Doode Bemde CASI-SWIR 2002: Hyperspectral sensing of moisture gradients. Set-up and first results of a combined field and airborne campaign.

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ABSTRACT

Determination and description of groundwater systems is essential for the management and development of ecological values, especially in the valley parts of river basins. At the land surface, groundwater systems appear as infiltration (relatively dry) and discharge zones (relatively wet). Groundwater discharge zones offer a high potential for nature values because of their constant moisture presence and their specific water quality. Current methods for the determination of discharge and infiltration zones use either detailed time-consuming fieldwork or data intensive numerical simulation models. Consequently, there is a direct need for repeatable, area covering, mapping possibilities for the determination of moisture gradients and more specifically discharge and infiltration zones. Within the framework of the CASI-SWIR campaign 2002, the Department of Hydrology and Hydraulic Engineering of the Vrije Universiteit Brussel (VUB) executed a combined airborne hyperspectral remote sensing and field campaign to analyze moisture gradients in the Doode Bemde, a riparian nature reserve. The main objective of the study is to test the best hyperspectral analysis method, using the hyperspectral CASI-SWIR data, for the known, based upon field and simulation data, moisture gradients in the Doode Bemde area. Simultaneously with the airborne hyperspectral campaign, field measurements of soil moisture, groundwater levels, vegetation temperature and spectral characteristics of some key vegetation species (phreatophytes) were performed. The method of analysis consists of statistical comparison of moisture gradients, obtained from measurements and simulations, with individual bands, a combination of bands and multivariate derivatives. The paper describes the set-up of the field and airborne measurement campaign, the methodology of analysis as well as first analysis results.

Keywords: Hyperspectral remote sensing, moisture gradients, land surface, hydrological modeling, vegetation

1. INTRODUCTION

Determination and description of groundwater systems is essential for the management and development of ecologically valuable areas, especially in the valley parts of river basins. At the land surface, groundwater systems appear as infiltration (recharge) and discharge zones; the latter are relatively wet because of the upward groundwater seepage, while the former are relatively dry. Figure 1 shows a typical situation of a groundwater system in valley areas. Precipitation infiltrates partly into the soil and recharges the groundwater body. Underground there is a groundwater flow towards the lower parts of the valley. In some of these parts, so called wetlands or discharge zones, the groundwater reaches (almost) the surface and is available for the vegetation. Groundwater discharge zones offer a high potential for nature values because of their constant moisture presence and their specific water quality.

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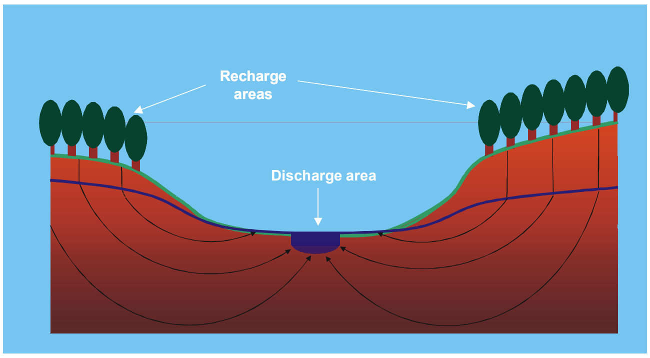

Figure 1: Typical groundwater system in lowland valleys.

Valleys usually have a complex pattern of moisture gradients and infiltration/discharge zones, caused by a complex interaction of regional groundwater flow with local influences of differences in soil type, vegetation and topography. Knowledge about infiltration- and discharge zones form therefore not only the basis for sound, quantitatively and qualitatively, water management of groundwater systems, but also for nature protection in valley areas.

To gain insight in groundwater systems numerical groundwater simulation models, such as MODFLOW[1], are often essential. These numerical models enable the calculation of groundwater levels and flow, as well as the determination of discharge and infiltration zones. The obtained hydrological parameters often form the input for ecological analysis and models[2,3,4]. Main disadvantage of this method is the fact that it is very data intensive. This type of modeling requires detailed data concerning topography (DEM), geology, soil type, land use, meteorological characteristics, etc. in a spatially distributed way, which is not always (completely) available. Often there is also a lack of data for the calibration. To meet the needs for this type of modeling, detailed time-consuming fieldwork is often required. These disadvantages clearly show that there is a direct need for repeatable, area covering, mapping possibilities for the determination of moisture gradients and more specifically discharge and infiltration zones. Remote Sensing can most probably be a very useful tool to do this[5].

Within the framework of the Belgian CASI-SWIR 2002 campaign, the Department of Hydrology and Hydraulic Engineering of the Vrije Universiteit Brussel (VUB) executed, in cooperation with the Flemish Institute for Technological Research (VITO) – operating on behalf of the Belgian Science Policy Office - an airborne hyperspectral remote sensing and field campaign to analyze moisture gradients and discharge/infiltration zones in the Doode Bemde, a riparian wetland (nature reserve). The main objective of the study is to test the best hyperspectral analysis method, using the hyperspectral CASI-SWIR data, for the known, based upon field and simulation data, moisture gradients in the Doode Bemde area. Extensive hydro-ecological research was carried out in the study area during the last five years, providing a detailed dataset and knowledge about the flow systems[3,4,6]. The area is hydro-chemically uniform, and has clear, relatively constant moisture gradients with associated differences in vegetation on a small scale caused by groundwater flow differences. Simultaneously with the airborne hyperspectral campaign, field measurements of soil moisture, groundwater levels, vegetation temperature and spectral characteristics of some key vegetation species (phreatophytes[7]) were performed. The method of analysis consists of statistical comparison of moisture gradients, obtained from measurements and simulations, with individual bands, a combination of bands and multivariate derivatives. The paper describes the set-up of the field and airborne measurement campaign, the methodology of analysis as well as first analysis results.

2. DATA AND METHODOLOGY

2.1 Study area

The study area is situated in the central part of Belgium, in Flanders, 8 km to the south of Leuven, in the middle course of the Dijle River (Fig. 2). The area contains large parts of the nature reserve ‘Doode Bemde’, a riparian wetland. This wetland, as well as the River Dijle, and several smaller rivers and ditches in the study area, are predominantly fed and determined by discharging groundwater[6]. The study area mainly consists of grasslands (partly agricultural), reed and forest, with some ponds, houses and streets in the western part (Fig. 4).

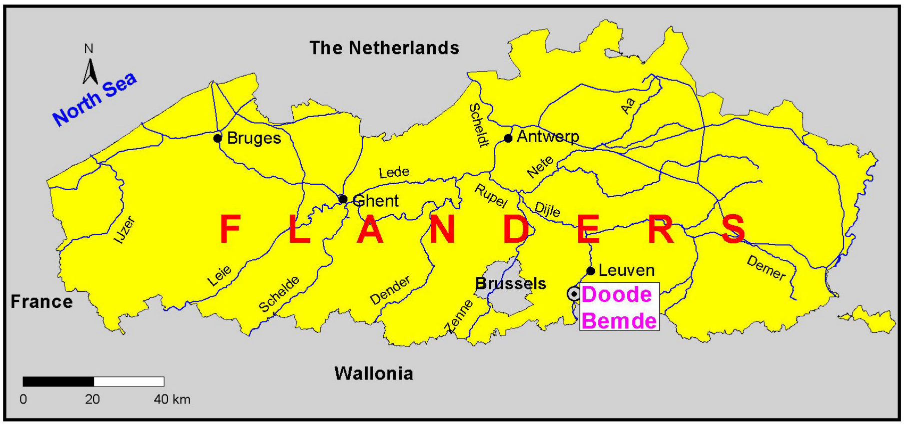

Figure 2: Location of study area 'Doode Bemde' in Flanders, Belgium.

2.2 Data collection and processing

Airborne hyperspectral remote sensing campaign

For thie hyperspectral campaign a combination of two sensors, on board of a Piper Navajo Chieftain, was used: the Compact Airborne Spectrographic Imager (CASI-2) and the Short Wave Infra Red (SWIR) sensor. This combined sensor collects data in approximately 250 contiguous spectral bands, covering a wavelength range of 400 to 2500 nm (Table 1).

	CASI-2	SWIR
# spectral bands	96	160
spectral range (nm)	400 - 950	850 - 2500
spatial resolution (m)	2,44	2,44

Table 1: Sensor characteristics.

The hyperspectral CASI-SWIR dataset was acquired on September 13, 2002, in the late afternoon, in three North-South oriented flight lines, covering the total study area.
The post-processing of the data was done by ITRES and VITO. First of all, a *radiometric calibration* of the sensors was done in the laboratory to convert the raw digital numbers (DN) to radiance units. The next step was a *geocoding* of the imagery to correct spatial and geometric distortions, caused by frequent motions of the airplane. All possible information, concerning sensor attitude and position (by the use of on-board GPS, dGPS base station and ground control points), and an accurate DEM for the area, was used to make these corrections. Finally, an *atmospheric correction* was executed as well. During the flight ground measurements with a handheld spectroradiometer (ASD Fieldspec Pro FR) for a few reference targets were done, as well as sun photometer measurements (Microtops II), to obtain the necessary information to atmospherically correct the images with ATCOR4 (Fig. 3). During the corrections of the dataset there appeared to be some problems with certain bands and thus were not useful for further analysis, so they where removed. It concerns the last bands of the CASI dataset[8] and 50 or 60 bands of the SWIR dataset. Finally 165 spectral bands were used for further analysis.

Hydrological field campaign

At the same day of the flight the Department of Hydrology and Hydraulic Engineering (VUB) executed an extensive hydrological field campaign. At many locations, widely spread over the study area, different type of measurements were performed:

- *Soil moisture* was measured in two different ways, with the gravimetric method (soil samples) and directly with a Theta Probe (Type ML2). Both methods showed relatively big absolute differences, but there was a high correlation ($r^2 = 0.8439$) between both datasets. Additionally, one parcel (grass field), of approximately 100 by 100 meter, was selected for detailed soil moisture measurements (Theta probe) at 85 locations. A Spline interpolation was used to create a spatially distributed soil moisture grid for this field, with the same spatial resolution (2.44 m) as the hyperspectral dataset (Fig. 5a). The western and northern part of this field are the wettest zone, with values up to 100% (near or in the ditches), while the eastern part is relatively dry (values varying from 20 to 50 %). This moisture gradient is strongly correlated with the topography, going from higher to lower from Southeast to Northwest.

- *Soil temperature* and *conductivity* (EC) was measured with an EC probe.

- *Vegetation temperature* was measured with an infrared temperature gun and vegetation height was estimated for most locations.

- *Spectral characteristics* of 10 vegetation targets were measured with handheld spectroradiometer (ASD). Figure 3 shows the measurements of one of the vegetation targets, on the selected grass field.

- Water level of rivers and groundwater level in piezometers.

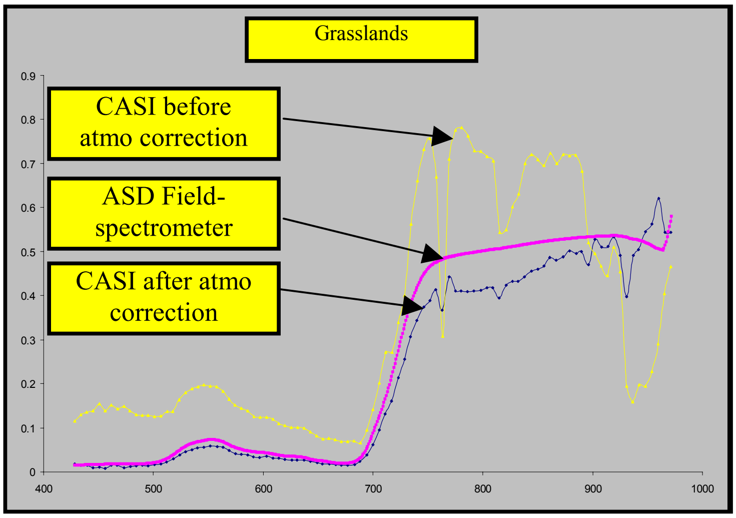

Figure 3: Spectral measurements and reflectance of CASI image of one vegetation targets (grass).

2.3 Groundwater modeling

To obtain additional indirect 'field information' (ground truth), a detailed numerical groundwater model, with the same spatial resolution of 2.44 by 2.44 meter, was developed for the study area. The groundwater modeling was performed with MODFLOW[1]. Since groundwater modeling requires a lot of spatially distributed input data (topography, geology, soil type, land use, meteorological characteristics, etc.), GIS was used to generate and prepare this data. Also, the output of the groundwater model was exported to GIS to be able to perform analysis and to present the results in a clear way. Calibration of the model was performed using the measured piezometric data. During the calibration the differences between measured and calculated piezometric heads were minimized. One of the main results of this modeling is a groundwater depth map (Fig. 4). The largest part of the valley has shallow groundwater, except near the Dijle River. Also in the Western and Eastern part of study area, around the higher parts of the valley, the groundwater reaches levels of 5 meters and even more below the surface. About 41% of the study area has a groundwater depth of 0.25 meter or less. It concerns mainly discharge zones or zones strongly influenced by groundwater. In Figure 5b the detailed groundwater depth map for the selected grass field is given. If we compare this groundwater depth map with the interpolated soil moisture map we notice a relatively good correspondence (r^2 = -0.6132); a drier part in the (South)East and a wetter part in the West and North of the field.

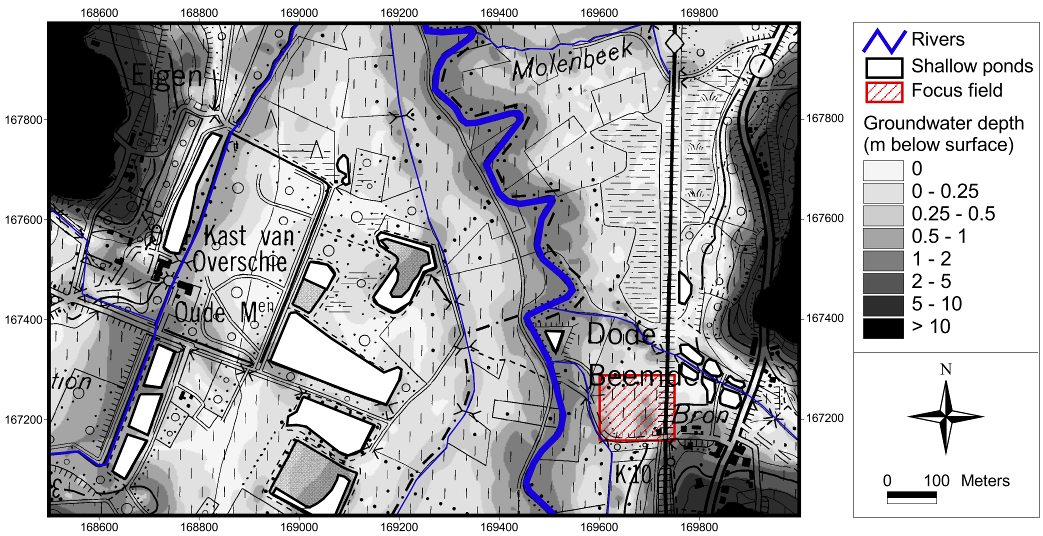

Figure 4: Groundwater depth map of the study area.

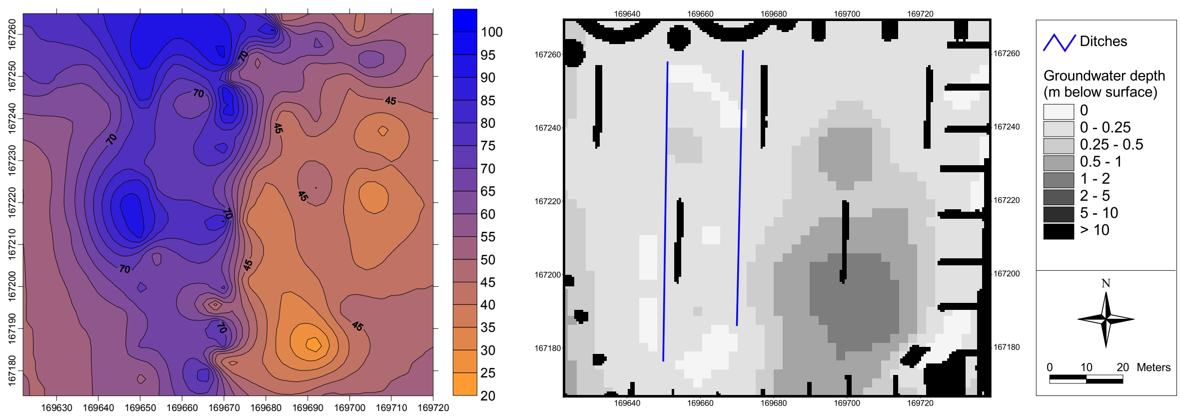

Figure 5: Interpolated soil moisture (a) and groundwater depth (b) for a selected grass field.

2.4 Vegetation

Within the framework of one of the previous studies[6] in the ‘Doode Bemde’ area vegetation data was collected for a part of the study area. For 527 grid cells, of 20 by 20 meter, plant species were mapped. The mapping was mainly limited to plant species growing under the influence of groundwater, so called phreatophytes[7]. The occurrence of these species has been linked to the maximum depth of the groundwater. In the selected grass field, 7 of these plant species (Carex acutiformis, Ranunculus Flammula, Lythrum Salicaria, Achillea ptarmica, Carex acuta and Polygonum amphibium) need a more or less constant shallow groundwater level. These plant species mainly occur in the western (and northern) part of the grass field and do not occur in the Southeast, side of the field (Fig. 6). This spatial distribution is in correspondence with the simulated groundwater levels and observed moisture gradients. So, the vegetation reflects the moisture situation in the field.

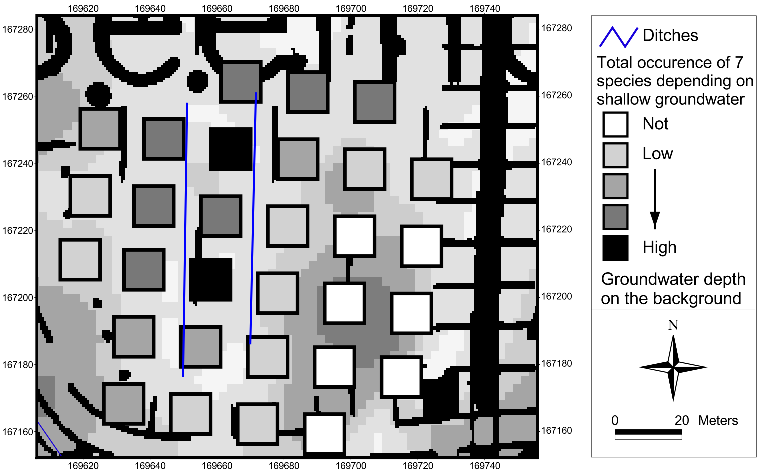

Figure 6: Total occurrence at each mapping grid cell of 7 plant species, depending on shallow groundwater levels.

2.5 Hyperspectral analysis and comparison with field measurements

Analysis of the results of the field campaign, in particular soil moisture, and of the numerical groundwater modeling, show clear differences in moisture or wetness in the study area. The main objective of this study is to find the best method for the analysis and mapping of these moisture gradients, using the hyperspectral CASI-SWIR dataset. A first step in this analysis is a statistical comparison of the obtained field measurements and simulation results with each individual spectral band. Also the use of a combination of two or more bands will be studied. This can be done using existing indices or ratios. Quite some water and vegetation indices have already been developed[9]. Some examples are the normalized difference vegetation index (NDVI[10]), a vegetation index (VI), a water index (WI[9]) and the normalized difference water index (NDWI[11]). The field and simulation results are statistically compared to each of these indices. Once a relationship between the field and simulation results and the hyperspectral dataset is established, the analysis results will be used for classification purposes, in order to try a mapping of moisture or wetness differences and gradients in the study area.

This methodology will be tested first for one selected field (grass), which was the subject of intensive field measurements, and will be in a later phase extended to the rest of the study area.

3. FIRST RESULTS AND DISCUSSION

The hypothesis is that the observed moisture differences in the field are reflected in the hyperspectral image. A comparison of the spectral signatures of a wet (northwest) and a dry (southeast) vegetation target, clearly show a difference in reflectance around 0.55 µm and in the near IR (Fig. 7). This difference is likely related to a difference in moisture content, but could also be caused by a difference in chlorophyll content, leaf structure, etc. Analysis of the hyperspectral dataset should give an answer to this, but the fact there is a difference already offers a possibility for differentiation of wetter and drier zones.

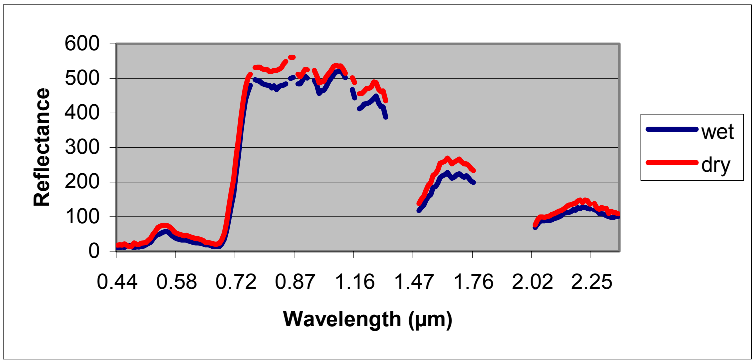

Figure 7: Spectral signatures of wet and dry vegetation target.

3.1 Soil moisture and groundwater depth

A statistical comparison of the interpolated soil moisture for the selected grassland with each individual band of the hyperspectral CASI-SWIR dataset shows the highest correlation (r^2 = -0.6871) for band 26 (0.5690 µm) and the surrounding bands (Figure 8). Another peak is reached around band 50 (0.7060 µm). The spectral bands 94 to 97 (around 1.29 µm) show the lowest correlation values (around -0.24). The correlation curve for the groundwater depth shows a similar pattern, but with lower correlation values (maximum around 0.45), except for the bands 55 to 75 (Figure 8).

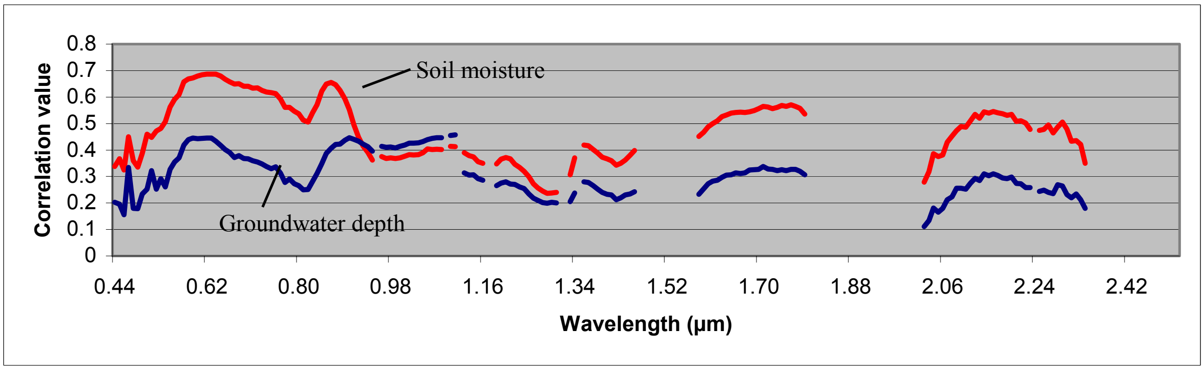

Figure 8: Correlation curve between soil moisture and groundwater depth and each individual CASI-SWIR band.

The use of existing indices, like NDVI or NDWI, did not give a better correlation than the individual bands. Possibly another index or combination of several bands might ameliorate the correspondence. Further analysis is needed and will be done.

3.2 Vegetation

The use of the available vegetation data was until know limited, but probably this detailed dataset will be very useful for further analysis of and comparison with the hyperspectral image. For sure, this dataset can be used as 'ground truth' for the classification and mapping of moisture differences and gradients in the area.

3.3 Mapping

Based on the first analysis results a first attempt for classification of moisture differences in the selected grass field was made. The objective is to use the hyperspectral dataset to determine or differentiate the wetter and drier zones. For this first attempt a supervised, as well as an unsupervised classification was performed (Fig. 9). For both classifications the bands 21 to 27 and band 50 will be used. These bands had the highest correlation with the interpolated soil moisture.

For the supervised classification, three known training classes were defined: one wet and one dry vegetation target, and a 'shadow' class were used (Fig. 7). A 'Maximum Likelihood' classification method was chosen[12]. This type of classification assumes that the statistics for each class in each band is normally distributed and calculates the probability that a given pixel belongs to a specific class. Each pixel is assigned to the class that has the highest probability, unless the probability is less than the threshold value (0.9).

For the unsupervised classification the 'K-means' method was used[13]. This type of classification calculates initial class means evenly distributed in the data space and then iteratively clusters the pixels into the nearest class using a minimum distance technique. For the classification four classes were chosen.

The results of these classifications are given in Figure 9. Both classification give similar results. The supervised classification clearly differentiates dry (white) zones at the southeastern and wet zones (gray) at the western and northern side of the field. There are a few non-classified pixels (black) and the shadow (dark gray) is also clearly visible in the southwest. In the case of the unsupervised classification four classes were used. Going from dry (white) to wet (dark gray), with a transition zone in between (light gray). The black color represents the shadow. A visual comparison with the field observations (soil moisture, vegetation, groundwater depth) clearly shows a good correspondence.

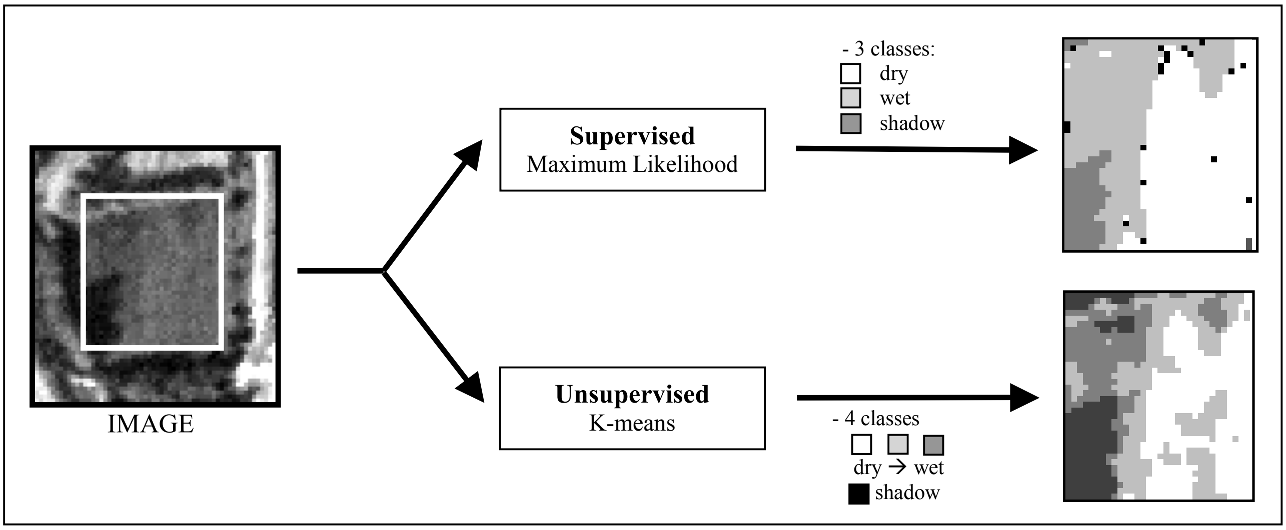

Figure 9: Supervised and unsupervised classification in an attempt to map moisture differences or gradients in the selected field.

The results of this analysis should, in a later phase, form the basis for a mapping method of moisture or wetness gradients in the study and other areas. These classification methods will be further analyzed and compared with other methods. Objective accuracy values will be used for the evaluation of further classifications.

4. CONCLUSIONS

The main objective of the study is to test the best hyperspectral analysis method, using the hyperspectral CASI-SWIR data, for the known, based upon field and simulation data, moisture or wetness gradients in the Doode Bemde area. The method of analysis consists of statistical comparison of moisture gradients, obtained from measurements and simulations, with individual bands, a combination of bands and multivariate derivatives. The first preliminary results look promising and show that hyperspectral remote sensing offers new possibilities, in combination with 'traditional' methods, for the analysis and mapping of moisture or wetness gradients in valley areas.

ACKNOWLEDGMENTS

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