

REMOTELY SENSED HYDROLOGICAL ISOLATION TO SUPPORT SUSTAINABLE USE OF FENS IN THE NETHERLANDS

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ABSTRACT

In the twentieth century many fens in The Netherlands were reclaimed for agriculture. The few fens left have a large biodiversity, which make them valuable nature reserves. Land use influences largely the vegetation structure, plant species composition and hydrology. Careless use of fens is a huge tread to their biodiversity. Aim of this study was to investigate the possibilities of remote sensing and GIS to define a hydrological model that supports sustainable land use and management practices. Remote sensing supplied hydrological parameters. A combination of aerial photo interpretation and digital image analyses of scanned false colour aerial photographs was applied. The results were input of a geographical model for hydrological isolation defined in GIS. The modelled hydrological isolation pattern was evaluated by comparing it to distribution patterns of plant species. The species represent a certain plant community, management practice and level of hydrological isolation. Statistical tests explored the relationship between observed plant species sites and the hydrological and management variables. Hydrological isolation and management turned out to be significant in explaining plant species habitat. Hence, the influence of management practices and land use on species habitat was successfully assessed with remote sensing and GIS. This implied the model's suitability to consider the pros and cons of land use changes and management practices regarding biodiversity. The method should be refined and applied to more plant species to become a more general applicable instrument.

1 INTRODUCTION



Figure 1. Location of De Weerribben in The Netherlands

Dutch inland wetlands are characterized by peat formation under specific geomorphological (floodplain) and climatic settings (mean temperature and precipitation) and human impacts (Verhoeven et al., 1992). Human impact, specifically the peat cutting and dredging in the 18th and 19th centuries formed a landscape of extensive rectangular peat ponds (ca. 30 by 1000 m) called *petgaten* (Figure 2). 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 reed fen began: the vegetation formed a floating raft (Haans & Hamming, 1962). During the 20th century most of the fens were drained and reclaimed for agricultural use. De Weerribben (3600 ha, Figure 1), now a nature reserve, is one of the remaining fen areas in the north of The Netherlands (6° 0' E and 52° 45' N).

In fens plant species composition is determined by land use and hydrology, particularly by water chemistry such as nutrient status (Verhoeven et al., 1988; Van Diggelen, 1996). Present land use comprises nature conservation, water retention, recreation and the harvesting of natural resources such as reeds and fish. 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. If harvested in summer, the vegetation is able to develop into a species-rich fen meadow. It is considered important to remove the hay, to reduce nutrient availability. Cutting reeds in winter (Figure 3) benefits reed production. Much water in De Weerribben is seeped away because of the low water level of the surrounding polders. 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. Base-rich and nutrient-rich surface water is let in to maintain the water level necessary for water retention. This water causes fens to become eutrophied, which leads to an increased biomass production. When parts of fens become isolated from surface water (hydrological isolation), it acidifies due to the dominance of acidic and oligotrophic rainwater.

The usual method to quantify the influence of land use and hydrology on biodiversity is fieldwork, but this is time consuming and thus very expensive, especially in large, inaccessible areas like wetlands. The objective of this study was to identify the possibilities of remote sensing and GIS to model hydrological isolation. The intend was to provide land use management with spatial quantitative information to support sustainable use of fens in The Netherlands.

Using GIS and remote sensing the study attempted to accomplish the following tasks:

- modelling hydrological isolation in GIS
- using remote sensing to obtain input for the hydrological model
- applying the model to assess plant species habitat.

2 METHOD

2.1 Hydrological isolation

A gradient of surface water influence determines plant species distribution. The surface water network is the source of base-rich water. A lateral influx of surface water compensates water loss to the surrounding polders. 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 driving force is the hydrostatic pressure maintained by water loss and thus proportional to the hinterland area. The hydraulic resistance is inversely proportional to the permeability. 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. In this model 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 (Darcy's law), is equal to the amount of water loss of the hinterland (equation 1).

$$H * (E + D - P) = k * A * dh / dL \quad (1)$$

H = hinterland area (m²)

E = evapotranspiration (m/day)

D = infiltration or discharge (m/day)

P = precipitation (m/day)

A = cross section (m²)

dh = water level rise (m)

dL = length (m)

k = permeability (m/day)

dh/dL = driving force

All site factors of equation 1 can be derived from maps or reports, enabling dh to be calculated. Rearranging equation 1 gives:

$$dh = H * (E + D - P) * dL / (A * k) \quad (2)$$

According to Vegt (1978), the degree of the hydrological isolation depends on the magnitude of water level fluctuations. The magnitude of the water level fluctuations was also 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). 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:

$$H_{i_y} = \sum_{x \in R_y} dh \quad (3)$$

H_{i_y} = the hydrological isolation of site y

R_y = the set of sites (x) that connect site y with the nearest water source
(the set R_y includes site y).

The parameters mentioned above were used to model hydrological isolation (equation 5) in the grid module of Arc/Info (Esri, 1994). The resolution of the grid was chosen $5 * 5 \text{ m}^2$, which is quite detailed and still manageable in a GIS. A site was considered synonym to the grid cell. Average values for precipitation (P), evapotranspiration (E) and infiltration (D) for the entire reserve were used because spatial data was not available. An average D of 1 mm/day was obtained from Hoogendoorn & Vernes (1994). The dimensions of the grid cell determine 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 following factors determine spatial variability in hydrological isolation:

- The thickness of the floating raft determines hydraulic resistance because the water below it has a higher permeability than the raft. A map with floating raft thickness classes (Haans & Hamming, 1962) was reclassified taking the permeability classes of Van der Perk and Smit (1975): very thin floating raft (1500 m/day), thin floating raft (178 m/day), thick floating raft (44 m/day).
- The hinterland area: the area between any site and the most hydrologically isolated site. De hinterland area was obtained by distance measures in GIS.
- The position of peat baulks: peat baulks are much more resistant to water through flow than floating rafts (Van der Perk & Smit, 1975), because they consist of clay or original peat that is denser than the root mat of the floating raft. Their permeability was considered negligible and they, therefore, form hydrological barriers. The peat baulks were mapped with remote sensing.
- The topology of the surface water network: this network of channels, petgaten and ditches supplies base-rich water. The distance from the network was considered to be one of the factors that determines the magnitude of the surface water influx. The surface water network was mapped with remote sensing.
- Irrigation was 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. Irrigation can be mapped with remote sensing.

2.2 Remote sensing

Vegetation classification based on aerial photography is a very difficult task because fen ecosystems are characterized by many plant species and gradients. When variables obtained by remote sensing are indicative for hydrological conditions, they offer information on species composition in an indirect way. Interpretation based on expert knowledge of the spectral values coincide with differences in biomass (Box et al. 1989; Tomer et al, 1997) of the vegetation and wetness of the floating raft. Wetness is defined as the amount of water on the floating raft. 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. Aerial photographs can be used for digital image processing (Lobo et al., 1998; Tomer et al., 1997; Sanders et al., 1997).

False colour photographs 1:22000 from May 1995 (Figure 4) were used for digital image processing and analogue interpretation. In early spring the vegetation is not developed and wetness is therefore the main feature. The photographs were scanned with 600 dots per inch and the image was georeferenced to the Dutch coordinate system and resampled to 1 m resolution in Imagine (Erdas Imagine Fieldguide, 1991). Radiometric distortion due to light fall off and sun angle was minimized by using only the middle parts of the images for analysis and by applying a histogram match. Comparison of absolute reflectance between images would require calibration by placing ground reference targets with known reflectance values. This means that the digital values are relative and best interpreted in terms of variability observed within the image. Visual photo interpretation was used to map watercourses and petgaten, peat baulks, reed fen and woodland because they were easily recognized thanks to their contrasting reflectance, texture and sharp boundaries. Within the reed fen segment digital image processing supplied information on wetness gradients. Unsupervised classification was used to classify the scanned photographs in "wet", "intermediate wet" and "dry". Contemporaneous ground truth on wetness was not available to evaluate the results. However, vegetation types mapped by fieldwork (Staatsbosbeheer, 1988) implicitly contain information on wetness. The vegetation types were defined by species responding to certain environmental conditions including wetness. This enabled the similarity between the spectral

classes and the vegetation types to be investigated. The vegetation types were grouped into wetness classes to make a one to one comparison possible (Sanders & Clevers, 1999). Random points were used to compare the vegetation types with the spectral classes because it would have cost too much effort to digitize the vegetation map. For each point, the accompanying vegetation type was looked up on the map, digitized and combined with the spectral classes in a GIS.

2.3 Plant species habitat

The plant species used in this study were selected for their expected ecological significance regarding to hydrology and vegetation management. *Scorpidium scorpioides* (Hedw.) Limpr and *Erica tetralix* L. were used to evaluate the model. *Scorpidium* is a rare moss indicative of wet base-rich conditions and an early stage of terrestrialization. The species is characteristic for the plant community Scorpidio-Caricetum diandrae. This typical rich-fen vegetation is a very species-rich and valuable vegetation type. 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). *Erica* is a dwarf shrub indicative of drier base-poor conditions and an advanced stage of terrestrialization. The species is characteristic for the plant community Sphagno palustris-Ericetum. This is a typical fen-bog vegetation. 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). Point-distribution maps (Figure 5) of *Scorpidium* and *Erica* were made for the management plan (Staatsbosbeheer, 1988) by vegetation mapping in 1985. Their scale is 1:25000.

Statistical tests were used to assess the relationship between observed plant species sites and the hydrological and management variables. The statistical tests require presence and absent points of species occurrence. The distribution of absence points must be representative of the coverage of all site factor classes, to prove that species distribution is not evenly distributed over all site factor classes. The absences were obtained by generating many random points (Sanders, 1999). The presences were on the point distribution maps. The point maps were combined with maps of the site factors. The statistical tests were executed in GENSTAT (Genstat 5 Committee, 1987). The marginal test is based on a simple regression, which takes account of only one site factor at a time. The conditional test analyses the significance of a variable taking in account all other variables at the same time. The statistical tests were applied to management type (reed cutting, summer mowing), wetness classes (wet, intermediate wet, dry), the hydrological isolation patterns (numeric) and to the components of the model such as distance to the surface water (numeric), the amount of hinterland (numeric) and the raft thickness (very thin, thin, thick). The significant site factor classes that determine the probable habitat characteristics were obtained with the predict command in GENSTAT.

3 RESULTS AND DISCUSSION

The result of the remote sensing interpretation and classification is a map of wetness classes (wet, intermediate wet, dry), forest, watercourses and peat baulks (Figure 6). The geometric accuracy is ca. 5 m. The wetness classes were evaluated by comparing them to a vegetation map (Staatsbosbeheer, 1988). The overall classification accuracy of the remotely sensed wetness classification is 76%. This percentage is only indicative because there is a time gap of ten years between collecting the field data and recording the photographs. Ideally, the recordings of the photographs and field data would be within the same year, which would probably result in a higher overall accuracy. Yet in spite of the influence of such interference, the spectral classes correspond reasonably well to the vegetation types.

The result of the hydrological model is a map of the hydrological isolation (Figure 7). It was to complicated to evaluate the map with field data. The accuracy depends on the input remote sensing interpretation and is therefore assumed to be around 5 m. The thematic content was evaluated by comparing it's patterns with the distribution of indicative plant species. The results of the evaluation executed with statistical tests are given in Table 1.

Site factor	Marginal test		Conditional test	
	<i>Erica</i>	<i>Scorpidium</i>	<i>Erica</i>	<i>Scorpidium</i>
Distance to open water	**	Ns	Ns	Ns
Distance to hinterland	Ns	Ns	Ns	Ns
Wetness classes	***	***	***	***
Raft thickness	***	***	***	***
Management	***	Ns	***	Ns
Hydrological isolation	***	***	Ns	Ns

Table 1. Statistical significance of site factors predicting the species occurrence obtained with marginal en conditional tests (* = 0.01 < p <= 0.05; ** = 0.001 < p <= 0.01; *** = p <= 0.001; Ns = p > 0.05).

The calculated hydrological isolation appears to be very significant in predicting species occurrence, except when other site factors, such as wetness, were taken into account. An explanation might be the 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. The Hi model can become more complete and its usefulness in predicting species occurrence will probably increase when wetness is taken into account and spatial information on evapotranspiration and infiltration becomes available for the entire area. Evapotranspiration is proportional to biomass and wetness that can be obtained by remote sensing.

Site factor	<i>Erica</i>	<i>Scorpidium</i>
Wetness	Dry	Wet
Raft thickness	Thick	Thin
Management	Summer mown	Ns

Table 2. Significant site factor classes

The significant site factors classes (Table 2) for both species agree closely with the environmental needs of *Scorpidium* and *Erica* found in literature. The results of the statistical test show that *Erica* occurs more often in areas where the raft is relatively thick, dry and the vegetation is summer mown. *Erica* was assumed to be indicative of base-poor and oligotrophic conditions. Base supply and surface water influence decrease with increasing thickness of the floating rafts. The results of the statistical tests show that *Scorpidium* occurs more often in areas where the floating raft is thin and wet. It is a species indicative of base-rich conditions and a beginning stage of terrestrialization. When the floating raft is thin and submerged, base supply will be relatively large. 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.

4 CONCLUSIONS

Hydrological isolation represented the influence of the base-rich and eutrophic 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. 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. It is possible to refine the model in the future because remote sensing offers information on biomass and wetness that can be used to estimate differences in evapotranspiration. 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 optimise field sampling, for land use planning and evaluation, and in scenario studies.

The model is suitable to prioritise management practices to support sustainable land use. The site factors indicate valuable sites with a high probability of plant species occurrence that are vulnerable. Identifying these vulnerable areas makes the method suitable to support sustainable land use planning. It is very important to study the possible impact of a new management regime before it is carried out; like digging ditches, change of water inlet, irrigation, mowing or cutting regime. To change for example from summer mowing to reed cutting might be such a scenario. GIS analyses of the results will lead to statements about the decrease or increase of potential habitat and their spatial changes, especially in relation to species whose distribution was well predicted by management type. The method should be applied to more plant species or species groups to become a more general applicable instrument.

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Figure 2. A bird's-eye view of De Weerribben



Figure 3. Reed cutting in winter

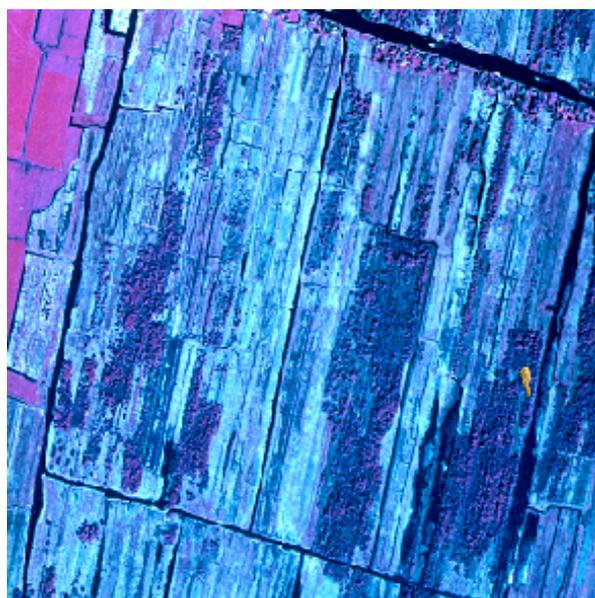


Figure 4. False colour aerial photograph May 1995

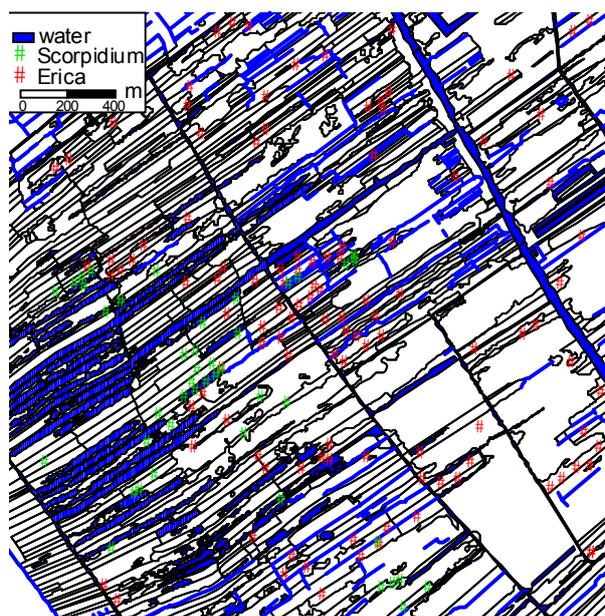


Figure 5. Point distribution map of plant species

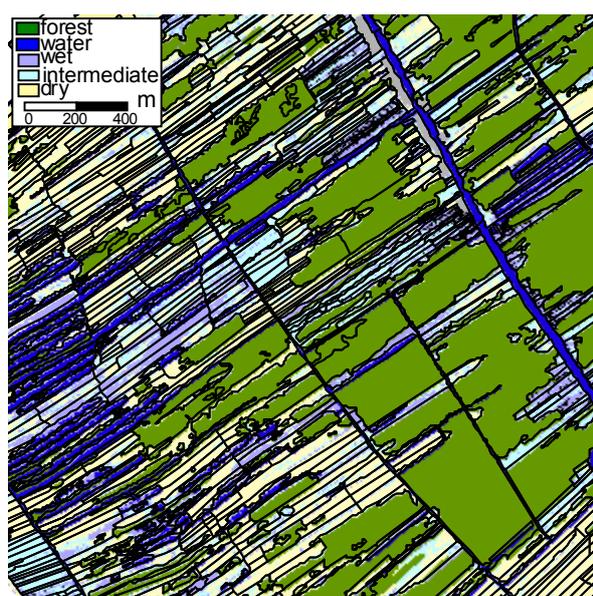


Figure 6. Photo interpretation and classification results

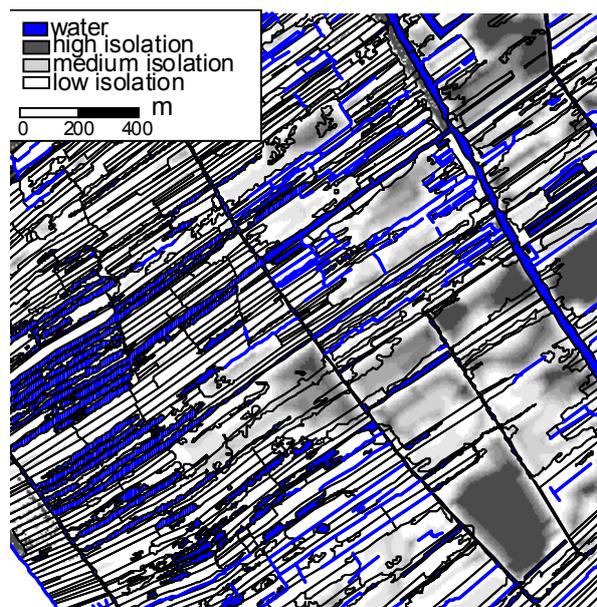


Figure 7. Hydrological isolation patterns