on the basis of the immediate source of water, mainly on the relationship between the wetland and its major contributing groundwater body. The Birmingham classification scheme separates wetlands into seven classes (see Figure 1.1 and Table 1.1).

The Birmingham classification is essentially qualitative, and while it is possible to draw general conclusions about the susceptibility of wetland sites, using their relationship to the major aquifer from which groundwater is likely to be abstracted (see Table 1.1), these general statements have to err on the side of caution, as the classification does not give a basis for discrimination between two wetlands of the same type. Moreover, wetland dossiers prepared by Birmingham University on each of the 60 sites used as a basis for their classification demonstrate that allocating a site to a class is not always a simple matter: it may be difficult to decide whether an aquifer is confined or unconfined, and many sites possess the characteristics of more than one class (Gilvear *et al.*, 1989).

2.2 Water requirements of different plant types

Most of the plant species occurring in wetlands have marked preferences in water availability, though the requirements of each species, the relationships between species, and the interaction between physical and chemical needs are not at all well known. When the water availability, measured for instance by a change in wetland water level, changes in a wetland site, there are consequent changes in the plant community which follow in a complicated way from a combination of: the ability of species to cope with non-optimal conditions, the seasonal variations in physical variables and in the needs of plants, and the increased competition from less specialised plant types.

The plants themselves are best placed to judge the impact of hydrological changes, and many assessments of the decline of wetland sites have been based on botanical indicators (Wheeler and Shaw, 1992). However, in the absence of a detailed understanding of plant water requirements, this approach can only be retrospective, and the prediction of hydrological behaviour, however imperfect, remains the only way of evaluating future impacts. The precautionary principle would dictate that abstraction should not be licensed unless it could be demonstrated that there would be no effect on water level in the wetland, but the more practical solution adopted by this report is to set a limit to acceptable drawdown of aquifer water level that is based on water requirements and makes some allowance for the natural fluctuations from year to year, which are tolerated by the wetland plant community.

The water level in a wetland site varies seasonally, and from year to year, in response to climate, and defining a physically and botanically useful measure of optimal, current or disturbed conditions is a scientific problem of some complexity. Average water table levels are of little use, winter water levels are defined by topography rather than by hydrology, while minimum summer levels are reached for only a short time. In a study of a fen site on Anglesey, Gilman (1994) used the duration of low summer water levels, and the difference between average winter and summer water table levels, as indicators of the success of water level management. Evidence collected by a MAFF-funded project carried out by Silsoe College and the Institute of Terrestrial Ecology (Gowing *et al.*, 1993) indicates that wetland communities respond to drought stresses imposed by low water levels in summer, the integrated effects of which are well expressed by the Sum Exceedance Value (SEV) (see Appendix A1). According to the SEV model plants are considered to be under stress once the water table has dropped to a distance *d* below ground level, where *d* is a selected depth threshold. The SEV is a measure of both the length of the drought period and the depth to which the water table falls. It can be computed from real data, or from simulations, for a single summer or as a long-term average.

Experimental work to establish the SEV model was carried out by Gowing and his colleagues on four wet grassland sites, Tadham Moor (Somerset), Wicken Fen (Cambridgeshire), Cricklade North Meadow (Wiltshire) and Upwood Meadow (Cambridgeshire). Water table levels generated for a period of 10-15 years were associated with quadrat analyses for a large number of microsites. The ranges of tolerance of sixty plant species, mostly those of wet grassland, to SEV's were investigated, and the technique was later extended to cover some grassland communities defined according to the National Vegetation Classification (NVC). In most cases it has been found that a suitable choice for the threshold *d* is 40 cm: for many species in the wet grassland communities investigated this value offers relatively narrow tolerance ranges.

A great deal of work goes into evaluating tolerance ranges for SEV's. The method works well only for communities which are stable in the long term, and the analysis has not yet been extended to cover fen communities, the Wicken Fen results having been complicated by the effects of management. Extension to a large number of sites would require a considerable increase in the investment of labour, but would improve confidence in the use of the method, possibly at the cost of an increase in the variance of the results.

In the absence of evidence relating to fens, which may be forthcoming in future, albeit in a simplified form, it is suggested in this report that the depth threshold be modified to 20 cm for fens, in recognition of the generally higher levels of saturation occurring in natural and semi-natural fen habitats. Drawdowns in excess of 40 cm do occur regularly on many fen sites, particularly at Wicken, but wetland plant communities are maintained by deliberate management, which tends to limit the impact of dehydration. It is considered likely that on natural and minimally-managed fens a depth threshold of 20 cm would offer increased sensitivity of the community to the SEV figure. In the assessment of the likely tolerance ranges account has been taken of the Ellenberg classification, which places each of a large number of plant species on a 12-point scale according to water regime preferences. The Ellenberg ranking has been applied widely to fen species, although Wheeler and Shaw (1992) note that the scale is rather insensitive: many typical fen plants are accommodated by two points (8 and 9) on the scale, point 7 relating to indicators of constantly damp but not wet soils and point 10 relating to indicators of sites occasionally flooded.

In the evaluation of the likely impact of groundwater abstraction, the SEV model has been used to refine estimates of the groundwater input to a wetland site, which is a measure of the vulnerability of the site to groundwater abstraction.

2.3 The wetland water budget - sources of water

Ultimately the source of water for all wetlands is rainfall. This statement, while self-evident, is important because it leads on to questions of the origin, development and continued existence of wetlands. In high-rainfall areas, wetlands, for instance blanket bog, can extend to cover great tracts of land wherever ground surface gradients are insufficient to carry off the excess water rapidly. Peat bogs can rise to form dome-shaped raised mires, whose shape is defined by the water table, and whose radially outward groundwater flow balances the rainfall input minus evaporative losses.

In contrast, East Anglia's low annual rainfall, distributed unevenly across the seasons, can support only localised wetlands, separated by swathes of drier land. Even the Black Fens were backed up by an even more extensive hinterland of catchment area now drained through high-level drainage systems. East Anglian wetlands cannot exist only on local rainfall: they must also have a catchment to supplement direct rainfall, both to contribute additional water over the year, and to exert a regulating influence tending to reduce water deficits in the summer, when transpiration demands can outstrip rainfall. The regulation of water inputs is the single most important factor defining the hydrological regime of East Anglian wetlands. This explains the central importance of groundwater in providing a reliable and regulated water supply.

Rain falling on the highland catchment of a wetland is partitioned into surface runoff and drainage, storage on wetted surfaces and in soils, and recharge to the groundwater body. Storage of water near the catchment surface is only temporary, as it is from this stored water that the demands of evaporation and transpiration are met. The quantity of surface runoff and soil drainage is principally defined by the status of the soil moisture store, in that low to moderate-intensity rainfall will infiltrate into dry soils, and the simplest model of this system assumes that the soil moisture deficit must be satisfied before runoff or drainage can occur. High-intensity rainfalls can bypass the soil moisture store and lead to summer flood flows.

Surface runoff and water draining from the soil increases river flows, and once or twice a year in a natural river channel this flow will overtop the banks and flood on to adjoining land of the floodplain. Under favourable conditions, i.e. with impeded return flow into the river, wetlands, especially those communities tolerant of wide variations in water level, can exist on this infrequent topping-up by floodwater, but modifications to floodplain hydrology by channel improvement, land drainage and other flood control methods have made overbank flow much less reliable than formerly. Though large wetlands depending entirely on surface flows do exist in regions of the world with a more predictable climate, it is doubtful that inundation by floodwater is an important factor in maintaining any of the East Anglian wetland sites considered in this study.

Surface flow, either as overbank flooding or direct runoff into the wetland from adjacent high ground, is not regulated: its timing depends on individual rainfall events, its frequency distribution is skewed towards winter, both by higher rainfall and lower soil moisture deficits, and the recession limb of the hydrograph rarely extends over more than a few days. There may be exceptions to this rule in wetlands adjacent to large bodies of open water, notably the Broads, where high water levels may persist rather longer. As a potential contributor to the consistent water regime required by wetlands, overbank flow and surface runoff from high ground have considerable disadvantages, and though for some sites they may amount to a significant term in the annual water balance, it is doubtful that surface flow has an important role to play in the long term maintenance of the wetland.

A proportion of rainfall on high ground recharges the groundwater body. In East Anglia the main aquifers are the Chalk and the Crag, but groundwater also occurs in more localised deposits of glacial sand and gravel which may or may not be in hydraulic continuity with the major aquifers. The groundwater store is a valuable contributor to the wetland water balance, and its relatively steady output of water tends to maintain water levels in wetlands over the summer, partly compensating for the increased evapotranspiration and reduced rainfall. The area of the ground surface contributing groundwater to the wetland, the 'wetland groundwater catchment', cannot be easily delineated, as it depends on the dynamically changing form of the water table or piezometric surface. It is also difficult to distinguish the 'wetland groundwater catchment' from the 'apparent groundwater catchment', the aquifer region upstream of the wetland which also contributes underflow beneath the wetland site.

A wetland site is more than a mass of saturated soil with defined inputs and outputs: it also has an internal structure of open water bodies and surface channels, both natural and artificial, which have important functions in distributing and controlling water within the site as well as in removing it from the site. The relationships between these surface water features and the points of major inflow and outflow are crucial in defining the hydrology of the wetland, in that past efforts to control water levels by tapping springs, transmitting surface streams rapidly though the site, or installing dendritic drainage networks to improve grazing may still be active, even if no longer maintained. The creation of channels within wetlands breaks up a wetland into a pattern of 'field' areas which are partly dependent on lateral seepage from streams and dykes. Channelling the flow of springs directly to the outflow, a frequent feature of attempts at drainage, can bring about radical changes in the overall water budget of the 'fields' by removing important sources of lateral seepage. In extreme cases, successful drainage schemes can destroy wetland sites by the efficient routing of water budget inputs. Conservation measures in wetland nature reserves often involve the manipulation of the internal drainage system to create higher or more constant water levels e.g a rising sector gate was installed on the River Waveney at Redgrave Fen in the late 1970's. Though such modifications of the internal workings of a site are outside the scope of this study, they can, by increasing summer storage on site, raising water levels in dykes and reducing otherwise 'wasted' outflows, have a significant though limited effect in mitigating the impact of changes in the overall water balance, and should not be overlooked in assessing potential impacts.

2.4 Estimation of present water balance and modelling the wetland water table

Water budget studies are fundamental to the science of hydrology, but the preparation of a water budget for a wetland area presents very different problems from conventional water budget analysis, which is based on clearly-defined catchments and the precise measurement of outflow in the stream channel. For a wetland area there are three input terms to the budget: direct rainfall on to the wetland surface and from surrounding high ground, surface flow and groundwater flow. Outputs of water from the wetland site comprise evaporative losses (evaporation, largely from open water, and transpiration) and surface runoff.

This simple concept is the basis of the MIROS (Mires In Receipt Of Seepage) model developed in Phase 1 of this study, and described in Appendix A1. The MIROS model makes it possible to demonstrate the effects of changing parameters, such as the wetland groundwater catchment (a surrogate for the groundwater contribution to the wetland), and to refine estimates of wetland parameters made on the basis of scarce and unreliable data.

Surface water drainage from the wetlands has been derived using a version of the soil moisture deficit model, in which surface runoff is zero as long as the water table is below the surface, and any excess water runs off.

Flows of water into the wetland from its highland catchment are mostly diffuse and difficult to measure, and in the preparation of the water budgets for this study it has been necessary to estimate the areas of the surface water and groundwater catchments. Assumptions also have to be made about the partition of rainfall into surface runoff and recharge to the groundwater body.

In the construction of a water budget for a wetland area, there is so much uncertainty in the major components of groundwater inflow and surface water outflow (either not measured or unmeasurable) that only a modelling approach can offer any confidence. It is not possible to apply the techniques of a detailed hydrological study (for example the investigations carried out at Badley Moor, Catfield Fen, Chippenham Fen, Redgrave and Lopham Fens and Weston Fen) to a site that is in need of urgent evaluation. The modelling approach makes it possible to examine the consequences of an estimated water budget in terms of wetland water levels, and provides for the prediction of the impact of changes in the groundwater supply.

The purposes of impact prediction are best served by a water budget model that can simulate a long period of record, embracing the full range of wet and dry years. In Phase 1 of this study, 1970 was selected as the starting point of the simulation period, which could then cover the drought years of 1975-6, 1983 and 1989-92. Bringing the record as close as possible to the present would take advantage of recent improvements in the wetland water level observation networks. For the Phase 2 sites, simulation has been carried out on the period from January 1970 to the end of October 1994, covering 24 complete years and 25 summers. Once a timescale of nearly 25 years has been adopted, a daily time interval for modelling calculations becomes impractical within the confines of rapid assessment using a spreadsheet package, so a monthly time interval was used for all Phase 2 studies.

The derivation of the various input data required to create a MIROS model for a wetland site are described in some detail below.

2.4.1 Rainfall

Rainfall has been estimated on a monthly basis from the daily records of nearby raingauges in the national network. The choice of gauges was made according to proximity to the wetland and the length of record, but even with the best gauges it was necessary to in-fill missing values in the record with data from other gauges, sometimes at a considerable distance from the site. The 1:250,000 map of 1916-1950 rainfall averages, prepared by the Water Resources Board, was used to estimate long term annual rainfall for each wetland site, and for each raingauge. In the preparation of the monthly rainfall record for each wetland site the record from each gauge was multiplied by an appropriate factor to correct for differences in the long term average rainfall at the gauge site and at the wetland site. Table 2.1 summarises the rainfall data used for the Phase 2 sites.

2.4.2 Potential Evaporation

For any given site, the potential evaporation can be estimated from the Meteorological Office's MORECS estimate, according to the rules:

- for a site near the centre of a MORECS 40 km square (i.e. between 10 and 30 km from any edge, the MORECS figure for that square is taken to represent the site,
- for a site near the boundary between two MORECS squares (i.e. less than 10 km from the boundary, but more than 10 km from any other edge), the actual evaporation is taken to be the average of the MORECS figures for the two squares, and
- for a site near the junction of four MORECS squares (i.e. less than 10 km from two intersecting boundaries), the actual evaporation is taken to be the average of the MORECS figures for the four squares.

This procedure, which is illustrated in Figure 2.1, has been followed for the MORECS potential evapotranspiration estimates (see Table 2.2), and for the MORECS SMD estimate, on a monthly timescale.

2.4.3 Actual Evaporation

In the simplified water budget model used in this study, it has been assumed that the actual evapotranspiration from a wetland site is a constant proportion of the potential evapotranspiration.

There has been considerable debate about the magnitude of actual evapotranspiration from wetland plant communities. The simplest hypothesis is that wetland plants, which are not subject to soil moisture tensions, transpire at the potential rate. The results of many experiments appear to indicate that in general wetland communities encroaching on water bodies (emergent plant communities growing in permanently flooded 'swamp' conditions) evapotranspire more than the open water that they replace. However, studies of marsh and fen communities have suggested that actual evapotranspiration rates may be much lower, because of the significant quantity of dead material present. For instance the 'litter' community at Wicken Fen, which consists largely of purple moor-grass and common reed, was found to transpire at around 70% of the potential rate (Gilman, 1993), and the Birmingham University

Table 2.1 Rainfall data for Phase 2 sites

Site	1916-50 average rainfall* (mm)	Nearest long-term gauges			1970-93 average rainfall** (mm)
		Location	1916-50 average rainfall* (mm)	No.	
Blo'Norton & Thelnetham Fens	625	Bressingham Old Ha.#1 Gislingham	645 640	209524 210150	589
Broad Fen	635	Barton Turf Coltishall Met Off.	630 660	215056 214042	607
Catfield Fen	635	Barton Turf Horning P Sta	630 625	215056 214578	621
Chippenham Fen	580	Isleham P. Sta Newmarket S.T. Wks	550 590	185144 185060	578
East Harling Fen	620	Bressingham Old Ha.#1 E.Harling (Harling Fm)	645 620	209524 190118	588
Foulden Common	635	Denton Lodge P. Sta Catsholm P. Sta	630 605	193758 191893	629
Hopton Fen	610	Bressingham Old Ha.#1 E.Harling (Harling Fm)	645 620	209524 190118	579
Kenninghall & Banham Fens & Quidenham Mere	635	Bressingham Old Ha.#1 E.Harling (Harling Fm)	645 620	209524 190118	624
Redgrave & Lopham Fens	640	Bressingham Old Ha.#1 Gislingham E.Harling (Harling Fm)	645 640 620	209524 210150 190118	604
Smallburgh Fen	630	Coltishall Met. Off. Barton Turf Hevingham	660 630 675	214042 215056 213939	603
Weston Fen	610	Bressingham Old Ha.#1 E.Harling (Harling Fm)	645 620	209524 190118	605

* from WRB map
** synthetic record

study of Catfield Fen also concluded that actual evapotranspiration was of the order of 70% of the potential (Gilvear *et al.*, 1989). For short fen vegetation, such as that present on Dersingham Bog, the ratio of actual to potential evapotranspiration may be even lower: a lysimeter study on a poor fen in mid-Wales has yielded a ratio of about 60% (Gilman, 1993). On wet grassland, whose vegetation cover is cropped or mown regularly, maintaining a green crop, evapotranspiration may approach the potential rate. Computation of actual losses from

Table 2.2 **Potential and actual evaporation at Phase 2 sites interpolated for 20-km squares from MORECS data, which is published on a 40-km square basis.**

Site	MORECS squares used in calculation	MORECS PE Average 1970-93 (mm)	MORECS AE Average 1970-93 (mm)
Blo'Norton & Thelnetham Fens	130,141	589	479
Broad Fen	121,131	598	489
Catfield Fen	121,131	598	489
Chippenham Fen	140	588	472
East Harling Fen	130,141	589	479
Foulden Common	129,130	592	493
Hopton Fen	130,141	589	479
Kenninghall & Banham Fens & Quidenham Mere	130,141	589	479
Redgrave & Lopham Fens	130,141	589	479
Smallburgh Fen	121,131	598	489
Weston Fen	130,141	589	479

West Sedgemoor, Somerset, using four independent methods, a catchment water balance, interpretation of groundwater level changes and two lysimeter experiments, gave an average ratio of 95% (Gilman, 1992; Gilman, Marshall and Dixon, 1990).

For the purposes of this study, it has been assumed that the following AE/PE ratios hold for the three main community types:

Tall fen, including carr	70%
Short fen	60%
Wet grassland	95%

The actual evaporation rate from each wetland site has been estimated by multiplying the monthly MORECS potential evaporation (calculated on a site-by-site basis as described above) by the appropriate ratio. For simplicity the ratios in the table are applied throughout the year.

2.4.4 Surface water and groundwater inputs

The effective rainfall for a given month (which provides the recharge and surface runoff components) is calculated as:

$$ER = P - AE - SMD'$$

where ER is effective rainfall
P is precipitation
AE is the interpolated MORECS actual evaporation
and SMD the interpolated MORECS soil moisture deficit at the end of the previous month.

The effective rainfall is further partitioned into groundwater recharge and surface flow by assuming that recharge is a fixed proportion of effective rainfall, that proportion being defined by the soil parent material: 90% for glacial sands and gravels, 60% for uncovered Chalk and Crag and 30% for boulder clay (East Suffolk and Norfolk River Authority, 1971).

To compute the inflows to the wetland from surface and near-surface flow and groundwater, it is necessary to estimate two catchment areas: the topographic catchment and the wetland groundwater catchment. The outline of the topographic catchment is largely defined by landform, as indicated on published maps by the topographic contours, but other factors may contribute, notably the diversion of runoff by drains (Figure 2.2). Once channelled, flow may be routed around the wetland, or may traverse the wetland site without taking a significant part in its hydrology. In the water budget computations for this study, diversion has been taken into account by estimating the percentage of the topographic catchment drained by watercourses mapped by the Ordnance Survey at 1:25000 scale. The wetland groundwater catchment is much less easy to define, so the evaluation of the groundwater component of the water budget, and hence the area of the wetland groundwater catchment, was approached by a recursive method based on the concept of the Sum Exceedance Value.

Groundwater flow into the wetland is calculated from the recharge on the high ground of the wetland groundwater catchment. In the absence of other information, the area of the local topographic catchment can be taken as a first estimate of the area of the wetland groundwater catchment. The discharge of groundwater from an aquifer is not immediate, and flow through the aquifer is delayed and dispersed in time, so that the output is a smoother function of time than the recharge. A simple way to simulate this process is to apply an arithmetic smoothing algorithm, for instance the exponential smoothing process:

$$G_{IN}^*(t) = \alpha \,.\, G_{IN}(t) + (1-\alpha) \,.\, G_{IN}^*(t-1)$$

where $G_{IN}(t)$ is the monthly groundwater input for month (t), calculated by multiplying the groundwater catchment area by the monthly infiltration rate
α is a smoothing coefficient
(t) is the current month
(t-1) is the previous month
and $G_{IN}^*(t)$ is the smoothed monthly groundwater input for month (t).

The choice of the smoothing coefficient α is made on the basis of springflow determinations.

As regular springflow measurements are scarce, the estimation of α for this study has been made from the only records available, those from Great Cressingham Fen, for which $\alpha = 0.164$ has been found to give good agreement between the time distribution of calculated flows and that of the smoothed groundwater input of the MIROS model (Figure 2.3) At Chippenham Fen, a detailed water budget study produced monthly estimates of springflow for the years 1975-1976 and 1984-1992. Comparison between these estimates and the recharge computed as part of the MIROS model of Chippenham Fen suggests that a smoothing coefficient of 0.09 would give a better fit (Figure 2.4) to this synthesised data set. The choice of the smoothing coefficient is one of several aspects of the MIROS model that could be refined by the collection of data from a wetland monitoring scheme. As the data for Chippenham Fen is synthesised from a water budget, for all of the Phase 2 sites, as for the Phase 1 sites, the value of 0.164, derived from measured spring flows, has been used.

2.5 Data requirements

The ease with which a water budget can be constructed (up to the stage of testing against measured wetland water level data) depends upon the acquisition, quality control and in-filling of climate data. Unfortunately, daily rainfall records, even for the longest-running stations, contain many gaps of a month or more and require frequent in-filling. In contrast, the MORECS evaporation and soil moisture deficit data are complete from 1961 and are easily obtained as computer data files. Thus the preparation of a long term monthly rainfall record for a wetland site is the most time-consuming process involved in the construction of the water budget.

For each of the 12 wetland sites considered in Phase 1 of this study, an estimated water budget (MIROS model) was set up for the years 1970 to 1992, using the Lotus 123 spreadsheet package on a PC-compatible computer. This water budget, based on estimates of the topographic catchment area and the wetland groundwater catchment, was used to predict the variation in the wetland water table over this long period; the SEV model was then used to refine this prediction, usually by reducing the area of the wetland groundwater catchment, to produce a more realistic range in water table variation.

This exercise was repeated for the Phase 2 sites. Climate data have been updated to include 1993, and January to October 1994, so that comparisons can be made with recent water level data from some sites. The results of this exercise are reported in Appendix B.

In general, the water budget of a wetland site will only be as good as the data underlying it. Inevitably there will be differences between a water budget based on data resulting from intensive instrumentation of a site, probably over several years, and a simple water budget computed from regional data and the nearest raingauge record. In the assessment of abstraction licence applications, only the simple water budget will generally be available, and the confidence with which predictions of water table levels can be made using a simple water budget model such as MIROS is much increased when a comparison with real data is possible. Some comparison plots are presented in Appendix B. The data sets available for most of the Phase 2 sites have been most useful in evaluating the methodology, and the proposed installation of piezometers at many wetland sites throughout East Anglia must be welcomed.

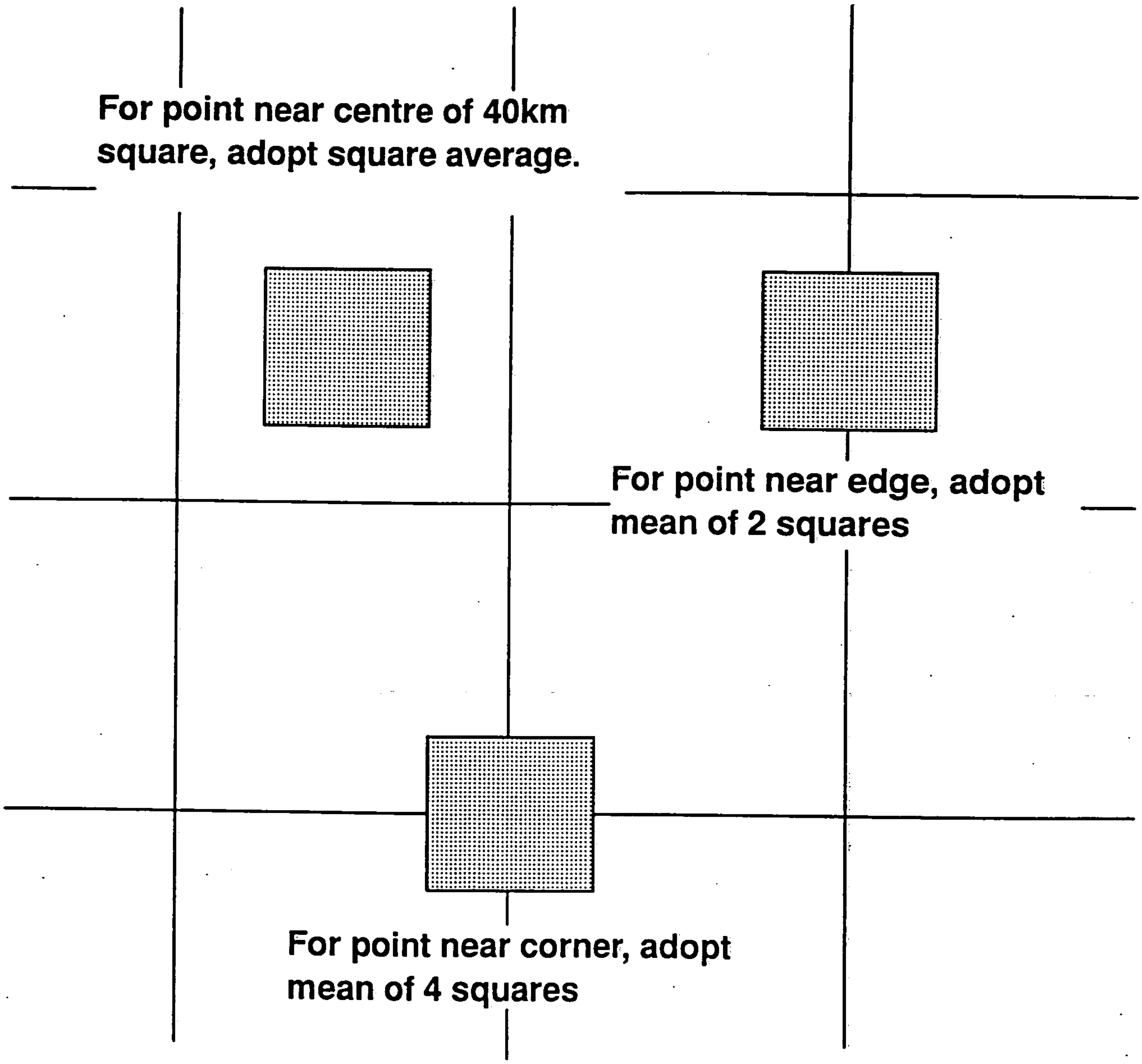

Figure 2.1 Refining the MORECS 40 km grid to obtain estimates of potential and actual evaporation

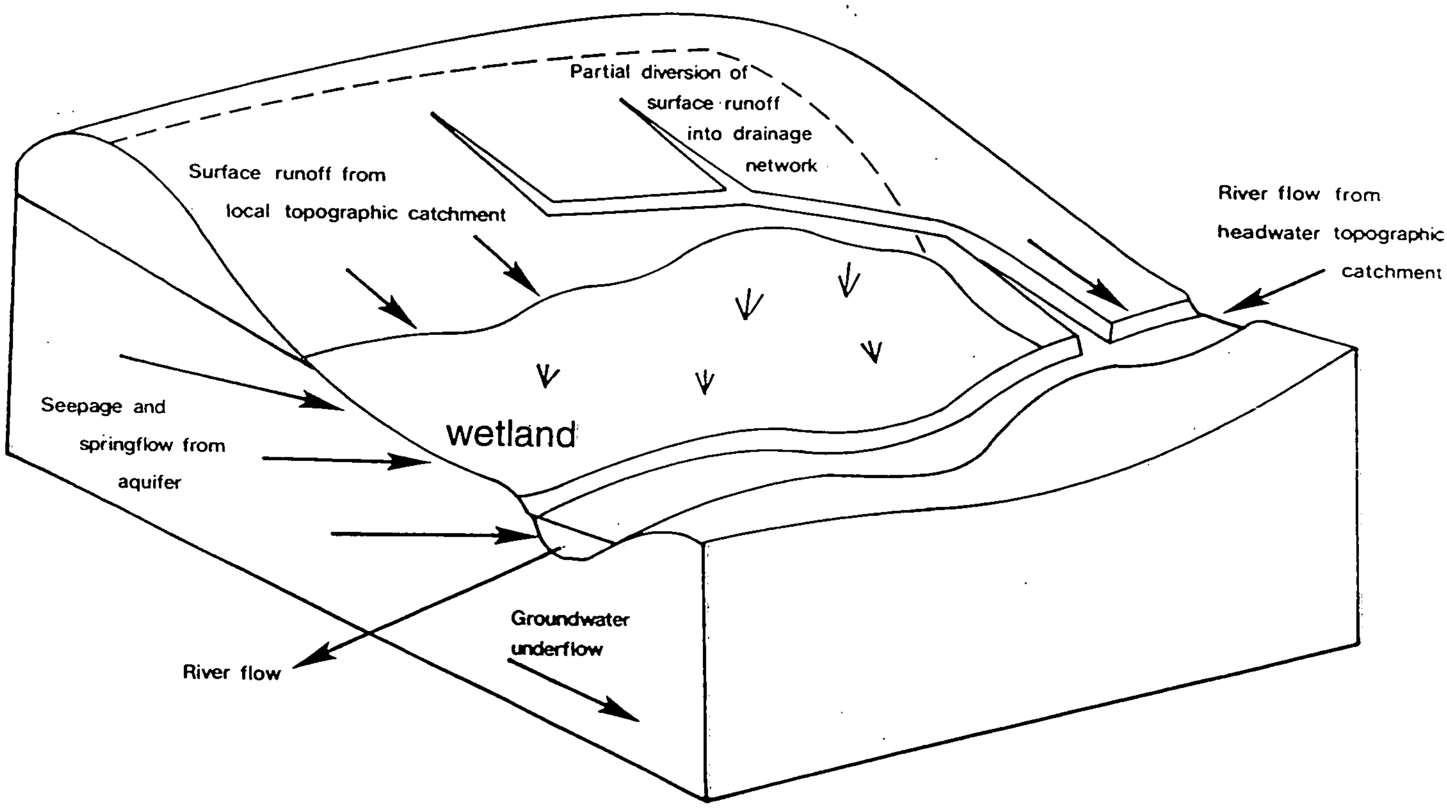

Figure 2.2 Schematic of a streamside wetland site, showing the effect of drainage on the topographic catchment.

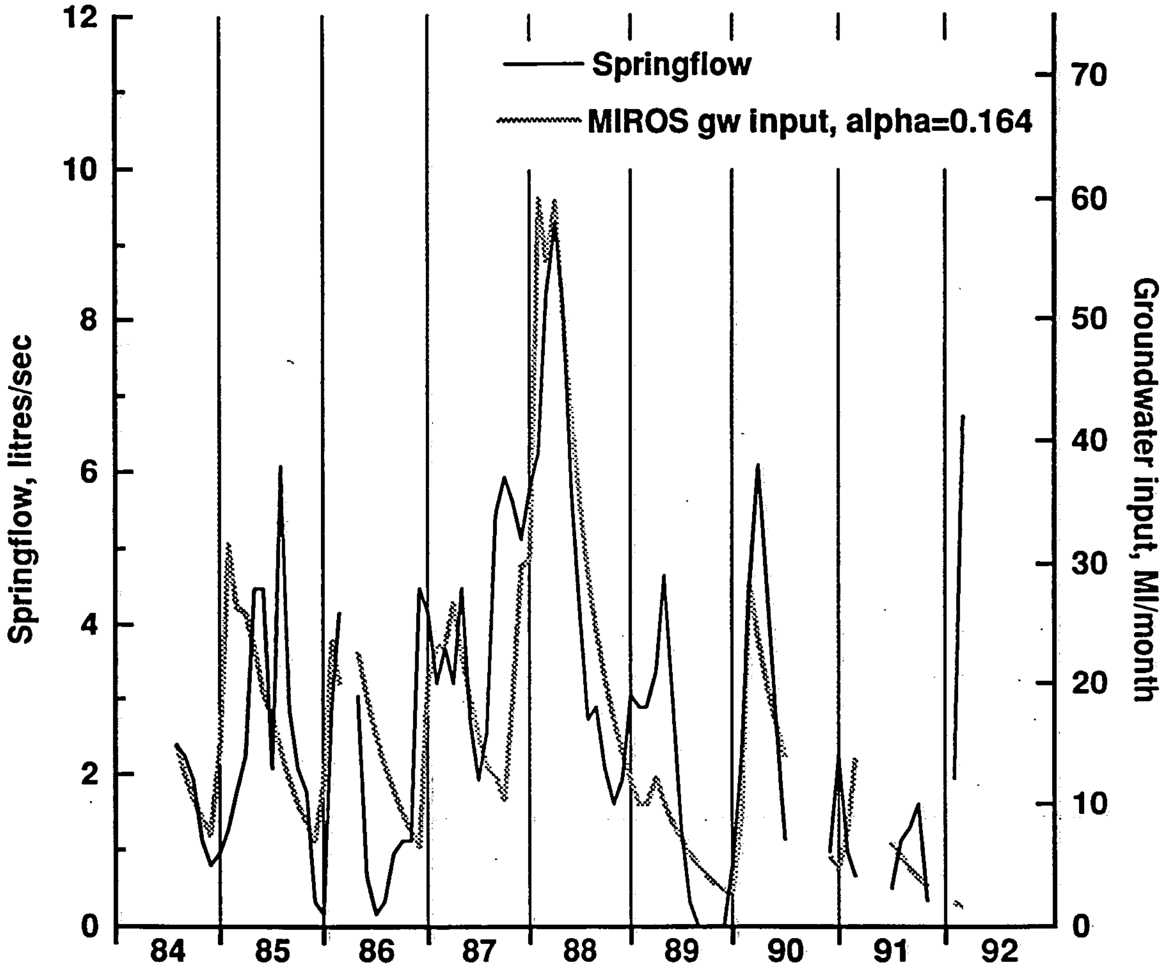

Figure 2.3 Comparison between monthly determinations of springflow at Great Cressingham Fen, 1984-1992, and the best estimates of groundwater discharge to the fen from the MIROS model.

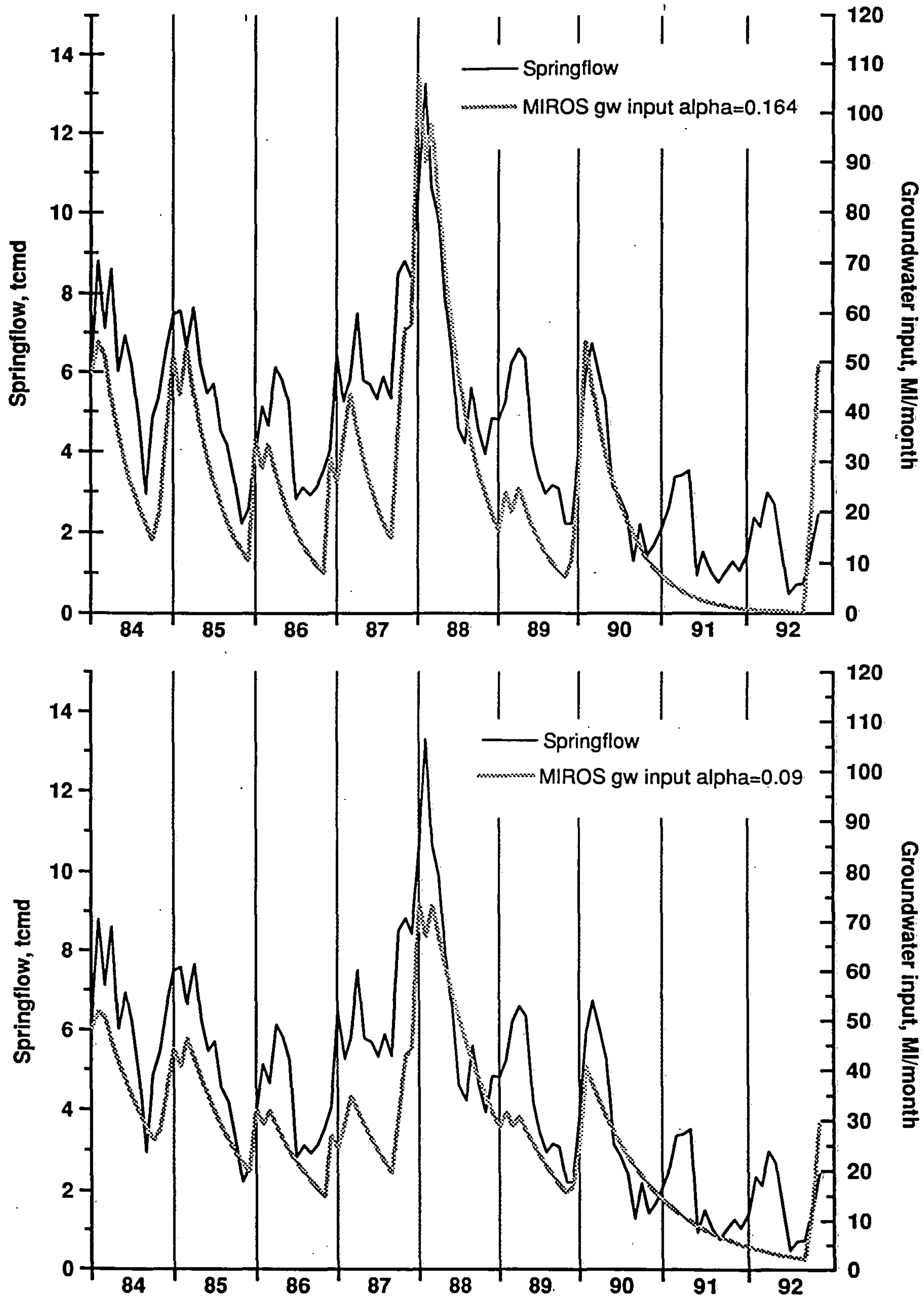

Figure 2.4 The effect of the smoothing parameter α on the seasonality of the MIROS estimates of groundwater discharge at Chippenham Fen.

3. Impact of groundwater abstraction on wetlands

3.1 Aquifer system water balance

Wetlands must be considered in the context of the overall aquifer system water balance. The amount of water available for the maintenance of wetland areas depends upon all the other constituents of the hydrological cycle in the aquifer unit. It must be accepted that the regime which exists at the present is in no way natural - man has been tinkering with the components of the system since time immemorial.

As described earlier, the wetlands now present in East Anglia are remnants of much more extensive wetland systems. Changes in agriculture, increases in water use - both domestic and industrial - and improved flood defences have all altered the water regime in the region significantly. These changes are still continuing. Changes in wetlands have historically been recorded as changes in the plant species present. Unfortunately long term records are scarce (Wheeler and Shaw, 1992), so it is difficult to build up a picture of historic changes in flora, which could be compared with known changes in the water regime.

Another part of the problem in assessing the effect of changes in the water regime on wetland communities is that the timescales of the effects of the various changes are, in general, different. There may well be a time lag between the wetland water regime being affected and the effects becoming apparent through changes in plant communities.

It is well understood that, in the long term, any abstraction of groundwater must normally be balanced by an equivalent reduction in outflow from the aquifer system. (In some unusual circumstances, it is possible for this not to be true as abstraction can lead to an increase in recharge.) Natural outflow from the aquifer usually occurs as baseflow to rivers, springs, wetlands or direct discharge to the oceans. Thus an increase in abstraction will lead to a reduction in natural discharges. However, in the short-term the effect may not be deleterious. If an abstraction point is situated sufficiently remotely from the nearest discharge area, the time lag between the pumping period and the effect reaching the discharge may be sufficient that winter recharge will mitigate the effect. Thus a reduction in, say, river baseflow, caused by abstraction during the summer months, may not become effective until the level in the river is controlled more by surface runoff from winter rains. In this instance it can be considered that, to maintain the necessary water balance, the abstracted water 'comes from' a reduction in winter streamflow, and possibly an alleviation of floods.

3.2 Role of wetlands in a regional context.

Historically wetlands have not been appreciated in the way that they are now. Generally, remaining wetlands have been left because of the difficulty in draining them, or the marginal nature of the agricultural land which they could produce. The role of wetlands in flood protection, for instance, has not been widely appreciated until relatively recently.

In the long-term, wetlands are usually discharge points within the regional groundwater system. This has to be the case in East Anglia as precipitation is not sufficient to supply the required water during summer periods. For some wetlands, the aquifer they discharge consists of the superficial deposits in the area - not the underlying Chalk, Crag or Greensand aquifer. These superficial aquifers provide sufficient groundwater to meet the requirements of the wetland communities, and are not threatened by abstraction from the underlying aquifer, unless they act as conduits for water originating in the major aquifer. However, these superficial deposits are susceptible to changes in agricultural practice which may drain these deposits upstream of the wetland.

In the short-term, particularly during the summer months, or in drought periods, wetlands can recharge water to the aquifer. Thus the wetlands affect the groundwater levels in their vicinity, as well as being affected by the groundwater levels. The high porosity of undrained peat deposits present in many wetlands provides a large storage capacity. On drainage, or following serious drawdown consequent on groundwater abstraction, this storage capacity may be lost as a result of desiccation of the peat. These factors must be borne in mind when water level measurements in the wetland and the aquifer are made and interpreted.

3.3 The effects of changes in water levels on wetland sites

The effect of changes in groundwater levels on a wetland site depends on how the aquifer and the wetland are linked. Using the classification scheme of Lloyd *et al.* (1993) (Figure 1.1), different types of wetlands can be discussed. Lloyd *et al.* (op. cit.) distinguish between superficial aquifers and the main aquifer, the implicit assumption being that they are not hydraulically connected.

In this scheme, East Anglian fens fall mainly into the categories which have a significant groundwater input (B-F). The wetland categories deemed to be most at risk from abstraction from the main aquifer are categories B, D, E and F (see Table 1.1). Category C wetlands are fed only from superficial aquifers. Needless to say changes in the water regime in these aquifers will affect the wetland. Such changes could be caused by drainage of adjacent fields, or small local abstractions from the superficial aquifer.

Categories B and E are distinguishable only by surface water contributions. Thus a change in groundwater levels will have the same impact on the groundwater contributions to these two types. However, a similar percentage reduction in groundwater input will not be as significant to the hydrodynamics of the wetland in cases where the surface water contributions are great.

The volume of water contributed by the aquifer to these types of wetland is proportional to a difference in head between the aquifer and the wetland. The wetland head is constrained by ground level - when it rises above this level, flooding followed by surface runoff usually occurs. The aquifer head directly below the wetland is affected by the presence of the wetland above. The significance of this effect depends on the degree of connection between the aquifer and the wetland. If they are in close hydraulic continuity then the aquifer head will also be constrained by the ground surface, and the measured head difference between the wetland and the aquifer beneath could be very small at some times of year. However, this does not mean that the aquifer is not contributing greatly to the wetland water balance. Conversely, this does not necessarily mean that a small change in the regional aquifer water level will affect the wetland significantly.

If the connection between the wetland and the aquifer is not great - e.g. when separated by a low permeability layer - then the aquifer head directly below the wetland is not affected to such a great extent by the wetland. In this case the difference in head between the aquifer and the wetland can be used to indicate how much a change in head in the aquifer will affect the flow into the wetland. In crude terms, a 10% change in head difference will lead to a 10% change in flow.

Category F wetlands occur where the water table in an unconfined aquifer intersects the ground surface, and surface runoff is restricted. In these cases, if the water table is lowered so that it no longer intersects the surface, the wetland will lose its water supply. In many cases the existence of the wetland has caused a less permeable substrate to develop within the wet area. This acts as a semi-confining layer at the wetland and can prove to be locally very significant. In cases where the present wetland is smaller than in historic times, this low permeability layer can extend up-slope away from the wetland, thus dividing it further from the underlying water source. This complicates what at first site seems to be a simple scenario. However, in essence the dynamics of the system are similar to those described for categories B and E. A reduction in aquifer head will lead to a reduction in groundwater flow until a water level is reached where the groundwater contribution ceases entirely.

Category D wetlands are intermediate between categories B/E and F. Their response to a change in head in the underlying aquifer is the same as the response of the category B/E wetlands described above. The significance of this change in water input on the wetland depends on the relative contributions of the superficial and main aquifers. These wetlands are also susceptible to changes in the superficial aquifers, as described for category C wetlands. In some areas, the confining layer between the superficial and main aquifers may not be continuous. This would lead to the two aquifers being, to a large extent, in hydraulic continuity. Thus abstraction from the main aquifer could also affect the flow in the superficial aquifer, which would have an effect on the wetland. In this case the effect of a change in water level would be similar to the effect on category F wetlands.

The preceding discussion has described qualitatively the likely effect of a lowering of groundwater levels on wetlands using the Birmingham University classification scheme (Lloyd *et al.*, 1993). However, although the relative effects on different types of wetland can be described, this wetland classification gives no scope for assessing what is a significant drawdown for a category of wetland.

3.4 Effect of groundwater abstraction on water levels

It is well known that abstracting water from an aquifer causes a depression in the water table (or potentiometric surface for confined aquifers) within the aquifer. The size and shape of the 'cone of depression' created by a pumping well is dependant on many factors. The most important factors are: transmissivity, storage coefficient, recharge rate, boundary conditions and the spatial and temporal variations in these. The pumping rate of the borehole is also important, but as this is the one variable which we can control it will not be considered further.

Transmissivity and storage coefficients are generally determined by pumping tests (e.g. Headworth and Skinner, 1986). The analysis of a pumping test involves making certain assumptions about the regional geology and hydrogeology around the borehole. These generally consist of assumptions of continuous, uniform aquifers with uniform recharge and as such give no indication of variations in these parameters with distance. The zone of influence of a well pumping in a uniform aquifer with uniform hydraulic gradient is circular, thus the effect of the well at a given distance is independent of direction.

The question of whether the effect of well abstraction on a wetland is dependant on the well's position with regard to the catchment area of the wetland was considered by use of numerical modelling and is discussed in Appendix A3. The conclusion reached is that the effect of abstraction on a wetland is greatly influenced by the presence of hydraulic boundaries which affect the shape of the well's cone of depression. The position of the well inside or outside of the wetland groundwater catchment area was not significant. Thus the delineation of wetland groundwater catchments (a primary objective of Phase 1 of this project) has not been considered in Phase 2 of the project.

In practice the effect of pumping is altered by changes in local geology and lithology as well as by the existence of features, such as rivers which can affect the hydrogeological regime. Thus, these features must be considered before the effect of groundwater abstraction on a wetland can be quantified. The major features affecting the relationship between East Anglian wetland sites and the aquifers are: the buried channel network; drift aquifers, such as glacial sands and gravels; and modern river channels and drainage features.

3.4.1 Buried channels

The upper surface of the East Anglian Chalk is dissected by an extensive network of deep buried channels, which originated as pre-glacial river valleys and were considerably deepened, at times of lower sea-level, by fluvial or fluvio-glacial processes which have been the subject of debate in the Quaternary literature (Cox, 1985). The distribution of buried channels may not always relate to the modern drainage network.

The presence of buried valley features may have important implications on the susceptibility of specific wetland sites to groundwater abstraction. For instance, a buried valley acting as a barrier boundary would tend to enhance the effects of drawdown on the same bank, or to lessen them on the opposite bank, while a buried valley acting as a permeable conduit would propagate the cone of depression along the axis of the valley and reduce effects close to the borehole on either bank. Butler and Wenzhi Liu (1991) used a modelling technique to demonstrate the effects of a less permeable or more permeable strip in an otherwise homogeneous aquifer. This method, or alternatively digital modelling of a generic valley system, could be used to improve on initial estimates of drawdown induced at a wetland site.

3.4.2 Drift aquifers

In addition to the major aquifer units, the Chalk and the Crag, there are bodies of glacial sand and gravel, often on the flanks of valleys, which act as minor aquifers. Drift aquifers provide a capacity for recharge and storage close to the periphery of valley wetlands, a conduit for lateral groundwater flow from the major aquifers even where these are isolated vertically from superficial wetland deposits by semi-permeable horizons, and a source of acidic waters which may have considerable ecological significance on some sites. Unfortunately information about the extent, thickness and hydrological significance of drift aquifers is sparse, and geophysical and hydrogeological investigations may be necessary to establish the function of drift aquifers at a given wetland site. The presence of large tracts of sand and gravel, recorded for instance by the drift edition of the geological map, should be taken as a warning that the wetland could be affected both in its water budget and water quality by drawdown propagating through the drift aquifer.

Water quality gradients arising from groundwater sources add to the diversity of wetland sites, and there are indications from water quality and plant communities that some sites may have more than one water source: in particular Roydon Common and East Ruston Common have both acidic and base-rich waters. At Roydon the source of bases may be chalky drift, while at East Ruston acidic flushes were attributed in the University of Birmingham wetland dossier to the presence of brickearth.

3.4.3 Modern river channels and ditches

The significance of rivers has been dealt with briefly in the discussion of topographic catchment areas. In view of channel deepening and maintenance, it is probable that streams adjacent to wetland sites work almost exclusively as drains.

Within the wetland site itself, surface water flow is carried by drainage ditches and natural features, and the internal structure of the site may have considerable significance to its conservation value. In general, a valley wetland site (Figure 3.1) consists of three zones:

- a groundwater discharge zone in which springs and seepages give rise to relatively constant wetland water levels. However, the same zone can be in receipt of surface runoff from the local topographic catchment in winter, and sudden rises in water level may result from heavy rain. The seasonal pattern of water levels depends on the relative proportions of groundwater and surface water inputs.

- a central zone where some seepage is lost to evaporation during the summer, the remainder is progressively channelled by drainage ditches and natural water tracks, and water levels follow a seasonal cycle.

- a riparian zone where, owing to river channel management, there is often a steep hydraulic gradient towards the stream, drainage is more effective and water levels are low and variable. At Booton Common, for instance, this riparian zone is crossed by shallow channels: at many wetland sites the first step in water level control has been the blocking of such channels to restrict the width of the zone of riparian influence. On some sites, for instance floodplain wetlands or wetlands adjacent to Broads, the riparian zone may instead be subject to frequent inundation, and will again be an area whose vegetation community contrasts with that of groundwater-fed parts of the site.

3.5 Quantification of the effect of abstraction on wetland flows

The preceding discussion has shown that the interactions between wetlands and the other components of the hydrological regime within a catchment are complex. However, for the purposes of protection it is necessary to develop quantitative methodologies for assessing the possibility of a wetland site being adversely affected by controlled changes in this regime. In this instance, we are concerned with assessing the effects of groundwater abstraction on the amount of groundwater discharging at the wetland. It can readily be seen that it is not possible for this to be done precisely: as described above, a complete understanding of the wetland hydrology (in the form of the definition of a wetland function) would be necessary, and this is not readily available.

To make the problem tractable a number of simplifying assumptions are required, so that the relationship between the wetland discharge and the aquifer head can be described by a simple model and quantified by the (few) parameters of the model.

The classification system of Lloyd *et al.* (1993) allows for seven different categories of wetland. The system does not, however, describe the mechanism of water transfer between the aquifer and the wetland. A closer examination of wetland behaviour leads to the conclusion that the discharge rate is some function of the difference in head between the aquifer and the wetland. The exact form of this relationship is uncertain, as there is no recognised means of measuring the discharge at a wetland, and the measurement of the head difference is fraught with difficulties.

One way around this problem would be the use of numerical modelling. This would allow lateral variations in aquifer parameters to be incorporated into the analysis. Rivers, buried channels, streams and existing abstractions could also brought in to such a model. However, the methodology described in this report is intended as a preliminary to such detailed investigations, should this prove necessary. The level of sophistication available through numerical modelling cannot be justified, at this stage in the protection process, in view of the extra assumptions which would have to be made. There are dangers inherent in the use of simplified modelling. For instance, if a 'generic' wetland model is set up, as described by Klink (1991), the assumptions made by the modeller are not obvious to the user. This can lead to the use of inappropriate parameters, and also to a tendency to 'believe' the results of the modelling exercise.

For the work described in the rest of this report the assumption is made that the discharge varies linearly with the head difference. This can be expressed mathematically as:

$$q = C\,(h-H)$$

where: q is the discharge per unit area of wetland [L T^{-1}]
H is the head in the wetland [L]
h is the head in the aquifer [L]
and C is a wetland leakage factor [T^{-1}]

This description of wetland behaviour is the same as the formulation used in many numerical models (e.g. MODFLOW, FLOWPATH) to simulate surface water nodes (rivers, streams, lakes, drains etc).

This simplified model of wetland behaviour has just one 'conductance' parameter (C) which needs to be defined. This is a measure of the resistance to flow between the aquifer and the wetland. A wetland fed from an underlying semi-confined aquifer (Categories B, D and E) will have a low value for C, whilst one fed from a superficial or unconfined aquifer will have a higher value.

The range of values which C can assume can be estimated by considering the data collected for the sites examined in this project. The SEV analysis for the wetland sites considered in this project shows that between 100 and 1000 mm groundwater per annum are supplied from the aquifer to the wetland. Head measurements available from various sites indicate a head difference between the wetland and the aquifer immediately below the wetland as being in the range 0-2 m. As described above (Section 3.2), the head of concern here is the average head in the aquifer in the vicinity of the wetland. This is of course very difficult to measure, but it is possible to consider the head near the boundaries of the wetland as being more indicative of the average aquifer head under natural flow conditions, than the head beneath the centre of the wetland. Thus the range a values likely for (h-H) is probably 0.2 - 2 m.

Using these values it can be seen that the parameter C will probably fall in the range of 0.00014 to 0.014 day^{-1}.

The adoption of this conceptual model for wetland behaviour has enabled the development of a mathematical description of the relationship between wetland flow and the water levels in the underlying aquifer. This formulation is described in detail in Appendix A2, where details can also be found of the computer program (WETLWELL) developed. The description takes the form of a new 'well function' which will simulate the effect of abstraction on an idealized wetland. For given values of transmissivity (T), storage coefficient (S), pumping rate (Q), time of pumping (t), distance of well from wetland centre (r), radius of wetland (R) and wetland leakage factor (C), the program can estimate: the drawdown beneath the wetland centre at the end of pumping, the *maximum* drawdown at the same point, and the time at which it occurs; as well as the estimates of these parameters which would be obtained if the Theis well function had been used. It also provides estimates of the reduction of flow to the wetland.

The well function assumptions are similar to those used for the Theis well function: infinite, confined, uniform aquifer with horizontal flow. The function further assumes that the leakage between the aquifer and the wetland is vertical and that the surface water level in the wetland is constant despite the effects of pumping. This last assumption implies that the wetland can supply an infinite amount of water to the aquifer, which is patently not the case. Thus the results of this well function must be treated with caution if the volume of water supplied by the wetland is large - this generally happens after pumping for long times. (The WETLWELL program provides adequate information for a decision on whether the results are meaningful.)

The assumption of constant head within the wetland is also at odds with the conceptual development of the MIROS and SEV formulations, described in Section 2.4, which are used for the water balance calculations. This does not imply that the two models are incompatible. Rather it should be considered that the water level changes which undoubtedly do occur in the wetland are perturbations on the WETLWELL model. As long as the head changes are not great (in comparison to the head difference between the aquifer and the wetland, h-H) the effect on the flow in the aquifer is within the uncertainty of the overall model formulation, especially given the lack of constraint on the value of C used in the model. However, this does again mean that the output from WETLWELL must be considered critically.

This well function was created to give a better estimate of the drawdown below a wetland caused by pumping than could be obtained by using conventional well functions (e.g. Theis). Its use requires an estimate of the parameter C described above, which implies some understanding of the wetland aquifer interaction. The effect of the value chosen for C is shown in Figure 3.2. (The Theis function corresponds to the special case of no leakage between the aquifer and the wetland, C=0.)

As described in Appendix A2, this conceptual model for the wetland also allows an estimation to be made of the reduction in flow to the wetland caused by a pumping well. The estimation made is doubly dependant on the value chosen for C: the magnitude of C affects the calculated drawdown below the wetland, and the value of C determines how much flow this change in head will produce.

In reality, the quantity that is of interest when deciding whether a wetland is likely to be adversely affected by pumping is the relative change in water flowing to the wetland from the aquifer. The emphasis in Phase 1 of the project on calculating drawdowns was pragmatic: there seemed to be no other easily available method for quantifying possible effects. However, with the development of the new 'well function' described above (and in Appendix A2), it is now possible to estimate the effects of pumping on wetland *flow*. (The Theis drawdown might also have been used to estimate a flux reduction, for a given C value, but in general this would have grossly overestimated those reductions.)

If a MIROS model (see Section 2.4) of the wetland system has been developed then the calculated reduction in leakage to the wetland can be compared to the wetland groundwater requirement to see if it is significant. This gives a comprehensive method for assessing the vulnerability of the wetland to degradation by an abstraction.

The value calculated by the WETLWELL program (Appendix A2) for reduction in leakage is highly dependant on the chosen value of C. For the wetlands considered in this study, C will probably be in the range 10^{-2} to 10^{-4} day^{-1}. The effect of using this range of values has been demonstrated using data for Redgrave and Lopham Fens. The abstraction data used to estimate the effect of all existing abstractions (Appendix B) has been used with the WETLWELL program to estimate changes in drawdown and leakage. The results are shown in Table 3.1

Another important observation is that the maximum drawdown at the wetland, caused by pumping, can occur a significant period after the end of pumping and can be many orders of magnitude greater than the drawdown at the end of pumping. (See Figures A2.2 and A2.4.) The effect increases with: decreasing pumping period and transmissivity and increasing storage coefficient and distance to pumping well. This is true for both the Theis and the newly developed well-function. The fact that such delayed 'pulsed' drawdowns are of relatively short duration is also relevant to the impact on wetlands.

Table 3.1 Demonstration of the sensitivity of drawdowns and leakage to the value of C.

	C (d^{-1})		
	0.01	0.001	0.0001
Total Theis drawdown (m)	1.08	1.08	1.08
Total WETLWELL drawdown (m)	0.23	0.82	1.05
WETLWELL leakage reduction (m^3/d)	3340	1040	130

Calculations using abstraction data for licensed pumping within 4 km of Redgrave and Lopham Fens (see Appendix B).
T= 3000 m^3/d, S=0.0005, R (wetland radius) = 630 m, t (pumping time)= 200 d

3.6 The 10% rule

In some cases it may not be feasible to use the WETLWELL program to investigate the effects of pumping on a wetland site. This may be for reasons of time, or it may not be possible to assign a realistic C value to a wetland site.

In this case a simple rule is required to allow an immediate assessment of the possibility of wetland derogation to be made. There are several criteria that could be used for testing the effect a proposed abstractions may have on a wetland. The one suggested here is based on the premise that, as the wetlands continue to survive, they must be able to cope with the natural fluctuations in the water table. Thus the additional change in head in the vicinity of the wetland caused by the abstraction should be compared in some way with the measured natural variations. The method recommended is to:

> Limit the change in head to a certain percentage of the range between mean summer water levels and minimum measured levels in the underlying aquifer.

This condition is based on the understanding that the wetland does not dry out during a 'normal' summer, and has not dried out completely in previous drought years. Thus the wetland will be maintained in a 'standard' year as long as the aquifer water level does not drop below the minimum measured value. However, if the water level is reduced this much then there is no leeway for future droughts. This is why only a percentage of this range should be used.

To investigate this suggested criterion, mean and minimum water levels were calculated from the water level monitoring points nearest the 12 Phase 1 wetlands. These were compared with estimates of drawdowns caused by existing abstractions, calculated using the Theis equation. The results are shown in Table 3.2.

Table 3.2 **Estimation of drawdown due to existing abstractions (Theis method), and its relationship to mean and minimum summer water levels for Phase 1 sites.**

	Nearest Water Level Monitoring Point	Minimum Summer Water Level A	Mean Summer Water Level B	Estimated Drawdown Due to Present Abstractions C	Percentage C/(B-A)
Dersingham Bog	TF62/029A	12.4	13.5	0.00	0
East Walton Common	TF71/005	6.9	8.3	0.74	53
Gt. Cressingham Fen	TF80/010	27.0	28.6	0.80	50
Middle Harling Fen	TL98/012	15.3	16.9	1.04	65
Roydon Common	TF62/030	5.1	5.8	0.21	30
Badley Moor	TG01/136	43.5	44.9	0.84	60
Booton Common	TG12/172	40.1	41.3	1.70	142
Ducans Marsh	TG30/572	1.5	3.0	0.62	41
East Ruston Common	TG32/760	0.5	1.4	1.61	179
Forncett Meadows	TM19/821	32.4	35.8	1.07	31
Potter&Scarning Fens	TF91/622	48.1	49.2	1.95	177
Shotesham Common	TM29/278	20.0	20.5	0.03	6

In view of the acknowledged difficulty in assigning the evidence of dehydration on a site to real hydrological causes, mostly either drainage or abstraction, rather than to other causes such as changes in management (Wheeler and Shaw, 1992), it has not been possible to present a precise, scientifically justified limit to the allowable drawdown at a site, as a result of new abstractions. Wheeler and Shaw's assessment of dehydration effects of 11 of the 12 Phase 1 sites has been examined in relation to the estimated drawdown due to existing actual abstractions, and it has been found that, in general, adverse effects are associated with drawdowns that exceed 10% of the difference in mean and maximum summer piezometric heads in the aquifer. Thus the suggested rule is that the effects of groundwater abstraction should be limited to 10% of the difference between the mean and minimum summer water levels in the aquifer underlying the wetland.

3.7 Relating drawdown in the aquifer to impact on the wetland water regime

The direct effect of an abstraction borehole is to lower the piezometric head in the aquifer. This lowering will have an impact on groundwater discharge to a wetland area, which will in turn change the water regime of the site, tending to increase SEV's. Without site-specific data it is difficult to predict the actual form of the relationship between groundwater discharge and piezometric head. Sites where there is a large upward hydraulic gradient driving vertical seepage, as at Badley Moor, appear to be scarce, and the recent programme of piezometer installation at East Anglian wetland sites has indicated that in general there is only a small difference in hydraulic head between the wetland and the aquifer. However the relationship is well researched for the Phase 1 site Great Cressingham Fen, where there is a close linear relation between the head measured in certain Chalk boreholes and the discharge of the spring. At Great Cressingham the discharge of the spring averaged 17 litres/sec (44.8 Ml/month) over the period July 1984 to February 1992 and linear regression on the groundwater level in two boreholes on site indicated that the discharge increased by 22.44 and 29.06 litres/sec for each metre change in water level (Hyatt, 1990).

If it can be assumed that other groundwater discharges to the Great Cressingham site vary in a similar way, the effect of a change in piezometric head bringing about a decrease in springflow would be to decrease the wetland groundwater catchment by the same factor. For any given change in the wetland groundwater catchment area, it is possible using the MIROS model to calculate the change in the long-term average SEV(>20).

Other factors being equal, the effect depends upon the numerical value of the wetland groundwater catchment area: if there is little groundwater input to a site (a very small wetland groundwater catchment area) a drawdown in the aquifer will have little effect on the SEV, while conversely if the wetland groundwater catchment area is very large, much of the supplied groundwater drains off, and wetland water levels are not changed appreciably by reducing the groundwater input. In the intermediate range of catchment area, the magnitude of the effect is not especially sensitive to the area. Figure 3.3 illustrates the general form of the relationship between drawdown in the aquifer, the wetland groundwater catchment area, and the change in the long-term SEV(>20).

If, for any wetland site, the relationship between piezometric head in the aquifer and groundwater discharge to the wetland were available, this method could be used to delineate the range of drawdowns which could be expected to have deleterious effects. For instance for Great Cressingham Fen, a drawdown in excess of 0.125 m would cause an increase of more than 0.5 metre-weeks in the average SEV(>20). In view of the large range of SEV(>20) from year to year, and the difficulty in assigning any given species to a small range of SEV(>20), it is suggested that a 0.5 metre-week increase be regarded as an acceptable change. If a drawdown due to abstraction were expected to cause a greater change than this there would be a strong case for a more detailed study of the site before abstraction could be permitted.

There are few data on which to base a more general model of the variation of springflow with potentiometric head. The linear relationship exhibited at Great Cressingham is a special case of the relationship proposed in Section 3.5 of this Report, but it is clear that the coefficient, analogous with the wetland leakage factor C, could vary from site to site. The only other evidence available to this investigation comes from Chippenham Fen, where a water balance study made it possible to estimate spring flows on a monthly basis (Mason, 1990). At Great Cressingham Fen, the linear model predicted that a decline in piezometric head of 0.65 m would be sufficient to reduce spring discharge from its long-term average value to zero: at

Chippenham Fen the corresponding drawdown was 1.45 m.

In the absence of more detailed springflow measurements, a conservative approach would be to assume that a drawdown of 0.5 m in the aquifer would suffice to eliminate groundwater discharge to the wetland. Lesser drawdowns would have pro rata effects on the groundwater discharge. This assumption makes it possible to prepare a version of Figure 3.3 for each of the Phase 2 sites (see Appendix B), and to estimate a maximum acceptable aquifer drawdown for each site. The maximum acceptable drawdown is such that the increase in long-term SEV(>20) does not exceed 0.5 metre-weeks.

For a number of the Phase 1 and Phase 2 sites, an attempt was made to relate the Wheeler and Shaw (1992) dehydration assessments, on a four-point scale, to the estimated drawdown due to existing actual abstractions (Figure 3.4). These two very different indices of hydrological impact would not be expected to correlate closely, but in general adverse effects, in the form of a dehydration value on point 1 of the scale or higher, are associated with a drawdown in excess of 2.5 times the maximum acceptable drawdown evaluated by the method set out above.

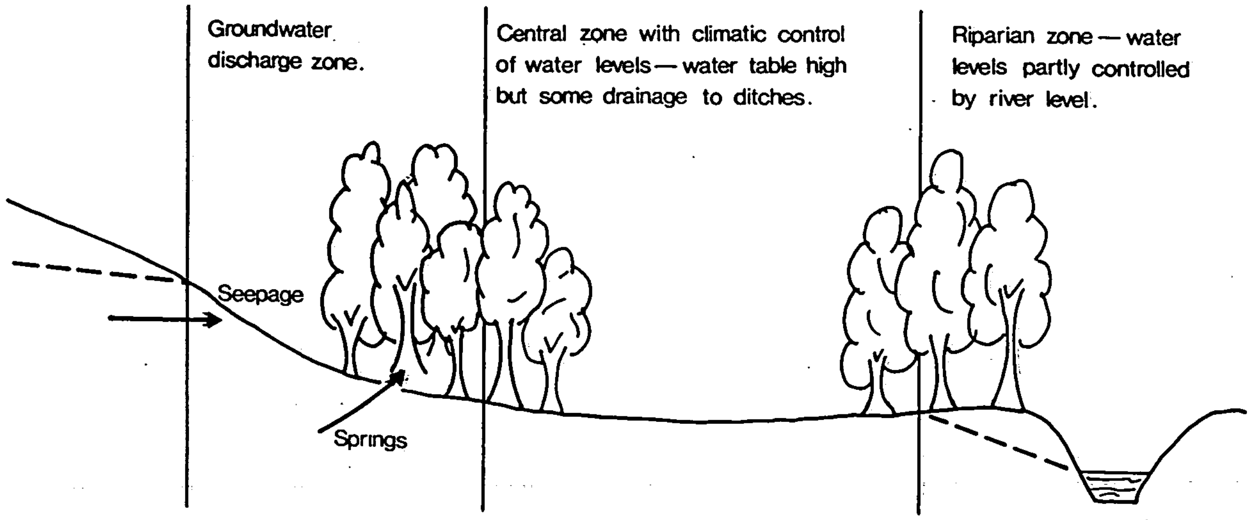

Figure 3.1 Three hydrological zones within a groundwater fed wetland site.

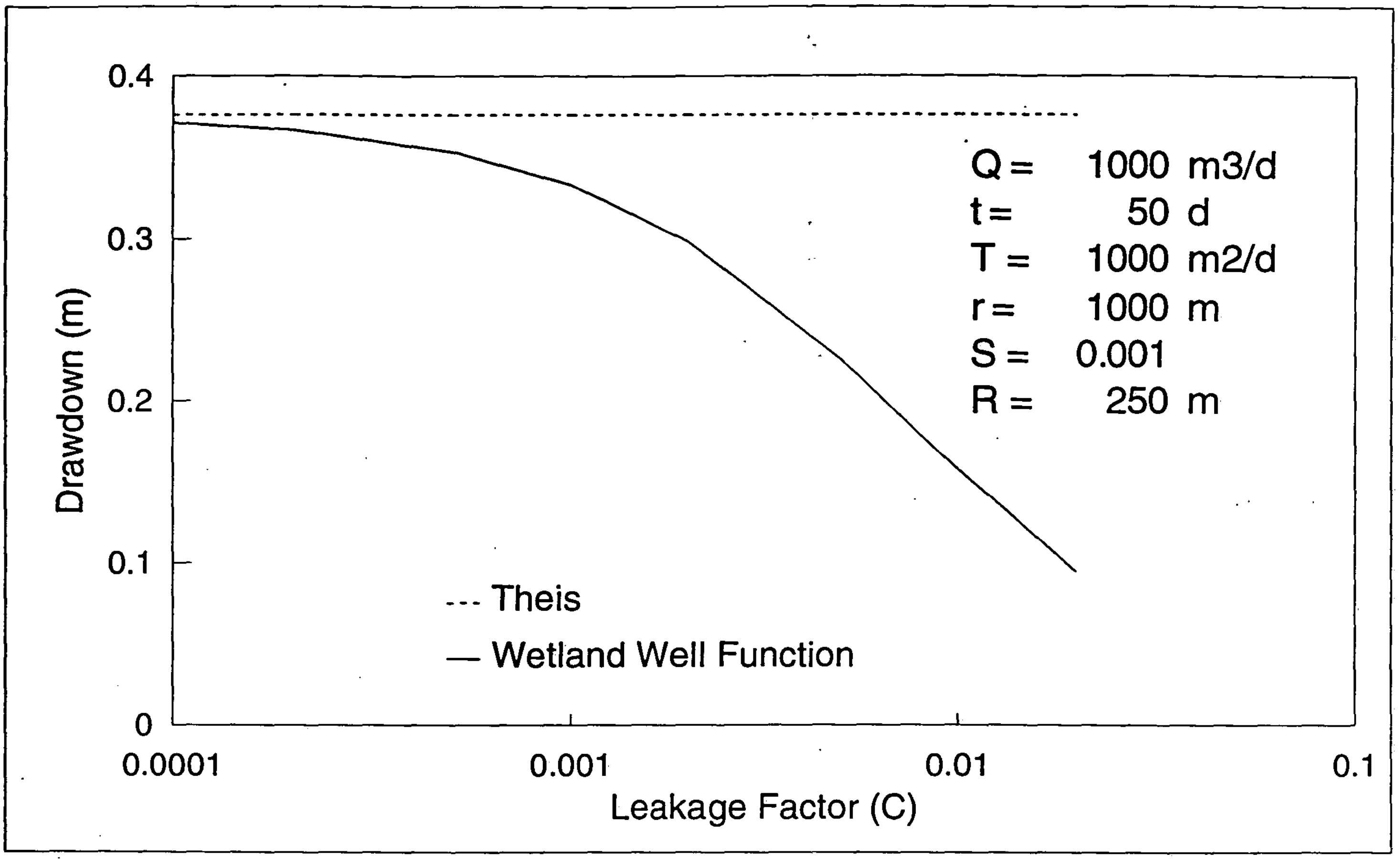

Figure 3.2 The effect of changing the value of wetland leakage factor (C) on drawdown beneath a wetland.

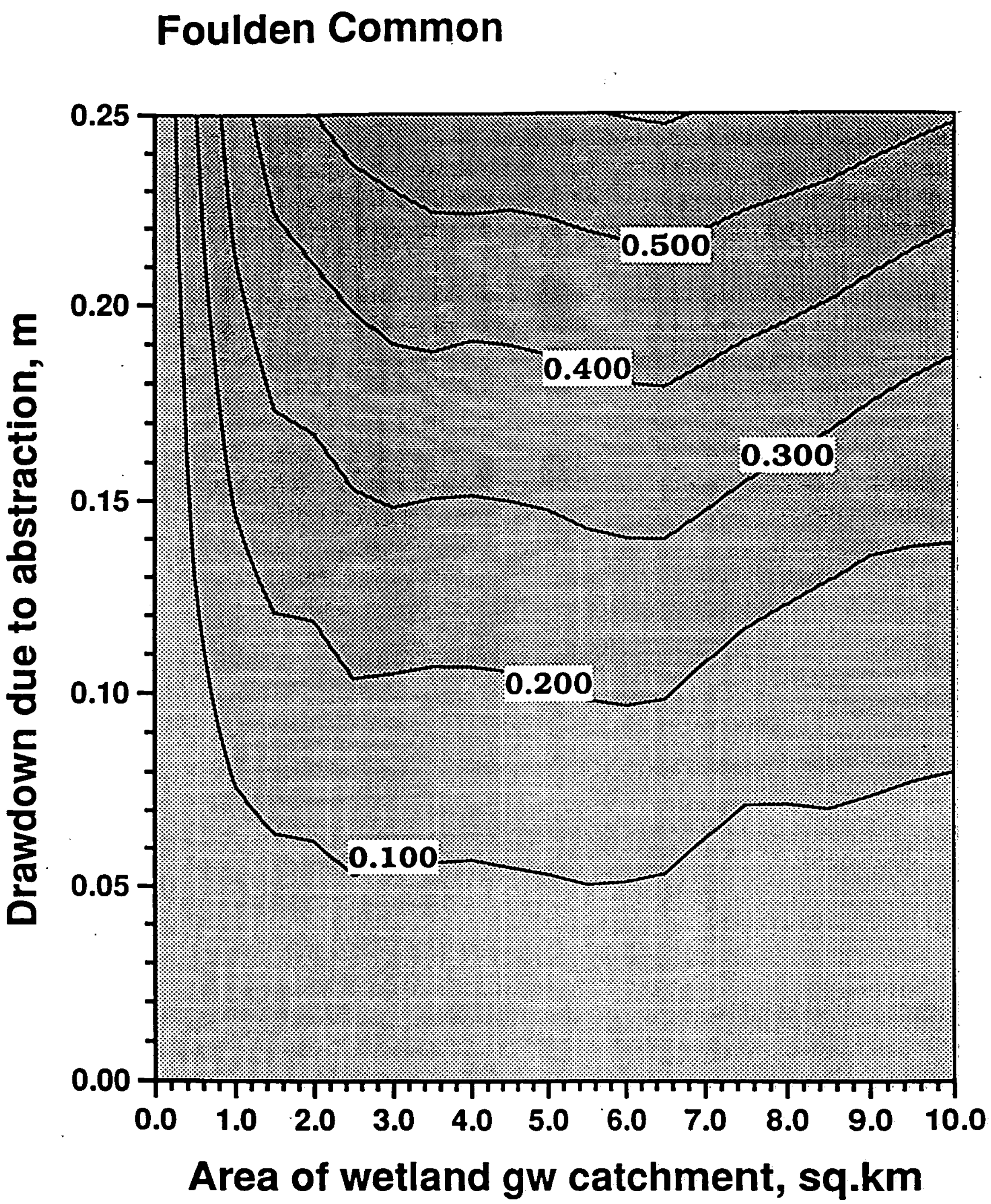

Figure 3.3 Contours of change in SEV>20 (expressed in metre-weeks) for ranges in drawdown and wetland groundwater catchment area.

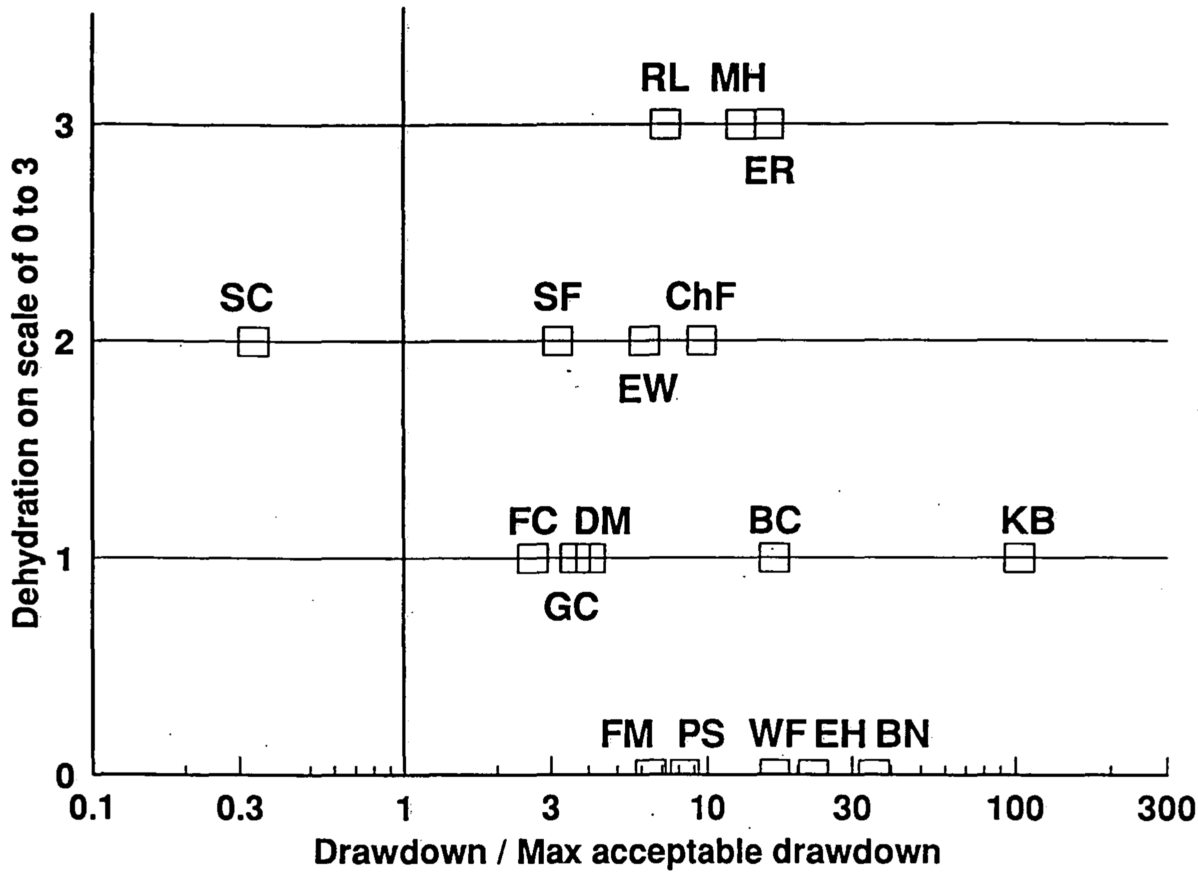

Figure 3.4 Existing groundwater abstractions may have brought about the dehydration effects observed by Wheeler and Shaw (1992) at Phase 1 and Phase 2 sites. There is little apparent correlation between the drawdown due to existing abstractions (see Appendix B), expressed as a ratio to the maximum acceptable aquifer drawdown computed from the MIROS/SEV model, and the dehydration index. (key: BC Booton Common, BN Blo'Norton Fen, ChF Chippenham Fen, DM Ducan's Marsh, EH East Harling Common, ER East Ruston Common, EW East Walton Common, FC Foulden Common, FM Forncett Meadows, GC Great Cressingham Fen, KB Kenninghall and Banham Fens, MH Middle Harling Fen, PS Potter and Scarning Fen, RL Redgrave and Lopham Fens, SC Shotesham Common, SF Smallburgh Fen, WF Weston Fen.)

4. Methodologies

A major objective of this project has been the development of methodologies for rapid assessment of the vulnerability of wetland sites to groundwater abstraction. The timescale over which such assessments will have to be made, and the likelihood that proposed abstractions will involve sites with no prior hydrological information, have been constantly borne in mind. The methodologies proposed are necessarily simplistic but, it is believed, reliable. They depend on a number of reasonable assumptions which can be tested against experience and the accumulating database on wetland hydrology. The underlying ideas behind the methodologies are:-

1. It is possible to construct a simple conceptual model of a wetland site, based upon annual topping up of the system by autumn and winter rainfall, the drainage of excess water to control maximum levels, and drawdown by evaporation in summer. Despite local factors such as important springs (e.g. at Badley Moor) and the influence of Broads (e.g. at Catfield Fen), wetlands within a region of the scale of East Anglia are broadly similar in their water budget requirements. Other factors, notably the build-up of peat, also work towards uniformity between sites. Wetland water level measurements demonstrate this homogeneity between sites. The variation within a given site, owing to non-uniformity in water supply, soil hydraulic properties and water level control, can exceed differences between sites.

2. Water level changes within a wetland depend for the most part on a measurable climatological variable, rainfall, and on quantities that are quite easily calculated, such as the potential evaporation rate and the soil moisture deficit. Once the effects of seasonal and year-to-year variations in climate are taken into account, and provided that there have not been significant man-induced changes in the supply of groundwater, seasonal wetland water level variations and changes in the summer drawdown from year to year can be explained. It is possible to predict the effect of small changes to a quasi-periodic water level regime with a wide range of variation, and even to draw plausible conclusions about effects during extreme drought years.

3. In general, the needs of the various wetland plant communities within a given site are met by landform, and by very localised hydrology, which define the range of soil moisture and water level variations. For instance, the sloping margins of an open water body provide a succession of hydrological conditions, and support a sequence of vegetation communities with requirements ranging (in simple terms) from wet to dry. Local changes in the water budget, if sufficiently small and gradual, may change the location of vegetation zones within a wetland, and some habitats, usually the wettest, may be in danger. However, if the overall water requirements of the site can be satisfied, in quantity and quality, the minor components of the ecosystem can be maintained by natural processes and if necessary by management, especially by the control of water levels within the site.

Although, as has often been asserted on ecological grounds, every wetland site is unique (Lloyd *et al.*, 1993), there are sufficient grounds for making the first approach to the problem of the impact of groundwater abstraction with a generalised methodology. This can give way to a more lengthy and detailed assessment for those sites found to be susceptible to water level change. The methodologies, which will be described in detail in this Section, fall into two categories.

The first category contains the methodologies to be used when a new, or altered, abstraction proposal is being considered by the NRA. Application of these methodologies will enable the NRA to assess whether such a proposal is likely to have an effect on the local wetland sites, and if so, the likely magnitude of that effect. This will enable the NRA to suggest suitable monitoring during pumping tests, for example, or to request a full site investigation. These methodologies are described in Section 4.1 and 4.2.

The second category contains those methodologies which will enable a particular wetland site to be investigated. This may be as part of an impact assessment or as part of a research programme designed to better understand wetland processes. By their very nature these methodologies will require a much greater input of time and effort if they are to be performed successfully. Needless to say, the assessment of the possible effects of abstraction can be much better quantified if this process has been carried out. These are described in Sections 4.3 and 4.4.

In some cases it will, of course, be appropriate to use some methods from each category. This should cause no problems as the methodologies are hierarchical and are all developed from the understanding of wetland hydrology and hydrogeology described in the preceding sections of this report.

4.1 Methodology to apply when considering an abstraction proposal

The impact of groundwater abstraction on wetland sites depends on the contribution made by groundwater to the water budget under natural conditions. Drawdown in the aquifer may reduce or reverse the hydraulic gradient towards the discharge area, and in extreme cases, a wetland may drain into the aquifer by reverse flow along the very pathways that formerly sustained it.

When a proposal is received for a new (or revised) groundwater abstraction license, the NRA Licensing Manual provides guidance on the steps that should be followed to ensure that other licenses in the area are not derogated. In the same way, an easily applied procedure is required to protect wetlands. The methodology described below is designed to fulfil this requirement.

1. Receive abstraction proposal	Use records to estimate possible T and S for the aquifer in this area - confined, unconfined, leaky (leaky parameters)
2. Is this abstraction likely to have an impact on a wetland ?	Use Theis/Hantush/de Glee to calculate a zone of influence - where drawdown is greater than (say) 1cm. Is there a wetland in this area?

3.	Collect available data about wetland	SSSI notification BU Dossier EN or other reports
4.	Decide which aquifer is feeding the wetland	Is this the same aquifer as the proposed abstraction?
5.	Consider the local hydrogeology	Is there a river between the wetland and the proposed abstraction? Is there a buried channel in the vicinity - if so, is it a barrier or a conduit?
6.	Calculate the possible drawdown in the aquifer below the wetland due to the proposed abstraction	Method used takes into account the local hydrogeology
7.	Is this a significant drawdown ?	Use '10%-rule' Compare with MIROS results if available (see Sections 4.3 and 4.4)

Guidance notes:

1. This step should be incorporated into the NRA Licensing Manual

2. The appropriate equation should be used depending on the local conditions. This calculation is similar to the one recommended in the Licensing Manual for specifying the area for monitoring during a pumping test. Alternatively the radius recommended in Section 4.10.1 of Chapter 3 of the Licensing Manual could be used.

3. When it has been decided that a wetland may be affected by the proposed abstraction, if a license were granted, then all available details about the wetland should be collated.

4. Available data and local geological and hydrogeological maps should be sufficient to enable the aquifer supporting the wetland to be determined. If there is not sufficient information then it should be assumed that the wetland is supported by the aquifer from which the proposed abstraction will take place - a conservative assumption.

5. As described in Section 3.4 hydrological and geological features will affect the shape of the cone of depression caused by abstraction. However in many cases the degree of connection between rivers and underlying aquifers is not well understood. In order to be certain of protecting the wetland it may be expedient at this stage to ignore the presence of possible recharge or barrier boundaries between the proposed abstraction and the wetland. Barrier boundaries in the direction away from the wetland, however, may cause increased drawdown in the vicinity of the wetland. If this is thought to be the case, or if the effects of recharge boundaries are known to be significant, the effects can be simulated by means of image wells. (For details of image well theory, see for example Freeze and Cherry (1979) p 330-331.)

6. The easiest method for this calculation, which also probably gives the 'worst-case' drawdown is to use the Theis equation. This is usually applied using appropriate values of T and S decided on in 1 above and a time limit of 200 days (chosen to represent a summer drought).

   The new well function described in Section 3.5 and Appendix A2 can also be used. This is appropriate for use with applications for time-restricted applications (e.g. for spray irrigation). For this method to be applied a value of the wetland leakage factor (C, see Section 3.5) must be assigned. (If C=0 is chosen the result is the same as for the Theis function but the program provided (WETLWELL) can include limited abstraction periods and multiple wells.) Section 3.5 gave a range within which this parameter would be expected but that range was wide (2 orders of magnitude) and so further refinement is required. If data exist about the water levels within the wetland and the underlying aquifer these can be used to restrict this range. Alternatively the Birmingham University classification may indicate whether the source aquifer is confined (Category B, D and E) and thus has a low value for C or unconfined (Category G or F) and has a high value.

   Whichever method is chosen, appropriate image wells should be incorporated at this stage.

7. Answering this question is fundamental to the protection of the wetland. However, as much of the preceding report has emphasised, the relationship between the groundwater levels and the health of the wetland is poorly understood. The method of answering this question will depend greatly on the understanding that exists of the hydraulic behaviour of the particular wetland. Where there are little or no data about the site, the '10%-rule' suggested in Phase 1 of the project (Adams *et al.*, 1994) and described in detail in Section 3.6 can be used.

   If the site has been investigated using the methodologies described in Sections 4.3 and 4.4 below, then a MIROS model for the site should exist and SEV calculations should have been carried out. In this case, the assessment should have given an indication of the likely C value appropriate to the site. The wetland well function program (WETLWELL) calculates a change in flow to the wetland caused by pumping. This value can be compared with the value of wetland seepage calculated by the MIROS model. If the estimated value is small compared to the estimated range of values for groundwater contribution to the wetland then it is probable that the wetland will not be significantly affected by the proposed pumping.

   Alternatively the effect of changing the groundwater input to the wetland, by the amount calculated by WETLWELL program on the mean SEV for the site can be calculated. If this is greater than 0.5 m.wks (see Section 3.7) then it is likely than the wetland will be derogated.

4.2 Impacts of current abstractions

It is impossible to imagine that the present licensed pumping regime has not already had an impact on groundwater levels in the vicinity of wetlands. However the effects of this water level change are difficult to establish. Groundwater has been abstracted in East Anglia for a considerable period of time, but during that time there have also been great changes in agricultural practice resulting in improved field drainage and the clearance of many stream channels. Thus, whilst it is possible to use a methodology similar to that described above to assess the probable impacts of pumping on groundwater levels in the vicinity of wetlands, it is not possible to say categorically that it is this change which has caused a noticed change in the wetland.

Most of the water level data which exist about wetlands have been collected relatively recently. Because of this, there is little evidence which would allow long term trends in the vicinity of wetlands to be examined. Wheeler and Shaw (1992) gave recommendations on how sites should be monitored for signs of change, but also pointed out that, as this had not been done systematically in the past, it was difficult to assess the effects of past changes in the hydrological regime.

The methodology described above for the assessment of the impact of new boreholes can be used to assess the impact of historical abstractions. Care must be taken when applying the '10%-rule' as the monitored groundwater levels have also been affected by the pumping that they are being used to assess.

4.3 Desk studies - classification of wetlands

If a wetland site is chosen for greater study than that required for a preliminary assessment of a licensing proposal, then the first stage should be a desk study of available information. The purpose of the desk study is to gain greater understanding of the local and regional hydrology and hydrogeology which will affect the wetland response to change.

The methodology presented in this Section is an expanded version of stage 3 in Section 4.1 above. This methodology is to be followed thoughtfully, using whatever information and data are to hand, and there is considerable value in making an initial qualitative assessment of the site:-

1. From topographic maps. Is the site adjacent to a large open water body, which could help to maintain water levels, particularly in summer, in the lowest parts of the site, as for example at Broad Fen and Catfield Fen (Gilvear *et al.*, 1994)? Does a surface stream, draining a large catchment area, perform the same function? In this case, channel improvement may have resulted in lowered wetland water levels. At the 1:10,000 scale, major springs may be marked, and there will be indications of flow directions in dykes, but because of ditch maintenance or the lack of it, it is impossible to judge the hydrological significance of ditches from the map (Gilvear *et al.*, 1989). Furthermore updating of water features by mapmakers is patchy and infrequent.

2. From available ecological records (for example an SSSI notification). The general ecological description of the site may be of some help, for instance fen will be more vulnerable to changes in aquifer water levels than wet meadow or heath. Specific details may be more significant: ecological survey will have identified important

springs (for example the description of the distribution of springs at Weston Fen given by Bellamy and Rose, 1960), and there may be indications of loss of species or a decline attributable to past wetland water level changes (Harding, 1992). On the other hand, assertions of ecological change resulting from the impact of abstraction should always be examined critically: the effects of cessation of management, cutting and grazing may be similar (Wheeler and Shaw, 1992).

3. From geological information. The source of groundwater to the site may be the same major aquifer unit as the proposed abstraction, or the site may be supplied from minor aquifers with or without hydraulic connection to the major aquifer. The presence of an apparently continuous drift cover need not be an obstacle to the movement of groundwater from the underlying aquifer. For instance, 'windows' in aquitard layers are known to exist beneath Badley Moor, Catfield Fen and Redgrave and Lopham Fens (Gilvear *et al.*, 1989).

4.4 Water requirements of wetlands - using a water budget model

In order to be able to make quantitative predictions about the effect of changing hydrological and hydrogeological inputs to a wetland site, the water balance of the wetland must be quantified. The vulnerability of a wetland site to the effects of groundwater abstraction will depend on the significance of groundwater inputs to its water budget, not as an annual average but as a regulating influence on summer water levels. Thus a monthly water budget model or the wetland should be constructed. A monthly water budget model can also be used to determine the effects of changed groundwater inputs on the Sum Exceedance Value.

4.4.1 Water budget components

Several components of the wetland water budget are estimated from climate records, and serve as input or independent variables in the MIROS model. These are the rainfall, surface water inflow, and evaporative losses. The preparation of monthly records for these components has been described in Section 2.4 of this Report, and presents no difficulty, though computation from a typical non-complete data set is time-consuming.

The groundwater input to a wetland is also derived from climate records, but requires a knowledge of the groundwater catchment area of the wetland. For many of the applications of the MIROS model, this parameter is the one that is used as the input variable. Changing the value used for the groundwater catchment area has the same effect as changing the contribution groundwater makes to the wetland water budget. The change in the volume of groundwater input is linear with the change in catchment area (i.e. if the value used for the catchment area is doubled, the groundwater input to the wetland will be doubled).

4.4.2 Water table elevation

The principal output from the MIROS model is an estimate of the wetland water table elevation at the end of each month. The inputs of the water budget are summed, the estimate of actual evapotranspiration for the month is subtracted, and the resulting net input is compared with the amount of storage available below the 'drainage level', which is set at 0.05 m below the ground surface.

Changes in storage are related to changes in water table elevation by the specific yield. For fen peat this is usually around 20%, and in the absence of more detailed information this estimate has been applied to all the Phase 2 sites. By analogy with the computation of an SMD, if the net input of water is positive in sign and takes the water table above the drainage level, excess water is deemed to have run off.

4.4.3 Sum Exceedance Values

Sum Exceedance Values (>20 cm) (see Section 2.2 and Appendix A1) are calculated in metre-weeks for each year of the record, using the trapezium rule to integrate the wetland water level estimates. The integration is carried out only for water table elevations in excess of 0.2 m below ground level (0.15 m below the drainage level). Of particular significance are the mean and maximum SEV>20 over the 25 year period: these vary according to the choice of the parameters of the model, especially the area of the wetland groundwater catchment. The MIROS model can be used to refine the estimate of the wetland groundwater catchment by making the reasonable assumption that the SEV for wetland sites exhibits some uniformity across the different sites occupied by similar vegetation communities.

In the Phase 1 Report, the assumption was made that the maximum SEV>20 over the period from 1970 to 1992 should be at least 7 metre-weeks, and that the mean SEV>20 over the same period should be less than 2 metre-weeks. The maximum SEV in a period is not a very satisfactory statistic, in that it does not integrate in any way over the period and is too sensitive to one extreme year. In this Report, for the Phase 2 sites, an alternative assumption is made, which takes into account the common experience that there is a moderate summer water level decline on all wetland sites. It is assumed that the mean SEV>20 over a long period will always be more than 1 metre-week. The limits on the mean SEV>20 impose limits on the size of the wetland groundwater catchment (see Table 4.1). For the Phase 1 sites, the ranges are broadly similar to those obtained by setting a lower limit on the maximum SEV, but it is felt that the limits imposed on the mean have a more scientific grounding. As more wetland water table measurements become available, it will be possible to redefine these limits.

The wetland groundwater catchment calculated using MIROS and the SEV method is the catchment providing the groundwater flow that sustains water levels within the 'field' areas of the wetland. It is possible for considerable quantities of discrete springflow to enter the wetland site, and to leave, without taking an active part in sustaining water levels. The method set out above does not account for this springflow, which must be estimated from local information, such as might be obtained by site investigation. The close examination of site dossiers (see Section 4.3) should yield clues to the presence of significant discrete springflow, but there are few actual flow measurements on which to base a more accurate model.

Table 4.1 Upper and lower limits on the area of the wetland groundwater catchments.

Site	Area of wetland groundwater catchment, sq.km. Lower limit Mean SEV(>20) = 2 m.wk	Upper limit Mean SEV(>20) = 1 m.wk
Phase 1		
Badley Moor	0.19	0.57
Booton Common	0.086	0.21
Ducans Marsh	0.19	0.44
East Ruston Common	1.23	2.6
East Walton Common	2.2	3.8
Forncett Meadows	0.23	0.53
Great Cressingham Fen	0.17	0.52
Middle Harling Fen	0.29	0.56
Potter and Scarning Fens	0.12	0.38
Shotesham Common	2.6	4.1
Phase 2		
Blo' Norton & Thelnetham Fens	1.05	2.1
Broad Fen	1.2	3.2
Catfield Fen	2.1	5.4
Chippenham Fen	3.1	6.9
East Harling Common	0.34	0.71
Foulden Common	1.8	5.8
Hopton Fen	0.27	0.55
Kenninghall & Banham Fens & Quidenham Mere	0.9	2.1
Redgrave & Lopham Fens	4.9	10.7
Smallburgh Fen	0.25	0.64
Weston Fen	1.65	3.8

4.4.4 Using MIROS and SEV to investigate wetland behaviour

The construction of a MIROS model for a wetland will lead to insights into the roles that the individual components of the water balance have on the specific wetland being considered. The MIROS model can also be used to investigate the susceptibility of the wetland to groundwater abstraction. This use of the MIROS model compliments the methods described in Sections 4.1 and 4.2, where the problem to be resolved was that of a *specific abstraction* on any number of nearby wetlands. Here we are concerned with investigating the effect of numerous abstractions on a particular wetland.

The methodology to be followed depends to a large degree on the type of investigation that is being carried out. A research based project will naturally wish to consider the effect of varying many of the assumptions inherent in the construction of the MIROS model, and its application to the SEV concept. An operational investigation will accept the ranges of these parameters recommended here (and adapted in the light of experience) to consider more practical aspects of wetland protection. Because of this multiplicity of potential uses, the methodologies that may be followed are described briefly. Reference to previous sections of this report will explain the details involved.

1. For a given groundwater catchment area (groundwater input) MIROS will calculate a mean SEV (>20) for the period modelled.

2. Changing the groundwater catchment area gives a different groundwater input (i.e. changes the flux) and a different mean SEV(>20).

3. Using WETLWELL we can calculate a change in flux and a change in aquifer head due to pumping.

4. If we assume that a change in mean SEV of more than 0.5 m.wks will adversely affect the wetland (this figure may be changed in light of more data), then, given 2 and 3 above, an assessment can be made as to whether a particular abstraction will adversely affect the wetland.

5. Using the assumption that a healthy wetland will have a mean SEV(>20) between 1 and 2 m.wks (these figures may be changed in light of more data), a range of likely groundwater catchment areas and a range of likely groundwater inputs can be estimated.

6. If we assume that all wetlands are similar to Great Cressingham Fen (i.e. dry out when the aquifer head changes by 0.5 m) then a drawdown that will give a change in SEV(>20) of 0.5 m.wks can be calculated.

Thus the MIROS model and the SEV concept gives a tool for investigating many aspects of wetland response to changing hydrological conditions.

5. Monitoring requirements and use of additional data

5.1 Wetland water levels

Although it has been the intention throughout this study to develop methodologies that could be used on sites with little or no hydrological data, the work described in this report has depended on the records of water level from a number of wetland sites. Water level data have been used to test the models in the course of their development, to check on the validity of the simplifying assumptions underlying the application of these models to new sites, and to establish suitable numerical values for the parameters of the models.

The installation of permanent piezometers and dipwells, and the collection of water level data on a regular basis, is expensive, and it is important to plan data collection networks to maximise the value of the data. Questions to be addressed in this planning process are the location and number of measurement stations, and the frequency of readings.

Within any wetland site, there are spatial variations in the annual range of water levels (Gilman, 1994). This is attributable to several causes:

1. The annual variation in water levels is generally due to evaporative demand, and the fluctuation can be suppressed by proximity to the point of discharge of a regulated flow into the wetland, e.g. a spring, or to the outflow point from the wetland, where water may be ponded by a hydraulic control, e.g. a weir, sill or a constricted channel.

2. The range of seasonal variations will be greater where the specific yield of the soil material is small. The development of fen peat tends towards uniformity of hydraulic properties in the lateral direction, and a relatively large specific yield for high water tables, while the hydraulic properties of soils with mineral components vary widely according to the organic and clay fractions. Thus fluctuations of greater amplitude may be found towards the edges of a site, where wetland grades into marginal land with mineral soils.

A single water level measurement point on a wetland site could be atypical of the major part of the site, and a small network of cheap, shallow dipwells is preferable. A dipwell suitable for the measurement of the water table in peat would consist of plastic tube perforated or slotted throughout its length and installed by hand. A compromise strategy would be to obtain a single year's records from a small network of five dipwells before deciding on a single station for long term observations. In the siting of these stations, preference should be given to sites in the centre of 'fields', as far away as possible from the boundary of the site and from open water bodies, including dykes.

In this study it has been found that monthly collection of wetland water levels is adequate to characterise the seasonal variation of water levels, and for the testing of the water budget model. It is recommended that a time interval of a minimum of one month be adopted for the monitoring of water levels, though it would be wise to add the proviso suggested by Dr P José to English Nature that "further records should be obtained in the critical dry periods of the year when the effects of single rainfall events might be missed" (Smith, 1993).

Provision must also be made to ensure that monthly readings over the summer are not omitted because of holidays.

A wide range of database software is available for the storage of water level measurements relative to a local datum (either a datum post as recommended by Dr W Fojt to Smith, 1993 or the rim of the dipwell) or to Ordnance Datum. Ancillary data, such as the precise location of the station, the depth of the open section or screen in a piezometer, or the elevation of ground level relative to the datum, is more easily misplaced, and should be archived with equal care. SEV calculations in particular require values of water table elevation relative to ground level, while in modelling wetland groundwater levels it is often helpful to know the ground level elevation. Clarity in naming or numbering water level measurement stations is especially to be recommended: records of piezometer installation are often kept separately from water level measurements.

5.2 Local aquifer water table measurements

If it were possible to map the potentiometric surface around a wetland, accurately, in three dimensions, it should be feasible to calculate directly the groundwater contribution to the wetland. The measurements necessary to perform this task would be water level measurements in a suite of piezometers around the wetland, at different depths and at different times. Also a knowledge of the hydraulic conductivity of the various aquifer materials in the wetland vicinity would be needed.

However the collection of this amount of data is unlikely to be economically feasible, and so no recommendations are made here as to how such piezometers should be sited. It is also apparent that such a suite of piezometers would be very site specific.

On a more practical level, it would be very useful to be able to obtain a better understanding of the value of the 'wetland leakage factor', C, introduced in Section 3.5. This parameter is conceptualised as a measure of the resistance to flow between the aquifer and the wetland, and is related in Appendix 2 (Section A2.14) to the vertical hydraulic conductivity (K) and thickness (b) of a semi confining layer beneath the wetland:

$$C = K / b$$

The leakage parameter arises because of the assumption that flow rate must be proportional to the head difference between the aquifer and the wetland. This essentially arises out of Darcy's law. There must, however, be some concern on how wetland geometry affects such an assumption. It is a very common and normally valid (ie confirmed by observations) assumption that the fluxes between surface water bodies and groundwater are proportional to the head differences: this is built into most groundwater flow models in the manner that rivers, streams, lakes, canals and drains are formulated. However, it is not always clear where the head should be measured in the aquifer and what the coefficient of proportionality should be; these are closely related problems.

Firstly, the measurement needs to be made quite close to the surface water body as there is an implicit assumption that the flow system is locally in a quasi-steady-state condition.

Unfortunately, the closer one gets to a surface-water body the more complex will be the flow system and variable the head with depth and horizontal distance; also, over short distances, local heterogeneities in the aquifer properties could have an effect. In order to design a monitoring system that will give the best chance of calculating C accurately it would be necessary to extensively monitor several wetlands and decide, on the basis of the collected data, which monitoring points gave the most useful and unambiguous results. This sort of data collection exercise is outside the scope of this project. In the longer term, it should be possible to determine effective wetland parameters, C and radius, from calibration of a model against such data.

The need to refine estimates of C is demonstrated by reference to Table 3.1 (Section 3.5). This shows that the value chosen for C has a considerable effect on the estimated effect of abstraction on a wetland. However in that example C ranged over two orders of magnitude. If C could be constrained to a smaller range, the 'wetland well function' could be used with greater confidence. Therefore, a crude estimate of C for a specific site will be great improvement over the present state of knowledge.

A refined estimate of C can be obtained by measuring water levels in the aquifer near the edge of the wetted area of the wetland and in the wetland substrate near to the middle of the wetted area. It is recommended that the aquifer head measurements be made at more than one point on the edge of the wetland - to ensure that the readings are representative. The MIROS model for the wetland can be used to estimate a range of probable groundwater contributions to the wetland. These values, in conjunction with the head differences measured as described above, can give a good estimation of the probable values of C relevant to that wetland.

Irrespective of the conceptual model used to describe the wetland behaviour, the ratio of the wetland discharge to the head difference between the wetland and any specific point in the aquifer can be related to wetland geometry, aquifer parameters and C. Therefore if the model described in Appendix A2 is found, after further specific work on the wetland, to be unsuitable, the head measurements described above will still be suitable for use with a different model to give estimates of the equivalent parameter to C.

5.3 Spring flow

Groundwater discharge to wetland sites is by both discrete and diffuse sources. Diffuse inputs may have a more significant role in the water budget of 'field' areas of the wetland, while the discharge of springs is usually channelled into the drainage network. Localised spring flow can have great significance to the ecology of a wetland: there are specialised spring communities that depend on springs for a flow of water of a suitable chemical quality and temperature, and the relatively constant flow of a spring can also exert a regulating influence on water table levels in the soil of its immediate surroundings.

The MIROS model and SEV analysis does not provide any means of estimating the flow of springs that are channelled off site, or have only localised effects. Comparison of the water budgets developed using MIROS for sites with large spring flows with either the budgets derived from intensive field measurements (Badley Moor, Weston Fen) or measured spring flows (Great Cressingham Fen) has shown that the actual measurement of spring flow should be an important part of the monitoring programme. Wetland sites with large springs should be singled out at an early stage for monitoring, as neither the MIROS model nor the complex and expensive groundwater models used in the Birmingham University studies is an adequate substitute for real data.

At Great Cressingham, a monthly programme of flow measurements was sufficient to characterise the seasonal pattern of spring flow and to establish the relationship between the water table in the local aquifer and the discharge of the spring.

5.4 Monitoring during pumping tests

When pumping tests are carried out in the vicinity of wetlands any piezometers in the wetland should be monitored closely. If no piezometers exist, then they should be installed, according to the guidelines set out in Section 5.1 (above). These could then be incorporated into a general wetland monitoring programme at the end of the pumping test.

5.5 Incorporation of new data into existing methodologies

The methodologies proposed in this report are intended to provide a rapid assessment technique that can be used on sites with little or no local data. The programme currently under way, involving the installation of new observation networks, will add to the database on wetland hydrology, and will make it possible to refine the methodologies and to increase the confidence with which they can be applied.

In Phase 2 of this study, the methodologies have been applied to a small group of sites chosen on the grounds of data availability. The methodology can be further developed if a wider range of sites are examined, and the predictions of the model tested against water level data. This testing is an essential part of the future programme: in comparison, the operational use of the methodology on a site with no data will not yield any useful information.

The most obvious way in which the methodology can be improved is in the revision of the various parameters of the model, notably the coefficients controlling the partition of precipitation inputs to the surface water and groundwater catchments, the smoothing factor which operates on the groundwater recharge to simulate spring discharge, the specific yield and the acceptable limits for the SEV.

6. Conclusions and Recommendations

6.1 Introduction

It was the aim of this study to provide techniques that could be used to assess the hydrological impact of groundwater abstraction on wetlands. The importance of hydrology to wetland conservation is central: it is unfortunate therefore that for many reasons the hydrological behaviour of wetlands is poorly understood, and there is little to bridge the gap between the qualitative appreciation of wetlands, built up from descriptive surveys, and the detailed quantitative understanding that can be provided at considerable cost in labour and time for a given site by scientific study, recording of hydrological variables and simulation studies. Classification of wetlands, developed for hydrological purposes for a large sample of sites in East Anglia by the University of Birmingham (Lloyd *et al.*, 1993), offers an approach to assessing wetland susceptibility, but it is difficult to use quantitatively. Faced with proposals for new abstraction, the NRA needs an intermediate range of methods that can be applied quickly and cheaply, if necessary to sites with little local hydrological data.

Wetland sites are complicated: although large expanses of open fen possess a high degree of homogeneity, the wetland site also comprises marginal land and transition zones, which often add considerably to the diversity of habitat for which the site is valued. Spatial inhomogeneity of habitat can reflect spatial variations in the hydrological processes underlying the wetland; and detailed hydrological study of a wetland site frequently poses more questions than it answers, exposing inhomogeneity in three dimensions and unaccountable temporal changes in the hydrological variables. Nevertheless, there are some factors tending towards uniformity, for instance the formation of peat which has relatively uniform hydraulic properties. The combination of a large storage of water on site and the tendency for vegetation growth to increase the resistance to flow create stable conditions, provided that there is a suitable supply of water, with an appropriate seasonal distribution.

Methods of analysis of wetland hydrology are restricted by issues of data availability. Seasonality can only be investigated thoroughly by the collection of data over a number of years, to cover a reasonable range of climatic conditions. In the short term, when it is not possible to await the completion of a research project, suitable data can be hard to find. The routine hydrometric networks are of limited usefulness in this context: although daily rainfall measurements are available from a widespread and intensive network of gauges, and evaporation measurements are spatially relatively uniform, flow measurement stations and observation boreholes are sparsely distributed and generally not associated with wetlands.

The shape of this study has been determined by two related constraints:

the need to use only available data from existing stations,

the need to act on a short timescale, for instance in response to a licence application.

These constraints have ruled out the use of the detailed hydrological study as a suitable tool for the assessment of the impact of groundwater abstraction, and have pointed the way to a range of simple methods, necessarily depending on assumptions that remain to be thoroughly tested. It is believed that the work described in this Report, in addition to furnishing methodologies to answer the immediate objectives, has also indicated how, with the collection of data from the growing network of wetland groundwater monitoring stations, the methods and our understanding of wetland hydrological processes can be advanced.

6.2 Protection of wetlands

It is clear that wetlands in East Anglia, as groundwater discharge areas, are potentially susceptible to the over-exploitation of major aquifers. Many wetlands are so small that very local drawdown can have a serious effect, and the complexities of the geometry of the aquifers, and the hydraulic connections between them, add to the problems of prediction. Even the effects of known abstractions on wetland habitats are not easy to identify, as similar degradation of wetland plant communities can result from changes in, or lack of, management, or from modifications to the drainage network (Wheeler and Shaw, 1992).

Where assessments of dehydration have been made, it has not been possible to obtain a clear relationship between the degree of impact and the likely drawdown in the piezometric surface, and perhaps this is due at least partly to the difficulty in making the assessment of dehydration, and partly to the problems of attributing effects unambiguously to groundwater abstraction.

Another possible complication is the time-varying nature of the drawdown: changes in the water regime of the wetland sufficiently great to be noticeable, or to have effects on the vegetation, may be considerably delayed, or mitigated by natural seasonal variations.

Given that wetlands are subject to a wide range of threats, mainly from agricultural drainage or river management, it is likely that any additional derogation brought about by groundwater abstraction would damage sensitive habitats. However, the ideal requirement, that groundwater abstraction should cause no change at all in wetland water levels, is both unrealistic and incapable of being tested.

Existing abstractions each cause a drawdown of the natural piezometric surface, and new abstractions within a certain distance of a wetland will add to this cumulative drawdown. The problem of setting an acceptable drawdown from any new or increased abstraction is one of relating drawdown in the aquifer to changes in the water regime of the wetland. In this study, two approaches, both depending on the ability of the wetland to withstand natural or existing fluctuations in the piezometric head in the aquifer, have been developed. Using these methodologies, it is possible to evaluate any new proposal and to decide whether further and more detailed investigative work is required.

6.3 Methodologies

The key to the assessment of the impact of abstractions is the water requirement of wetland plants. The water regime of a wetland is characterised by a seasonally varying water table, high water levels in winter when the evaporative demand is low and a summer decline which can be correlated with the build-up of the potential soil moisture deficit. As the soil moisture deficit varies from year to year, so does the summer water regime, and wetland plants are obviously adapted to survive these fluctuations. On some wetland sites, water level decline in the summer is moderated by the discharge of groundwater from major aquifers, and in these cases the plant community is also adapted to fluctuations in the groundwater supply brought about by changes in the piezometric surface.

The simplest approach to impact prediction, the use of the '10% rule' is based on the concept of adaptation to 'natural' fluctuations in the piezometric surface in the aquifer. There is some room for refinement of this method, particularly in the criteria for the choice of observation wells for the definition of piezometric head variations. Obviously, for a given wetland site, the choice will be limited, but further study could improve the confidence with which the method could be applied, by providing criteria for ranking observation wells for this purpose.

The second approach, using a water budget model and a simple model of the dependence of springflows on the piezometric head, offers an alternative means of determining the maximum acceptable drawdown, and the combination of simple models like these with the Sum Exceedance Value, which relates plant performance to water regime, is an attractive and innovative technique which is also capable of considerable refinement in the light of the improving database.

The Sum Exceedance Value (SEV) is a promising indicator of the wetland water regime, whose value has been demonstrated in the Netherlands and in the UK. For some species and communities, notably those associated with wet meadows, the SEV has been found to determine optimal water conditions more accurately than other indices such as average or spot winter or summer water levels. There is considerable potential for extension of the database relating SEV to plant performance, and a pressing need to apply the methods to fen ecosystems.

It is simplistic to consider a wetland as a small homogeneous site whose behaviour can be defined by a single water table level, and whose relationship with the underlying aquifer can be characterised in terms of piezometric head in a single deep piezometer or borehole. The wetland is affected by, and in turn affects, the aquifer piezometric head, and the selection of suitable sites for monitoring piezometric heads can be aided by the use of the wetland well function developed as part of this study. In particular, the wetland well function offers a means of assessing the sensitivity of the relationship between wetland and aquifer to the various parameters.

The most important parameter is the 'wetland leakage factor' ,C, which characterises the flow of water between aquifer and wetland in response to a hydraulic gradient. C is also implicit in the springflow model used in the evaluation of the maximum acceptable drawdown. The evaluation of C, or its equivalent, for a number of sites is a priority if the techniques recommended in this report are to see wide application.

6.4 The way forward

This project has been tightly constrained by time, and there has been little scope for detailed examination of the data available from some wetland sites in the Phase 2 list. The expansion of groundwater monitoring across a larger number of wetland sites will offer the opportunity for a longer-term evaluation of the methods proposed here, and for the development of alternative methodologies. Exploration of the variation in the wetland leakage factor, and a more thorough interpretation of fluctuations in wetland water levels in response to climate and hydrogeological factors, will add to the confidence with which these simple methods can be applied.

The effect of varying the various parameters that have been used in the MIROS models to produce SEV estimates should be examined critically. This could take the form of some sort of sensitivity analysis. The parameters which could be varied include coefficients which are used to partition rainfall, the α-parameter used to lag the groundwater inputs and the drainage level in the wetland. The use of values other than 20 cm for the SEV calculation could also be investigated.

The combination of the WETLWELL function and the MIROS model has not yet been fully investigated. It should be possible to combine the outputs of WETLWELL, in terms of flux reduction, to the inputs of MIROS to give changes in SEV for existing and proposed abstractions.

Estimation of cumulative drawdown due to existing and new abstractions has been carried out for the Phase 2 sites on the basis of very simple assumptions. In particular the role of local features such as rivers and buried channels has not been considered. There is considerable room for improvement in the hydrogeological aspects of the proposed methodologies, and local knowledge may suggest, for example, the use of image wells to improve the quality of predictions of drawdown.

The workload in assembling, quality controlling and in-filling data for the MIROS model, and selecting and interpreting water level records from observation wells is considerable, taking several days for each site. This difficulty will also confront NRA staff trying to use the methodologies operationally. The enlarged database created by the wetland monitoring scheme will provide the potential for more detailed analysis, permitting a more individual approach to wetland sites, but there is little point in collecting water level information is time is not allocated for examination and interpretation. The value of the data collection exercise will be directly related to the investment of time and effort in analysis, cross-comparison and the dissemination of results to those with an interest in the conservation of wetlands.

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British Geological Survey
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- Andy Butcher - numerical modelling
- Anna Matthews - producing data from the databases

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- Geoff Mason - Project manager
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APPENDIX A

APPENDIX A1: WETLAND WATER BUDGETS, THE MIROS MODEL AND THE SUM EXCEEDANCE VALUE

In this Appendix the calculations leading up to the estimation of the maximum acceptable drawdown at a wetland site are outlined. The methods are essentially similar to those described in the Phase 1 Report, and the justification for some of the assumptions is set out more fully in that Report (Adams *et al.* 1994) and in Sections 2.3 and 2.4 of this report.

A1.1 Surface water inputs to wetland sites

A monthly rainfall record is assembled from available data for nearby gauges. The actual evaporation in the vicinity of the wetland is calculated from the monthly MORECS 40-km square values by a simple interpolation formula (Adams *et al.* 1994). The soil moisture deficit is calculated in the same way from the MORECS estimate.

For each month effective rainfall is estimated as the excess of rainfall over actual evaporation, after the soil moisture deficit is satisfied. The effective rainfall, in mm, is partitioned into surface runoff and recharge according to a simple infiltration percentage: 90% for glacial sands and gravels, 60% for uncovered Chalk and 30% for boulder clay (East Suffolk & Norfolk River Authority, 1971).

The surface runoff component originates on the local topographic catchment. The area of this catchment is evaluated from mapwork (Adams *et al.* 1994), and the percentage of the area of the topographic catchment subject to drainage diversion, which prevents water reaching the wetland expanse, is estimated from maps and/or site investigation. The surface runoff component reaching the wetland is computed in Ml/month.

A1.2 Groundwater discharge to wetlands

The monthly recharge to the groundwater body in the wetland groundwater catchment is obtained from the effective rainfall as above. Multiplying by the area of the wetland groundwater catchment (in the first instance the area of the topographical catchment may be used, and refined later by SEV analysis) gives the recharge in Ml/month.

Groundwater is stored within the aquifer and released later through springs and seepages to the wetland. The delay and smoothing of the recharge to give the groundwater discharge is simulated by applying an exponential smoothing technique (see Section 4.5.1). The smoothing coefficient is open to refinement in the light of new springflow data, but the value of 0.164 (based on data from Great Cressingham Fen) has been found satisfactory as a first estimate.

A1.3 Rainfall onto, and evapotranspiration from, the wetland area

Direct rainfall on to the wetland area is calculated by multiplying the monthly rainfall by the wetland area. As the project did not allow sufficient time for field investigations, the SSSI area has been taken as an estimate of the area of the wetland.

Evapotranspiration is assumed to take place from the wetland at a rate proportional to the potential evapotranspiration, which is computed from the published monthly MORECS figures using the interpolation formula (Adams *et al.* 1994). The constant of proportionality depends on the wetland community: values used in this study have been 70% for tall fen and carr, 60% for short fen and 95% for wet grassland.

A1.4 The MIROS model

The MIROS (Mires In Receipt of Seepage) model is a monthly water budget model based on a number of simplifying assumptions. It resembles a soil moisture deficit model, in that excess water drains off once the water table reaches a certain "drainage level". MIROS can be refined as a daily model incorporating a more sophisticated drainage function, but the choice of parameters for the more complex model demands a significant increase in the quantity of water level data and information about the site (Adams *et al.* 1994). As a tool for rapid assessment, the monthly MIROS model is adequate. The MIROS model takes the form of a Lotus-123 spreadsheet for use on a PC-compatible computer.

The conceptual model consists of a single storage unit representing the groundwater store of the wetland, for instance as saturated peat. Inputs to the store are surface runoff, direct rainfall on the wetland area and groundwater discharge, and outputs are evapotranspiration and drainage.

Changes in the water table elevation and the quantity of water in the store are related by the specific yield of the wetland substrate, which is usually expressed as a percentage. In the absence of direct measurements of the specific yield, or sufficient field data to calculate it from the response of the wetland water table to climatic stimuli such as heavy rainstorms, a typical value (for fen peat) of 20% has been adopted. More accurate estimating of the specific yield would be a very useful refinement of the methodology, but for most sites there will be insufficient information.

For each month, the change in water table elevation is equal to

$$(P + Q_{in} + G_{in} - AE) \times 100 / S$$

where P is the direct rainfall on the wetland
Q_{in} is the surface runoff input
G_{in} is the groundwater discharge to the wetland
AE is the estimated actual evapotranspiration
and S is the specific yield expressed as a percentage.

In summer the new water table elevation is generally negative, representing a water table below the drainage level. If the new water table elevation turns out to be positive (for instance in response to a high net input in autumn or winter) it is reset to zero, and drainage from the wetland is deemed to have taken place.

A1.5 Sum Exceedance Values

The Sum Exceedance Value (SEV) is an indicator of the seriousness of summer drought conditions in a wetland soil. According to the SEV model, plants are supposed to be under drought stress once the water table falls below some reference depth below ground level. Although wetland plants are also affected by other factors, notably winter flooding which helps to eliminate competing weed species, the SEV has been found to correlate well with plant performance. It integrates both the depth to which the water table falls and the duration of drought conditions, and is defined for each summer season as the integral over time of the depth of the water table below the reference depth. Periods when the water table is above the reference depth are not included.

In SEV calculations for wet grassland (Gowing *et al.* 1993) a suitable reference depth was found to be 40 cm (0.4 m). In this study a reference depth of 20 cm (0.2 m) has been used, and the SEV calculated for this depth is denoted by SEV(>20).

The SEV can be computed from a set of discrete measurements of the water table elevation by a summation process, using for instance the trapezium rule (for unequally-spaced data points) or Simpson's rule (for equally-spaced data points). The usual unit is the metre-week.

The presence of wetland plant communities on a site implies the existence of acceptable SEV's in the long term, though occasional drought years with very high SEV's may be tolerated. It appears reasonable that the long-term average SEV would be a useful indicator of good wetland conditions, though there are no field data to support this assumption, data collection for the work of Gowing et al having been limited to a short sequence of years.

In this study the long-term SEV(>20), calculated from the water table predictions of the MIROS model, has been used in recursive mode to refine the estimates of the groundwater input to the site, defined by the area of the wetland groundwater catchment. It is expected that the groundwater input will be such as to maintain a long-term average SEV of between 1 and 2 metre-weeks. Collection of data over a longer term and from a larger number of wetland sites will improve on our understanding of how SEV's vary in natural wetlands.

A1.6 References

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APPENDIX 2: A NEW WELL FUNCTION FOR ESTIMATING DRAWDOWN AT A WETLAND AND INDUCED LEAKAGE

A2.1 Introduction

A new well function has been developed in order to simulate the effect of abstraction on an idealized wetland. This function has been designed to take account of leakage between the aquifer and the wetland but otherwise to behave in the same way a the Theis well function (which is a special case of the new function). Given that so little is known about wetland hydrology, it was also considered important that the new function should relate to a simple model of a wetland and have few parameters.

A Fortran code has been developed to evaluate the well function. It operates in a variety of modes facilitating the study of individual cases and the investigation of parameter ranges.

Importantly, the code also includes the facility to find the maximum drawdown due to a finite period of pumping. That maximum will not in general occur until some time after the end of pumping and can be significantly greater than the drawdown at the end of pumping.

In order to obtain a relatively simple mathematical solution, novel use has been made of the 'Reciprocity Principle' which is explained below.

A2.2 Conceptual model

The system envisaged is as depicted in Figure A2.1. The aquifer is confined except beneath the wetland where it is semiconfined. The wetland is of circular shape and at a constant head. This latter assumption will not apply in all cases and will only represent an approximation. One alternative would be to model the wetland as a constant discharge area, but that approach was not taken as it is very difficult to measure such discharges but easy to measure the head in a wetland.

The pumping reduces the head beneath the wetland which in turn reduces the leakage rate from the aquifer into the wetland, that change in leakage can be estimated from the drawdown change. (The Theis equation, for confined conditions, gives a larger drawdown beneath the wetland which corresponds to a proportionately bigger reduction of leakage into the wetland.)

The validity of the adopted model and its generality are discussed at the end of this appendix.

A2.3 Use of the reciprocity principle

The situation depicted in Figure A2.1(A) is extremely difficult to handle mathematically because of the lack of radial symmetry around the well. The situation in Figure A2.1(B) is relatively easily to deal with and fortunately gives an excellent approximation to all aspects of the original problem. This comes about from the 'Reciprocity Principle' - a very general principle relating to the symmetry between stress and response in systems described by diffusive equations.

Applied to Figures A2.1(A) and A2.1(B), the reciprocity principle states that the drawdown at point A due to pumping at point B is the same as the drawdown at point B due to pumping at point A.

This remarkable result is true for heterogeneous as well as homogeneous systems and applies no matter how complex the pumping pattern provided Darcy's law applies throughout the system.

The main restriction when applied to the current problem is that by solving the problem depicted in Figure A2.1(A), the resulting drawdown applies only to the point in the aquifer below the centre of the wetland.

A2.4 Assumptions

All of the assumptions that relate to the Theis solution apply to the current situation but there are additional assumptions that relate to the wetland.

(1) The aquifer is homogeneous and isotropic, and it is confined except beneath the wetland where it is semiconfined.

(2) Flow in the aquifer is horizontal (or, equivalently, that there are no vertical head gradients in the aquifer).

(3) Leakage between the aquifer and the wetland is vertical and quasi-steady-state, and the rate of leakage is governed by Darcy's law. (So the leakage per unit area is proportional to the head difference between the aquifer and the wetland at every point.)

(4) The surface water of the wetland is constant (despite the effects of pumping).

(5) If there is no pumping the head distribution tends to a steady-state condition.

(6) The well is of infinitesimal diameter and has no storage capacity.

(7) There is no pumping prior to time zero and pumping is at a constant rate up until a finite time when pumping ceases.

(8) The wetland is of circular shape.

(9) The total (pumping-induced) leakage from the wetland at any time is proportional to the induced drawdown in the aquifer beneath the centre of the wetland. (The reason for introducing this assumption relates to the use of the reciprocity principle.)

(Standard hydrogeological symbols are used throughout the mathematical analysis that follows and only less common symbols will be explained in the text. All symbols are defined in the 'Notation' at the end of this appendix.)

A2.5 Mathematical formulation

The following equations relate to the situation depicted in Figure A2.1(B) with a well pumping from the aquifer below the centre of the wetland.

Combining Darcy's law and mass conservation, the head variation in the aquifer is described by

$$\frac{T}{r}\frac{\partial}{\partial r}\left[r\frac{\partial h}{\partial r}\right] = C(h-h_w)\ \mathcal{H}(R-r) + S\frac{\partial h}{\partial t} \tag{1}$$

where C is a leakage factor (per unit area of the wetland) and $\mathcal{H}(.)$ is the Heaviside step function.

The quantity C would normally be equated with the vertical hydraulic conductivity of the layer beneath the wetland divided by the thickness of that layer.

The flow into the well given by Darcy's law is equal to the pumping rate

$$\lim_{r\to 0}\ 2\pi r T\frac{\partial h}{\partial r} = Q_p \tag{2}$$

A2.6 Solution for the drawdown

The aquifer head is written as the sum of the head without pumping, $h_0(r)$ minus the drawdown due to pumping, $s(r,t)$:

$$h(r,t) = h_0(r) - s(r,t) \tag{3}$$

Since the head without pumping is assumed to be steady state, it must be described by

$$\frac{T}{r}\frac{d}{dr}\left[r\frac{dh_0}{dr}\right] = C(h_0-h_w)\ \mathcal{H}(R-r) \tag{4}$$

Using (4) to separate equation (1) gives the following equation for the drawdown in the aquifer

$$\frac{T}{r}\frac{\partial}{\partial r}\left[r\frac{\partial s}{\partial r}\right] = Cs\ \mathcal{H}(R-r) + S\frac{\partial s}{\partial t} \tag{5}$$

The pumping rate relates to the drawdown through

$$\lim_{r\to 0}\ 2\pi rT\frac{\partial s}{\partial r} = -Q_p \tag{6}$$

and the drawdown must tend to zero at sufficiently large distances from the well

$$\lim_{r\to\infty} s(r,t) = 0 \tag{7}$$

As there is no pumping prior to time zero, the initial drawdown must be zero

$$s(r,0) = 0 \tag{8}$$

A2.7 Solution of the drawdown equations

The last four equations can be solved for the aquifer drawdown; the derivation is outlined below.

First equation (4) is reduced to an ordinary differential equation by taking Laplace transforms with respect to time:

$$\frac{T}{r}\frac{d}{dr}(r\frac{d\bar{s}}{dr}) = C\bar{s}\,\mathcal{H}(R-r) + pS\bar{s} \tag{9}$$

where p is the transform variable and use has been made of equation (8). Equation (9) is the modified Bessel equation which in general will have a solution of the form

$$\left.\begin{aligned}\bar{s}(r,p) &= AK_0(\lambda r) + BI_0(\lambda r) \qquad r\le R\\ &= DK_0(\mu r) + EI_0(\mu r) \qquad r\ge R\end{aligned}\right\} \tag{10}$$

where factors A, B, D and E are to be determined,

$$\mu^2 = \frac{pS}{T} \tag{11}$$

and

$$\lambda^2 = \frac{pS+C}{T} \tag{12}$$

It follows immediately from equation (7) that $E=0$.

From equation (6)

$$A = \frac{Q_p}{2\pi Tp} \tag{13}$$

The remaining factors, B and D, are determined from the fact that at $r=R$ the two head solutions in equation (10) must match and the gradients of those function must also match for mass conservation (from Darcy's law).

After some manipulation the Laplace transform solution for the drawdown beyond the wetland is found to be given by

$$\bar{s}(r,p) = \frac{Q_p\, K_0(\mu r)}{2\pi TRp\ [\lambda\, I_1(\lambda R)\, K_0(\lambda R)\ +\ \mu\, I_0(\lambda R)\, K_1(\mu R)]} \qquad r \geq R \tag{14}$$

This is the central result from which all other results of interest follow.

No attempt has been made to 'invert' the Laplace transform solution given by equation (14), to obtain $s(r,t)$ as very efficient and accurate software is available to evaluate the drawdown $s(r,t)$ from the Laplace transform.

A2.8 Long-term solution

The drawdown beneath the wetland increases until the leakage from the wetland (or reduced leakage into the wetland) equals the pumping rate of the well. Mathematically, such a situation is represented by the infinite time solution or, equivalently, the steady-state solution of the flow equations. The result is

$$s(r,\infty) = \frac{Q_p}{2\pi T\sqrt{\alpha}\ I_1(\sqrt{\alpha})} \qquad R \leq r < \infty \tag{15}$$

where

$$\alpha = \frac{CR^2}{T} \tag{16}$$

(The solution for $r<R$ is not required.)

It is of some mathematical interest to note that the solution given by equation (15) is not truly steady state in the sense that it does not apply at infinite distance from the well. Physically what develops is that the drawdown beneath the wetland tends to a steady state distribution. The aquifer outside the wetland area can be regarded as responding to the drawdown at $r=R$; no steady-state solution exists for cylindrical flow with a fixed drawdown at some radius, although at every point the drawdown tends to that same drawdown at large times.

A2.9 Pumping induced leakage reduction

The leakage from the aquifer into the wetland is reduced due to the pumping. The relationship between the drawdown and that leakage change is given by Darcy's law. The mathematical analysis given here, based on the reciprocity theorem, only gives the drawdown at the centre of the wetland. In order to derive a general formula over time of the leakage change the assumption has been made that the *total* leakage change is proportional to that drawdown.

The reduction in leakage into the wetland, based on this assumption, can be derived from knowledge of the long-time drawdown which corresponds to the total pumping rate:

$$\Delta Q_w = \frac{s(r,t)}{s(r,\infty)} Q_p \tag{17}$$

where the transient and steady-state (infinite time) drawdowns are given by equations (14) and (15), respectively.

Some insight into the validity of equation (17) is required. In the (infinite-time) steady-state condition, the average leakage per unit area of the wetland induced by the pumping will equal the pumping rate divided by the wetland area. The leakage rate at the centre of the wetland will be given by the infinite-time drawdown times the leakage factor, C. The ratio of these two is

$$\frac{Q_p / \pi R^2}{C s(r,\infty)} = \frac{2 I_1(\sqrt{\alpha})}{\sqrt{\alpha}} = 1 + \frac{\alpha}{8} + \frac{\alpha^2}{192} + \ldots \tag{18}$$

So the factor on the right-hand side of equation (18) provides a measure of the accuracy of (17). It is evident from the expansion that the ratio will be greater than unity but by less than about 25% provided α is less than 2.

The assumption that the ratio of leakage reduction to drawdown change is reasonably constant over time needs to be verified and this probably requires numerical modelling. The ratio will depend both on the time of pumping and the distance from the wetland to the well.

A2.10 Dimensionless solution

Both for computational simplicity and for mathematical elegance the above drawdown solution (equation (14)) can be written in the form:

$$s(r,t) = \frac{Q_p}{4\pi T} W(\tau,\rho,\alpha) \tag{19}$$

where

$$\tau = \frac{Tt}{Sr^2} \tag{20}$$

and

$$\rho = \frac{R}{r} \tag{21}$$

From equation (14), the function $W(\tau,\rho,\alpha)$ has a Laplace transform

$$\begin{aligned} \overline{W}(\hat{p},\rho,\alpha) &= \int_0^\infty e^{-\hat{p}\tau}\, W(\tau,\rho,\alpha)\, d\tau \\ &= \frac{2\, K_0(q)}{\hat{p}\ [q_\lambda I_1(q_\lambda)\, K_0(q_\lambda) + q_\mu I_0(q_\lambda)\, K_1(q_\mu)]} \end{aligned} \tag{22}$$

where

$$\left.\begin{aligned} q &= \sqrt{\hat{p}} \\ q_\mu &= \rho q \\ q_\lambda &= \sqrt{q_\mu^{\ 2} + \alpha} \end{aligned}\right\} \tag{23}$$

The function $W(\tau,\rho,\alpha)$ is regarded as a *wetland well function.* This is related to the Theis well function, $W(u)$, through

$$W(u) = W(1/4u,\rho,0) \quad \forall\rho \tag{24}$$

This simply expresses the fact that, if there is no leakage ($C=\alpha=0$), then the aquifer drawdown is given by the normal Theis equation for a fully confined aquifer.

A2.11 Finite pumping period

It has to be realized that when pumping is performed for a finite period of time the drawdown that results does not in general reach a maximum value for a finite period. At large distances from the well the drawdown caused by the pumping may be negligible at the end of pumping but rise significantly to a peak at a later time.

This situation can be dealt with mathematically by superposition of solutions: the drawdown for a period equal to the current time minus the pumping time is subtracted from the drawdown for continuous pumping from time zero. The details are not given.

The problem is that a closed form mathematical solution cannot be obtained either for the time when the maximum drawdown occurs or for that drawdown itself. A relatively complicated Fortran program has been written to obtain those values. In principle, what it calculates is a new well function which we can regard as the *maximum wetland well function for pulse pumping*:

$$W_{pulse}(\tau_p,\rho,\alpha) = \max_{\tau} \left[W(\tau,\rho,\alpha) - W(\tau-\tau_p,\rho,\alpha)\right] \tag{25}$$

where

$$\tau_p = \frac{Tt_p}{Sr^2} \tag{26}$$

and t_p is the period of pumping.

Again taking $\alpha=0$ gives a similar function for the Theis solution (which has not appeared in the literature).

A2.12 Numerical implementation

A2.12.1 Introduction

Two Fortran subroutines have been developed to evaluate the well functions in equations (19) and (25), for continuous pumping and a finite period of pumping, respectively. These both depend on code to evaluate the inverse Laplace transform and further codes to evaluate the Bessel functions involved. Those latter codes have been developed by BGS over a long period.

The code for evaluation the 'pulse' well function, equation (25), also involves code to find the maximum of a function of a single variable.

To facilitate use, the well functions have been implemented within a single Fortran code WETLWELL.FOR compiled to give the executable code WETLWELL.EXE which will run on a personal computer with or without a maths coprocessor. It deals with four cases:-

CASE 0: This allows investigation of the well functions by the construction of tables for ranges of values of dimensionless time, τ, and parameters ρ and α. This was used, for example, to construct Figures A2.2 to A2.4 (discussed below).

CASE 1: Given a set of real parameter values and the pumping period of a single well, this case gives both Theis and 'wetland' drawdowns, both at the end of pumping and the maximum values. The corresponding times and induced leakage changes at those times are also given.

CASE 2: This is essentially the same as CASE 1, except the results are given for a range of pumping periods in a large table that facilitates graph production.

CASE 3: This is a multiple well case. Total drawdown is computed for a number (up to 100 in the current version) of wells each with a single period of pumping. Multiple periods for a single well can be accommodated by representing that well by a set of wells: one for each pumping period.

It is envisaged that the NRA will be most interested in the CASES 1 and 3 but may also want to use CASE 2 for scoping studies.

A2.12.2 Data file description

Control of WETLWELL.FOR is via a single data input file WETLWELL.DAT and output is directed to the file WETLWELL.OUT. Any number of the above cases can be run from one data file, the different data sets simply follow one another.

ALL CASES:-

i. The first record (line) of any WETLWELL.DAT file should be the title of the run. (Up to 80 characters.) All other records will be part of a set for a particular case, as described below.
ii. The first line of any set is the case number. A case number outside the range 0 to 3 will terminate execution with an error message (unless it is 999).
iii. Terminate all sets with either end-of-file or CASE=999. The use of 999 allows a large data set to be terminated early without an error message during trial runs.
iv. Any number of sets of data (cases) can follow one another.
v. Use consistent units in CASES 1-3 (CASE 0 is dimensionless). Results are in the same units.
vi. Use free format without commas. (Parameters for a single record - as described below - can therefore stretch over several records, but this is not advised.)

CASE 0 DATA:-

RECORD	CONTENTS	NOTES
1	0	
2	NRHO	1
3	RHO1 RHO2 RHO3 ...	2
4	NALPHA	3
5	ALPHA1 ALPHA2 ALPHA3 ...	4
6	LOGT1 LOGT2 DLOGT	5

NOTES:-

1. The number of ρ values in record 3 ($\leq$10).
2. Up to 10 values.
3. The number of α values ($\leq$10).
4. Up to 10 α values
5. The start time, end time and time interval, all as log base 10 of time. (Maximum of 200 times in all.)

CASE 1 DATA:-

RECORD	CONTENTS	NOTES
1	1	
2	NWELLS (The number of wells)	
3	Q t_p r T S R C (For first well)	1
2+NWELLS	Q t_p r T S R C (For last well)	

NOTES:-

1. See the *Notation*.

CASE 2 DATA:-

RECORD	CONTENTS	NOTES
1	2	
2	NWELLS (The number of wells)	
3	$Q\ t_{p1}\ t_{p2}\ \Delta t_p\ r\ T\ S\ R\ C$ (For first well)	1
2+NWELLS	$Q\ t_{p1}\ t_{p2}\ \Delta t_p\ r\ T\ S\ R\ C$ (For last well)	

NOTES:-

1. See the *Notation* for an explanation. t_{p1} t_{p2} and Δt_p are the start time, end time and time interval.

CASE 3 DATA:-

RECORD	CONTENTS	NOTES
1	3	
2	NWELLS T S R C	1
3	$Q\ \ r\ \ t_{start}\ \ t_{end}$	2
2+NWELLS	$Q\ \ r\ \ t_{start}\ \ t_{end}$	

NOTES:-

1. Up to 100 wells (NWELLS ≤100). See *Notation*.
2. t_{start} and t_{end} are the time of the start and end of pumping. For multiple pumping periods for the same well add extra wells at the same radius.

A2.12.3 Using the WETLWELL program

The executable file WETLWELL.EXE should be copied to the working directory that will contain the input data file, WETLWELL.DAT, and the output file, WETLWELL.OUT, that is created by the program.

WETLWELL.DAT should be created with an ASCII text editor.

The program is run by simply issuing the command 'WETLWELL' at the DOS prompt.
eg C:\WETLAND>WETLWELL

During the run, the results will be displayed on the PC monitor and also written to the file WETLWELL.OUT. This will overwrite the previous contends of the output file! It is therefore advisable, after checking that the results are as required, to rename the WETLWELL.OUT file or copy it to another drive or directory in order to save it.

A2.13 Some CASE 0 program runs

A2.13.1 Run 1

Figure A2.2 shows the results of a program run which shows how various well functions (dimensionless drawdowns) vary with the time of pumping for fixed values of ρ and α. The two upper curves represent the Theis solution both at the end of pumping and at the maximum. Similarly the two lower curves correspond to the new wetland well function. The horizontal line is the steady state wetland well-function drawdown to which the two wetland curves tend at large times.

Not that the Theis drawdowns are more than an order of magnitude greater than the wetland results, the latter values are smaller due to the wetland leakage.

For both the wetland and Theis cases the maximum drawdown and the drawdown at the end of pumping converge for dimensionless times of the order of unity. This is explained by the fact that the end of pumping has an effect at the wetland for a dimensionless time of the order of one (from the fact that the aquifer flow equation is a diffusion equation).

The early linear portions on the 'maximum' curves have slopes of unity. This is explained by the fact that for pumping periods significantly less than the diffusion time from the well to the wetland, the wetland sees an effectively instantaneous abstraction of water. The resultant drawdown will be proportional to the total abstraction which is proportional to the pumping time. Therefore the drawdown is proportional to the pumping time.

A2.13.2 Run 2

Figure A2.3 shows the variation of dimensionless drawdown with the parameter α, which is a measure of the leakiness of the wetland. For this run a relatively large time ($\tau=10$) was used and gave indistinguishable results between the drawdowns at the end of pumping and the maximum drawdowns (as would be expected from the results in Figure A2.2).

The wetland results tend to the Theis results as α, and hence leakage, tends to zero. The same curves tend to the steady-state curve as the leakage tend to infinity.

A2.13.3 Run 3

Run 3 results shown in Figure A2.4 represent exactly the same situation as Run 2 except the pumping time is smaller by two orders of magnitude (τ=0.1). This brings about a very significant difference between the drawdowns at the end of pumping and the maximum drawdowns.

A2.13.4 Comments

Although the well function (dimensionless drawdown) was plotted in Figures A.2 to A.4, almost exactly the same graphs would have been obtained if the change of leakage to the wetland had been plotted. The leakage scale would have a value equal to the pumping rate along the steady-state wetlands curve.

What these preliminary program runs show is that the wetland response to pumping can vary significantly with the leakage parameter and the dimensionless pumping time; the latter is inversely proportional to the aquifer diffusivity.

In particular, it is seen that the drawdown at the end of pumping may differ by more than an order of magnitude from the maximum value attained some time after the end of pumping. Also, the Theis well function and the new wetland well function (and hence the drawdowns they give) can differ by several orders of magnitude. This applies especially at very long times when the Theis function is continuing to increase while the wetland well function is tending to a maximum (steady-state) value.

A2.14 Comments on the validity and generality of the adopted model

The validity of any model can only be demonstrated when adequate data are available. Data on wetland hydrology are currently very limited insofar as they provide information on the nature of the interaction of wetlands and aquifers. The model depicted in Figure A2.1 is clearly a gross simplification of reality and one which inevitably will not serve for some, perhaps many, wetlands. The choice of this model was based on:-

(i) The need to keep the number of parameters describing the wetland to a minimum. (This model has only two parameters which relate to the wetland.)
(ii) The need to adopt a model for which the values of the wetland parameters could be bracketed.
(iii) The need to adopt a model which could, given adequate data, be calibrated.
(iv) The need to adopt a model which would cover, or approximate, a wide variety of wetland scenarios.

This last point needs some elaboration. It is considered likely that this model will be adequate for a variety of wetland scenarios, some quite different geometrically from Figure A2.1. This 'adequacy' is intended in the sense that it seems likely that for many wetlands it will be possible to estimate effective values of the parameters used in the model developed here. This is based on the fact that the two parameters involved represent the size of the wetland, which will surely enter most models, and the leakage from the aquifer into the wetland per unit head difference.

That leakage parameter arises because of the assumption that flow rate must be proportional to the head difference between the aquifer and the wetland. This essentially arises out of Darcy's law; there must, however, be some concern on how wetland geometry affects such an assumption. It is a very common and normally valid (ie confirmed by observations) assumption that the fluxes between surface water body and groundwater are proportional to the head differences: this is built into most groundwater flow models in the manner that rivers, streams, lakes, canals and drains are formulated. However, it is not always clear where the head should be measured in the aquifer and what the coefficient of proportionality should be; these are closely related problems.

Firstly, the measurement needs to be made quite close to the surface water body as there is an implicit assumption that the flow system is locally in a quasi-steady-state condition. Unfortunately, the closer one gets to a surface-surface water body the more complex will be the flow system and variable the head with depth and horizontal distance; also, over short distance, local heterogeneities in the aquifer properties could have an effect. There is no obvious answer to this problem for a wetland but it is clear that some forethought is required in designing monitoring systems for wetlands that take these considerations into account.

The constant of proportionality can be calculated once the geometry and rock permeabilites are known. Often the constant is written as the product of an effective permeability or transmissivity and a dimensionless factor, often termed a 'shape factor', characterizing the flow geometry; although this will often contain factors which relate to permeability such as the ratio of horizontal to vertical permeability. For a wetland of the geometry assumed in this appendix, taking the head measurement in the aquifer at the outer edge of the wetland, a shape factor can be defined from equation (15) as

$$\frac{Q_p}{s(r,\infty)\,T} = 2\pi\sqrt{\alpha}\; I_1(\sqrt{\alpha}) \qquad (27)$$

where

$$\alpha = \frac{CR^2}{T} = \frac{KR^2}{bT} \qquad (28)$$

where C has been replaced by K/b: the ratio of the vertical hydraulic conductivity of the rock immediately underlying the wetland and the thickness of that layer. (This demonstrates that only geometrical and permeability parameters are involved.) Either α or the group containing α on the right of equation (27) could reasonably serve as the 'shape factor' for the wetland. These factors should be less variable from one wetland to another than the C parameter.

A2.15 Notation

b	Thickness of horizonal layer underlying the wetland.
C	Flux between aquifer and wetland per unit head difference.
$h(r,t)$	Head in the aquifer.
h_0	Head in the aquifer when there is no pumping.
h_w	Head in the wetland.
$\mathcal{H}(x)$	Heaviside step function.
K	Hydraulic conductivity of the layer underlying the wetland.

p	Laplace transform variable.
$\hat{p}$	See equation (22).
q	See equation (23).
q_λ	See equation (23).
q_μ	See equation (23).
Q_p	Pumping rate for time greater than zero.
r	Distance from centre of wetland.
R	Radius of the wetland.
$s(r,t)$	Drawdown in the aquifer due to pumping.
S	Storage coefficient.
t	Time.
t_p	Period of pumping.
T	Transmissivity of the aquifer.
u	Parameter of the Theis well function ($=1/4\tau$).
$W(\tau,\rho,\alpha)$	Wetland well function.
$W_{pulse}(\tau_p,\rho,\alpha)$	Wetland maximum well function for a finite pumping period.
α	See equation (16).
λ	See equation (12).
ΔQ_w	Pumping-induced reduction in leakage to the wetland.
μ	See equation (11).
ρ	Ratio of the wetland radius to the distance to the well.
τ	See equation (20).
τ_p	See equation (26).
$\bar{f}(p)$	Laplace transform of any time-dependent function $f(t)$.

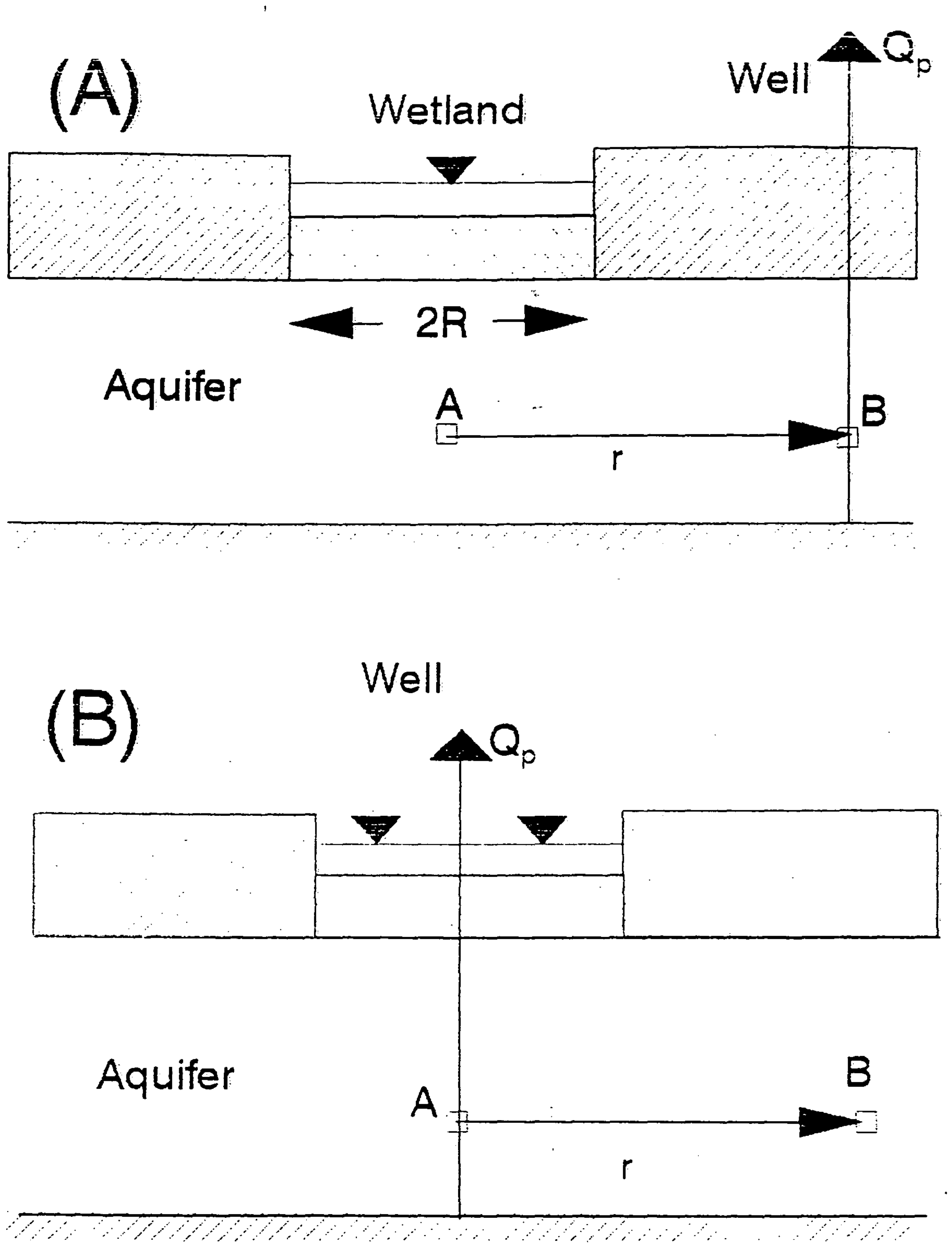


Figure A2.1 Schematic diagram of wetland model used to develop new well function.

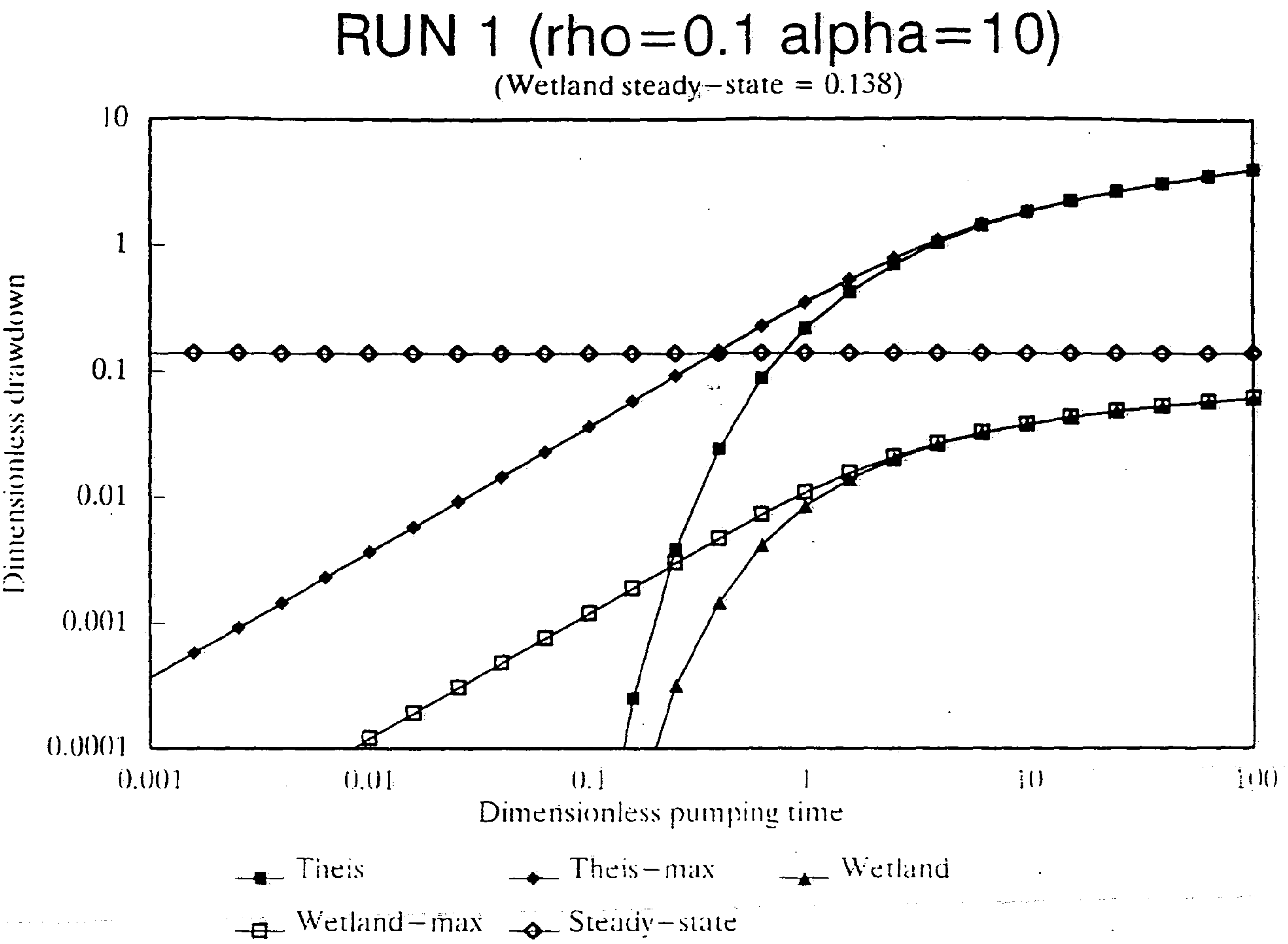


Figure A2.2 Drawdown variation with pumping time for a well at radius ten times the wetland radius and a fixed leakage parameter $\alpha = 10$. The wetland results tend to a steady state value while the Theis results increase continuously with time.

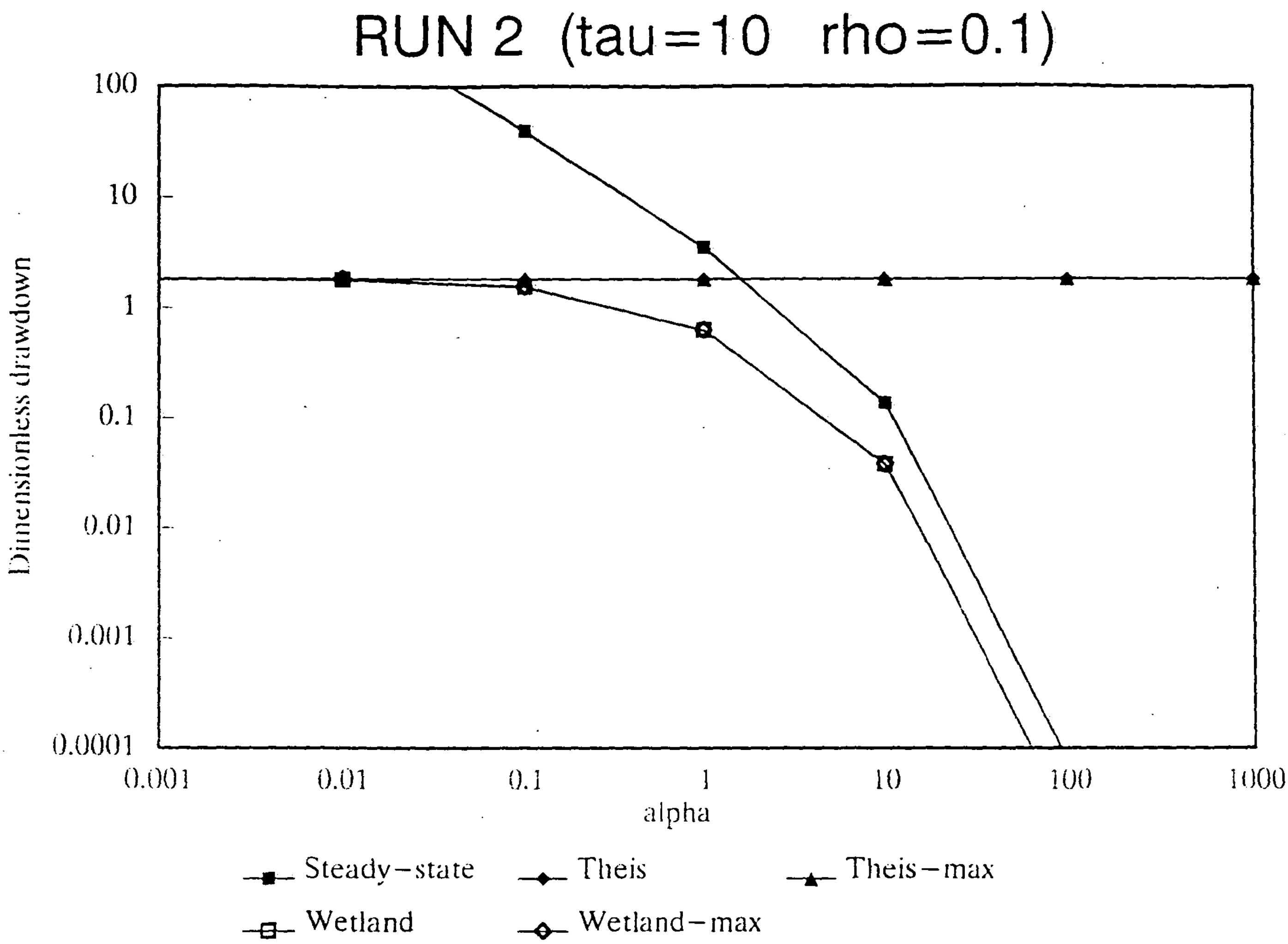


Figure A2.3 Drawdown variation with leakage parameter, α, for a given (relatively large) time and fixed well position. Drawdowns at the end of pumping coincide with the maximum values. The wetland results tend to the Theis results for small values of the leakage parameters and to the steady-state curve for large values.

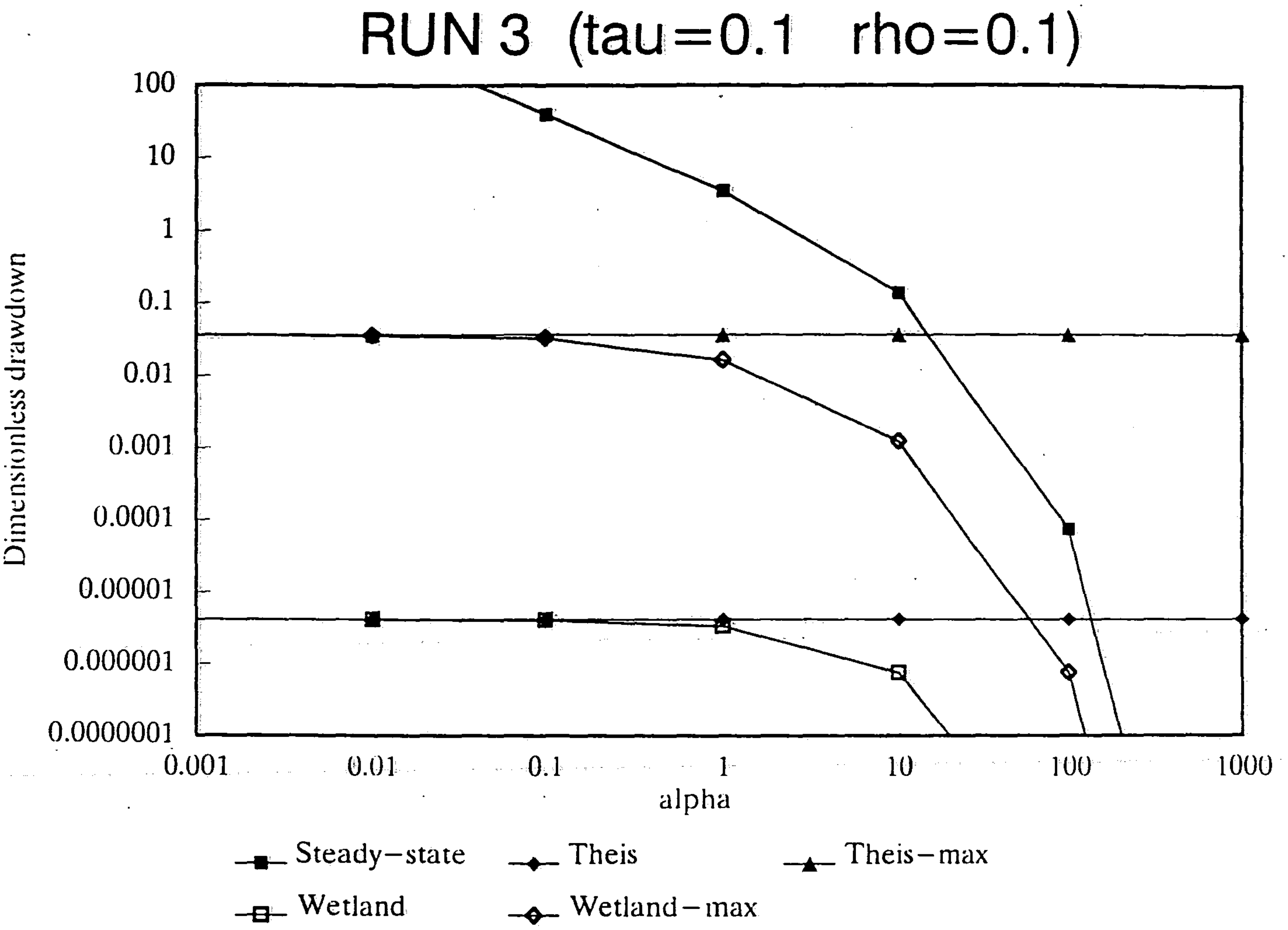


Figure A2.4 Drawdown variation with leakage parameter, α, for a given (relatively small) time and fixed well position. Drawdowns at the end of pumping differ significantly from the maximum values.

APPENDIX A3: NUMERICAL MODELLING

A3.1 Introduction

The aim of the numerical modelling work carried out in Phase 2 of this project was to attempt to resolve a difference of opinion which had arisen as a result of the work carried out in Phase 1 (Adams *et al*, 1994). This concerned the importance of the groundwater catchment area of the wetland to the protection of the wetland from the adverse effects of groundwater abstraction.

The initial Phase 1 Terms of Reference placed great emphasis on the requirement to delineate this catchment area. This was done because it was felt that this area was more in need of protection than other surrounding areas. Whilst it was agreed that this area was important for protection from quality changes, Adams *et al* (1994) argued that the delineation of this area would not be necessary for protection of the wetland from the effects of water level changes caused by pumping. The basis of their argument was that, in a uniform aquifer, the cone of depression caused by a pumping well is circular. Thus, its effects on the water levels in the vicinity of a wetland (or any other point) in the aquifer was a function of distance only and not direction.

Whilst this argument was accepted in the general sense, there remained a feeling, in the case of wetlands with their special interaction with the water levels and ground levels, that the catchment area might still prove to be important. To resolve this question a short programme of numerical modelling was introduced into Phase 2 of the project.

A3.2 Modelling approach

The USGS modelling package MODFLOW (McDonald and Harbaugh, 1988) was chosen for this work. This public domain software was chosen because it is well documented, widely used and tested and includes a variety of suitable features which could be used to simulate wetlands.

The approach chosen, was to imitate the wetland by a series of 'drains'. These have the property, within this modelling package, that the flow into the drain is proportional to the difference between the level of the drain and the water level in the aquifer. When the water level drops below the level of the drain flow ceases. The flow in the drain is removed from the model. This was felt to be a reasonable description of the behaviour of a wetland. The removal of the water is equivalent to the use of the water by the plants, evaporation and outflow from the wetland by surface drains. The drain level is equivalent to depth below which the wetland ceases to function.

The parameters required by the model to simulate drains are i) the drain level, and ii) the constant of proportionality which represents the conductance of the drain-aquifer interface. This parameter is equivalent to the parameter C described in Section 3.5 and Appendix A2.

A3.3 Model description

The model was set up for a steady-state simulation, as this was the case that was being tested.

A rectangular region of aquifer was simulated with no-flow boundaries on three sides and a constant-head (0 m) boundary on the western side (Figure A3.1). The aquifer base was set at -50m, the hydraulic conductivity was 10m/d and the recharge rate set at 1mm/d. This led to flow from the eastern no-flow boundary towards the western constant-head boundary. A block of 25 drains was placed near the constant head boundary and an array of wells placed radiating outwards from this 'wetland'. The wetland conductance was chosen to be in the range suggested in section 3.5 (a value of C of 0.004 was used) and the depth parameter was set so that the flow out of the wetland was around $600m^3/d$. (This value was chosen as being representative of the smaller Phase 1 sites.)

A3.4 Results

The various wells were pumped in turn and the change in flow out of the wetland was recorded. Figure A3.2 shows the response of the wetland to this pumping. As can be seen, the direction of pumping from the wetland does have an effect. (The catchment area of the wetland is to the east - only the eastern line of wells falls inside the catchment area.) It was thought that this was primarily due to the presence of the river - the wells on the northern line are much closer to the river than those to the east. Thus the northern wells would preferentially take their water from the river rather than from the wetland.

To see if this was the case more 'aquifer' was added to the model between the wetland and the constant-head boundary. The wetland 'drain level' had to be altered to give a similar outflow from the wetland area. After this was done the wells were pumped again and the results shown in Figure A3.3. As can be seen, there is more change in the wetland flow, but the difference between the northern and eastern lines is reduced. This is obviously showing the effect of the constant-head boundary which has been imposed in the model.

This boundary acts in a similar way to a river - providing the mechanism for the water balance in the model. If such a river existed in a real case then image wells would be invoked to represent its effect. The image wells required for a simulation with the eastern wells would be further from the wetland than the image well required for one of the northern wells. Thus the combined drawdown would be greater for the eastern wells (the image wells for a recharge boundary are injection wells and so increase the water level), which would lead to a greater influence at the wetland. This is what has been seen.

Figure A3.3 shows that the difference in effect between the wells in the north-eastern direction and those in the eastern direction is smaller than the difference between those in the north-eastern and northern directions. As both these latter lines are outside the wetland groundwater catchment area, whereas one of the former is inside, this shows that the wetland catchment area is not a significant feature affecting the change in wetland seepage rate. Thus it seems that the delineation of the wetland catchment is not necessary to predict the change in the wetland. However the modelling work has shown that the other boundary conditions, such as rivers or buried channels may be very significant and the use of image wells should be strongly advised.

A3.5 Reference

McDonald M G and Harbaugh A W. 1988 A modular three-dimensional finite-difference ground-water flow model USGS Techniques of Water-Resources Investigations Book 6, Chapter A1, 586pp

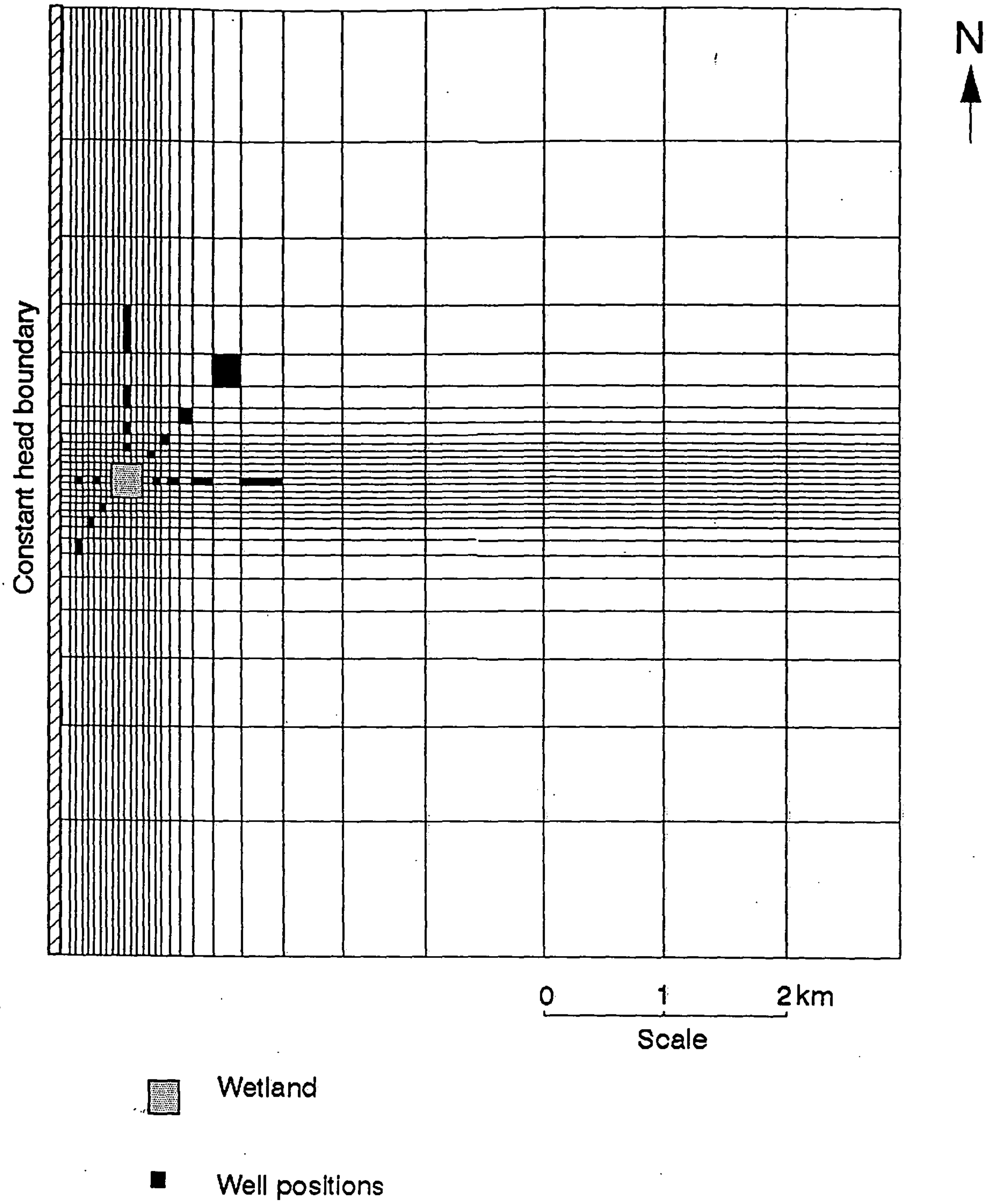


Figure A3.1 Diagram of initial model set-up showing positions of wells.

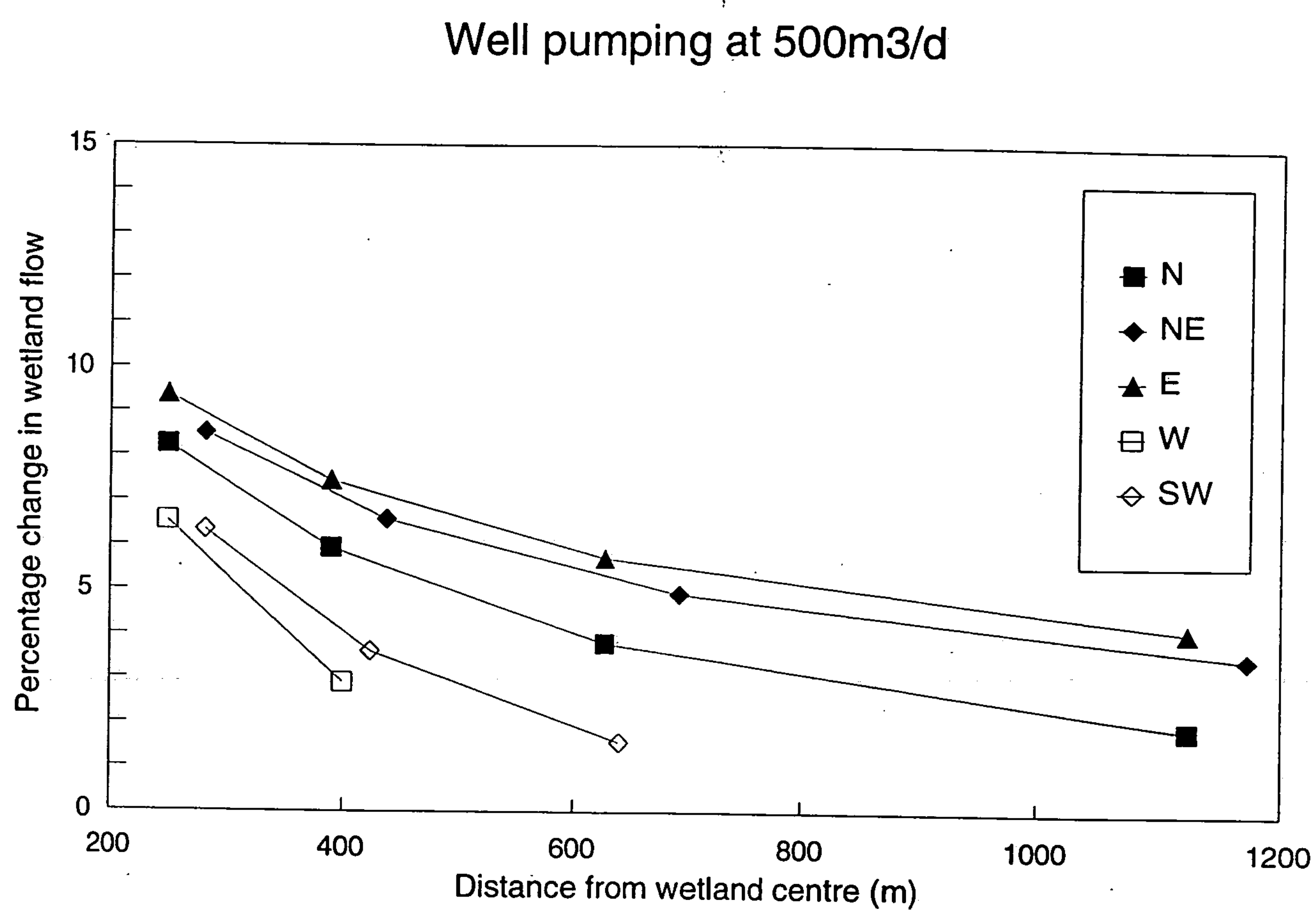


Figure A3.2 Change in wetland seepage caused by pumping different wells at $500m^3/d$. Simulation done on model as shown in Figure A3.1

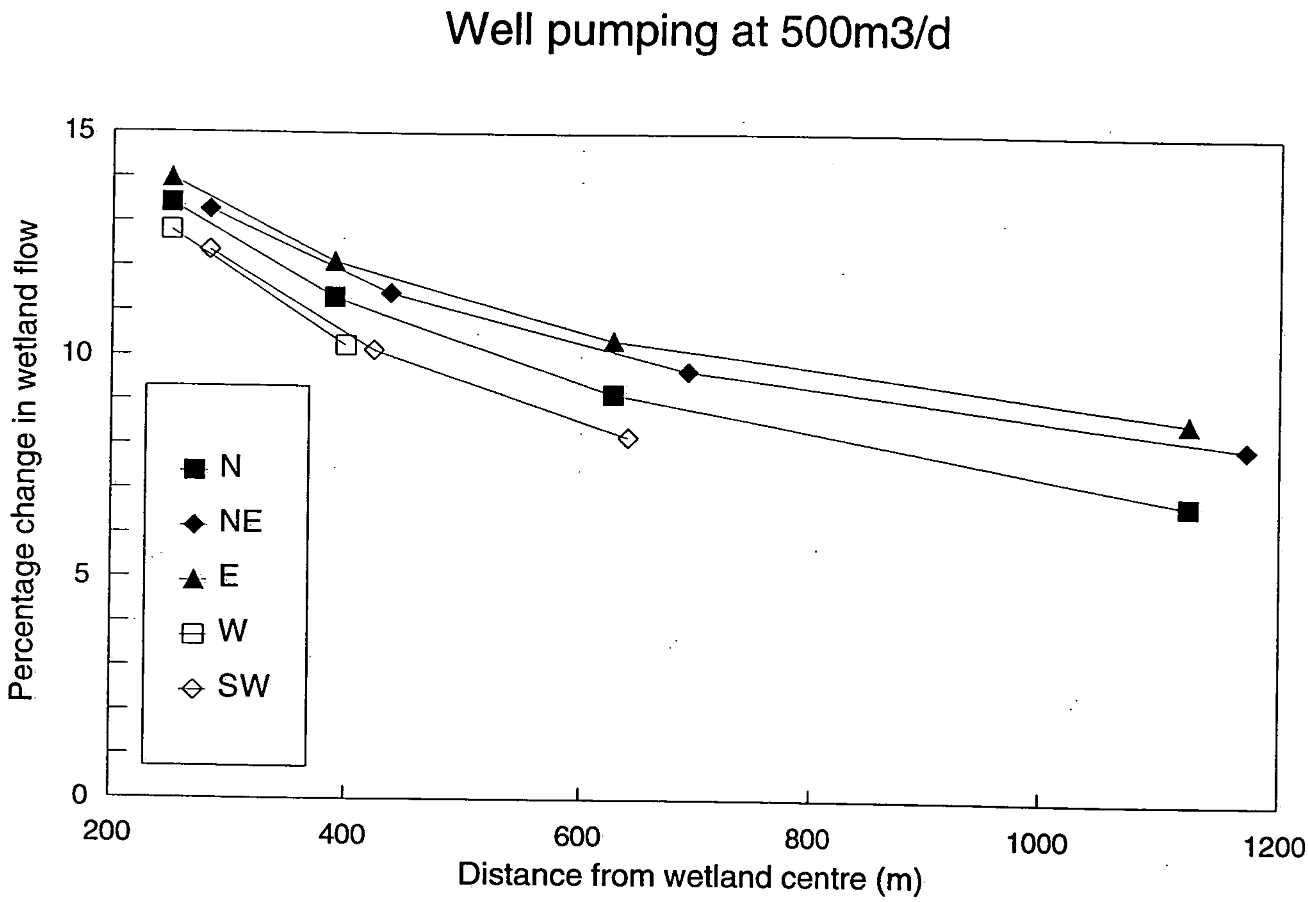


Figure A3.3 Reduction in wetland seepage caused by pumping at 500m³/day. Wetland now 1km from constant head boundary, as described in text.

APPENDIX 4: DIMENSIONLESS GROUPS CHARACTERIZING THE 'DRAIN' MODEL

The system under consideration is depicted in Figure A4.1. Geometrical parameters introduced below are clearly explained by that figure and will not be defined below. The wetland is chosen to be square in shape but a circle would be equally convenient, being described by a single geometrical parameter. The wetland leakage is taken to be of the form implicit in the drain function available in the MODFLOW model. The well is taken to be a point source at an arbitrary position with respect to the wetland. The aquifer meets a no-flow boundary to the right (positive x direction) and a fixed-head stream to the left. The whole system is regarded as of infinite extent in the y direction.

For an isotropic homogeneous unconfined aquifer with uniform recharge, combining Darcy's law with conservation of mass gives:

$$Kh\frac{\partial^2 h}{\partial x^2} + Kh\frac{\partial^2 h}{\partial y^2} = R + q(x,y) + Q_p\,\delta(x-x_p,y-y_p) \qquad (1)$$

where R is the recharge, Q_p is the pumping rate of the well, $q(x,y)$, is the leakage per unit area:

$$q(x,y) = \begin{cases} C[h(x,y)-h_w] & \max(|x|,|y|)<w \quad h>h_w \\ 0 & otherwise \end{cases} \qquad (2)$$

where C is the wetland leakage factor.

The fixed head boundary condition at the stream is

$$h(-L,y) = h_s \qquad (3)$$

There is no flow at the right-hand side of the model:

$$\frac{\partial h}{\partial x}(D,y) = 0$$

At large distances from the wetland and well the flow will be in the x direction, so

$$\lim_{|y|\to\infty} \frac{\partial h}{\partial y} = 0 \qquad (4)$$

The above equations are now reduced to dimensionless forms by replacing variables by non-dimensional equivalents (indicated by ^):

$$x = L\hat{x} \quad y = L\hat{y} \quad w = L\hat{w} \quad x_p = L\hat{x}_p$$
$$y_p = L\hat{y}_p \quad h = h_w\hat{h} \quad h_s = h_w\hat{h}_s \tag{5}$$

The resulting equations are

$$\hat{h}\frac{\partial^2\hat{h}}{\partial\hat{x}^2} + \hat{h}\frac{\partial^2\hat{h}}{\partial\hat{y}^2} = \frac{RL^2}{Kh_w^2} + \frac{qL^2}{Kh_w^2} + \frac{Q_p}{Kh_w^2}\delta(\hat{x}-\hat{x}_p,\hat{y}-\hat{y}_p) \tag{6}$$

$$\hat{q} = \frac{qL^2}{Kh_w^2} = \begin{cases} \frac{CL^2}{Kh_w}[\hat{h}(x,y)-\hat{h}_w] & \max(|\hat{x}|,|\hat{y}|)<\frac{w}{L} \quad \hat{h}>1 \\ 0 \quad otherwise \end{cases} \tag{7}$$

$$\hat{h}(-1,\hat{y}) = \frac{h_s}{h_w} \tag{8}$$

$$\frac{\partial\hat{h}}{\partial\hat{x}}\left(\frac{D}{L},\hat{y}\right) = 0 \tag{9}$$

$$\lim_{|\hat{y}|\to\infty}\frac{\partial\hat{h}}{\partial\hat{y}} = 0 \tag{10}$$

From the last four (dimensionless) equations we extract the dimensionless groups:

$$\frac{RL^2}{Kh_w^2} \quad \frac{Q_p}{Kh_w^2} \quad \left[\frac{x_p}{L},\frac{y_p}{L}\right] \quad \frac{CL^2}{Kh_w^2} \quad \frac{w}{L} \quad \frac{h_s}{h_w} \quad \frac{D}{L} \tag{11}$$

Alternate sets can be obtained by combining these. Also the well position relative to the wetland can be rewritten in terms of dimensionless radius and angle (both of which could be written in terms of dimensionless x and y values). An alternate set is

$$\frac{RL^2}{Kh_w^2} \quad \frac{Q_p}{Kh_w^2} \quad \left(\frac{r_p}{L}, \theta\right) \quad \frac{Cw^2}{Kh_w^2} \quad \frac{w}{L} \quad \frac{h_s}{h_w} \quad \frac{D}{L} \tag{12}$$

We conclude that for this model the dimensionless drawdown at the wetland is a function of eight parameters.

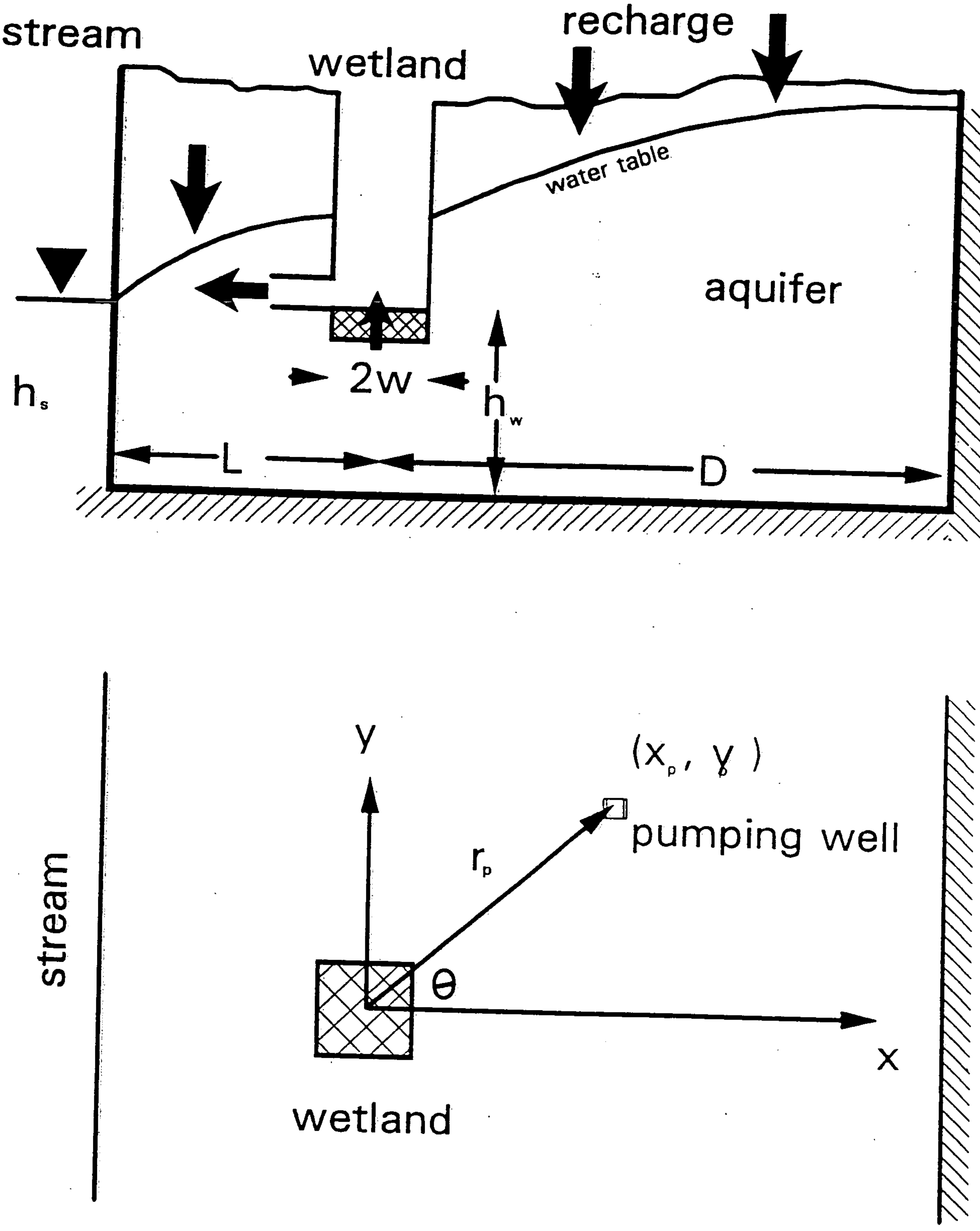


Figure A4.1 Schematic diagram of wetland simulation using the drain function of MODFLOW: (a) section (b) plan.

APPENDIX B

Blo'Norton & Thelnetham Fens

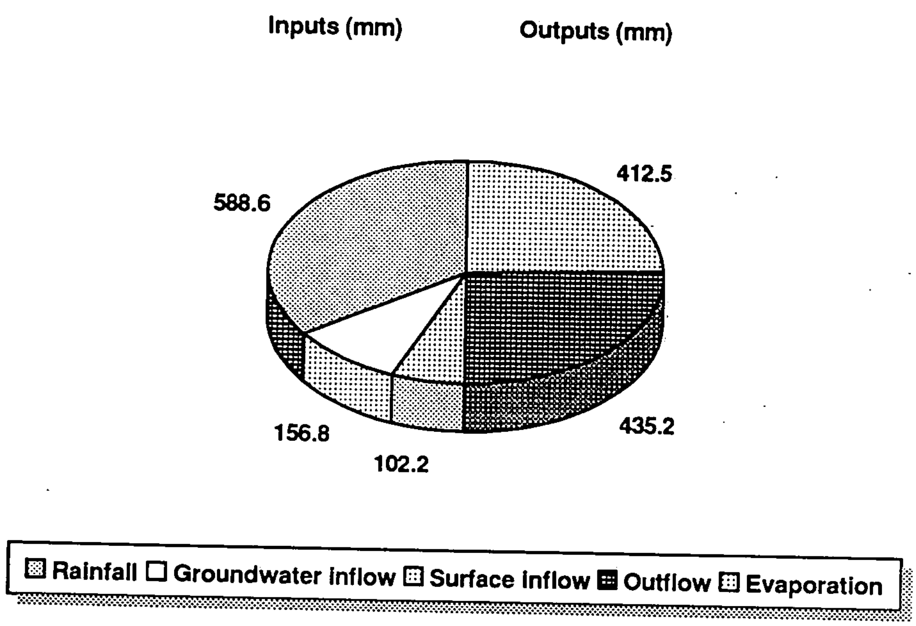
This fen site has been invaded by scrub, but still supports some calcareous valley fen vegetation, with deep peat near the river. Two pairs of dipwells have been installed by English Nature, and a deep/shallow piezometer pair was installed by the NRA in 1993. To date the deep piezometer (TM07/166) has recorded levels almost identical with those in the shallow piezometer (TM07/167). The range of variation in water levels over 1993 and 1994 is large than that predicted by the MIROS model: this may indicate recent dehydration effects or an over-estimate of the specific yield for the precise location of the piezometers. Superficial soil at the piezometer site is sandy clayey peat.

Aquifer drawdown to produce an increase in SEV($>$20) of 0.5 metre-weeks: 0.15 m

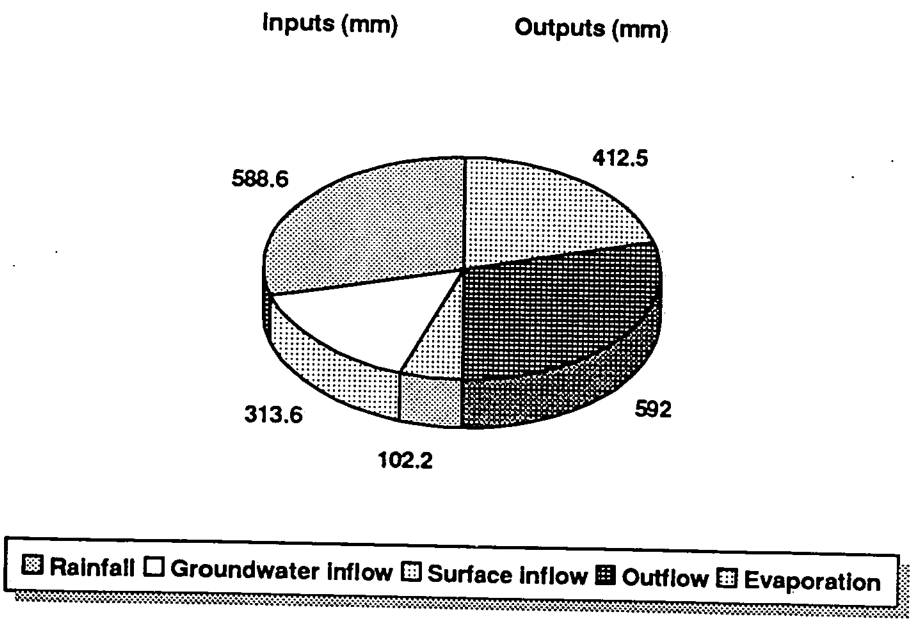
Blo'Norton & Thelnetham Fens

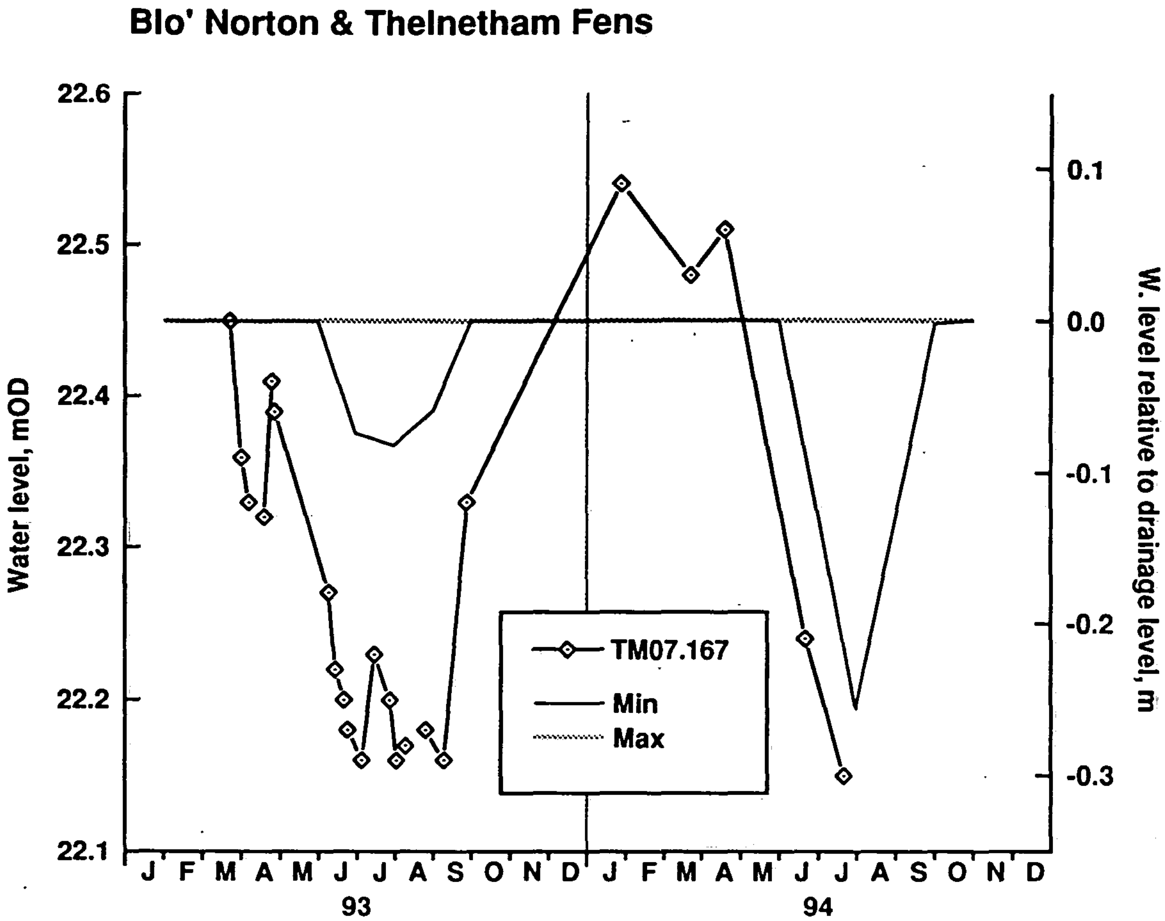
Infiltration:	30 % of effective rainfall
Evaporation:	70 % of potential
SSSI area	0.210 sq.km
Local topographic catchment:	0.277 sq.km
Diverted runoff:	0 %
Specific yield:	20 %

Water budget for wetland groundwater catchment 1.05 sq.km

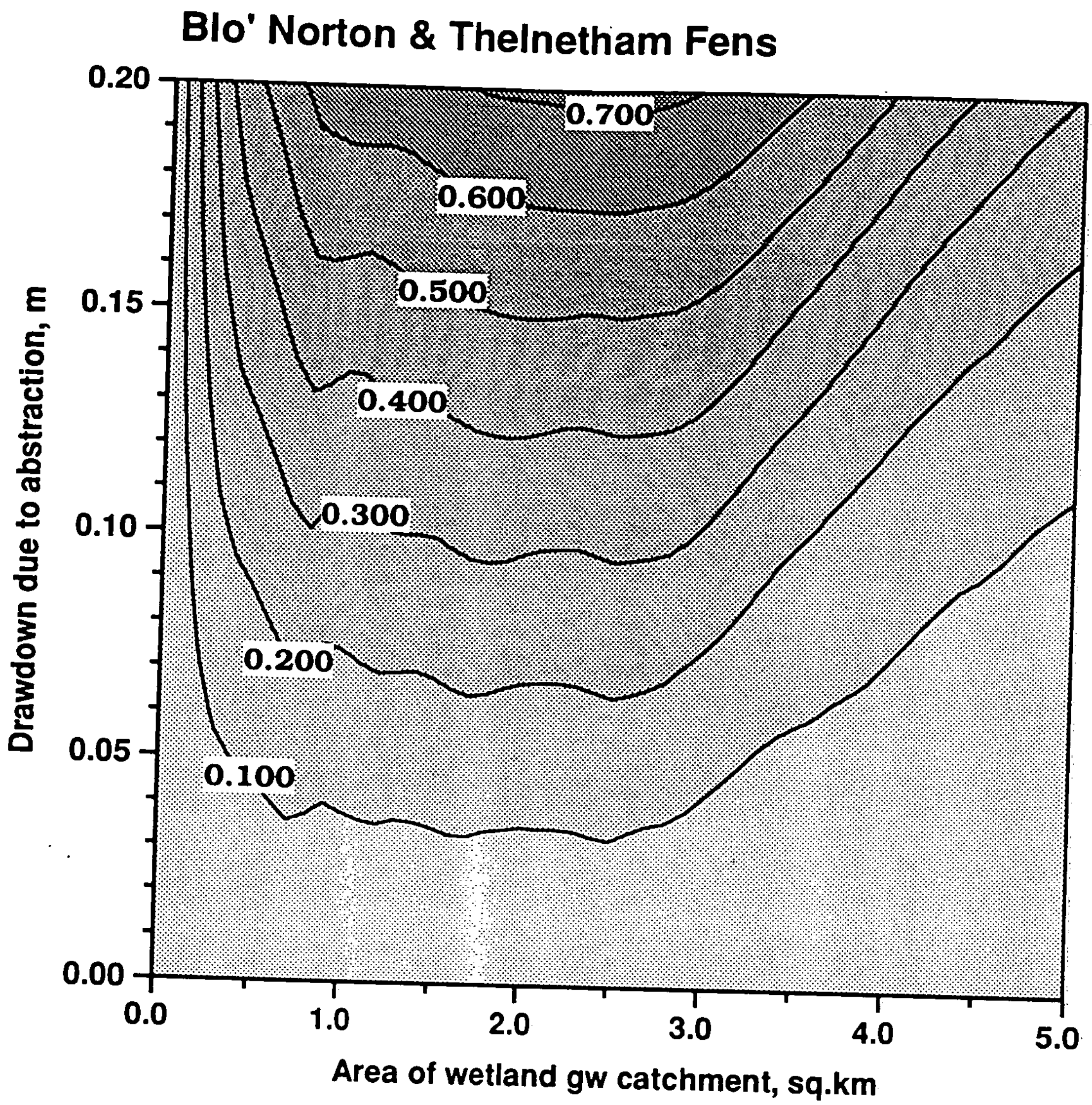


Water budget for wetland groundwater catchment 2.1 sq.km





Blo'Norton & Thelnetham Fens - observed water levels (piezometer TM07/167) and water levels predicted by MIROS model with wetland groundwater catchment areas of 1.05 sq.km (Min) and 2.1 sq.km (Max).



Blo'Norton & Thelnetham Fens - contours of change in SEV>20 for ranges of drawdown and wetland groundwater catchment area.

Blo'norton and Threlnetham

The water level monitoring point at Lodge Farm, Threlnetham (TM07/145), 1.4 km from the wetland site was used to calculate the parameters for the application of the 10% rule. The minimum recorded water level at this site is 22.29 m AOD on 23/8/89. The mean summer (June -September) water level was 23.69 m AOD giving a range of 1.40 m. 10% of this is 0.14 m

Calculations of expected drawdown at the wetland site, using the Theis equation and abstraction rates from the NRA licensing data archive have been carried out. The transmissivity value used in these calculations were derived from a pumping test on a borehole at TM 001 806 (2.2 km from the wetland), and the storage coefficient was obtained from a pumping test at Redgrave PWS (TM 0460 7913) (2.9 km from the wetland).

	Distance	Q (m3/d)	T (m/d)	S	H (m)
	3584	2.27	500	0.0005	0.001
	1081	9.09	500	0.0005	0.009
	4079	2.27	500	0.0005	0.001
	3721	1.82	500	0.0005	0.001
	3992	13.63	500	0.0005	0.007
	670	2.27	500	0.0005	0.002
	2416	1.36	500	0.0005	0.001
	4509	4.55	500	0.0005	0.002
	3157	4.55	500	0.0005	0.003
	4472	1.36	500	0.0005	0.001
	3911	11.82	500	0.0005	0.006
	1140	15.91	500	0.0005	0.015
	3847	8.18	500	0.0005	0.004
	3269	4.55	500	0.0005	0.003
	2580	2.27	500	0.0005	0.002
	2780	0.91	500	0.0005	0.001
	1843	18.18	500	0.0005	0.014
	4770	5.45	500	0.0005	0.003
	3176	25	500	0.0005	0.015
	2236	3.41	500	0.0005	0.002
	2507	19.63	500	0.0005	0.013
	1897	181.85	500	0.0005	0.14
***	4186	1000	500	0.0005	0.52
***	3312	2780	500	0.0005	1.649
***	4669	1510	500	0.0005	0.734

	Distance	Q (m3/d)	T (m/d)	S	H (m)
	1208	45.5	500	0.0005	0.042
**	3201	150	500	0.0005	0.091
	3800	109.1	500	0.0005	0.06
	2193	40	500	0.0005	0.029
	4965	5.45	500	0.0005	0.003
**	4887	300	500	0.0005	0.142
	4846	1.1	500	0.0005	0.001
	4244	20	500	0.0005	0.01
***	2906	2740	500	0.0005	1.738
	3935	19	500	0.0005	0.01
**	2823	5	500	0.0005	0.003
	5000	1.82	500	0.0005	0.001
			Total drawdown (m)		5.28

** Actual return value (average) spread over 200 days
*** Actual return value (average) spread over 365 days

This calculated drawdown is well in excess of that which woul be deemed acceptable by the 10% rule.

Broad Fen

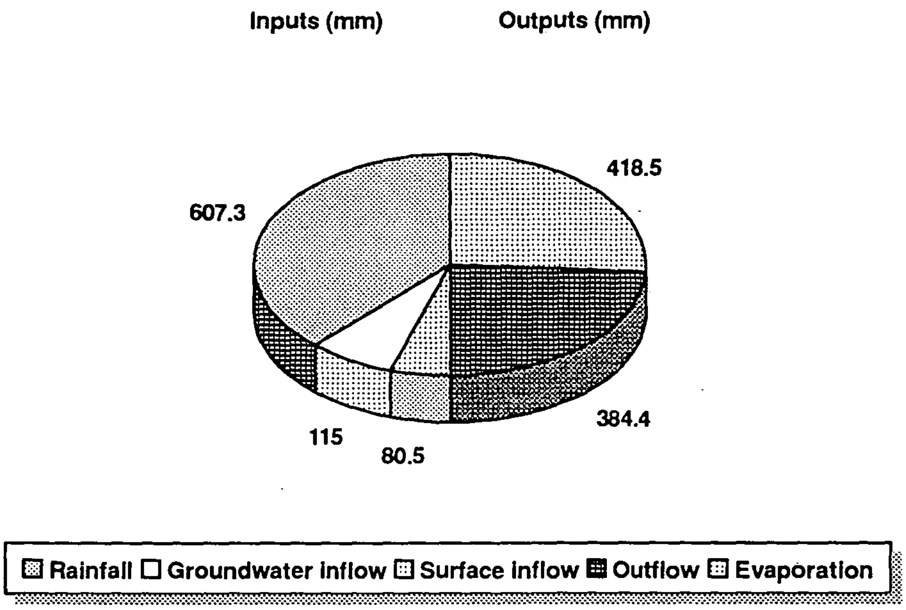
Fen supporting mixture of fen, fen meadow, open water and alder carr vegetation. A pair of piezometers was installed to monitor drawdown effects of a pumping test in response to a licence application. It is not known whether readings are continuing.

Aquifer drawdown to produce an increase in SEV(>20) of 0.5 metre-weeks: 0.18 m

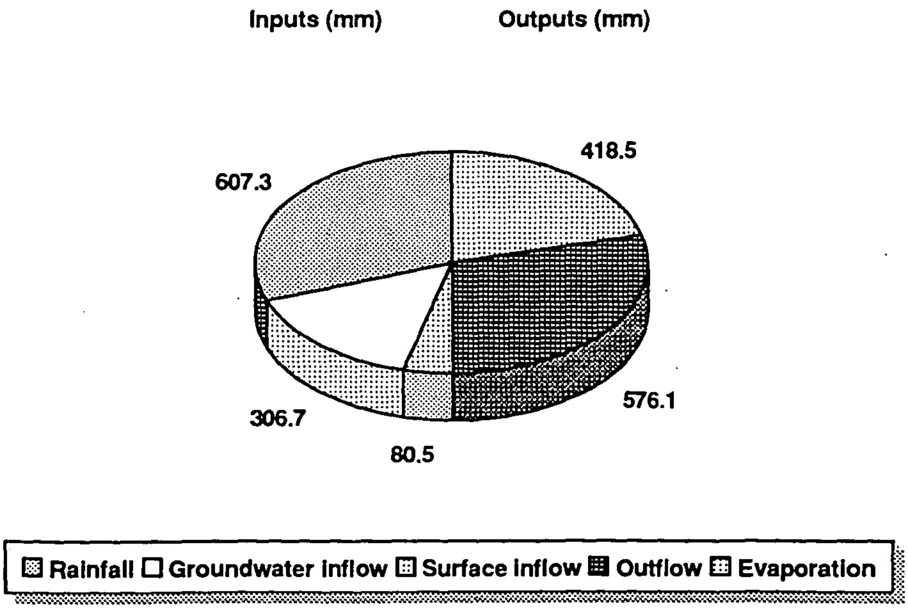
Broad Fen

Infiltration:	30 % of effective rainfall
Evaporation:	70 % of potential
SSSI area	0.369 sq.km
Local topographic catchment:	0.400 sq.km
Diverted runoff:	10 %
Specific yield:	20 %

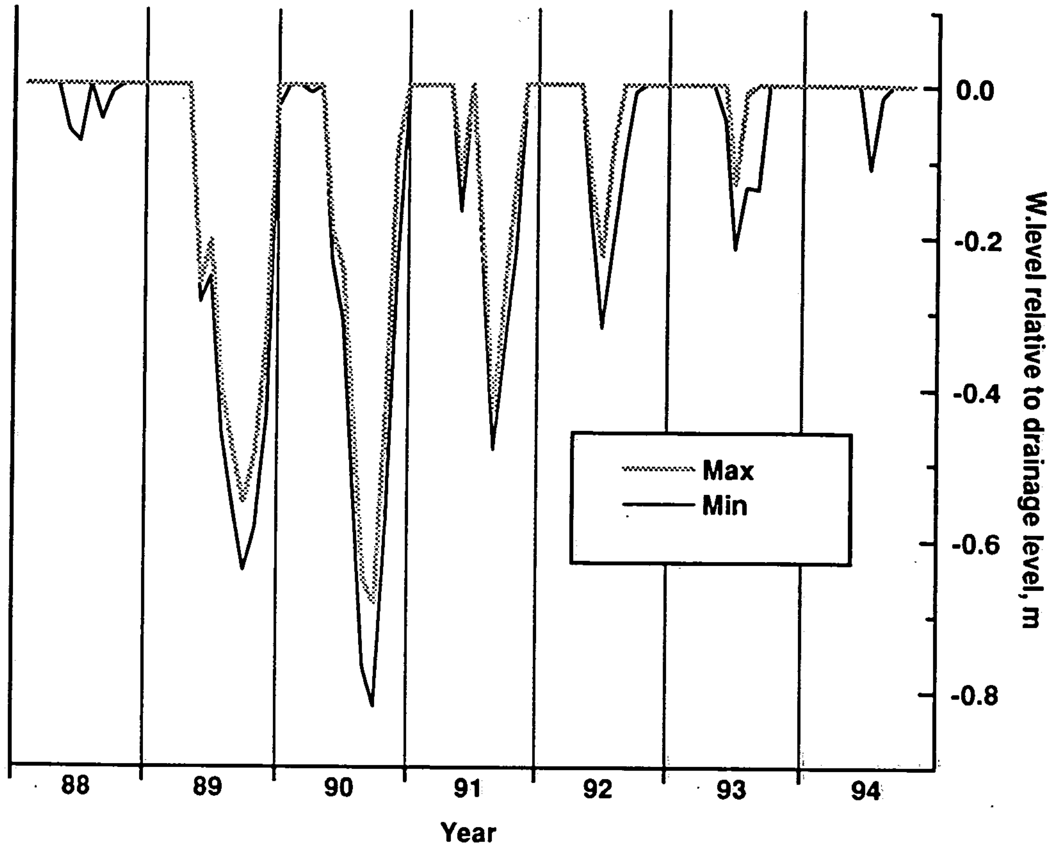
Water budget for wetland groundwater catchment 1.2 sq.km



Water budget for wetland groundwater catchment 3.2 sq.km

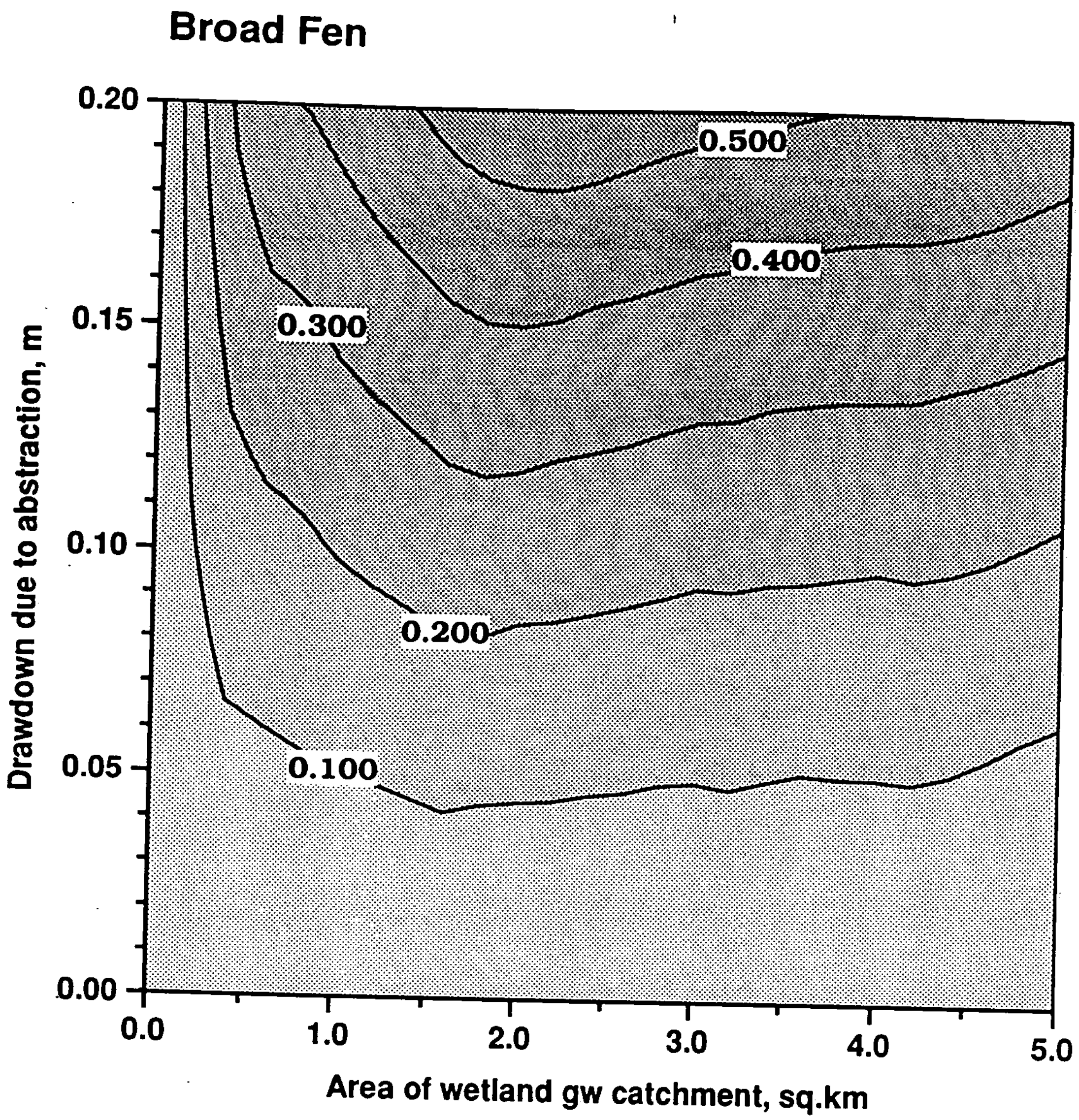


Broad Fen



Broad Fen - water levels predicted by MIROS model with wetland groundwater catchment areas of 1.2 sq.km (Min) and 3.2 sq.km (Max).

Broad Fen



Broad Fen - contours of change in SEV>20 for ranges of drawdown and wetland groundwater catchment area.

Broad Fen, Dilham

The NRA do not have any water level monitoring points in the Crag near this wetland, thus it has not been possible to calculate an acceptable drawdown using the 10% rule.

Calculations of expected drawdown at the wetland site, using the Theis equation and abstraction rates from the NRA licensing data archive have been carried out. The assumption has been made that these abstractions are all from the Crag. In the (few) cases where this is known not to be the case, the abstraction has not been included. However the total drawdown calculated below should be checked carefully with geological records.

The transmissivity and storage coefficient values used in these calculations were derived from a pumping test on a borehole at TG 373 226 (4.1 km from the wetland). Because of the uncertainties about this abstraction data, no effort has been made to use recorded returns - total daily licensed rate has been used in all cases.

Distance	Q (m3/d)	T (m/d)	S	H (m)
5411	55	100	0.05	0.000
4244	5	100	0.05	0.000
3780	14	100	0.05	0.000
4567		100	0.05	0.000
4562	32	100	0.05	0.000
4553	1026	100	0.05	0.000
4734	7	100	0.05	0.000
5090	655	100	0.05	0.000
3411	9.1	100	0.05	0.000
3014	14	100	0.05	0.000
4204	2	100	0.05	0.000
2628	3	100	0.05	0.000
5296	19	100	0.05	0.000
7408	28	100	0.05	0.000
5394	55	100	0.05	0.000
4746	2500	100	0.05	0.000
2899	1	100	0.05	0.000
2574	1	100	0.05	0.000
2273	1	100	0.05	0.000
1431	2	100	0.05	0.000
3892	1	100	0.05	0.000
3803	2.27	100	0.05	0.000
792	5	100	0.05	0.003
3845	9	100	0.05	0.000

Distance	Q (m3/d)	T (m/d)	S	H (m)
5182	1.1	100	0.05	0.000
1882	23	100	0.05	0.001
5146	1.3	100	0.05	0.000
3218	9	100	0.05	0.000
5827	18	100	0.05	0.000
5599	636	100	0.05	0.000
5705	1555	100	0.05	0.000
6569	45	100	0.05	0.000
4077	27	100	0.05	0.000
3175	5	100	0.05	0.000
1888	23	100	0.05	0.001
2394	9	100	0.05	0.000
5138	2	100	0.05	0.000
2633	7	100	0.05	0.000
5391	73	100	0.05	0.000
2452	34	100	0.05	0.000
4095	7	100	0.05	0.000
924	32	100	0.05	0.013
4400	1092	100	0.05	0.000
1872	14	100	0.05	0.000
866	91	100	0.05	0.043
7000	2273	100	0.05	0.000
2419	2728	100	0.05	0.012
1850	1500	100	0.05	0.048
5213	1200	100	0.05	0.000
2605	1900	100	0.05	0.004
3981	1290	100	0.05	0.000
5126	820	100	0.05	0.000
6407	600	100	0.05	0.000
5816	1400	100	0.05	0.000
548	180	100	0.05	0.183
1612	570	100	0.05	0.038
3041	9.1	100	0.05	0.000
		Total drawdown (m)		0.35

Catfield Fen

A fen site with deep peat lying on drift and alluvium, and divided into two hydrological units by a peat baulk. One of these units, the 'external' system, is linked hydraulically with Barton Broad. One of three sites selected in the first instance for detailed study by Birmingham University (with Weston Fen and Badley Moor), Catfield Fen was instrumented with 17 piezometers, and water level readings are available for 1988-1990. There is good agreement between the MIROS model and observations for these years.

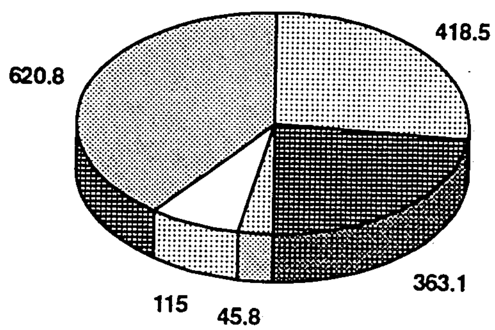
Aquifer drawdown to produce an increase in SEV(>20) of 0.5 metre-weeks: 0.18 m

Catfield Fen

Infiltration:	**60 % of effective rainfall**
Evaporation:	**70 % of potential**
SSSI area	**1.32 sq.km**
Local topographic catchment:	**1.49 sq.km**
Diverted runoff:	**20 %**
Specific yield:	**20 %**

Water budget for wetland groundwater catchment 2.1 sq.km

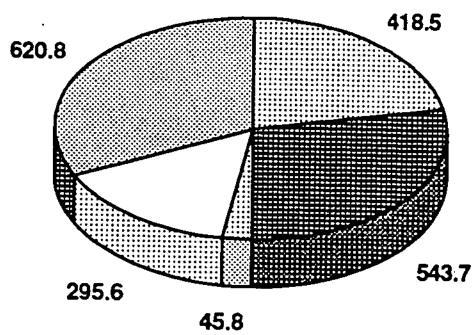
Inputs (mm) Outputs (mm)



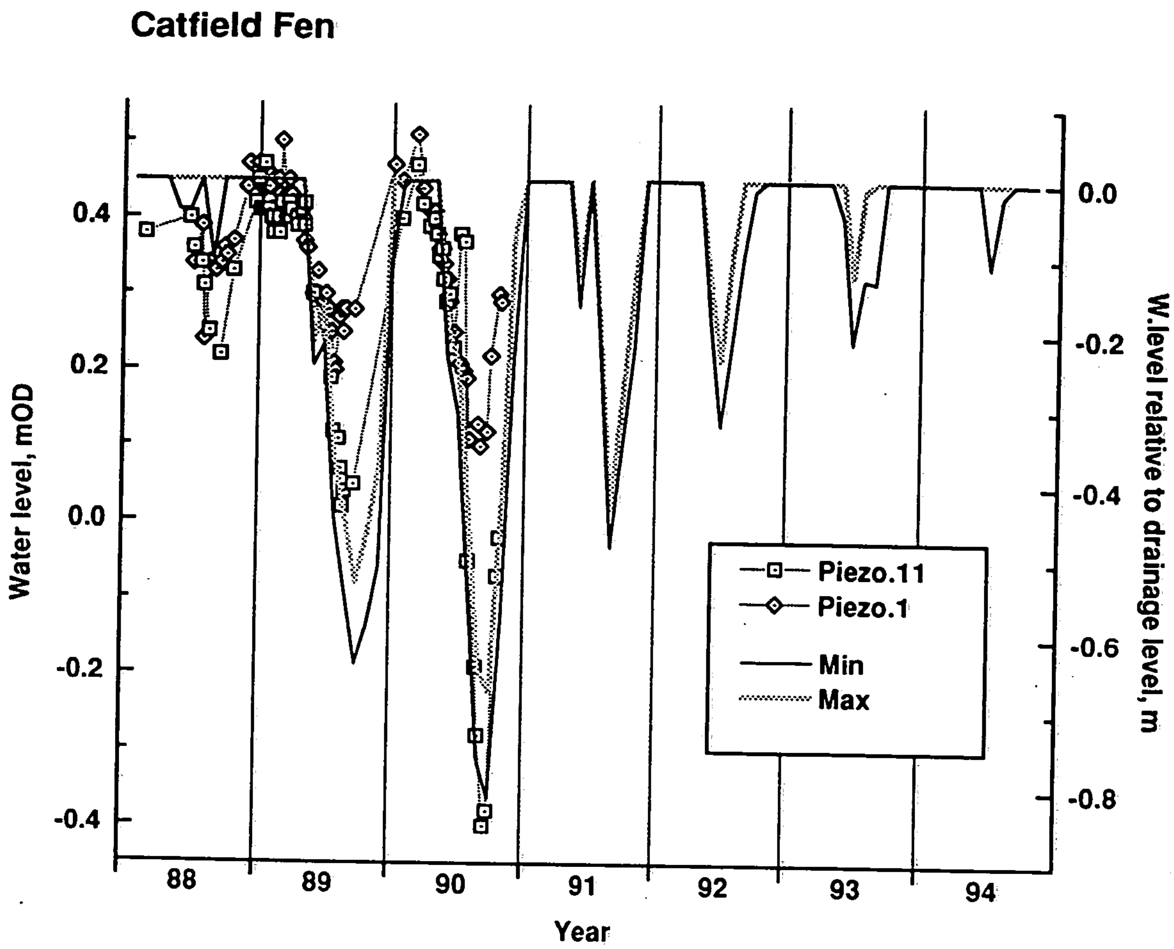
Rainfall Groundwater inflow Surface inflow Outflow Evaporation

Water budget for wetland groundwater catchment 5.4 sq.km

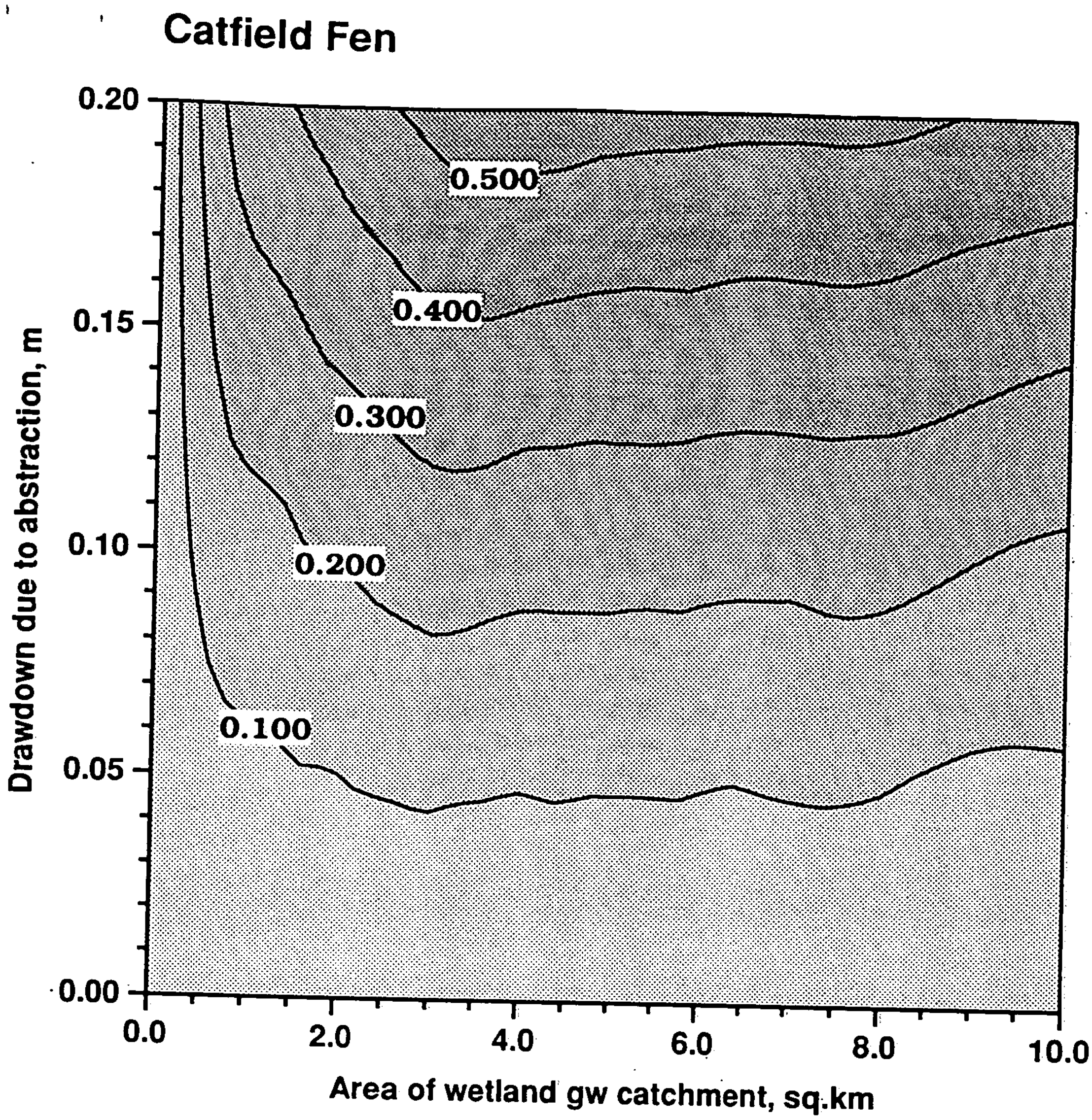
Inputs (mm) Outputs (mm)



Rainfall Groundwater inflow Surface inflow Outflow Evaporation



Catfield Fen - observed water levels (piezometers 1 & 11) and water levels predicted by MIROS model with wetland groundwater catchment areas of 2.1 sq.km (Min) and 5.4 sq.km (Max).



Catfield Fen - contours of change in SEV>20 for ranges of drawdown and wetland groundwater catchment area.

Catfield Fen

Anglian NRA have no long term water level monitoring points in the Crag aquifer within 5 km of this wetland site. Piezometers have recently been emplaced at the site but only two years of data has so far been collected. This data cannot be used to assess the effects of pumping that already exists as it will have been affected by any pumping that causes an effect.

Calculations of expected drawdown at the wetland site, using the Theis equation and abstraction rates from the NRA licensing data archive have been carried out. The assumption has been made that these abstractions are all from the Crag. In the (few) cases where this is known not to be the case, the abstraction has not been included. However the total drawdown calculated below should be checked carefully with geological records.

The transmissivity and storage coefficient values used in these calculations were derived from a pumping test on a borehole at TG 377 188 (2.3 km from the wetland). Because of the uncertainties about this abstraction data, no effort has been made to use recorded returns - total daily licensd rate has been used in all cases.

Distance	Q (m3/d)	T (m/d)	S	H (m)
3238	9	300	0.001	0.006
3238	2	300	0.001	0.001
3920	2	300	0.001	0.001
1910	1	300	0.001	0.001
4477	5	300	0.001	0.003
4016	9.1	300	0.001	0.005
3275	1.1	300	0.001	0.001
3008	6	300	0.001	0.004
4860	23	300	0.001	0.011
4753	5	300	0.001	0.002
2280	91	300	0.001	0.079
2801	14	300	0.001	0.011
728	9	300	0.001	0.013
4609	91	300	0.001	0.047
1860	2273	300	0.001	2.217
7523	2728	300	0.001	0.789
4920	1500	300	0.001	0.722
2308	275	300	0.001	0.237
4750	594	300	0.001	0.296
2884	1091	300	0.001	0.816
1529	710	300	0.001	0.765
4205	30	300	0.001	0.017

Distance	Q (m3/d)	T (m/d)	S	H (m)
1769	1090	300	0.001	1.092
1552	800	300	0.001	0.856
4827	570	300	0.001	0.280
5119	23	300	0.001	0.011
2340	2	300	0.001	0.002
3138	2	300	0.001	0.001
4614	91	300	0.001	0.047
2729	1200	300	0.001	0.931
2236	5	300	0.001	0.004
				9.27

Chippenham Fen

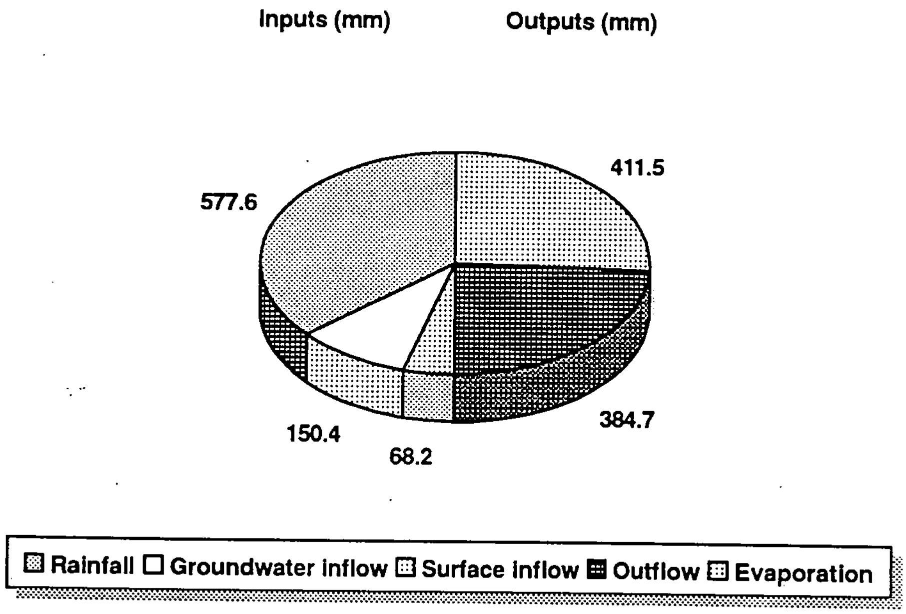
The site consists of base-rich fen supporting tall fen and sedge communities, meadow, carr and woodland. There is approximately 1 m of peat. A network of 15 piezometers was installed in 1986 and 1991 and read at fortnightly intervals. A detailed analysis of the water budget by Mason (1990) was carried out to assess the need for water supply to the dykes to counteract effects of abstraction from the Chalk. Piezometer levels between 1986 and 1993 are broadly consistent with the MIROS model, but a more detailed analysis might have permitted a better choice of index piezometer or the inclusion of a spatial component in the model. Differences between the minimum water levels reached by the piezometer and the MIROS model in summer 1990 suggest that the estimated specific yield of 20% may be rather too high.

Aquifer drawdown to produce an increase in SEV(>20) of 0.5 metre-weeks: 0.11 m

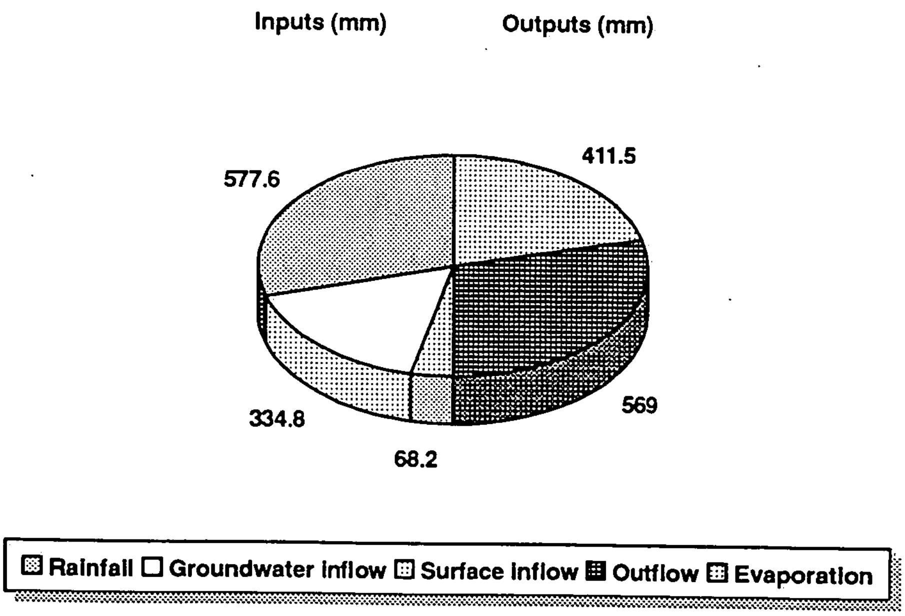
Chippenham Fen

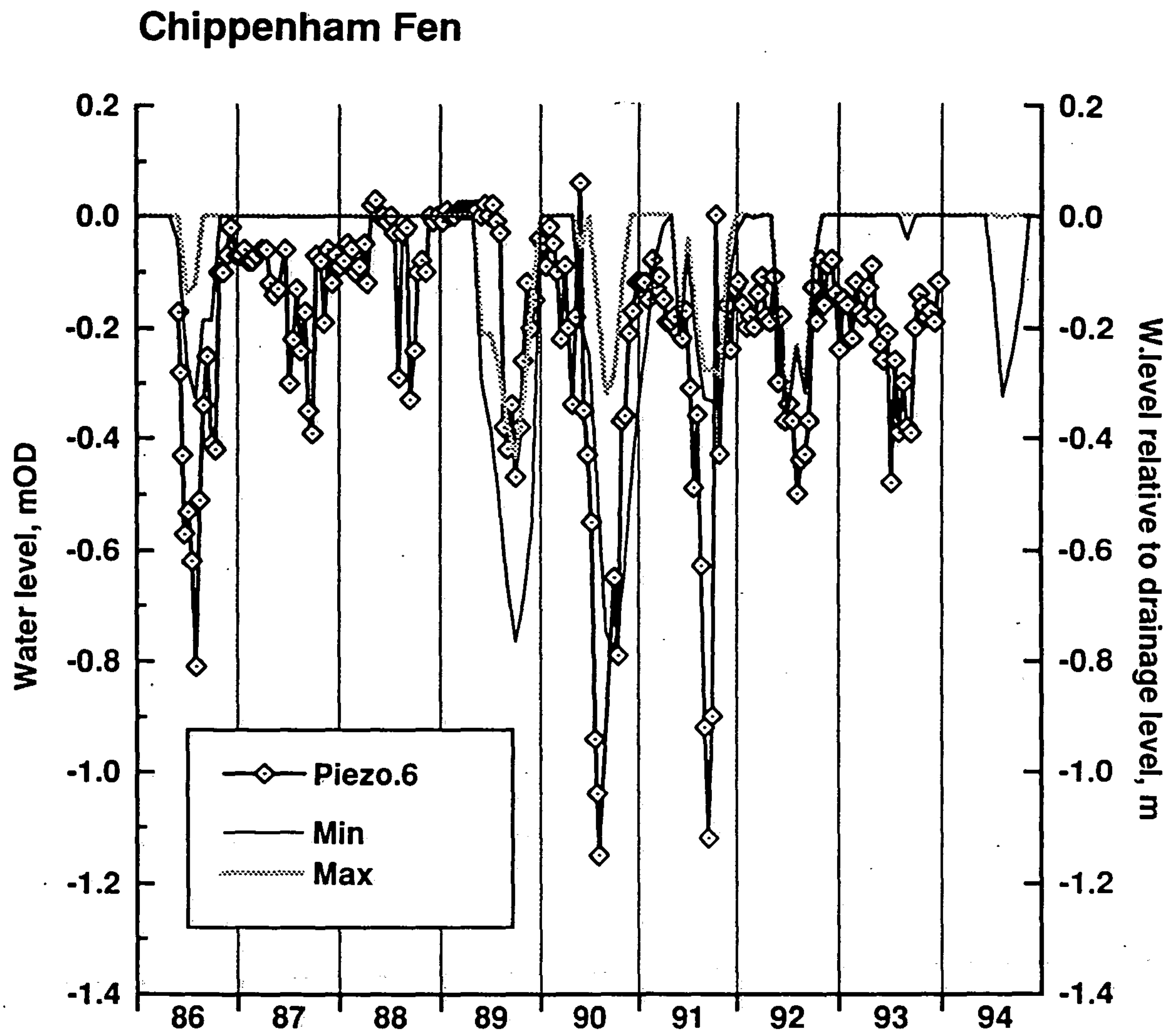
Infiltration:	60 % of effective rainfall
Evaporation:	70 % of potential
SSSI area	1.1478 sq.km
Local topographic catchment:	5.27 sq.km
Diverted runoff:	60 %
Specific yield:	20 %

Water budget for wetland groundwater catchment 3.1 sq.km

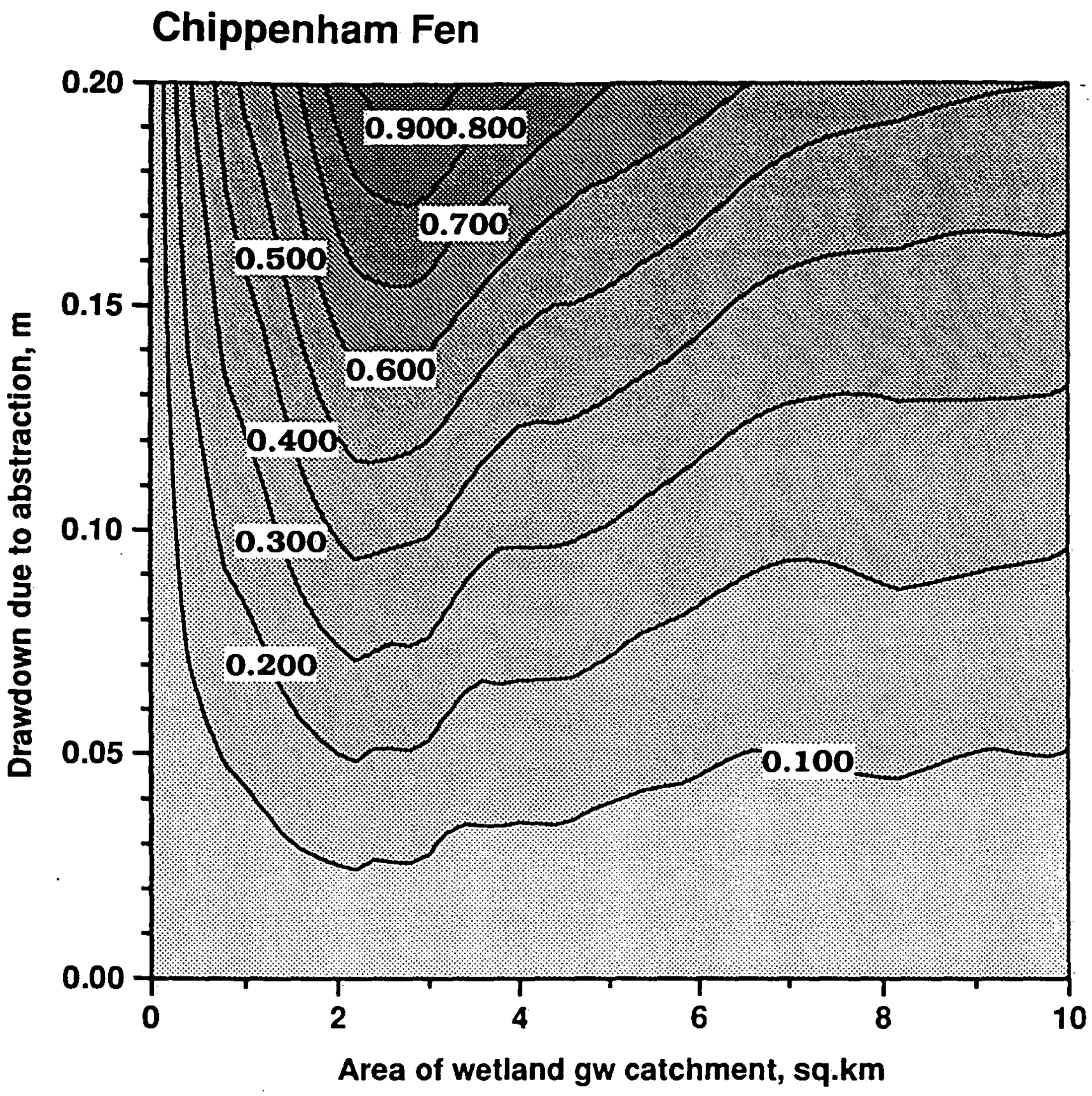


Water budget for wetland groundwater catchment 6.9 sq.km





Chippenham Fen - observed water levels (piezometer 6) and water levels predicted by MIROS model for wetland groundwater catchment areas of 3.1 sq.km (Min) and 6.9 sq.km (Max).



Chippenham Fen - contours of change in SEV>20 for ranges of drawdown and wetland groundwater catchment area.

Chippenham Fen

Regional water level variations were taken from montoring point TL66/089 (1.7km from the wetland). This record gives a mean summer (June - September) water level of 14.53 mAOD and a minimum recorded level of 12.86 mAOD (27/9/91), a difference of 1.67 m. The drawdown caused by all abstractions is calculated as 1.05 m which is 63% of the range.

The values of transmissivity and storage coefficient used were taken from a pumping test at Chippenham Pumping Station (TL 673 667).

	Distance	Q (m3/d)	T (m/d)	S	H (m)
**	3701	1851	1000	0.01	0.199
**	3828	206	1000	0.01	0.021
	2800	72	1000	0.01	0.011
	2624	818	1000	0.01	0.128
	2158	1.82	1000	0.01	0.000
	2256	4.54	1000	0.01	0.001
	1524	4.55	1000	0.01	0.001
	4103	18.18	1000	0.01	0.002
	3008	54.55	1000	0.01	0.007
	3413	800	1000	0.01	0.095
	3067	38.18	1000	0.01	0.005
	2402	3.64	1000	0.01	0.001
	2886	45.45	1000	0.01	0.006
	1676	18.2	1000	0.01	0.004
**	4472	250	1000	0.01	0.021
**	4172	190	1000	0.01	0.017
**	4401	80	1000	0.01	0.007
**	4049	143	1000	0.01	0.014
***	3200	4000	1000	0.01	0.510
		Total drawdown (m)			1.05

** using recorded returns spread over 200 days
*** using average recorded returns for whole license spread over 365 days

East Harling Common

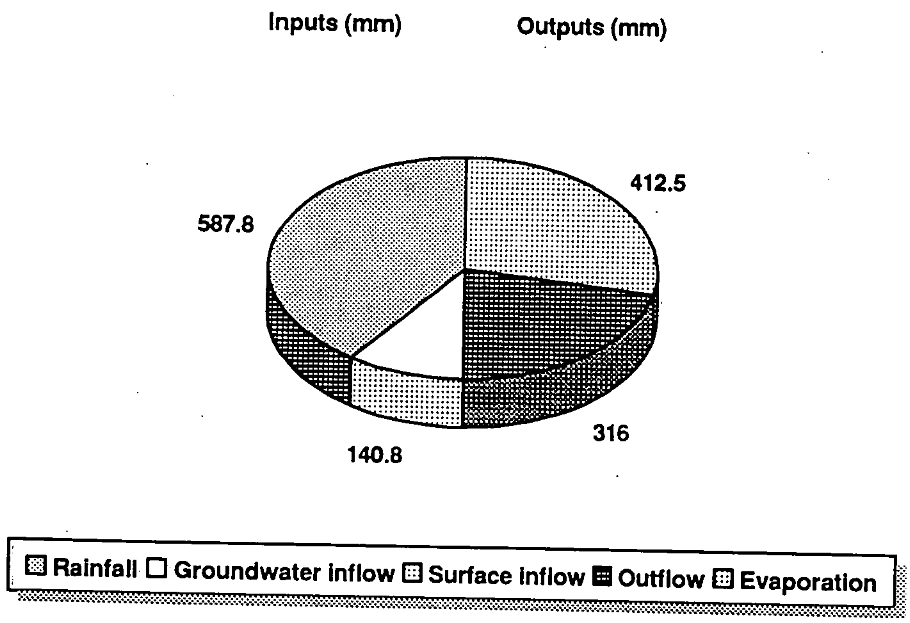
This site consists of rich fen vegetation occupying about 20 ground-ice depressions in an area of chalk grassland. There is one deep permanent mere. A deep/shallow piezometer pair was installed in 1993: records so far show that there is little difference between piezometric heads in the superficial soil and the underlying Upper Chalk. The shallow piezometer went dry in the summer of 1993; levels in the deep piezometer fell to 19.39 mOD in August 1993. The range in observed water level variations is much greater than those predicted by the MIROS model, and it may be that the specific yield should be much smaller. The spatial structure of the site may be important in maintaining fen conditions in the depressions and around open water.

Aquifer drawdown to produce an increase in SEV(>20) of 0.5 metre-weeks: 0.15 m

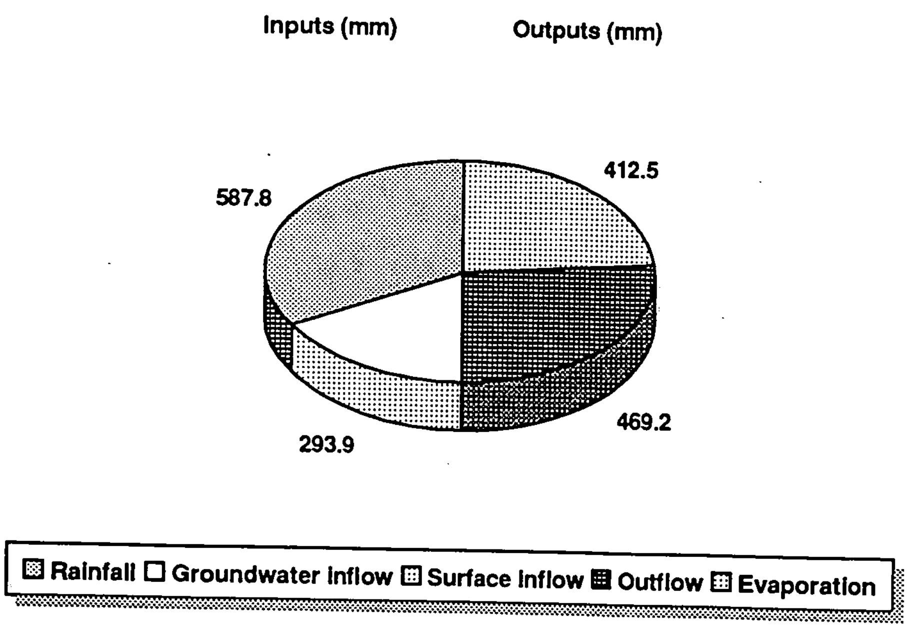
East Harling Common

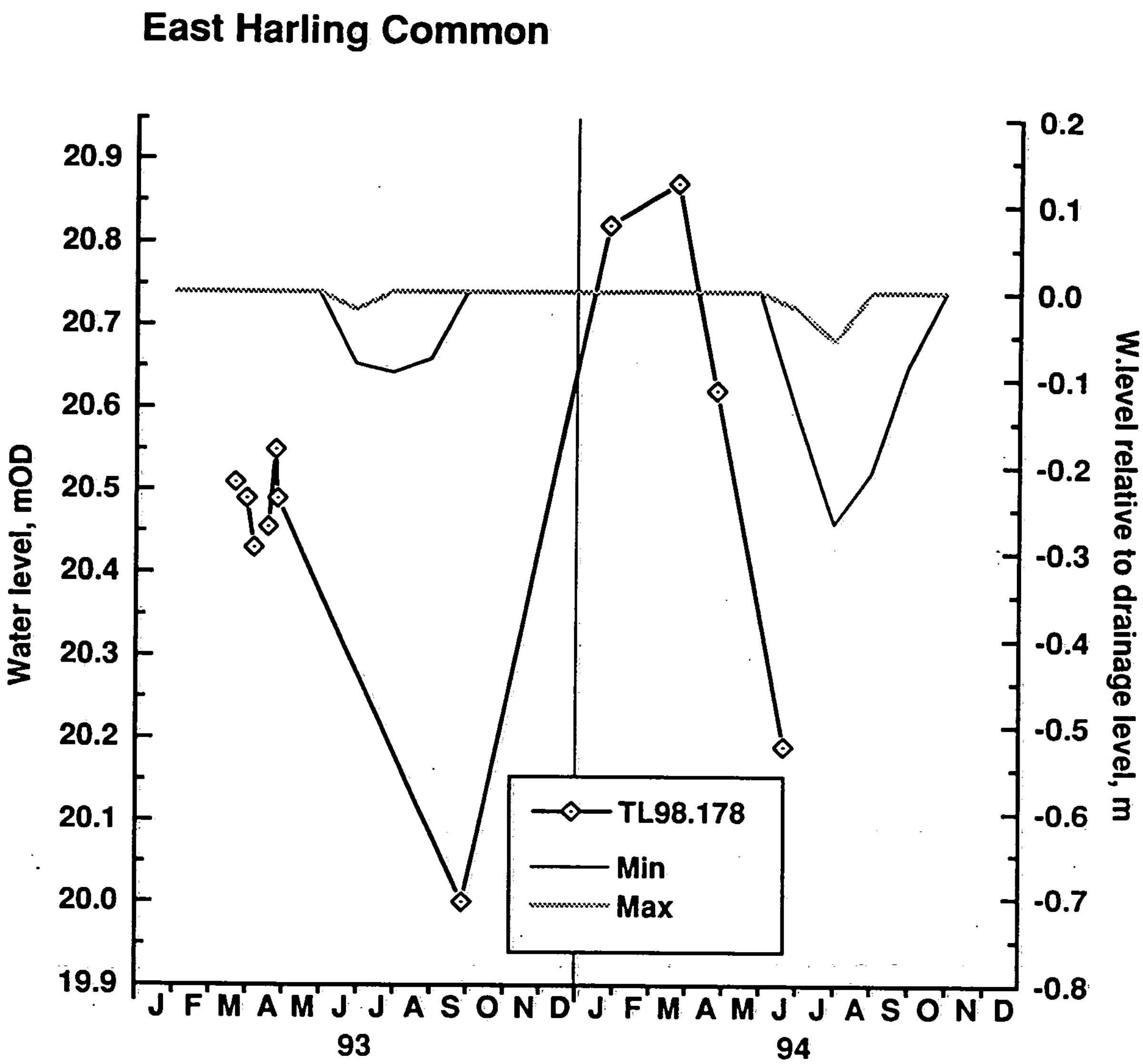
Infiltration:	60 % of effective rainfall
Evaporation:	70 % of potential
SSSI area	0.149 sq.km
Local topographic catchment:	0 sq.km
Diverted runoff:	100 %
Specific yield:	20 %

Water budget for wetland groundwater catchment 0.34 sq.km

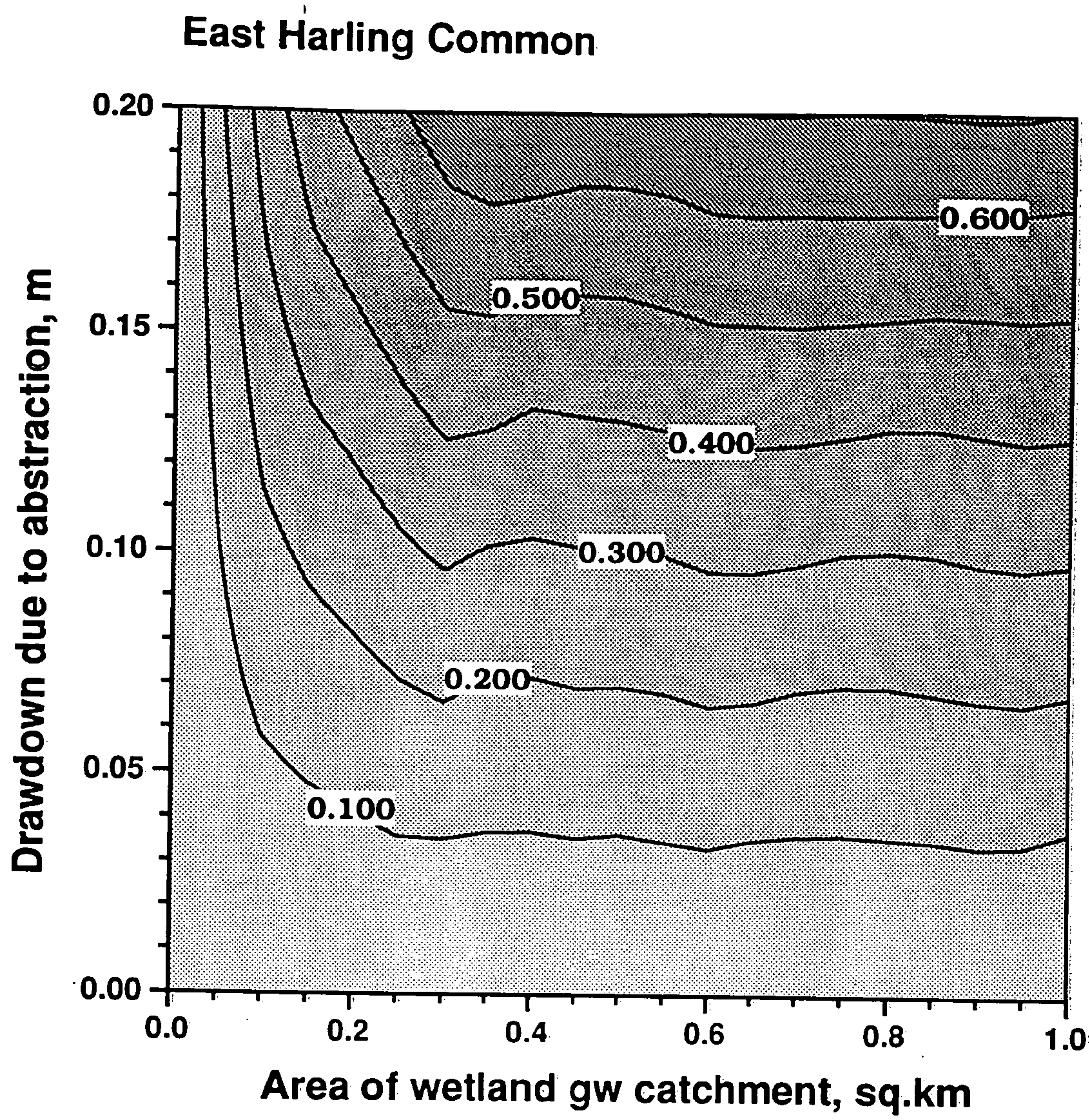


Water budget for wetland groundwater catchment 0.71 sq.km





East Harling Common - observed water levels (piezometer TL98/178) and water levels predicted by MIROS model with wetland groundwater catchment areas of 0.34 sq.km (Min) and 0.71 sq.km (Max).



East Harling Common - contours of change in SEV>20 for ranges of drawdown and wetland groundwater catchment area.

East Harling Common

The water level monitoring point at Overy Cottages, Quidenham (TL98/030), 0.4 km from the wetland site was used to calculate the parameters for the application of the 10% rule. The minimum recorded water level at this site is 17.15 m AOD on 3/10/91. The mean summer (June - September) water level was 20.34 m AOD giving a range of 3.19 m. 10% of this is 0.32 m

Calculations of expected drawdown at the wetland site, using the Theis equation and abstraction rates from the NRA licensing data archive have been carried out. The transmissivity and storage coefficient values used in these calculations were derived from a pumping test on a borehole at TM 024 874 (2.5 km from the wetland).

	Distance	Q (m3/d)	T (m/d)	S	H (m)
***	4973	1510	1300	0.007	0.127
*	3758	362	1300	0.007	0.041
	4001	4.55	1300	0.007	0.000
**	3945	25	1300	0.007	0.003
	4418	5.45	1300	0.007	0.001
	4909	15.91	1300	0.007	0.001
	4870	2.27	1300	0.007	0.000
	1615	92.73	1300	0.007	0.020
	670	13.73	1300	0.007	0.004
	4177	4.55	1300	0.007	0.000
	3522	20	1300	0.007	0.002
***	2022	2740	1300	0.007	0.510
	4527	136.36	1300	0.007	0.013
**	2906	150	1300	0.007	0.022
***	4254	1370	1300	0.007	0.138
***	3765	1123	1300	0.007	0.128
***	3920	1370	1300	0.007	0.150
***	3828	1370	1300	0.007	0.154
***	2846	1000	1300	0.007	0.146
***	4248	500	1300	0.007	0.050
***	3956	250	1300	0.007	0.027
***	1984	1000	1300	0.007	0.189
***	1697	1000	1300	0.007	0.207
***	3354	1000	1300	0.007	0.127
***	412	500	1300	0.007	0.190
***	2501	500	1300	0.007	0.081

	Distance	Q (m3/d)	T (m/d)	S	H (m)
***	2282	1000	1300	0.007	0.172
**	4738	500	1300	0.007	0.045
**	2729	150	1300	0.007	0.023
**	3606	1000	1300	0.007	0.119
**	4870	250	1300	0.007	0.022
	1627	13.63	1300	0.007	0.003
**	3423	150	1300	0.007	0.019
**	2121	250	1300	0.007	0.045
**	4767	300	1300	0.007	0.027
**	2720	250	1300	0.007	0.038
***	2473	2361	1300	0.007	0.384
**	4816	750	1300	0.007	0.066
**	3138	100	1300	0.007	0.013
**	3466	300	1300	0.007	0.037
	4491	150	1300	0.007	0.014
	2720	120	1300	0.007	0.018
			Total drawdown (m)		3.38

** Actual return value (average) spread over 200 days
*** Actual return value (average) spread over 365 days

This is a lot of drawdown.

Foulden Common

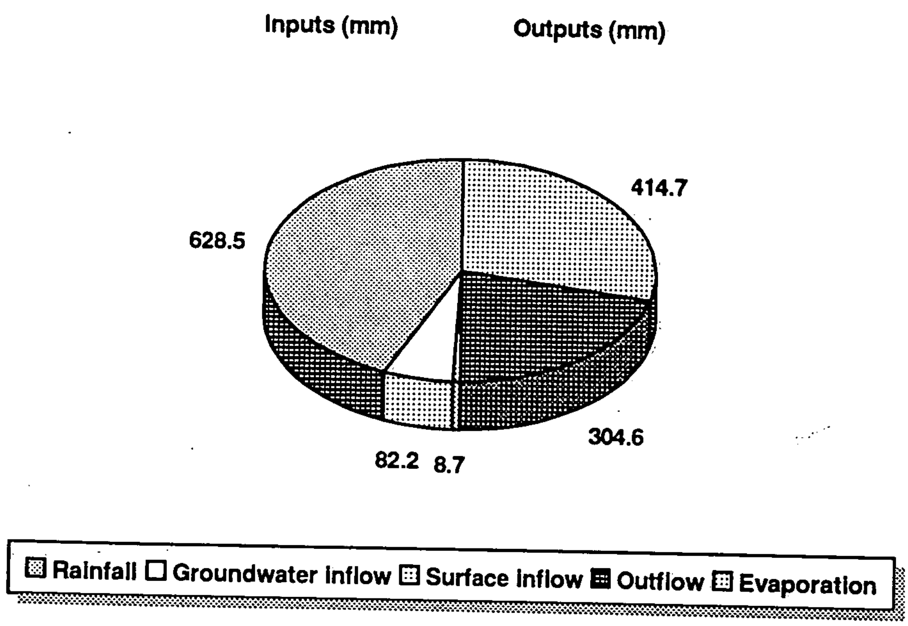
Rich fen has developed in ground-ice depressions between areas of chalk grassland, now largely invaded by scrub. One large basin is dominated by reed and saw-sedge. A deep/shallow piezometer pair was installed in 1985 as a condition of an abstraction licence. Up to summer 1989 the deep piezometer (TF70/098) and the shallow piezometer (TF70/097) followed each other very closely, but in succeeding summers paradoxically it has been the shallow piezometer that has shown a decline, the last results in early 1993 showing up to a half-metre piezometric head difference. The annual range of observed water levels is greater than that predicted by the MIROS model: this is thought to indicate that the piezometers are representative of the drier grassland rather than of the fen communities.

Aquifer drawdown to produce an increase in SEV(>20) of 0.5 metre-weeks: 0.17 m

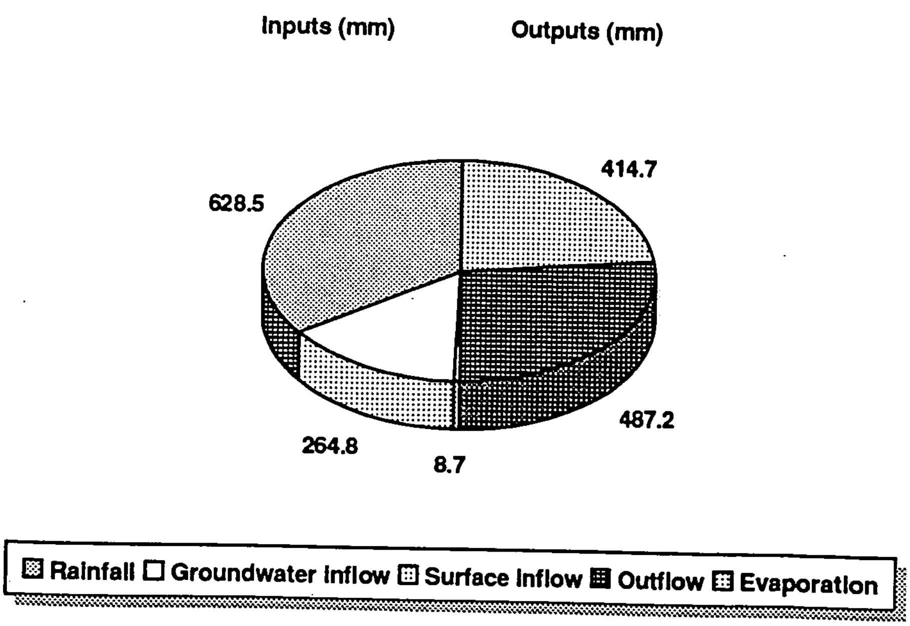
Foulden Common

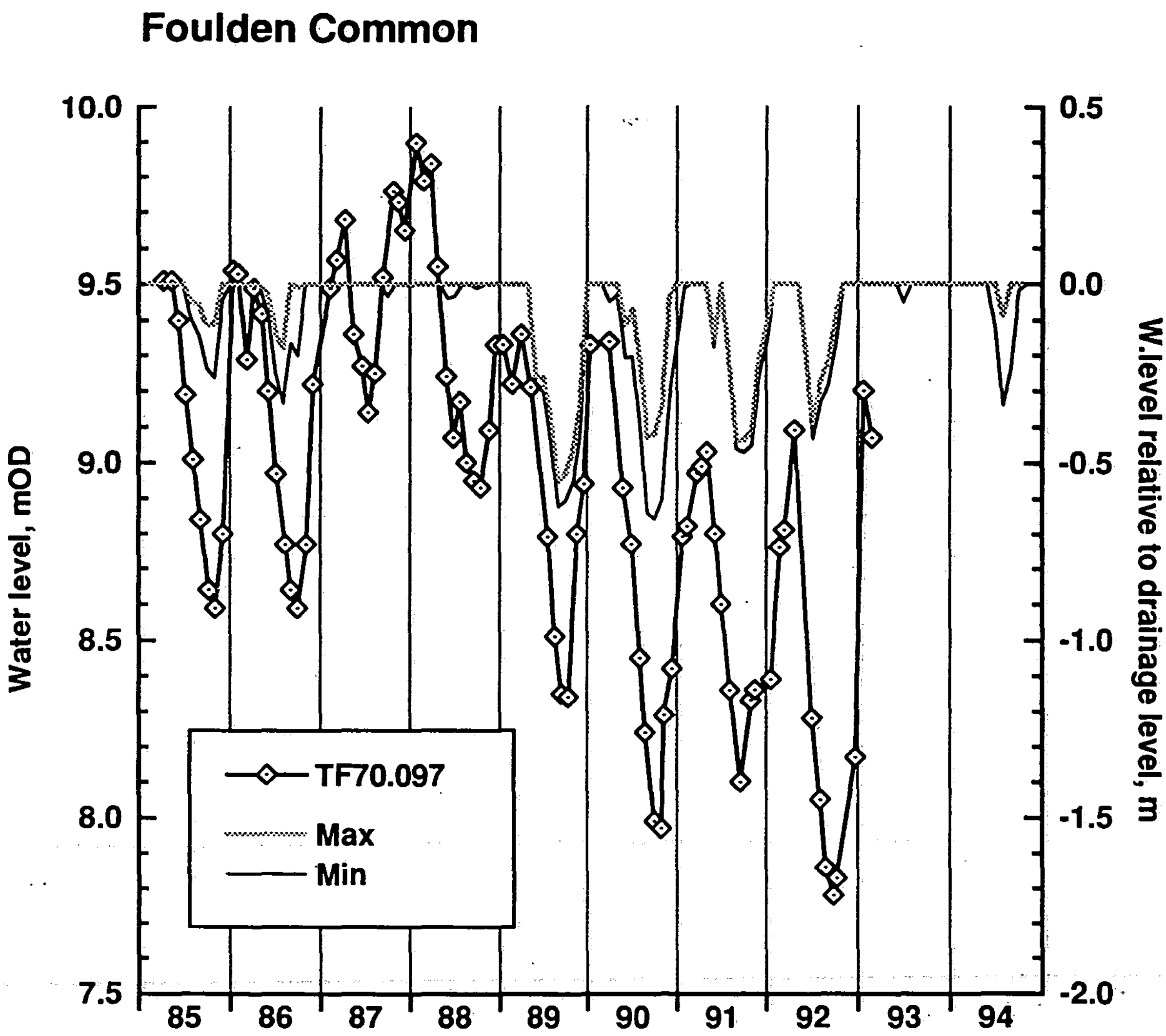
Infiltration:	60 % of effective rainfall
Evaporation:	70 % of potential
SSSI area	1.406 sq.km
Local topographic catchment:	1.35 sq.km
Diverted runoff:	80 %
Specific yield:	20 %

Water budget for wetland groundwater catchment 1.8 sq.km



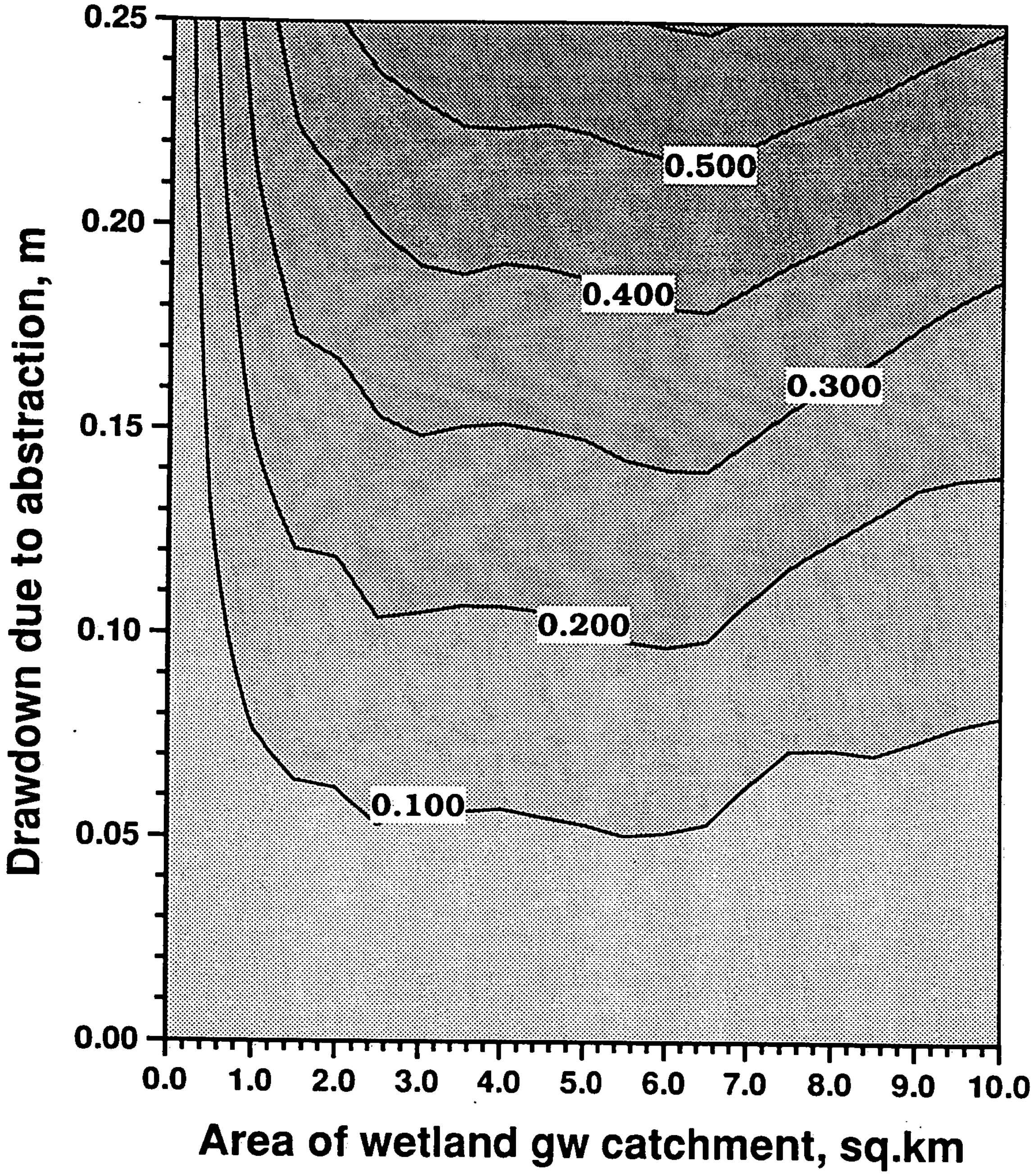
Water budget for wetland groundwater catchment 5.8 sq.km





Foulden Common - observed water levels (piezometer TF70/097) and water levels predicted by MIROS model for wetland groundwater catchment areas of 1.8 sq.km (Min) and 5.8 sq.km (Max).

Foulden Common



Foulden Common - contours of change in SEV>20 for ranges of drawdown and wetland groundwater catchment area.

Foulden Common

Piezometers TF70/097 and TF70/098 show that something has changed in the water regime at the wetland since ~ October 1990.

Wheeler and Shaw (1992) see no signs of dehydration at the site

Total licensed abstractions have been used to calculate drawdowns at the wetland, using Theis and licensed daily amounts. These show no great effect at the wetland except for license 6/33/48/*G/209. Using returns, as is shown in the Table below,for this site reduces its apparent effect. It appears that this license was only used in 1993 and so could not have caused the effect seen in the piezometer readings - also its effects would not have been seen by Wheeler and Shaw. It is possible that this license may affect the wetland.

As other abstractions appear to have little effect on the site the results from the Theis equation are deemed to be sufficient for this assessment.

Regional water level variations were taken from montoring point TL79/024 (1.0km from the wetland. This record gives a mean summer (June - September) water level of 7.25 mAOD and a minimum recorded level of 5.17 mAOD (21/8/92), a difference of 2.08 m. The drawdown caused by all abstractions except 6/33/48/*G/209 is calculated as 0.2m which is 10%.

The value of transmissivity used was taken from a pumping test at TL79/024. Storage coefficient was taken as representative of unconfined chalk.

	Distance	Q (m3/d)	T (m/d)	S	H (m)
	1303	2.27	50	0.01	0.002
	2983	13.66	50	0.01	0.001
	2088	90.9	50	0.01	0.027
	3956	1000	50	0.01	0.007
	3383	1200	50	0.01	0.030
	4976	1200	50	0.01	0.001
	4870	2400	50	0.01	0.001
	2983	1527.3	50	0.01	0.087
***	1868	816	50	0.01	0.355
	4875	2018.3	50	0.01	0.001
	4675	2400	50	0.01	0.003
	3765	818	50	0.01	0.009
	3765	818	50	0.01	0.009
	4517	13638	50	0.01	0.022
			Total drawdown		0.554
	Percentage of range		28.4 %		

*** using Annual Returns spread over 100 days.

Hopton Fen

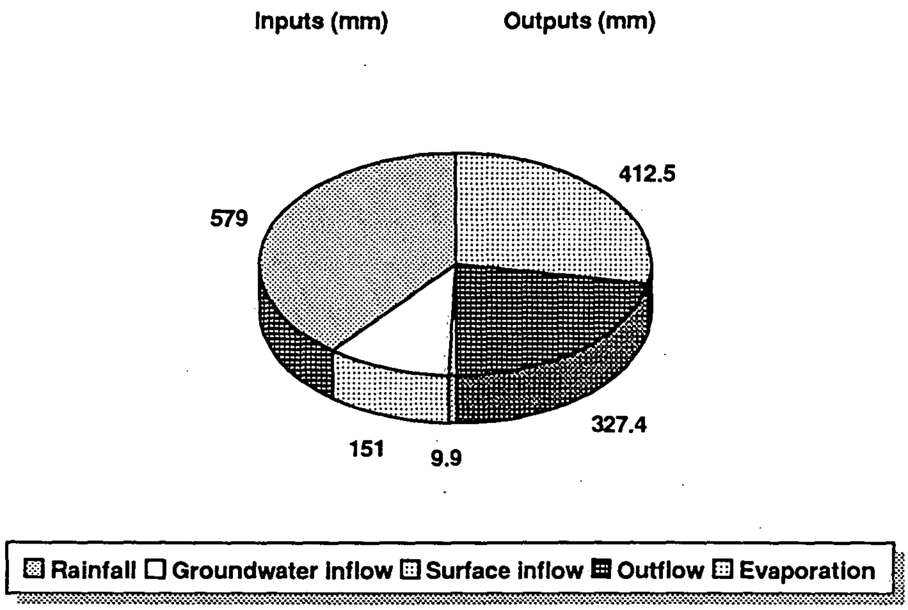
This small valley-bottom site is dominated by reed and saw-sedge with scrub on the margins. There has been recent digging to establish an area of shallow open water . Two dipwells were installed in 1992, but no results have been available for this study.

Aquifer drawdown to produce an increase in SEV(>20) of 0.5 metre-weeks: 0.15 m

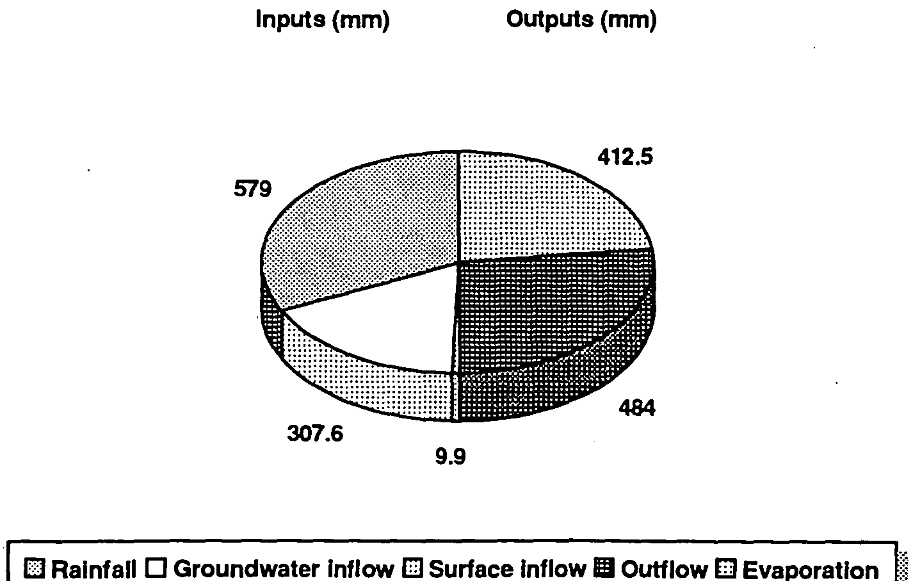
Hopton Fen

Infiltration:	**90 % of effective rainfall**
Evaporation:	**70 % of potential**
SSSI area	**0.16 sq.km**
Local topographic catchment:	**0.20 sq.km**
Diverted runoff:	**25 %**
Specific yield:	**20 %**

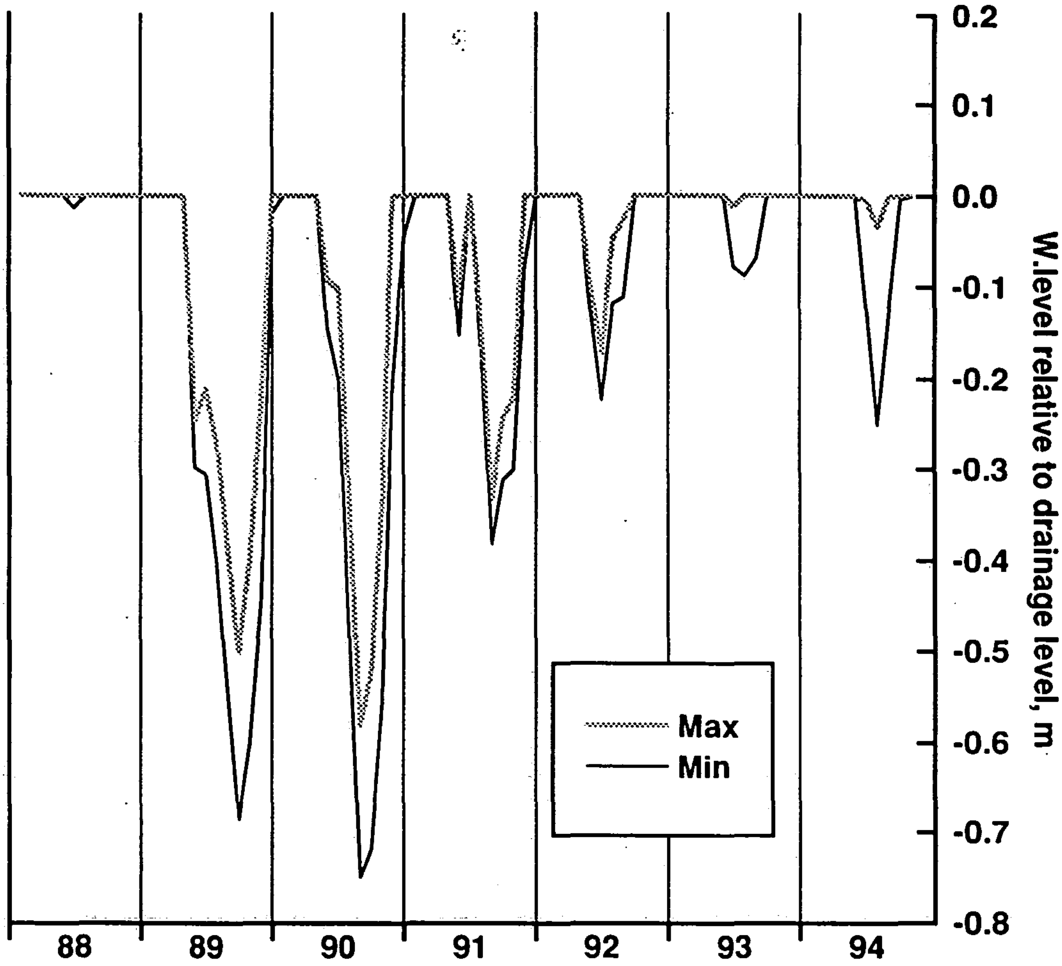
Water budget for wetland groundwater catchment 0.27 sq.km



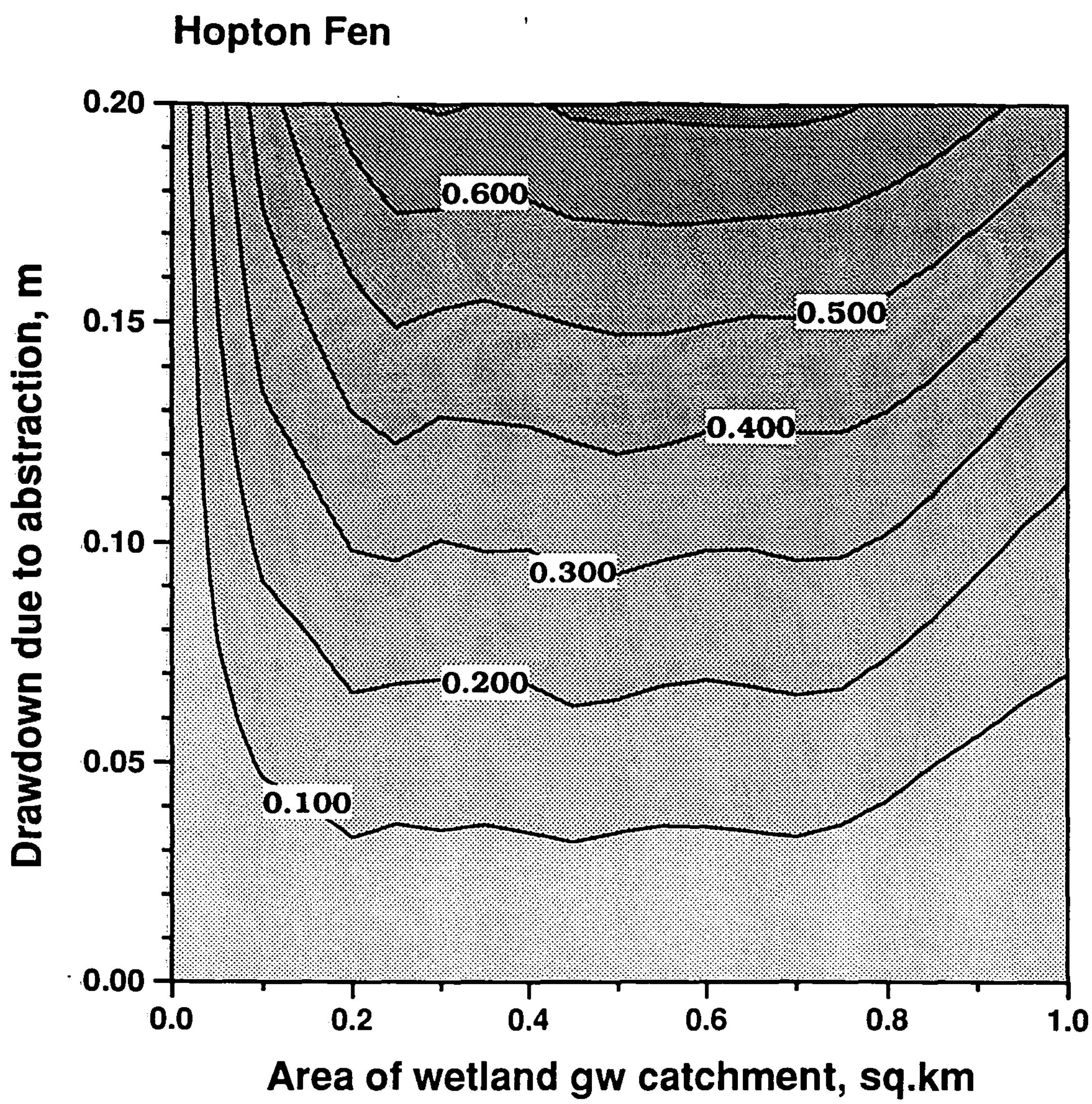
Water budget for wetland groundwater catchment 0.55 sq.km



Hopton Fen



Hopton Fen - water levels predicted by MIROS model for wetland groundwater catchment areas of 0.27 sq.km (Min) and 0.55 sq.km (Max).



Hopton Fen - contours of change in SEV>20 for ranges of drawdown and wetland groundwater catchment area.

Hopton Fen

The water level monitoring point at Cinque Farm, Market Weston (TL97/001), 1.8 km from the wetland site was used to calculate the parameters for the application of the 10% rule. The minimum recorded water level at this site is 21.23 m AOD on 1/4/77. The mean summer (June - September) water level was 23.60 m AOD giving a range of 2.37 m. 10% of this is 0.24 m.

Calculations of expected drawdown at the wetland site, using the Theis equation and abstraction rates from the NRA licensing data archive have been carried out. The transmissivity and storage coefficient values used in these calculations were derived from a pumping test on a borehole at TL 001 806 (1.2 km from the wetland).

	Distance	Q (m3/d)	T (m/d)	S	H (m)
	4964	13.64	500	0.005	0.002
	2473	2.27	500	0.005	0.001
	3939	9.09	500	0.005	0.002
	3551	6.82	500	0.005	0.002
	2220	2.27	500	0.005	0.001
	4275	1.82	500	0.005	0.000
***	3900	500	500	0.005	0.101
	2469	2.27	500	0.005	0.001
	4328	2.73	500	0.005	0.000
	3623	1.36	500	0.005	0.000
	565	4.55	500	0.005	0.004
**	3189	1	500	0.005	0.000
	1063	8.18	500	0.005	0.005
	2319	4.55	500	0.005	0.002
	2570	2.27	500	0.005	0.001
	3352	0.91	500	0.005	0.000
	4712	18.18	500	0.005	0.003
	4957	19.63	500	0.005	0.003
***	3466	750	500	0.005	0.175
***	1772	1000	500	0.005	0.430
***	2195	3000	500	0.005	1.094
***	2607	0	500	0.005	0.000
***	3354	0	500	0.005	0.000
***	3894	0	500	0.005	0.000
***	3601	0	500	0.005	0.000
***	2325	0	500	0.005	0.000

	Distance	Q (m3/d)	T (m/d)	S	H (m)
	3201	45.5	500	0.005	0.012
**	3405	200	500	0.005	0.048
	3008	250	500	0.005	0.068
**	2451	500	500	0.005	0.166
**	3189	375	500	0.005	0.096
	1208	40	500	0.005	0.022
	3551	5.45	500	0.005	0.001
**	4617	5	500	0.005	0.001
***	4219	250	500	0.005	0.045
**	3206	250	500	0.005	0.064
**	4123	5	500	0.005	0.001
			Total drawdown (m)		2.35

* Licensed annual quantity spread over 200 days
** Actual return value (average) spread over 200 days
*** Actual return value (average) spread over 365 days

The wetland site dossier for this site is uncertain as to its classification, as the connection with the underlying Chalk aquifer is uncertain. Thus the effect of abstractions from this aquifer may not be as significant as the above calculation suggest.

Kenninghall & Banham Fens & Quidenham Mere

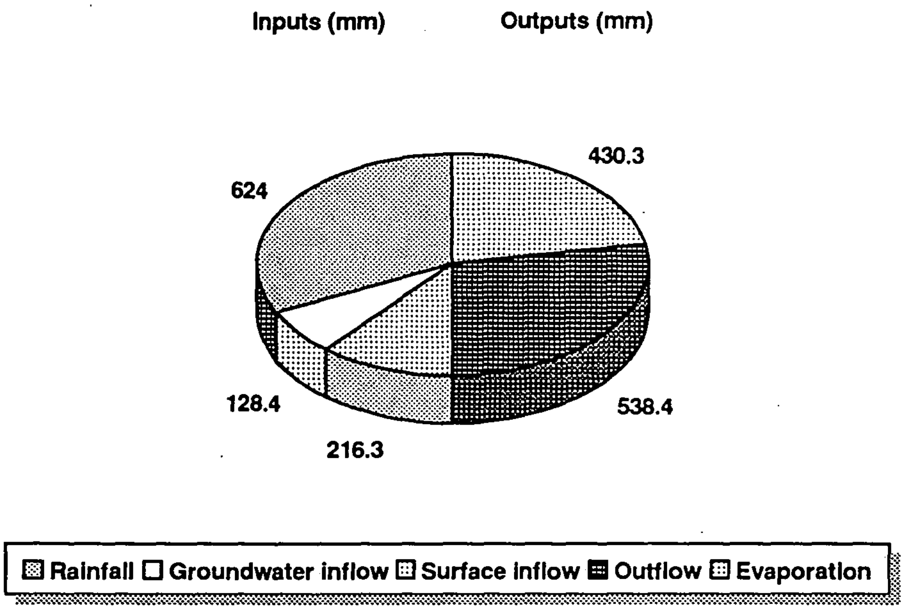
This is a complex site comprising fen adjacent to a deep non-fluctuating mere. Dominant fen vegetation is reed and saw-sedge, but other communities, chalk grassland, fen meadow and wet woodland are also present. A deep/shallow piezometer pair was installed on Kenninghall Fen in 1993. Initial results indicated a consistent hydraulic head difference of about 0.2 m during 1993, eliminated by precipitation events, but results in early 1994 suggested an increase up to more than 0.3 m. Readings in late 1993 and summer 1994 readings were too infrequent to be of much use for comparison purposes, and it may be that the piezometer site is too close to the margin of the site to indicate water level changes in the main fen areas. There is a relatively large local topographic catchment providing a significant input of surface water, but the mere, which is connected with the drainage network, may exercise a regulating influence on fen water levels close to the valley axis.

Aquifer drawdown to produce an increase in SEV(>20) of 0.5 metre-weeks: 0.16 m

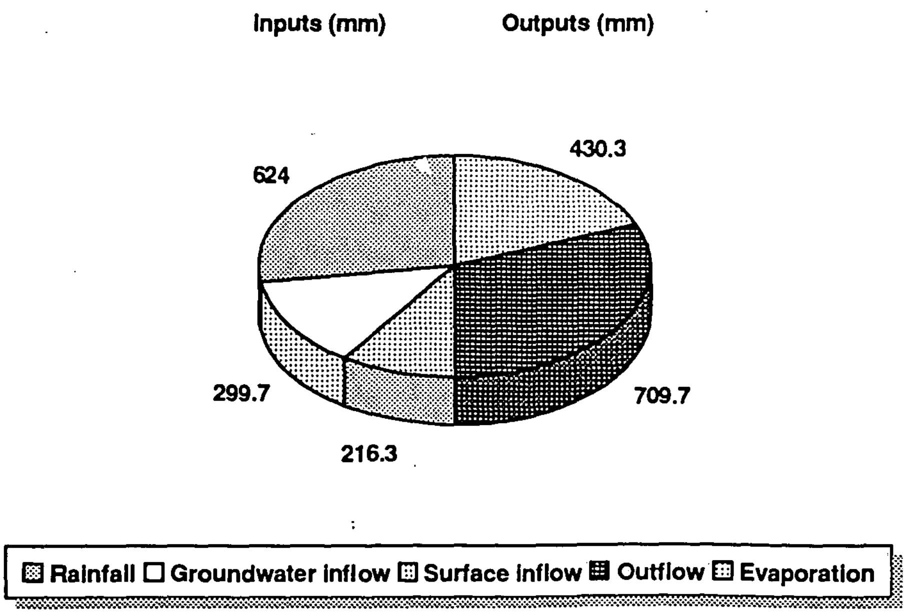
Kenninghall & Banham Fens & Quidenham Mere

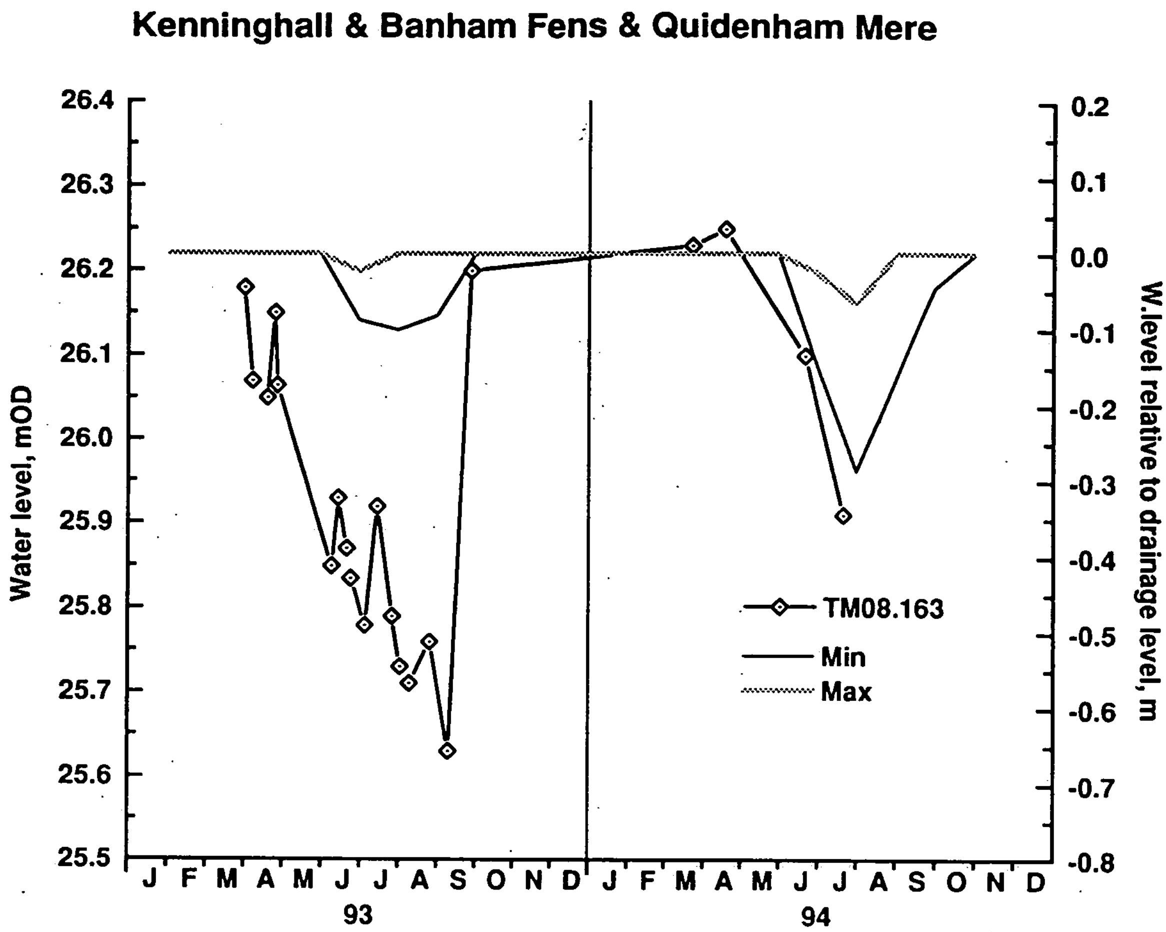
Infiltration:	**60 % of effective rainfall**
Evaporation:	**70 % of potential**
SSSI area	**0.489 sq.km**
Local topographic catchment:	**2.49 sq.km**
Diverted runoff:	**10 %**
Specific yield:	**20 %**

Water budget for wetland groundwater catchment 0.9 sq.km

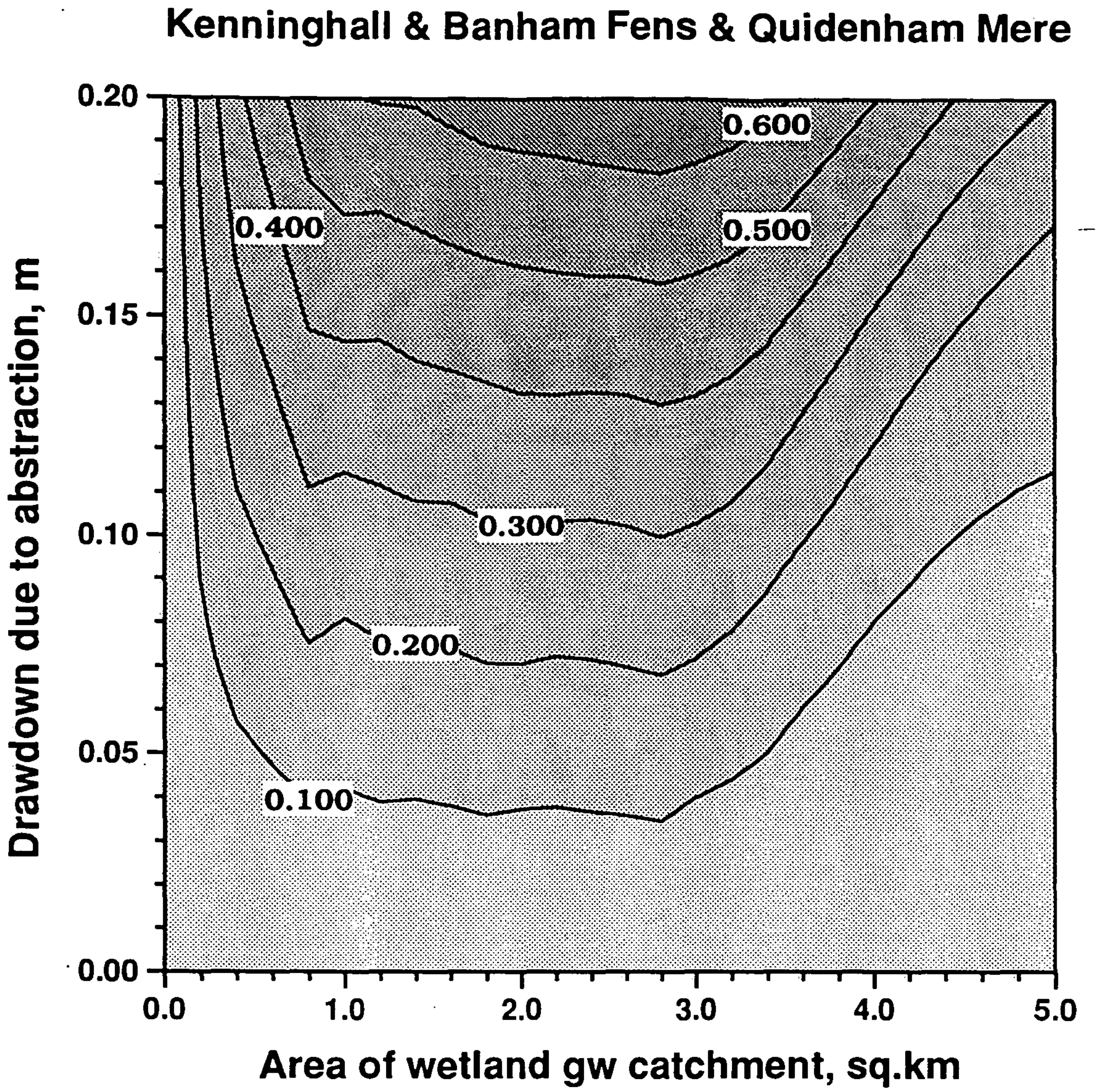


Water budget for wetland groundwater catchment 2.1 sq.km





Kenninghall & Banham Fens & Quidenham Mere - observed water levels (piezometer TF08/163) and water levels predicted by MIROS model with wetland groundwater catchment areas of 0.9 sq.km (Min) and 2.1 sq.km (Max).



Kenninghall & Banham Fens & Quidenham Mere - contours of change in SEV>20 for ranges of drawdown and wetland groundwater catchment area.

Kenninghall and Banham Fens

The water level monitoring point at Gipsies Lane, Banham (TM08/104), 0.8 km from the wetland site was used to calculate the parameters for the application of the 10% rule. The minimum recorded water level at this site is 15.16 m AOD on 28/11/91. The mean summer (June - September) water level was 27.81 m AOD giving a range of 12.65 m. 10% of this is 1.26 m

Calculations of expected drawdown at the wetland site, using the Theis equation and abstraction rates from the NRA licensing data archive have been carried out. The transmissivity and storage coefficient values used in these calculations were derived from a pumping test on a borehole at TM 0509 8710 (1.1 km from the wetland).

	Distance	Q (m3/d)	T (m/d)	S	H (m)
***	4215	1510	300	0.0004	1.190
*	3701	360	300	0.0004	0.308
	3551	13.64	300	0.0004	0.012
	3805	13.73	300	0.0004	0.012
	4827	20	300	0.0004	0.014
	2102	2740	300	0.0004	3.155
***	4561	1370	300	0.0004	1.024
***	984	2740	300	0.0004	4.254
***	3551	1000	300	0.0004	0.877
***	4079	500	300	0.0004	0.403
***	4517	500	300	0.0004	0.376
***	3400	1000	300	0.0004	0.900
**	2668	150	300	0.0004	0.154
**	1920	250	300	0.0004	0.300
**	3676	150	300	0.0004	0.129
***	1711	2000	300	0.0004	2.520
**	1843	500	300	0.0004	0.610
**	3966	300	300	0.0004	0.246
	4763	3.4	300	0.0004	0.002
*	4545	20	300	0.0004	0.015
	4044	1.1	300	0.0004	0.001
	4539	1.82	300	0.0004	0.001
			Total Drawdown (m)		16.50

* Licensed annual quantity spread over 200 days
** Actual return value (average) spread over 200 days
*** Actual return value (average) spread over 365 days

This is a large amount of drawdown. The site dossier for this wetland categorises it as an unconfined wetland (Class F). It is possible that the value of S derived from the pumping test a kilometer from the site is for a confined part of the aquifer - the hygrogeological map of the area is not sufficiently detailed to distinguish the boundary of the boulder clay in this area. If a value of storage coefficient more suitable for an unconfined aquifer is used (0.005) the total drawdown is reduced to 7.0 m. This wetland site is in close proximity to Quidenham Mere and it is probable that this Mere will have a significant effect on the hydrdynamics of this site. Thus the simplistic approach undertaken in the above calculations is unlikely to give a true representation of the effect of pumping on the site.

Redgrave & Lopham Fens

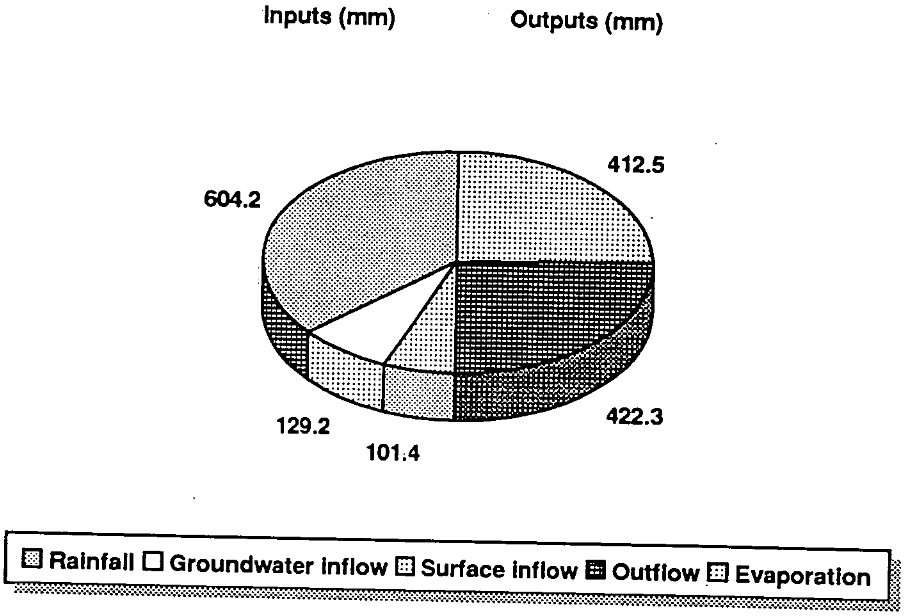
This site is large and internationally important. There are large areas of reed and sedge-dominated fen, wet heath and rush-dominated fen, surrounded by carr and woodland. Redgrave & Lopham Fens have a long history of hydrological investigation, since it was noted that large-scale abstraction of groundwater from a borehole on the southern margin had dried up seepages and created a cone of depression above an inferred "window" in the drift. Temporary cessation of pumping in 1990 brought about a return to conditions of upwelling from the Chalk (Harding 1992). There is an extensive network of dipwells and piezometers, with readings dating back to 1976, but data in numerical form was not available to this study. Data presented in graphical form by Aspinwall & Co. (1992) are in general agreement with the MIROS predictions, particularly for the drought years 1989-91.

Aquifer drawdown to produce an increase in SEV(>20) of 0.5 metre-weeks: 0.15 m

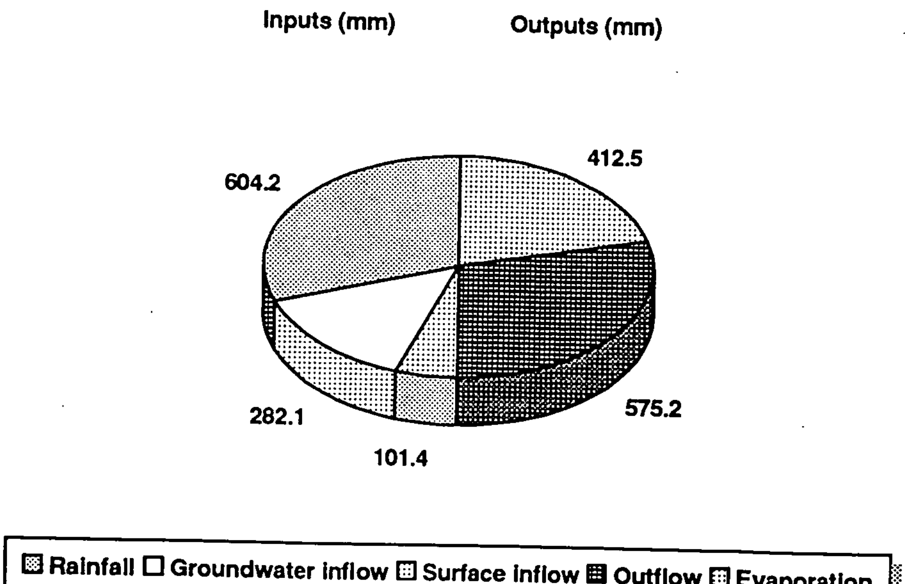
Redgrave & Lopham Fens

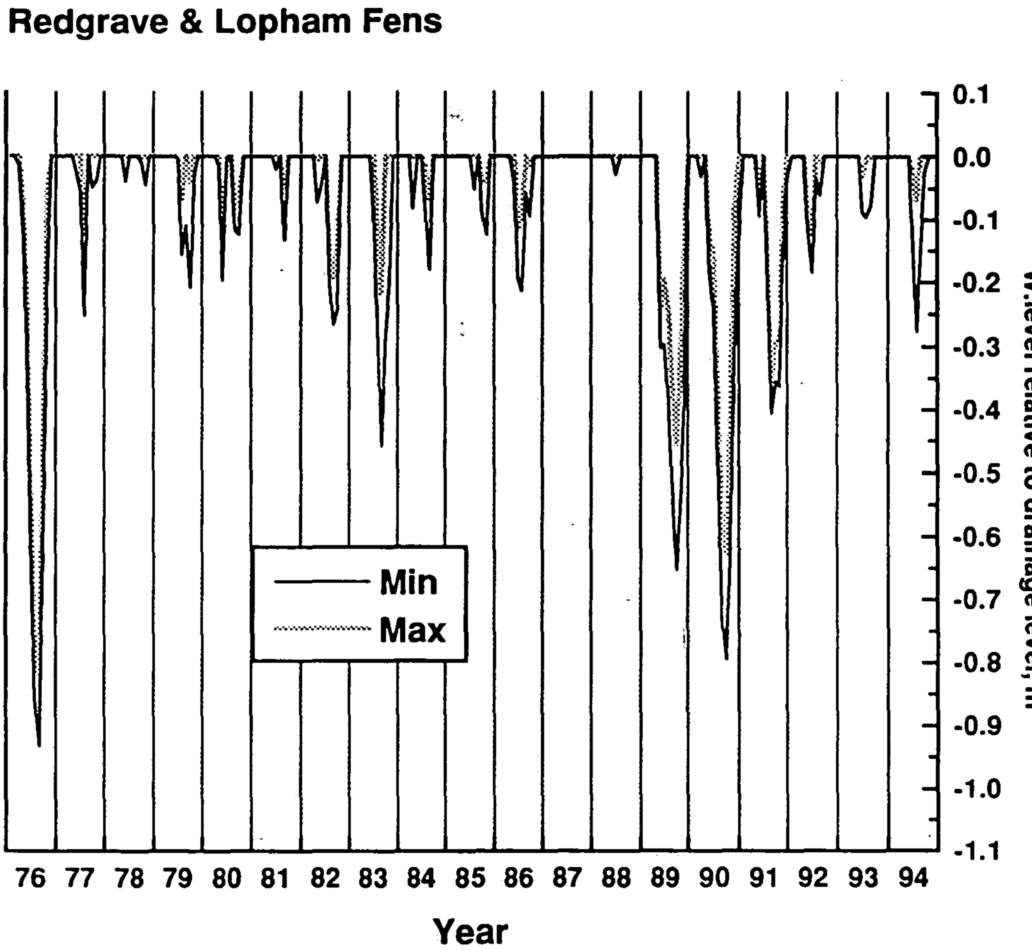
Infiltration:	30 % of effective rainfall
Evaporation:	70 % of potential
SSSI area	1.2492 sq.km
Local topographic catchment:	1.56 sq.km
Diverted runoff:	0 %
Specific yield:	20 %

Water budget for wetland groundwater catchment 4.9 sq.km

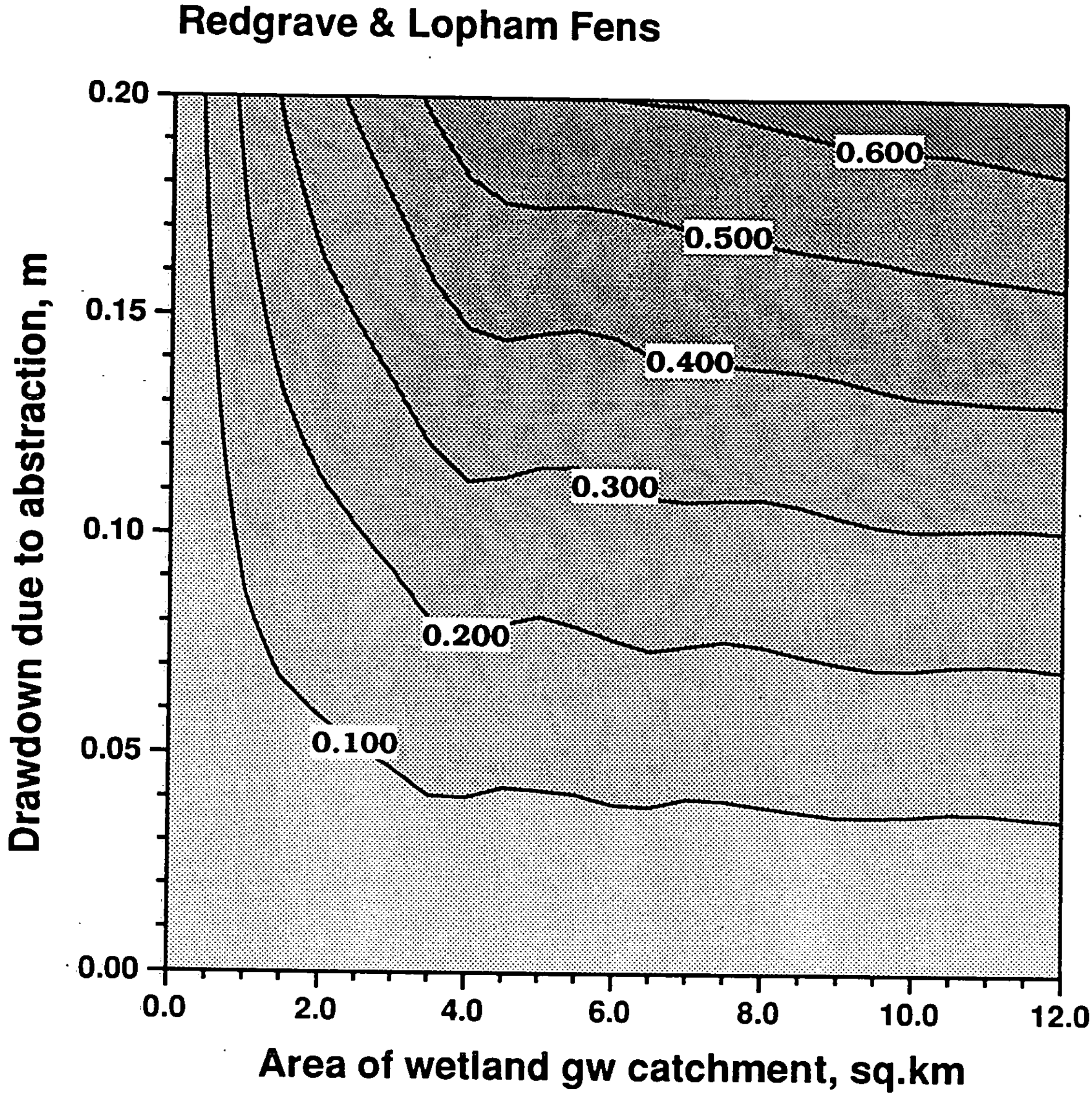


Water budget for wetland groundwater catchment 10.7 sq.km





Redgrave & Lopham Fens - water levels predicted by MIROS model with wetland groundwater catchment areas of 4.9 sq.km (Min) and 10.7 sq.km (Max).



Redgrave & Lopham Fens - contours of change in SEV>20 for ranges of drawdown and wetland groundwater catchment area.

Redgrave and Lopham Fens

The water level monitoring point at Low Common, South Lopham (TM08/500), 0.5 km from the wetland site was used to calculate the parameters for the application of the 10% rule. The minimum recorded water level at this site is 25.41 m AOD on 12/12/91. The mean summer (June - September) water level was 25.91 m AOD giving a range of 0.5 m. 10% of this is 0.05 m. It was thought that this small range may be due to the influence of the water in the fen, as this monitoring point is very close to the boundary of the fen. The data from the water level monitoring point at Church Way, Redgrave (TM07/003) was examined to see if this gave significantly different values. At this site the mean water level was 25.10 m AOD, with a minimum of24.64 m AOD, a range of 0.46 m. However thae data at this site are suspect as the water level in the well was measured at 24.64 mAOD for most of 1990 and 1991. This suggests that the well was dry in this period, and that the real minimum level is in fact lower. However it must also be noted that for the period of these records, the pumping at the Redgrave Public Water Supply well would have had an influence.

Calculations of expected drawdown at the wetland site, using the Theis equation and abstraction rates from the NRA licensing data archive have been carried out. The transmissivity and storage coefficient values used in these calculations were derived from a pumping test on a borehole at Redgrave PWS (TM 0460 7913) (0.7 km from the wetland).

	Distance	Q (m3/d)	T (m/d)	S	H (m)
	2729	9.09	3000	0.0005	0.001
	4753	13.63	3000	0.0005	0.002
	4026	2.27	3000	0.0005	0.000
	4609	5	3000	0.0005	0.001
	4025	15.91	3000	0.0005	0.002
	1860	18.18	3000	0.0005	0.003
	4472	0.91	3000	0.0005	0.000
	3373	5.45	3000	0.0005	0.001
	3624	6.81	3000	0.0005	0.001
	2256	25	3000	0.0005	0.004
	1555	3.41	3000	0.0005	0.001
	3780	17.27	3000	0.0005	0.002
	1923	2.36	3000	0.0005	0.000
	1984	181.85	3000	0.0005	0.031
***	3436	0	3000	0.0005	0.000
***	4632	1250	3000	0.0005	0.160
***	4964	0	3000	0.0005	0.000
***	3405	0	3000	0.0005	0.000
***	4110	0	3000	0.0005	0.000
	2828	45.5	3000	0.0005	0.007
**	4244	50	3000	0.0005	0.007
**	4220	200	3000	0.0005	0.027

	Distance	Q (m3/d)	T (m/d)	S	H (m)
**	3959	5	3000	0.0005	0.001
**	3667	1	3000	0.0005	0.000
	4964	40	3000	0.0005	0.005
	4903	13.64	3000	0.0005	0.002
	1700	7	3000	0.0005	0.001
	3087	14	3000	0.0005	0.002
	2109	3	3000	0.0005	0.001
	4883	12	3000	0.0005	0.002
	4161	4	3000	0.0005	0.001
	3301	7	3000	0.0005	0.001
	2683	1.1	3000	0.0005	0.000
	2549	2.2	3000	0.0005	0.000
	4085	1.1	3000	0.0005	0.000
	4512	25	3000	0.0005	0.003
	1969	20	3000	0.0005	0.003
**	2912	100	3000	0.0005	0.015
**	3569	125	3000	0.0005	0.018
**	2469	125	3000	0.0005	0.020
***	640	3000	3000	0.0005	0.700
	4709	10	3000	0.0005	0.001
	2000	9.1	3000	0.0005	0.002
	3465	9	3000	0.0005	0.001
	4883	91	3000	0.0005	0.011
**	3231	200	3000	0.0005	0.029
	3176	19	3000	0.0005	0.003
	2906	41	3000	0.0005	0.006
	1860	9	3000	0.0005	0.002
	3313	1.82	3000	0.0005	0.000
			Total drawdown (m)		1.08

* Licensed annual quantity spread over 200 days
** Actual return value (average) spread over 200 days
*** Actual return value (average) spread over 365 days

This value is very large compared with the range in water levels measured at nearby monitoring points. However, this wetland site is thought to have been deleteriously affected by the pumping at Redgrave PWS, which is responsible for 70% of this calculated drawdown.

Smallburgh Fen

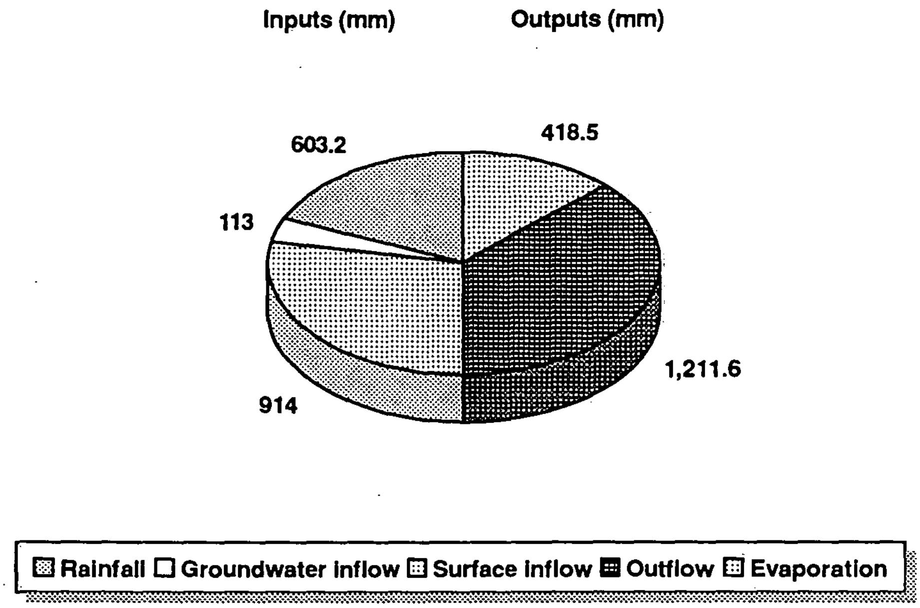
This small spring-fed valley fen supports a short fen vegetation with abundant mosses, surrounded by rather taller fen vegetation and carr woodland. Three piezometers were installed in 1989, a deep/shallow pair in the fen and a single piezometer in the woodland. As far as can be deduced from the records, there is no consistent piezometric head difference between the deep and shallow piezometers, but confusion as to numbering casts doubt on which piezometer relates to which measurement. The sequence of successively wetter summers from 1990 to 1994 shows good agreement between observations and the MIROS model, but the range of actual fluctuations is significantly less than that predicted by MIROS, and the groundwater component may be under-estimated. An assessment of SEV's from actual measurements of water table elevation might have been a better approach at this site, though as the contour plot shows, under-estimation of the wetland groundwater catchment area would not have a great influence on the maximum.

Aquifer drawdown to produce an increase in SEV($>$20) of 0.5 metre-weeks: 0.18

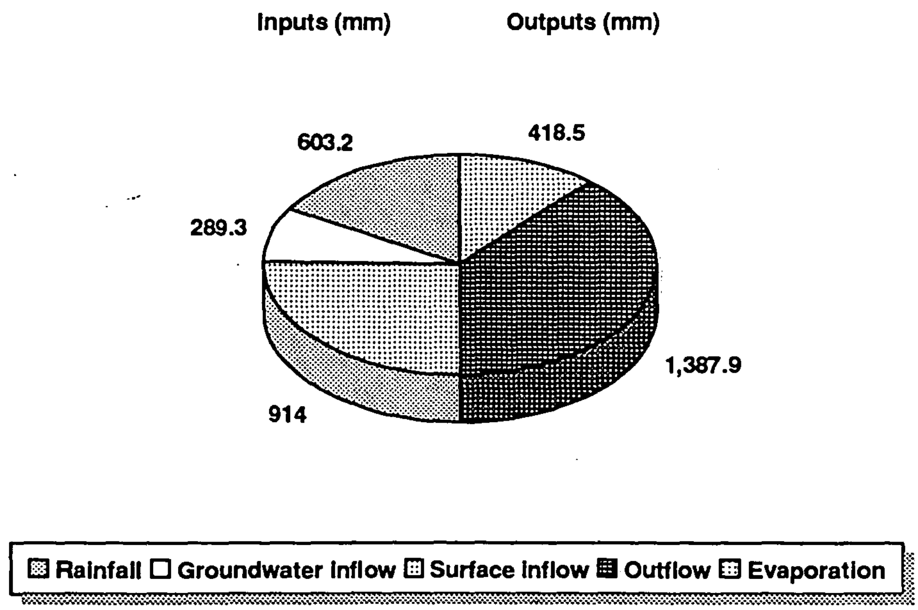
Smallburgh Fen

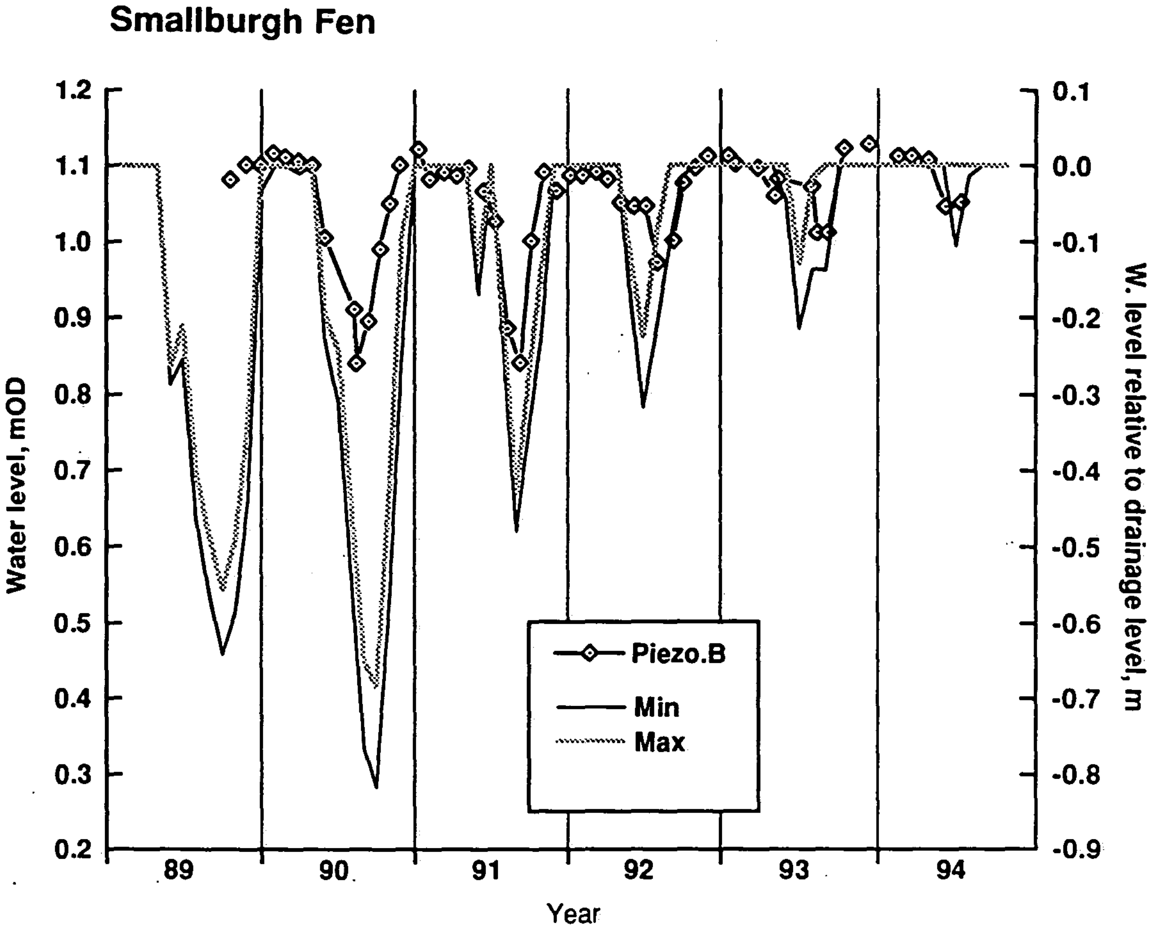
Infiltration:	30 % of effective rainfall
Evaporation:	70 % of potential
SSSI area	0.0727 sq.km
Local topographic catchment:	0.91 sq.km
Diverted runoff:	10 %
Specific yield:	20 %

Water budget for wetland groundwater catchment 0.25 sq.km

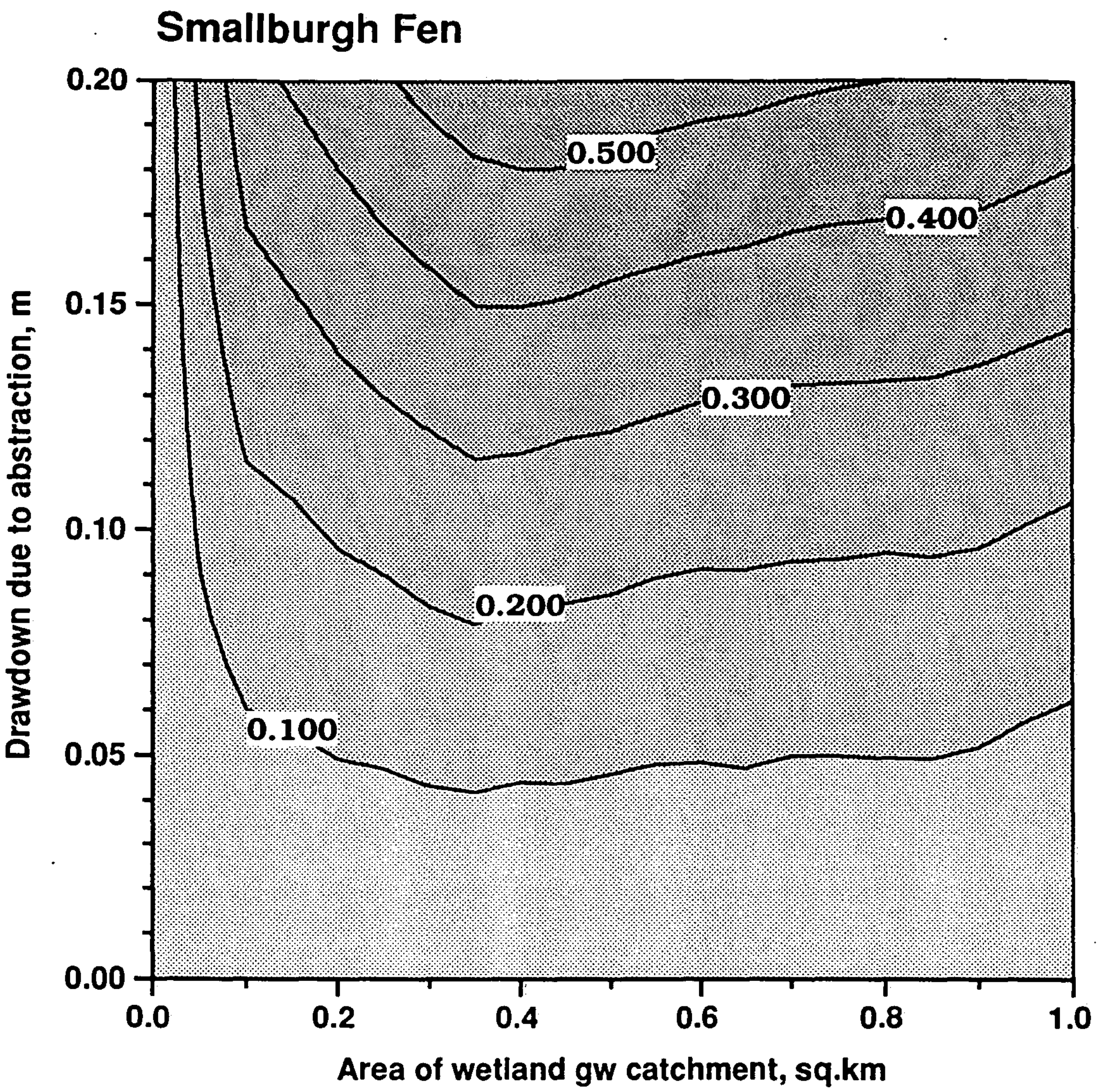


Water budget for wetland groundwater catchment 0.64 sq.km





Smallburgh Fen - observed water levels (piezometer B) and water levels predicted by MIROS model with wetland groundwater catchment areas of 0.25 sq.km (Min) and 0.64 sq.km (Max).



Smallburgh Fen - contours of change in SEV>20 for ranges of drawdown and wetland groundwater catchment area.

Smallburgh Fen

The water level monitoring point at Hillfield Estate (TG32/341), 460 m from the wetland site was used to calculate the parameters for the application of the 10% rule. The minimum recorded water level at this site is 2.26 m AOD on 24/8/76. The mean summer (June - September) water level was 2.70m giving a range of 0.44 m. 10% of this is 0.04 m

Calculations of expected drawdown at the wetland site, using the Theis equation and abstraction rates from the NRA licensing data archive have been carried out. The transmissivity and storage coefficient values used in these calculations were derived from a pumping test on a borehole at TG 3168 2522 (1.2 km from the wetland).

	Distance	Q (m3/day)	T (m/d)	S	H (m)
	4201	55	800	0.02	0.003
	3808	5	800	0.02	0.000
	3985	14	800	0.02	0.001
	4639	32	800	0.02	0.001
***	3698	150	800	0.02	0.010
	3745	7	800	0.02	0.000
***	4414	0	800	0.02	0.000
	3232	9.1	800	0.02	0.001
	3290	14	800	0.02	0.001
	4035	2	800	0.02	0.000
	2666	3	800	0.02	0.000
	4802	19	800	0.02	0.001
	7267	28	800	0.02	0.000
	4603	55	800	0.02	0.002
**	3171	1250	800	0.02	0.108
	4669	1	800	0.02	0.000
	3866	1	800	0.02	0.000
	3858	1	800	0.02	0.000
	2037	2	800	0.02	0.000
	4831	1	800	0.02	0.000
	2207	2.27	800	0.02	0.000
	2198	5	800	0.02	0.001
	2024	9	800	0.02	0.001
	4405	1.1	800	0.02	0.000
	790	23	800	0.02	0.008
	3522	1.3	800	0.02	0.000
	5024	9	800	0.02	0.000

	Distance	Q (m3/day)	T (m/d)	S	H (m)
	4056	18	800	0.02	0.001
**	3918	50	800	0.02	0.003
**	4060	100	800	0.02	0.005
	4827	45	800	0.02	0.002
	2890	27	800	0.02	0.003
	1599	5	800	0.02	0.001
	386	23	800	0.02	0.011
	760	9	800	0.02	0.003
	3665	2	800	0.02	0.000
	1114	7	800	0.02	0.002
	3965	73	800	0.02	0.004
	4275	34	800	0.02	0.002
	4789	7	800	0.02	0.000
	1058	32	800	0.02	0.009
**	2700	150	800	0.02	0.017
	3627	14	800	0.02	0.001
	2498	91	800	0.02	0.011
***	7465	1095	800	0.02	0.008
***	3547	2470	800	0.02	0.175
**	759	150	800	0.02	0.052
**	4370	150	800	0.02	0.007
**	1168	200	800	0.02	0.052
**	3842	75	800	0.02	0.005
**	3648	75	800	0.02	0.005
*	4580	340	800	0.02	0.014
**	4056	150	800	0.02	0.008
**	1295	75	800	0.02	0.018
*	3384	150	800	0.02	0.012
	4876	9.1	800	0.02	0.000
			Total drawdown (m)		0.57

* Licensed annual quantity spread over 200 days
** Actual return value (average) spread over 200 days
*** Actual return value (average) spread over 365 days

This drawdown is far in excess of that 'acceptable' by comparison with the 10% rule. However, Wheeler and Shaw (1992) do suggest that the site has been degraded due to groundwater abstraction.

Many of these licensed abstractions may be hydraulically remote from the wetland site because of the effect of the River Ant. This effect has not been accounted for.

Weston Fen

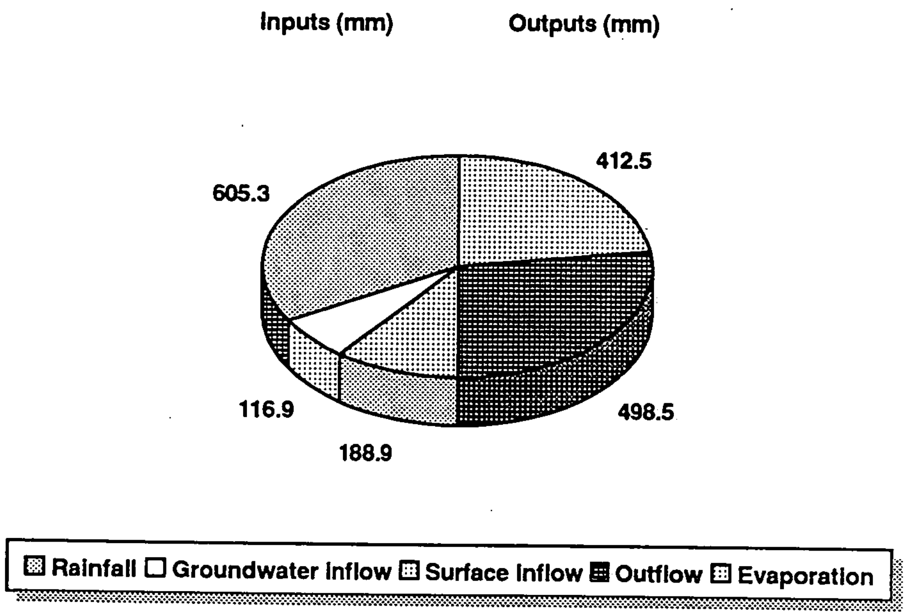
This valley-bottom site contains species-rich fen dominated by reed and saw-sedge, and bordered by tall fen grassland, heath and scrub. There is a series of wet hollows on the southern edge of the site. An intensive network of piezometers at various depths was installed by Birmingham University in 1988, and some of these have recently been reinstated by the Suffolk Wildlife Trust (SWT). Some new tubes were installed in 1993, and the tubes now number from A to Z. There is a need for levelling and correlation of numbering systems so that the later SWT dataset can be related to the Birmingham University study. The Birmingham University water budget assigned a much greater importance to groundwater discharge throughout the year, but this is inconsistent with the observed annual range of water levels. Channel flow from the springs could divert much of the spring supply into the stream, and groundwater supply to the fen areas would be limited, as at Chippenham Fen (Mason 1990).

Aquifer drawdown to produce an increase in SEV(>20) of 0.5 metre-weeks: 0.17

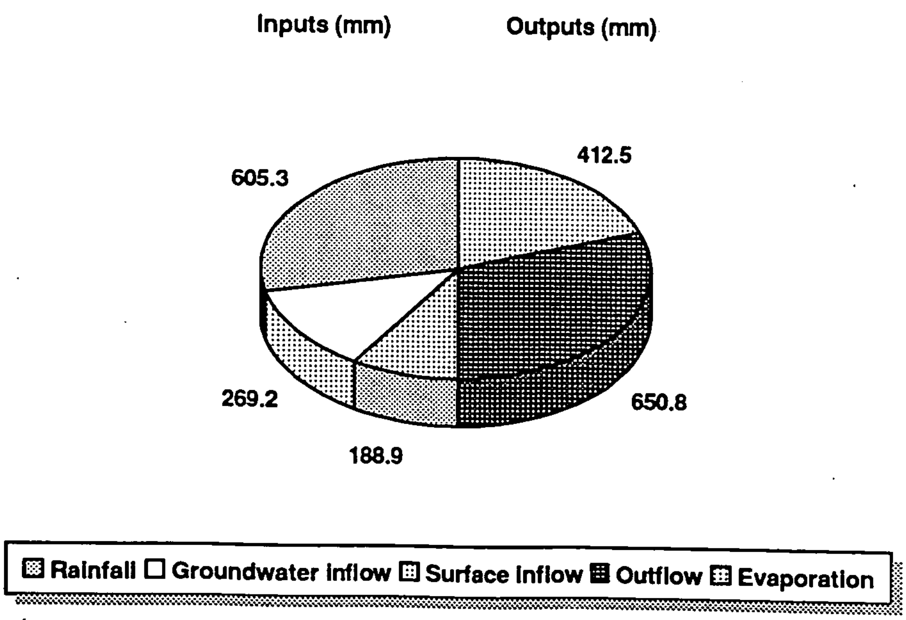
Weston Fen

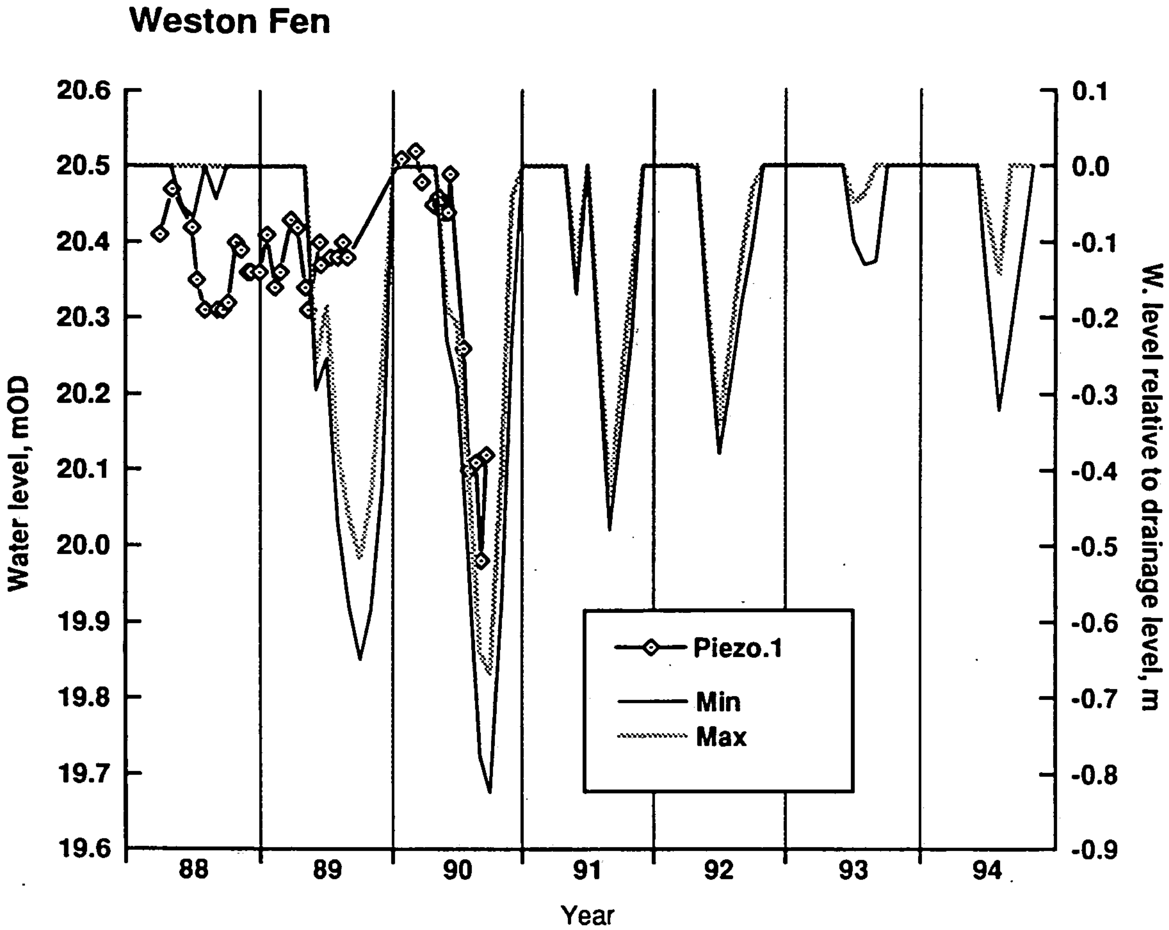
Infiltration:	30 % of effective rainfall
Evaporation:	70 % of potential
SSSI area	0.486 sq.km
Local topographic catchment:	4.35 sq.km
Diverted runoff:	75 %
Specific yield:	20 %

Water budget for wetland groundwater catchment 1.65 sq.km

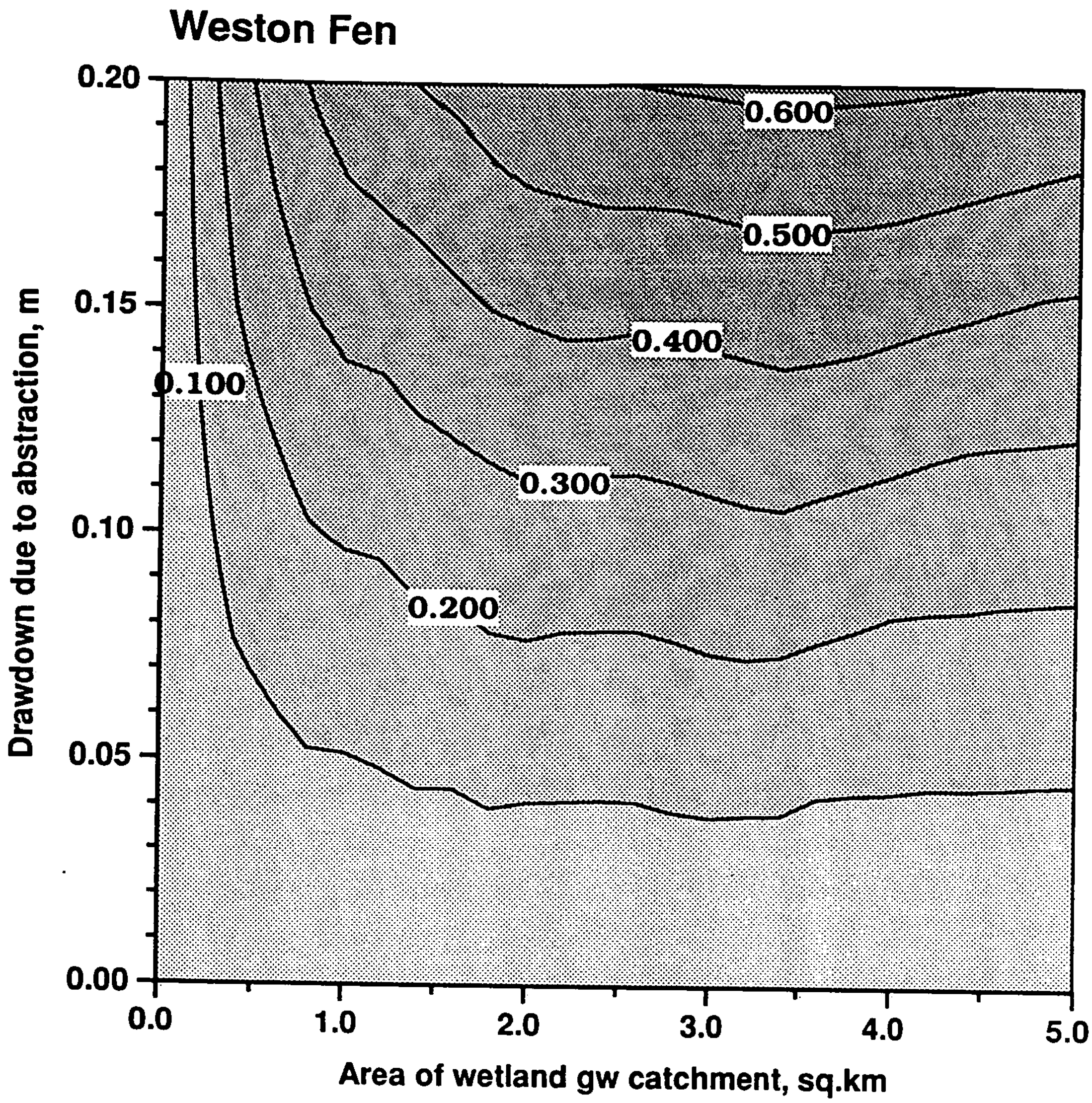


Water budget for wetland groundwater catchment 3.8 sq.km





Weston Fen - observed water levels (piezometer 1) and water levels predicted by MIROS model with wetland groundwater catchment areas of 1.65 sq.km (Min) and 3.75 sq.km (Max).



Weston Fen - contours of change in SEV>20 for ranges of drawdown and wetland groundwater catchment.

Weston Fen

The water level monitoring point at Cinque Farm, Market Weston (TL97/001), 1.8 km from the wetland site was used to calculate the parameters for the application of the 10% rule. The minimum recorded water level at this site is 21.23 m AOD on 1/4/77. The mean summer (June - September) water level was 23.60 m AOD giving a range of 2.37 m. 10% of this is 0.24 m.

Calculations of expected drawdown at the wetland site, using the Theis equation and abstraction rates from the NRA licensing data archive have been carried out. The transmissivity and storage coefficient values used in these calculations were derived from a pumping test on a borehole at TL 001 806 (2.8 km from the wetland).

	Distance	Q (m3/d)	T (m/d)	S	H (m)
	4373	2.27	500	0.005	0.000
	3601	13.64	500	0.005	0.003
*	4509	8000	500	0.005	1.313
	1140	2.27	500	0.005	0.001
	4509	9.09	500	0.005	0.001
	3827	6.82	500	0.005	0.001
	640	2.27	500	0.005	0.002
	3361	1.82	500	0.005	0.000
**	3889	500	500	0.005	0.101
	3000	2.27	500	0.005	0.001
	3492	2.73	500	0.005	0.001
	3220	1.36	500	0.005	0.000
	1029	4.55	500	0.005	0.003
	4964	1.36	500	0.005	0.000
	4883	11.82	500	0.005	0.002
**	3395	1	500	0.005	0.000
	2109	8.18	500	0.005	0.003
	1166	4.55	500	0.005	0.003
	3905	6.36	500	0.005	0.001
	1920	2.27	500	0.005	0.001
	2687	0.91	500	0.005	0.000
	4837	9.09	500	0.005	0.001
***	4317	750	500	0.005	0.131
***	3206	1000	500	0.005	0.255
***	3773	3000	500	0.005	0.630
***	3807	0	500	0.005	0.000

	Distance	Q (m3/d)	T (m/d)	S	H (m)
***	4356	0	500	0.005	0.000
***	4178	0	500	0.005	0.000
***	2500	0	500	0.005	0.000
***	2385	0	500	0.005	0.000
***	2507	0	500	0.005	0.000
***	2061	0	500	0.005	0.000
***	4964	0	500	0.005	0.000
	4332	45.5	500	0.005	0.008
**	4949	200	500	0.005	0.028
**	3061	250	500	0.005	0.067
**	2343	500	500	0.005	0.173
**	3716	375	500	0.005	0.080
**	3313	0.25	500	0.005	0.000
	2690	40	500	0.005	0.012
**	4632	250	500	0.005	0.039
			Total drawdown (m)		2.86

* Licensed annual quantity spread over 200 days
** Actual return value (average) spread over 200 days
*** Actual return value (average) spread over 365 days

As at Hopton Fen, the connection between this wetland and the Chalk aquifer in uncertain. Thus the importance of the drawdown figure calculated above, on the health of the wetland, cannot be determined.

APPENDIX C

APPENDIX C1: INITIAL PROJECT TERMS OF REFERENCE

Terms of Reference

Anglian Regional Operational Investigation: 558

The Protection of East Anglian Wetlands

Project Leader:

Dr G Mason
Hydrogeologist, Water Resources, Peterborough

Introduction:

In order to protect wetland sites and to assist in water resource planning the National Rivers Authority wants to be able to:

1. Define groundwater catchment areas to these wetlands,
2. Estimate the effects of groundwater abstraction on these catchment areas,
3. Estimate the total groundwater resource required by the wetland.

Previous work on wetlands undertaken for Anglian Water/NRA includes a Birmingham University Study, " The Hydrodynamics of East Anglian Fen Systems ". This included site dossiers summarising available data on 58 wetland sites, and a hydrogeological classification of wetland sites (Fig. 1).

Methodologies for the protection of wetlands, which are to be identified and evaluated in this present study, must be appropriate for the use by graduates, but who may not necessarily have further degrees in hydrogeology. Any computer packages used must be "user friendly" and readily available for application both inside and outside the NRA (ie: Public Domain software).

In considering various methodologies, some may be appropriate to particular hydrogeological regimes and not to others. The Wetland Class designations given in the Birmingham University site dossiers, and referred to in Tables 1 and 2, should not be used uncritically.

The investigation will be assessed after objective (g), when an Interim Report will b e presented. The Authority will then assess whether the project continues into the further investigations identified in objectives (h) and (i). The first sequence of objectives, up to the assessment stage, will include the identification and evaluation of methodologies. This will be on 12 specific sites. It is envisaged that for any further work, the methods selected from the methodology evaluation stage will be applied to another 25 sites.

The Project Objectives are detailed as follows:

(a) To identify methodologies for defining groundwater catchment areas to wetlands.

These will include basic methods which can be applied where there is only limited information. If models are considered, they must not be of steady-state type, since springflow (a groundwater abstraction) at wetland sites varies seasonally, as will some licensed abstractions such as spray irrigation.

(b) To apply these methodologies to the 12 sites shown in Table 1.

This work will include identification of surface water catchments and the production of water balances to allow a check on the groundwater catchment areas produced. The water balances must cover a representative period of at least 10 years, including the 1988 - 1992 drought, and must, at least, differentiate between seasons.

Changes in shape, if any, of groundwater catchment areas between years of mean rainfall conditions and those of extreme drought conditions must be considered.

(c) To evaluate these methodologies.

Consideration must be given to those methodologies which can be used with the basic data commonly available, and those which would represent a significant improvement if more data were available. The acquisition of such data must be on a practical scale which can be applied to the many wetland sites in East Anglia. The method of producing the water balance must also be evaluated.

(d) To make recommendations for general monitoring requirements.

These will include types, frequencies and general locations for such monitoring. Consideration must be given to minimise the costs both to the NRA and other bodies who might be implementing the recommendations.

(e) To identify and evaluate methodologies for determining the impact upon wetlands of groundwater abstraction both within and outside the groundwater catchment area.

Where groundwater abstraction is outside the catchment area there may be direct drawdown effects upon the wetland, or indirect effects where the abstraction reduces the resource available. Consideration will be given to the fact that the impact may vary seasonally, not simply due to seasonal licensed groundwater abstractions, but also as a result of seasonal variation in springflow (" abstraction ") at the wetland site. It is important to identify the impact of licensed abstractions (some of which may be operating only for part of the year, eg: spray irrigation) on wetlands during periods when they are under maximum stress.

A means of estimating the minimum requirements of the wetlands in terms of groundwater and surface water inputs must be considered, and at what level of impact groundwater abstractions become ecologically unacceptable.

Methodologies may differ for different hydrogeological regimes.

(f) To consider on what basis water resources should be allocated to a wetland, within water resource plans, in order to protect it adequately.

Water resource planning currently uses assessments which are generally made on a lumped catchment basis using annual average figures. A policy by which the groundwater needs of wetlands can be incorporated into water resource assessments must be considered.

(g) To make an assessment of the impact of existing groundwater abstractions on each of the wetland sites included in this phase.

A review of the work programme to this item will be undertaken at this stage. progression to further work items will be dependent upon satisfactory progress and presentation of the Interim Report.

(h) To apply the preferred methodology(s) identified in Phase 1 to the 25 sites shown in Table 2.

This work will include the identification of surface water catchments and the production of water balances to provide a check on the groundwater catchment areas produced.

(i) To assess the impact of existing groundwater abstractions on each of the wetland sites included in this phase.

Water level, well log, hydrological and pump test data for sites in the Central Area will be available to the contractor from the NRA Brampton Office, and in the Eastern Area from the NRA Norwich Office. Groundwater and surface water abstraction data (licensed and actual) and MORECS data can be obtained from the NRA Regional Headquarters in Peterborough. The data provided will be for use in this study only. The reports from the Birmingham University study, including the site dossiers where available, can also be obtained from the Peterborough Headquarters.

Ecological data on the sites and, possibly further reports, can be obtained from English Nature's Norwich Office.

A review of hydrological methods of wetland process analysis is given in a recent report for the NRA by Hogan and Maltby (1992). This NRA R&D Note should not define the remit of this study.

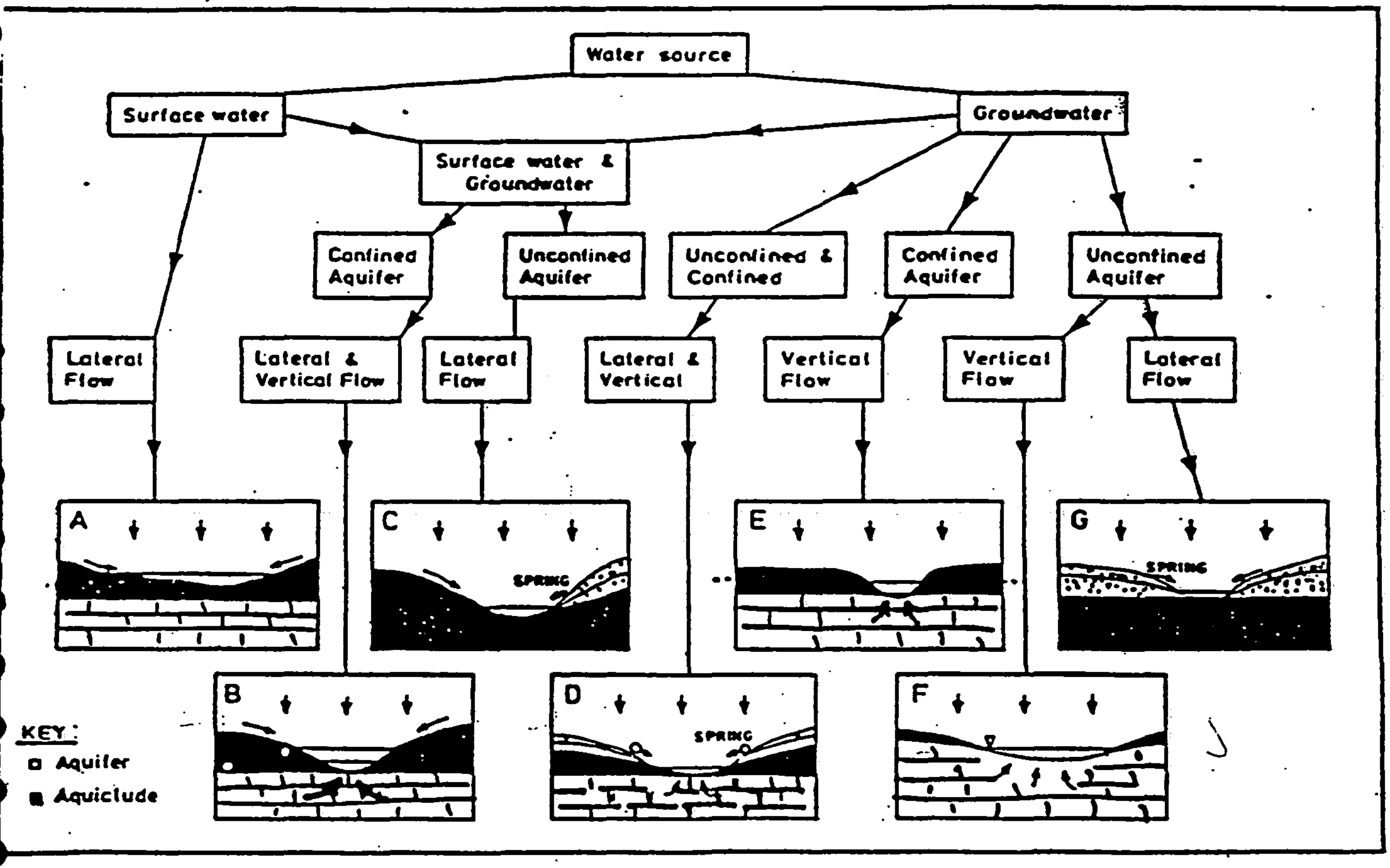
A listing of some available reports is given in Table 3.

<u>Outputs Required</u>:

Quarterly Progress Reports
Interim Progress Report (after methodology evaluation stage "g")
Draft Final report (including all work undertaken up to item "i")
Final Report

The Tenderer is requested to present financial information as specified in Schedule 5 of the Tender Document. The Tenderer is requested to specify a suitable timescale for the work, commencing 1st February 1993. The Tenderer is also requested to identify in the foregoing the costs and timescales for the work up to item "g", including report presentation, and for items "h" and "i".

Figure 1 Hydrogeological Classification of East Anglian Wetlands (from Gilvear et al., 1989)



Representation of Classification

Table 1. Wetland Sites - Phase I

	Wetland Sites	County	BU Dossier	Hydro Study	Hydrological Monitoring Past	Hydrological Monitoring Present	Hydrological Monitoring Future	BU Wetland Class (see Fig.1)
	Central Area							
#	Dersingham Bog	N	Y	UEA		Y	?	F (orig. G)
#	East Walton Common	N	Y					F
#	Gt. Cressingham Fen	N	Y		?	?		F
#	Middle Harling Fen	N	Y				Y?	F or B
#	Roydon Common	N	-			Y	Y	
	Eastern Area							
#	Badley Moor, Dereham	N	Y	BU,MSc	Y	Y	Y	B
#	Booton Common	N	Y					D or C
#	Ducans Marsh, Claxton	N	Y					C or D
#	East Ruston Common	N	Y					F
#	Forncett Meadows	N	Y					B?
#	Potter & Scarning Fens	N	Y			Y	Y	B?
#	Shotesham Common	N	Y		Y			B

Key: N = Norfolk
UEA = study by University of East Anglia
BU = study by University of Birmingham
MSc = subject of M.Sc. thesis

Table 2. Wetland Sites - Phase II

	Wetland Sites	County	BU Dossier	Hydro Study	Hydrological Monitoring Past	Hydrological Monitoring Present	Hydrological Monitoring Future	BU Wetland Class (see Fig.1)
	Central Area							
#	Caudle Common	N	Y					D or F
#	East Harling Common	N	-					
#	East Winch Common	N	Y					F (orig. G?)
#	Foulden Common	N	Y		?	?		F
#	Leziate, Sugar & Derby Fens	N	Y					D
#	Swangey Fen	N	Y					D
#	Thompson Common	N	Y				Y	D or F
	Eastern Area							
#	Aslacton Parish Land	N	Y					B?
#	Beetley & Hoe Meadows	N	Y					F or G
#	Broad Fen, Dilham	N	Y					F?
#	Bryant's Heath	N	Y					G (or D)
#	Buxton Heath	N	Y			Y	Y	D or C
#	Coston Fen	N	Y					B?
#	Flordon Common	N	Y					B?
#	Holly Farm Meadow, Wendling	N	Y					B?
#	Holt Lowes	N	Y					D or G
#	Poplar Farm Meadows, Langley	N	Y					?
#	Shelfanger Meadows	N	-					
#	Sheringham & Beeston Regis Common	N	-					
#	Smallburgh Fen	N	Y		Y?			B?
#	Southrepps Common	N	Y?					
#	Swannington Upgate Common	N	Y					G
#	Syderstone Common	N	Y	MSc		Y	Y?	C or G
#	Upton Broad & Marshes (also called Upton Fen)	N	Y			Y	Y	B?
#	Whitwell Common	N	Y					B?

Table 3

Andrews, R. (1989). Badley Moor: A Hydrogeological Study. Unpubl. M.Sc. thesis. Univ. Birmingham.

Collins, F.B. (1988). A Hydrochemical Study of Two Norfolk Wetlands, Badley Moor and Catfield Fen. Unpubl. M.Sc. thesis. Univ. Birmingham.

Gilvear, D.H., Tellam, J.H., Lloyd, J.W., & Lerner, D.N. (1989). The Hydrodynamics of East Anglian Fen Systems. Final Report. Univ. Birmingham. October 1989.

Gray, R.C. (1986). Hydrogeological Investigation of Syderstone Common, Norfolk. Unpubl. M.Sc. thesis. Univ. Birmingham.

Hogan, D.V. and Maltby, E. (1992). Water Resource Management and the Protection of Wetland Functioning. Research and Development Priorities for NRA. NRA R&D Note 114.

Lloyd, J.W., Tellam, J.H., Rukin, N. & Lerner, D.N. (in press). Wetland Vulnerability in East Anglia: A Possible Conceptual Framework and Generalised Approach. J. Env. Management.

Metcalf, B.J. (1988). A Hydrogeological Study of Selected Sites in the East Anglian Wetlands. Unpubl. M.Sc. thesis. Univ. Birmingham. (Study of Weston Fen & Catfield Fen.)

Sadler, P.J.K. (1989). The Hydrodynamics of Catfield Fen: An East Anglian Wetland. Unpubl. M.Sc. thesis. Univ. Birmingham.

Soley, R. (1986). Hydrogeological Investigation of the East Wretham Meres, Breckland, East Anglia. Unpubl. M.Sc. thesis. Univ. Birmingham.

University of Birmingham (1987). Hydrodynamics of East Anglian Fen Systems. Final report of Phase I, October 1987.

University of Birmingham (1988a). Hydrodynamics of East Anglian Fen Systems. Interim 6 Month Report, Phase II, April 1988.

University of Birmingham (1988b). Hydrodynamics of East Anglian Fen Systems. Interim 12 Month Report, Phase II, October 1988.

University of Birmingham (1989). Hydrodynamics of East Anglian Fen Systems. Interim 18 Month Report, Phase II, May 1989.

University of Birmingham (1991). Hydrodynamics of East Anglian Fen Systems. Phase III Report, March 1991.

University of East Anglia (1992). An Assessment of the Impact of the A149 Dersingham-Ingoldisthorpe-Snettisham Bypass on the Hydology of Dersingham Bog SSSI. Report for English Nature. February 1992.

APPENDIX C2: REVISED TERMS OF REFERENCE FOR PHASE 2

Proposal for Phase 2

A. Background and Phase 2 key objectives

Phase 1 of the project has led to the suggestion of methodologies for estimating wetland groundwater demands and assessing risks to wetlands due to pumping. However, the poor level of understanding of the hydrology of catchments, individually and as a group, limits confidence in the robustness of these methodologies under the wide range of conditions that may be encountered at wetlands.

The main aim of Phase 2 will be to investigate, and if necessary develop further, the methodologies for wetland protection, ensuring that they are defensible and providing improved confidence in them.

The Phase 2 work will include:

1. Investigation of a set of characteristic (hypothetical) wetland scenarios using analytical and numerical models in order to gain insight into the possible effects of groundwater abstraction.

2. Investigation of a further group of 9-15 wetland sites in order to gain further understanding of wetland hydrology and to assess the robustness and validity of the proposed methodologies.

3. Brief 'miscellaneous investigations' of a set of peripheral issues that have been identified and on which some guidance would benefit the NRA.

4. Making recommendations for actions that might be implemented by the NRA. These should include making recommendations for:
   i) the appropriate practical methodology, or methodologies, for assessing the risks to wetlands due to groundwater abstraction
   ii) the means of assessing wetland resource requirements
   iii) appropriate monitoring requirements of wetland sites
   iv) needs for further work

5. Reports as given in the Contract.

B. Outline of Approach

1. Simulation studies

The main objective of the simulation studies will be to assess and, if necessary, develop the proposed methodology, or methodologies, for estimating the effects of groundwater abstraction on wetland hydrology. Existing methodologies may be refined, the aim being to provide confidence in a practical method (or methods) which provides a robust, defensible and safe means for assessing the impact of pumping on wetlands.

The first task will be to construct a set of 'generic' wetland scenarios. This set needs to provide adequate coverage of the range of situations that are likely to be encountered and will be agreed between the NRA and BGS/IH.

A particularly challenging task will be to construct a wetland hydrology model that will be considered sufficiently realistic and general; a particular difficulty will be that of incorporating spring flows. Nevertheless, even a crude representation of wetland behaviour is likely to be worthwhile. The effort will have the additional benefit of guiding the monitoring work that is needed to understand wetland hydrology.

Both analytical and numerical models will be used, as appropriate, to investigate the wetland response to abstractions and the effect of the position of the abstraction point on the wetland water levels. Particular attention will be given to unconfined situations, especially where seepage faces develop. Three-dimensional modelling will probably prove necessary for some scenarios.

Transient conditions will need to be considered, at least for a limited number of cases, in order to establish a better understanding of the relationship between pumping periods, temporal rainfall distribution and wetland response.

Where it seems reasonable to do so, the work will consider 'worst cases'.

2. Investigations of further wetlands

The aim of this part of the work is to refine the assumptions and estimates made in the Phase 1 methodologies, using data from further wetlands: 9 to 15 wetland sites will be investigated. The robustness of the water-balance and SEV calculations will also be tested as part of this exercise. (Delineation of groundwater catchments will not necessarily form part of this work.)

A careful choice of wetlands will need to be made. Consideration will be given to different geological and topographical settings and to different states of data availability. The set will be agreed between NRA and BGS/IH.

3. Miscellaneous investigations

The bulk of the Phase 2 work will be geared towards the modelling and methodology refinement described above. Additionally, the NRA will be provided with guidance on the implementation of the results of that work and on the broader issues. Topics covered are likely to include:-

a) **Long-term needs**
Consideration could be given to the types of investigation, monitoring and modelling that are possible or are likely to become possible as technology improves.

Recommendations would be made for phased and iterative programmes of monitoring, data analysis, and improvement in wetland protection methodology.

This would be done in relation to the national NRA project on monitoring currently being undertaken by BGS and would consider the need for a central plan for data storage and handling.

b) **Combining methodologies**
The SEV method gives an estimate of the area of the wetland groundwater catchment, but not its position. It should be possible to devise a method for locating this area within the, larger, apparent groundwater catchment derived from measured water levels. However, this could be difficult to implement in a unique manner. One approach considered will be that based on isochrones.

c) **Computational procedures for drawdown estimation**
Assuming the proposed drawdown method for assessing the impact of pumping on wetlands is adopted, it still remains for the NRA to decide the details of how to implement that method.

Some advice would be given on the relative merits and problems in using the FLOWPATH code, the MODFLOW code, existing local models used by the NRA, and other codes or techniques (including analytical methods) that might be effective. This would take into account the need to deal with multiple wetlands and multiple abstraction points. In the longer term, the possibility arises of using regional models and GIS systems and some recommendations will be made on how the NRA should position itself for the exploitation such developments.

d) **The 10% rule for drawdown**
The drawdown methodology suggests that the drawdown at the wetland due to further abstractions should be limited to 10% of the difference between mean and minimum summer piezometric heads in the aquifer. It should be possible to interpret this 10% value (or any other percentage) in terms of the consequent probability of taking the groundwater head below any particular level, and that should provide an improved view of this aspect of the robustness of the methodology.