Remotely sensed hydrological isolation:

a key factor predicting plant species distribution in fens

Promotor: dr.ir. M. Molenaar
hoogleraar in de geo-informatica en de ruimtelijke gegevensinwinning

Co-promotor: dr. G.B.M. Pedroli
senior wetenschappelijk onderzoeker, DLO-Instituut voor Bos- en Natuuronderzoek

Remotely sensed hydrological isolation:
a key factor predicting plant species distribution in fens

M.E. Sanders

PROEFSCHRIFT
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Contents

STELLINGEN

1. Remote sensing is voor moerasgebieden een efficiënt hulpmiddel bij het modeleren van hydrologische isolatie (*dit proefschrift*).

2. Hydrologische isolatie biedt een eenvoudig en betrouwbaar concept om het vóórkomen van plantensoorten en daarmee hun potentiële habitat te voorspellen (*dit proefschrift*).

3. Digitale waarden van gescande "false colour" luchtfoto's zijn direct bruikbaar voor classificatie van verschillen in biomassa en natheid in moerasgebieden (*dit proefschrift*).

4. De "overall" classificatie-nauwkeurigheid is een slechte maat voor de waardering van een classificatie omdat de gebruiksmogelijkheden van remote sensing verschillen per vegetatietype (*dit proefschrift*).

5. Beschikbaarheid van gegevens over verdamping van natuurlijke vegetatie vergroot de bruikbaarheid van remote sensing voor het modeleren van hydrologische isolatie (*dit proefschrift*).

6. Vegetatietypen hebben geen fuzzy karakter: noch in ruimte en noch in tijd. De vegetatie zelf heeft dit echter wel.
   W.J. Droesen (1999), Spatial modelling and monitoring of natural landscapes (Thesis Wageningen Agricultural University).

7. De opleiding van "Assistent in Opleiding" en "Onderzoeker in Opleiding" sluit niet aan bij de huidige vraag op de arbeidsmarkt. Hun wordt geleerd zelfstandig onderzoek te doen, kennis te vergaren en daarover te publiceren. Modern onderzoek vereist een flexibele marktgerichte instelling, gericht op samenwerking.

8. Het groeiend gebruik van computertechnieken in ecologisch onderzoek heeft een verschuiving van veldbiologie naar ecologische modellering teweeggebracht. Geografische bestanden rijzen als paddestoelen uit de bodemkaart. Verontachtzaming van de afkomst van deze bestanden zorgt voor redundantie van gegevens waardoor een adequate toetsing van de modellen aan de werkelijkheid wordt belemmerd.

9. De stelling dat door uitbreiding van het oppervlak moeras de kans op malaria en door uitbreiding van het oppervlak bos de kans op de ziekte van Lyme toeneemt, getuigt van een onrealistische en pessimistische kijk op natuurontwikkeling.

10. Onderzoekers en beleidsambtenaren verschillen van mening over de mogelijkheden van remote sensing voor het in kaart brengen van natuurlijke vegetatie. Voor sommigen is het een universele detectiemethodiek en voor anderen heeft zij weinig toegevoegde waarde. Beide meningen berusten op vooroordelen en niet op een actuele beoordeling.

11. Het gekozen referentiekader bepaalt de ernst van een probleem.

12. Natuurbeheer is met hamer en nijptang een fijn uurwerkje gelijkzetten, natuuronderzoek is met muis en toetsenbord het mechanisme van een digitale klok bestuderen, natuurbeleid is aan de hand van de digitale tijd hamer en nijptang aansturen het uurwerkje een uur voor te zetten; de wintertijd wordt zomertijd zodat het langer licht blijft.
    Naar Midas Dekkers, Vroege Vogels 1990.

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Aan mijn ouders

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Preface and acknowledgements

This thesis is the result of a PhD project that started in 1993, was funded by the DLO Institute for Forestry and Nature Research and supervised by Prof.dr.ir. M. Molenaar of the Laboratory of Geo-information Science and Remote Sensing of Wageningen Agricultural University. During this period, I worked on three projects related to my PhD project. The first, 'sequential vegetation mapping' was for the Survey Department of Rijkswaterstaat. In the other two projects I worked with Anne Schmidt. One was a project for the National Forest Service called 'wetland vegetation mapping' and the other was a BCRS project called 'monitoring nature target types'.

I wish to thank many people for their contribution one way or another to the realization of this thesis. First of all I wish to thank my supervisor Martien Molenaar and co-supervisor Bas Pedroli for their inspiration and confidence. My special thanks go to Anne Schmidt, Ruut Wegman and Pieter Slim. They were always there, through good times and bad times. Geert van Wirdum I thank for giving me the opportunity to start this project. Without the motivating guidance of Han van Dobben I would never have finished it. Jan Clevers is acknowledged for his valuable comments. Cajo ter Braak from the DLO Centre for Biometry Wageningen proposed the statistical methods. Arjan Griffioen helped me with some of the GIS work. I thank Dick Verkaar for doing the right thing at the right moment. I had many stimulating discussions with the other PhD students of WAU and my colleagues in the Ecohydrology section: Wieger Wamelink, Eric Schouwenberg, Diana Prins, John van Smalen, Sytze de Bruin and especially Elisabeth Addink who always had a listening ear. I wish to thank the students and volunteers, who have helped me: Jacqueline, Veronique, Ciska, Dieuwke, Ingeborg, Phil, Mark and René. This thesis has come about by the help of Ruut Wegman, Jan van Beek, Roel van Beek, Mieke Pijfers, Joy Burrough-Boenisch and Thom van Rossum. I wish to thank them for their contributions.

In two seasons I learned so much about De Weerribben. I enjoyed every second. I want to thank the people of the National Forest Service: Piet op het Hof, Edo Jans, Harry Veenstra, Jeroen Bredenbeek and Dirk Hoen. They were always prepared to help me and to tell me many things about the area and kindly let me use their false colour aerial photographs.

1 Introduction

1.1 Background of the present study

Wetlands are one of the world's most important and most threatened environmental resources (Maltby 1991). Studies expressing concern regarding the decline of conservation values of wetland nature reserves are not new (Vermeer & Joosten 1992; Hogg et al. 1994). In The Netherlands, fens face many threats. First, they are at threat from acidification, which is enhanced by acid rainwater. Secondly, heavy fertilization in agricultural areas is polluting groundwater and surface water, causing wetland reserves to become eutrophied. Another threat is water loss to surrounding polders that have a lower water table. Furthermore, fens are being isolated or lost due to an increase of roads, built-up area, etc. Disturbance by tourists and hunters can be added to this list. Traditional management practices, such as reed cutting by hand to harvest reeds for thatch, have been abandoned for economic reasons. Nowadays, reed fens are mown with machinery, irrigated with pumps and sometimes even herbicides are used. When the yield of a reed-bed is too low, it will be abandoned and change into woodland within a couple of years.

The long-term nature conservation policy of the Ministry of Agriculture, Nature Management and Fisheries in The Netherlands, formulated to minimize the threats mentioned above, was set out in the Nature Policy Plan (Natuurbeleidsplan 1990). This plan points out that important ecosystems in The Netherlands, like fens and bogs, have a large biodiversity and must, therefore, be preserved. In nature conservation, the value of an area is often expressed in terms of the occurrence of rare and declining plant species, species richness and variation in landscape elements or vegetation structure. Species richness and the number of rare plant species are positively related (Wheeler 1988). The Nature Policy Plan advocates the sustainable preservation, restoration and development of relevant animal and plant communities and the conservation of species belonging to them. It acknowledges that human influence should be minimized, but that the historical values, such as traditional use and occupation, should be kept undisturbed. It is the nature management organizations in The Netherlands that execute this policy. Their management administration, planning and evaluation would benefit from a quantitative insight into both the geographical variation and temporal change of species composition and vegetation structure.

The species composition, vegetation structure and succession rate in Dutch fens are determined by water chemistry, in particular base status (Ca and HCO_3) and nutrient status, vegetation management and age (Van Wirdum 1991; Van Diggelen et al. 1996). Rare plant species occur under a specific water regime and water quality (Van Wirdum 1991). Many Dutch fens lose water to surrounding polders that have a lower water table. Base-rich and nutrient-rich surface water is let in to keep the water table at a constant level. This water causes fens to become eutrophied, which leads to an increased biomass production. A few common tall and fast growing herbs are favoured, but species depending on base-rich but nutrient-poor water decline (Verhoeven et al. 1988; Roelofs & Smolders 1993; Schouwenberg et al. 1993). When parts of the fens become more or less isolated from this base-rich and eutrophic water (hydrological isolation), they become acidified, because rainwater (base poor and nutrient poor) becomes their dominant source of replenishment. For each rare plant species there is an optimal place in the gradient from surface water influence to rainwater influence (Van Wirdum 1979). Spatial information, such as vegetation characteristics obtained by remote sensing can be used to relate the occurrence of rare plant species to their position in the hydrological gradient.

Remote sensing (RS) and geographical information systems (GIS) techniques have great potential for extrapolating ecohydrological models based on field investigation of sample areas to a much larger area. The rapid technical development of hardware and software have strongly stimulated the use of RS and GIS as research techniques. Remote sensing means observing from a distance. It is defined as 'the instrumental means, techniques and methods to observe the earth's surface and to interpret the resulting images or values to obtain information from certain objects on earth' (Buiten & Clevers 1993). GIS is defined as 'combination of mutually referring data sets of various kinds of position-bound thematic data and the necessary software to visualize this database, to manipulate it interactively and to analyse it in order to attain significant results' (Buiten & Clevers 1993).

1.2 Objectives

The aim of this study was to investigate the feasibility of using remote sensing and geographical information systems to obtain a measure of hydrological isolation that is used, together with vegetation management, to predict the distribution of rare plant species. In order to understand the causes of the observed plant species distribution, relevant processes and environmental variables have to be quantified and their relations need to be studied. Fieldwork is the usual method to obtain information on environmental variables and the distribution of species. However, fieldwork in large inaccessible areas such as wetlands is time-consuming and thus very expensive. Furthermore, base status and nutrient status cannot be sampled at sufficient density or sufficient intensity because of their extremely high spatial and temporal variability. The level of hydrological isolation is assumed to represent the base status and nutrient status of a site. Remote sensing and GIS were expected to be helpful to obtain a measure of hydrological isolation. This study sets out to test the hypotheses formulated below and to develop a methodology using RS and GIS, based on these hypotheses, to obtain a measure of hydrological isolation that helps to identify the potential habitat of rare plant species to support nature management. The two working hypotheses were:

Hypothesis 1
Remote sensing yields ecologically significant information, related to relevant vegetation structure types that can be used to obtain a measure of hydrological isolation.

> The advantages of remote sensing over data collection in the field is that it offers a synoptic view of an entire area in a very short time period and that the data collection is non-destructive. However, it is much more difficult to apply

remote sensing techniques in natural vegetation than in farmed areas because of the problem of thematic and geometrical vegetation definition: agricultural areas normally consist of homogeneous units of land with sharp boundaries whereas natural ecosystems are characterized by many plant species and gradients. Remote sensing does not yield information on species composition, however, if the remote sensing characteristics are indicative of hydrological isolation, they can be interpreted so as to offer information on vegetation (i.e. species composition). *The central question is: what is the ecological interpretation of variables measured by RS techniques and do these variables offer information that may predict plant species distribution?*

Hypothesis 2
Hydrological isolation, representing base status and nutrient status, and vegetation management are powerful indicators of plant species distribution.

An important aspect in this study is the analysis of the distribution patterns of rare plant species or, in other words, the conservation value of an area. The type of spatial environmental information needed depends on the nature and scale of the processes of interest. Two important threats in fens are acidification and eutrophication. It was for this reason that rare plant species indicative of base status and nutrient status were chosen in this study. A geographical information system (GIS) was used to integrate different types of environmental data, obtained with remote sensing for example, for spatial modelling. *The central question is: how can one define spatial models, that can be handled by a GIS, to predict the distribution of rare plant species?*

1.3 Strategy

To be able to preserve rare plant species in fens it is important to understand the site factors that determine their distribution. Site factors are all environmental variables, such as hydrological isolation and vegetation management that are expected to correlate with the occurrence of plant species on a given site. In this study, the emphasis was on site factors collected and analysed by RS and GIS techniques, which excludes base status and nutrient status. RS and GIS techniques have great potential for modelling the hydrological isolation that is thought to be a key factor explaining plant species distribution. The study described in this thesis focussed on the Dutch nature reserve De Weerribben because a vast amount of knowledge and data was available on this area, including aerial photographs and maps.

The strategy developed in this thesis is presented in Figure 1.1. The first part of the figure represents the remote sensing aspect. The choice of the RS and associated methods of image interpretation depends on the scale of the process of interest and data availability. 'Image processing' covers analogue photo interpretation as well as digital processing. Both analogue and digital interpretation have their pros and cons and should therefore be considered complementarily. Analogue photo interpretation is an important technique for landscape ecological stratification. Within these strata, digital image analysis can offer gradient

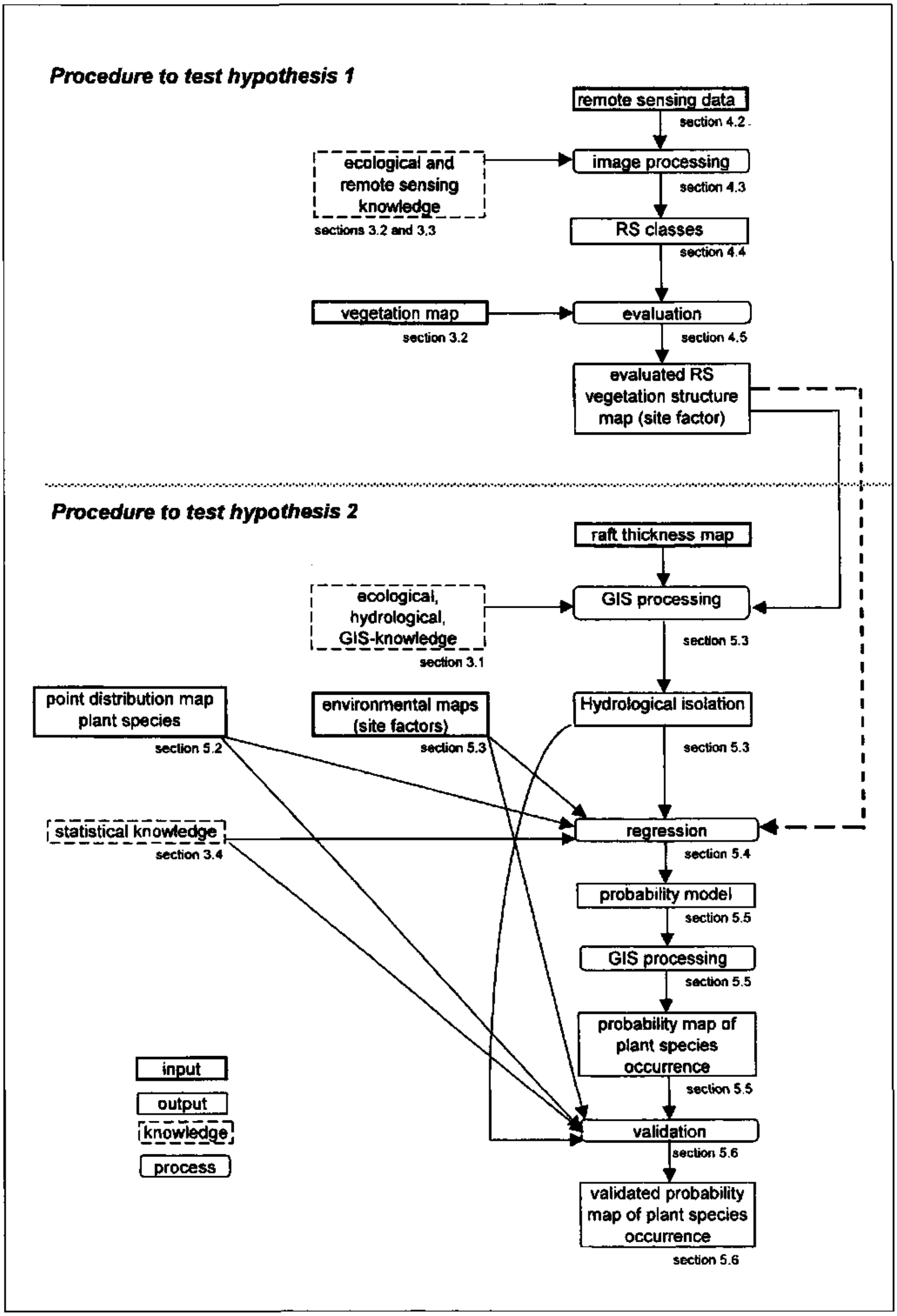

Figure 1.1

Flow-chart to illustrate the procedures to test the hypotheses of this study.

information. The results of the interpretation were related to relevant vegetation types, to give them an ecological significance. If the variables obtained by remote sensing indicate hydrological conditions, they offer information on species composition in an indirect way. If hypothesis 1 is accepted, the remote sensing results can be used to predict plant species distribution. This is why the arrow between the RS results and the spatial analysis is broken.

The second part of Figure 1.1 represents the GIS manipulation to model hydrological isolation and the multiple regression technique used to predict the distribution of rare plant species. The input of the GIS analyses are the results of the remote sensing analysis and other spatial data of the environment called 'site factors'. Along with digitizing, storage and presentation, a GIS was used to calculate spatial relations, to reclassify and to integrate the site factors. Multiple regression analysis was used to explore relations between species and site factors. The result is a spatial representation of the predicted plant species distribution as a function of site factors.

In summary, vegetation and hydrological characteristics obtained with remote sensing were used to model hydrological isolation, representing base status and nutrient status, in a GIS which in turn was used to predict species distribution. If the techniques developed in this thesis are adequate, this study is not only relevant for the chosen study area or for the plant species the method is applied to, but may have a much wider application area. The ecological information obtained via remote sensing techniques could be valuable for other fen areas in The Netherlands and possibly for many fens in Europe. Similar methods could be applied not only to plant species but also to animal species.

1.4 Synopsis

De Weerribben nature reserve is presented in Chapter 2. The level of detail is necessary to fully understand the mechanisms influencing the distribution of rare plant species. Geology, history, soil, hydrology and vegetation are described. Figure 1.1 yields information on which section deals with which part of the procedure developed. The theoretical framework and approach are discussed in Chapter 3. First, the relevant hydrological and ecological knowledge and models are described. The hydrological model explains water movement and the ecological model explains vegetation change in relation to processes such as eutrophication and acidification. Furthermore, the concepts of the remotely sensed vegetation characteristics, GIS techniques and multiple regression, applied in this study, are described. Chapter 4 deals with the remote sensing component concerning hypothesis 1. The RS platform, photo interpretation, the scanning process and digital image analysis are discussed. Chapter 5 presents the GIS component of this study concerning hypothesis 2. The results from remote sensing data processing, digital maps and the hydrological isolation modelled in GIS are combined with point distribution maps of rare plant species to predict plant species occurrence with multiple regression. The ecological and hydrological models described in Chapter 3 are applied here. The results of the regression analyses and the predicted distribution of the indicative species are validated, explained and compared with conditions found in literature. Chapter 6 gives general conclusions and future prospects including a proposal to set up a monitoring system and scenario studies to support nature management.

2 Site description of De Weerribben nature reserve

2.1 Introduction

Inland wetlands (fens) in The Netherlands are characterized by peat formation under specific geomorphological and climatic settings and human impacts (Verhoeven 1992). Fens and bogs arose in the Holocene period, on flat floodplains subjected to marine and fluvial flooding. In this period the climate settings, a mean temperature of ca. 9 °C and an annual precipitation of 700 mm or more, were very suitable for peat accumulation (Streefkerk & Casparie 1987). Human impact, particularly the peat cutting and dredging in the 18th and 19th centuries, left a characteristic landscape of extensive rectangular bodies of open water called '*petgaten*' (Photo 2.1, page 136). *Petgaten* are very long (up to 1000 m) and narrow (ca. 30 m wide) peat ponds. During the 20th century much of this land was drained and reclaimed for agriculture. Some fens remain, thanks to their value for nature conservation, recreation and their use as water reservoirs for the surrounding agricultural polders. The present area of fens in The Netherlands is estimated to be 14 000 ha. This area can be subdivided into reed fen (26%), water (28%), wooded fen (32%) and mown fen meadow (14%) (Van Leerdam & Vermeer 1992).

De Weerribben nature reserve (Fig. 2.1) is a fen area in the north of The Netherlands (6° 0' E and 52° 45' N). It covers 3600 ha, and together with De Wieden (4500 ha, Fig. 2.3), south of De Weerribben, it forms the largest fen area in The Netherlands. The Pleistocene 'upland' of Paaslo and the Drenthian plateau lie to the east; they are about 5 m above present sea level. In the other directions are low-lying polders (1-3 m below sea level). De Weerribben is 0.5 m below sea level. The aim of the nature management organization that owns the area, is to preserve nature (including rare plant species) in a multifunctional context. These functions include water storage for the surrounding polders, tourism but also commercially viable reed harvesting. This chapter describes the area and its functions. The geology, history, soils, hydrology and vegetation of De Weerribben nature reserve are discussed. These descriptions of the situation are important to understand the plant species distribution in De Weerribben modelled in this study.

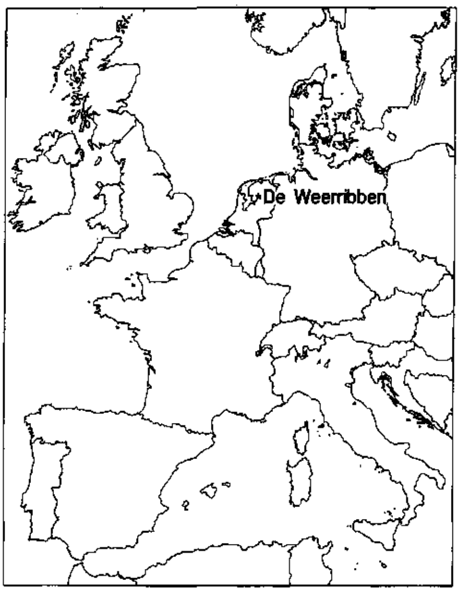

Figure 2.1
Location of De Weerribben nature reserve in Europe.

2.2 Geology

Pons (1992) described the geomorphology of fens in The Netherlands including De Weerribben and surrounding areas. In the Saalien glacial (200 000 years BP) the ice reached The Netherlands and pushed up ridges of unconsolidated material near Paaslo east of De Weerribben. In front of the ice the river Vecht formed a valley and eroded the glacial sediment (Ter Wee 1966). In the Weichselien glacial (70 000 years ago) the ice did not reach The Netherlands. There was a tundra climate and the wind blew sand into dunes and ridges (Veenenbos 1950). These Pleistocene aeolian cover sands lay 2.5 to 3.5 m below the current ground level. The tops of the dunes, however, were sometimes just below present ground level. In the Holocene period (10 000 years ago) the sea level started to rise. Sand dunes were formed along the coast. The rising sea level pushed up the fresh groundwater level, so freshwater could stagnate behind the sand dunes. In this environment peat accumulated. Fen peat developed along the coast and along peat rivers draining parts of the Drenthian plateau. Oligotrophic bogs developed in the centre of the areas (Veenenbos 1950). Figure 2.2 shows the extent of the different types of peat in De Weerribben and surrounding areas (Haans & Hamming 1962). Marine transgressions, beginning in the Subatlanticum (3000 BP), caused peat erosion and, further inland, clay deposition

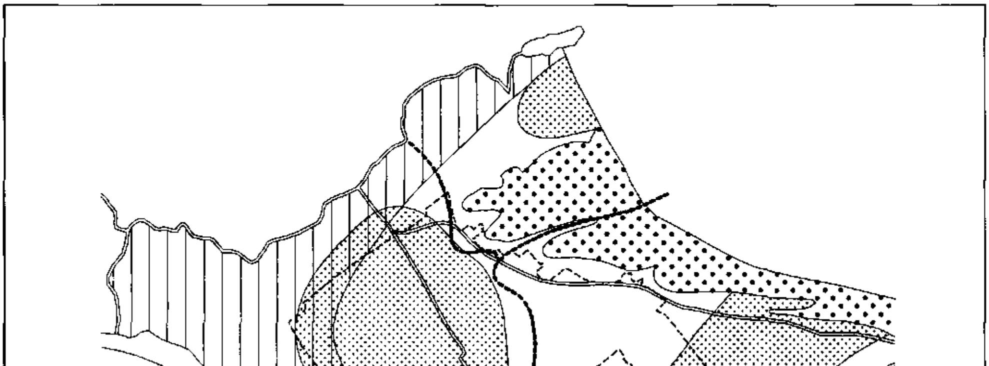

Figure 2.2
Original soil types of De Weerribben and surrounding areas (after Haans & Hamming 1962; Gonggrijp et al. 1981).

over the peat (Veenenbos 1950). Many raised bogs were drowned when the water table rose as a result of rising sea level. They did not lose their oligotrophic character but just became very wet bogs. The coast slowly retreated to the east. It reached its present shoreline after a disastrous storm in 1170. Wave erosion and clay sedimentation were constrained, because people started to build dikes (Veenenbos 1950).

2.3 History and land use

Peat excavation

The first human settlements in the area date from the twelfth century (Veenenbos 1950). The peat area was drained superficially and people dug small amounts of peat for household fuel. In the subsequent centuries towns started to expand and the need for fuel increased (Borger 1992). At first, bog peat above the groundwater level was dug. From the 17th century until the beginning of the 20th century, the fen peat below the groundwater level was dredged. First the peat workers dug a ditch or an already existing ditch was used. They filled the ditch with some of the clay cover, the resulting baulk was used as strip of land on which the turves were prepared. When there was no clay cover, a strip of original peat was kept for preparing the turves. Then, the peat along the baulk was dredged and put in a trough on the peat baulk. The peat workers mixed this peat with water and trampled on it until it was a uniform slurry (Photo 2.2). When the peat slurry had dried out sufficiently, they cut it into turves (Photo 2.3) and stacked it to let it dry out completely. The clay cover not used to make the peat baulk was dumped into the peat pond (Haans & Hamming 1962; Borger 1992).

The peat dredging in the region of De Weerribben first started in the nearby De Wieden. There were no regulations so the *petgaten* became very wide and the peat baulks very narrow. Storms in the 18th century wreaked havoc. Peat baulk erosion created large shallow lakes (Haans & Hamming 1962; Borger 1992). An entire village disappeared into the waves and many people and cattle drowned. Most of the peat dredging in De Weerribben took place in the 18th and 19th centuries. By then there were strict regulations describing dimensions of *petgaten* to avoid disasters. The peat was dredged from areas about 30 m wide, 100-1000 m long and the baulks were 3-5 m wide. Peat dredging stopped at the end of the 19th century, because most of the peat suitable for fuel had been removed. The workers turned to reed cutting and fishery for a living. Nowadays, recreation is an important source of income for the local population.

Water management

Human impact on the water management in this region through the centuries is immense. It started in the medieval period with building dikes (Haans & Hamming 1962; Veenenbos 1950) and superficial drainage. Until 1919, the water level varied between 80 cm below and 8 cm above present sea level. When the Stroink pumping station was opened in 1920, water levels could be kept at 50 cm below present sea level. From 1930 onward the water levels were kept at 70 cm below present sea level. In 1932 a huge dike, the Afsluitdijk, was completed, closing off the Zuiderzee arm

Photo 2.2
The peat was dredged from the *petgaten* and put in a through on a peat baulk (Haans & Hamming 1962).

Photo 2.3
After the peat was trampled, equalised and dried, turves were cut to be transported (Haans & Hamming 1962).

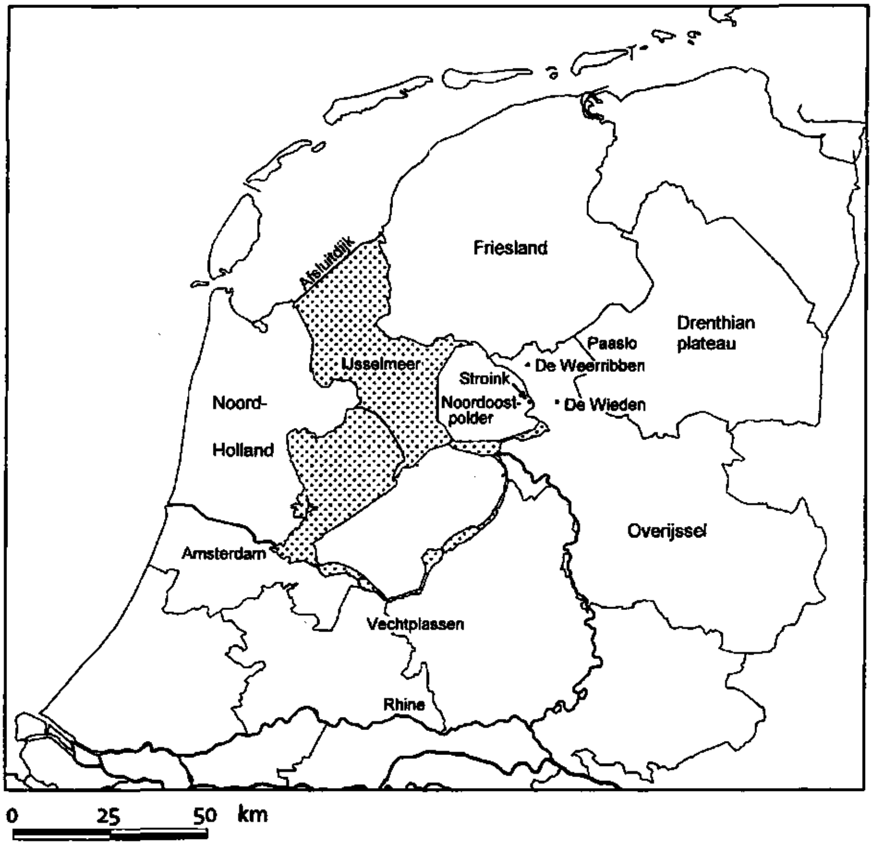

Figure 2.3
Location of places in The Netherlands mentioned in the text.

of the sea and creating a lake: the IJsselmeer (Fig. 2.3). Flooding and dike breaches became history. In 1942 the Noordoostpolder was reclaimed within the IJsselmeer. Much water in De Weerribben is seeped away because of the low water level of this polder: 4 m below present sea level. This induced a water deficit for reed cultivation. To keep reed production profitable, dikes were built around reed fens and the reed fens were irrigated with wind pumps.

Many fens disappeared from 1928 to 1968 because they were reclaimed for agriculture. In the fifties a nature conservation organization started to buy large parts of the remaining fens in De Weerribben, to preserve them. Present land use comprises nature conservation, water retention, recreation and the harvesting of natural resources such as reed and fish. Water management (section 2.5) and vegetation management (section 2.6) are undertaken to preserve biodiversity. Awareness raising and restricted access are the most important measures applied to control disturbance and pollution from visitors. Fishery and reed cutting is subject to strict regulations, to ensure sustainable use within the reserve.

2.4 Soils

The original peat in De Weerribben consisted partly of *Sphagnum* peat and partly of *Carex* peat (Fig. 2.2). Some parts of the original peat have survived, because its high clay content makes it useless for fuel. However, most of the peat was dug in long (100-1000 m) and narrow (about 30 m) peat ponds separated by peat baulks consisting of original peat or clay material. After the *petgaten* were abandoned a process of terrestrialization from open water to fen vegetation took place (Fig. 2.4, Haans & Hamming 1962). Peat workers had thrown clay or poor quality peat back into the *petgaten* after they had dredged all the good quality peat. Dead plant material from aquatic plants, such as water lily and water soldier, accumulates on this. When this detritus is about 1 m below the water level, reed and cattail roots grow into it horizontally. Slowly the former peat pond becomes covered with vegetation floating on the detritus. At first the root carpet of this vegetation (a floating raft) is very thin and is frequently submerged. But as it thickens, mosses establish. After some time it can be walked on (Haans & Hamming 1962). The terrestrialization process did not start at the same time everywhere, because the area was excavated in several stages. Many factors influence the terrestrialization process: depth and width of the *petgaten*, nutrient status of the surface water etc. (Haans & Hamming 1962). Present soils are described in terms of the differences in thickness of the raft and by the original peat or clay content found in peat baulks or in the areas that were never dug or dredged for peat.

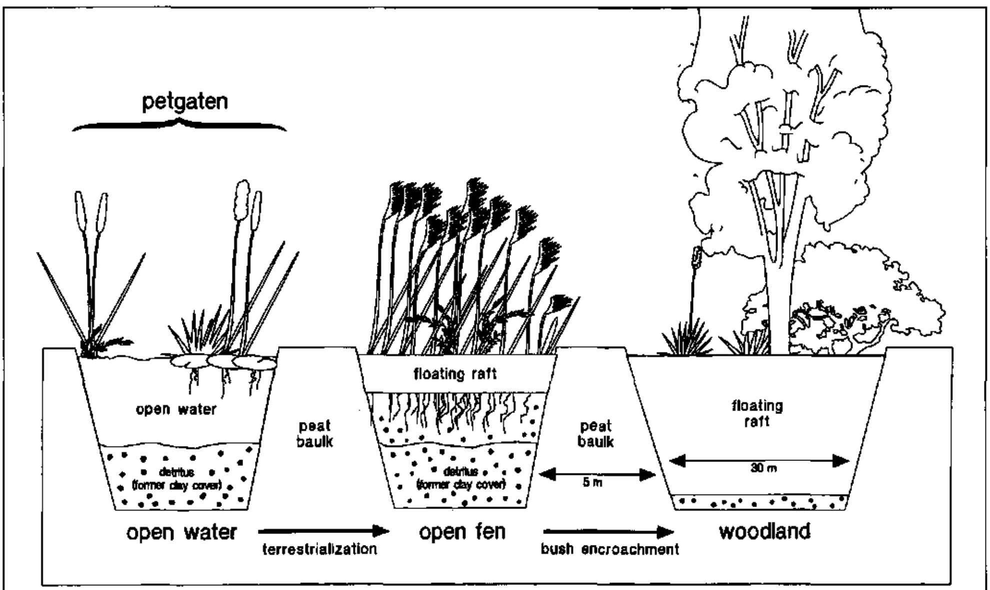

Figure 2.4

Schematic cross-section of the *petgaten* illustrating the process of terrestrialization.

2.5 Hydrology

Hydrological gradient

The Vollenhove water board is responsible for the quantitative water management of 33 000 ha polders, 8000 ha of which have a water storage (retention) function. De Weerribben nature reserve is part of this storage reservoir. Hence, the hydrological influence of the surrounding agricultural land is large. The main water sources are (Fig. 2.5): (1) water from the Drenthian plateau entering the area via the Steenwijk-Ossenzijl canal, (2) rainfall, (3) water supplied from the Rhine system via a sluice north of the area and (4) discharge of polder water (Van Wirdum 1991). The surface water from the Drenthian plateau is similar to the groundwater, being both base-rich and eutrophic. This water is very important for the area because it supplies bases. Rainfall is relatively oligotrophic and acid. These two complementary water sources

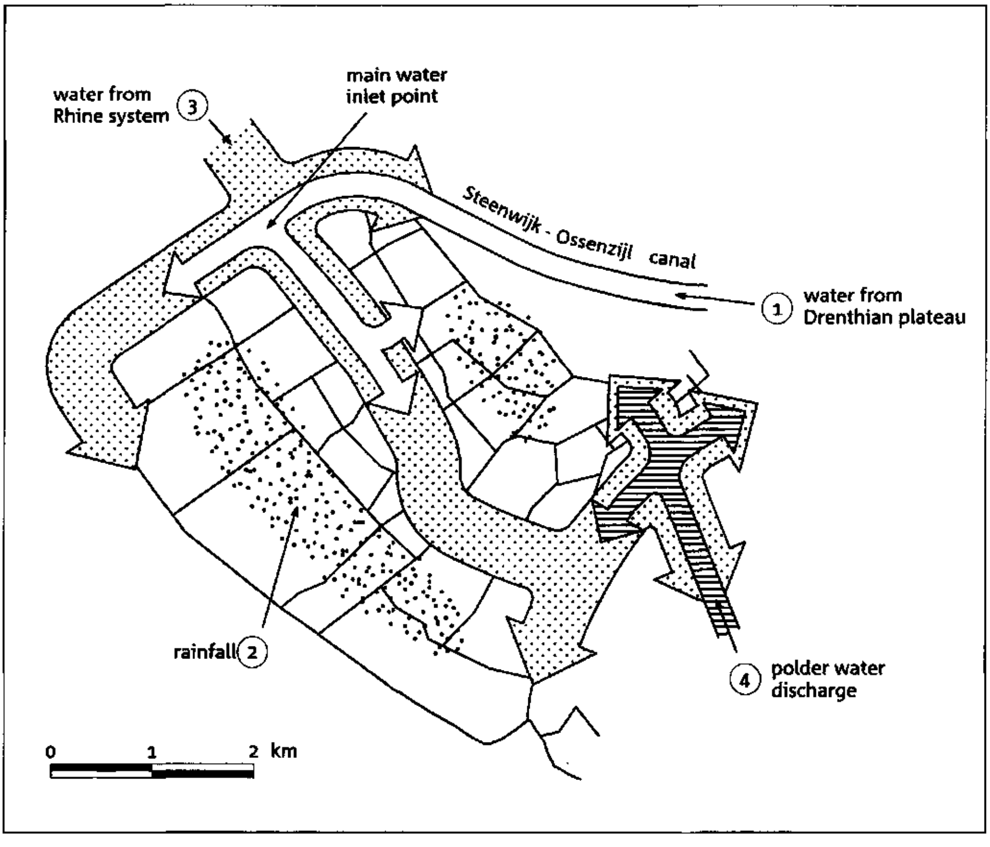

Figure 2.5
Water sources of De Weerribben (after Van Wirdum 1991): 1. The white arrows represent water from the Drenthian plateau passing through De Weerribben; 2. Rainfall is a diffuse water source that is represented as dots; 3. The thick dotted arrows represent water from the Rhine system passing through De Weerribben; 4. The hatched arrows represent the local polder water discharge.

form a hydrological gradient from base-rich surface water to areas where acidic rainwater dominates. A change in the balance between surface water and rainwater immediately results in acidification or eutrophication. It is only in very dry years that the water supply is not enough to compensate for evapotranspiration and infiltration, and water from the Rhine system is let in. Rhine water contains high concentrations of chlorine, sodium, nutrients, sulphate and heavy metals. The discharge of polder water only causes local eutrophication (Van Wirdum 1991).

Within the area the water is distributed via a network of watercourses. Infiltration, evapotranspiration, pumping, inflow of water and wind drive the circulation of water. Losses occur through evapotranspiration and through percolation towards the underlying body of groundwater. In the surrounding polders the water table is maintained at 1-3 m below the water table in the reserve. As a result of hydraulic head, water flows through the underlying aquifers from the reserve towards the polders. There has never been any substantial upwards seepage into the fens in De Weerribben (Van Wirdum 1991; Hoogendoorn & Vernes 1994).

In summer, more water is lost due to infiltration and evapotranspiration than can be supplied by rain. This water deficit in the fens is compensated for by surface water influx. Hence, the influx, driven by water shortage, results in a hydrological gradient from the watercourse (source) to the more isolated parts. As the wetland is criss-crossed by open watercourses, there is a complex of hydrological gradients. Hydrological isolation, a measure of the isolation of a site from surface water influence, determines the base status and nutrient status of a site, as the surface water is the main carrier of bases and nutrients. Where a site is located in the hydrological gradient, as a result of the degree of hydrological isolation is crucial for that site's species composition (Van Wirdum 1981, 1991).

Water management

Nowadays, water management in De Weerribben refers to water level control (0.7 m below present sea level in summer and 0.8 m below in winter) exerted through the supply and discharge of surface water. From a nature conservation point of view, water management must aim at conservation of the local body of water and inflow from the Drenthian plateau. Polluted water from the Rhine system should only be let in when there is a serious shortage of water. Discharge and inlet works are best located on the same side of the area, as otherwise the polluted water from the Rhine system will flow through the entire area (Schouwenberg et al. 1993). Another current management measure is to dredge or clean ditches and canals to control their discharge capacity. New ditches are being dug to direct base-rich surface water towards species-rich vegetation to avoid acidification. It is considered important that base-rich water reaches the vegetation and rainwater surplus does not accumulate but is discharged to the ditch. To ensure a sufficient water supply, the ditches must be cleaned regularly. The main water inlet should be as far as possible from the species-rich vegetation, to allow the water to lose as much of its nutrient load as possible.

The water management in De Weerribben is also intended to increase reed production for commercially viable reed harvesting. This involves irrigating reed fens by means of wind pumps that pump surface water on the raft of vegetation. After the reeds have been cut, the rafts are irrigated to stimulate reed growth by the nitrogen supplied in the water and to protect young shoots from frost (Haans & Hamming 1962). The raft becomes thicker much faster than without irrigation due to this nitrogen supply. Ultimately, the production of reed will decrease because tall forbs favoured by the nitrogen supplied in the water and species like *Molinia* will take over.

2.6 Vegetation

Fen vegetation develops (Fig. 2.4) from open water to open fen (terrestrialization) and, if not mown, to woodland (bush encroachment). Diversity in vegetation structure, species composition and the occurrence of rare or declining plant species are very important values that merit nature conservation. The attribute of conservation value chosen in this study is the occurrence of rare species. Van Wirdum (1991) published a list of rare plant species of De Weerribben. Two representative species indicative of totally opposite environmental conditions in terms of hydrological isolation, were chosen from this list and used in this study: *Scorpidium scorpioides*, which is characteristic of the Scorpidio-Caricetum diandrae vegetation type and *Erica tetralix*, which is characteristic of the Sphagno palustris-Ericetum vegetation type. The former vegetation type is characteristic of base-rich conditions and the initial stage of terrestrialization, the latter for base-poor conditions and an advanced stage of terrestrialization. These two open fen vegetation types important for this study are briefly described below; the species are described in Chapter 5. The definition and description of the vegetation types are according to De Vegetatie van Nederland (1995-1999).

Scorpidio-Caricetum diandrae is a very species-rich and valuable vegetation type. It is a typical rich-fen vegetation with species such as *Scorpidium scorpioides, Carex diandra, Utricularia intermedia* and *Rhizomnium pseudopunctatum*. Accompanying species are *Liparis loeselii, Campylium stellatum* and *Pedicularis palustris*. The vegetation is typical of a base-rich, mesotrophic environment in contact zones between lithotrophic and atmotrophic water. It develops from Stratiotetum, Typho-Phragmitetum thelypteridetosum vegetation where *Equisetum fluviatile* or *Carex rostrata* dominates, or from Cicuto-Caricetum pseudocyperi. It develops into Pallavicinio-Sphagnetum, Carici curtae-Agrostietum caninae. Its structure is a hummock-hollow pattern with an open reed vegetation and much *Carex diandra* and *Carex lasiocarpa*. Its distribution within Europe is limited to the temperate region. In The Netherlands its distribution is limited to fens in the Vechtplassen (Fig. 2.3) and Noordwest-Overijssel. To ensure its survival, management focuses on the supply of base-rich water, to prevent the accumulation of acidic rainwater (De Vegetatie van Nederland 1995-1999).

The other important vegetation type is Sphagno palustris-Ericetum. This is a typical fen-bog vegetation. The characteristic species are *Erica tetralix, Sphagnum palustre, Anthoxanthum odoratum, Phragmites australis, Polytrichum commune, Pohlia nutans, Calypogeia fissa* and seedlings of *Betula pubescens, Rhamnus frangula* and *Salix cinerea*. One of the accompanying species is *Oxycoccus palustris*. This vegetation is characteristic of an oligotrophic and mesotrophic acidic environment of a thick raft or organic layer. It develops from Pallavicinio-Sphagnetum to Erico-Sphagnetum magellanici or *Betula* woodland. The structure is dwarf shrub with open reed vegetation. The microrelief depends on management. *Sphagnum* hummocks will not develop if mown every year. The centre of distribution in Europe is Germany, England and The Netherlands. Within The Netherlands the vegetation is present in the province of Noord-Holland (Fig. 2.3), the Vechtplassen and Noordwest-Overijssel. The best management of this vegetation is to mow it in summer to prevent *Betula* seedlings developing into woodland (De Vegetatie van Nederland 1995-1999).

Vegetation management

After the peat has been dredged the terrestrialized *petgaten* were used for haymaking and reed cutting. In the early seventies reed cultivation collapsed because of the import of cheap reed from eastern Europe. Many reed fens were abandoned. This resulted in ditches silting up and reed fens being overgrown by *Molinia* and young trees. Within a couple of years much of the open fen had become woodland. The importance for nature conservation (rare plant and animal species), as a heritage area and for its recreational (landscape diversity) and economic (employment) importance, led the government to decide to subsidize reed cutting. Many reed fens were restored by sod cutting, removing trees, irrigating and by cleaning ditches alongside. The National Forest Service owns most of De Weerribben, but leases much of the area to farmers. These tenant farmers have to comply with regulations in order to protect rare plant and animal species and to maintain the diversity in ecosystems. The Service itself manages the most valuable reed fens and fen meadows.

Differences in vegetation management strongly influence the structure of the vegetation. Vegetation management comprises summer mowing, winter mowing, burning and removing the floating raft. If harvested in summer, the vegetation is able to develop into a species-rich fen meadow. The fen meadows are mown with light machines from June until October. It is considered important to remove the hay, to reduce nutrient availability. Many fen meadows are mown by tenant farmers, once every two years. There is no market for this hay of poor quality and its transport is too expensive. Sometimes the farmers put the hay just inside the woodland to shelter breeding and overwintering snakes. Mostly, they stack the hay on a peat baulk and burn it. This results in local eutrophication and tall forbs grow on these spots. Reed fens, *Molinia* tussocks and vegetation at the water's edge are also sometimes burned when it is impossible to mow. This irregular burning is not desirable but it removes litter and it prevents trees from establishing so it is considered better than doing nothing. The winter mowing (Photo 2.4, page 136) is cutting reeds between November and April. Mowing in winter benefits reed production. The litter is burned similarly to the hay, on the peat baulks. Not all the reeds are mown every year because birds like the reed warbler nest in last year's reeds. Spots along terrestrializing *petgaten*, therefore, tend to be left undisturbed.

As terrestrialization and succession continue, open water, species-rich fen meadow and their communities gradually disappear. To counteract this development, *petgaten* have to be dug again to restart the process of terrestrialization and succession. Only areas with a low value for nature conservation are subjected to such a drastic treatment. In the seventies and eighties the technique involved using a heavy excavator to dig down to the sandy subsoil and to put the floating raft and the peat slurry on the side of the re-excavated pond. This resulted in eutrophication. The new *petgaten* did not terrestrialize but remained open water. A new machine has recently been developed to dig new *petgaten*. Called the 'floating raft eater', this floating machine eats its way through the floating raft, while material is transported to boats behind it and removed from the area. The new *petgaten* are not as deep as before and the sides are not as steep. It is not yet known how the terrestrializing process will proceed after these measures.

3 Theory and concepts

The theoretical framework of ecological and hydrological concepts and the remote sensing and GIS techniques are discussed in this chapter. The hydrological model (section 3.1) explains water movement in De Weerribben. The ecological model is a succession scheme of vegetation structure types (section 3.2). This model explains and predicts vegetation change as a function of hydrology and vegetation management. Image characteristics, vegetation characteristics and their relation are discussed in section 3.3, together with the theoretical aspects of modelling geographical data. The theoretical aspects of the statistical procedures are described in section 3.4. The last section (3.5) briefly deals with reliability related to these specific data and procedures.

3.1 Hydrology

A site's base status and nutrient status are very difficult to estimate as they vary greatly in space and time and depend not only on surface water supply. *Sphagnum*, for example, makes its environment more acid by exchanging hydrogen ions for mineral cations (Van Breemen 1995). Furthermore, the floating raft has the capacity to supply or to store bases when there is a shortage or surplus (Schouwenberg 1994). Nutrient status depends on the management regime. Removing the mowings and with them the nutrients is assumed to reduce nutrient availability. This study is based on the assumption that hydrological isolation, defined by the magnitude of surface water influx, influences the supply of bases and nutrients of a site. Factors indicative of hydrological isolation and the scale at which they are effective are considered below.

3.1.1 Hydrological scales

The most important factors determining hydrological isolation can be considered at different levels of scale: reserve, site and microlevel. These are determined by the optimal spatial resolution required to model water movement and by the scale at which the relevant factors operate. The first level is the entire reserve. At this level information on spatial variability within the reserve is not important. The following factors play a role at reserve level:

- climate: rain and evaporation;
- water management: the place and the amount of inflow and outflow of water;
- groundwater hydrology: the amount of infiltration depending on the difference in water table between the reserve and the surrounding polders.

These factors are elements of the water balance of the reserve (equation 3-1). The balance equation is illustrated in Figure 3.1.

$$P + I + S = E + D + L + O \tag{3-1}$$

P = Precipitation
I = Inflow
S = upwards Seepage
E = Evapotranspiration
D = infiltration (Discharge)
L = storage (water Level)
O = Outlet

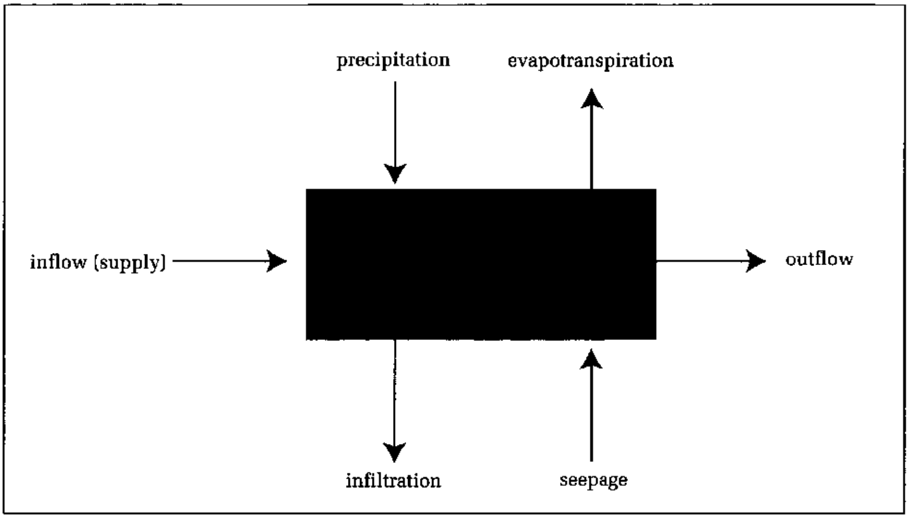

Figure 3.1
Schematic representation of the water balance in De Weerribben.

The hydrological unit of study was considered as a black box. However, if more spatial information becomes available, it is possible to subdivide the black box into a number of smaller black boxes. In this study information was available about the surface water network, the peat baulk pattern, vegetation structure etc. Hence, it was possible to subdivide the area into smaller units, e.g. sites. In this study, a site is defined as a small area (25 m^2) at which the spatial variation of the environmental variables, called site factors, is considered to be a black box and thus to be homogeneous.

The factors at reserve level play also a role at site level. The following factors, however, determine spatial variability in hydrological isolation at the site level:

- The position of peat baulks: peat baulks are much more resistant to water through flow than floating rafts (Vegt 1978b), because they consist of clay or original peat that is denser than the root mat of the floating raft. They, therefore, form hydrological barriers.

- The topology of the surface water network: this network supplies base-rich water. The distance from the network is considered to be one of the factors that determines the magnitude of the surface water influx.
- The thickness of the floating raft: a thin floating raft has a lower hydraulic resistance than a thick one because the water below it has a higher permeability than the raft (Van der Perk & Smit 1975).
- The hinterland area: water loss through evapotranspiration and infiltration is the driving force that makes water flow from the source to the most isolated site on the floating raft. The area between any site and the most hydrologically isolated site is called the hinterland area. The water loss is proportional to the hinterland area.

The third scale level is the microlevel. Spatial variability is present within a site. Microrelief influences small-scale differences in water chemistry and thus the distribution pattern of species (Van Wirdum 1991). However, these differences in microlevel are extremely variable in space and time and are therefore not suitable to be studied with RS and GIS. For this reason the study concentrated on the site level because, considering the entire reserve, the spatial variability of the factors involved at this scale influencing the distribution patterns of species are most relevant for management.

3.1.2 Hydrological models

The difference between precipitation and infiltration plus evapotranspiration is compensated for by an influx of surface water, as far as driving force and resistance allow (Van Wirdum 1991). The driving force is the hydrostatic pressure, which is maintained by water loss of the hinterland, and the hydraulic resistance is inversely proportional to the permeability. Water supply (and hence, base supply) decreases as the hydraulic resistance between any site and the supply source increases or the driving force decreases. The surface water network is the source of base-rich water and the peat baulks are assumed to be hydrological barriers. The resulting gradient of surface water influences species distribution. Irrigation is considered to be a hydrological short cut, as it enables the surface water to reach a site without taking the driving force or hydraulic resistance into account. Flooding has a similar effect. The volume of water that actually flows to a site, depends on the hydraulic resistance and the driving force, as described by Darcy's law:

$$I = k * A * dh / dL \qquad (3\text{-}2)$$

I = inflow or amount of water which flows to a site (m^3/day)
A = cross section (m^2)
dh = water level rise (m)
dL = length (m)
k = permeability (m/day)
dh/dL = driving force

The volume of water that flows from one site to another (equation 3-3) caused by infiltration and evapotranspiration is proportional to the hinterland area.

$$O = H * (E + D - P) \tag{3-3}$$

O = outflow, water loss of the hinterland (m^3/day)
H = hinterland area (m^2)
E = evapotranspiration (m/day)
D = infiltration or discharge (m/day)
P = precipitation (m/day)

In the model used in this study it is assumed that in an average year the water table does not change and there is no upwards seepage (Van Wirdum 1991). Another assumption is that the water loss of a site is caused mostly by water that flows to other sites (hinterland) which makes precipitation, evapotranspiration and infiltration at that site negligible, because of its small area compared to the hinterland area. This implies that the amount of water that could potentially flow to a site, is equal to the amount of water loss of the hinterland (O = I).

$$H * (E + D - P) = k * A * dh / dL \tag{3-4}$$

Hydrological isolation

According to Vegt (1978b), the degree of the hydrological isolation depends on the magnitude of water level fluctuations, the peat baulk pattern and the distance to the surface water network. However, these factors are not independent. Water level fluctuation depends on the distance to the surface water network, the peat baulk pattern and, furthermore, on the permeability of the floating raft. As a result, the magnitude of the water level fluctuations is considered the best indicator for hydrological isolation (Hi) in the framework of this study. When the water level is within reach of plant roots it is assumed to supply bases. The water level of a site can be calculated by accumulation of the water level rise (dh). All site factors of equation 3-4 can be derived from maps or reports, enabling dh to be calculated. Rearranging equation 3-4 gives:

$$dh = H * (E + D - P) * dL / (A * k) \tag{3-5}$$

For every site in the entire reserve, the Hi value can be calculated in a GIS by accumulation of dh values of sites forming the shortest route to the water source. In formula, the Hi value of site y is:

$$Hi_y = \sum_{x \in Ry} dh_x \tag{3-6}$$

where Ry is the set of sites (x) that connect site y with the nearest water source (the set Ry includes site y). The Hi values were considered to be an important site factor and subsequently used, in combination with other site factors, to explain rare plant species distribution (Chapter 5).

3.2 Vegetation structure

Dansereau (1957) describes vegetation structure as 'the organization of individuals in space, which form a vegetation stand'. The main elements of vegetation structure are: growth form (trees, shrub, herb and moss), stratification and cover. Mueller-Dombois and Ellenberg (1974) conclude that the word 'structure' should be used for the structure of plant biomass. They describe biomass structure as 'the distribution in space of plants that form the vegetation'. In this study, vegetation structure was defined as 'the vertical distribution of living, green, plant material' or in other words the amount of biomass of a site. Differences in vegetation structure are caused by differences in management (reed fen, fen meadow) and nutrient availability. High nutrient levels (supplied by surface water inflow and irrigation) favour tall forbs in the reed fens. Fen meadows are mown to remove aboveground biomass and thus to reduce nutrient availability. Differences in biomass, therefore, offer information on nutrient status and hence, indirectly, on rare plant species. Biomass differences and height are visible on remote sensing images (section 3.3) while a vegetation type defined by its species composition could not be recognized on remote sensing images (Appendix 2).

3.2.1 Hierarchical vegetation classification

The vegetation classification system used in this study reflects the abiotic conditions (base status and nutrient status) and management. This classification system has an ecological basis and allows causes of vegetation change to be interpreted. This is necessary for the land managers to be able to intervene in undesired processes. The vegetation class levels were defined without taking the hydrological scales into account. In contrast to the hydrological scales considered in section 3.1.1 which are spatially defined (geometrical resolution), the vegetation class levels are conceptual (thematic). The vegetation classes of the classification system are not spatially defined but can be considered at different scales, which makes a comparison with the hydrological scale levels possible. Reserve level (section 3.1.1) is related to wetland vegetation versus surrounding agricultural land, site level is related to the vegetation class level 3 (Table 3.1) and microlevel is related to individual plant species.

Four functional levels of classification were defined (Table 3.1). The vegetation structure types at the first level of classification can be described in general terms because they are not typical of fens. They reflect the general succession (from water via open fen to woodland) and management. Knowledge of the area is not necessary. The vegetation structure types were derived from analogue photo interpretation and used for stratification (Chapter 4). The vegetation structure types at the second level of classification are related to the vegetation management regimes. These types contain information about the succession of vegetation in relation to its management. Management details were derived from the management administration and used to subdivide the remote sensing images into segments. The vegetation structure at the third level of classification is related to differences in base status and nutrient status. At this level knowledge of the ecology is essential to explain the vegetation structure types. The types were defined so that the main abiotic processes of acidification and eutrophication could be studied. They were assessed by digital image analyses of scanned aerial photos. This third level of classification is most suitable to relate vegetation characteristics to hydrology (site level). Both the vegetation at this level of classification and hydrology at the site level contain information on base status and nutrient status. Hence, this level of classification was essential for the purpose of this study. The vegetation types at the fourth level of classification were identified and mapped through fieldwork. The vegetation types were defined locally, their code is explained in Table 3.2. They are described by dominant species and species composition. So there is a direct relation with rare plant species. Detailed information about the abiotic conditions (base status and nutrient status) of a site can be derived from the vegetation types. The types were used to give remote sensing classes an ecological significance.

The relation of the vegetation structure types to vegetation management and water chemistry at three hierarchical levels are shown in succession diagrams (Fig. 3.2) based on Smittenberg (1974) and Van Wirdum (1995). The third diagram gives the succession stages in relation to management, base status and nutrient status. This is important for interpretation and monitoring vegetation change. Management is divided into summer mowing, winter mowing and no management. The horizontal axis represents differences in nutrient status within each management type. The vertical axis represents succession and concomitant acidification i.e. differences in base status.

Table 3.1
Hierarchical vegetation classification system: level 1 represents the main succession; level 2 subdivides level 1 by differences in vegetation management; level 3 is a further subdivision representing differences in base status and nutrient status; level 4 are vegetation types described on the basis of fieldwork (the codes are explained in Table 3.2).

LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 4
1. water	1.1 water	1.1.1 water	
	(no management)	1.1.2 floating aquatic plants	w4
2. open fen	2.1 reed fens	2.1.1 wet reed fens	r1, r2
	(winter mowing)	2.1.2 brown moss reed fens	r3, z2
		2.1.3 tall forbs reed fens	r4, r5, r6
		2.1.4 *Sphagnum* reed fens	r7
	2.2 fen meadows	2.2.1 brown moss fen meadows	t1
	(summer mowing)	2.2.2 *Sphagnum* fen meadows	t2, h3, v1, v2
		2.2.3 wet tall forbs vegetation	z4, z1, L3
		2.2.4 tall forbs vegetation	L7, v3,
3. woodland	3.1 woodland	3.1.1 woodland	b1, b5, b7
	(no management)		

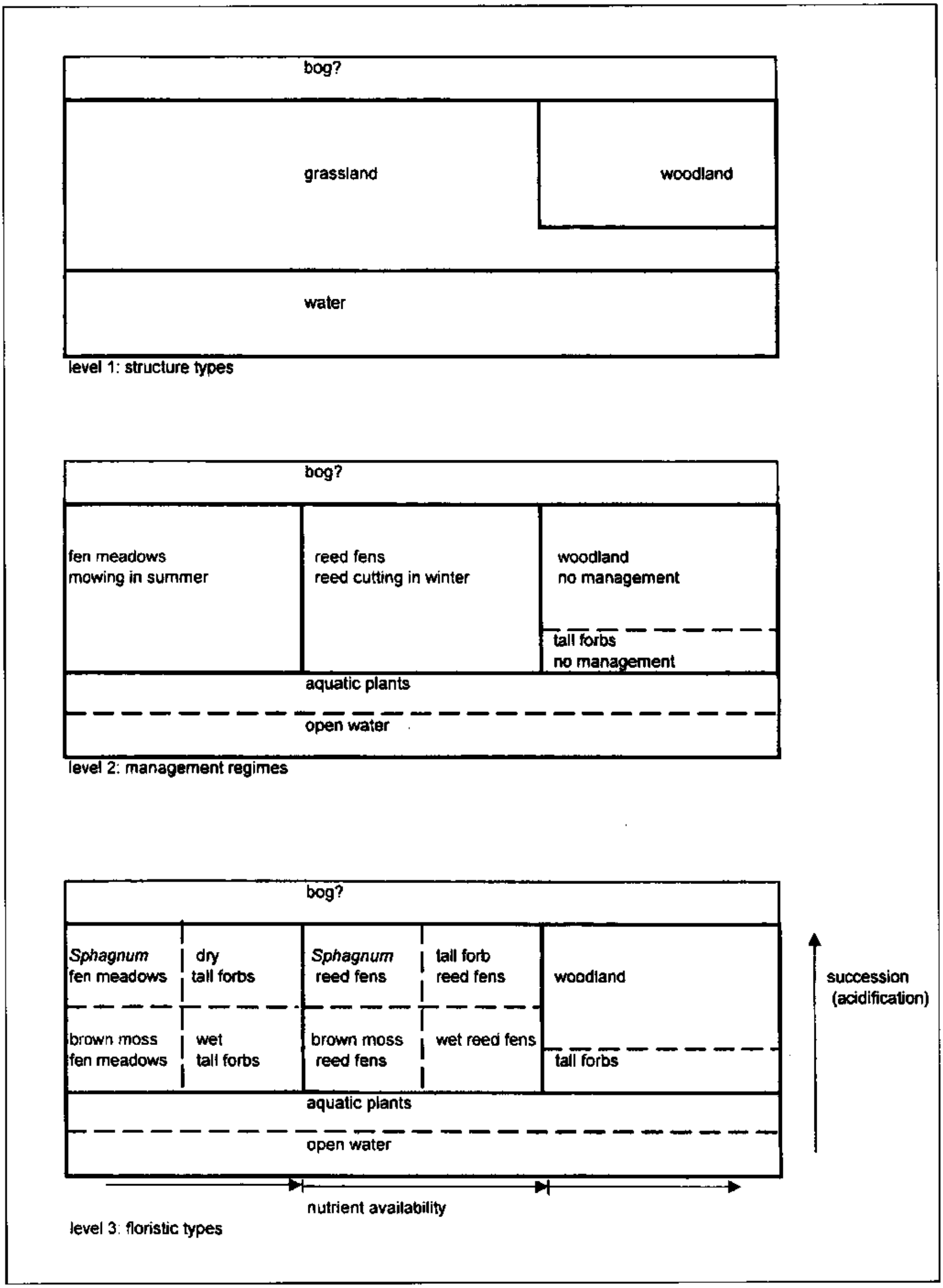

Figure 3.2
Hierarchical vegetation succession diagrams. The vertical axis (level 3) represents the direction of the succession by different levels of nutrient status in a given management regime (horizontal axis).

Table 3.2
Relation between the vegetation classification system and reference systems.

THIS STUDY	MAP 1986 (LOCAL)	DE VEGETATIE VAN NEDERLAND (1995-1999) (NATIONAL)
aquatic plants	w4 aquatic plants	Nymphaeion, Hydrocharition morsus-ranae
wet reed fens	r1 water reed fens	Phragmition australis
	r2 *Calliergonella* reed fens	Phragmition australis
brown moss reed fens	r3 *Scorpidium* reed fens	Caricion davallianae
	z2 *Cladium* reed fens	Cladietum marisci
tall forb reed fens	r4 species-rich tall forb reed fens	Filipendulion
	r5 tall forb reed fens	Filipendulion
	r6 *Lysimachia* tall forb reed fens	Filipendulion
Sphagnum reed fens	r7 *Sphagnum* reed fens	Pallavicinio Sphagnetum
brown moss fen meadows	t1 *Scorpidium* fen meadows	Caricion davallianae
Sphagnum fen meadows	t2 *Sphagnum* fen meadows	Caricion lasiocarpae Carici curtae-Agrostietum caninae
	h3 oligotrophic *Sphagnum* fens	Pallavicinio-Sphagnetum Parvocaricetea
	v1 *Erica-Oxycoccus* fen meadows	Oxycocco-Sphagnetea
	v2 species-rich fen meadows	Cirsio dissecti-Molinietum
wet tall forbs vegetation	z1 *Carex acutiformis* vegetation	Phragmition, Caricetum paniculatae
	z4 *Carex elata* vegetation	Caricetum elatae
	L3 *Phalarus* vegetation	soc. Phalaris arundinacea [Phragmitetalia]
tall forbs vegetation	v3 *Molinia* fen meadows	Junco-Molinion
	L7 tall forb vegetation	Epilobion hirsuti
woodland	b1 *Salix* shrub	Salicion cinereae
	b5 *Alnus* woodland	Alnion glutinosae
	b7 *Betula* woodland	Betulion pubescentis

Classification level 3 was used to investigate whether the information obtained by remote sensing techniques could be used to identify vegetation types or ecological information so that such techniques could be used to explain species distribution. To place level 3 in a wider context it is linked to reference classifications (Table 3.2) namely the vegetation map of 1986 accompanying the management plan for De Weerribben and the national reference system described in De Vegetatie van Nederland (1995-1999).

3.3 Vegetation and its geographical and remotely sensed characteristics

Remote sensing is a useful technique to observe natural vegetation and vegetation change (Kuechler & Zonneveld 1988), especially in large, remote and inaccessible areas such as wetlands. Stereoscopic interpretation of aerial photographs has been used to map vegetation in the last forty years (Howland 1980; Van Dorp et al. 1985;

Bakker et al. 1994). The most promising way of increasing the accuracy of vegetation maps based on remote sensing is digital image processing. This section discusses the relation between image and vegetation characteristics. A thematic aspect and a geometrical aspect describe the remotely observed vegetation characteristics (Molenaar 1993). The context, i.e. the problem to be solved, should be clear before objects are defined and before a certain remote sensing technique is applied. In this study the results of remote sensing image processing and interpretation were expected to offer ecological information, so that they could be used for further spatial analysis to explain rare plant species distribution.

Remote sensing properties

Certain image properties are required in order to be able to apply remote sensing techniques in vegetation ecology. These properties are characterized by spectral, radiometric and geometrical resolution. Geometrical (spatial) resolution is defined as the smallest area in the terrain that has been measured by a sensor. Radiometric resolution is the smallest observable difference in reflectance that can be measured. Spectral resolution is a measure of the width of the wavelength band regarding its location in the electromagnetic spectrum (Buiten & Clevers 1993). The spectral bands should render characteristic information on vegetation. In literature there is consensus that the red, green and near infrared bands should be used for vegetation characteristics. A spectral band of an image (spectral resolution) consists of picture elements called pixels (grid cells, Fig. 3.3). The width of a pixel represents the geometrical resolution. To observe sufficient detail in an area such as De Weerribben the geometrical resolution must not exceed a few square metres. The numerical value of a pixel is called a digital number (DN) and represents the radiometric resolution. The DN is a value between 0 and 255 in the case of a 8-bit recording system.

3.3.1 The thematic aspect

Thematic data represent the semantic description of an object. These data contain information about what is the object. In this context: what is the significance of the reflectance of vegetation observed by remote sensing. Seasonal shifts like leaf position, biomass, dead material, phenology (state of growth: vegetative, flowering, dead) have a big influence on the spectral characteristics of a vegetation (De Boer 1993; Van Wirdum 1977). These seasonal shifts do not actually change the vegetation, which is why ecologists are less interested in them. Instead, they are interested in species composition and vegetation change caused by natural succession or environmental changes such as acidification or eutrophication. These important ecological processes are reflected in vegetation structure, but even more in species composition, which is very poorly represented by reflectance or spectral image patterns (Appendix 2, Droesen 1999). The reflectance of these vegetation types can be similar because of, for example, the dominance of one species or the presence of dead material in several vegetation types. On the other hand, the reflectance of a single vegetation type can vary greatly because of 'unimportant' differences in dead material. This makes it very difficult to classify vegetation on the basis of reflectance (Van Wirdum 1977; Wardley et al. 1987) even when hyperspectral data is used. Several studies have tried to distinguish vegetation types on the basis of differences in reflectance, using a variety of techniques including principal component analyses (Vegt 1978a; Tjalma 1979), spectral unmixing (Adams et al. 1995; Van Kootwijk et al. 1995), supervised classification (Duhaime et al. 1997; De Nies & Lebouille 1984; Van Kootwijk 1985) and unsupervised classification (Townshend 1984; Jewell 1989; Sanders et al. 1997). The results have only a local validity or are only applicable on a more general scale, i.e. only common vegetation structure types instead of detailed vegetation types can be distinguished.

Another remotely sensed vegetation characteristic is the reflectance pattern or textural differences. These patterns occur because the vegetation differs, for example, in height and cover of dominant species. On remote sensing images, woodland areas are easily recognized by their texture. Trees are large enough to be recognized individually on an aerial photograph. They have a bright side and a shaded side. A complication is the irregularity of the variation in reflectance since this variation is caused by more factors than vegetation alone. It depends, for example, also on the sun angle, the location on the photograph, the height of the trees, the density of the trees, etc. Texture measures can be used as extra features in classifications, to improve classification accuracy (Weszka et al. 1976; Kushwaha et al. 1994) or for the characterization of natural vegetation (Meesters 1989; Jalink 1990; Bijlsma 1993; Van der Genugten 1994). The results usually only slightly improve the classification, because of the irregularity in the reflectance patterns.

As a result of the factors mentioned above, direct estimation of species composition or vegetation classification from remote sensing will have only limited value for this study. However, many studies have demonstrated that remote sensing images contain information on vegetation characteristics such as biomass and wetness (Lillesand & Kiefer 1994; Hodgson et al. 1987; Paruelo et al. 1997; Tomer et al. 1997). In this study biomass is defined as the amount of green living plants and wetness is defined as the amount of water on a floating raft. Biomass and wetness can be used as indicators for acidification and eutrophication. Differences in wetness and biomass imply differences in water and nutrient supply. If the variables obtained by remote sensing are indicative of hydrological conditions, they offer information on species composition in an indirect way (section 3.3.4). It is assumed that biomass and wetness are key variables that form the link between remote sensing, hydrological isolation, vegetation structure types and rare plant species distribution.

3.3.2 The geometrical aspect

The geometrical or positional data is the geographical part of an object, i.e. the position of an object in a coordinate system, its shape and size. The representation of the geometry of an object can be in two forms: grid and vector. A grid is a collection of sample points or cells that cover the terrain in a regular grid. Primitives of a vector map, representing all or part of an object, are: point (position), line (position, length) and area (position, perimeter, area). For example, a vegetation relevé is represented by a point because it is a small feature in the context of this type of ecological study. A ditch or a peat baulk is represented by a line since it is a long linear feature and a woodland is represented by a polygon as it covers a relatively large and, due to vegetation management, sharply bounded area. A vegetation boundary is defined as a line dividing between two vegetation types. Depending on the purpose of the map, the difference between the two vegetation types can be based on the presence or absence of one indicative plant species, an entire group of species or a few dominant species. Boundaries can, therefore, be either sharp or vague. Sharp boundaries occur when, for example, soil or management change abruptly. Gradients in the vegetation are often related to hydrological gradients. Both gradients and sharp boundaries are found frequently in De Weerribben.

Analogue photo interpretation and field mapping normally result in a vector-structured terrain description because objects are identified. A vector presentation is very suitable for nominal data (objects) with sharp boundaries. The application of digital image processing or the use of scanned aerial photography will result in a grid-structured terrain description, because of the acquisition (sample) technique. A grid presentation is more suitable for numerical data, especially real values, e.g. in gradient situations.

3.3.3 Methodology for deriving remotely sensed vegetation characteristics

A skilled interpreter is able to recognize many differences in reflectance on aerial photographs thanks to his field knowledge. He knows the context, the differences in structure, texture and species composition. He also knows about the ecology of the plant species. He can make a distinction between relevant and meaningless differences in reflectance. However, these skills are difficult to formalize. A large geometrical and thematic uncertainty is introduced when gradients in vegetation, for example those caused by differences in hydrology, are visually interpreted and mapped on analogue photos by different interpreters. Digital image processing has much potential for indicating gradient situations. One advantage of digital image processing is its statistical foundation, which makes class assignment less subjective. A disadvantage of digital classification is the limited use of expert knowledge. A knowledge-based approach can be used if the expert knowledge can be formalized. Interpreters apply discrete models for terrain descriptions and rules (a photo key, Kuechler & Zonneveld 1988) on how to map terrain objects (conceptual data models). Hence, the objects are assigned to crisp classes (Fig. 3.3, Van Dorp et al. 1985; Bakker et al. 1994) while in gradient situations assignment to fuzzy classes by digital image processing seems to be more appropriate. Many authors (Foody 1996; Droesen 1996) propose digital image processing methods, such as fuzzy classification.

Fuzzy classification

The vegetation characteristics of remote sensing images can be approached with fuzzy set theory. The classes to which the pixels are assigned to can be fuzzy (Fig. 3.3). For example, the classes representing 'wet' and 'dry' can be considered fuzzy: there are no sharp boundaries to discriminate between members and nonmembers of the class. A fuzzy set can be defined mathematically by assigning to each possible pixel a value representing its grade of membership in the fuzzy set (Klir & Folger 1988). Yet although it would seem logical to use the fuzzy set theory, it was decided to use a conventional (supervised or unsupervised) classification method, assigning the pixels to a crisp class (Chapter 4). There were two reasons for this decision. First, the radiometric variance due to reasons other than reflectance of the vegetation (Chapter 4) influences the accuracy of the membership value to a large extent. It was

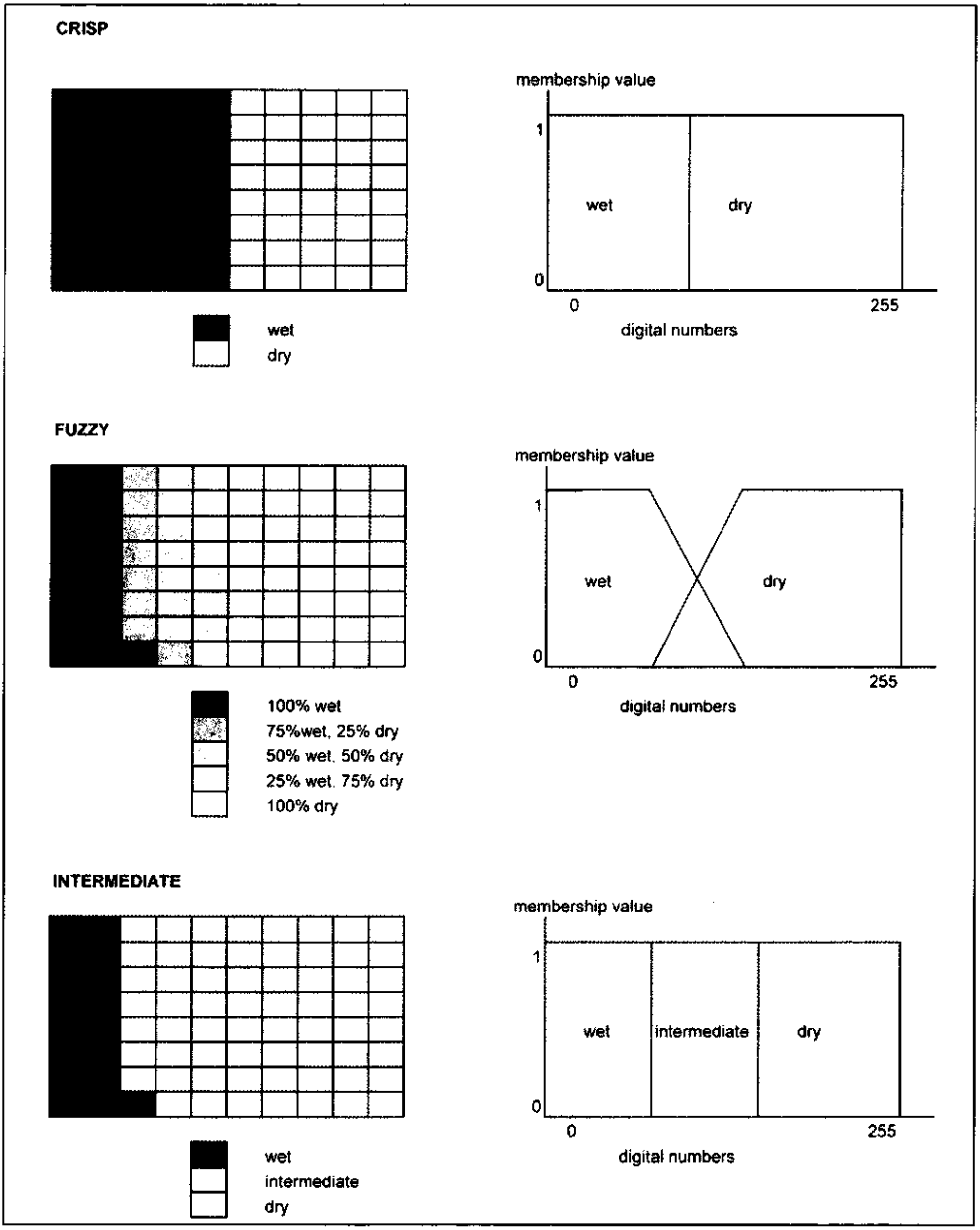

Figure 3.3

Mapping fuzzy and crisp classes: the grids on the left represent classified images; the graphs on the right represent the membership functions of the pixels assigned to the classes.

impossible to check a membership value because there was no ground truth available. Furthermore, changes in wetness within a short period do not substantially change the vegetation. Hence, to achieve a closer resemblance with the vegetation types discerned in the field, the degree of fuzziness would have to decrease dramatically. In the context of this study, it was considered to be not ecologically significant to characterize wetness by many different membership values. Fuzzy classes, in general, are introduced because the distinction between the classes is not abrupt but gradual. To approach the fuzziness of the classes in this study, an intermediate class between 'wet' and 'dry' was introduced (Fig. 3.3). The use of only three wetness classes was considered sufficient for this study.

Supervised classification

Supervised classification requires a priori information on the data. The user selects pixels that belong clearly to a certain cover class (vegetation type). A group of pixels, a training set, is selected per class. Then all pixels of the image are assigned to the classes defined by these training sets. Different statistical rules can be used (Buiten & Clevers 1993). It is important to have sufficient good quality terrain data as a priori information because these data control the quality of the classification. To make a good training set for supervised classification the vegetation types should be homogeneous, characteristic and relatively common within the area.

A small area was chosen to test the spectral separability of training sets from several vegetation types discerned in the field. Good quality ground truth, such as detailed vegetation maps and vegetation relevés, was available on the vegetation types (Sanders et al. 1997). The feature space plot (Appendix 2) illustrates that the spectral separability of the training sets is too low, so therefore it would be very difficult and time-consuming to classify these vegetation types. The spectral separability of the hypothetical reflectance caused by wetness and biomass is much better than the spectral separability of the hypothetical reflectance caused by vegetation types (Fig. 3.4). Contemporaneous ground truth on biomass and wetness was not available and thus an unsupervised classification seemed to be the most appropriate method.

Unsupervised classification

An unsupervised classification means that the computer does a statistical clustering on the digital numbers (DN). The method does not use training data but examines pixels and aggregates them into a number of classes based on the natural groupings or clusters present in an image (Lillesand & Kiefer 1994). The classification algorithm is an iterative procedure to establish class means. The result is a number of spectral classes. The identity of the classes must be established by comparing them with reference data. The method is very useful when information on data or ground truth is scarce and the method is more likely to produce good results for data that are not normally distributed (ERDAS IMAGINE Field Guide 1991).

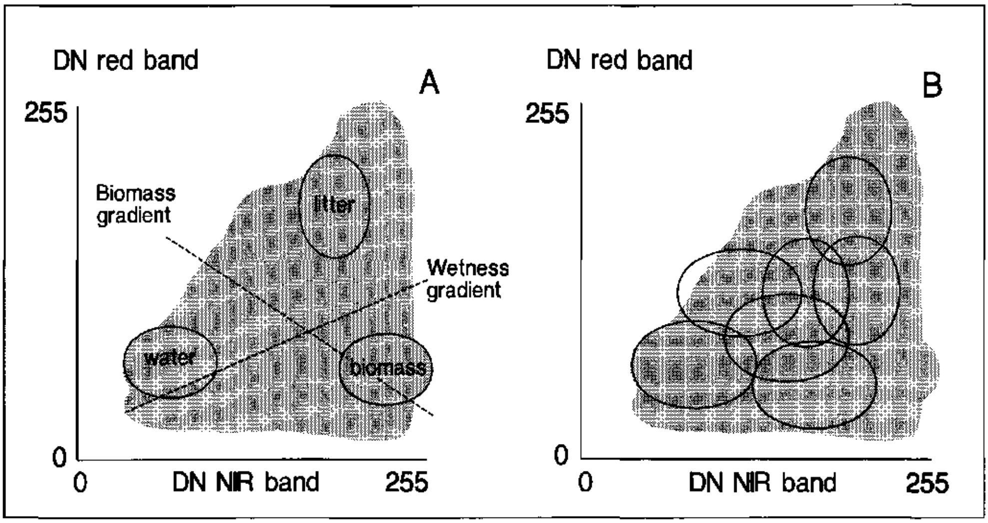

Figure 3.4
Hypothetical feature space plots representing the distribution of the digital numbers (DN) over the NIR band and red band of the electromagnetic spectrum for natural vegetation. The ellipses represent the spectral signature based on the training sets of a certain class. The lines in A represent the wetness and biomass gradients in the spectral signatures of the data. The ellipses in B represent the signatures of the vegetation types discerned in the field. The actual feature space plot of B can be found in Appendix 2.

Concluding remarks

The best and most objective combination of methods was used to derive significant information from remote sensing data without relying too much on the skill of an interpreter. Analogue photo interpretation was suitable to map water, open fen and woodland (level 1) because they were easily recognized thanks to their contrasting reflectance, texture and sharp boundaries. These classes were used for stratifying the landscape. Within the strata digital image processing has potential to derive information on gradients. Subsequently, unsupervised classification was used to classify 'wet', 'intermediate wet', 'dry', 'little biomass', 'intermediate biomass' and 'much biomass' within open fen. Management information (level 2) was incorporated later.

3.3.4 The ecological significance of the remotely sensed vegetation characteristics

Above it was assumed that there is a relation between the spectral reflectance and wetness and biomass respectively. The relation could not be confirmed with our data because contemporaneous ground truth on biomass and wetness was unavailable, but support is found in literature (Paruelo et al. 1997; Tucker et al. 1985; Box et al. 1989; Tomer et al. 1997). Since both vegetation structure types (level 3, section 3.2.1) and the spectral classes contain information on differences in biomass and wetness, they were assumed to be highly correlated. The ecological interpretation of the vegetation structure types with respect to wetness and biomass differences is described below.

- Wet reed fens (r1, r2) are 'wet' because they are irrigated or are on a thin floating raft. *Phragmites* grows very fast because nutrients are supplied by irrigation water so it forms much biomass.
- Brown moss reed fens (r3, z2) are 'wet' because they are on a thin floating raft or are irrigated. Compared with the wet reed fens they are further away from the source of the eutrophic surface water, which implies that they will produce less biomass.
- Tall forbs reed fens (r4, r5, r6) are 'dry' because much litter stays behind after mowing. Tall forbs grow very fast and form much biomass. Nutrients are supplied by irrigation.
- *Sphagnum* reed fens (r7) are 'dry' because *Sphagnum* forms a closed cover. The vegetation is oligotrophic (low biomass) as water supply is dominated by precipitation.
- Brown moss fen meadows (t1) are similar to brown moss reed fens. They are mown in summer, which implies a less dense *Phragmites* cover.
- *Sphagnum* fen meadows (t2, h3, v1, v2) are similar to *Sphagnum* reed fens.
- Tall forbs vegetation (v3, L7, L1) and grassland (g) are 'dry' because the tall forbs may leave much litter after mowing, or because they are growing where the water level is below the surface. Tall forbs grow fast and form much biomass because of former irrigation or fertilization.
- Wet tall forbs vegetation (z4, z1, L3) grows in flooded places. It forms much biomass because the water supplies nutrients.

These vegetation structure types contain only two wetness and two biomass classes for fen meadows and reed fens. No vegetation structure types representing intermediate wet and intermediate biomass could be defined at this level. As a result, the spectral classes representing 'intermediate wet' and 'intermediate

Table 3.3
Assumed positive relationship (#) between spectral classes (W+ = wet, W- = 'dry', B+ = much biomass, B- = little biomass) and vegetation structure types (level 3).

		SPECTRAL CLASSES			
MANAGEMENT	VEGETATION STRUCTURE TYPE	W+B-	W+B+	W-B-	W-B+
winter mowing	brown moss reed fens	#			
	wet reed fens		#		
	Sphagnum reed fens			#	
	tall forbs reed fens				#
summer mowing	brown moss fen meadows	#			
	wet tall forbs vegetation		#		
	Sphagnum fen meadows			#	
	tall forbs vegetation				#

biomass' were added to the 'wet' and to 'much biomass' classes respectively, to allow a comparison to be made with single relations instead of multiple relations between the vegetation structure types and the spectral classes. It was assumed that the intermediate classes were more closely related to 'wet' and 'much biomass' than to 'dry' and 'little biomass' because the amount of wetness and biomass may change rapidly within a short period. The spectral classes were coded W+ to indicate wet vegetation and W- to indicate dry vegetation or litter. The classes representing the differences in biomass were coded B+ (much biomass) and B- (low or no biomass). The contingency table (Table 3.3) illustrates the assumed positive relations between spectral classes and vegetation structure types (level 3, section 3.2).

3.3.5 Further spatial analysis

The remote sensing classes, as defined in the previous section, together with other site factors were used to model hydrological isolation in a GIS by calculating spatial relations such as distance, data integration and reclassification of geographical data. The procedures are applied to maps with a grid structured terrain description. Reclassification means assigning a grid cell, or an object, to another class of a new classification system on the basis of the class it belongs to. For example, a raft thickness class was assigned a permeability value on the basis of a deterministic relationship found in literature. Data integration (equation 3-7) means that the values of several maps are added, multiplied, subtracted, etcetera, per grid cell. To apply equation 3-5 in a GIS is an example of data integration.

$$\text{Output map}_{ij} = a^*A_{ij} + b^*B_{ij} + c^*C_{ij} \qquad (3\text{-}7)$$

attributes A, B, C are different grid maps;
$_{ij}$ is a grid cell at row i and column j in a grid map;
a, b, c is a constant to weight the influence of the specific grid map.

The distance measure used in this study calculates, for each cell, the least-accumulative cost distance over a cost surface to a source cell or a set of source cells (Fig. 3.5). This distance measure was used to simulate water movement from the watercourses (source) through the floating raft (cost surface). The cost surface is a grid defining the impedance or cost of moving through a given cell. For each cell, the value in the cost grid is assumed to represent the cost per unit distance of passing through the cell, where a unit distance corresponds to the cell width or height. The impedance of the cost surface depends on the permeability of the floating raft. The impedance of the peat baulks has been made infinite: they are barriers in the cost surface.

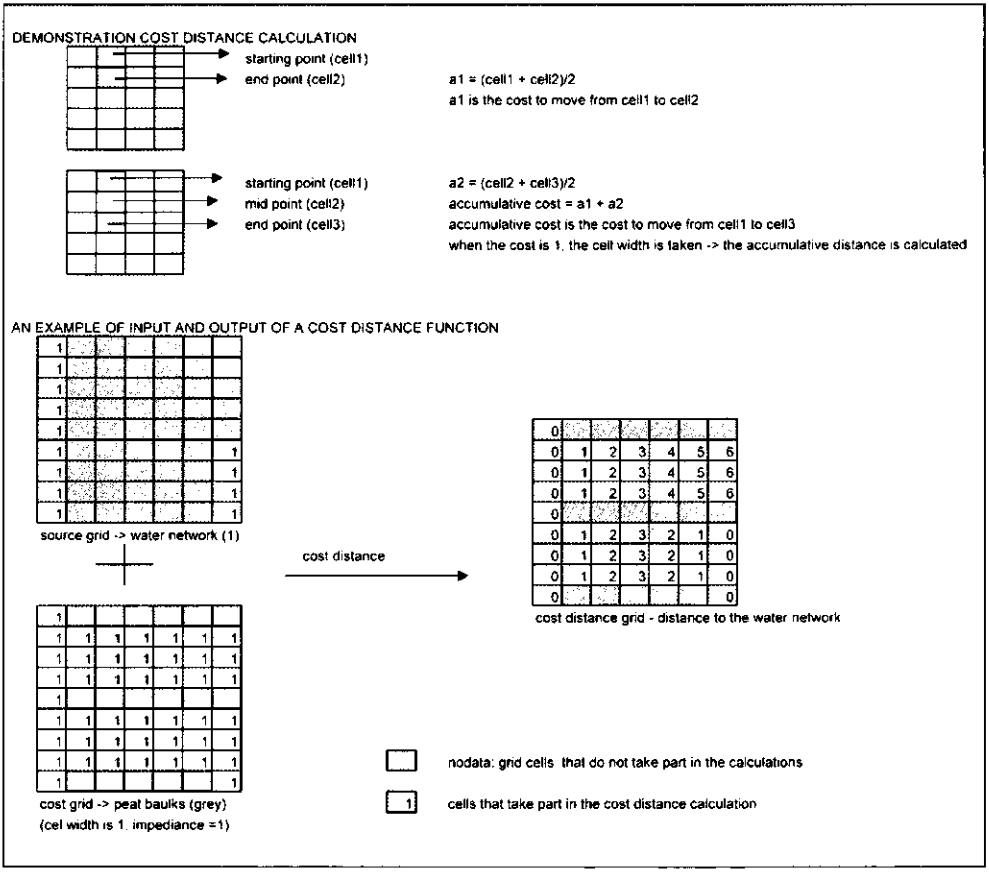

Figure 3.5
Schematic representation to demonstrate distance measurement with a cost distance function.

3.4 Statistical methods

Regression analysis can be used to explore the relation between species and their environment. Many studies have combined GIS and regression techniques to assess the distribution of animal and plant species or their potential habitat (Austin et al. 1996; Sperduto & Congalton 1996; Narumalani et al. 1997; Bian & West 1997). Regression analysis focuses on how a particular species is related to environmental variables (such as raft thickness, vegetation management, distances in the hydrological field). The method is intended to assess which environmental variables a species responds to most strongly and which environmental variables are unimportant. Such an assessment proceeds through tests of statistical significance (Jongman et al. 1987). A standard statistical test could not be used here, because of the following:

1. nominal, quantitative and ordinal explanatory variables had to be tested simultaneously;
2. species were recorded as presences, there was no recording of absences;
3. the species presences were presented as points but represent a certain area;
4. several classes of the site factors did not contain any presences.

3.4.1 Nominal, quantitative and ordinal variables

A relevant question is whether the occurrence of a species depends systematically on an independent variable, for example vegetation management (nominal variable). The null hypothesis is that the occurrence of a species does not depend on management. Usually, nominal explanatory variables are tested with the chi-square test (Jongman et al. 1987):

$$\chi 2 = SUM(o-e)^2/e \quad (3\text{-}8)$$

o = the observed number of points with the species in each of the management classes

e = the expected number of points with the species in each of the management classes.

When the statistical relationship is statistically significant, it is useful to calculate the amount of variance accounted for by the explanatory variables. In this study several explanatory variables are quantitative or ordinal, and therefore the usual chi-square test could not be used. Quantitative and nominal variables can be tested simultaneously with logit regression. In logit regression the statistical significance of the effect of quantitative explanatory variables is assessed by deviance tests (Jongman et al. 1987). For nominal explanatory variables the deviance test is closely related to the usual chi-square test. Regression techniques can easily cope with nominal and quantitative environmental variables, but not with ordinal ones. When there are few possible values, it is better to treat an ordinal value as a nominal value (Jongman et al. 1987).

3.4.2 Presences and absences

Logit regression attempts to express the probability that a species is present as a function of the explanatory variables (Hosmer & Lemeshow 1989; Jongman et al. 1987) and requires presence and absence data. Field sample methods usually comprise visits to a predetermined (random) number of points (plots) where the species presence or absence is noted. These field sample methods supply presence and absence data (Skidmore 1998; Hepinstall & Sader 1997) whereas the distribution map of the plant species (described in section 5.2) used in this study only supplies presences. Somehow a number of absences need to be added.

Table 3.4
Difference between the cover percentage and the point distribution percentage (pt%) of some site factor classes.

CLASSES	COVER %	PT% 1000	PT% 10 000
manage 1	87.5	89.8	86.9
manage 2	12.5	10.2	13.1
wet 1	10.4	5.4	12.6
wet 2	17.9	6.7	17.9
wet 3	71.7	87.9	69.5

Proportional cover

The problem can be illustrated by examining a simple question, namely whether the probability of occurrence of a species depends systematically on management. The chi-square test (equation 3-8) is commonly used to test the null hypothesis, that is, that the occurrence does not depend on management. It is important to understand how 'e' should be calculated. Under the null hypothesis the expected number of points with the species in each management class is proportional to the cover percentage of each class in the region sampled:

$$e = N f \quad (3\text{-}9)$$

e = the expected number of points with the species in the management class,
N = the total number of points with the species and
f = the proportional cover of a management class.

This method works for nominal variables but the test can only be extended to quantitative predictor variables by classifying the predictor into discrete classes, which implies a loss of information. Therefore a way was developed to simulate the above test without the need to explicitly calculate the proportional covers. An approximate solution is to add to the data a large number of random points, for each of which the values of the environmental values have been determined from the GIS. The distribution of the random points over the classes of the environmental variables should approach the proportional cover of these classes. Table 3.4 illustrates that the point percentage based on 10 000 random points is closer to the cover percentage of the class than the percentage based on 1000 random points.

The approximate solution works not only for single nominal predictors but also multidimensionally, because the proportional cover of combinations of classes of different variables is also estimated. The distribution of each quantitative variable is also approximated by its sample distribution. In fact, the multivariate distribution of both quantitative and qualitative variables is approximated in the sample. The more dimensions the logit model has, the larger the random data set should be. The quantitative variables make it impossible to determine the exact size. Many studies, however, have paid little attention to the size of the random data set and have chosen a small number (Austin et al. 1996; Sperduto & Congalton 1996; Narumalani et al. 1997; Bian & West 1997).

Absences

The random points can also represent absences instead of proportional cover. Each such random point adds a unit for which the species is considered absent. The logit regression is carried out on the data set of presences and absences thus created. The solution is expected to work well, if the size of the random sample is large compared with the number of presences of the species. One reason why the random data set should be large is that the observed presences should not change the frequencies of the environmental class covers too much as can be seen from the chi-square example test. The chi-square test is presented here as a 2 x R table where R is the number of classes, e.g. R=4.

class	1	2	3	4
presences	o_1	o_2	o_3	o_4
'absences'	r_1	r_2	r_3	r_4

where o_k is the number of sites in class k with the species and r_k is the number of sites in class k in the random data. The expected numbers in the columns are proportional to $o_k + r_k$ and this should not deviate much from being proportional to r_k. If these deviations become negligible, the contributions from the absence row vanish and the chi-square calculated from the 2 x R table corresponds to the original chi-square. The correspondence between the different methods to calculate the chi-square and the logit regression is illustrated in Appendix 4. In this study, 10 000 random points were assumed to represent absences and multiple logit regression was applied.

A relative probability measure

Absolute probability estimates of species occurrence are impossible to obtain because the probability estimates depend on the number of random points taken. When the number is large the absolute probability becomes unreasonably small. Hence, only a relative measure is appropriate. One commonly used measure is the log-odds ratio (Hosmer & Lemeshow 1989),

$$\text{log-odds} = \log [\, p_1 (1-p_2) / (p_2 (1-p_1)) \,] \tag{3-10}$$

p_1 = the probability of occurrence in site 1
p_2 = the probability of occurrence in site 2

which in a typical logit regression situation is merely a difference on the logit scale for two sets of values of the predictor variables. When p_1 and p_2 are very small, as will be the case with very many random points, a difference on the logit scale simply models the logarithm of the relative probabilities, namely

$$\text{log-odds} \approx \log(p_1/p_2). \tag{3-11}$$

3.4.3 Point distribution

The species distribution is available as a point distribution map. However, a species never occurs as a point but covers a certain area. This area can range from 1 m^2 to several dozens. In this area, a species can be dominant but can also occur only occasionally. This information cannot be recovered. In this study the spatial variation of the environmental variables, called site factors, is considered homogeneous for a site covering an area of 25 m^2 (section 3.1.1). A species distribution point can be appointed to a site because a site is considered homogeneous. Still, there is a chance that a species will cover an area larger than 25 m^2. For this reason the sites neighbouring a site with a species presence have a higher than average probability of containing this species too. To minimize this spatial autocorrelation, random points within 30 m (average raft width) from the species presence were not taken into account (Chapter 5).

Furthermore, the log ratio (equation 3-11) can also be interpreted in another way. If a species occurrence is considered as a point, the distribution map is the outcome of a stochastic point process (Diggle 1983). A point process can be characterized by the intensity function l(x) where x is a set of predictor variables, which often, but not necessarily, includes the geographic coordinates of that point. The intensity of a particular point is formally defined as the limit of p/A where p is the probability of occurrence in a spot of area A around the point and where the area A has shrunk to zero. The intensity is therefore proportional to the probability of occurrence in sites covering a small area. The log ratio of probabilities in sites can therefore be considered as an approximation of the log ratio of the intensities l1 and l2 of the underlying point process. In conclusion, when sites are small enough, the area they cover is unimportant: it has no influence on the relative probability. The size of a site in this study is considered small enough.

3.4.4 Empty classes

One technical problem in the application of logit regression is that regression coefficients are unbounded if the observed proportion of presences is exactly 0 or 1. This problem occurred in our data when the species was not observed under a particular combination of classes. Adding a small value to the data can circumvent the problem. This addition is done in such a way that the average probability of occurrence is not affected. This is achieved as follows. If the response is first coded as y = 0 (absence) or y =1 (presence) with a binomial total of 1, the data become $y + p_a.c/n$ with a binomial total of $1 + c/n$. The symbol p_a is the average probability, n the number of data points in the regression and c a constant, the number of 'pseudo-data points' used to regularize the regression problem. As a result of this approach, the regression coefficients shrink slightly towards zero (which represents the null hypothesis of no relationship), with the amount of shrinkage being determined by the constant c (in this study c = 1).

3.5 Accuracy and reliability

When using a GIS, many errors can be introduced without the user being aware of them. In a GIS there are almost no restrictions or indications to warn a user when such an error is introduced. So it is very important to be aware of possible errors by knowing the terrain and the limitations of procedures and models. A model is an abstraction of reality and to obtain results, the researcher has to make assumptions and exclude parameters. To draw sensible conclusions it is essential to test the data for accuracy and reliability. The New Shorter Oxford Dictionary defines these words as follows:

Reliability= the extent to which a measurement made repeatedly in identical circumstances will yield concordant results.

Accuracy = the degree of refinement in measurements or specifications, as given by the extent of conformity with a standard or true value.

The accuracy and reliability in geometrical and thematic data important for this study are considered below. Measures to increase accuracy and reliability are considered and the methods used in this study to evaluate the classification accuracy and the regression results are described.

3.5.1 Geometrical data

Measurement techniques, procedures or human failure introduce stochastic variation. However, the character of the data and objects also influence the uncertainty. One of the causes of this variation is the radiometric and geometrical accuracy of a scanner (a machine used to make an analogue photograph digital) and by the geometrical accuracy of the digitizer (a machine used to make an analogue map digital). The accuracy of a photo interpretation depends on the thickness of the pen used to delineate boundaries. To minimize this variation in this study a minimal mapping unit (Kuechler & Zonneveld 1988) and enlarged photo prints were used. Another source of variation is that when several interpreters draw a boundary around the same object, the exact location of these boundaries will vary. The amount of variation depends on the character of the boundary: sharp or more gradual. The polygons created by these varying boundaries are called spurious polygons (Burrough 1986). The inaccuracy introduced by human failure or measuring techniques, can be expressed by means of variances. These variances can be visualized, for example, as an Epsilon band around the location of an average boundary (Blakemore 1984) obtained by interpreting the same photographs several times. In this study, to minimize the geometrical variation of a boundary only objects with relatively sharp boundaries were visually interpreted. A topographic map (1:10 000) was used as a basis to map other themes like management and raft thickness, to reduce the described variation such as spurious polygons. The topographic boundaries only have to be interpreted and digitized once. An advantage of a grid map is the absence of spurious polygons. In this study all vector data have been transformed to grid and are presented as such. Since the measures mentioned above had been taken, it was assumed that the accuracy was only a few metres.

3.5.2 Thematic data

Similar to the geometrical attributes, inaccuracy and reliability of thematic data is also caused by human failure, measurement techniques or procedures. Visual photo interpretation depends on the interpreter's skill in recognizing objects. The judgement involved in recognizing objects is generally qualitative and thus difficult to evaluate or to compare with interpretations made by others. This is especially true when there is large natural variation in the vegetation. An interpreter with field knowledge recognizes more field characteristics and makes fewer mistakes than one without. The accuracy varies, depending on scale and homogeneity of vegetation (Christensen et al. 1988; Butera 1983; Jensen et al. 1984; Glaser 1989). Vegetation types discerned in the field may be very similar and thus hard to recognize on the photographs. To determine how well field vegetation types can be distinguished, their similarity can be calculated (Sanders & Van Wirdum 1994). To minimize errors introduced by the judgement of an interpreter in this study, only homogeneous easily recognizable classes like woodland, water and grassland were interpreted on analogue photographs.

Classification accuracy

Normally, the accuracy and reliability of the results of image processing, the spectral classes, are evaluated with ground truth. In this study, no ground truth had been collected due to considerable vegetation change between the recording time and the moment the photos were available. Therefore the usefulness of the remote sensing techniques for this study was quantified by comparing the spectral classes with the vegetation structure types (level 3, section 3.2). The vegetation types (level 4) mapped in the field were grouped to make a vegetation structure map (level 3). It would have taken too much effort to digitize the vegetation map (level 4) and thus random points were used to make the comparison. The spectral classes and the vegetation structure type of these random points were put in a contingency table. An example is given in Table 3.5. Note that it is assumed that a spectral class ($class_1$) agrees with only one vegetation structure type ($vegetation_1$) and vice versa. This assumption is sensible, because the vegetation structure types (level 3) and spectral classes are both indicative of biomass and wetness. The overall classification accuracy, reliability and accuracy per vegetation type were calculated to obtain an indication of the usefulness of the remote sensing techniques. An example to calculate accuracy and reliability is given below:

Table 3.5

Hypothetical contingency table to illustrate the validation of the image classification results: $a_{1.1}$ - $a_{2.2}$ = a certain numbers of random points; r = row totals, c = column totals; t = total number of random points.

	SPECTRAL CLASSES		
FIELD MAP	$CLASS_1$	$CLASS_2$	ROW TOTAL
$vegetation_1$	$a_{1.1}$	$a_{1.2}$	r_1
$vegetation_2$	$a_{2.1}$	$a_{2.2}$	r_2
COLUMN TOTAL	c_1	c_2	t

The percentage of pixels belonging to vegetation$_1$ but erroneously assigned to class$_2$, is called the omission error of vegetation$_1$. The accuracy depends on this error (equation 3-12).

$$\text{accuracy vegetation}_1 = a_{1.1} / r_1 * 100 \qquad (3\text{-}12)$$

The pixel percentage of classification result class$_1$ which belongs to vegetation$_2$, is called the commission error of vegetation$_1$. The reliability depends on this error (equation 3-13).

$$\text{reliability vegetation}_1 = a_{1.1} / c_1 * 100 \qquad (3\text{-}13)$$

The overall classification accuracy is calculated as follows:

$$\text{classification accuracy} = (a_{1.1} + a_{2.2}) / t * 100 \qquad (3\text{-}14)$$

Much research has been performed to improve classification accuracy by means of object classification (Janssen 1993), using ancillary data for stratification, sorting or modifying a classification (Hutchinson 1982), various statistical methods, majority filters etc. In this study ancillary data ware used for stratification to improve the classification accuracy.

Validation of the regression results

The results of the regression analysis to predict species occurrence could not be used to determine the reliability of the predictions. The calculated variances are based on the assumption that the sites are independent. This assumption is, however, unlikely to be true because of spatial autocorrelation and the arbitrariness of the number of absences. No independent data from a different area were available to check the predictions based on regression analysis. Therefore, a cross validation to evaluate the results was carried out as follows. The regression analysis was performed several times, excluding a different part (subarea) of the area each time. Instead of leaving out a number of random points (presences and absences) which assumes spatial independence, a continuous subarea, as large as possible, was left out to minimize spatial autocorrelation. However, if only a few subareas, for example four, are taken a site factor class may be completely excluded due to its irregular distribution. A somewhat arbitrary choice for nine subareas was made by subjectively drawing two transverse lines and two perpendicular lines (Fig. 3.6). The nine subareas differ in size, the amount of woodland (woodland was not taken into account) and therefore, in the number of random points and the cover of the site factor classes.

The regression analysis was carried out nine times, each time excluding one of the subareas. The resulting model was used to make predictions per site for the excluded subarea. Hence, the predictions of the sites situated in the excluded subarea are an extrapolation of the regression results over the other eight subareas. The result is called the 'predicted' probability map which was compared with the regression result for the entire area without any exclusion: the probability map. The stability of the model under modification of the data, was tested by comparing the

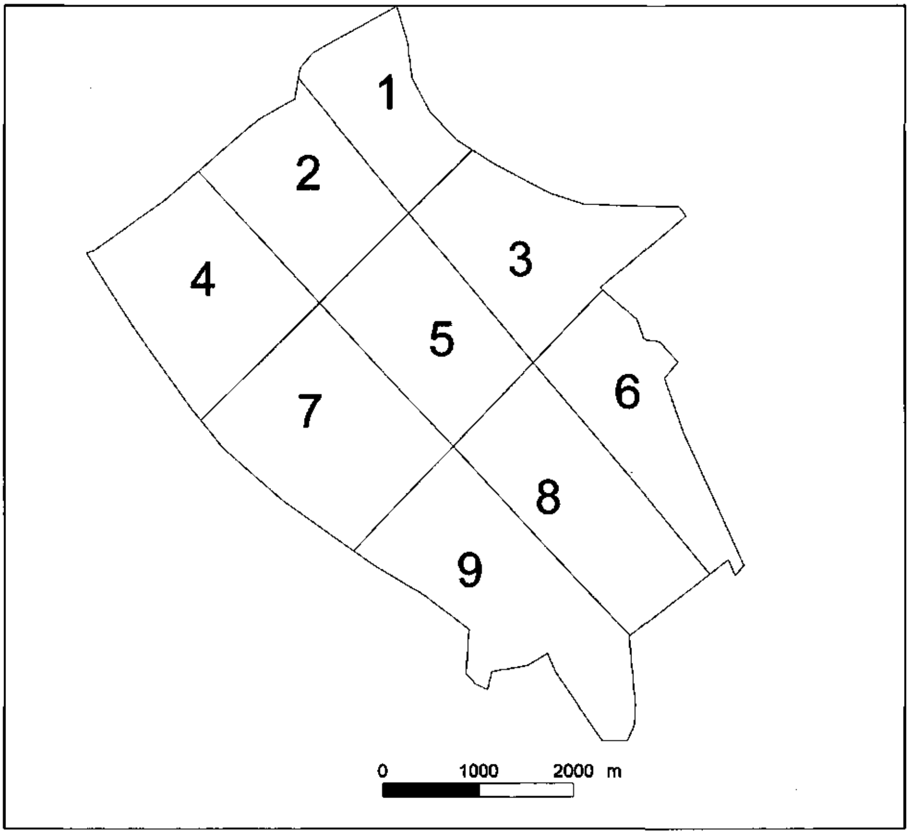

Figure 3.6
De Weerribben split up into nine subareas for cross validation.

'predicted' probability map with the probability map. The accuracy can be determined by comparing the 'predicted' probability map with the actual species distribution, using simple regression. The cross validation method is illustrated in a flow diagram (Fig. 3.7).

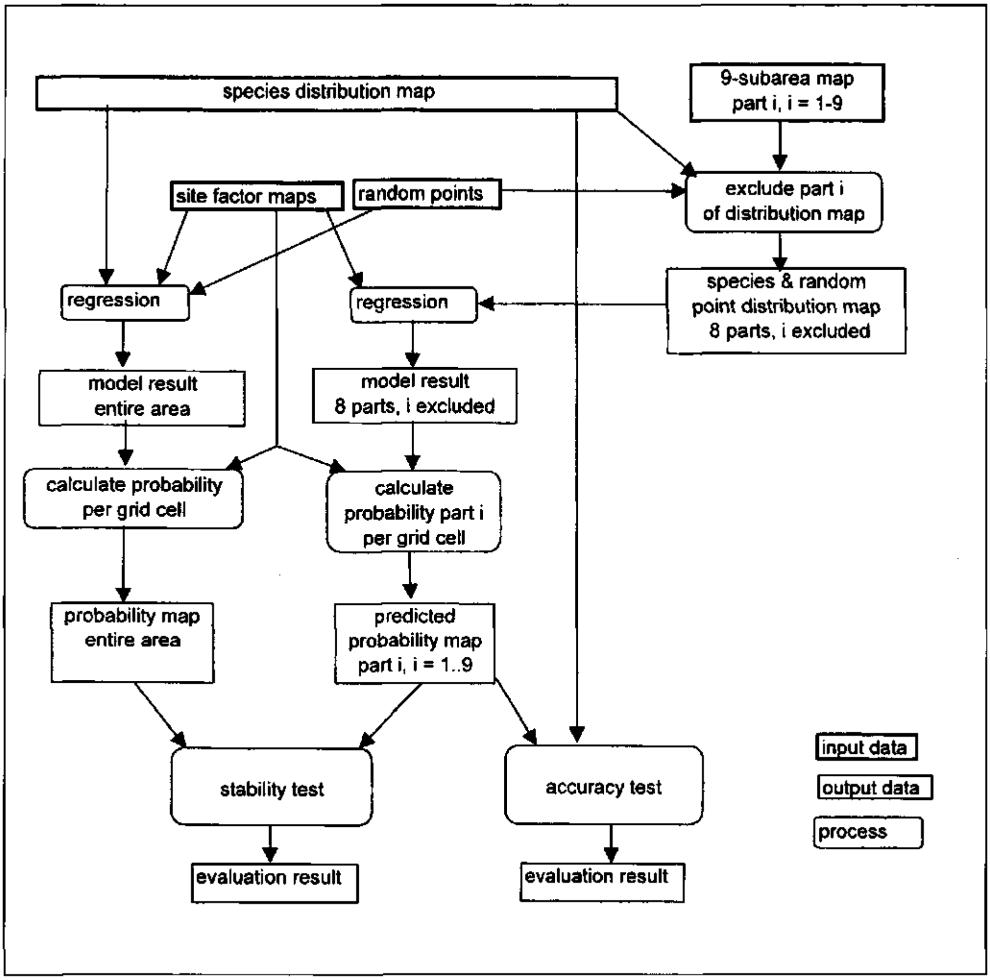

Figure 3.7
Flow-chart to illustrate the cross validation process.

4 Remote sensing and vegetation structure

4.1 Introduction

This chapter sets out to obtain the best and most objective combination of methods to derive significant information on fen vegetation from remote sensing data without relying too much on the skill of an interpreter. The potential for remote sensing for deriving spectral classes related to vegetation characteristics (biomass and wetness) in this study was discussed in Chapter 3. The spectral classes will then be used as site factors to predict plant species occurrence. The remotely sensed images used to obtain information on biomass and wetness are described in section 4.2. Then, a combination of methods (analogue and digital interpretation) to use the images optimally is proposed (section 4.3). The results from image processing are presented in section 4.4. They are compared with the vegetation types discerned in the field (section 4.5) to test their ecological significance. The images and image processing methods used and their results are discussed in section 4.6.

4.2 Material

4.2.1 Remotely sensed imagery

Many different types of remote sensing imagery are available: satellite images (Landsat, Spot), airborne scanner images (Daedalus, CASI, CAESAR) and aerial photographs (False Colour, True Colour and Panchromatic). Which platform is chosen depends on the purpose of the study. To obtain characteristics from fen vegetation, images with a high geometrical resolution were required. Furthermore, as the images were for use in GIS they needed to be geometrically correct. And, last but not least, the images had to contain information on desired vegetation characteristics (section 3.3).

Although satellite images have a good radiometric and spectral resolution, when this study began their geometrical resolution was too poor for an area like De Weerribben. To distinguish vegetation characteristics within the narrow floating raft (ca. 30 m wide) a sensor with a high spatial resolution had to be used. For these reasons, satellite images were not useful for the purpose of this study. However, future studies of this type will undoubtedly be able to use high spatial resolution satellite imagery.

One possible alternative to satellite imagery considered for this study was multispectral scanner (CAESAR, Daedalus and CASI) imagery. These images are very promising for the recognition of natural vegetation types (Janssen et al. 1996) because they have a good spectral, radiometric and geometrical resolution. The available scanner images (CASI, Daedalus) of De Weerribben, however, had much internal geometrical distortion caused by movements of the plane. As it was impossible to correct the internal geometry of these images sufficiently (Moen et al. 1996) they were not useful for the purpose of this study, because they could not be used in a GIS for further analysis. To overcome this problem of distortion, a GPS would have to record the position of the platform simultaneously with the image.

The third option was aerial photos. Panchromatic and False Colour aerial photos have been used widely for vegetation mapping. Similar to satellite and scanner images, the spectral characteristics of an object on the photograph are determined by electromagnetic radiation reflected by that object. However, spectral bands in a false or true colour film overlap (Fig. 4.1; Buiten 1993) and there is much radiometric distortion towards the edges of the photos, due to light fall-off and sun angle effects. Although they have only moderate spectral and radiometric resolution, the photos contain detailed information that an interpreter with good field knowledge can extract. An advantage of aerial photos is their very high geometrical resolution. Furthermore, a geometrical correction with photogrammetric procedures make the photographs match with other data sets or maps very accurately, which makes them most suitable for use in a GIS. For this reason, aerial photographs were used in this study. There was aerial photo coverage of the entire reserve from 14 June 1986 (Photo 4.1, page 129) and 4 May 1995 (Photo 4.2, page 129). More specific information on the photographs can be found in Appendix 1.

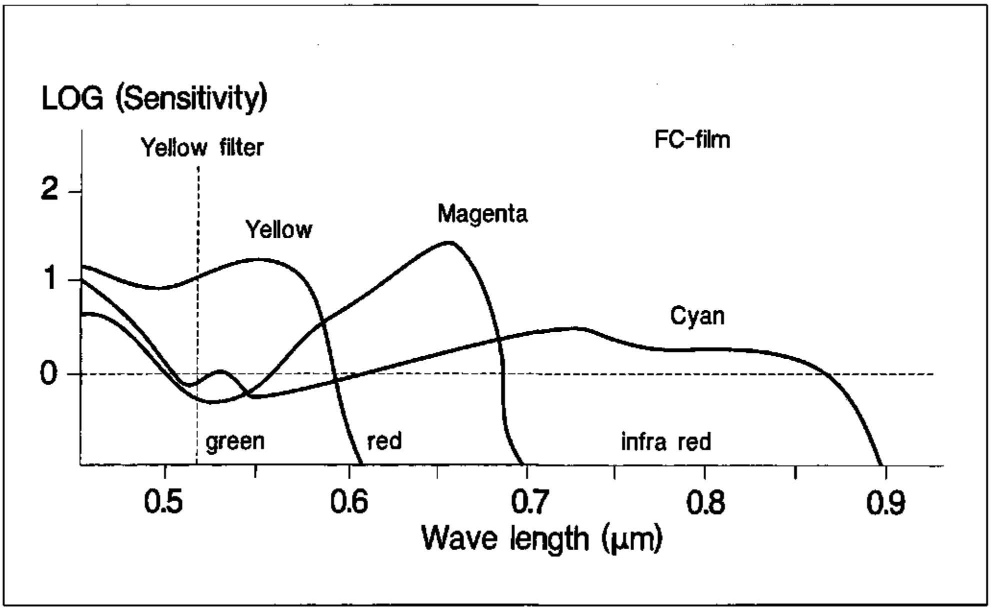

Figure 4.1
Spectral sensitivity for the three bands of the FC photos. Y = sensitive layer for green, M = sensitive layer for red, C = sensitive layer for near infrared (Buiten & Clevers 1993).

Geometrical requirements

There is a difference in what can be recognized (visible) and what is practically mappable with analogue interpretation. As guideline Kuechler and Zonneveld (1988) propose a minimal mappable unit of 0.5 by 0.5 cm on a photo or print to be interpreted. Since the floating rafts in De Weerribben are ca. 30 m wide, a scale of

1:5000 (minimal mapping unit 25 by 25 m) was considered just suitable for aerial photo interpretation. The scale of the false colour diapositives was 1:5000 (1986) and 1:22 500 (1995). Enlarged prints of the 1995 diapositives (scale 1:5000) were used for photo interpretation, but were too big to be examined stereoscopically. The diapositives were scanned, to improve their mappable resolution. For example, instead of 0.25 cm^2, 0.0025 cm^2 could be distinguished on the photograph. The smallest spatial resolution depends on the granularity of the film and is determined by the signal/noise ratio (Buiten & Clevers 1993). The desired spatial resolution depends on the purpose of the study. Differences in reflectance within the floating raft were analysed to obtain information on the vegetation. In view of the level of detail and the amount of data to process, it was decided to use a spatial resolution of 1 m^2. This implies that for digital interpretation in comparison to analogue interpretation, photographs at a smaller scale than 1:5000 (e.g. 1:22 500) were also suitable. A smaller scale has the advantage that fewer photographs have to be processed.

Thematic requirements and information

The season at which the photographs were taken is very important, because it determines what can be recognized on the photograph. The optimum date depends on the purpose of the study: in this case, the vegetation types of interest. This moment depends on weather, season and terrain type. The optimal date for obtaining information on wetness of the terrain is early in the growing season when the vegetation is not developed. When biomass has formed, it is difficult to recognize differences in wetness. The 1995 FC photographs were taken on 4 May, which is early in the growing season and the time at which the differences in wetness, i.e. amount of water on the floating rafts, were most explicit. The optimal date for obtaining information on biomass differences is slightly later in the growing season. At that moment the differences in biomass between fast growing tall forb vegetation and species-rich vegetation will be maximal. After a relatively short optimal period all vegetation types have more biomass and the differences in reflectance become less pronounced. The 1986 FC photographs were taken on 14 June: the right moment for differences in biomass. The tall fast growing forbs and reeds were already much further developed than the other vegetation types.

Clearly, to obtain maximum information on biomass and wetness, both the May and June photos were used. This introduced a reliability problem, because of the possibility that biomass and wetness could have changed in the ten years between the two photo series. However, wetness and biomass also change considerably within a growing season. Furthermore, it would not have been possible to quantify the accuracy or reliability of the information gleaned from the photos, because no contemporaneous ground truth on biomass and wetness was available. However, after quantifying the usefulness of the remote sensing techniques by comparing the spectral classes with the vegetation types mapped in 1986 (section 4.4), it could be assumed that wetness had not changed dramatically between 1986 and 1995.

4.2.2 Maps

Vegetation maps

The management plan for De Weerribben (Staatsbosbeheer 1988) contains an analogue 1:5000 vegetation map made by collecting field data. The most important vegetation types were described in section 3.2 (level 4).

Management administration

In order to make a distinction between fen meadow and reed fen, information on land parcel attributes held by the management organization was digitized. The management information was added to the 1:5000 topographic map made by aerial photo interpretation (section 4.3.2) to create a management map. The administrative details included information about the owner, the tenant farmer and the frequency and type of management of each parcel of land. Most important was the management type: summer mowing (fen meadows) or winter mowing (reed fens). All information on the summermown parcels of land was reliable, up to date and had been checked. The information on the wintermown reed fens was not up to date. The managers of De Weerribben keep records about which parcels the tenant farmers have paid to cut reeds from and not about which parcels are actually mown in winter. The information on summer mowing is more accurate because, in contrast to winter mowing, the managers of De Weerribben pay tenant farmers to mow at that time. The information on winter mowing was checked in the field and only a few parcels turned out to be abandoned and contained flourishing tall forbs and young trees.

4.3 Methods

The photo interpretation and image analysis procedure followed are illustrated in Figure 4.2. The input data were described above. The procedures described in this section resulted in a 'remote sensing vegetation structure' map (section 4.4) based on analogue photo interpretation and digital image processing combined with management information.

4.3.1 Pre-processing

Many aspects need to be taken into account when aerial photographs are used for image processing. The photos have to be pre-processed before image analysis can take place. The scanning procedure and subsequent geometrical and radiometric correction are discussed below.

Scanning

Analogue photographs (in this study, diapositives) intended for digital image processing must first be scanned. A scanner measures the transmission (i.e. the amount of light passing through a diapositive) on a sample location sensitive to a certain spectral band (red, green and infrared). The transmission depends on the shades of blackness of the diapositive and is thus representative of the amount of radiation in a particular spectral band. The number of measurements (dots per inch, dpi) taken

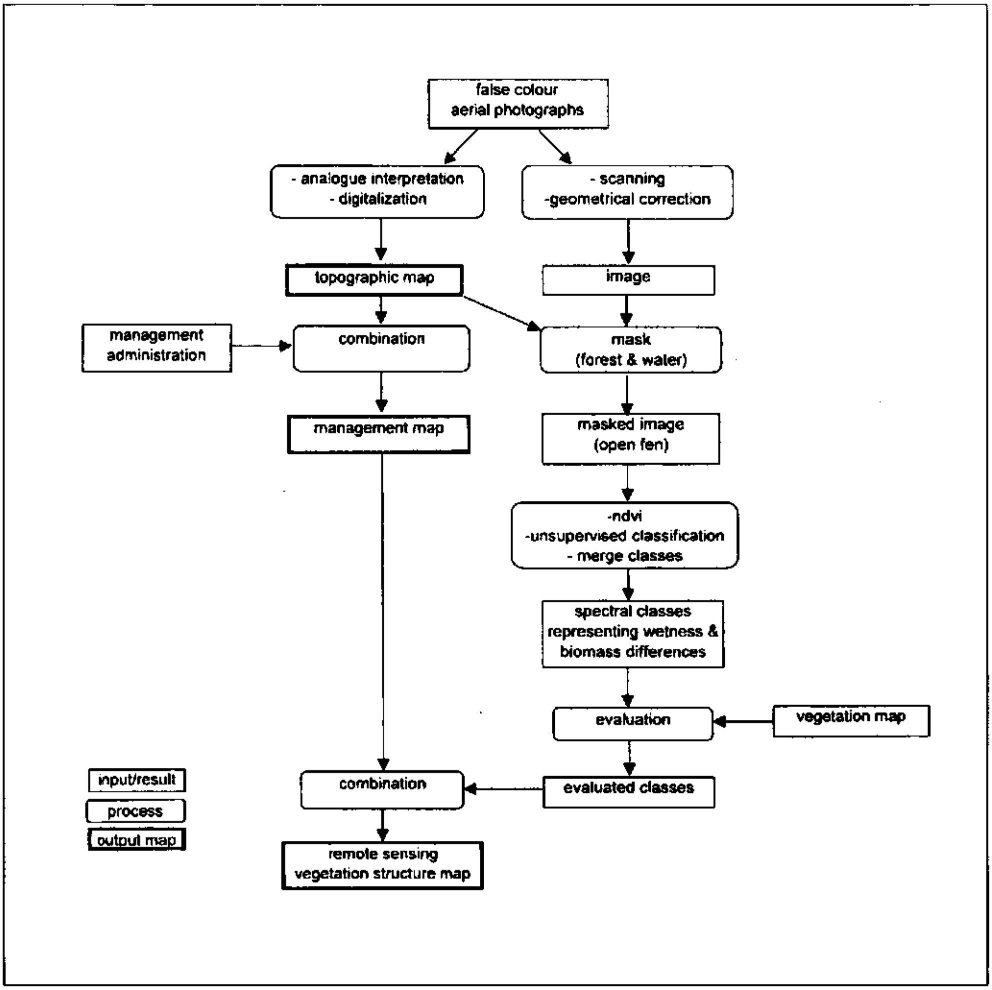

Figure 4.2
Flow-chart to illustrate analogue interpretation, data integration and classification of aerial photographs.

depends on the geometrical resolution required. Scanning results in an image that consists of grid cells called picture elements (pixels). The transmission is stored as an integer value between 0 and 255 called a digital number (DN). These digital numbers can be transformed into reflectance percentages with the help of the light fall-off correction, reference panels (in this study there were none) and a correction with the characteristic curve (Clevers 1988b; Sanders et al. 1992).

The eight diapositives from May 1995 (scale 1:22 500) were all scanned with 500 dpi which resulted in a geometrical resolution of approximately 1 m (section 4.2.1). One diapositive of June 1986 was scanned with 300 dpi and resampled to a resolution of also 1 m. After the diapositives had been scanned the measured transmission was linearly converted to digital numbers and stored. The statistics of the images can be found in Appendix 1.

Geometrical correction

The images had to be combined with each other and with other data, which made an accurate geometrical correction essential. Given the flatness of the terrain, relief displacement of trees on the photographs was considered negligible, and thus correction for relief displacement was deemed unnecessary. The image coordinates (pixel row and column numbers) were transformed to the Dutch national reference coordinate system. The 'block adjustment' application made it unnecessary to collect many ground control points on every image, because neighbouring images can be linked by transfer points. These are points that can be recognized in the overlap area of several images. The images formed a block that was linked with a couple of ground control points to the national coordinate system. A programme called SOFTPLOTTER was used to correct the eight digital FC images of May 1995 geometrically. The accuracy of the correction was 2-3 m in XY directions (Sanders et al. 1997). The middle part of the images was used to make an image mosaic of the entire area. The resulting image mosaic had a geometrical resolution of 1 m.

The accuracy of the correction influences the results of further analysis. The geometrical distortion between the individual images within the mosaic was very small: less than one pixel (1 m). The absolute accuracy of the 1:10 000 topographic map, used to supply ground control points, varied between 2 and 10 m. So, the geometry of the mosaic could not be more accurate than 2 to 10 m. The FC photo of June 1986 was geometrically corrected to the mosaic with a linear transformation and nearest neighbour resampling in ERDAS IMAGINE. The geometrical error between the 1986 photo and the mosaic was measured as approximately six pixels.

Radiometric correction

Radiometry literally means 'radiation measurement' (Buiten & Clevers 1993). The radiometric accuracy is the accuracy of radiation measurement. Photographic film, scanners and satellites record the reflected electromagnetic radiation, or reflectance, from objects. When using aerial photographs for digital image processing, the radiometry is influenced by light fall-off, sun angle and the atmosphere. Light fall-off is the decrease in illumination towards the edge of the photograph, caused by the lens. The reflectance of an object, therefore, depends on the angle between incidence and the optical axis of the camera (Buiten & Clevers 1993; Fig. 4.3B). The reflectance of an object also depends on the sun angle; the angle between the sun and the earth's surface. The sun angle differs per season and time of the day. When the sun is low, there is much shadow. These shadow parts contain no information. When the sun angle is kept as large as possible, the shadowed area is minimal. Furthermore, the sun angle creates a 'hot spot' on the photo, which is presented as an asymmetrical deviation in the radiometry (Fig. 4.3C). The atmosphere is another factor that influences radiometry. The atmosphere is not homogeneous, but variable in space and time. Radiometric distortion due to atmospheric differences was assumed to be negligible within and between photographs because of the relative smallness of the study area (3600 ha - 8 photographs) and the relatively shortness of the recording time.

The FC photos of May 1995 have much radiometric distortion: the radiation decreases towards the edge of the image. It is necessary to correct this for digital image processing. As there were no standard methods for radiometric correction of aerial photographs, three methods were tried:

1. Light fall-off (Fig. 4.3B) was corrected by calculating a 1/cos4a function (Clevers 1986) from the centre of the image to the edge. Unfortunately, the resulting images were not sufficiently corrected. The radiometric distortion in the 1995 images did not change uniformly from the centre to the edges of the image (Fig. 4.3C) because of the large influence of the sun angle mentioned above.

2. Trends in reflectance caused by light fall-off and sun angle were corrected with a FOCALMEAN function. The FOCALMEAN function calculates the mean value of a pixel in a large area (for example, 3600 contiguous pixels). The result is an image with the main trend in reflectance (Fig. 4.3D). A radiometrically correct image results from dividing the original image by the main trend. The FOCALMEAN function assumes that objects are not relatively large (cover a large part of the photo) and that differences in reflectance of the objects are regularly distributed over the image. However, in De Weerribben there are parts where water covers a large area and parts where it does not. The function also changes the reflectance of large objects like those water bodies which are characteristic of De Weerribben (Fig. 4.3E). From this it is clear that this function is not suitable for radiometric correction in this study.

3. Another approach was to assume that a certain vegetation type has the same average DN at every location at every image. Differences in reflectance of a single vegetation type caused by radiometric distortion were corrected by fitting a function through the average DN of many training sets selected from one known vegetation type regularly distributed over all images (Droesen 1996). From every training set the mean value was calculated. Through these mean values and their position a second-degree polynomial was fitted:

   $$MDNi = aXi + bYi + cXiYi + dXi^2 + eYi^2 + f \qquad (4\text{-}1)$$

   MDNi is the average pixel value from training set i on spot X,Y. The constants a to f were calculated with the help of many training sets. The radiometry of every pixel j was corrected by multiplying its original digital number (DNOj) by the average value of the entire image (MEAN) for the specific band and divided by the result (MDNi) of equation 4-1:

   $$DNCj = DNOj * MEAN / MDNi \qquad (4\text{-}2)$$

   DNCj is the radiometric corrected pixel value or digital number. This procedure was applied to every spectral band separately.

Although, the vegetation in De Weerribben is very heterogeneous, the class 'dry reeds' seemed to be sufficiently homogeneous and well distributed to apply the

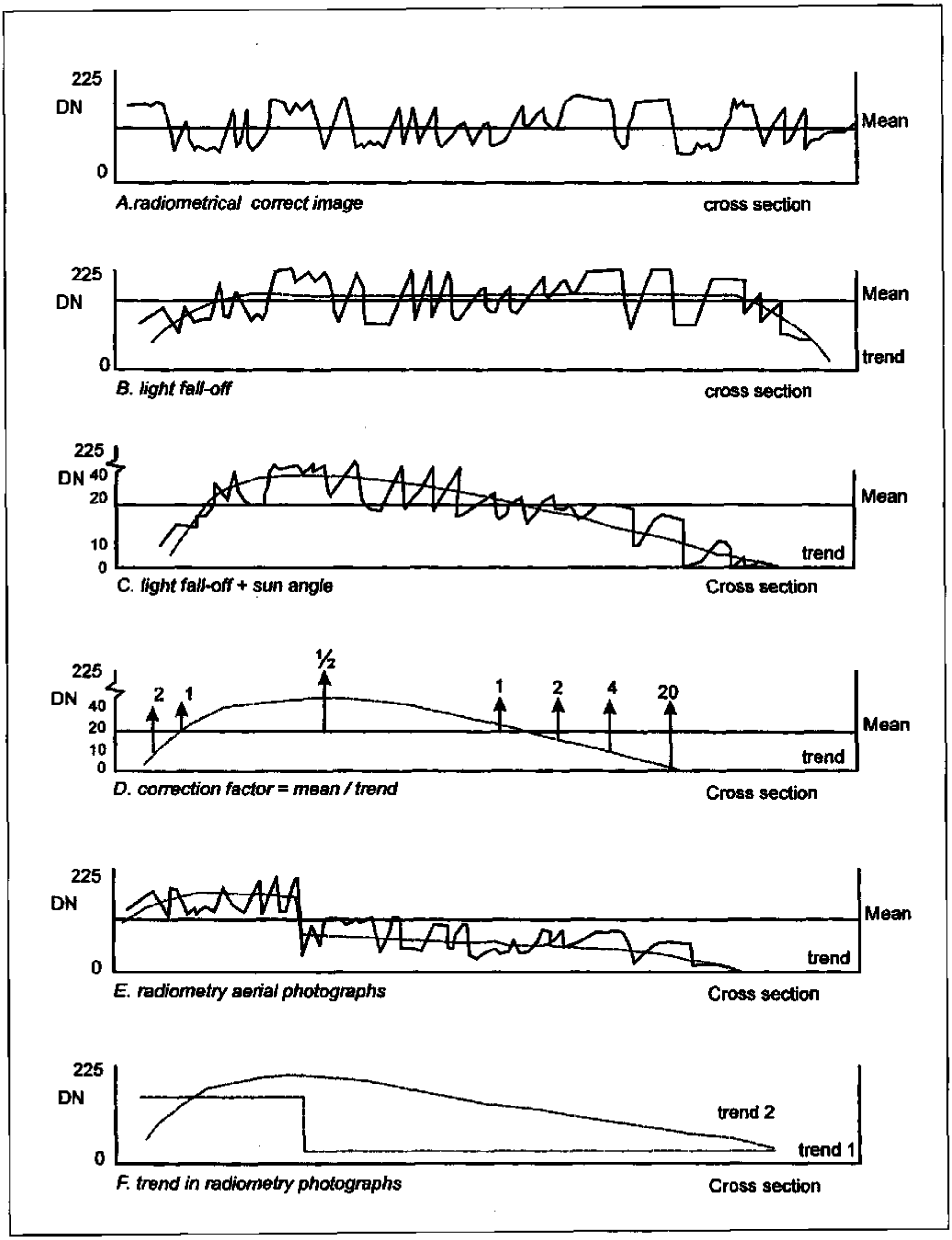

Figure 4.3
Schematic representation to demonstrate variation in pixel radiometry of a cross section (from left to right) on an image. A. an ideal radiometric image; B. the radiometry is influenced by light fall-off; C. the radiometry is influenced by both light fall-off and sun angle; D. correction according to Droesen 1996; E. the radiometry of the available photographs; F. two separate trends in radiometry can be observed in the available photographs, but only trend 2 must be corrected.

above correction method. The fit of regression equation 4-1 was good; 90% of the variation was accounted for. However, the radiometric distortion at the edges of the image did not disappear after correction (Sanders et al. 1997). This suggests that the class 'dry reeds' may not be as homogeneous as expected. But, more important it shows that it cannot be assumed that a vegetation type should have the same DN at every location on the photograph, because so many aspects other than species composition influence reflectance (section 3.3).

In view of the poor results of the above radiometric corrections, it was decided to use only the centre parts of the images, as it can be assumed that the radiometric distortion is negligible here. A histgram match was applied to correct for radiometric differences between the images. Furthermore, the images were classified separately so radiometric differences between them had no influence on the result. This could be done because the spectral differences between the classes of interest were large and were present in all images. Many studies using scanned aerial photographs for digital image analysis neglect the radiometric distortion (Dale & Chandica 1996; Tomer et al. 1997; Duhaime et al. 1997) or apply a histogram match (Gao & O'Leary 1997; Lobo et al. 1998). To compare the absolute reflectance from one image to the reflectance of another image with a different recording time, a calibration should be carried out. For this calibration, ground reference panels with known reflectance must have been placed in the terrain at the time of recording and be recognizable on the photographs (Tomer et al. 1997; Buiten & Clevers 1993). As this was not done, only relative differences in digital numbers within one image could be examined.

4.3.2 Analogue interpretation

Vegetation may be identified on aerial photographs by differences in colour, darkness, pattern, texture, height, context, shape, etc. The judgement of an interpreter is qualitative and therefore difficult to evaluate or to compare with interpretations of others. When sharp boundaries in vegetation can be observed, the interpretation can be considered reasonably reliable. Other ways of analysis, such as digital image processing, can be applied to exclude the subjectivity of drawing boundaries in gradients (section 4.3.3).

In this study, analogue photo interpretation was used to map the topography of the terrain. The available topographic maps made by the Topografische Dienst did not contain sufficient information: the peat baulks so important topographically in De Weerribben as borders of the floating rafts and hydrological barriers, were missing. Therefore a new topographic map (Fig. 4.4) was made by interpreting analogue 1:5000 prints of the FC diapositives of May 1995. The first step was to digitize the main watercourses from a 1: 10 000 map (Topografische Dienst) to make a geometrical basis for photo interpretation. The watercourses were plotted on a transparent sheet, which was laid over the photo prints. Woodland, water and peat baulks were interpreted and drawn on the transparent sheet. Woodland was easily recognized thanks to its texture of the bright and shaded sides. In De Weerribben, woodland has relatively sharp boundaries because of the vegetation management regime (trees grow only in vegetation that is not mown). The minimal mapping unit of 0.25 cm^2 was applied (i.e. approximately 625 m^2 for a 1:5000 photo). Although peat baulks have a slightly different reflectance from the surrounding vegetation on

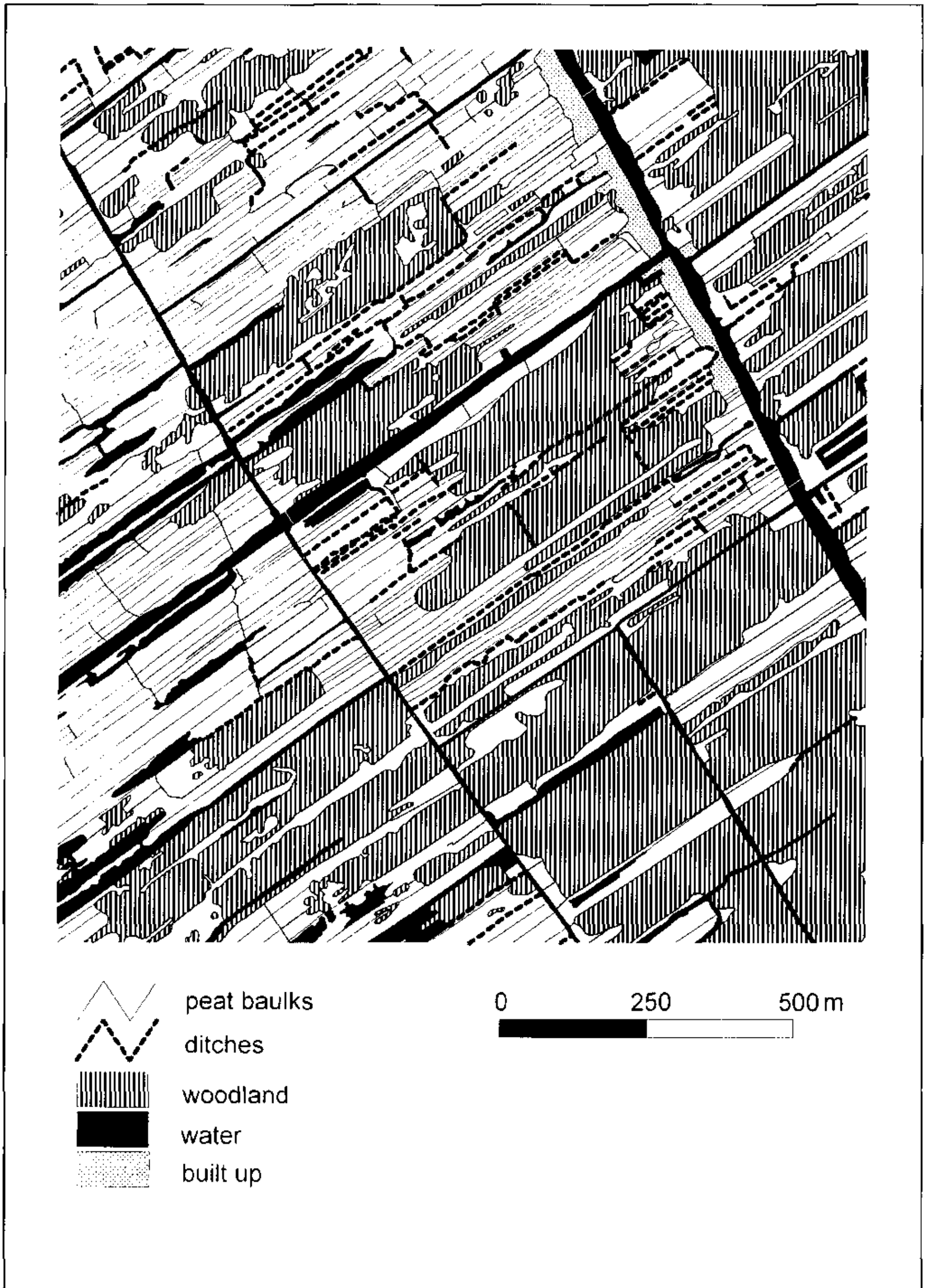

Figure 4.4
Topographic map resulting from analogue photo interpretation for a part of De Weerribben.

the floating raft and are long linear features, it was sometimes very difficult to properly interpret the peat baulk pattern. Baulks situated within woodland, bordering a watercourse, or with gaps, could not be recognized on the photographs. The surface water network was relatively easy to interpret thanks to its low reflectance (black on the photographs), the absence of interference from vegetation, and sharp boundaries. In the beginning of May the vegetation was not developed and aquatic plants were not yet floating. The width of the flow channel could be obtained from remote sensing but most ditches were too small for their width to be mapped, so they were represented as line features on the map. Furthermore, farmed meadows and built-up areas within the reserve were mapped.

4.3.3 Digital processing

The photomosaic of May 1995, covering the entire area, and one photograph from June 1986 were used for the digital image processing. Processing of the May images resulted in spectral classes representing wetness differences; the June image yielded spectral classes representing biomass differences. Before classification the images were masked so that only 'open fen' would be processed; a vegetation index was applied to the June image, to emphasize biomass differences. The images (e.g. scanned photographs) were processed in ERDAS IMAGINE.

Masking

Data from a different source can be used to improve the result of a classification by increasing the accuracy (Janssen et al. 1990). There are several ways of combining these data (Hutchinson 1982). One method is to stratify the image before classification. This method is employed to make more homogeneous units or to separate different objects that are spectrally similar (Sanders et al. 1997). Stratification should be done with maps containing objects that have sharp boundaries by nature. In this study, the classes 'woodland' and 'water' from the topographic map were used for stratifying the landscape ecologically to minimize the overlap in spectral characteristics of the classes (section 3.3) For example, the spectral characteristics of shadow of trees, open water and the 'wet' class overlap. The pixel values of the image lying within the woodland and water strata were excluded for further processing (masked) by making their values zero.

Normalized Difference Vegetation Index

High reflection in near infrared is related to leaf area index (LAI; Clevers 1986). A leaf layer reflects about 50% and transmits 50% of the near infrared radiation. When there are several leaf layers, more near infrared is reflected. Various researchers have explored red and near infrared differences of the reflectance pattern of dead and living vegetation and their relation to LAI, primary production and biomass in vegetation indices (Tucker et al. 1985; Box et al. 1989; Van Kootwijk et al. 1990; Lillesand & Kiefer 1994; Paruelo et al. 1997). These indices are used for the estimation of vegetation parameters (plant cover, biomass etc.). The Normalized Difference Vegetation Index (NDVI, equation 4-3) partly corrects for sun angle and atmospheric influence (Buiten & Clevers 1993). The NDVI has no correction for soil background reflectance. Other indices like the weighted difference vegetation index

(Clevers 1988a) and the perpendicular vegetation index (Richardson & Wiegand 1977) correct for soil background differences. In this study the NDVI was used as it is considered a simple, generally applicable vegetation index and because in fens the influence of bare soil is minimal.

$$NDVI = (Rnir - Rr) / (Rnir + Rr) \qquad (4\text{-}3)$$

Rnir is the reflectance in the near infrared part and Rr is the reflectance in the red part of the electromagnetic spectrum. This formula is used on satellite data. The digital values of the scanned diapositives were transmission values. It could be assumed that measured reflectance is linearly related to the measured transmission (Buiten & Clevers 1993). Thanks to these linear relationships the digital numbers of the images were used to calculate the NDVI. The NDVI was applied to the 1986 June image. The NDVI was very useful because biomass differences were most explicit at this time: vegetated areas generally yielded high values for the NDVI in contrast to wet reed fen and litter fen that yield negative index values (Lillesand & Kiefer 1994).

Classification

The unsupervised classification procedure ISODATA (ERDAS IMAGINE Field Guide 1991) was applied to the masked images. The images of May 1995 only showed differences in wetness and the NDVI image of June only showed differences in biomass (section 4.2.1). In each case, three classes were assumed to be sufficient to explain species distribution (Chapter 3): 'dry', 'intermediate wet', 'wet' for the wetness and 'little biomass', 'intermediate biomass' and 'much biomass'. A problem occurred when extreme pixels influenced the classification. The influence of deviating pixels was minimized by entering more classes than the desired number and merging the classes after classification, on the basis of expert judgement. Two extra classes were sufficient to classify the deviating pixels. They were merged with the other three after classification. The data from the management map were used to subdivide the wetness classes to distinguish between reed fens and fen meadows (Table 3.3).

4.4 Results

Photo interpretation and digital image analysis of the photographs of 1995 combined with management information resulted in a 'remote sensing vegetation structure' (RS-VS) map (Fig. 4.5, page 130; Sanders et al. 1997). The RS-VS map contains the wetness classes resulting from digital image analysis, the woodland, water and agricultural grassland resulting from analogue photo interpretation and the fen meadows and reed fens from the management administration. The identified RS-VS classes, in hectares and in a percentage of the entire area, are in Table 4.1. The analysis of 'biomass' was done from only one photo from 1986 and thus covered only part of the reserve (Fig. 4.6, page 131). To make a comparison between wetness and biomass class areas, wetness was obtained for the same part of the reserve; the combination is presented in Table 4.2. The intermediate classes were added to 'wet' and 'biomass' for the comparison with the level 3 vegetation structure types.

Table 4.1
Area of the image classification concerning wetness, analogue photo interpretation results and management information (RS-VS map).

RS-VS MAP	AREA IN %	AREA IN HECTARES
water	11	357
'wet' reed fens	5	192
'intermediate wet' reed fens	9	293
'dry' reed fens	27	970
'wet' fen meadows	1	23
'intermediate wet' fen meadows	2	65
'dry' fen meadows	3	119
agricultural grassland	12	435
woodland	30	1061
TOTAL	100	3515

Table 4.2
Area percentage of the spectral classes concerning wetness, biomass and combination classes for a small subarea of the reserve (W+ = wet; W- = 'dry', B+ = much biomass, B- = little biomass).

SPECTRAL CLASSES		AREA IN PERCENTAGE
biomass	B +	33
	B -	67
wetness	W+	42
	W -	58
biomass & wetness	B + W+	15
	B + W -	18
	B - W+	27
	B - W -	40

4.5 Evaluation

It was difficult to evaluate the spectral classes of wetness and biomass because there was no contemporaneous ground truth on wetness and biomass. However, the vegetation types mapped in the field contain this information implicitly (section 3.3.4). The vegetation types are based on species composition and structural differences, which are indicative of environmental conditions to a certain extent. The spectral classes could not be directly compared with the vegetation types: first, the vegetation types (level 4, section 3.2) were grouped into vegetation structure types (level 3, Table 3.1) according to their ecological significance (wetness, biomass). There were types indicative of wet conditions, dry conditions, oligotrophic and eutrophic conditions. Finally, for the combination of wetness and biomass the vegetation types were grouped into the following vegetation structure types: wet reed fens, brown moss reed fens, tall forb reed fens, *Sphagnum* reed fens, brown moss fen meadows, *Sphagnum* fen meadows, tall forb vegetation and wet tall forb vegetation (Table 3.1).

It would have cost too much effort to digitize the vegetation map of 1986, and therefore, random points were used to compare the vegetation types with the spectral classes. For each point, the accompanying vegetation type was looked up on the map, digitized and combined with the spectral classes in a GIS. The drawback of this procedure is that vegetation classes covering small areas (resolution 1-100 m^2) were not present on the vegetation map (minimal mapping unit ca. 100 m^2). To improve the comparison, the points in these small class areas were deleted and points were randomly added to several large class areas that did not contain any points.

Table 4.3 contains the number of random points per grouped vegetation structure type and spectral class for the wetness classification of the 1995 photographs. The overall classification accuracy of the remotely sensed wetness classification is 76%. Table 4.4 shows these results for the biomass classification of the 1986 photograph. The overall classification accuracy for biomass is 85%. The combination of the two classification results compared with the vegetation types (level 3) is presented in Table 4.5. The overall classification accuracy of the combination is 66%.

Table 4.3
Contingency table presenting the number of random points comparing the grouped vegetation types with the image classification results concerning wetness classes (W+ = wet, W- = 'dry').

	SPECTRAL CLASSES		
VEGETATION TYPES	W+	W-	ROW TOTAL
wet vegetation	52	7	59
dry vegetation	35	81	116
COLUMN TOTAL	87	88	175

Table 4.4
Contingency table presenting the number of random points comparing the grouped vegetation types with the image classification results concerning biomass (B+ = much biomass, B- = little biomass).

	SPECTRAL CLASSES		
VEGETATION TYPES	B+	B-	ROW TOTAL
N-rich vegetation	68	4	72
N-poor vegetation	22	82	104
COLUMN TOTAL	90	86	176

Table 4.5

Contingency table presenting the number of random points to compare vegetation types (level 3) with the image classification concerning wetness and biomass (B+ = much biomass, B- = little biomass W+ = wet, W- = 'dry') and management information.

	SPECTRAL CLASSES, REED FENS				SPECTRAL CLASSES, FEN MEADOWS				ROW
VEGETATION TYPES	W+B-	W+B+	W-B-	W-B+	W+B-	W+B+	W-B-	W-B+	TOTAL
brown moss reed fens	6								6
wet reed fens	1	18		7					26
Sphagnum reed fens	11	1	21	2					35
tall forb reed fens	4	5	2	15					26
brown moss fen meadows					0				0
wet tall forb vegetation					11	16			27
Sphagnum fen meadows					8	1	22		31
wet tall forb vegetation					1	4	2	17	24
COLUMN TOTAL	22	24	23	24	20	21	24	17	175

There are several possible explanations for misclassified points. Only when the number of misclassified points in Tables 4.3, 4.4 and 4.5 is greater than 5, a possible explanation is given here. Much of the dry vegetation (35 points) but also the *Sphagnum* reeds fens (11 points) and *Sphagnum* fen meadow (8 points) were classified as W+ (wet). A probable explanation is that the farmer started irrigating this vegetation to increase the reed production. The areas covered by brown moss fen meadow were too small to obtain any random points and so the method was not sufficiently accurate and reliable to obtain information on brown moss fen meadow. Many wet reed fens (7 points) were classified as W- (dry). This misclassification may be due to succession. Furthermore, the farmer could have stopped the irrigation or left much litter on the raft after mowing. Much of the N-poor vegetation (22 points) was classified as B+ (much biomass) and wet tall forb vegetation (11 points) as B-

Table 4.6

Accuracy and reliability of the classification results concerning biomass (B+, B-) and wetness (W+, W-) compared to the vegetation structure types.

SPECTRAL CLASSES - VEGETATION TYPE	ACCURACY %	RELIABILITY %
W+ - wet vegetation	88	60
W- - dry vegetation	70	92
B- - N-poor vegetation	94	76
B+ - N-rich vegetation	79	95
W+B- - brown moss reed fens	100	27
W+B+ - wet reed fens	69	75
W-B- - *Sphagnum* reed fens	60	91
W-B+ - tall forb reed fens	58	63
W+B- - brown moss fen meadows	-	0
W+B+ - wet tall forb vegetation	59	76
W-B- - *Sphagnum* fen meadows	71	92
W-B+ - tall forb vegetation	71	100

(little biomass). A plausible explanation is the scale difference between the field map and the remote sensing data.

The accuracy and reliability per vegetation type are given in Table 4.6. A high accuracy means that most of the points from the remote sensing class correspond to the appropriate vegetation type. N-poor vegetation and brown moss reed fens have a high accuracy. However, brown moss reed fens have a low reliability, which means that most points from the remote sensing class belong to another vegetation type. Hence, all brown moss reed fens belong to class W+B- but most W+B- does not belong to brown moss reed fens. As a result, the spectral classes can be used to stratify the area to reduce the search space for mapping brown moss reed fens. Tall forb vegetation has a reliability of 100% which implies that all points classified as W-B+ belong to tall forb vegetation but not all tall forb vegetation was classified as W-B+. As a result, the RS classes can be used to find places where tall forb is certainly present, but it cannot be used to map the vegetation very accurately.

4.6 Discussion

The results from image processing must have ecological significance and they must be indicative of the distribution and cover of vegetation types obtained by field mapping. How far this aim is met, is discussed in this section. Aspects that influence the quality of the results, such as material and methods, are discussed, as well as the results themselves.

4.6.1 Material and methods

Radiometry

The best scanning procedure (scanner type, gamma correction) for digital image processing could not be determined. To minimize the influence of the scanner, the photographs of one period were scanned at the same time, with the same procedure. It is not known how much the scan procedure influences the results, but it is probably minimal by comparison with radiometric distortion caused, for example, by light fall-off. None of the methods for radiometric correction applied appeared to be satisfactory, and no method was available in standard image processing software (ERDAS IMAGINE). Correcting for these radiometric distortions would have involved much more research than warranted, but using only the centre of the images, the distortion was minimized and acceptable for the purpose of this study.

Data integration

When data from different sources are used, they must match geometrically. Every source has its own geometrical inaccuracy and when these files are combined, the error is propagated. When the topographic map made by photo interpretation was laid over the digital photo mosaic, in some places the error was up to 10 m, which is very large given the variation of De Weerribben. However, mostly the error was around 2 m, which is acceptable for this study. This geometrical deviation created errors when the topographic map was used to mask woodland and water of the FC photographs. The borders of *petgaten* may not have been masked and would thus have been classified as wet reed fens instead of water, which is feasible. The geometrical deviance would have been minimal if the interpretation had been done directly on a digital image. However, the available hardware was not powerful enough for this kind of interpretation.

The efficacy of generating random points to compare the spectral classes with the vegetation structure types (level 3) was reduced because there were no small areas on the 1:5000 vegetation map and therefore only large areas could be used. A comparison between the RS-VS classes and a digitized vegetation structure map would have given better results, because the entire area of a spectral class within a vegetation type would have been compared instead of individual points; this would have diminished the influence of small areas.

4.6.2 Results

If the result of comparing the spectral classes on biomass and wetness with the mapped vegetation types reveals that the classification is less accurate or reliable, this does not mean that the vegetation does not agree with spectral classes. Many factors have a large influence, which implies that the situation at the moment of recording may differ significantly from the situation prevailing when the vegetation was mapped. The time gap of ten years, for example, may have greatly influenced the accuracy of the wetness classification. The overall accuracy of biomass is therefore better than the overall accuracy of wetness. Ideally, the recordings would have been for two time periods within the same year. Another potential source of inaccuracy is a change in management within a very short period. A tenant farmer may start irrigating or stop it, mow a vegetation every year or leave parts not mown for a year or more. He may clear the litter more thoroughly, burn the vegetation etc. These management changes make dry vegetation types wet (when a farmer starts to irrigate) or a wet vegetation type dry (when the farmer leaves a lot of litter after mowing). Yet in spite of the influence of such interference, the spectral classes corresponded reasonably well to the vegetation structure types. Several vegetation structure types have a high reliability and a reasonable accuracy. The poor results for brown moss vegetation are attributable to the small area this vegetation covers. The results would have been better if another part of the reserve with more brown moss vegetation had been studied. Summing up, therefore, it can be concluded that the spectral classes contain ecological information on wetness and biomass and can be used to explain species distribution.

5 GIS and indicative plant species

5.1 Introduction

In this chapter a spatial model for measuring hydrological isolation and statistical models to predict the occurrence of rare plant species will be formulated. The hypothesis tested is that the occurrence of these species depends on hydrological isolation and management. Given that hydrological isolation is an indicator of base status and nutrient status and the surface water is the main carrier of bases and nutrients, the amount of bases the vegetation will receive depends on its isolation from the surface water (Chapter 3). As the wetland is dissected by watercourses, De Weerribben is a complex of hydrological gradients. The species composition is further influenced by irrigation, vegetation management and history.

The present chapter describes how GIS and statistical methods were used to develop a spatial model of hydrological isolation, to develop a statistical model that describes the relationship between the occurrence of rare species and site factors and to apply the latter model to the entire study area to map the probable occurrence of the species.

5.2 Indicative plant species

Indicative plant species are assumed to indicate that certain conditions are present at a given site and hence, from their appearance or disappearance the processes that take place at that site can be inferred. The environmental conditions of interest in this study are nutrient status and base status. However, plant species indicative of a eutrophic environment were not shown on point distribution maps. Therefore, it was decided to choose two species indicative of base status. Both the species had to be indicative of oligotrophic conditions and of extreme base conditions (basic and acidic). *Scorpidium scorpioides* (Hedw.) Limpr. and *Erica tetralix* L. were chosen because they occur over the entire area, are indicative of similar environmental conditions except for base status, were mapped in 1986 and were not very rare in De Weerribben itself.

Scorpidium scorpioides (Fig. 5.1) is a relatively rare moss (Margadant & During 1982). Its leaves are oriented to one side, which makes the top of the stem curved like the tail of a scorpion. The colour is dark brown and the top is brown-green. *Scorpidium* is characteristic of a rare vegetation type: Caricion davallianae (section 2.6; De Vegetatie van Nederland 1995-1999). The annual input of base-rich surface water is considered a key factor determining the presence of *Scorpidium* (Van Wirdum 1991). *Scorpidium* appears to occur most frequently in a zone near the open water, but not in the immediate reach of the eutrophic water in the large canals (Van Wirdum 1991). In general the species is characteristic of base-rich circumstances and an early stage of terrestrialization. *Scorpidium* is almost absent in the central parts of De Weerribben, which used to be *Sphagnum* peat without clay deposits before the peat was excavated. Most of this area is at an advanced stage of terrestrialization (section 2.6) and has no regular management.

Figure 5.1
Scorpidium scorpioides (Hedw.) Limpr.

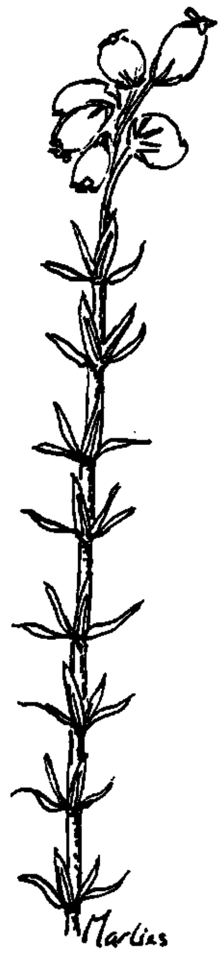

Figure 5.2
Erica tetralix L.

Erica tetralix (Fig. 5.2) is a dwarf shrub, 10 to 60 cm in height with pink flowers and lanceshaped leaves in whorls of four around the stem (Van der Meijden 1996). The plant, which is not as rare as *Scorpidium*, is a characteristic species of Sphagno palustris-Ericetum (section 2.6; De Vegetatie van Nederland 1995-1999). This vegetation is typical of the transition from fen to bog. Hence, it is indicative of base-poor circumstances and an advanced stage of terrestrialization. This vegetation is typically mown in summer.

Ellenberg (1991) provides indicator values for environmental conditions of many vascular species. He defined species preferences with respect to each other and not with respect to actually measured environmental conditions. The most important conditions for the purpose of this study are light, wetness, acidity and nutrient availability. Ellenberg's values are ordinal indicator scales with scores from

1 to 9 giving a species' preference for environmental conditions (1 = dark, dry, acid, oligotrophic; 9 = light, wet, base-rich, eutrophic; for wetness there are three additional values, 10-12, partly - totally submerged). Siebel (1993) expanded Ellenberg's scale for mosses. Van Wirdum (1991) gave environmental indicator values for plant species occurring in De Weerribben. The indicator values for *Scorpidium* and *Erica* are shown in Table 5.1. The table illustrates that the indicator values for light are the same for the two species, wetness and nutrient status differ only a little. The most important factor differentiating the environment of the two species is base status.

Table 5.1
Indicator values of *Erica* and *Scorpidium* according to Ellenberg (1991), Siebel (1993) and Van Wirdum (1991).

SPECIES	AUTHOR	LIGHT	WETNESS	BASE STATUS	NUTRIENT STATUS
Erica	Ellenberg	8	8	1	2
	Van Wirdum			atmotrophic	oligotrophic
Scorpidium	Siebel	8	10	8	1
	Van Wirdum			lithotrophic	oligotrophic

Field workers made point distribution maps of *Scorpidium* (Fig. 5.3) and *Erica* (Fig. 5.4) for the management plan in 1986 by mapping vegetation in the field. The scale of these maps, 1:25 000, is very coarse in comparison to a site resolution of 25 m^2 used in this present study and the scale of the other maps (1:5000, 1:10 000) available in the management plan and thus implies a large inaccuracy. However, the species distribution points correspond with a vegetation type (*Scorpidium* reed fens/ *Scorpidium* fen meadows and *Erica-Oxycoccus* vegetation, Table 3.2) on the 1:5000 vegetation map of the management plan made at the same time. The digitized points had to be moved slightly sometimes, due to scale-related inaccuracy, to put them on the same site as the corresponding vegetation type.

5.3 Spatial environmental data (site factors)

The site factors in this study are all spatial environmental data available in a GIS that may determine plant species occurrence. Some of the site factors were obtained by remote sensing techniques, some were available on maps and some were constructed by GIS procedures. All site factors maps (vector, pixels) and the species distribution maps were transformed into grid maps to simplify digital data integration (as a result, spurious polygons, for example, were avoided). Grid cells, representing a site, were made 25 m^2 because peat baulks (boundary elements) were up to 5 m wide, five is a round number easy to calculate with, the resolution was able to cover geographical variation within the raft (30 m wide) and the amount of data could still be handled by a GIS. The geometry and thematic aspects of the site factors used are described in this section.

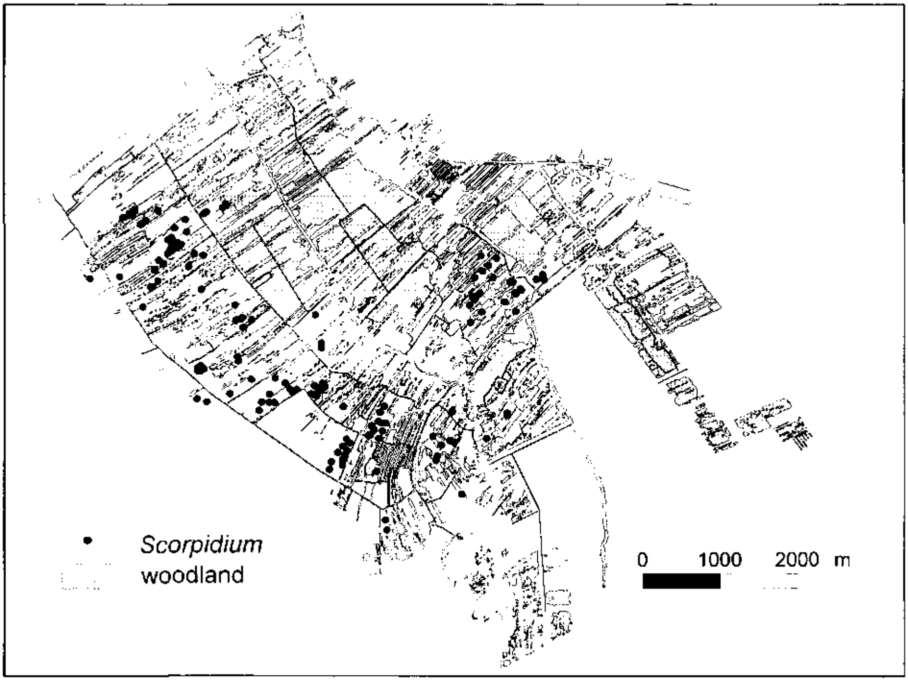

Figure 5.3
Point distribution map of *Scorpidium* (management plan 1986).

Figure 5.4
Point distribution map of *Erica* (management plan 1986).

5.3.1 Site factors obtained by remote sensing techniques

The vegetation characteristics obtained by remote sensing techniques were used as site factors because they contain information on biomass and wetness. These site factors resulted from digital image processing.

Site factor 1: wetness
As explained in Chapter 4, the spectral classes obtained by the digital image processing of the 1995 photos are indicative of wetness expressed in three classes: 'wet' (**wet1**), 'intermediate' (**wet2**) and 'dry' (**wet3**). The area covered by these classes is given in Table 5.3. The wet and intermediate class represent water on a thin floating raft, or irrigation. The dry class represents a moss or litter cover. The images, 1 m^2 pixels, were resampled into 25 m^2 grid cells. The 25 m^2 cells were assigned to the class to which the majority of their constituent pixels belonged.

Site factor 2: biomass
The spectral classes representing differences in biomass were obtained by digitally image processing the 1986 photos. They are indicative of biomass expressed in three classes: little biomass (**bio1**), intermediate biomass (**bio2**) and much biomass (**bio3**). These classes did not cover the entire reserve. Therefore, the influence of biomass differences on species occurrence was ascertained only by simple regression and not by multiple regression. Simple regression was applied only for *Erica*. *Scorpidium* was not used since there were so few distribution points within the area.

5.3.2 Site factors on available maps

Some site factors were available on analogue maps or in the records of the land managers. These data (vector maps) had to be digitized first and then transformed into 25 m^2 grid cells. The site factors available are described below.

Site factor 3: management map
As pointed out in Chapter 2, vegetation management comprised two classes: winter mowing (**manage1**) and summer mowing (**manage2**). The area covered by these classes is shown in Table 5.3.

Site factor 4: raft thickness map
The permeability of the floating raft profile depends upon the thickness and the specific hydraulic resistance of the following layers: the floating raft, the root/water layer and the detritus layer. The raft thickness is roughly indicated on the 1:10 000 soil map (Fig. 5.5, page 122) of 1951 (Haans & Hamming 1962). The thickness classes are:

1. a floating raft stabilized with mud (**raft1**);
2. aquatic plants (open water, **raft2**);
3. detritus less than 75 cm below water level (preterrestrialization, **raft3**);
4. floating raft 5 - 20 cm thick, mostly submerged (thin floating raft, **raft4**);
5. floating raft between 20 and 60 cm thick (medium thick floating raft, **raft5**);
6. floating raft between 50 and 100 cm thick (thick floating raft, **raft6**).

The area these classes cover is given in Table 5.3.

Site factor 5: former soil type

Besides the raft thickness classes, the 1:10 000 soil map of 1951 contains two general boundaries (Fig. 5.6, page 123). One indicates the approximate boundary between the former sedge peat (**peat1**) and the *Sphagnum* peat area (**peat2**). The surface area of these classes is given in Table 5.3. Most of the original peat has been removed by peat excavation. However, the difference between the areas may be roughly indicative of the age of the raft. The *Sphagnum* peat is a better fuel than the sedge peat. Therefore, the *Sphagnum* peat was probably excavated first.

Site factor 6: former clay cover

The other general boundary on the 1:10 000 soil map indicates roughly the area where clay was deposited by sea transgressions (**clay2**) and where it was not (**clay1**). This clay cover may have been dumped into the *petgaten* after excavation or may have been used to make baulks. Clay dumped into the *petgaten* may influence infiltration of water to the underlying aquifer. The surface area these classes cover is given in Table 5.3.

5.3.3 Site factors generated by GIS procedures

GIS procedures used to generate site factors are illustrated in Figure 5.7 and described below. In this study, the procedures mostly used were reclassification, data integration and distance measurement. The procedures were carried out in a GIS programme called Arc/Info (Esri 1994).

Site factor 7: shortest distance from a site to the surface water network

The hydrological source (surface water network) and hydrological barriers (peat baulks) from the 1:5000 topographic map made by aerial photo interpretation were transformed into 25 m^2 grid cells (sites) and combined to calculate the distance between a grid cell and the surface water network (Fig. 5.8, page 124). The availability of surface water, and hence the availability of bases, at a site was assumed to be linearly related to the shortest distance to the network (Van Wirdum 1991). The peat baulks were assumed to be impermeable and therefore the distance measurement could not cross a peat baulk. Statistical information on the measured distances is given in Table 5.2.

Site factor 8: hinterland

The grid map of the peat baulks and surface water network (topographic map) was used to calculate the hinterland area (section 3.1.1). The 'sources' to which the distance was calculated were 'breakpoint' grid cells in the distance values to the surface water network (site factor 6), i.e. the cells where the distance to the surface water network reached a local maximum. Therefore, all cells neighbouring these breakpoint cells are closer to the surface water network (have a lower value). These breakpoint grid cells are most remote from the surface water: they have no hinterland themselves. The breakpoints were identified by a 'conditional focal' function (Fig. 5.10): if the distance values of all eight neighbours of a cell were lower than the value of the cell itself, then the programme returns '1' (breakpoint) else it returns '0' to the breakpoint map. The distance from a grid cell to the nearest

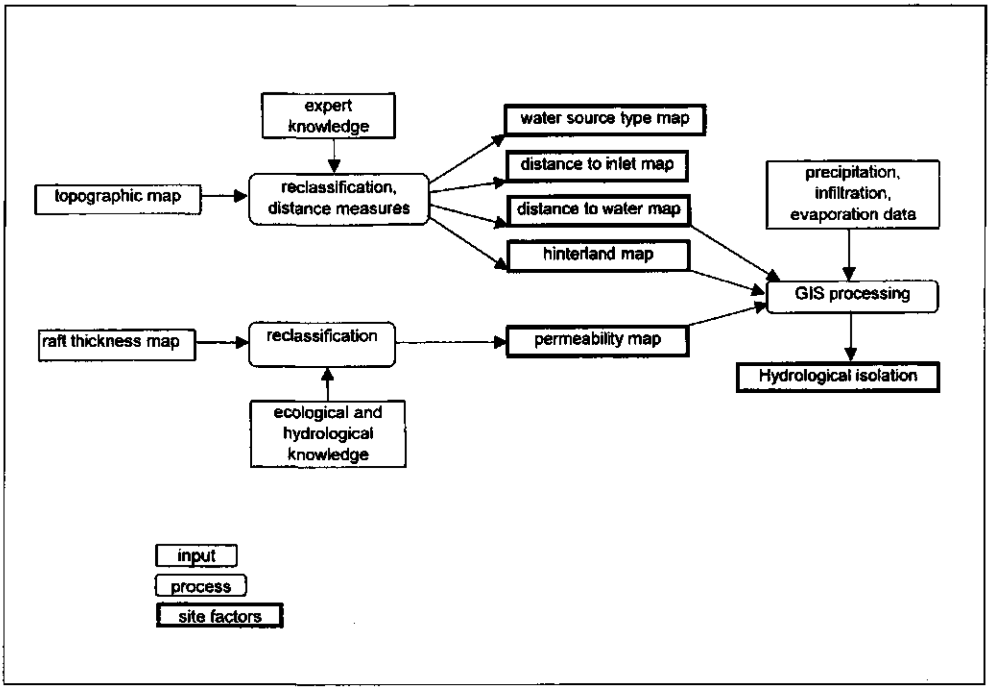

Figure 5.7
Flow-chart illustrating GIS procedures to generate site factors.

breakpoint cell was calculated to determine the hinterland (Fig. 5.9, page 125). Statistics of the measured distances from the cells to their remote hinterland (breakpoint cells) are given in Table 5.2. The shape of a floating raft is rectangular which implies that the hinterland area is the distance from a grid cell to the breakpoint cell multiplied by the cell width.

Site factor 9: shortest distance from a site within the surface water network to the water inlet

Van Wirdum (1991) found that base status and nutrient status change when water is distributed within the network. The water supply to a given grid cell depends primarily on water distribution from the inlet through the surface water network and then the distribution from the surface water to a grid cell on the floating raft. The water distribution within the floating raft was dealt with above (site factor 6). A distance measure was used to determine the distance from a grid cell within the surface water network to the main water inlet point (Fig. 5.11, page 126). Statistics of the distance from a grid cell within the surface water network to the inlet point are given in Table 5.2. All grid cells on the floating raft were allocated to the distance value of a grid cell within the surface water network (distance to the water inlet), i.e. the value with the shortest distance to the grid cell.

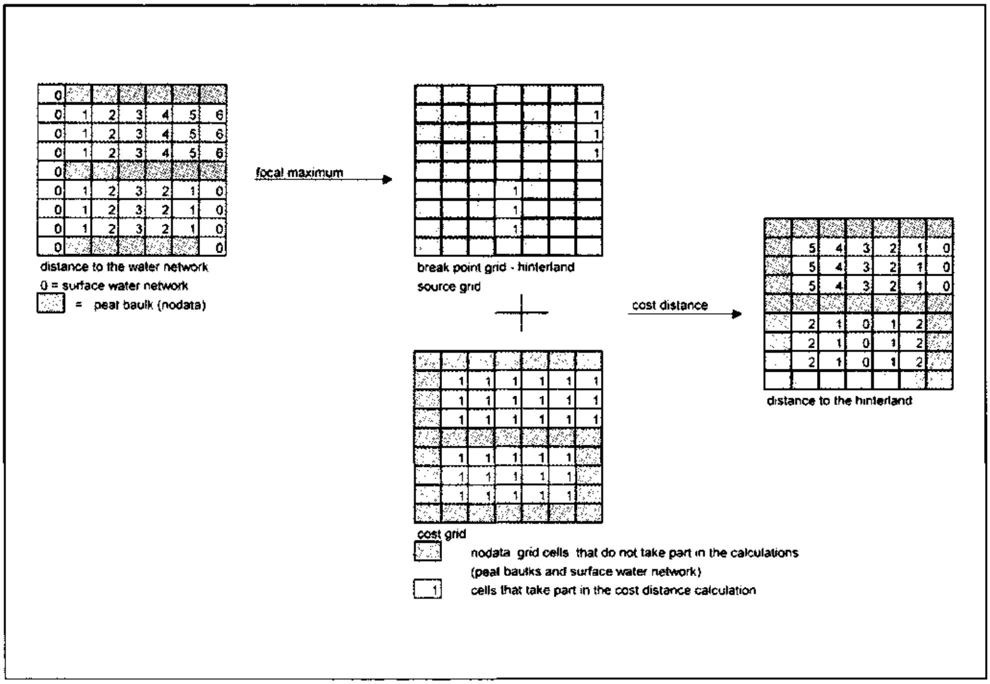

Figure 5.10
Schematic representation to demonstrate distance measurement (Fig. 3.5) from a grid cell to the hinterland (breakpoints).

Site factor 10: water source type

The surface water network (topographic map) was reclassified into different water source types. The water, and hence base, supply depends on the watercourse type. As the ditches are narrower and shallower than the main canals, less water flows through them. Four water source types within the surface water network could be distinguished on the map:

1. the main canals (Kalenbergergracht, 20 m wide, **course1**);
2. the main watercourses (ca. 5-20 m, **course2**);
3. *petgaten* (ca. 10-50 m wide, **course3**) ;
4. ditches (up to 5 m wide, **course4**).

These classes differ in flow velocity, depth, width, aquatic plants etc. determining water supply. They were identified on the topographic map and reclassified into the four categories mentioned above. The ditches were easy to distinguish because in contrast to the other watercourse types they are linear features on the topographic map. The main canals and watercourses were digitized from a map of the Topografische Dienst used for interpreting the photographs. The (two) main canals were separated from the main watercourses manually. All watercourses that remained unidentified after these procedures were reclassified as *petgaten*. Each grid cell (site on the floating raft) was allocated to a certain watercourse type, which supplies its surface water (Fig. 5.12, page 127); this was the course nearest to it. The area influenced by the watercourses can be found in Table 5.3.

Site factor 11: hydrological isolation

As noted in Chapter 3, the water level difference compared to the surface water network was assumed to be a measure of the hydrological isolation (Hi). When the water level is within reach of plant roots, there is a supply of bases. To obtain the hydrological isolation per grid cell (equation 5-1), equations 3-5 and 3-6 were combined.

$$Hi_y = \sum_{x \varepsilon Ry} c * H_x / k_x \qquad (5\text{-}1)$$

Hi_y = the hydrological isolation of grid cell y
c = constant (per day), $c = (E + D - P) * dL / A$
H_x = hinterland area of grid cell x (m^2)
k_x = permeability of grid cell x (m per day)
Ry = the set of grid cells (x) that connect grid cell y with the nearest water source (the set Ry includes grid cell y).

The surface water network (the hydrological source) and peat baulks (the hydrological barriers) derived from remote sensing as explained in Chapter 4 were used to calculate the shortest route from the surface water network and the hinterland area (H). The permeability (k) of the floating raft is proportional to raft thickness, so therefore, the thickness of the floating raft was reclassified into permeability values. Several earlier studies in the area resulted in values for permeability of the floating raft. Vegt (1978b) studied the permeability of the different layers illustrating the very low permeability of the peat baulks:

raft	> 75 m/day
roots/water	> 409 m/day
detritus	1.8 +/- 0.9 m/day
peat baulk (clay)	1.7 +/- 1.1 m/day
peat baulk (peat)	0.7 +/- 0.4 m/day

Van der Perk and Smit (1975) had the following results for the nearby and comparable Wieden:

very thin floating raft	1500	m/day
thin floating raft	178	m/day
thick floating raft	44	m/day
peat baulks	5.5	m/day

The floating raft thickness classes were reclassified taking the permeability classes of Van der Perk & Smit (1975) into account. The medium thick floating raft (not distinguished by them) was assigned to a permeability class, in between the thick and thin floating rafts. The following permeability values were assigned to the raft thickness classes:

1. open water	1500	m/day
2. starting terrestrialization	1500	m/day
3. thin floating raft	180	m/day
4. medium thick floating raft	110	m/day
5. thick floating raft	40	m/day
6. stabilized raft	40	m/day
7. peat baulks	0	m/day

The constant (c) was derived by using average values for precipitation (P), evapotranspiration (E) and infiltration (D) for the entire reserve because no data were available on spatial variation. Evapotranspiration is proportional to vegetation structure (biomass differences) and wetness and can be determined by remote sensing (as shown in Chapter 4). However, information on biomass was only available for a small part of the reserve and therefore could not be used to model Hi for the entire reserve. P (2 mm/day) and E (4 mm/day) were obtained from nearby weather stations. A very dry growing season (1994) was chosen because in this situation the Hi values, the difference between the water level at a site and the level of the surface water, should be maximal in this situation. An average D of 1 mm/day was obtained from Hoogendoorn & Vernes (1994). The grid cell was the basis for determining the cross section (A) and the length (dL) of the flow channel. A is the grid cell width (5 m) multiplied by the depth to the sandy subsoil (ca. 2.5 m).

The values mentioned above were used to program a measure of hydrological isolation (equation 5-1) in GIS. The result is a Hi value per grid cell. Statistics of the Hi values are given in Table 5.2.

Statistical summary

Table 5.2 shows some general statistics of the quantitative site factors and Table 5.3 (page 80) shows the area of the nominal site factor classes. The total area of the nominal site factor classes depends on the extent of the available data. The means and standard deviations of the quantitative site factors were calculated from the values of all grid cells in the reserve. These statistics show the possible values of the grid cells.

Table 5.2

General statistics of the quantitative site factors in De Weerribben.

QUANTITATIVE SITE FACTORS	MEAN (M)	STANDARD DEVIATION (M)
water	18.1	46.8
hinterland	14.7	48.6
inlet	1898	2943
Hi	0.168	0.802

Figure 5.13
Hydrological isolation ranging from 0 (black) up to 0.97 m (white).

5.4 Statistics

The regression analysis used in this study focused on how *Scorpidium scorpioides* and *Erica tetralix* occurrence are related to the site factors. The procedure is illustrated in Figure 5.14. It is based on observations on species and environmental variables in a series of sites (grid cells). Species were only recorded as present; absent recordings were created by random point generation. For each point indicating the presence of *Erica*, *Scorpidium* or random absence points, the site factors were added in the GIS and used as input for a logit multiple regression. The regression resulted in a probability model. The statistical techniques were described in section 3.4.

Table 5.3
Area of the nominal site factor classes in De Weerribben.

NOMINAL SITE FACTOR CLASSES	AREA IN HA	TOTAL AREA IN HA
wet1	169	
wet2	288	
wet3	1155	1612
manage1	1411	
manage2	200	1611
raft1	176	
raft2	113	
raft3	293	
raft4	218	
raft5	1041	
raft6	368	2209
peat1	1461	
peat2	2016	3477
clay1	2087	
clay2	1390	3477
course1	167	
course2	478	
course3	1473	
course4	1015	3133
bio1	98	
bio2	37	
bio3	14	149

5.4.1 Random points

To determine whether *Scorpidium* and *Erica* distribution was random or depended on site factor distribution, it was necessary to add points at which the species is absent (section 3.4). The random points, representing absences, were located in the 'open fen' areas because it was known the species would not be present in woodland areas (Fig. 5.15, page 128). For reasons explained in Chapter 3 a circular buffer with a cross section of 30 m (which is the average raft width) was laid around the species distribution points and all random points within this buffer were eliminated. As the number of random points generated must be very large (section 3.4), 10 000 random points were taken (approximately 1% of the open fen area).

5.4.2 Site factors

The following site factors were used as terms in the regression analysis. The first class of each nominal site factor was taken as a reference class and is, therefore, not needed in the regression analysis (Jongman et al. 1987).

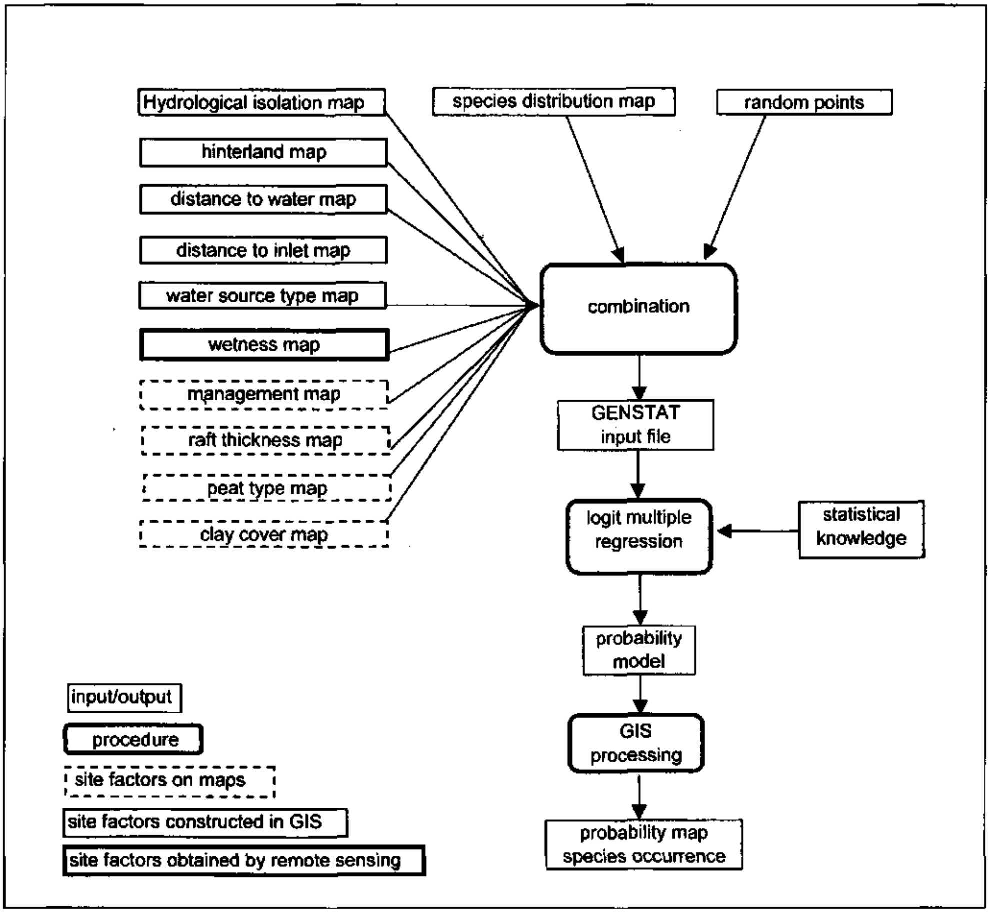

Figure 5.14
Flow-chart to illustrate GIS and statistical procedures to generate a probability map of species occurrence.

1. wetness classes (nominal, 3 classes) [wet]
2. biomass (nominal, 3 classes) [bio]
3. management regime (nominal, 2 classes) [manage]
4. raft thickness classes (nominal, 6 classes) [raft]
5. former peat moss or sedge moss area (nominal, 2 classes) [peat]
6. former clay cover (nominal, 2 classes) [clay]
7. distance from a site to the surface water network (numeric) [water]
8. distance from a site to the hinterland (numeric) [hinter]
9. distance from a site to the water inlet (numeric) [inlet]
10. watercourse type (nominal, 4 classes) [course]
11. hydrological isolation (numeric) [Hi]

The numeric variables were transformed to their logarithms because of their skewed distribution.

5.4.3 Logit multiple regression

The technique used in this study is logit regression. The following regression equation was used:

$$\ln(p/(1-p)) = a + \Sigma_{i=1..n1}\, b_i\, wet_i + \Sigma_{i=1..n2}\, c_i\, manage_i + \Sigma_{i=1..n3}\, d_i\, raft_i + \Sigma_{i=1..n4}\, e_i\, peat_i + \Sigma_{i=1..n5}\, f_i\, clay_i + \Sigma_{i=1..n6}\, g_i\, course_i + h\, inlet + j\, water + k\, hinter + m\, Hi \qquad (5\text{-}2)$$

p is the probability of occurrence ($0 < p < 1$), n1 .. n6 are the number of classes per site factor (variable) and the parameters b through m are regression coefficients that represent the influence of site factor classes.

The factor 'bio' was not used in equation 5-2 because it was only obtained in a small area of De Weerribben and thus only simple regression could be applied (section 5.3.1). The logit regression was executed in GENSTAT (Genstat 5 Committee 1987) with marginal and conditional tests. The marginal test is based on a simple regression, which takes account of only one site factor at a time. This test indicates which factors may determine the species occurrence. The marginal test was used only to investigate which variables were likely to be useful in subsequent multiple regression. The conditional tests were carried out by stepwise regression. Stepwise regression selects a term to include or exclude from a generalized linear model according to the ratio of residual mean squares of models with and without these terms (the variance ratio). Hence, the procedure tries to drop or add a term one at a time and permanently modifies the current model according to the change that was most successful. When the variance ratio is smaller than the 'outratio', the term is dropped and when it is bigger than the 'inratio' the term is added. The value taken for the inratio and outratio was seven: the variance ratio F with unlimited degrees of freedom in the denominator and 1 in numerator for which $p \approx 0.008$. As a result, the procedure was stopped if no variable improved the model significantly at the 0.8% level.

5.5 Results

5.5.1 Regression analyses

The results of the marginal tests are given in Table 5.4. The probability of occurrence of all nominal factors in each of the classes can be found in Table 5.5. These probabilities, based on regressions on one site factor at a time, have relative values because they are proportional to the number of random points taken. For example, the probabilities cannot be used to conclude that the probable occurrence of *Erica* on a thick floating raft is 61% but it can be used to conclude that *Erica* occurs significantly more often when the floating raft is thick (raft6) than in the other thickness classes.

The relationships between the occurrence of *Scorpidium* and *Erica* and the site factors are expressed quantitatively in equations 5-2 and 5-3. These equations are the results of the stepwise multiple regression. The model only contains site factors that contribute significantly to predicting the occurrence of the species. The

Table 5.4
Statistical significance of site factors predicting the species occurrence obtained with marginal tests (* = 0.01<p<=0.05; ** = 0.001<p<=0.01; *** = p<=0.001; Ns = p > 0.05; - = not tested).

SITE FACTOR	*ERICA*	*SCORPIDIUM*
water	**	Ns
hinter	Ns	Ns
inlet	***	***
course	**	**
wet	***	***
manage	***	Ns
raft	***	***
clay	***	Ns
peat	***	Ns
Hi	***	***
bio	*	-

Table 5.5
Relative probability (p) and standard error per site factor class of *Erica* and *Scorpidium* occurrence to determine statistically significant differences between the classes.

	ERICA		*SCORPIDIUM*	
	PROBABILITY	STANDARD ERROR	PROBABILITY	STANDARD ERROR
raft1	0.14	0.04	0.00	0.00
raft2	0.04	0.04	0.11	0.06
raft3	0.03	0.02	0.30	0.05
raft4	0.09	0.03	0.24	0.04
raft5	0.25	0.02	0.13	0.02
raft6	0.61	0.08	0.00	0.00
wet1	0.08	0.02	0.25	0.04
wet2	0.22	0.03	0.25	0.04
wet3	0.21	0.02	0.08	0.01
manage1	0.11	0.01	0.13	0.01
manage2	0.71	0.07	0.11	0.03
clay1	0.34	0.03	0.11	0.01
clay2	0.06	0.01	0.14	0.02
peat1	0.05	0.01	0.11	0.02
peat2	0.24	0.02	0.13	0.01
course1	0.22	0.08	0.03	0.03
course2	0.22	0.04	0.09	0.02
course3	0.26	0.02	0.15	0.02
course4	0.14	0.02	0.18	0.02
bio1	0.67	0.10	-	-
bio2	0.30	0.10	-	-
bio3	0.14	0.13	-	-

classes are explained in section 5.3. The probability value of a grid cell was calculated by totalling the values in the formula below. The value of the nominal site factor classes taken depends of the site factor class of that specific grid cell. If, for example, the site factor class of that grid cell was raft3, then 0.536 was added and the values of the other raft classes were excluded.

***Erica* model**

$$\ln(p/(1-p)) = -0.77 + \begin{matrix} 0.000\ \text{manage1} \\ 1.522\ \text{manage2} \end{matrix} + \begin{matrix} 0.000\ \text{raft1} \\ 0.700\ \text{raft2} \\ 0.536\ \text{raft3} \\ 1.327\ \text{raft4} \\ 1.943\ \text{raft5} \\ 2.006\ \text{raft6} \end{matrix} \begin{matrix} 0.000\ \text{clay1} \\ -1.234\ \text{clay2} \end{matrix} - 0.699 * \text{inlet} - 0.323 * \text{water} \qquad (5\text{-}2)$$

***Scorpidium* model**

$$\ln(p(1-p)) = -17.31 + \begin{matrix} 0.00\ \text{raft1} \\ 6.41\ \text{raft2} \\ 7.79\ \text{raft3} \\ 7.98\ \text{raft4} \\ 7.25\ \text{raft5} \\ 0.23\ \text{raft6} \end{matrix} + \begin{matrix} 0.000\ \text{wet1} \\ 0.297\ \text{wet2} \\ -1.028\ \text{wet3} \end{matrix} + 0.765 * \text{inlet} \qquad (5\text{-}3)$$

Several more site factors seemed to influence the occurrence of *Scorpidium* and *Erica* significantly when simple regression was applied (Table 5.4). However, they had no significant influence when other site factors were taken into account in multiple regression. This was also the case with the hydrological isolation. Hi did not significantly ($P > 0.01$) improve the fit of the regression model if the variables mentioned in equations 5-2 and 5-3 were taken into account. However, when Hi was the only explanatory variable, the factor turned out to be very significant in predicting species occurrence (Table 5.4). To test if Hi really did not have a surplus value compared to the site factors that are the components of Hi (raft thickness, distance to the surface water network, hinterland area), multiple logit regression was applied for these site factors only. Hi significantly improved the model predicting *Erica* occurrence (change in residual mean deviance was -17) but the model predicting *Scorpidium* occurrence was not significantly improved (change in residual mean deviance was -2). From this it was concluded that Hi has a surplus value compared to its component site factors for predicting *Erica* occurrence.

5.5.2 Probability maps

To evaluate the results the probability surface of species occurrence was depicted spatially. Equations 5-4 and 5-5 were programmed in GIS and resulted in a value of ln(p/(1-p)) per grid cell. Figures 5.16 and 5.17 show the frequency distribution of these values. The values were reclassified into eight probability classes emphasizing the differences in high and low probability of species occurrence. The intervals of the probability classes were equally sized, so that the classes could be compared. The probability maps are presented in Figures 5.18 (pages 132 and 133) and 5.19 (pages 134 and 135).

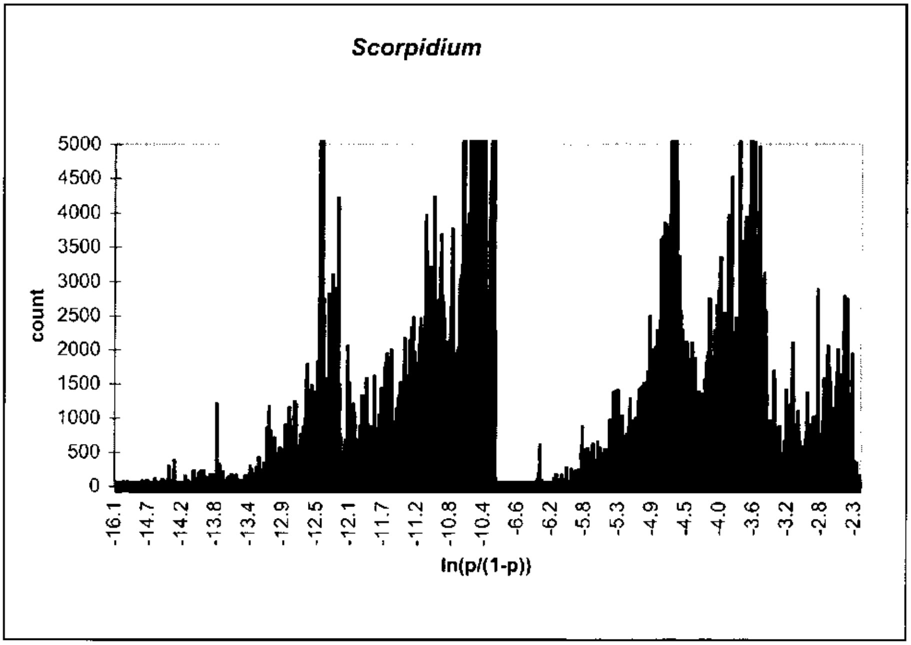

Figure 5.16
Frequency distribution of the probability values (ln(p/1-p)) for *Scorpidium*.

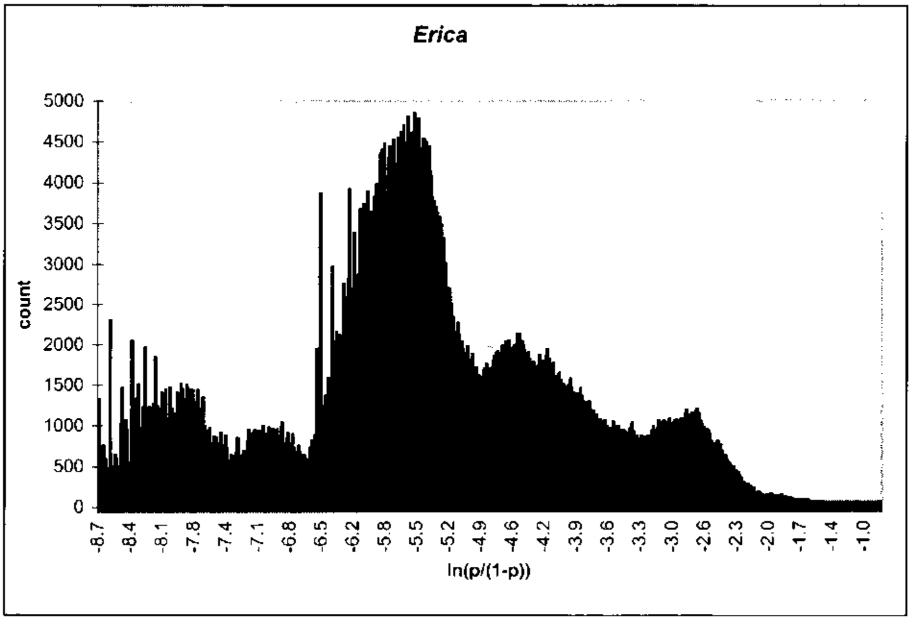

Figure 5.17
Frequency distribution of the probability values (ln(p/1-p)) for *Erica*.

The frequency distributions of *Scorpidium* and *Erica* show that *Erica* has a higher maximum probable occurrence in De Weerribben than *Scorpidium*. Furthermore, *Scorpidium* has a much lower minimum probability than *Erica*. These two aspects imply that a larger part of De Weerribben is a better habitat for *Erica* than for *Scorpidium*. The legend of the maps and the quantitative information they contain is presented in Table 5.6. There is a clear difference in sites of high and low probable occurrence of *Scorpidium*, whereas the sites at which *Erica* may occur change more gradually in probability.

Table 5.6
Legend of the probability maps.

CLASS NUMBER	LN(P/(1-P)) PROBABILITY CLASSES	MAP COLOUR	*SCORPIDIUM* AREA IN HA FIGURE 5.18	*SCORPIDIUM* NUMBER OF DISTRIBUTION POINTS	*ERICA* AREA IN HA FIGURE 5.19	*ERICA* NUMBER OF DISTRIBUTION POINTS
1	-1 to –2.5	red	23	1	42	55
2	-2.5 to –4	pink	303	89	143	60
3	-4 to –5.5	yellow	459	39	466	66
4	-5.5 to –7	light green	51	0	467	13
5	-7 to –8.5	green	0	0	134	0
6	-8.5 to –10	light blue	0	0	5	0
7	-10 to –11.5	blue	138	1	0	0
8	<= –11.5	dark blue	369	1	0	0

Furthermore, from a comparison of the probability maps it can be observed that the areas with high probability values ($\ln(p/(1-p)) > -4$; the two highest probability classes) for both *Scorpidium* and *Erica* are mostly mutually exclusive; high probabilities of *Scorpidium* coincide with low probabilities of *Erica* and *vice versa*. The comparison of the two probability maps was quantified and is presented in Table 5.7. There is only a small area with high probability values for both species. This exclusion confirms the statement that *Scorpidium* and *Erica* are indicative of opposite environmental conditions (base status).

Table 5.7
Area (in ha) cross-classified by probability values for *Erica* and *Scorpidium* (low = $\ln(p/(1-p)) < -4$; high = $\ln(p/(1-p)) > -4$).

	SCORPIDIUM	
ERICA	HIGH	LOW
HIGH	14	118
LOW	288	835

5.6 Validation

The regression model was evaluated using cross-validation. The regression analysis was executed nine times, excluding another part of the area in every calculation (Fig. 3.6). The nine probability models can be found in Appendix 3. From these models it can be observed that sometimes site factors may or may not contribute significantly to the fit of the model depending on the area under consideration. This is the case with the site factors clay cover and peat type. The nine models were used to test the stability of the prediction and to test the accuracy.

5.6.1 Stability test

The nine probability models were programmed in a GIS to calculate a 'predicted' probability map. The stability of the predictions was quantified per site for each of the nine subareas by obtaining the absolute difference in probability (ln(p/(1-p)) between the 'predicted' probability map and the probability map (Table 5.8).

The mean difference in ln(p/(1-p)) between the 'predicted' probability map and the probability map is smaller than one except for subarea 6. The relatively large value of that subarea is due to the irregular distribution of a site factor mentioned in section 3.5.2. When studying the nine models (Appendix 3) it can be observed that the site factor peat type has a large influence on the resulting probability of model 6 while in the other models peat type is not included at all or, in one case, has only a small influence. In general, the 'predicted' probability map is not very different from the probability map because most values are smaller than one. Hence, the grid cells of the 'predicted' probability map and the probability map were assigned to the same probability class.

5.6.2 Accuracy test

The accuracy of the predictions can be tested by comparing the 'predicted' probability map with the actual species distribution. The predictions were classified into eight probability classes using the class boundaries of section 5.5.2 to make simple weighted regression possible. The relation between the logit of the actual species distribution per unit area (lnf; logarithm of the number of cells where *Erica* is present divided by the total number of cells per probability class) and the average logit of the 'predicted' probability of occurrence (lnp) per class was quantified with simple regression. The weights in the regression were the area of the classes. The variance accounted for by this regression was 80% for *Erica* and 79% for *Scorpidium*. This result implies a high accuracy, which confirms the suitability of the method.

Table 5.8
Statistics of the absolute difference in the probability values (ln(p/(1-p)) between the nine subareas and the values of the entire area.

ERICA	MIN	MAX	MEAN	STD
1	0.047	0.955	0.299	0.310
2	0.11	4.66	0.49	0.55
3	0	1.07	0.32	0.45
4	0	0.31	0.15	0.07
5	0.17	0.83	0.37	0.20
6	0.29	2.70	1.61	0.29
7	0.02	1.31	0.31	0.35
8	0.33	1.61	0.54	0.22
9	0.04	1.12	0.1	0.09
overall mean	0.11	1.62	0.47	0.28
SCORPIDIUM	MIN	MAX	MEAN	STD
1	0.01	1.13	0.65	0.40
2	0	2.8	0.92	0.68
3	0	2.16	0.90	0.83
4	0.09	2.76	0.72	0.58
5	0.05	1.13	0.70	0.48
6	0.21	3.77	2.47	0.61
7	0	1.34	0.36	0.39
8	0.07	0.92	0.28	0.33
9	0.34	0.66	0.51	0.06
overall mean	0.09	1.85	0.85	0.48

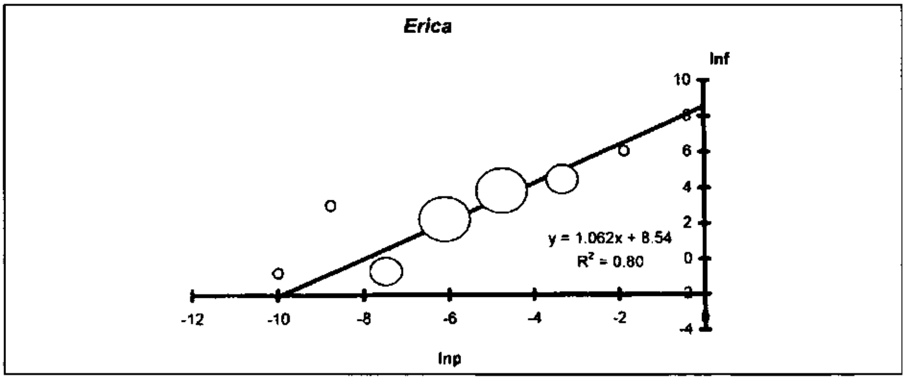

Figure 5.20
Relation between the logarithm of the actual species distribution per unit area (lnf) and the average logit of the 'predicted' probability of occurrence (lnp) per class for *Erica*. The size of the circles indicates the weight of the area classes within the regression.

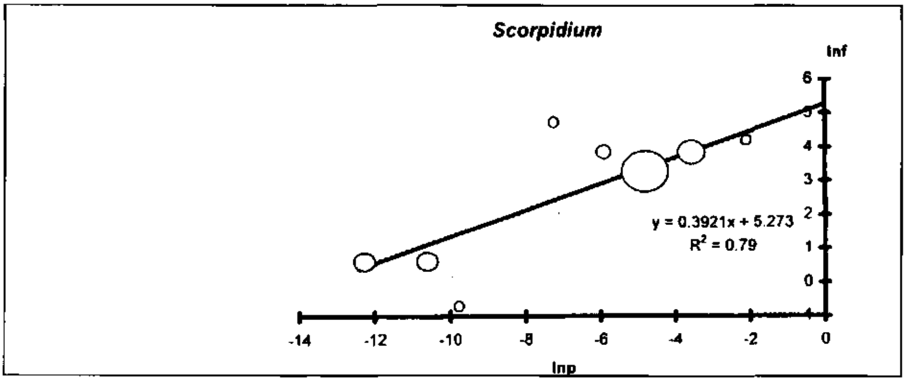

Figure 5.21
Relation between the logarithm of the actual species distribution per unit area (lnf) and the average logit of the 'predicted' probability of occurrence (lnp) per class for *Scorpidium*. The size of the circles indicates the weight of the area classes within the regression.

5.7 Discussion

The objective of this chapter was to formulate a spatial model to measure hydrological isolation to predict rare plant species occurrence that can be handled by a GIS. In De Weerribben the distribution of many rare plant species depends on site factors that are indicative of water chemistry and management. Several site factors proved to be statistical significant in predicting the spatial distribution of the species. In this section the geometrical and thematic accuracy of the input data, the validity of the method and the results are discussed.

5.7.1 Material and methods

Geometrical accuracy of the input data

The accuracy of the model is limited by the precision of the input data. The remote sensing site factors were dealt with in Chapter 4. The topographic map was used as a basis to add management and raft thickness data and to calculate distance measures. This way of combining data minimizes positional errors. In other words: the maps match very well, but their geometrical accuracy in comparison to the terrain depends upon the accuracy of the topographic map. Furthermore, the boundaries of clay cover and former peat type are approximations: in reality the classes change gradually. Fortunately, there is only one boundary, so most of the area is reliably classified.

Thematic accuracy of the input data

The raft thickness, mapped in 1951, has changed in 35 years. It was assumed that the pattern of differences in raft thickness remained unchanged. There was no indication of differences in growth rate between the rafts. Furthermore, vegetation management may also have changed. However, if a floating raft is not managed at all, it becomes woodland in only a couple of years. And, last but not least, small habitats with inconspicuous species such as *Scorpidium* can easily be overlooked in field mapping. These errors are inherent to fieldwork.

Method

The correlation between the site factors and the species occurrence does not necessarily imply a causal effect. The site factors were chosen because of their probable biological significance and their availability. Regression provides a statistical foundation for explaining and predicting plant species occurrence. The choice of the nine subareas for cross validation, however, was somewhat arbitrary. If many subareas are chosen, the results will be influenced by spatial autocorrelation. But if only a few subareas are chosen (for example four) a site factor class may be completely excluded because of its irregular distribution. The influence of irregular distribution can be observed in the model result of one of the nine subareas. The nine subareas differed in size, the amount of woodland (this was not taken into account) and therefore, in the number of random points and the cover of the site factor classes. The results of the cross validation method were satisfactory.

5.7.2 Results

Hydrological isolation

The calculated hydrological isolation appears to be very significant in predicting species occurrence. However, when other site factors, such as wetness, were taken into account Hi did not further improve the fit of the model significantly. Therefore the surplus value of Hi in predicting species occurrence compared to its component site factors (raft thickness, hinterland area and distance to the surface water network) was tested. Hi had a surplus value in predicting *Erica* occurrence but did not have a surplus value in predicting *Scorpidium* occurrence. An explanation is the statistical significance of wetness for predicting the occurrence of *Scorpidium*. The wet class represents irrigation and water overflow, which can be interpreted as a hydrological short cut, i.e. the surface water reaches a site in spite of the hydrological isolation. The added value of Hi for predicting species occurrence will, therefore, be minimal. When wetness is taken into account and when spatial information on evapotranspiration (related to biomass and wetness) and infiltration becomes available for the entire area, the Hi model can become more complete and its usefulness in predicting species occurrence will probably increase.

Ecological interpretation

The regression analyses reveal the site factors' effectiveness as predictors of the occurrence of *Erica* and *Scorpidium*. The statistical significant site factors for both species agree closely with the environmental needs of *Scorpidium* and *Erica* found in literature. The regression results show that *Erica* occurs more often in areas where the vegetation is mown in summer (manage2), the raft is relatively thick (raft6), clay cover is absent (the parameter of clay2 is negative), the distance to the water inlet is relatively short and the distance to the surface water network is relatively large (water). This result shows a close agreement with what was expected in literature (section 2.6). The vegetation is mown in summer. Furthermore, *Erica* was assumed to be indicative of base-poor and oligotrophic conditions. Base supply and surface water influence decrease with increasing distance to the supply source and increasing thickness of the floating raft (the hydraulic resistance). The oligotrophic circumstances agree with *Erica*'s occurrence in the 'little biomass' and 'intermediate biomass' classes obtained by digital image processing. The relatively short distance to the water inlet is less easy to explain because given that *Erica* is indicative of base-poor and oligotrophic conditions, it would be logical to expect a large distance to the water inlet. However, it is possible that the large distance to the surface water network may compensate for the short distance to the water inlet. Furthermore, this part of the area is considered to be in an advanced stage of terrestrialization, and *Erica* is indicative of an advanced stage of terrestrialization.

The regression results show that *Scorpidium* occurs more often in areas where the floating raft is thin or medium thick, where the floating raft is wet (wet2) and where the distance to the water inlet is relatively large. It is a species indicative of base-rich conditions and a beginning stage of terrestrialization (section 2.6). The model agrees closely with the vegetation description. When the floating raft is thin and submerged, base supply will be relatively large. The distance from a site to the surface water also determines the base status. However, because of the 'hydrological short cut' (irrigation), this distance is not a significant site factor. The relatively large distance to water inlet is attributable to the decrease in nutrients with increasing distance from the water inlet.

It can be concluded that remote sensing is a useful technique for identifying characteristics that can be used to model hydrological isolation in a GIS. Furthermore, it can be concluded that the developed method is useful for predicting plant species distribution. The model can be used to identify potential habitat that is currently unoccupied. It is very useful to apply this method to find out the most effective improvement that could be obtained from limited management resources. Future verification of the models and continued development of digitally available site factors should improve the current models and improve prediction.

6 Concluding remarks, recommendations and prospects

The extent to which the aim of this study was met, is described in section 6.1. Ways in which the results could be improved are discussed in the recommendations (section 6.2) and the prospects for using this study for monitoring and scenario studies to support nature management planning and evaluation are described in section 6.3.

6.1 Annotated conclusions

Hydrological isolation was a powerful indicator of the distribution of *Erica* and *Scorpidium*; two species with opposite environmental requirements in relation to base status.

Hydrological isolation (Hi) represented the influence of the base-rich surface water. It was formulated as a mathematical model, based on the water balance and Darcy's law, so that a GIS can handle it. It made the statistical regression less complicated by reducing the number of explanatory variables and it had a surplus value in predicting species occurrence compared to its component site factors. Hi significantly predicted the distribution of plant species in fens.

Remotely sensed images yielded information to input in the hydrological isolation model.

Several parameters necessary to calculate Hi were supplied by remote sensing. Peat baulks (the hydrological barriers) and watercourses (hydrological source) were mapped by analogue aerial photo interpretation and used to calculate the distance measures that are part of the Hi model. Furthermore, digital image analyses offered information on wetness representing water overflow and irrigation. Irrigation decreases the hydrological isolation of sites regardless of their distance from the hydrological source and thus can be considered as a hydrological short cut. Remote sensing also offered information on biomass and wetness that can be used to estimate differences in evapotranspiration when information on biomass for the entire area becomes available.

One intermediate class to account the fuzzy character of wetness proved to be sufficient.

Digital image processing was used to identify gradients, such as wetness, within the strata obtained by analogue photo interpretation. The fuzzy character of the continuous spatial variation in wetness was taken care of by introducing an intermediate class between wet and dry. This simplified approach of the fuzzy character was justified because differences in membership values relating to wetness did not yield information on differences in vegetation and thus membership values were not considered as being ecologically significant. The intermediate class proved to be sufficient in predicting species distribution.

There appeared to be a fairly good relationship between vegetation types and the remote sensing (spectral) classes.
Digital image analysis of scanned photographs offered information on wetness and biomass. Contemporaneous ground truth on biomass and wetness was not available. However, vegetation types mapped by fieldwork implicitly contain information on biomass and wetness. The vegetation types were defined by species responding to certain environmental conditions such as base status, nutrient status and vegetation management. This enabled the similarity between the spectral classes and the vegetation types to be investigated. There appeared to be a fairly good relationship between vegetation types and the spectral classes.

The remote sensing classes were important factors predicting plant species occurrence.
The fairly good relationship between the vegetation types and the spectral classes confirmed that the spectral classes contained ecologically significant information on biomass and wetness and thus base status and nutrient status. The spectral classes were, therefore, used as site factors to predict plant species occurrence and proved very successful in doing so.

The modified multiple logit regression method successfully predicted species occurrence.
Multiple logit regression was used to explore the relation between species and their environmental needs. The conditions of this study required that nominal and quantitative variables were tested simultaneously. Furthermore, the usual field sampling methods provide sample plots at which a species is recorded as present or absent, whereas the species distribution maps used, only give points at which the species is present. Since logit regression requires both presence and absence points, the latter were generated by taking a large number of random points. The number of random points required must be very large because they should represent an estimate of the proportion of cover of the site factor classes to prove that the area of these classes did not influence the predictions. The predictions did not result in absolute probabilities but in relative differences in probability of sites, because of their dependence on the number of random points taken.

The relation between the occurrence of plant species and site factors was in agreement with the results of earlier studies on their ecology.
It is known that water chemistry (base status and nutrient status) and vegetation management determine species composition in fens. The site factors used in this study were selected for their expected ecological significance regarding to water chemistry and vegetation management. *Erica* and *Scorpidium*, two species indicative of contrasting environmental conditions in relation to base status, were used to confirm these expectations. The predicted distribution of the two species was mutually exclusive, with *Erica* most common in a base-poor environment and *Scorpidium* in a base-rich environment.

6.2 Recommendations

Remote sensing and GIS turned out to be useful techniques to model hydrological isolation. The accuracy of the results of these techniques can be improved still further and the number of possible applications can be increased.

The hydrological isolation model should be refined.
The advantage of investing in a better model for hydrological isolation is that it reduces the number of variables in the regression analysis and it has great potential for dynamic spatial hydrological modelling suitable for monitoring the potential distribution of rare plant species. In the present case study spatial information on evapotranspiration and infiltration was not available for the entire area and should be added to the model in future studies. As spatial differences in evapotranspiration are proportional to differences in biomass and wetness, which can be collected with remote sensing, it would be relatively easy to add an estimation of the evapotranspiration to the model. To model spatial differences in infiltration would require much more effort because infiltration cannot be deduced from visible terrain features.

High-resolution satellite images or hyper-spectral images should be applied.
Images taken during different seasons will soon be available at low cost, thereby eliminating the problems of time gaps between desired images. Radiometric, spectral, geometrical and temporal resolutions will improve, enhancing the results for nature management efficiency. The potential of high-resolution satellite images for mapping fen vegetation is certainly worth exploiting.

Fieldwork should not be skipped.
Although the spectral classes were positively related to the vegetation types, this study showed that it would be best to validate the results of image classification with field data because it will lead to a more accurate and reliable validation. Fieldwork at the time the aerial photographs are taken is recommended because biomass and wetness change much within a growing season.

The method should be applied to more species.
The method should be applied to more species, because this may result in a more generally applicable instrument for management planning and evaluation in fen ecosystems. Although other plant species might behave differently than the two used in this study, the method is considered to be suitable in a broader context. It seems, for example, likely that the method will be suitable to predict the occurrence of the indicator species for the Dutch government's 'nature target types' (Bal 1995). Besides plant species similar methods can be applied to predict animal distribution (Austin et al. 1996; Bian & West 1997). The method is assumed to be suitable for all species that are neither too common nor too rare. Either way, the relation between the species and the site factors is difficult to formalize.

It is recommended to apply the method to other fen areas in The Netherlands.
The vegetation structure and hydrology in other fen ecosystems in The Netherlands are similar to De Weerribben and thus, equally satisfactory results can be expected when the method is applied for such fen areas.

6.3 Prospects

Monitoring
The methods and experiences presented in this study are intended as a step towards a monitoring system for plant species based on remote sensing, GIS and additional fieldwork. In such a system, the relations between spectral classes, vegetation types, site factors and rare plant species distribution must be quantified similar to what was done in this study. The resulting probability maps of one period could support management planning. In order to be able to evaluate management on the basis of monitoring the distribution of rare plant species, it is essential to have detailed information from at least two distinct periods. Every site factor has its typical turn over time that makes it difficult to collect data from two distinct time periods. New ditches are dug every year, vegetation management may change within a couple of years and a period of ten years is considered suitable to study raft thickness and vegetation structure. The model for hydrological isolation has great potential for supporting a monitoring system in fens. Several of its parameters have a high temporal resolution: for example, precipitation measurements are available daily. Values for hydrological isolation can become available for every possible period. However, in this study only the spatial influence of Hi on species distribution was investigated. The temporal relation between Hi and the species distribution needs to be studied to determine the full potential of the Hi model.

Scenarios
The method presented is also suitable for scenario studies. It is very important to study the possible impact of a new management regime before it is carried out. To change the position of the water inlet point might be such a scenario. A distances-to-the-new-water-inlet-point map should be prepared to input logit multiple regression that will result in a new probability map. GIS analyses of the probability maps representing different managment regimes will lead to statements about the decrease or increase of potential habitat and its spatial changes, especially in relation to species whose distribution was well predicted by distance from the water inlet point. The method may, therefore, contribute to more efficient management planning.

Summary

In fens the species composition, vegetation structure and succession rate are determined by vegetation management and water chemistry, particularly by the base status and nutrient status. Base-rich and nutrient-rich surface water causes fens to become eutrophied, which leads to an increased biomass production. When part of fens becomes isolated from base-rich and eutrophic surface water (hydrological isolation), it acidifies due to the dominance of acidic and oligotrophic rainwater. One consequence of decreasing water quality due to continuing acidification and eutrophication, is the disappearance of the rare plant species that depend on base-rich but oligotrophic water. It is important to obtain quantitative information on the influence of these processes on vegetation structure types and the distribution of rare plant species for nature management, planning and evaluation. The usual method to obtain this information is fieldwork, but this is time-consuming and thus very expensive, especially in large, inaccessible areas like wetlands. The aim of this study was therefore to investigate the efficiency of remote sensing and geographical information systems (GIS) to identify hydrological isolation in order to predict the potential distribution of rare plant species.

De Weerribben study area

Dutch inland wetlands are characterized by peat formation under specific geomorphological (floodplain) and climatic settings (mean temperature and precipitation) and human impacts. The latter, specifically the peat cutting and dredging in the 18th and 19th centuries, formed a landscape of extensive rectangular bodies of open water (ca. 30 by 1000 m) called *petgaten*. Narrow strips of the original peat, used for making the turves, separate the *petgaten*. After the petgaten were abandoned, a process of terrestrialization from open water to fen vegetation began, in which the first stage is the formation of a floating raft of vegetation. The reeds on the floating rafts were mown every year for thatch. When not mown, the open fen becomes a woodland within a few years. During the 20th century most of the fens were drained and reclaimed for agricultural use. De Weerribben (3600 ha), now a nature reserve, is one of the remaining fen areas in the north of The Netherlands (6° 0' E and 52° 45' N).

Differences in hydrology strongly influence the species composition in De Weerribben. Much water in De Weerribben is lost via infiltration to the surrounding polders that have a lower water table. Water loss caused by this infiltration and by evapotranspiration is compensated for by an influx of surface water, precipitation and (locally) by irrigation. This influx creates a complex of gradients from surface water dominance to rainwater dominance.

Remote sensing

The available remote sensing material was satellite imagery, scanner imagery and aerial photographs. The resolution of the satellite images was too low to distinguish differences in the vegetation within a floating raft. The scanner imagery was not suitable for further analyses in a GIS because their internal geometry varied too much. Although aerial photographs have only a moderate spectral and radiometric

resolution, they contain detailed information that can be extracted by an interpreter with good field knowledge. Therefore the false colour aerial photographs were used for digital image processing and analogue interpretation. The best and most objective combination of methods was used to derive significant information from the photographs without relying too much on the skill of an interpreter. Analogue photo interpretation was suitable to map water, peat baulks, open fen and woodland because they were easily recognized thanks to their contrasting reflectance, texture and sharp boundaries. These classes were used for stratifying the landscape. Within the strata digital image processing was suitable to derive information on gradients. Interpretation based on expert knowledge of the spectral values coincided with differences in biomass of the vegetation and wetness of the floating raft. The definitions of wetness and biomass are fuzzy. However, differences in membership values regarding wetness do not yield information on differences in vegetation because wetness may vary within a growing season and thus were considered to be not ecologically significant. An intermediate class between the 'wet' and 'dry' classes was sufficient to approach the fuzziness. Digital image processing was used to classify the scanned photographs.

Vegetation scientists and nature management organizations are mainly interested in species composition. Although species composition and reflectance are both characteristics of a vegetation type, it was not possible to map the desired vegetation types of the entire area solely on the basis of reflectance. The vegetation types mapped in the field are based on species composition and structural differences that are indicative of environmental conditions to a certain extent. They were grouped into vegetation structure types indicative of differences in biomass, wetness and vegetation management. The reliability and accuracy of the remote sensing classification were determined as an 'indication' of the ecological significance of the spectral classes. It could be concluded that the spectral classes corresponded reasonably well with the grouped vegetation types of the vegetation map. Subsequently, the results of the remote sensing interpretation were used to model hydrological isolation and to predict species distribution.

Hydrological isolation in a GIS environment to predict plant species distribution

Field information on base status and nutrient status was only available for a few selected sample points in De Weerribben. Information on water chemistry covering the entire area was, therefore, obtained by modelling hydrological isolation spatially. The water balance and Darcy's law were used to define a spatial mathematical model for hydrological isolation. A GIS was used to calculate hydrological isolation by determining topological relations and data integration. The variables input into this model were: precipitation, infiltration, evapotranspiration, permeability, distance to the surface water and hinterland area. Permeability values were obtained by reclassifying the raft thickness classes of the soil map on the basis of literature. Average values for precipitation, infiltration and evapotranspiration were used as input constants because the spatial variation of these variables was not known. The results of the remote sensing interpretation were used as hydrological source (watercourses) and hydrological barriers (peat baulks) for calculating the distance to the surface water and the amount of hinterland. Wetness was assumed to be a hydrological short cut, decreasing the influence of the hydrological isolation model.

A wet site received surface water by irrigation or flooding instead of an influx through the floating raft.

The hydrological isolation was used to predict the species distribution. Two plant species indicative of opposite environmental conditions in relation to base status were selected to model species distribution: *Scorpidium scorpioides* (Hedw.) Limpr. and *Erica tetralix* L. *Scorpidium* is a rare moss characteristic of base-rich conditions and an early stage of terrestrialization. *Erica* is a dwarf shrub that is not very rare. It is indicative of base-poor conditions and an advanced stage of terrestrialization.

Regression analysis was used to determine how *Erica* and *Scorpidium* are related to environmental variables and to predict their occurrence. The regression analysis was adapted to take account of the specific conditions of this study. A major problem was 'missing absences' on the point distribution maps of the plant species, i.e. points representing the absence of a species had not been recorded. These absences, which were necessary to apply logit regression, were obtained by generating random points. It was important for the distribution of absence points to be representative of the area of all site factor class combinations, to prove that species distribution is not evenly distributed over all site factor classes. Therefore, there had to be very many such points. As a result, the predicted probabilities of occurrence were relative instead of absolute, because they depended on the number of random points.

Environmental variables that appeared to have a statistically significant effect on the occurrence of either species agreed well with the environmental needs of these species reported in literature. The calculated hydrological isolation significantly explained the species occurrence. When other site factors were taken into account too, the predictive ability of hydrological isolation did not further improve the model significantly. For example, Hi did not have a surplus value in predicting *Scorpidium* occurrence while the species was assumed to be very sensitive to hydrological isolation. This might be explained by the significance of wetness predicting *Scorpidium* occurrence. The wet class represents irrigation and a submerged raft, which can be interpreted as a hydrological short cut, i.e. the surface water reaching a site in spite of the hydrological isolation.

It can be concluded that remote sensing and GIS are useful for obtaining a measure of the hydrological isolation in fens, which is a predictor of the distribution of rare plant species. In the future, it might be possible to refine the model by adding more spatial environmental information on evapotranspiration when it becomes digitally available. The remote sensing and GIS techniques turned out to be very suitable and promising for determining potential habitat for plant species; information can be used to optimize field sampling, for management administration, planning and evaluation, and in scenario studies.

Samenvatting

In moerasgebieden hangt het voorkomen van zeldzame plantensoorten vooral samen met de chemische samenstelling van het water, zoals basen- en nutriëntenrijkdom, en het vegetatiebeheer. Het oppervlaktewater in sloten en kanalen is basenrijk en eutroof. Er wordt verondersteld dat het moeras onder invloed van dit water zal eutrofiëren, hetgeen tot een verhoogde biomassaproductie zal leiden. Wanneer echter delen van het moeras hydrologisch geïsoleerd raken van deze oppervlaktewaterinvloed, zullen zij verzuren door een grotere invloed van regenwater dat zuur en oligotroof is. Een consequentie van een afname van de waterkwaliteit door voortgaande eutrofiëring en verzuring is de achteruitgang van plantensoorten die indicatief zijn voor een basenrijk maar oligotroof milieu. Het verkrijgen van kwantitatieve informatie over de invloed van deze processen op de verspreiding van vegetatiestructuurtypen en zeldzame plantensoorten is van belang voor een effectief natuurbeheer. De gebruikelijke methode om deze informatie te verkrijgen is veldwerk. Veldwerk, in grote ontoegankelijke gebieden zoals moerassen, kost erg veel tijd en is dus duur. Deze studie heeft tot doel de bruikbaarheid van remote sensing en GIS te onderzoeken door de invloed van hydrologische isolatie en het vegetatiebeheer op de verspreiding van minder algemene plantensoorten te modeleren.

Proefgebied De Weerribben

Nederlandse laagveenmoerassen zijn gekarakteriseerd door veenvorming onder specifieke geomorfologie en klimaat en door menselijke invloed. Deze menselijke invloed, vervening in de 18e en 19e eeuw, creëerde een landschap met lange rechthoekige (ca. 30 bij 1000 m) waterlichamen, petgaten genaamd. Smalle stroken veen tussen de petgaten, de ribben, werden gebruikt om het gebaggerde veen uit de petgaten te drogen en er turf van te maken. Nadat de petgaten aan hun lot waren overgelaten, begon een verlandingsproces van water naar rietland. Plantenwortels vormden op de overgebleven veenprut een drijvende wortelmat, de kragge. Het riet op de kragge wordt jaarlijks gemaaid. Wanneer het maaien wordt gestaakt, ontstaat binnen enkele jaren een moerasbos. In de 20e eeuw zijn de meeste laagveenmoerassen ontwaterd en ingepolderd voor landbouwkundig gebruik. De Weerribben (3600 ha) is een van de overgebleven laagveenmoerassen in het noorden van Nederland.

De soortensamenstelling van de vegetatie in De Weerribben wordt beïnvloed door verschillen in hydrologie. Veel water in De Weerribben infiltreert naar omringende polders door het verschil in waterstand. Watertekort als gevolg van deze wegzijging en verdamping wordt gecompenseerd door neerslag, het pompen van oppervlaktewater op de kragge, en een laterale aanvoer van oppervlaktewater door de kragge. Deze laterale aanvoer zorgt voor een complex van hydrologische gradiënten van oppervlaktewaterinvloed naar regenwaterinvloed.

Remote sensing

Het beschikbare remote sensing-materiaal omvatte satellietbeelden, scannerbeelden en luchtfoto's. De satellietbeelden hadden een veel te lage geometrische resolutie voor het maken van onderscheid in de vegetatie van een petgat en de scannerbeelden waren door een slechte interne geometrie niet geschikt voor het gebruik in GIS. De luchtfoto's bevatten echter zeer gedetailleerde informatie voor iemand met ervaring op dit gebied hoewel zij ten opzichte van de satellietbeelden en scannerbeelden een matige spectrale en radiometrische resolutie hebben. De false colour luchtfoto's werden gebruikt voor digitale beeldverwerking en analoge foto-interpretatie waarbij werd gestreefd naar een minimalisering van de subjectieve inbreng van degene die interpreteert.

Objecten met scherpe grenzen zoals bossen, ribben en water werden op analoge luchtfoto's geïnterpreteerd. De interpretatie werd gebruikt om de gescande luchtfoto's te stratificeren. Binnen deze strata is digitale beeldverwerking gebruikt om gradiënten in de vegetatie te bestuderen. Interpretatie van de spectrale waarden kwam overeen met verschillen in biomassa van de vegetatie en natheid van de kragge. Gradiënten in biomassa en natheid hebben een *fuzzy* karakter. Zij zijn echter zo veranderlijk binnen een seizoen dat 'kleine' verschillen in *membership*-waarden geen ecologische betekenis hebben. Het onderscheiden van een 'tussenklasse' bijvoorbeeld 'vochtig' tussen 'nat' en 'droog' bleek voldoende om het *fuzzy* karakter van biomassa en natheid te benaderen. Digitale beeldverwerking bestond uit een classificatie van de spectrale waarden van een gescande luchtfoto tot spectrale klassen.

Remote sensing levert informatie over de reflectie van de vegetatie in het elektromagnetisch spectrum. Vegetatiekundigen zijn vooral geïnteresseerd in de soortensamenstelling van de vegetatie. Hoewel soortensamenstelling en reflectie beide karakteristiek zijn voor een vegetatie, was het onmogelijk de gewenste vegetatietypen gebiedsdekkend op basis van reflectie te onderscheiden. De in het veld gekarteerde vegetatietypen zijn gedefinieerd op basis van soortensamenstelling en structurele verschillen in de vegetatie en zijn dus tot op zekere hoogte indicatief voor milieuomstandigheden. De vegetatietypen werden gegroepeerd naar hun indicatie van biomassa en natheid. De betrouwbaarheid en de nauwkeurigheid van de classificatie gaven ecologische betekenis aan de spectrale klassen. Er kan geconcludeerd worden dat de spectrale klassen ecologische informatie bevatten over verschillen in biomassa en natheid. De resultaten van analoge foto-interpretatie en digitale beeldverwerking werden vervolgens gebruikt om de hydrologische isolatie te modeleren en om de verspreiding van zeldzame plantensoorten te voorspellen.

Hydrologische isolatie in een GIS-omgeving om de verspreiding van zeldzame planten te voorspellen

Gegevens over basen- en nutriëntenrijkdom van het water waren alleen van een aantal monsterpunten voorhanden. Vlakdekkende informatie over de waterchemie was daarom verkregen door de hydrologische isolatie kwantitatief ruimtelijk te modelleren in GIS. De waterbalans en de wet van Darcy werden gebruikt voor de definitie van een ruimtelijk model dat de mate van hydrologische isolatie modelleert. GIS werd gebruikt om de hydrologische isolatie te berekenen door middel van het vaststellen van ruimtelijke relaties en gegevensintegratie. Invoergegevens voor het model waren: neerslag, wegzijging, verdamping, doorlatendheid van de kragge, afstand tot het oppervlaktewater en hoeveelheid achterland. De ruimtelijke verschillen in neerslag, wegzijging en verdamping waren niet bekend waardoor alleen gemiddelden voor het gehele gebied zijn ingevoerd. De kraggediktekaart werd omgerekend naar doorlatendheid van de kragge op basis van gegevens uit de literatuur. Remote sensing-resultaten werden gebruikt als hydrologische bron (watergangen) en hydrologische barrières (ribben) om de afstand tot het oppervlaktewater en de hoeveelheid achterland te berekenen. De natheid van de kragge werd verondersteld een kortsluiting in de hydrologische isolatie te zijn. Natte kraggen ontvangen oppervlaktewater door middel van bemaling of overstroming in plaats van laterale aanvoer door de kragge. De hydrologische isolatie werd gebruikt om de verspreiding van zeldzame planten te voorspellen. De gekozen plantensoorten zijn indicatief voor tegengestelde milieuomstandigheden met betrekking tot basentoestand. *Scorpidium scorpioides* (schorpioenmos) is een zeldzaam mos. In het algemeen is deze soort indicatief voor basenrijke omstandigheden en een beginnende verlanding van de kragge. *Erica tetralix* (dophei) is een dwergstruik en minder zeldzaam dan *Scorpidium*. De soort is indicatief voor zure milieuomstandigheden en vergevorderde verlanding van de kragge.

Om de verspreiding van *Erica* en *Scorpidium* te correleren met milieufactoren als hydrologische isolatie en vegetatiebeheer werd regressieanalyse toegepast. De regressieanalyse werd speciaal voor dit onderzoek aangepast. De soortverspreidingskaarten bevatten namelijk alleen punten die aanwezigheid van de soort aanduiden; 'afwezigheid is afwezig'. Punten die de afwezigheid van een soort aanduiden, werden verkregen door het nemen van random punten. Het was belangrijk om een groot aantal random punten te nemen omdat ze representatief moeten zijn voor de oppervlakte die milieufactorklassen innemen. Deze representativiteit moet bewijzen dat de voorspelling niet afhankelijk is van een onevenredige verdeling van de milieufactoren. De grote hoeveelheid random punten bracht met zich mee dat er geen absolute maar alleen een relatieve kans op het voorkomen van de soorten kon worden voorspeld.

De milieufactoren die significant de verspreiding bepaalden, kwamen overeen met de specifieke eisen van de soort beschreven in de literatuur. Hydrologische isolatie bepaalde significant het voorkomen van de soorten maar was niet de belangrijkste factor. Van *Scorpidium* werd bijvoorbeeld verwacht dat het voorkomen zou afnemen met een toenemende mate van hydrologische isolatie. Het niet uitkomen van deze verwachting werd verklaard door de invloed van de factor 'natheid'. Bemaling of overstroming van de kragge veroorzaken een 'hydrologische kortsluiting'.

Geconcludeerd werd dat remote sensing, GIS, in combinatie met regressieanalyse geschikte methoden zijn om de verspreiding van zeldzame soorten in moerasgebieden te karteren en te voorspellen. Uitbreiding van het model voor hydrologische isolatie met meer ruimtelijke gegevens zoals verdamping zal de toepasbaarheid van de methode vergroten. De methode is zeer bruikbaar voor het bepalen van het potentiële habitat voor soorten en daarmee voor het administreren, plannen en evalueren van het beheer en het opzetten van een monitoringsyteem.

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Abbreviations and symbols

A	= cross section (hydrology)
A	= area (statistics)
b1, b2	= willow shrub
b5	= alder woodland
b7	= birch woodland
B+	= much biomass
B-	= low biomass
bio1	= low biomass
bio2	= intermediate biomass
bio3	= much biomass
c	= constant
clay1	= clay cover
clay2	= no clay cover
course1	= area influenced by water from the Kalenbergergracht
course2	= area influenced by water from the main canals
course3	= area influenced by water from the *petgaten*
course4	= area influenced by water from the ditches
D	= infiltration (hydrology)
D	= density (remote sensing)
dh	= water level rise
dL	= length
DN	= digital number
DNOj	= original digital number of pixel j
DNCj	= corrected digital number f pixel j
dpi	= dots per inch
dWi	= accumulated by distance to the water source
E	= evapotranspiration
e	= expected number (statistics)
f	= proportional cover
FC	= false colour
G	= grassland
GIS	= geographical information systems
H	= hinterland area
h3	= *Sphagnum* fen meadows
Hi	= hydrological isolation
hinter	= distance to the hinter-land
inlet	= distance to the water inlet
I	= input
k	= permeability
L	= storage
L3	= *Phalarus* vegetation
L4	= *Carex acutiformis* vegetation
L7	= tall forb vegetation
LAI	= leaf area index
l	= intensity
manage1	= winter mowing
manage2	= summer mowing
MDNi	= mean digital number of training set i
N	= total number (statistics)
n	= number of data points (statistics)
NDVI	= normalized difference vegetation index
O	= outlet
o	= observed number (statistics)
P	= precipitation
p_1	= probability of cell 1
p_a	= average probability
peat1	= former sedge peat
peat2	= former moss peat
Q	= illumination
R1	= water reed fens
R2	= *Calliergonella* reed fens
R3	= *Scorpidium* reed fens
R4	= tall forb reed fens
R5	= eutrophic tall forb reed fens
R6	= *Lysimachia* tall forb reed fens
R7	= *Sphagnum* reed fens
R8	= *Sphagnum* reed fens (+ young trees)
raft1	= floating raft stabilized with mud
raft2	= open water
raft3	= starting terrestrialization
raft4	= thin floating raft
raft5	= medium thick floating raft
raft6	= thick floating raft
RMS	= root mean square
Rnir	= reflectance of near infrared
Rr	= reflectance of red
RS	= remote sensing
RS-VS	= remote sensing vegeta-tion structure
S	= seepage
T	= transmission
t1	= *Scorpidium* fen meadows
t2	= *Sphagnum* fen meadows

Appendix 1

Technical information

Software

ERDAS IMAGINE version 8.2 for MICROSOFT WINDOWS NT version 3.5
ARC/INFO version 7.21 DIGITAL Alpha station 200 4/233
GENSTAT version 5.3 for VAX

Aerial photographs

date: 4 May 1995
material: diapositives and prints
scale: 1:22 500
owner: National Forest Service
camera: RC10 -15 cm
lens type: 15UAG no 1034, focal distance 151.64
numbers: 4541-4545, 4546-4552, 4553-4559

date: 14 June 1986
material: diapositives
scale: 1:5000
owner: National Forest Service
numbers: 41041

Statistics of scanned images

false colour photos May 1995, scanned with 500 dpi, resampled to 1 m^2 field resolution

PHOTONR	#COLUMNS	# ROWS	BAND	MIN	MAX	MEAN	MEDIAN	MODUS	STD
4540	4274	4961	near infrared	1	255	27.49	28	1	25.41
			red	1	255	25.87	22	18	22.97
			green	1	240	51.30	53	52	22.96
4541	4272	4676	near infrared	1	255	22.58	21	10	17.01
			red	1	255	28.26	25	25	15.57
			green	1	254	51.22	52	53	17.99

false colour photos June 1986, scanned with 300 dpi, resampled to 1 m^2 field resolution

PHOTONR	#COLUMNS	# ROWS	BAND	MIN	MAX	MEAN	MEDIAN	MODUS	STD
41041	2107	2102	near infrared	30	251	149.8	157	168	35.76
			red	23	242	103.0	103	103	34.28
			green	23	216	146.2	153	154	33.74

Appendix 2

Statistics of a training set from vegetation types obtained from the vegetation map of 1986 for Supervised Classification of False Colour photos made in June 1986 (the photos of May 1995 are presented in Sanders et al. 1997). The training sets are presented in a feature space plot to show the overlap in spectral signature. The intention is to illustrate that supervised classification of vegetation types discerned in the field is inappropriate for the situation described in this study.

Signature file: c:/vegtypen.sig
Source image file: c:/cross_mask1.img
Number of signatures: 58, Number of layers: 3

Signature: h3total
Number of pixels: 74

			STATISTICS	
Layer	Mimimum	Maximum	Mean	Sigma
1	89.000	210.000	147.514	35.299
2	75.000	187.000	117.068	32.259
3	125.000	212.000	164.959	22.755

			COVARIANCE
Layer	1	2	3
1	1246.007	1037.211	722.405
2	1037.211	1040.612	723.441
3	722.405	723.441	517.793

Signature: r1total
Number of pixels: 56

			STATISTICS	
Layer	Mimimum	Maximum	Mean	Sigma
1	116.000	172.000	148.571	16.849
2	0.000	68.000	36.446	25.142
3	68.000	130.000	106.214	20.315

			COVARIANCE
Layer	1	2	3
1	283.886	354.049	304.748
2	354.049	632.106	501.557
3	304.748	501.557	412.717

Signature: r2total
Number of pixels: 27

			STATISTICS	
Layer	Mimimum	Maximum	Mean	Sigma
1	124.000	157.000	141.259	10.527
2	21.000	45.000	31.630	7.354
3	94.000	113.000	102.333	6.038

			COVARIANCE
Layer	1	2	3
1	110.815	46.677	46.218
2	46.677	54.088	37.744
3	46.218	37.744	36.462

Signature: r3total
Number of pixels: 15

			STATISTICS	
Layer	Mimimum	Maximum	Mean	Sigma
1	46.000	76.000	57.800	7.903
2	30.000	48.000	36.267	5.738
3	51.000	85.000	64.133	11.006

			COVARIANCE
Layer	1	2	3
1	62.457	9.486	-13.757
2	9.486	32.924	54.890
3	-13.757	54.890	121.124

Signature: r5total
Number of pixels: 27

			STATISTICS	
Layer	Mimimum	Maximum	Mean	Sigma
1	129.000	161.000	145.963	7.901
2	19.000	87.000	63.593	21.347
3	95.000	145.000	126.741	16.552

COVARIANCE

Layer	1	2	3
1	62.422	63.407	46.759
2	63.407	455.712	351.083
3	46.759	351.083	273.969

Signature: r4total
Number of pixels: 9

STATISTICS

Layer	Mimimum	Maximum	Mean	Sigma
1	137.000	158.000	146.444	7.780
2	61.000	84.000	74.778	7.412
3	125.000	143.000	135.667	6.185

COVARIANCE

Layer	1	2	3
1	60.528	-19.764	-21.333
2	-19.764	54.944	45.417
3	-21.333	45.417	38.250

Signature: r7total
Number of pixels: 27

STATISTICS

Layer	Mimimum	Maximum	Mean	Sigma
1	89.000	221.000	162.333	44.850
2	61.000	205.000	139.333	45.618
3	120.000	221.000	180.519	29.948

COVARIANCE

Layer	1	2	3
1	2011.538	2000.077	1287.590
2	2000.077	2081.000	1357.013
3	1287.590	1357.013	896.875

Signature: r8total
Number of pixels: 10

STATISTICS

Layer	Mimimum	Maximum	Mean	Sigma
1	94.000	172.000	116.700	24.254
2	85.000	121.000	96.700	10.874
3	142.000	170.000	153.100	8.279

COVARIANCE

Layer	1	2	3
1	588.233	108.567	36.589
2	108.567	118.233	85.478
3	36.589	85.478	68.544

Signature: v1total
Number of pixels: 20

STATISTICS

Layer	Mimimum	Maximum	Mean	Sigma
1	127.000	159.000	141.500	8.853
2	91.000	133.000	111.350	11.820
3	148.000	179.000	163.400	8.911

COVARIANCE

Layer	1	2	3
1	78.368	64.921	44.474
2	64.921	139.713	104.589
3	44.474	104.589	79.411

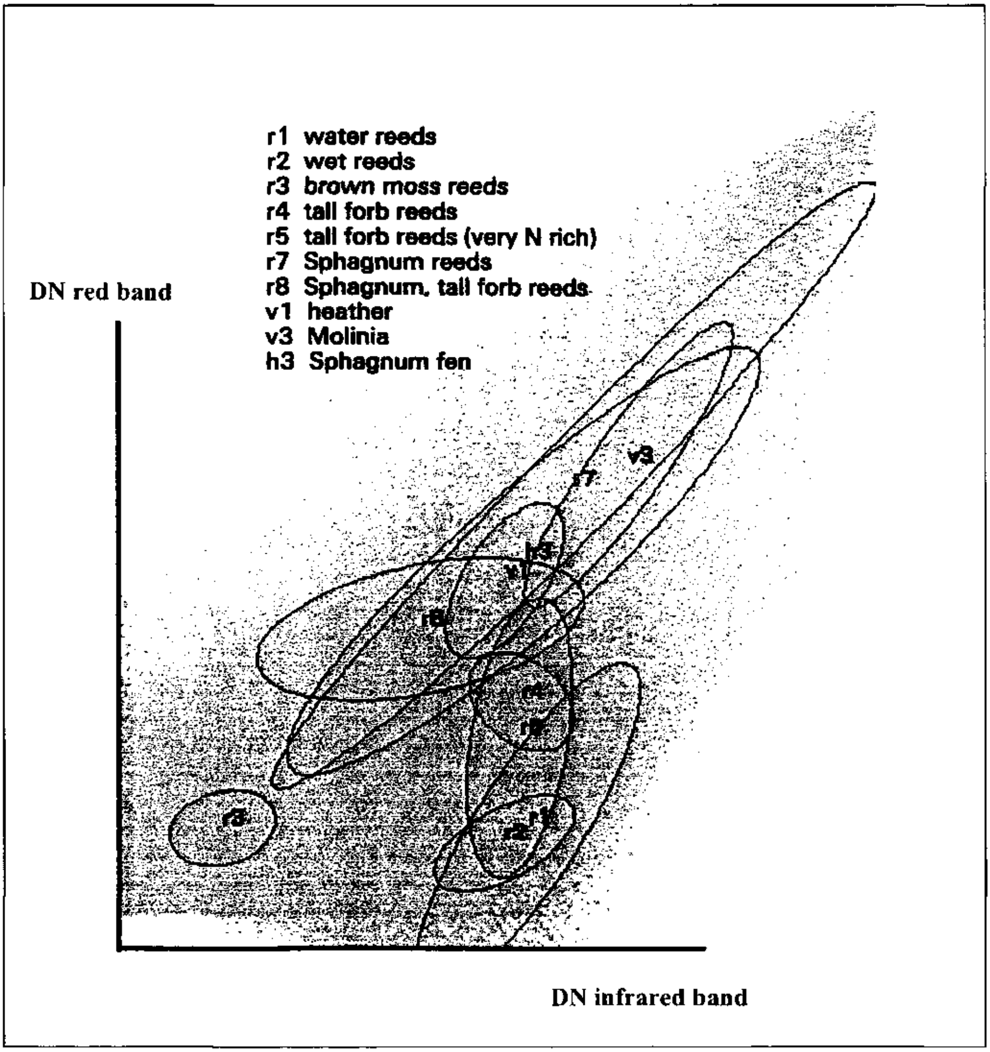
Signature: v3total
Number of pixels: 11

STATISTICS

Layer	Mimimum	Maximum	Mean	Sigma
1	157.000	215.000	178.636	15.648
2	113.000	184.000	146.091	21.314
3	163.000	208.000	185.273	14.029

COVARIANCE

Layer	1	2	3
1	244.855	302.836	192.509
2	302.836	454.291	297.973
3	192.509	297.97	196.818


r1 water reeds
r2 wet reeds
r3 brown moss reeds
r4 tall forb reeds
r5 tall forb reeds (very N rich)
r7 Sphagnum reeds
r8 Sphagnum, tall forb reeds
v1 heather
v3 Molinia
h3 Sphagnum fen
DN red band
DN infrared band
v3
r7
h3
v1
r8
r4
r5
r3
r1
r2

Appendix 3

The nine probability models

Scorpidium1 = -15.93 + ((	5.60 raft2 +	0.300 wet2) / 1000) + (0.701 inlet)
	6.97 raft3	-1.022 wet3
	7.14 raft4	
	6.42 raft5	
	0.25 raft6	
Erica1 = 0.17 + ((1.550 manage2 +	0.820 raft2 + -1.255 clay2) / 1000) + (-0.803 inlet) + (0.3074 water)	
	0.405 raft3	
	1.343 raft4	
	1.344 raft5	
	1.345 raft6	
Scorpidium2 = -10.21 + ((	5.94 raft2 +	0.313 wet2) / 1000)
	7.26 raft3	-1.041 wet3
	7.35 raft4	
	6.61 raft5	
	0.19 raft6	
Erica2 = 0.69 + ((1.337 manage2 +	-3.40 raft2 + -1.353 clay2) / 1000) + (-0.831 inlet) + (0.2767 water)	
	-0.394 raft3	
	1.123 raft4	
	1.770 raft5	
	1.912 raft6	
Scorpidium3 = -17.39 + ((	6.11 raft2 +	0.288 wet2 + -0.649 clay2) / 1000) + (0.903 inlet)
	7.30 raft3	-0.989 wet3
	7.35 raft4	
	6.56 raft5	
	0.21 raft6	
Erica3 = -0.92 + ((1.376 manage2 +	1.31 raft2 + -1.367 clay2) / 1000) + (-0.671 inlet) + (0.3050 water)	
	0.862 raft3	
	1.405 raft4	
	2.108 raft5	
	2.210 raft6	
Scorpidium4 = -21.80 + ((	6.27 raft2 +	0.657 wet2) / 1000) + (1.276 inlet)
	6.83 raft3	-0.682 wet3
	7.95 raft4	
	7.13 raft5	
	0.26 raft6	
Erica4 = -1.56 + ((1.729 manage2 +	0.88 raft2 + -0.434 clay2) / 1000) + (-0.646 inlet) + (0.3805 water)	
	-0.434 raft3	
	1.593 raft4	
	1.838 raft5	
	2.019 raft6	
Scorpidium5 = -15.68 + ((	5.37 raft2+	0.277 wet2) / 1000) + (0.699 * inlet)
	6.75 raft3	-1.044 wet3
	6.93 raft4	
	6.25 raft5	
	0.21 raft6	
Erica5 = -0.68 + ((1.568 manage2 +	0.93 raft2 + -1.217 clay2) / 1000) + (-0.725 inlet) + (0.2805 water)	
	0.817 raft3	
	1.605 raft4	
	2.202 raft5	
	2.204 raft6	
Scorpidium6 = -24.83 + ((	7.47 raft2 +	0.612 wet2 + 2.767 peat2) / 1000) + (1.315 inlet)
	8.39 raft3	-0.692 wet3
	7.97 raft4	
	6.87 raft5	
	0.25 raft6	

Erica6 = -2.72 + ((1.477 manage2+ 1.40 raft2 + -1.301 clay2 + 1.805 peat2) / 1000) + (-0.664 inlet) + (0.3112 water)
0.856 raft3
1.347 raft4
1.953 raft5
1.981raft6

Scorpidium7 = -10.95 + ((6.16 raft2 + 0.014 wet2) / 1000)
8.12 raft3 -1.073 wet3
7.77 raft4
7.46 raft5
0.20 raft6

Erica7 = -0.66 + ((1.704 manage2+ 0.99 raft2 + -1.301 clay2) / 1000) + (-0.758 inlet) + (0.3849 water)
-0.765 raft3
1.119 raft4
1.906 raft5
2.045 raft6

Scorpidium8 = -17.83 + ((5.77 raft2 + 0.338 wet2) / 1000) + (0.836 inlet)
7.89 raft3 -1.045 wet3
7.90 raft4
7.14 raft5
0.20 raft6

Erica8 = -3.08 + ((-3.08 manage2 + 1.461 raft2 + -1.374 clay2 + 0.982 peat2) / 1000) + (-0.503 inlet) + (0.3223 water)
1.13 raft3
0.680 raft4
1.240 raft5
1.928 raft6

Scorpidium9 = -20.55 + ((6.48 raft2 + 0.157 wet2) / 1000) + (1.186 inlet)
7.73 raft3 -1.418 wet3
7.91 raft4
7.24 raft5
0.34 raft6

Erica9 = -1.41 + ((1.519 manage2 + 0.70 raft2 + -1.048 clay2) / 1000) + (-0.614 inlet) + (0.3150 water)
0.540 raft3
1.285 raft4
1.942 raft5
2.004 raft6

Appendix 4

Presence-absence data are required in order to calculate the probability that a species is present as a function of the explanatory variables. Field sampling supply presence and absence, but the map of the plant species distribution used in this study only supplies presences. Four different ways of calculating the statistical significance of site factors predicting plant species occurrence were considered. The problem is illustrated by examining a simple question, namely whether the probability of occurrence of a *Scorpidium* depends systematically on wetness (three classes: wet, intermediate wet, dry). The chi-square test (nominal data) and logit regression (quantitative data) are commonly used to test the null hypothesis which means that the occurrence does not depend on wetness.

1 Using proportional cover of the wetness classes to calculate the expected number of cells

Under the null hypothesis the expected number of cells containing the species in each management class is proportional to the cover percentage of each class in the region sampled:

$$e_k = N * f_k$$

e_k = the expected number of cells with the species in the wetness class k (k = 1,2,3).
N = the total number of cells with the species, and
f_k = the proportional cover of a wetness class k.

When e is obtained the chi-square can be calculated:

$$\chi^2 = \sum_{k=1..3} ((o_k - e_k)^2 / e_k)$$

o_k = the observed number of cells containing the species in the wetness class k (k = 1,2,3).
e_k = the expected number of cells containing the species in the wetness class k (k = 1,2,3).

	WET (1)	INTERMEDIATE WET (2)	DRY (3)	ROW TOTAL
observed (o)	33	44	53	130
frequency (f)	0.105	0.179	0.716	1
expected (e)	13.5	23.3	93.2	130

χ^2 = (33-13.5) ^{2}/13.5 + (44-23.3) ^{2}/23.3 + (53-93.2)^2/93.2 = 28.2 + 18.4 + 17.3 = 63.9

This is to be compared with a chi-square distribution with two degrees of freedom. The critical value at the 5% significance level is 5.99.

2 Using random points to calculate proportional cover of the wetness classes

Many site factors make it difficult to calculate the proportional cover per combination class. An approximate solution is to add to the data a large number of random points, and to determine the values of the environmental variables of each of these from the GIS. The distribution of the random points over the classes of the environmental variables should approach the proportional cover of these classes. A large number of random points approach the proportional cover better than a small number of points.

$$e_k = R_k / (R_{tot} * N)$$

e_k = the expected number of cells with the species in the wetness class k (k = 1,2,3)
N = the total number of cells with the species (observed row total)
R_k = the random number of cells in wetness class k
R_{tot} = the total number of random points (random row total = $R_1+R_2+R_3$)

CA. 1000 POINTS	WET (1)	INTERMEDIATE WET (2)	DRY (3)	ROW TOTAL
observed (o)	33	44	53	130
random (R)	66	79	1052	1197
expected (e)	7.2	8.7	114.3	130

χ^2 = (33-7.2) ^{2}/7.2 + (44-8.7) ^{2}/8.7+ (53-114.3)^2/114.3 = 92.5 + 143.2 + 32.9 =268.6

CA. 10 000 POINTS	WET (1)	INTERMEDIATE WET (2)	DRY (3)	ROW TOTAL
observed (o)	33	44	53	130
random (R)	1314	1854	7211	10379
expected (e)	16.5	23.2	90.3	130

χ^2 = (33-16.5) ^{2}/16.5 + (44-23.2) ^{2}/23.2 + (53-90.3)^2/90.3 = 16.5 + 18.6 + 15.4 = 50.5

Both chi-square values are to be compared with a chi-square distribution with two degrees of freedom. The critical value at the 5% significance level is 5.99.

3 Using random points to represent absence points for chi-square test

Each random point adds a unit for which the species is considered to be absent. The chi-square test is carried out on the data set of presences and absences created in this way. The solution is expected to work well if the size of the random sample is large compared with the number of presences of the species. The influence of the absence points on the chi-square is minimal.

$f = N / T$
$e_{pk} = f * t_k$
$e_{ak} = t_k - e_{pk}$

f = the relative overall frequency of the species occurrence
N = the total number of cells with the species present (observed presence row total)
T = total number of 'absent' and 'present' cells.
t_k = the total number of 'present' and 'absent' cells in wetness class k (k = 1,2,3)
e_{pk} = the expected number of cells with the species present in wetness class k
e_{ak} = the expected number of cells without the species (absence) in wetness class k

CA. 1000 POINTS	WET (1)	INTERMEDIATE WET (2)	DRY (3)	ROW TOTAL
observed presence (o_p)	33	44	53	130 (N)
observed absence (o_a)	66	79	1052	1197
total	99 (t_1)	123 (t_2)	1105 (t_3)	1327 (T)
expected presence (e_p)	9.9	12.3	110.5	
expected absence (e_a)	89.1	110.7	994.5	

$\chi^2 = \chi^{\text{presence}} + \chi^{\text{absence}}$

$= \sum_{k=1..3} ((o_{pk} - e_{pk})^2 / e_{pk}) + \sum_{k=1..3} ((o_{ak} - e_{ak})^2 / e_{ak})$

$= (33-9.9)^2/9.9 + (44-12.3)^2/12.3 + (53-110.4)^2/110.4 + (66-89.1)^2/89.1 + (79-110.7)^2/110.7 + (1052-994.5)^2/994.5$

$= 53.9 + 81.7 + 29.8 + 6 + 9.1 + 3.3 = 165.4 + 18.4 = 183.9$

CA.10 000 POINTS	WET (1)	INTERMEDIATE WET (2)	DRY (3)	ROW TOTAL
observed presence (o_p)	33	44	53	130 (N)
observed absence (o_a)	1314	1854	7211	10379
total	1347 (t_1)	1898 (t_2)	7264 (t_3)	10509 (T)
expected presence (e_p)	16.2	22.8	87.2	
expected absence (e_a)	1330.8	1875.2	7176.8	

$\chi^2 =$

$(33-16.2)^2/16.2 + (44-22.8)^2/22.8 + (53-87.2)^2/87.2 + (1314-1330.8)^2/1330.8 + (1854-1875.2)^2/1875.2 + (7211-7176.8)^2/7176.8$

$= 17.4 + 19.7 + 13.4 + 0.2 + 0.2 + 0.2 = 50.5 + 0.6 = 51.1$

Both chi-square values are to be compared with a chi-square distribution with two degrees of freedom. The critical value at the 5% significance level is 5.99.

4 Using random points to represent absence points for logit regression

Each random point adds a unit for which the species is considered to be absent. The logit regression is carried out on the resulting data set of presences and absences. The approximate solution works not only for single nominal predictors but also multidimensionally. The distribution of each quantitative variable is also approximated by its sample distribution. In fact, the multivariate distribution of both quantitative and qualitative variables is approximated in the sample. The more dimensions of the logit model has, the larger the random data set should be.

CA. 10 000 POINTS	DEGREES OF FREEDOM	DEVIANCE	MEAN DEVIANCE	DEVIANCE RATIO
regression	2	47	23.38	23.38
residual	10511	1397	0.13	
total	10513	1444	0.13	
change	-2	-47	23.38	23.38

In the example, the deviance test to test the effect of wetness gives a value of 47 which is to be compared with the critical value of a chi-square distribution with two degrees of freedom (Jongman et al. 1987). Logit regression on the extended data set (ca. 10 000 points) thus gives approximately the same value as the original chi-square test on the same data set (47 compared to 50.5), which in turn is close to the original chi-square (63.9).

Conclusion

The results of the chi-square and the logit regression have about the same value (approximately 50) when a large number of random points are taken. This implies that all four methods have a similar result. This confirms that logit regression approaches the chi-square test and can validly be used within this study. An advantage of logit regression compared to the chi-square test is the possibility of using quantitative variables without classifying them. The above example illustrates the need for a large random data set.

Curriculum vitae

Maria Elisabeth (Marlies) Sanders was born in Beneden Leeuwen, The Netherlands on 3 December 1967. In 1987, having completed her secondary education at the Dominicus College in Nijmegen she started to study biology at the Wageningen Agricultural University (WAU). She graduated in 1993 with nature management and remote sensing as her major subjects. Part of her study included a placement at the remote sensing department of the Institute of Terrestrial Ecology, Monks Wood Experimental Station Huntingdon, England. In 1993 she started this PhD project on remote sensing and vegetation change in wetlands at the Laboratory of Geo-information Science and Remote Sensing (WAU). In this period she worked mostly at the Institute for Forestry and Nature Research (IBN-DLO), in the department of Vegetation Ecology which funded this study. During this period she carried out projects related to her research for the National Forest Service and the Survey Department of Rijkswaterstaat. Furthermore, she spent many delighted months in De Weerribben, studying the vegetation. She currently works at IBN-DLO in Wageningen.

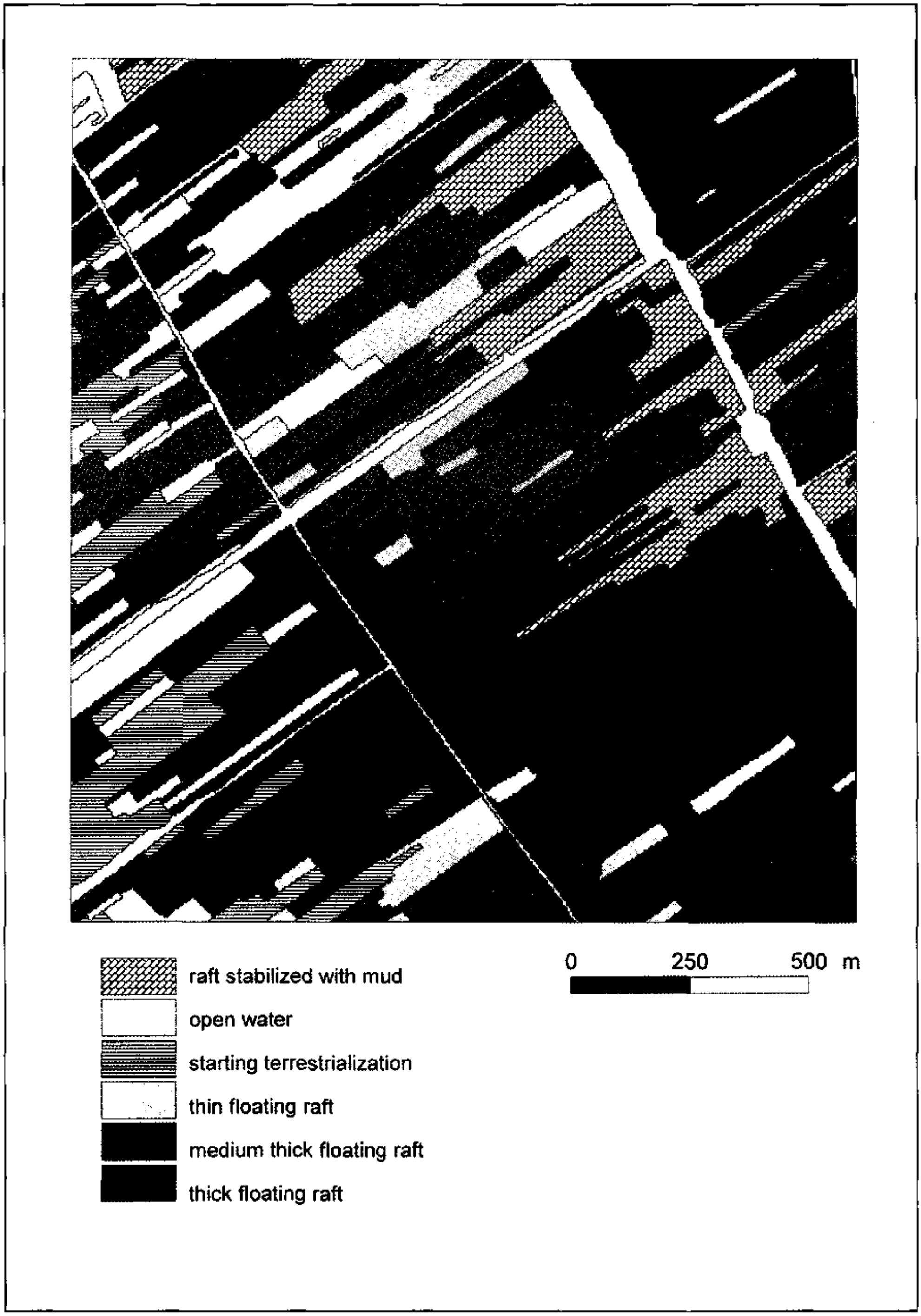


Figure 5.5
Soil map 1951 (Haans & Hamming 1962).

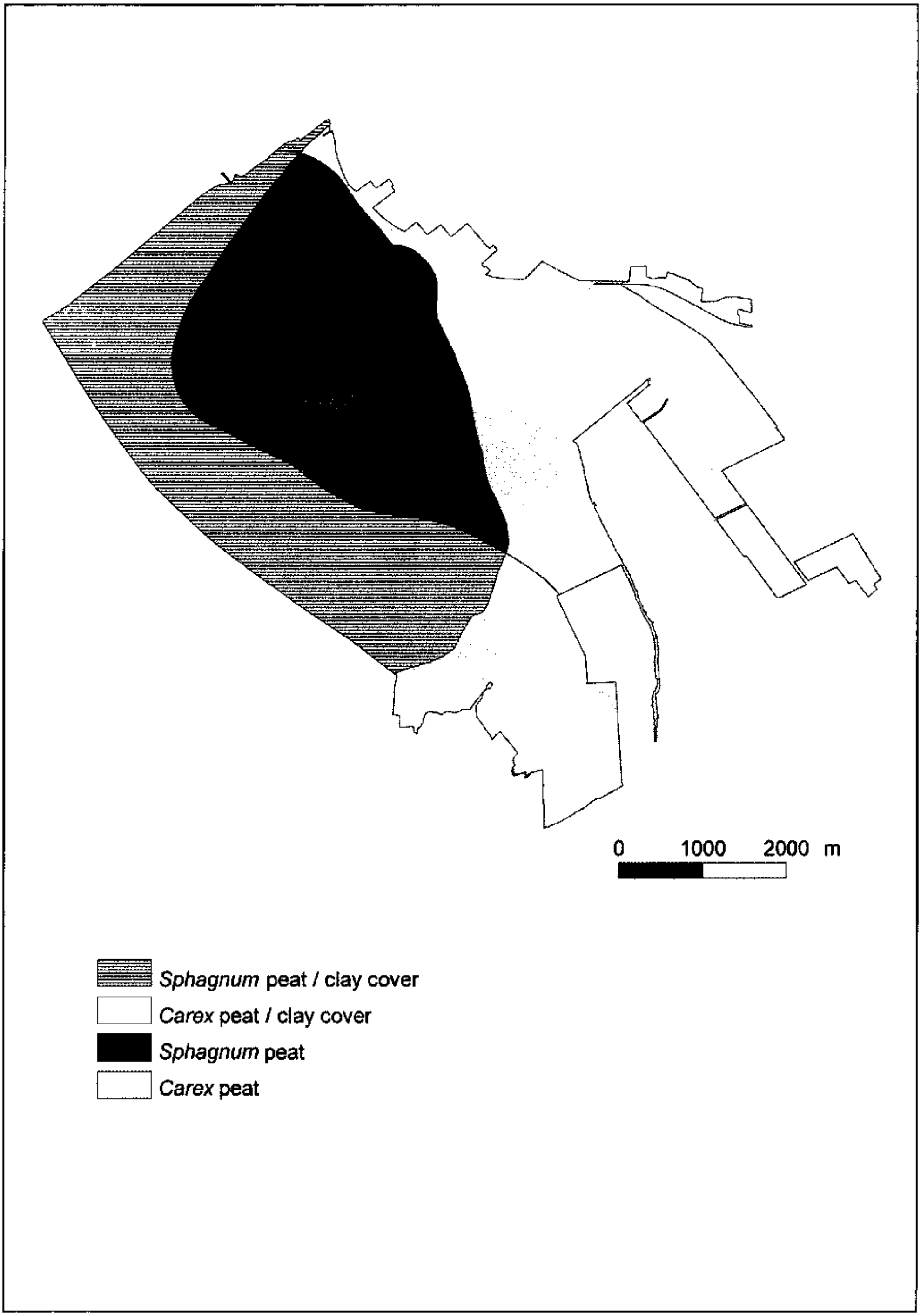


Figure 5.6
Clay cover and original peat type (Haans & Hamming 1962).

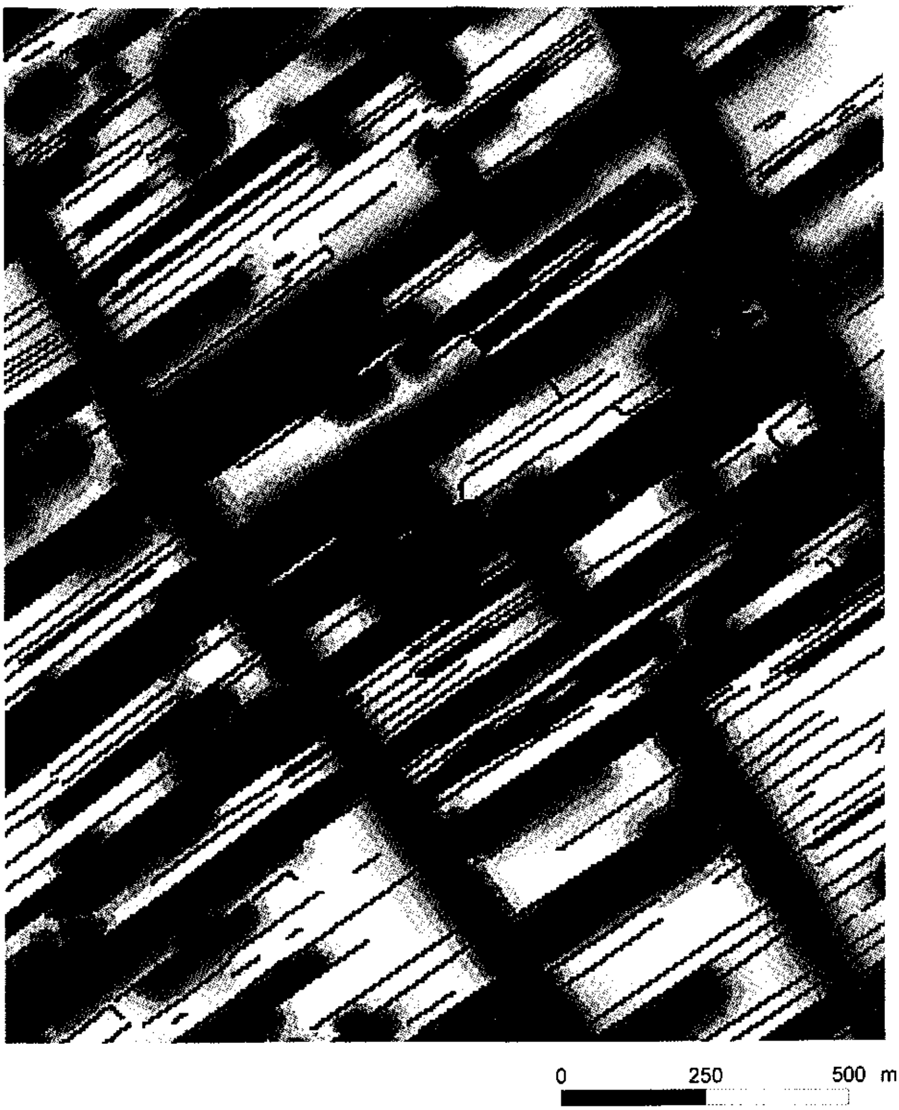


Figure 5.8
Distance to the surface water network ranging from 0 (black) up to ca. 65 m (white).

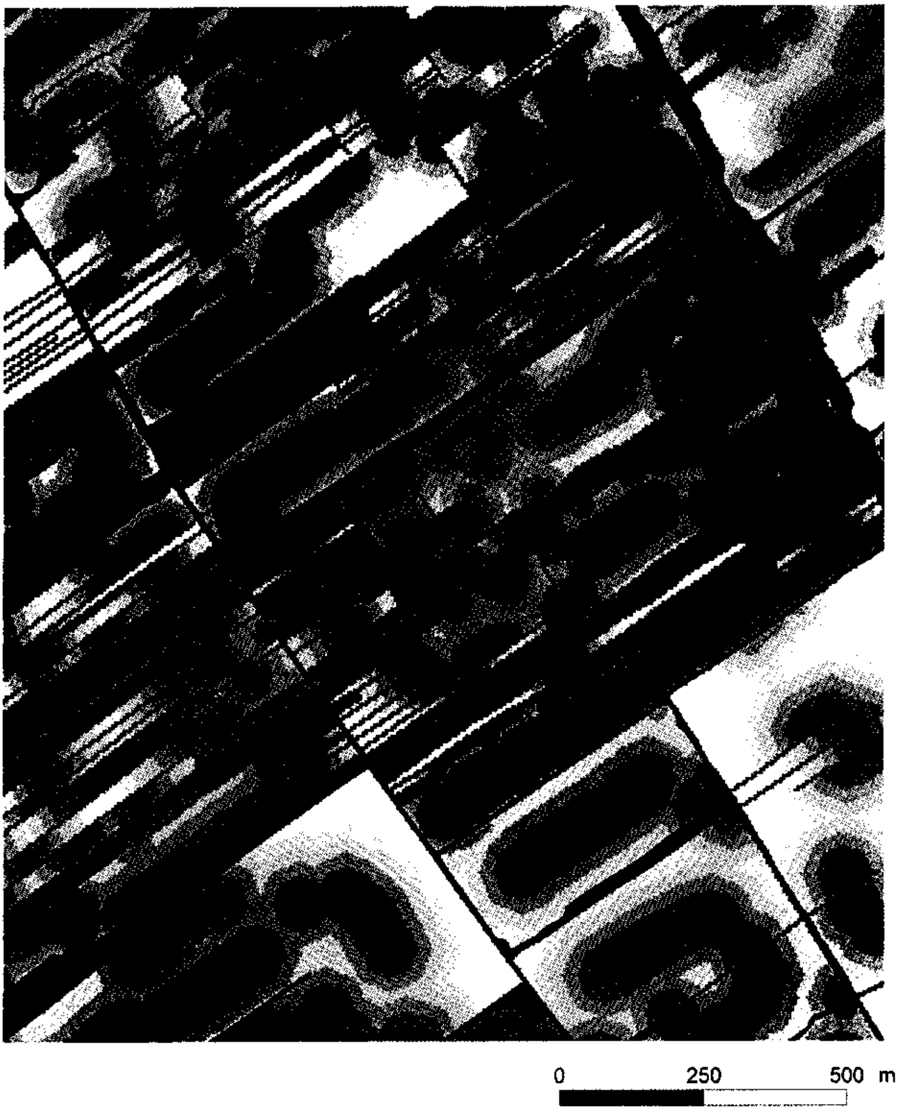


Figure 5.9
Distance to the hinterland ranging from 0 (black) up to ca. 65 m (white)

Figure 5.11
Distance to the water inlet point ranging from 0 (black) up to ca. 2000 m (white).

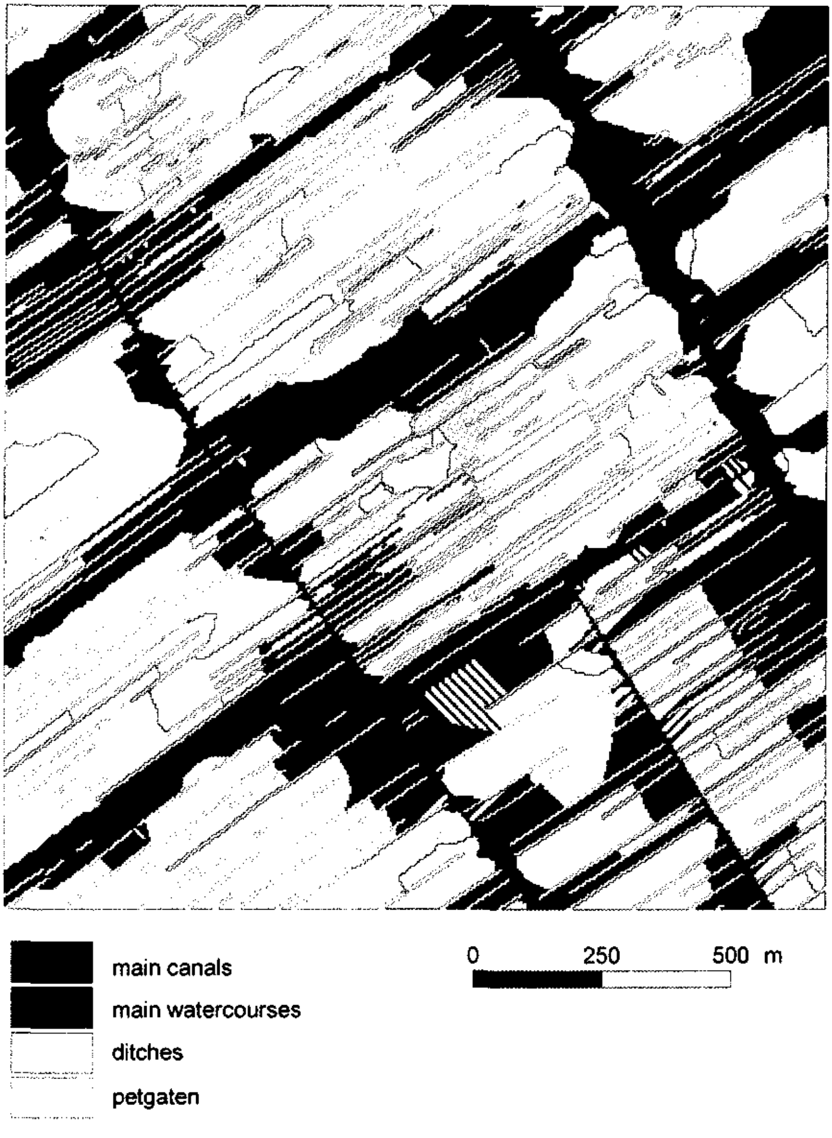


Figure 5.12
Water supply source of a grid cell.

Figure 5.15
Distribution of the random points.

Photo 4.1
False colour aerial photograph,
14 June 1986.

Photo 4.2
False colour aerial photograph,
4 May 1995.

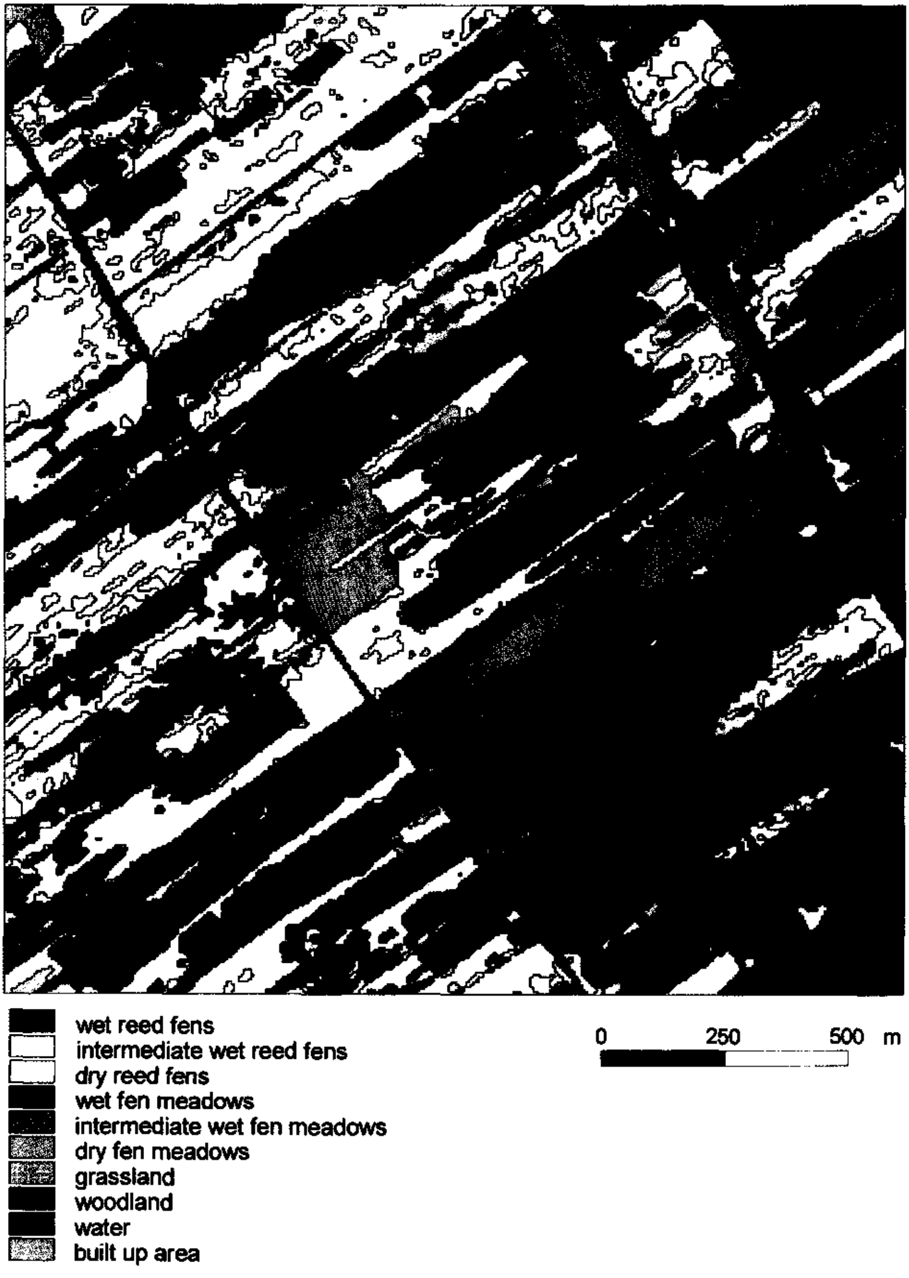


Figure 4.5
Result of image classification concerning wetness differences (combined with the photo interpretation results and management information -> RS-VS map).

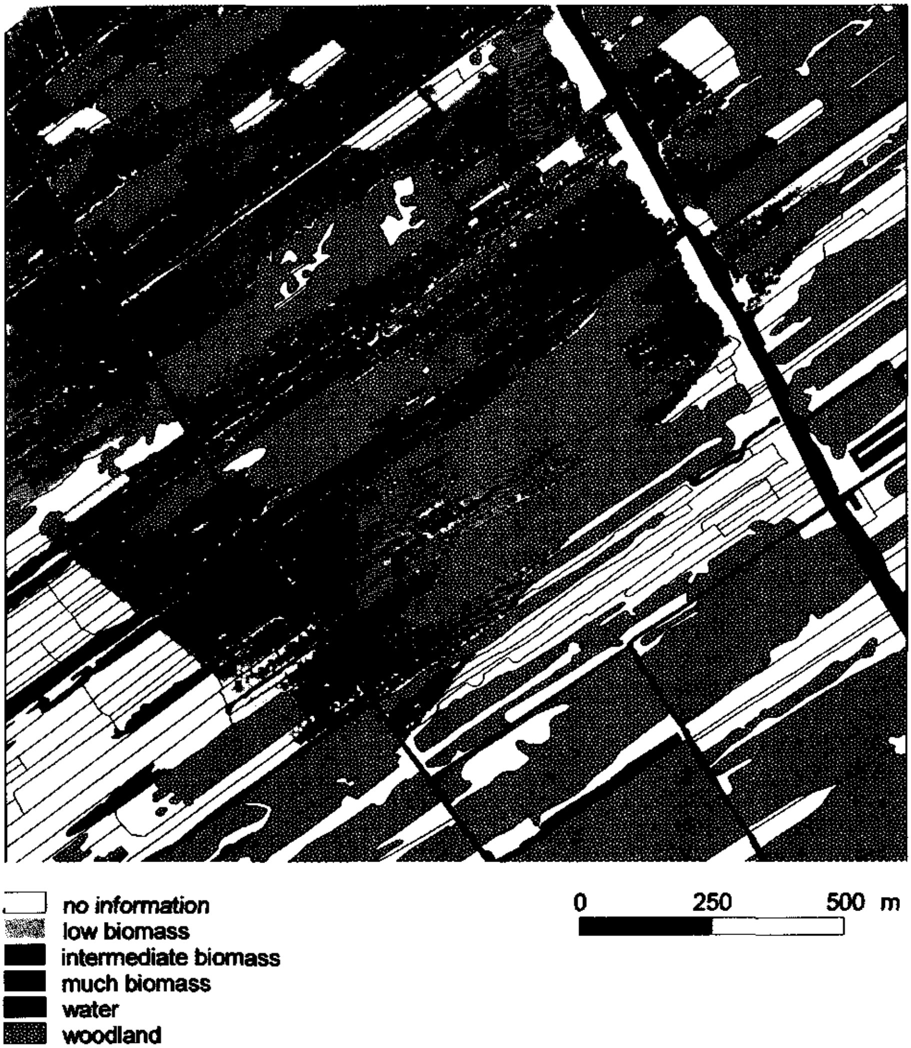


Figure 4.6

Result of image classification concerning biomass differences, combined with woodland and water from the topographic map.

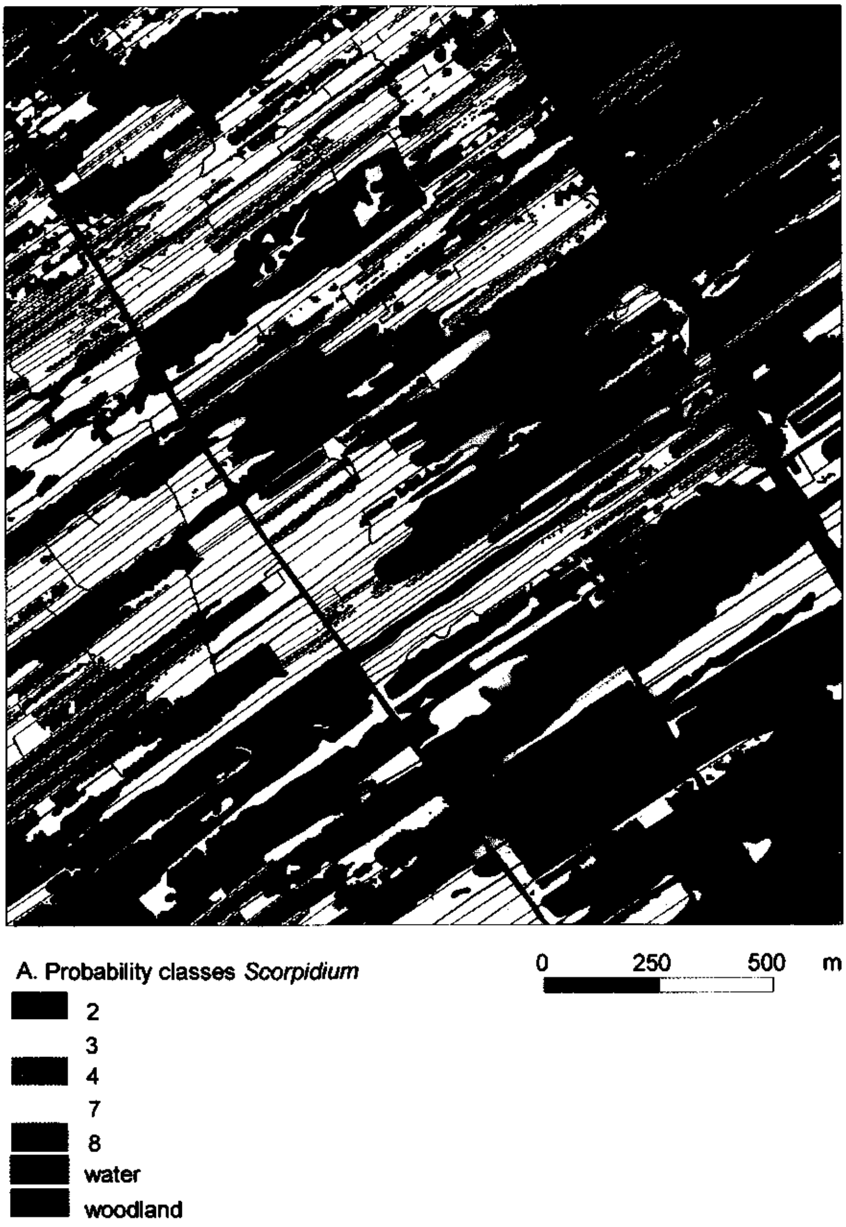


Figure 5.18
Probability map of *Scorpidium* occurrence.
A: test area
B: De Weerribben


B. Probability classes *Scorpidium*
1
2
3
4
7
8
woodland
water
0
1000
2000
m

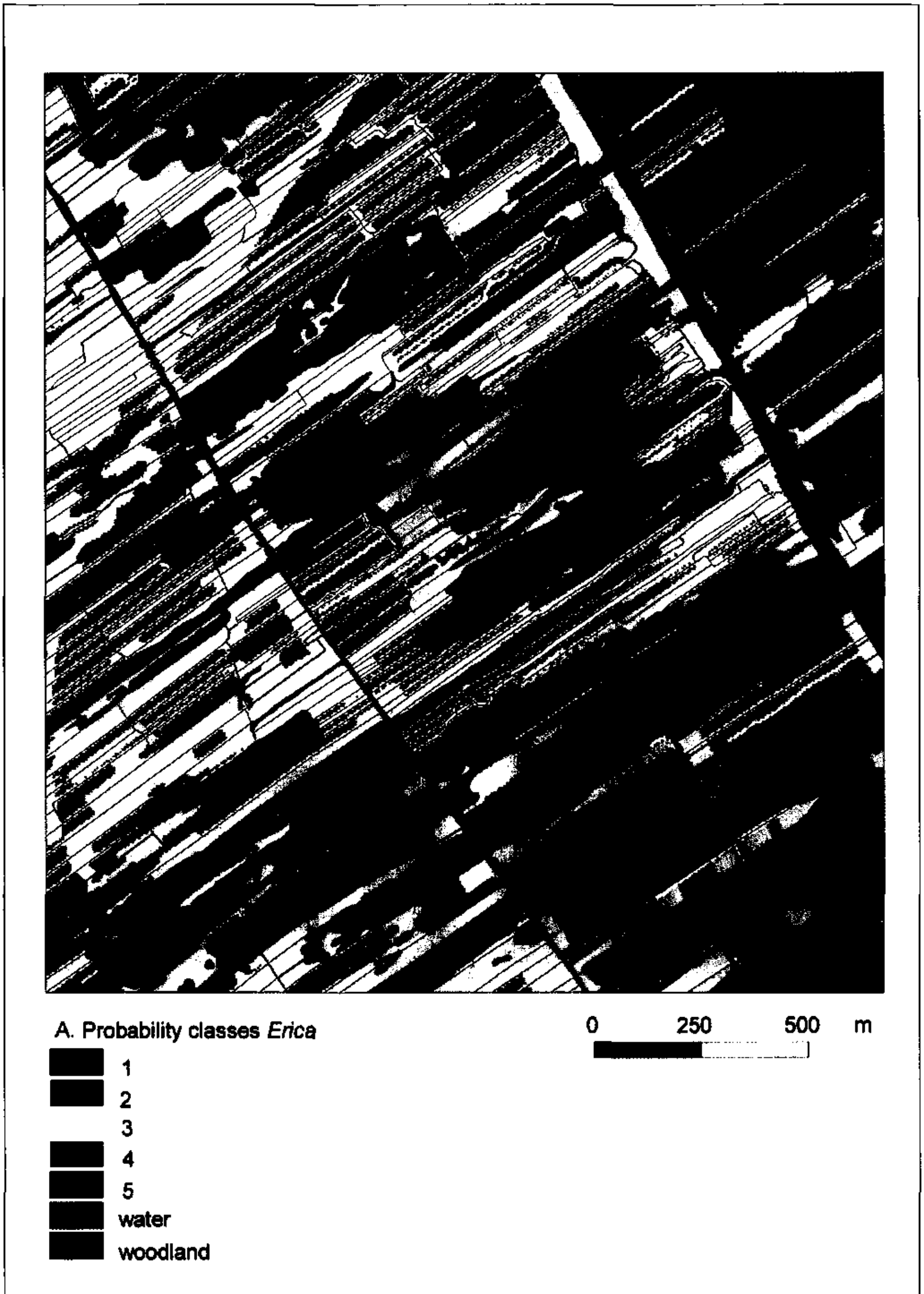


Figure 5.19
Probability map of *Erica* occurrence.
A: test area
B: De Weerribben

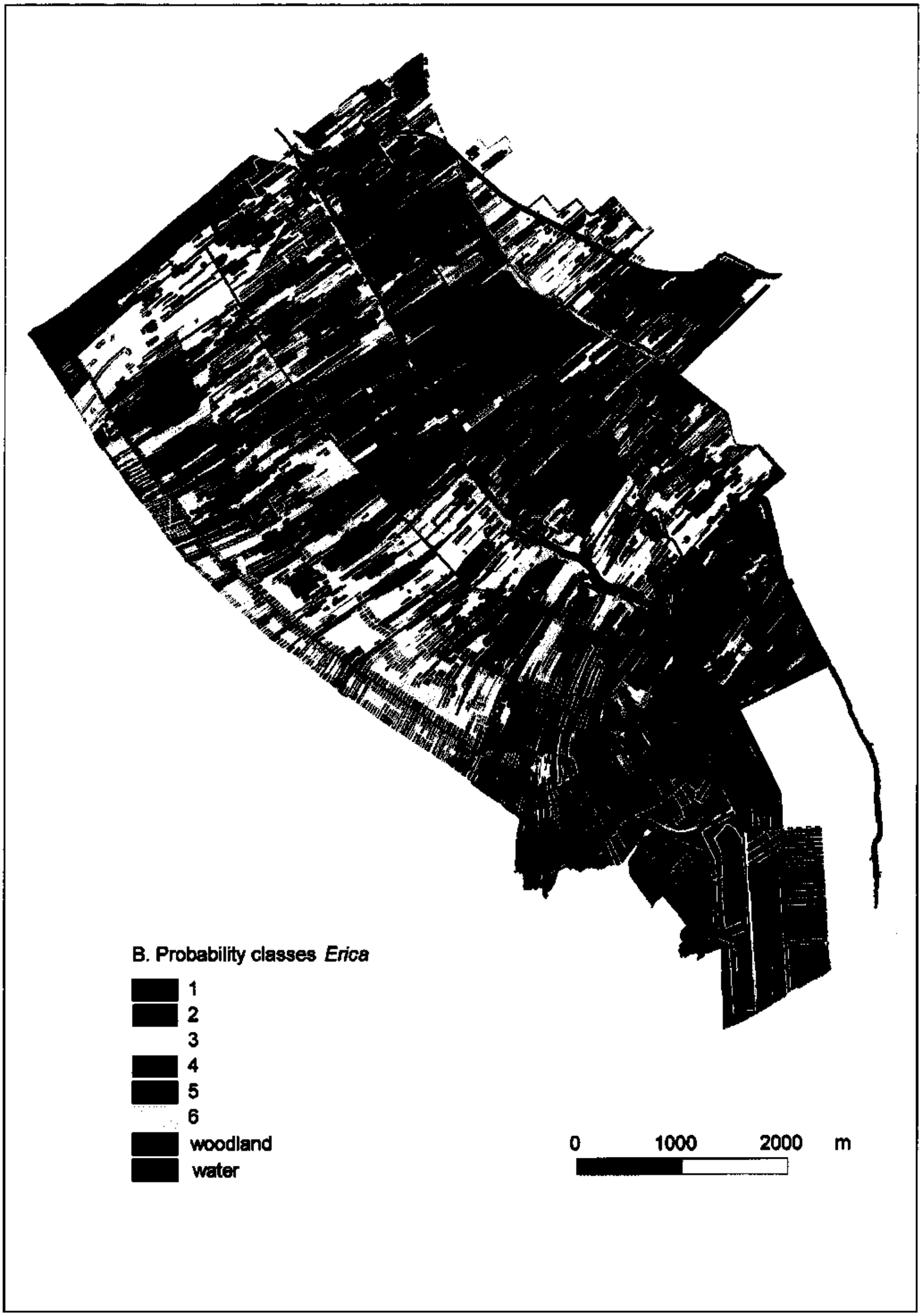

B. Probability classes *Erica*
1
2
3
4
5
6
woodland
water
0
1000
2000
m

Photo 2.1
A bird's-eyeview of De Weerribben.

Photo 2.4
Winter mowing.