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Digital false colour aerial photographs for discrimination of aquatic macrophyte species

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Abstract

Digital false colour aerial photographs of four areal samples of three lakes in the Vuoksi drainage basin, Finland, that differ in trophic state and water quality were used to clarify the reflectance characteristics of various life forms and species of aquatic macrophytes at green, red and near-infrared (NIR) wavelengths. The results indicated that the classification of aquatic macrophytes is affected by the density of the vegetation, the openness of the canopies and the amounts, forms and orientations of the leaves. A dense helophyte vegetation differed from nymphaeids in having a higher reflectance in the near-infrared wavelength area than at green or red wavelengths, whereas a sparse helophyte vegetation eventually merged with nymphaeids, and the reflectance properties of the sparsest vegetation of all the life forms did not differ from those of unvegetated water areas. In general, the best classification accuracies (80–91%) were achieved when aquatic macrophytes were categorized according to life forms or phenotype groups and not species. The macrophyte categories differed from one area to another due to variation in species composition and density. In lakes with good Secchi disc transparency, classification was disturbed by reflectance from the lake bottom, while in lakes with a low Secchi disc depth, the substances contained in the water had an effect on the total reflectance.

Keywords: Digital false colour aerial photograph; Aquatic macrophytes; Helophytes; Nymphaeids

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1. Introduction

Traditional approaches for surveying the macrophyte composition of an aquatic vegetation are based on ground measurements, e.g. the transect, quadrat and zone methods (e.g. Mueller-Dumbois and Ellenberg, 1974; Chapman, 1976). These give accurate information on aquatic macrophytes, but are time consuming when used for mapping large areas. Remote sensing can offer a supplementary and time-saving means of achieving a better spatial picture.

Aerial photographs are the most commonly used form of remote sensing data for mapping aquatic vegetation (Lehmann and Lachavanne, 1997), and the manual data, photographs and slides that are still widely used for this purpose can be digitized afterwards (e.g. Welch and Remillard, 1988; Porter et al., 1997; Ward et al., 1997). Digital images are an improvement over manual ones in that they provide better geographical positioning and geometrically rectified images can be superimposed on and compared with other geographical data in order to study the interactions between parameters or temporal changes (Welch and Remillard, 1988; Jensen et al., 1992; Lehmann et al., 1997; Narumalani et al., 1997; Williams and Lyon, 1997). If the aerial data are in digital form, digital images can be visually photo-interpreted on a screen. Interpretation based on spectral sorting, i.e. differences in digital number (DN) values, is a way of automating image analysis (Lehmann and Lachavanne, 1997; Lehmann et al., 1997). In addition to aerial photographs, satellite, video and airborne multi-spectral scanner data have been used for surveying aquatic vegetation (Jensen et al., 1986; Ackleson and Klemas, 1987; Armstrong, 1993; Jensen et al., 1995; Norris et al., 1997; Ward et al., 1997; Zhang, 1998). Aerial photographs have an advantage in that they are cheaper to acquire than airborne multi-spectral scanner data and have a better spatial resolution than satellite images. Another great advantage is that data can be acquired under ideal cloud cover conditions (Jensen et al., 1993), which is a drawback with satellite data. One disadvantage is the poorer spectral resolution of aerial photography, especially compared with airborne multi-spectral scanner data (Jensen et al., 1986).

A combination of the green, red and near-infrared (NIR) wavelengths, i.e. bands, has proved to be the most appropriate for aquatic macrophyte discrimination when studying the differences in the reflectance of given species using spectroradiometric measurements and Airborne Thematic Mapper (ATM) imagery data (Malthus and George, 1997). Previous studies of the reflectance characteristics of selected aquatic macrophyte species have shown that their reflectance is influenced by the amount and geometry of the foliage, the density or openness of the canopies and the depth and quality of the water above and near the vegetation (Ackleson and Klemas, 1987; Armstrong, 1993; Penuelas et al., 1993; Malthus and George, 1997). Most of the helophytes and nymphaeids, at least above moderate density values, have similar reflectance curves to terrestrial vegetation, and curves of this kind are also typical of underwater vegetation if sufficiently dense and not growing too deeply or in a manner dependent on water quality (Armstrong, 1993; Penuelas et al., 1993; Malthus and George, 1997). One characteristic of such curves is a distinct increase at the red/infrared boundary (Malthus and George, 1997), because of the strong reflectance of the vegetation compared with the water and the underlying bottom in the near-infrared band (Engman and Gurney, 1991).

The reflectance properties of water are highly dependent on its quality (Engman and Gurney, 1991). Blue light has the best penetration property in the clearest natural waters, and the infrared energy is effectively attenuated because of absorption by pure water (Smith and Baker, 1981; Engman and Gurney, 1991). The presence of inorganic and organic substances increases the reflectance at visible wavelengths and changes the reflectance peaks from blue light to longer wavelengths (Bricaud et al., 1981; Engman and Gurney, 1991; Pierson et al., 1999). Secchi disc depth is dependent on the amounts of substances present in the water (Engman and Gurney, 1991), and it also affects the visibility of the underlying bottom, along with water depth. The presence and amount of phytoplankton can be estimated with the aid of single or multi-band algorithms based on the wavelengths that appear to have a reflectance or absorption maximum for phytoplankton and a low correlation with other water quality parameters such as non-organic substances (Mayo et al., 1995; Arenz et al., 1996; George, 1997; Kallio et al., 2001). Surface roughness, i.e. the magnitude and direction of waves, can also have an effect on the detection of aquatic macrophytes, and for this reason a knowledge of the wind speed and direction prevailing at the time of image acquisition is important (Ferguson and Korfmacher, 1997).

The aim of this study was to explore the suitability of digital aerial photographs for aquatic macrophyte mapping and to determine how the various life forms of aquatic macrophytes, especially helophytes and nymphaeids, and separate aquatic macrophyte species differ in their reflectance characteristics in certain wavelength areas. In addition, attention will be paid to the main factors interfering with discrimination. The results will be used to assess the suitability of remote sensing combined with GIS as a monitoring method for mapping aquatic macrophyte vegetation in accordance with the Water Policy Framework Directive of the European Union (EU—Water Framework Directive, 2002). The term aquatic macrophyte is used here in a broad sense to apply to both the aquatic vegetation and species present in the shore vegetation, but restricted entirely to vascular plants.

2. Materials and methods

2.1. Lakes studied

The lakes surveyed for this purpose, Onkivesi (63°10′–63°25′N, 27°10′–27°25′E), Haukivesi (61°56′–62°12′N, 27°50′–28°50′E) and Puruvesi (61°42′–62°02′N, 29°15′–29°50′E), are located in the Vuoksi drainage basin, which forms the core of the Finnish Lake District. Separate samples, N. Onkivesi and S. Onkivesi, were obtained from the northern and southern parts of Onkivesi.

2.2. Data

The aerial photographs were acquired in summer 2000, the flights over Onkivesi taking place between 12:00 and 12:30, local time, on 26 August and those over Haukivesi and Puruvesi between 9:15 and 9:30 on 18 August. The photographs were taken with a Leica RC30 camera equipped with a 153.28 mm focal length lens, using Kodak Aerochrome II Infrared Film 2443 and a combination of a filter cutting out 20% of the reflectance in the near-infrared band and an anti-vignetting coating to prevent the light falloff phenomenon (Lillesand and Kiefer, 1994; Roberts, 1995). The wavelength sensitivities of the film type were situated in the green (500–575 nm), red (575–675 nm) and near-infrared (675–900 nm) wavelength areas (Teng et al., 1997). A strict flight planning method was followed to ensure optimal data acquisition. The aerial photography coincided with the period of maximum abundance of aquatic macrophyte vegetation. The minimum useful solar elevation angle was deemed to be 33°, in order to avoid long shadows on the shores. Optimum weather conditions were defined to be clear sky and wind not higher than 4.0 m s^{-1}. The other flight parameters were: scale, 1:20,000; endlap, 80%; and sidelap, 30%. The scale was chosen to cover enough terrestrial area in each image for geometrical correction. A scanning resolution of 28 μm produced a spatial resolution of 0.5 m, which was considered to provide sufficiently exact information for species discrimination with a file size (200 Mb) that was still manageable. An endlap of 80% was chosen in order to acquire a glint-free image mosaic.

The reference data on aquatic macrophytes were collected by the transect, zone and 3 m × 3 m quadrat methods for 17 transects marked with white crosses on the ground before the flights in order to define their location and direction as exactly as possible on the images. Also specific reference areas were surveyed using Trimble Geo Explorer 3 GPS equipment. The transect data were collected from 1 m^2 quadrats located at variable intervals depending on the uniformity of the vegetation, until the outer limit of the aquatic vegetation was reached. The following parameters were recorded for each quadrat: species composition, density, coverage and frequency, height of the three highest individuals of helophytes, water depth and bottom quality. Zone data were collected in an areas of width 10 m on certain sides of the transects. The vegetation was divided into zones according to the change in life forms. The zone data contain information on species composition and abundance. Areas of size 3 m × 3 m were delineated amongst the *Nuphar lutea* and *Phragmites australis* vegetation, the density and coverage of *Nuphar lutea* and respective water depths being measured in every 1 m^2 quadrat together with the heights of the three highest individuals of *Phragmites australis* and the fresh biomass of the same species. The locations of the 3 m × 3 m areas on the transects were determined at random. The reference areas were dispersed throughout each study area in order to involve different species and densities of aquatic macrophytes. Species composition and density, height of the three highest individuals of helophytes, water depth and bottom quality were recorded for five randomly chosen quadrats in each area. The entire field survey for Onkivesi was performed within a few weeks of the flights (from 30 August to 7 September), while in the case of Puruvesi and Haukivesi, the reference and 3 m × 3 m area measurements were performed after the flights (on 22 and 29 August, 6 and 7 September) and the other surveys before the flights (from 17 July to 11 August).

2.3. Methods

The aerial photographs were geo-referenced to Finnish digital base maps of scale 1:20,000 using approximately 20 ground control points for each image. The impact of bi-directional reflectance on the aquatic macrophyte vegetation was evaluated and when shown to be strong, the brightness variations were reduced by a method developed by Pellikka (1998). For image manipulation purposes, the areas used in the classification were combined from different images if there was specular reflectance in the images or if the area was situated on several images. Since terrestrial areas were not a target of interest, they were eliminated using a mask derived from the Finnish digital base map, scale 1:20,000. The maximum likelihood supervised classification method was used at the classification stage, the training areas for the algorithm being assessed according to the field survey results. An important part of supervised classification is accuracy assessment (Lillesand and Kiefer, 1994; Pellikka, 1996), the accuracy of a vegetation category in the classified image being defined by counting all the misclassified and correctly classified pixels in the training area. Altogether 96 areas in N. Onkivesi, 87 in S. Onkivesi, 38 in Haukivesi and 31 in Puruvesi were used as training areas for classification and accuracy assessment. In addition, in order to determine the factors which interfere with the classification of aquatic macrophytes, training areas were chosen in different depth zones of unvegetated water areas, mainly with muddy bottoms in Onkivesi and with sandy bottoms in Haukivesi and Puruvesi. The image manipulation and classification and the pre-processing stages that preceded this were performed using the Erdas Imagine image processing software. Despite the fact that the DN values of the 8-bit data were not converted to absolute reflectance values by absolute calibration, the term reflectance will be used in the discussion later to characterize the reflectance from the water and vegetation canopies.

3. Results

3.1. Vegetation composition

Helophytes and nymphaeids were the dominant life forms in Onkivesi. Several species of elodeids were present, especially in N. Onkivesi, one ceratophyllid species was found only in S. Onkivesi, and lemnids were present in both. Isoetids were totally absent. In Haukivesi and Puruvesi helophytes and isoetids were the most frequent life forms, but nymphaeids, elodeids and lemnids were also found. *Phragmites australis* was the most frequent among the helophytes in all the four areas, *Nuphar lutea* among the nymphaeids, *Sparganium* species among the elodeids in Onkivesi and Haukivesi at least, and *Isoetes lacustris* among the isoetid species in Haukivesi and Puruvesi. The 10 most frequent species of aquatic macrophytes in the areas concerned are listed as shown in Table 1.

Table 1
The 10 most frequent species (or genera) of aquatic macrophytes in the four areas

N. Onkivesi	S. Onkivesi	Haukivesi	Puruvesi
Nuphar lutea	*Phragmites australis*	*Phragmites australis*	*Isoetes lacustris*
Phragmites australis	*Nuphar lutea*	*Isoetes lacustris*	*Lobelia dortmanna*
Potamogeton natans	*Equisetum fluviatile*	*Eleocharis acicularis*	*Phragmites australis*
Equisetum fluviatile	*Ceratophyllum demersum*	*Isoetes echinospora*	*Eleocharis acicularis*
Sparganium emersum	*Potamogeton natans*	*Ranunculus reptans*	*Isoetes echinospora*
Schoenoplectus lacustris	*Sparganium emersum*	*Lobelia dortmanna*	*Myriophyllum alterniflorum*
Stratiotes aloides	*Lemna minor*	*Sparganium* sp.	*Subularia aquatica*
Hydrocharis morsus-ranae	*Hydrocharis morsus-ranae*	*Carex acuta*	*Equisetum fluviatile*
Lemna minor	*Carex* sp.	*Nuphar lutea*	*Carex acuta*
Utricularia vulgaris	*Elodea canadensis*	*Equisetum fluviatile*	*Elodea canadensis*

The most frequent species were defined in terms of the numbers of quadrats in which they were present. The quadrats were located on 36 transects situated in different parts of the areas.

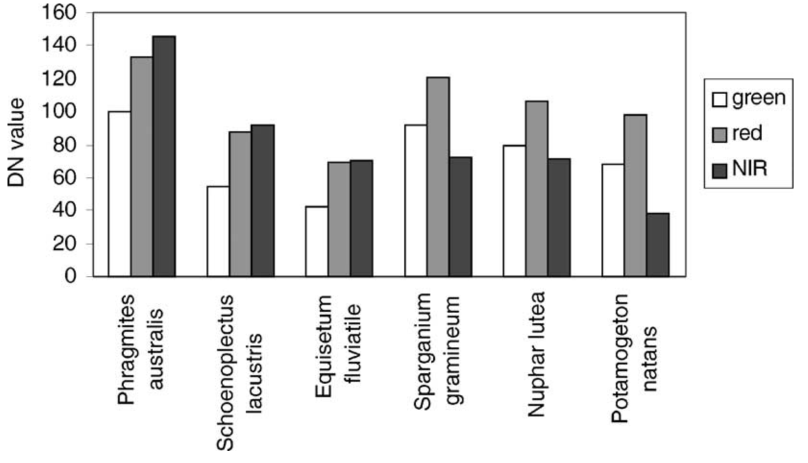

Fig. 1. DN values in the green (500–575 nm), red (575–675 nm) and near-infrared (675–900 nm) bands for three species of helophytes and nymphaeids in N. Onkivesi. The image was constructed using the averages of the DN values for all the training areas taken for the classification.

3.2. Life form and species discrimination

Dense helophyte stands were in general distinguished from nymphaeids by their stronger reflectance in the near-infrared band than in the green or red band (Fig. 1), with the exception of the nymphaeid species *Sagittaria sagittifolia*, which had DN values characteristic of a dense helophyte vegetation. A sparse helophyte vegetation, on the other hand, was easily confused with nymphaeids, the density value below which this confusion took place varying from one species to another. Both helophytes and nymphaeids merged with unvegetated water areas if the vegetation was very sparse. It was difficult to find distinct examples of extensive elodeid areas in all the areas, and although a few dense *Elodea canadensis* areas were marked off in the field in N. Onkivesi, the DN values did not differ from those of the nymphaeids or the sparse helophyte vegetation. A few areas of isoetids in Haukivesi and Puruvesi were also identified but did not have a strong enough reflectance on account of the attenuation of light in the water, so that the areas were classified as unvegetated water.

A helophytic *Phragmites australis* vegetation had the highest reflectance in all the bands and the sharpest increase at the red/infrared boundary (Fig. 1). Because of a fairly wide variation in reflectance, several density categories could be distinguished (Table 2, Fig. 2). The *Phragmites australis* category, with the highest reflectance in all the bands, was confused with the vegetation on the shore, especially *Carex* sp. (Table 2), but also with *Calla palustris* and *Menyanthes trifoliata*. *Schoenoplectus lacustris* and *Equisetum fluviatile* differed from the other helophytes in that they had a lower reflectance in all the bands. In addition, the increase in the reflectance at the red/infrared boundary was not as sharp as for other forms of helophyte vegetation (Fig. 1). The same phenotype also applies to *Stratiotes aloides*, which was relatively common in some parts of N. Onkivesi, growing densely above the water surface (Table 2, Fig. 3). None of these three species could be assigned to a category of its own.

Table 2
Vegetation categories used for supervised classification in N. Onkivesi, S. Onkivesi, Haukivesi and Puruvesi

N. Onkivesi	S. Onkivesi	Haukivesi	Puruvesi
Phragmites australis $5 < d \leq 15$	*Phragmites australis* $5 < d \leq 15$	*Phragmites australis* $d < 5$	*Phragmites australis* $d < 5$
Phragmites australis $15 < d \leq 20$	*Phragmites australis* $15 < d \leq 20$	*Phragmites australis* $5 \leq d < 15$	*Phragmites australis* $5 \leq d < 15$
Phragmites australis $d > 20$, *Carex* sp.	*Phragmites australis* $d > 20$, *Carex* sp.	*Phragmites australis* $15 \leq d < 25$	*Phragmites australis* $15 \leq d < 25$
Schoenoplectus lacustris, *Equisetum fluviatile*, *Stratiotes aloides*	Sparse nymphaieds, sparse helophytes	*Phragmites australis* $d \geq 25$, *Carex* sp.	*Phragmites australis* $d \geq 25$, *Carex* sp.
Sparganium gramineum, *Potamogeton natans*	Dense nymphaieds, sparse helophytes	Nymphaeids	Nymphaeids
Other nymphaeids, sparse helophytes	*Equisetum fluviatile*	Water or shadow	Water or shadow
Water or shadow	Water or shadow		

d-Values for *Phragmites australis* are density $0.25\,m^{-2}$.

In N. Onkivesi the nymphaeids, *Sparganium gramineum* and the dense *Potamogeton natans* vegetation formed one category, while *Nuphar lutea* dominated the vegetation in another (Figs. 2 and 3). As shown in Fig. 1, *Nuphar lutea* did not have as distinct a decrease at the red/infrared boundary as *Sparganium gramineum* or *Potamogeton natans*. The sparse helophyte vegetation found here merged mainly with the *Nuphar lutea*-dominated vegetation. In S. Onkivesi, the dense *Nuphar lutea* vegetation formed one category and the sparse nymphaeid vegetation with varying species composition another (Table 2), the sparse helophyte vegetation merging with both of these categories. In Haukivesi and Puruvesi a nymphaeid vegetation was found only in a few areas and was placed in only one category (Table 2).

The classification accuracy values were 91% for N. Onkivesi, 82% for S. Onkivesi, 82% for Haukivesi and 80% for Puruvesi (Tables 3–6). The most obvious confusion between the vegetation categories concerned the *Phragmites australis* categories of different densities.

3.3. Sources of disturbance

Water quality, expressed in general terms, improved from the headwaters of the Vuoksi drainage basin towards the central area, and was ranked as tolerable in Onkivesi, good in Haukivesi and excellent in Puruvesi. The trophic state of the lakes followed the same order, Onkivesi being eutrophic, Haukivesi mesotrophic and Puruvesi ultraoligotrophic. Among the water quality parameters and geo-morphological features of the three lakes listed in Table 7, Secchi disc depth is the one that was assumed to be the most important for the interpretation of digital false colour aerial photographs when describing the aquatic vegetation. This parameter followed the same order explained previously, with Secchi disc transparency increasing from the headwaters to the central parts of the Vuoksi watercourse.

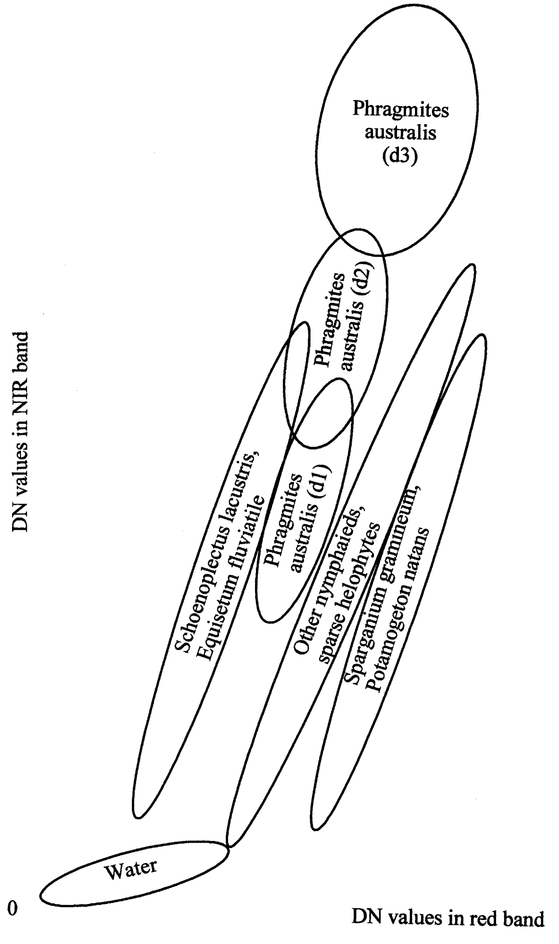

Fig. 2. Feature space image for N. Onkivesi between red (575–675 nm) and near-infrared (675–900 nm) bands. The ellipses describe combinations of training areas used in the classification. *d*-Values for *Phragmites australis* are density values, $d1$ representing the sparsest vegetation and $d3$ the densest (rough density values for the categories are $5 < d1 \leq 15$, $15 < d2 \leq 20$ and $d3 > 20$ individuals $0.25\,\mathrm{m}^{-2}$).

The effect of water quality and the lake bottom on the reflectance of the unvegetated water areas in Onkivesi, Haukivesi and Puruvesi is illustrated in Table 8. The results indicate that the dependence of the DN values on the water depth increases from the headwaters of the drainage basin towards the central area (from left to right as shown in Table 8). In N. Onkivesi, the reflectance from the water areas is caused by substances in the water, since the DN values do not alter with water depth, but in Puruvesi, the reflectance from the lake bottom is even more important, since the DN values decrease with increasing water depth. Visible light penetrates much deeper into the water in Puruvesi than in Onkivesi, as indicated by the Secchi disc transparency (Table 7). The effect of phytoplankton on DN values is difficult to assess, because the wide wavelength areas of the bands cover the peak

Table 3
Confusion matrix for supervised classification of the aquatic macrophytes in N. Onkivesi

Classification data	Ground truth data								
	Water or shadow	*Phragmites australis*, $5 < d \leq 15$	*Phragmites australis*, $15 < d \leq 20$	*Phragmites australis*, $d > 20$, *Carex* sp.	*Equisetum fluviatile*	*Sparganium gramineum*	Other nymphaeids	Total	Percentage
Water or shadow	1179	–	–	–	–	–	3	1182	99.7
Phragmites australis, $5 < d \leq 15$	–	149	23	–	6	–	54	232	64
Phragmites australis, $15 < d \leq 20$	–	60	100	49	46	–	3	258	39
Phragmites australis, $d > 20$, *Carex* sp.	–	6	34	528	21	–	1	590	89
Equisetum fluviatile	–	–	23	28	765	–	–	816	94
Sparganium gramineum	–	–	–	–	–	1027	84	1111	92
Other nymphaieds	42	20	3	4	–	15	1405	1489	94
Total	1221	235	183	609	838	1042	1550	5678	–
Percentage	97	63	55	87	91	99	91	–	91

d-Values for *Phragmites australis* are density $0.25\,m^{-2}$. The vegetation categories are described more precisely in Table 2.

Table 4
Confusion matrix for supervised classification of the aquatic macrophytes in S. Onkivesi

Classification data	Ground truth data								
	Water or shadow	*Phragmites australis*, $5 < d \leq 15$	*Phragmites australis*, $15 < d \leq 20$	*Phragmites australis*, $d > 20$, *Carex* sp.	*Equisetum fluviatile*	Dense nymphaieds	Sparse nymphaeids	Total	Percentage
Water or shadow	417	–	–	–	1	–	5	423	99
Phragmites australis, $5 < d \leq 15$	–	170	29	18	39	15	–	271	63
Phragmites australis, $15 < d \leq 20$	–	7	55	40	5	1	–	108	51
Phragmites australis, $d > 20$, *Carex* sp.	–	3	–	333	–	–	–	336	99
Equisetum fluviatile	–	4	4	2	136	19	–	165	82
Dense nymphaieds	–	10	–	4	22	301	38	375	80
Sparse nymphaieds	10	9	–	–	3	133	483	638	76
Total	427	203	88	397	206	469	526	2316	–
Percentage	98	84	63	84	66	64	92	–	82

As described in Table 3.

Table 5
Confusion matrix for supervised classification of the aquatic macrophytes in Haukivesi

Classification data	Ground truth data							
	Water or shadow	*Phragmites australis*, $d < 5$	*Phragmites australis*, $5 \leq d < 15$	*Phragmites australis*, $15 \leq d < 25$	*Phragmites australis*, $d \geq 25$, *Carex* sp.	Nymphaeids	Total	Percentage
Water or shadow	343	76	–	–	–	13	432	79
Phragmites australis, $d < 5$	–	277	32	–	17	45	371	75
Phragmites australis, $5 \leq d < 15$	–	32	61	1	–	4	98	62
Phragmites australis, $15 \leq d < 25$	–	–	–	72	32	1	105	69
Phragmites australis $d \geq 25$, *Carex* sp.	–	1	–	20	395	1	417	95
Nymphaeids	1	32	7	–	7	358	405	88
Total	344	418	100	93	451	422	1828	–
Percentage	99.7	66	61	77	88	85	–	82

As described in Table 3.

Table 6
Confusion matrix for supervised classification of the aquatic macrophytes in Puruvesi

Classification data	Ground truth data							
	Water or shadow	*Phragmites australis*, $d < 5$	*Phragmites australis*, $5 \leq d < 15$	*Phragmites australis*, $15 \leq d < 25$	*Phragmites australis*, $d \geq 25$, *Carex* sp.	Nymphaeids	Total	Percentage
Water or shadow	238	93	8	–	–	–	339	70
Phragmites australis, $d < 5$	–	146	44	–	–	–	190	74
Phragmites australis, $5 \leq d < 15$	–	4	202	2	–	2	210	96
Phragmites australis, $15 \leq d < 25$	–	–	38	139	23	–	200	70
Phragmites australis $d \geq 25$, *Carex* sp.	–	–	5	8	177	–	190	93
Nymphaeids	7		2	1	–	61	71	86
Total	245	243	299	150	200	63	1200	–
Percentage	97	60	68	93	89	97	–	80

As described in Table 3.

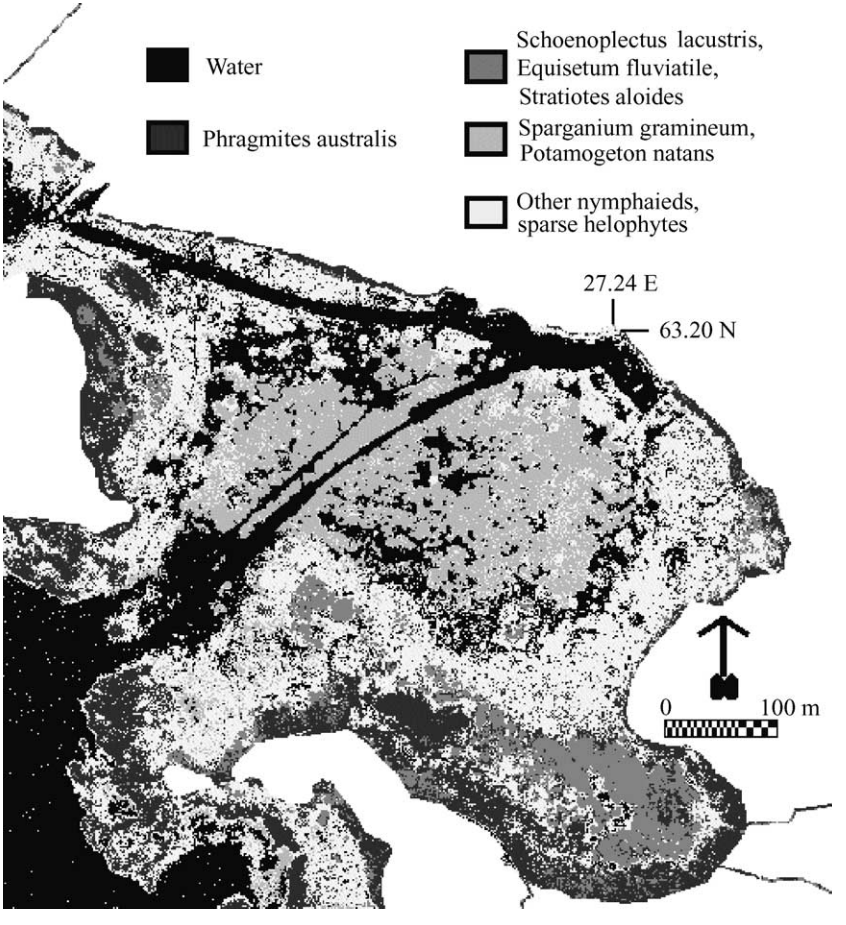

Fig. 3. Excerpt from the aquatic macrophyte classification image for N. Onkivesi. The *Phragmites australis* categories of different densities (Table 2) are combined here.

absorption and reflection values for phytoplankton. Several algal blooms were observed in Onkivesi during the field survey, which must have influenced the reflection coming from alga-affected areas. The magnitude of the waves cannot have been significant, however, because the wind strength at the nearest observation stations (located from 5 to 60 km away) was no more than 1 or 2 $m\,s^{-1}$ during the flights.

4. Discussion

The planning of the present flights according to the theme and needs of the study proved to be effective in preventing interference and the problems that commonly arise in digital image processing. The image manipulation and classification stages were executed fluently

Table 7
Water quality parameters and geo-morphological features of the lakes

	Onkivesi	Haukivesi	Puruvesi
Chl-*a* ($\mu g\, l^{-1}$)	28	4.9	1.2
Tot-N ($\mu g\, l^{-1}$)	760	390	210
Tot-P ($\mu g\, l^{-1}$)	55	10	4
pH	7.0	7.2	7.5
Colour (Pt mg l^{-1})	105	35	5
Secchi disc depth (m)	1.0	2.7	5.7
Average depth (m)	3.3	12	17
Maximum depth (m)	15	51	66
Size of water basin (km^2)	114	460	330

The water quality parameters for Onkivesi are presented as mean summertime values (June–August) in the surface water (1–5 m) for the 10-year period 1991–2000. Those for Haukivesi and Puruvesi are single measurements performed in the surface water (1–5 m) near the sampling areas during the field survey (1 and 3 August 2000).

and the classification results were satisfactory. Definition of the exact location of the training areas proved to be a fundamental aspect of the work. In order to obtain data for the purposes of vegetation analysis by digital image processing, reference areas defined using GPS equipment would have been the most effective and adequate means of gathering ground information. Species composition and density data for several quadrats in one reference area (at least five) would constitute an adequate amount of information. The green, red and near-infrared bands formed an effective combination for classifying the aquatic macrophyte vegetation, but the selection of narrower bands would have given data with better spectral resolution, and thereby a more exact picture of the species distribution. It would be possible to achieve an optimal combination of bands with the aid of spectrometers widely used in water quality monitoring (Lindell et al., 1999).

The difference in reflectance properties between helophytes and nymphaieds arose from the more closed nature of the helophyte canopies, which in turn caused the reflectance from the vegetation to dominate over that from the water and underlying bottom. The specific reflectance properties of *Sagittaria sagittifolia* can be explained both by the closed nature of the canopy and by the vertical position of the leaves, which is not typical of the other nymphaeids growing in the area. The high DN values for *Phragmites australis* were

Table 8
DN values for unvegetated water areas in N. Onkivesi, S. Onkivesi, Haukivesi and Puruvesi

Water depth	N. Onkivesi			S. Onkivesi			Haukivesi			Puruvesi		
	Green	Red	NIR	Green	Red	NIR	Green	Red	NIR	Green	Red	NIR
<1.5 m	39.74	3.70	14.09	13.84	27.51	1.81	15.87	32.37	5.10	16.30	31.90	4.54
1.6–3.0 m	39.74	3.67	13.26	13.26	25.64	1.49	12.67	26.11	4.44	13.24	28.21	3.92
3.1–6.0 m	39.49	3.59	12.83	12.83	26.31	1.44	13.74	25.70	4.15	11.63	26.67	3.96
6.0–10.0 m	40.21	3.47	13.86	12.86	24.57	1.20	14.00	26.07	4.20	10.48	25.37	3.81

The DN values in all the bands (green, 500–575 nm, red, 575–675 nm, and near-infrared, 675–900 nm) were determined from the averages of 10 training areas in each depth zone.

due to its dense, rather closed canopies. There was a clear dependence of the DN values for *Phragmites australis* on density, and for that reason several density categories were defined (Table 2), but their boundaries are only roughly estimates, due to the interrupted nature of the density series. The specific reflectance properties of *Schoenoplectus lacustris* and *Equisetum fluviatile* can be explained by the more open canopies than for the other helophytes, because their stems lack the flat leaves typical of most helophytes (Malthus and George, 1997). *Nuphar* sp. and *Nymphaea* sp. differed from *Sparganium gramineum* and *Potamogeton natans* in having larger leaves with thick cuticles, which gave them different reflectance properties.

The discrimination of species and life forms of aquatic macrophytes by digital image processing methods is highly dependent on species diversity, composition and variations in density in the given area. Even if some species might be clearly distinguished in one area, the situation could be totally different in another. This becomes evident when comparing the classifications for the areas studied here. It appeared to be crucial to take the water quality and morphological features of the areas into account when interpreting the results. The effect of the lake bottom on the total reflectance of aquatic macrophyte areas was found to be more problematic than the effect of water quality, since the reflectance from the lake bottom altered with water depth. This caused difficulties in classifying the aquatic macrophytes. In addition of the water quality, the difference in the bottom quality between the training areas of the studied lakes is explaining the amount of reflectance from the lake bottom. The differences in reflectance between N. and S. Onkivesi point to the water quality differences between the two. The DN values for the four areas cannot be compared, however, since no calibration was performed between them.

Although the spatial distribution of aquatic macrophytes can be defined quite rapidly and effectively by digital image processing, the method is nevertheless a coarse one and in most of the cases some species-specific information is lost. In order to improve the classifications, visual interpretation could be combined with digital image processing. In N. Onkivesi, for example, circular patches of *Sagittaria sagittifolia* are easily identified visually (Fig. 4), but these areas become confused with other vegetation in digital image processing. In

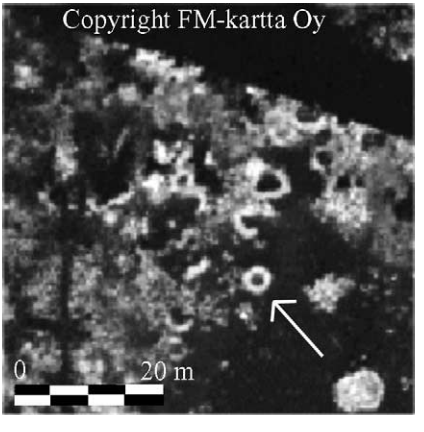

Fig. 4. Circular patches of *Sagittaria sagittifolia* in N. Onkivesi.

addition, areas of *Schoenoplectus lacustris* and *Equisetum fluviatile*, for example, could be distinguished from each other quite easily here using ground observations.

The results were to a great extent consistent with those of the previous studies of the spectral characteristics of aquatic macrophytes and the effect of disturbance factors on their classification (Ackleson and Klemas, 1987; Penuelas et al., 1993; Ferguson and Korfmacher, 1997; Malthus and George, 1997). The fact that there was not as distinct an increase at the red/infrared boundary as had been expected was due to the use of a filter during the flight to cut out 20% of the reflectance in the near-infrared band. In any case, differences in the sensors and the wavelength distribution, in circumstances during acquisition of the data and in the species compositions of the areas make exact comparison between the reports impossible.

The differences in reflectance between species and life forms of aquatic macrophytes could be used as key information when defining temporal changes on the basis of historical data on the aquatic macrophyte vegetation in a constant area. This would be possible if the environmental variables (type of data, data acquisition characteristics (shutter speed, aperture), date of flight, time of day, atmospheric conditions, etc.) could be kept as similar as possible. When transferring to different areas and different kinds of data, prediction of the composition of the aquatic macrophyte vegetation becomes more difficult. Ground survey information, e.g. in the form of reference areas investigated using GPS equipment, is therefore very important. Remote sensing does not remove the need for a ground survey, but on the contrary, the acquisition of ground data is an essential part of the remote sensing method. The next theme to be pursued in the context of the present research programme will be temporal changes in the spectral characteristics of an aquatic macrophyte vegetation. In addition, the biomass of such a vegetation will be studied in relation to the density and reflectance characteristics.

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