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THE USE OF SCATTEROMETER DATA IN RELATION TO ARTEMIS - AGROMET CROP CONDITIONS MONITORING IN THE AFRICAN SAHEL

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FINAL REPORT

NEO, Netherlands Geomatics & Earth Observation B.V.,
Lelystad, The Netherlands

Food and Agriculture Organization of the United Nations, Rome, Italy

Colophon

Authors
M. Dorresteijn
E. Nobbe
R. Beck
J. Hielkema
Fred Snijders

This document contains the final report of the 'DEMONSTRATION PROJECT FOR THE USE OF SCATTEROMETER DATA IN RELATION TO OTHER REMOTE SENSING DATA IN ARTEMIS - AGROMET CROP CONDITIONS MONITORING IN THE AFRICAN SAHEL, executed in the framework of the National Remote Sensing Programme of The Netherlands, project code 3.2/DE-08. This final report has been completed on June 26, 2000. The project has been executed by NEO, Netherlands Geomatics & Earth Observation BV, from Lelystad The Netherlands, in association with FAO, the Food and Agriculture Organization of the United Nations in Rome, Italy.

Abstract
The ARTEMIS system is operated by FAO in support of various early warning systems concerning food and agriculture (e.g. GIEWS, IGAD, SADC). ARTEMIS provides satellite remote sensing derived information to these information systems. Soil moisture indices, derived from the ERS-scatterometer backscatter, can be a useful tool to improve the information that is provided by ARTEMIS. In this project the relationships between scatterometer data and ARTEMIS data are evaluated and methods are analysed to integrate scatterometer data into ARTEMIS. The project is based on a dataseries of several years for the crop growing region of Mali in the Sahel region. The project indicates that scatterometer soil moisture data can be a valuable source of information to ARTEMIS as an independent additional data source. Further product development and exploitation of the land application of the ERS-scatterometer are discussed.

Executive Summary

Since 1988 an operational monitoring service on environmental and agricultural crop production for Africa and the Middle East is provided by ARTEMIS, a system operated by FAO. ARTEMIS supports with this service e.g. the FAO Global Information and Early Warning System (GIEWS) on food and agriculture, the Desert Locust Plague Prevention Programme and regional and national food security early warning systems in Eastern and Southern Africa (IGAD, SADC). ARTEMIS provides satellite remote sensing information to these services. The system has been operational since 1988, but obviously has its limitations, inherent to the basic data sources. The integration of new remote sensing methods has been a subject of many research activities since the establishment of the FAO-ARTEMIS programme in 1985. A new possibility to further improve ARTEMIS is situated in the integration of soil humidity information produced from the ERS-scatterometer data as well as derived indices.

The potential of the ERS-scatterometer in measuring soil moisture content and forecasting of yields has been demonstrated in various projects (e.g. SCATMALI, Beck et al. 1999, SCATYIELD, Beck et al, 2000). In this project, the usefulness of scatterometer data is tested as an addition to the other remotely sensed (Meteosat, NOAA/AVHRR) and ground data in the ARTEMIS system.

The operational objectives of this project are to:

- compare rainy season data of a zone around the African Sahel in Mali as obtained from the field and Meteosat derived Cold Cloud Duration (CCD) data and NOAA AVHRR derived Vegetation Index (NDVI) data with scatterometer data of the rainy season of the years 1991-1998;
- assess how scatterometer data could be integrated within the operational ARTEMIS system (preliminary system design-like activities);
- assess costs and benefits of such an integration.

The data provided by ARTEMIS that are used in this project consist are the so-called Cold Cloud Duration (CCD) and the Normalized Difference Vegetation Index (NDVI). CCD values are derived from METEOSAT data and regarded as indicative for rainfall amounts and rainfall days. NDVI values are a ratio of two channels of the Advanced Very High Resolution Radiometer (AVHRR) instrument onboard the NOAA polar orbiting satellites. The NDVI is related to the amount of green biomass. In addition to these data, rainfall data from meteorological stations are used as “ground-truth”.

The scatterometer data used in this project is measured with an instrument on board the European Remote Sensing Satellites, ERS-1 and ERS-2. It emits microwaves and measures the reflected electromagnetic radiation on the same antennas. This backscatter is measured as a coefficient (the ratio of received over emitted power). The measurements are executed using three antennas, each ‘looking’ at the earth surface under a different angle.
The spatial resolution of the ERS scatterometer measurements is approximately 50 kilometres. Between 2 and 3 observations per week are made of Africa.
The backscatter coefficient from the ground surface depends on three principal variables:

- soil water content (which influences the dielectric constant, the conductivity of the top soil as a reflector/scatterer);
- vegetation (the structure of plants scatter the microwaves as a function of their mass and structure);

- surface roughness, often having a certain geometric pattern at micro- meso- or macro scale creating interference with the microwave radiation.

Since soil water content is the only variable of interest to this project, methods have been developed to eliminate the effect of the other two variables. The methods used in this project are based on the methods documented in the PhD-thesis of W. Wagner, 1999, and have been adapted for Mali, (from which the thesis also benefited).

The elimination of the vegetation component in the signal is based on the differences in backscatter behaviour between the three antennas. Relations between backscatter coefficients, incidence angles and soil wetness have been empirically established. The vegetation independent measure of soil humidity is obtained at an incidence angle of 40°, to which value all measurements are transformed.

The result of this processing is a scatterometer based soil moisture index:

MS: Measurement of the soil moisture in approximately the upper 5 centimetres of the soil as measured by the scatterometer. The MS is calculated by linear interpolation of the calculated backscatter values ($\sigma 40°$);

SWI: The Soil Water Index. The SWI is based on the MS, depicting the available water content in the rooting zone. A mathematical model was empirically developed for soils in the Ukrain, which simulates the propagation of soil humidity from the top soil to the first meter of the soil profile.

The evaluation of the convergence of SCAT-, ARTEMIS- and field-data can be divided in two parts. SWI is indicative for the amount of water available for vegetation in a soil. A shortage of water, indicated by low SWI values, will result in a less healthy and less full grown vegetation. This should be reflected by the NDVI. Therefore a description of the relationship between SWI and NDVI is attempted.

Assuming that CCD is closely related to the amount of precipitation, rainfall and CCD are expected to be descriptors of the same process. MS is an ad-hoc measurement of the topsoil and is not derived indirectly from other data. The relationship between these variables involves the whole process from precipitation, via evapotranspiration, infiltration and percolation, to topsoil moisture. This chain is too dependent of external variables to be described using an analytical approach with only CCD (i.e. rainfall) and MS as input. The relationship between CCD and MS is therefore described using statistical correlation coefficients.

It can be concluded that the variation in the considered data is fairly high. Extreme values influence the data significantly and make a convergence analysis rather complicated. The characteristics of the data are on the other hand not so that the outliers can be sifted out of the analysis using a spatial and temporal clustering.

It can be concluded from this analysis that in both considered cases a convergence in a general trend can be observed by the human eye. The development of both the NDVI and SWI shows a clear beginning and climax of the growing season (Figures 6-3 and 6-4). It can be imagined that these data types can be used as indicators for vegetation or crop growth and therefore also for agricultural monitoring systems such as ARTEMIS. Quantifying the convergence however does not provide satisfactory results.

As for the use of MS and CCD as rainfall-related data and the convergence between the two, the outcome is partially identical. MS is a value for moistness of the topsoil and is therefore strongly influenced by meteorological as well as pedological factors. This is a fundamental difference with rainfall-related data, such as CCD. Apart from considering any resampling concequences, a relationship between CCD and MS will have to take into account the pedologic aspects of the drying-up and moisting processes. The modelling of these processes however is not within the scope of this project.

It is concluded that it is not possible to use SCAT-data in a straightforward procedure to calibrate or validate ARTEMIS-output. SWI-data can in this respect be considered as an additional and valuable data source in ARTEMIS. An alternative method of analysis has been described in Annex 1 of this report, but an extensive application and evaluation of this alternative is not within the scope of this report. Concerning MS and CCD convergence, it can be concluded that MS can be a valuable addition to the ARTEMIS system as a source of information in itself.

While a quantitative relationship between the four variables can not be described, a qualitative analysis shows a clear complementarity between SCAT- and ARTEMIS-data. The conclusion that the indices have a strong complementarity leads to a second conclusion. The scatterometer derived indices really have an additional value and a physical relationship with what happens with crops in the region under study. In other studies it is being researched whether this relationship can be quantified to the extent that crop conditions can be monitored and yields can be forecasted. An overview of these studies is presented (SCATMALI and SCATYIELD). From this material, in combination with the results of this project, it can be concluded that scatterometer derived information has the potential of leading to better crop monitoring and yield forecasting than what is currently possible.

If the costs and benefits of implementation and use of the scatterometer data into the ARTEMIS system are evaluated one must make a differentiation between three different cost components:

- the cost of system development to provide the indices on a routine basis;
- the costs of the basic data sets;
- the costs of the periodical (weekly or per decade) production of indices.

In the current situation the data costs for ARTEMIS are provided from external sources and are free for FAO. Either the data distributors supply the funds for this or external funds are sought as in the case of the newly acquired SPOT VEGETATION data.
When these costs are compared to the scatterometer data (costs for the African data is approximately 5,000 EURO per year) one can say that the already used data are more economic to FAO, but of course this is an artificial comparison. If the real costs for the scatterometer data is compared to the real costs of the other data the scatterometer data is very economic.

The experiences in this and the other two projects has learnt us which scatterometer products can be provided now to the market on an operational basis. We have also learnt which R&D efots are required to improve and widen the scope of these products.

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1. Introduction

1.1 General

Since 1988 an operational monitoring service on environmental and agricultural crop production for Africa and the Middle East is provided by ARTEMIS, a system operated by FAO. ARTEMIS supports with this service e.g. the FAO Global Information and Early Warning System (GIEWS) on Food and Agriculture, the Desert Locust Plague Prevention programme and regional and national food security early warning systems in Eastern and Southern Africa (IGAD, SADC). ARTEMIS provides satellite remote sensing information to these services. ARTEMIS in itself is an operational remote sensing data acquisition, processing, archiving and product dissemination system for vegetation and drought monitoring in Africa and the near East. It is based on the use of hourly Meteosat TIR data and daily NOAA AVHRR data. ARTEMIS products are used at global level at FAO Headquarters in Rome and at regional and national levels in Eastern and Southern Africa. The FAO Agromet Group regularly collects, processes and disseminates meteorological ground observations in the context of global, regional and national early warning programmes for Food Security.

ARTEMIS has been operational since 1988. The system has its limitations, inherent to the basic data sources. The integration of new remote sensing methods has been a subject of many research activities since the establishment of the FAO-ARTEMIS programme in 1985.

The potential of the ERS-scatterometer in measuring soil moisture content and forecasting of yields has been demonstrated in two projects. These projects are the so-called SCATMALI and SCATYIELD projects in which scatterometer information has been tested in respectively drought and yield monitoring in Mali and Russia. In these projects method development, field validation and business planning has been undertaken. In order to be able to evaluate the results of this project in the perspective of the other projects a resumé of these projects has been included in Section 8 of this report. In short, the conclusions drawn from these projects are that:

- the scatterometer measurements closely correspond to topsoil moisture content (measured in different manners, not all of them in the tradition of pedological humidity measurements);
- the very good instrument calibration of the ERS-scatterometer enables a comparison of observations over time and space;
- the $\sigma 40°$ approach permits the reduction of the vegetation effect on the soil humidity measurement under not too arid and not too vegetated conditions, being more or less applicable to the principal agricultural areas of the world.

In this demonstration project, it has been proposed to test the usefulness of scatterometer data tested as an addition to the other remotely sensed (Meteosat, NOAA/AVHRR) and ground data in ARTEMIS. The proposal has been forwarded to the Netherlands Remote Sensing Board (BCRS) in 1997. The project has become operational in 1998 as part of the National Remote Sensing Programme of The Netherlands.

1.2 Objectives

The operational objectives of this project are to:

- compare rainy season data of a zone around the African Sahel in Mali as obtained from the field and Meteosat derived Cold Cloud Duration (CCD) data and NOAA AVHRR derived Vegetation Index (NDVI) data with scatterometer data of the rainy season of the years 1991-1998;

- assess how scatterometer data could be integrated within the operational ARTEMIS system (preliminary system design-like activities);
- assess costs and benefits of such an integration.

Associated questions regarding these project objectives are:

- the possibility for calibration of NOAA-NDVI-values with scatterometer data;
- the analysis of convergence and divergence between 7.6 km resolution CCD data, field data and scatterometer data;
- the possibility to reconstruct rainfall incidents by a combination of both sensors

In order to compare indices as present in ARTEMIS with indices as derived from scatterometer observations a very thorough and advanced mathematical approach is required to compare index values over space and time. In this report this approach is described in Sections 2, 3, 4and 5 of this report, introducing the data, the approach to a quantitative comparison, the results and conclusions of this comparison.

In doing this work also a very important qualitative impression has been obtained from the data. This is reported in Section 6. In Section 7 an analysis is presented of costs and benefits. In Section 8 the results of this project are evaluated regarding the achievements in two other projects on the same method, executed in more or less the same time frame. In this Section 8 also aspects of market evaluation, products and business planning are included. In Annex 1 an example is given of another approach for quantitative comparison of the indices through physical modelling.

2. Description and sources of the data

Artemis data

Two data products provided by ARTEMIS have been compared with the scatterometer derived products. These products are:

- the CCD (Cold Cloud Duration) and
- the NDVI (Normalised Difference Vegetation Index),

CCD

Data from the METEOSAT satellite infra-red sensor have been received by FAO-ARTEMIS since 1988 (Hielkema, 1999). The infra-red channel data indicate temperatures at the tops of clouds, or the Earth's surface if there are no clouds. The CCD-values are the result of comparison of a reference value, the METEOSAT temperature value for each picture element (pixel) of every image. This reference value varies according to location and time of year, but are generally in the range of -40° to -60° Celsius. If the pixel is colder than the appropriate reference value it is assumed to contain a very cold cloud, which over the tropics is likely to be a rain-bringing, convective storm cloud, and the 'duration' value for that pixel is increased by one hour. This is done for the whole image, after which the image from the next hour is processed.

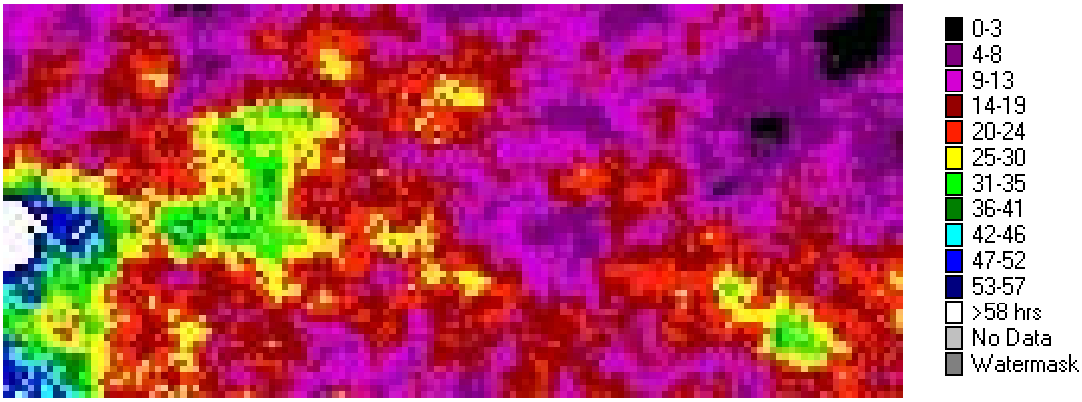


Figure 2-1 - Example of CCD provided by Artemis for the project area

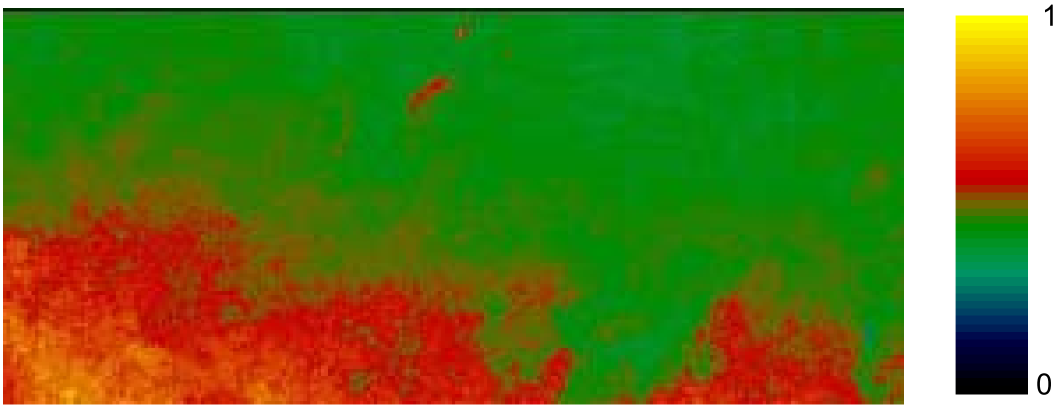


Figure 2-2 – Example of NDVI provided by Artemis for the project area

NDVI

The Vegetation Index values are derived from data from the Advanced Very High Resolution Radiometer (AVHRR) instrument onboard the NOAA polar orbiting satellites. Data from the visible (Channel 1) and near infrared (Channel 2) channels are combined into a ratio, the Normalized Difference Vegetation Index. Data from the thermal channel (Channel 5) is used for cloud masking. For the Africa data set, AVHRR data at "Global Area Coverage" (GAC) resolution is used, which is derived from the original AVHRR data by resampling. This is performed on board the satellite, in order to reduce the storage requirements.
Resultant values roughly represent the following:
High vegetation: > 0.4
Medium vegetation: 0.2 to 0.4
Light vegetation: 0.1 to 0.2
Bare soil: < 0.1
Clouds: < 0.001

2.2 Meteorological data

In order to compare the remotely sensed data with "ground truth"-values, rainfall data from meteorological stations is used. The rainfall data used consist of daily measurements of precipitation in millimetres for 128 rain stations which are spread over Mali. For most stations the data range starts well before 1940, recent data is in most cases not provided. In general the rainfall data range up to 1992 or 1994 and in some cases 1995. This data set is produced by the national meteorological service in Bamako where country-wide all the collected data is stored, analysed and made available in digital format.
Because the extent of the rainfall database is limited to the years up to 1995 the comparison of the rainfall with the scatterometer data used is confined to the years 1994 and 1995.

2.3 Soil moisture detection with ERS

The scatterometer data used in this project is measured with an instrument on board the European Remote Sensing Satellites, ERS-1 and ERS-2. It emits microwaves and measures the reflected electromagnetic radiation on the same antennas. This backscatter is measured as a coefficient (the ratio of received over emitted power). The measurements are executed using three antennas, each 'looking' at the earth surface under a different angle).
The spatial resolution of the ERS scatterometer measurements is approximately 50 kilometres. Between 2 and 3 observations per week are made of Africa.
The backscatter coefficient from the ground surface depends on three principal variables:

- soil water content (which influences the dielectric constant, the conductivity of the top soil as a reflector/scatterer);
- vegetation (the structure of plants scatter the microwaves as a function of their mass and structure);
- surface roughness, often having a certain geometric pattern at micro- meso- or macro creating interference with the microwave radiation.

Since soil water content is the only variable of interest to this project, methods had to be developed to eliminate the effect of the other two variables. The methods used in this project are based on the methods documented in the PhD-thesis of W. Wagner, 1999, and have been adapted for Mali, (from which the thesis also benefited).

The elimination of the vegetation component in the signal is based on the differences in backscatter behaviour between the three antennas. Relations between backscatter coefficients, incidence angles and soil wetness have been empirically established. The vegetation independent measure of soil humidity is obtained at an incidence angle of 40°, to which value all measurements are transformed.

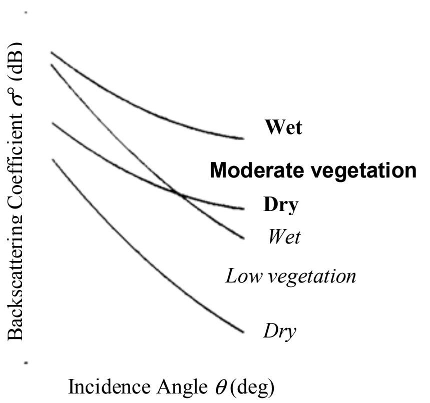


Figure 2-3 Illustration of the dependency of the backscattering function $\sigma 0(\theta)$ on vegetation and soil state

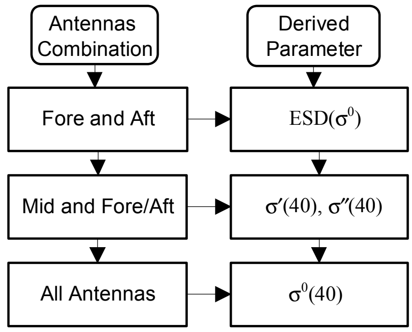


Figure 2-4 Flow chart of processing steps for ERS Scatterometer data. In the processing four parameters are obtained: The estimated standard deviation of $\sigma 0$, ESD($\sigma 0$), the slope σ'(40) and the curvature σ''(40), and the backscattering coefficient at 40 degree, $\sigma 0$(40).

Model corrections relate to the scaling of the backscatter to wet and dry soils, bare and heavily vegetated areas, the reduction of the impact of surface roughness, etc. In desert areas surface geometry in shifting sands sometimes may disturb the scatterometer soil humidity signal.
The result of this processing is a scatterometer based soil moisture index:
MS: Measurement of the soil moisture in +/- the upper 5 centimetres of the soil as measured by the scatterometer. The Ms is calculated by linear interpolation of the calculated backscatter values (σ40°);
The growth of a plant depends on the water content of that part of the soil in which a plant can root and really not on the humidity of the top 5 centimetres. However it is thought that Ms values with a repetition rate of 1-2 per week can be seen as a mirror on the soil surface of the succession of rainfall events in which rain drops on the surface and infiltrates in deeper soil layers, evaporates or disappears into the ground water. As a simple approximation for the moisture throughout the used part of the soil profile the Soil Water Index has been derived:
SWI: The Soil Water Index. The SWI is based on the MS, depicting the available water content in the rooting zone. A mathematical model was empirically developed for soils in the Ukrain, which simulates the propagation of soil humidity from the top soil to the first meter of the soil profile.
A third index that has been developed, the **DSWI**, is calculated as the deviation of the SWI from the average SWI over the last seven years on a weekly basis. The 1991- 1997 data series functions as a reference for the actual situation. For a full description of the methodology for the derivation of SCAT-data reference is made to the method by Wagner (1998).

3. Methodology for a quantitative comparison of the data

3.1 Method

A relationship between two variables can be described in two ways. Either a statistical correlation can be quantified or alternatively, an analytical model can be built with the two variables as input.
When the second method is used, in practice the model will be a statistical "best fit" through the observed data, because of the fact that most processes are too complex to be described on a mathematical basis. In both approaches the outcome can be used to predict one variable on the basis of previous data for that variable in combination with other variables. For example, an estimation can be made for the NDVI of the next decade using the values of SWI and NDVI of this decade.
The evaluation of the convergence of SCAT-, ARTEMIS- and field-data can be divided in two parts. SWI is indicative for the amount of water available for vegetation in a soil. A shortage of water, indicated by low SWI values, will result in a less healthy and less full grown vegetation. This should be reflected by the NDVI. Therefore a description of the relationship between SWI and NDVI is attempted.
Assuming that CCD is closely related to the amount of precipitation, rainfall and CCD are expected to be descriptors of the same process. MS is an ad-hoc measurement of the topsoil and is not derived indirectly from other data. The relationship between these variables involves the whole process from precipitation, via evapotranspiration, infiltration and percolation, to topsoil moisture. This chain is too dependent of external variables to be described using an analytical approach with only CCD (i.e. rainfall) and MS as input. The relationship between CCD and MS is therefore described using statistical correlation coefficients.
To come to a comparison, the data have to be spatially and temporally corresponding. SCAT-derived data (i.e. SWI and MS) are therefore spatially resampled to the ARTEMIS resolution of 14 km using a bilinear resampling algorithm. Temporally the SWI values are resampled by interpolation to decade-values.

The selected project area includes the cultivated zones of Mali, Burkina Faso and surrounding countries and is illustrated in Figure 3-1.

3.2 Convergence of SWI and NDVI

The growth of vegetation and the implied increase of biomass in relationship with water content in soils has been and is subject of numerous extensive studies. It is a widely accepted notion that a straightforward correlation is not to be found, because of the large number of processes and factors concerning the process of plant growth. As NDVI is a vegetation index and SWI is a measurement of soil moisture, the relationship between the two shall be a reflection of the processes involved. In (semi-)arid regions, like the study area, these processes will be mostly dominated by water availability, so the relation between SWI and NDVI will be most explicit.
A direct correlation test is discarded as a method of analysis. Although it may produce a result, the value of such an outcome will have little meaning, as it is only a number on a black box. Spatial and temporal influences will have to be taken into account to produce results with more significance.

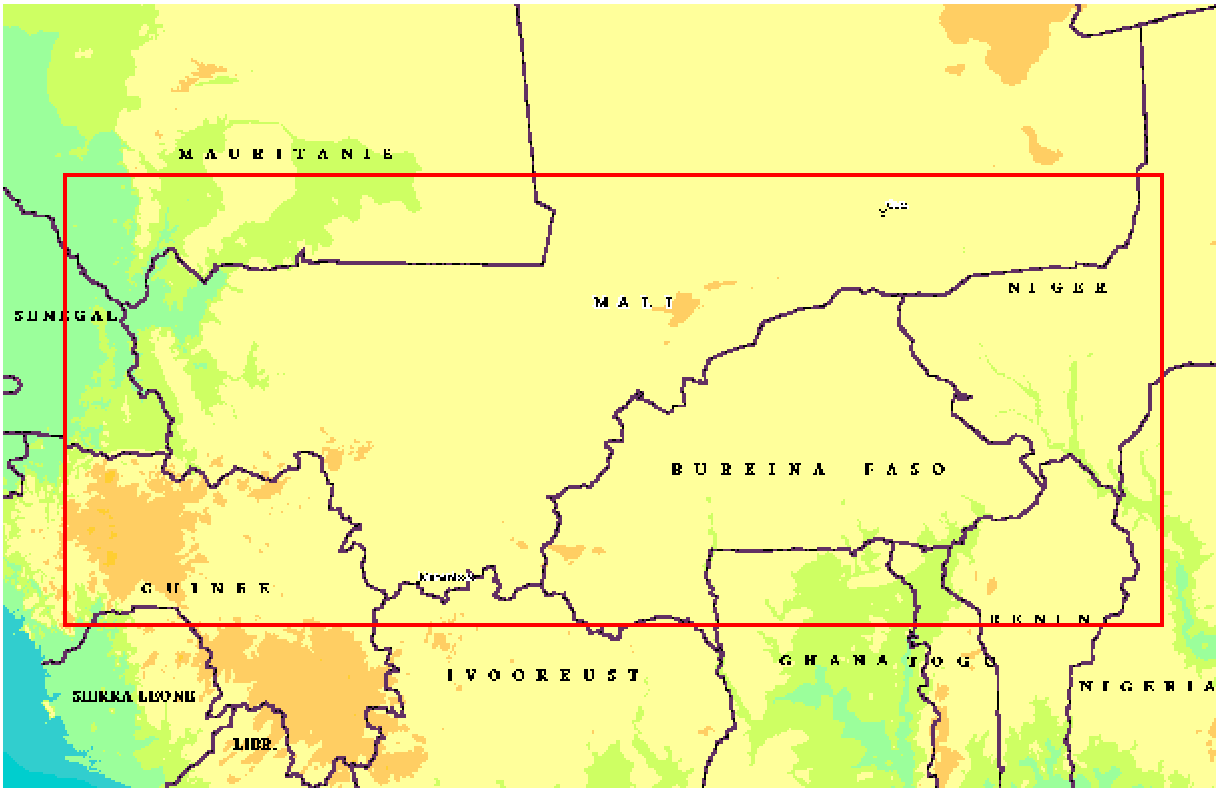


Figure 3-1. Map of the project area indicated as the rectangle.

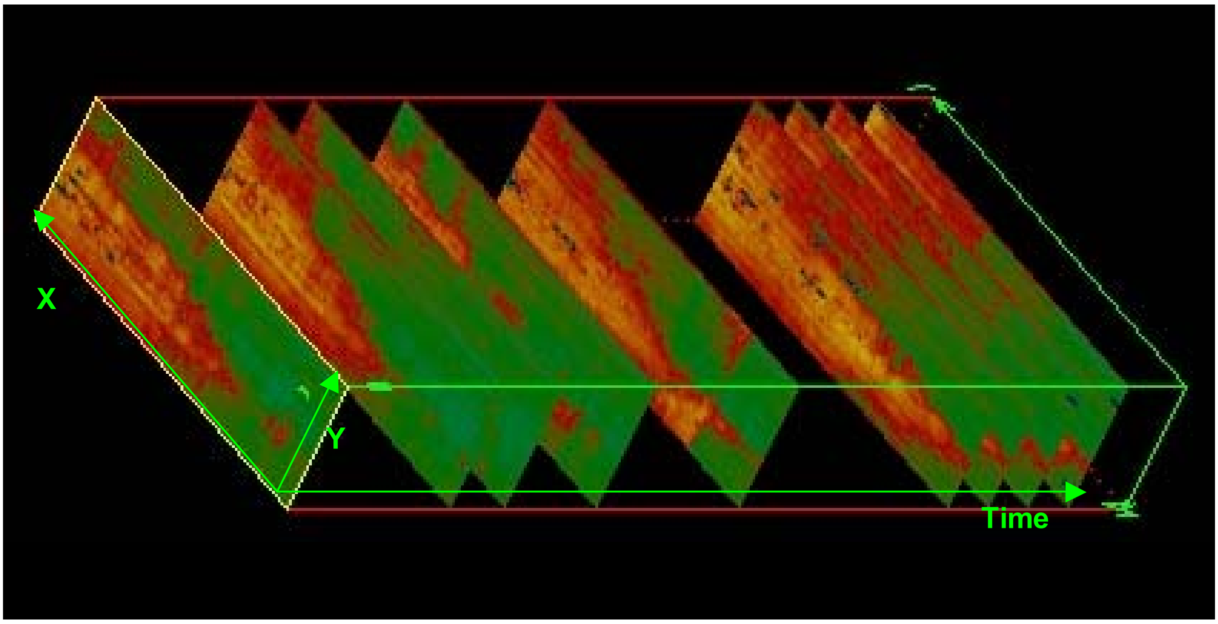


Figure 3-2 Example of multitemporal data-cube. Here only some ndvi-images are shown

In this case, the convergence between NDVI and SWI is statistically analysed while taking into account the structures within the data set in space and time. This means that the data have to be grouped into clusters that are more or less homogenous through time and space. This clustering process should take into account physical determined structures, such as soil types, and artefacts. The values of these artefacts will influence calculated means or
standard deviation of larger (generalised) areas significantly, because of their highly deviating values. Said otherwise, these generally small areas introduce a lot of noise in the data. However with the proposed segmentation the artefacts will be handled separately, which will reduce the observed variation within the structure.
The clustering of the data is done creating a “data cube” of NDVI and SWI (separately) for each year. This 3-dimensional array of data can be considered as a multispectral image with the temporal images as bands (Figure 3-2)
This array is clustered through time using the isodata clustering algorithm. Next the data is spatially segmented. The resulting clusters should produce statistical parameters which are significantly better than an average of the whole area. For the resulting clusters mean, minimum and maximum values through time are evaluated.

3.3 Convergence of CCD, rainfall and MS

It is supposed that CCD is highly indicative for the amount of rainfall. Soil moisture (MS) is a direct result of rainfall, and therefore CCD and MS values are related in a much more direct way, than SWI and NDVI. The black box has become a grey box, where factors (such as rainfall evapotranspiration and soil types) can be pointed out more clearly. Furthermore the rainfall data are point data. To prevent the introduction of noise in the data resulting from interpolation methods, the analysis is to be carried out for these points. Therefore a direct analysis without a previous clustering is feasible. The various data types however have different intervals and in the case of MS the intervals vary. This complicates the analysis in such a way that data have to be temporally resampled to comparable intervals.

In this analysis rainfall data are considered to be the ‘groundtruth’ reference data. On the other hand the amount of rainfall is the connecting link between the meteorological CCD and pedological MS. CCD and MS are therefore compared with rainfall and not directly with each other. The outcome of such an analysis will give more insight in the linking relationships than carrying out a correlation-analysis between MS and CCD.

The rainfall measurements are done at points (meteostations). For the analysis two stations are selected: Gao in the arid north and Manankoro in the more humid soutwestern part of the area of interest. CCD and MS values are extracted from the pixels covering the corresponding co-ordinates.
CCD is a mean value for a decade (i.e. ten days). Rainfall data is easily resampled by calculating the mean over the same decade. For the years 1992-1995 a correlation coefficient is calculated.
The temporal resampling of rainfall to MS is less straightforward, because the interval between two MS measurements is highly irregular. Several resampling methods are initially tested. For every day an MS-value is measured, the mean over the previous 10 days, a weighted mean over the previous 3 days, the mean over the previous 4 and succeeding 5 days and a weighted mean over the previous 2 and succeeding 2 days (all including the relevant day). Based on the outcome of the correlation analysis the best resampling method is applied to the rest of the data (i.e. the other years and station).

4 Results of the comparison of the data sources

4.1 The results of the convergence between SWI and NDVI

The analysis of convergence between SWI and NDVI is first carried out for 1995, as it is neither a very wet or very dry year and therefore supposed to be representative for other (average) years. The results of the other years under consideration are listed in the appendices.
The **temporal** clustering, using an isodata-algorithm, is basically an unsupervised classification. The number of classes is determined with trial and error: when an extra class shows extra spatial information this class is kept, until the point where extra classes only divide existing classes into smaller ones without altering the spatial structure. This results for the project area for both NDVI and SWI in a clustering into 6 classes (7 including the null-class in the SWI-image), Figures 4-1 and 4-2.

An eye-catching aspect of these images is the smoothness of the SWI-clustering especially in comparison with the NDVI-clustering. This effect is caused by the resampling of the 50 km-resolution SWI to the about 14 km-resolution of NDVI. The null-class in the SWI clustering is introduced by the fact that the coverages of the datatypes are not identical due to their different resolution.

It can be observed that a distinct zonation is apparent in both cases that show clear resemblance. This is further illustrated by the plots of the mean SWI and NDVI values per cluster for 1995 (Figures 4-3 and 4-4). The mean curves are, especially for SWI, clearly distinguishable from each other. However a closer look at the statistical parameters of the SWI-curves (i.e. minimum, maximum and standard deviation, figure 4-5) reveals that the variability within a cluster is still rather high and that the clusters are statistically spoken not so discriminative. This is probably caused by spatial artefacts that can be related to small areas with deviating physical factors, such as soil type or land use. The **spatial** segmentation should be used to indicate these artefacts.

Figure 4-1. Result of the temporal clustering of SWI-data of 1995, with the segments displayed in different colours

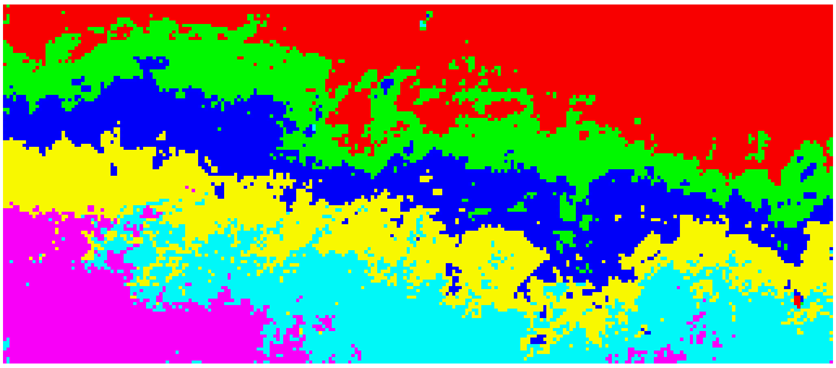
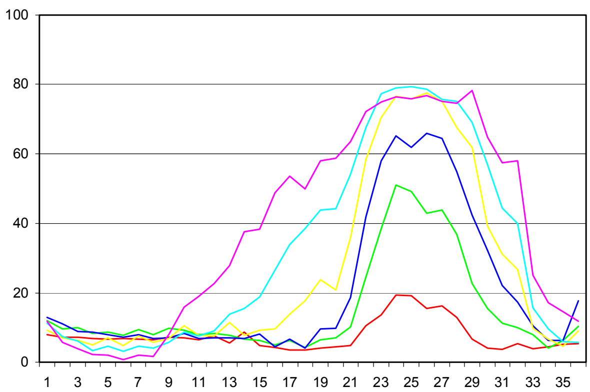


Figure 4-2 Result of the temporal clustering of NDVI-data of 1995



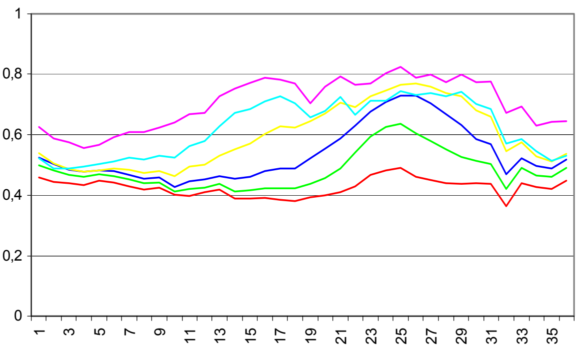


Figure 4-3 Mean SWI in 1995 per cluster The colours correspond to the colours of the segments in Figure 4-1. The numbers on the horizontal axis represent decade numbers.

Figure 4-4. Mean NDVI in 1995 per cluster. The colours correspond to the colours of the segments in Figure 4-2. The numbers on the horizontal axis represent decade numbers.

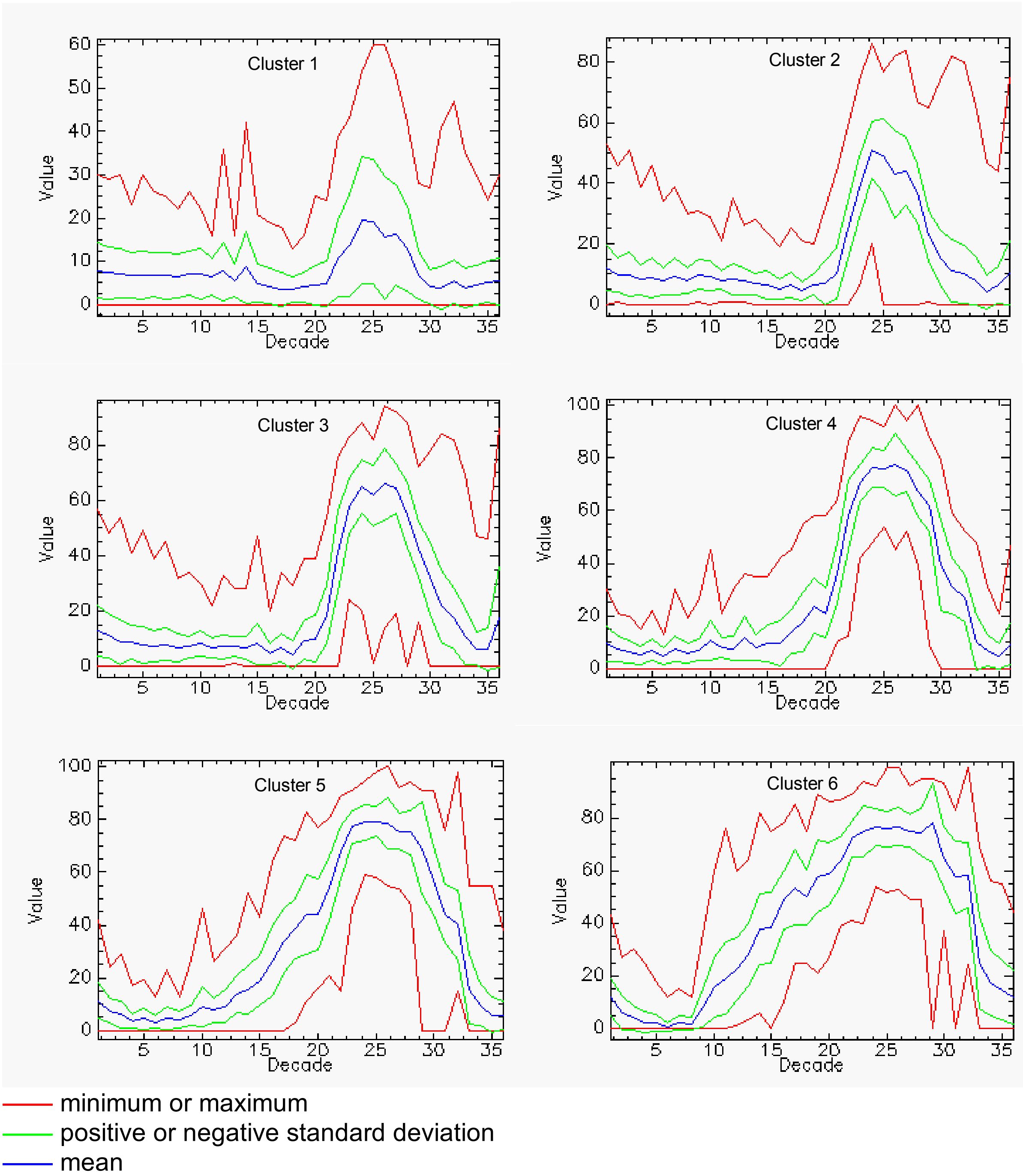


Figure 4-5 Mean NDVI in 1995 per cluster. The numbers on the horizontal axis represent decades

The spatial segmentation is applied to identify spatially homogeneous areas. To prevent the extraction of an obscuring large number of spatial segments that are one pixel in size, due to outliers in the data, a 3x3-majority filter is applied to the data. Next the spatial segmentation is carried out and analysed in order to remove the spatial artefacts. Partly due to the lack of extra data-sources regarding the abiotic factors, only a rough topographical map could be applied in this analysis. This results in the fact that the segments cannot be identified as spatial artificial areas. As a result it should be stated that the segments should not be treated seperately from the clusters as derived from the temporal clustering. Although an analysis of the combined cluster/segements after the spatial segmentation may reduce the noise in the data, this is not warranted by any arguments. Therefore the segmentation can not be used for an improved minimum-, maximum- and standard deviation-approach. However the larger segments can be used for further, analytical investigations (Annex 1).

4.2 The results of the convergence between CCD, MS and rainfall

For the two selected sites (Gao in the northeast and Manankoro in the southwest of the area of interest) CCD, MS and rainfall are plotted against time for the considered years (appendix B). An example of such a plot is given in figure 6-7.

Some features can be observed in these plots. First it is apparent that rainfall events are not indicated very accurately by CCD as well as MS. A high CCD value is perhaps a good estimator of the mean rainfall over the ten-day-period over which it is measured but rainfall events cannot be appointed. In that respect MS values are a better indication because these are ‘direct’, instant measurements, so they give an ‘actual’ value. However the interval between the recordings are so that in some cases the soil has already (partially) dried up after a rainfall event before a MS-measurement is acquired. Therefore rainfall events can only be reconstructed using MS-values when the data-acquisition is carried out during or directly after a shower. In other cases the rainfall event will pass by unnoticed by MS-measurements. On the other hand within a 50*50 km-pixel of MS a local shower can be averaged out.
Secondly MS-values show a certain inertia regarding the meteorological conditions. After the end of the rainy season MS is still high for some time, because the process of drying up of the soil takes not place instantly, due to water storage in the soil. This is especially the case when the soil is moisturised during an extensive period of time, i.e. the rainy season. It is therefore not surprising that this effect is more apparent in the more humid areas.
In order to quantify a relationship between rainfall and respectively CCD and MS, the rainfall data is resampled using the methods described previously. Next a correlation coefficient is calculated. The results are given in Table 6-1.

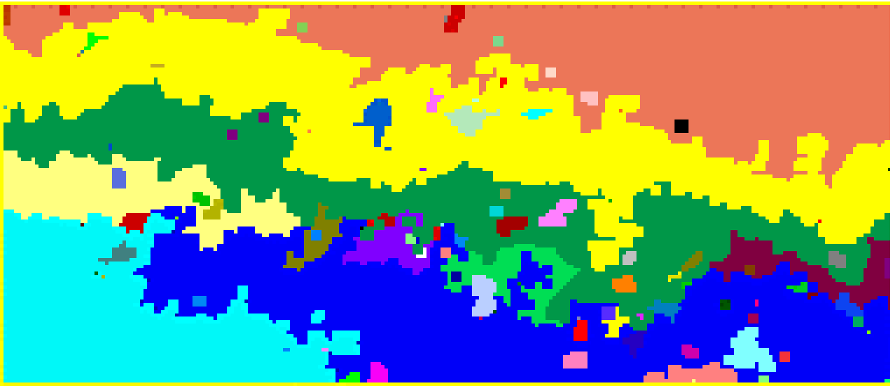


Figure 4-6 Example of the result of a spatial segmentation: segmentation of NDVI in 1995

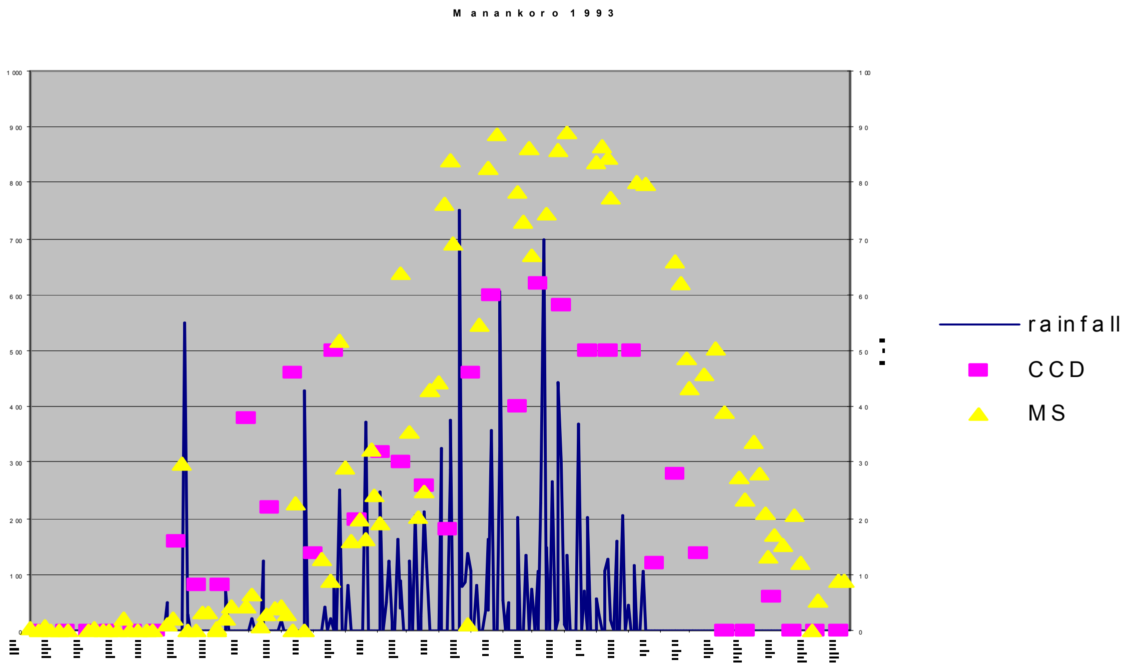


Figure 4-6 Example of CCD , MS and rainfall plotted against time for the station of Manakoro for the year 1993

5 Conclusions on the quantitative comparison of the data

The variation in the considered data is fairly high. Especially NDVI is sensitive to the fact that radiometric corrections are not performed. Minimum NDVI-values are equal to 0 over extended periods of time. This can be explained by the existence of cloud cover over a decade for a particular area. The maximum NDVI may also be rather high for a small area due to the local existence of well watered plantations or natural vegetation along river banks. These extreme values influence the data significantly and make a convergence analysis rather complicated. The characteristics of the data do not permit to sift outliers out of the analysis using a spatial and temporal clustering.
It can be concluded that in both considered cases a convergence in a general trend can be observed. The development of both the NDVI and SWI shows a clear beginning and climax of the growing season (Figures 6-3 and 6-4). It can be imagined that these data types can be used as indicators for vegetation or crop growth and therefore also for agricultural monitoring systems such as ARTEMIS. Quantifying the convergence however does not provide satisfactory results. The variation in the data is so high that a statistical estimation on the basis of these parameters is not feasible. Both data types can be used as input in their own right, but are basically different. Where SWI is a value for the soil moisture, NDVI is in a way a delayed reflection of this value. This 'reflection-process', i.e. the black-box-model of soil moisture to plant growth to biomass to NDVI, is still subject to studies and widely discussed in literature. Considering this, it may not be surprising that a quantifiable relationship between SWI and NDVI cannot be found. On the other hand, the preparation of the data (resampling, temporal and spatial clustering and checking the data with ground truth input for artefacts) is extensive. One of the purposes of this analysis was to explore the possibilities to integrate SCAT-data in ARTEMIS. It is concluded that it is not possible to use SCAT-data in a straightforward procedure to calibrate or validate ARTEMIS-output. SWI-data can in this respect be considered only as an additional but most valuable data source in ARTEMIS. An alternative method of analysis has been described in Annex 1 of this report, but an extensive application and evaluation of this alternative is not within the scope of this report.

The convergence between MS and CCD as rainfall-related data is partially identical. The MS is a value for moistness of the topsoil and is strongly influenced by meteorological as well as pedological factors. This is a fundamental difference with rainfall-related data, such as CCD. Apart from considering any resampling concequences, a relationship between CCD and MS will have to take into account the pedologic aspects of the drying-up and moisting processes. The extensive modelling of these processes however is not within the scope of this project.

It is concluded that the MS-index can be a valuable additional source of information in ARTEMIS. The relevance of the MS-index is also supported by the SCATMALI and SCATYIELD projects.

It is not feasible to reconstruct rainfall events from either data source. CCD is a mean value over a period of ten days and therefore any short-term events will be averaged out. The data source is only applicable to long-term processes. MS can be suitable for the reconstruction of rainfall events only when measurements are done with a short interval (half a day). In that case the drying-up of the soil will not have taken place yet. Also when this requirement is met, the reconstruction is only suitable for (spatially) extensive showers, due to the resolution of the SCAT-data of 50*50 km. On the other hand MS can never be used to quantify the amount of rainfall, because processes such as surface runoff are not taken into account. However in monitoring vegetation development or crop yield, one is less interested in the water that runs off but is interested in the water that stays on the surface.

6 Qualitative analysis

6.1 Observations on the data

The described work on relationships between the 'classic' ARTEMIS-indices CCD and NDVI and the SCAT-indices Ms and SWI has yielded very little statistically significant results: There have been no physical models developed that lead to integration or replacement of any of the four indices. However from the working with the data it has become very obvious that there is a strong complementarity between the four indices and that there is significant added value of combined use, since all four explain different environmental conditions of importance to the understanding of seasonal dynamics and plant growth.

In the following pages a comparison is made between the SWI and NDVI and between the Ms and CCD. Images of the year 1995 of the different data sets are placed side by side and an interpretation is given of the differences and resemblances (Figures 6.1-6.-4).

From these data, the complementarity of the data is easily noticeable. The conclusion presented above must than be interpreted as that in some way the data sources represent other, more or less independent abstractions of the physical reality of the project area. For this reason, the distinct complementarity may be important for monitoring purposes. In the next Section remarks on this aspect are presented.

6.2 Remarks on the complementarity of the indices

In the following points a comparison is made of the four indices for four moments during the growing season:

- beginning of the growing season;
- establishment of crops and natural vegetation
- vegetative development phase, middle part of the growing season;
- end of the season, ripening of crops

Beginning of the growing season
The beginning of the cropping season can both be obtained from Ms and CCD-values. Ms-values have been only tested in this respect in the SCATMALI project (Beck et al., 1999) for one year of measurements. This evaluation is very positive but of course this result is not enough to conclude that Ms-values are a reliable source of information to determine the start of the growing season. On the other hand CCD-values do not have a reputation to yield accurate and reliable information on this aspect. NDVI's have a slower response than the SWI and both are not suitable to measure the start of the main growing season.
The Planting Date Estimators developed under the SCATMALI-project are algorithms based on Ms-values which separate small non-significant rainfall events from the 'real' start of the growing season successfully for the year 1998 in Mali.

Establishment of crops and natural vegetation
The establishment of natural vegetation and crops can well be followed from NDVI's and SWI's. It is observed that the SWI seems to be more stable over time than the NDVI. The NDVI shows stronger fluctuations even when resampled to 50 * 50 km grids, corresponding to the SCAT-pixel areas. This is explained from the poor calibration of the AVHRR-instrument and from atmospheric interference. However also in cases where SCAT-observations are too scarce, (due to competing ERS-SAR operations), SWI's are not always available and therefore not as reliable as would be required for operational application.

There is a distinct advantage of using SWI's above Ms-values since the latter have relatively much more noise.

Vegetative development phase, middle part of the growing season
For the development of crops, respectively natural vegetation, during the middle part of the growing cycle, monitoring can be undertaken using either SWI and NDVI.
Soil moisture is the factor that permits vegetation development. In this respect somehow a relationship can be described where the SWI is an input for NDVI. However this relationship cannot be described in any simple physical model, other than through the partially successful but impractical method explained in Annex 1.

Problems in soil humidity (too much or too little) are only translated in vegetation development with a time lag of a decade or a forthnight. Accordingly the SWI provides a more direct basis for monitoring. Also the nature of the variables is somewhat different:. NDVI-values are for the larger part composed of a response from natural vegetation (since this is the dominant land cover in most of the study area). The SWI is defined as an index for agricultural land (soils with relatively good infiltration rates).
There may be a difference in relative importance for the two indices in function of the objective of monitoring. For crop monitoring the SWI may be more suitable, while for natural vegetation, total biomass, etc. NDVI's provides a more relevant basis.

End of the season, ripening of crops
At the end of the growing season all four indices show decreasing values. The last one to decrease is the NDVI, the first one to decrease is the CCD. NDVI-values decrease finally when trees loose leaves and depressions grow yellow. CCD-values decrease when rain clouds disappear. Ms and SWI-values decrease when top soils dry out.

The final decrease in NDVI-values presumably correlates better to available water for trees and other non-crops.
The final decrease in SWI-values may correspond closer to the water requirements of an annual crop.

In the more humid south this drying out of top soils happens relatively slower than in the north after the rains stop (observed from the precipitation measurements and the CCD-values). In this period crops in the south are still green and in the north they are ripening already. This ripening event is more or less synchronous with the final decrease in MS- and SWI-values, later than the decrease in CCD and earlier than the decrease in NDVI.

6.3 The pilot for Mali, growing season 1998

A qualitative evaluation of the SCAT-data as well as the ARTEMIS-data was carried out regarding the growing season in 1998 in Mali. During this growing season no exceptional events were to be observed, as the 1998 was not a very dry or wet year. However, the end of August and early September can be used for this qualitative evaluation. The SCAT-output for this period is displayed in figure 6.1.

The SCAT-indices show distinctive dry areas around Segou in week 36 and in the northwestern area of the Mopti district in week 37. These observations were confirmed by observations, carried out in the context of the Malinese pilot-project. A short period of drought was pointed out, independent of the SCAT observations, for these areas. The areas and period, where drought is an issue are relatively small respectively short, but are correctly indicated by the SCAT output. This confirms the presumption of the accuracy of the SCAT-indices.

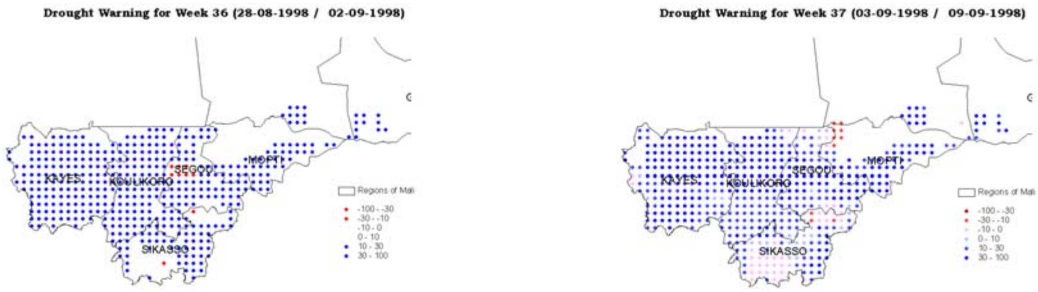


Figure 6-1 SCAT drought warning output in Mali in 1998

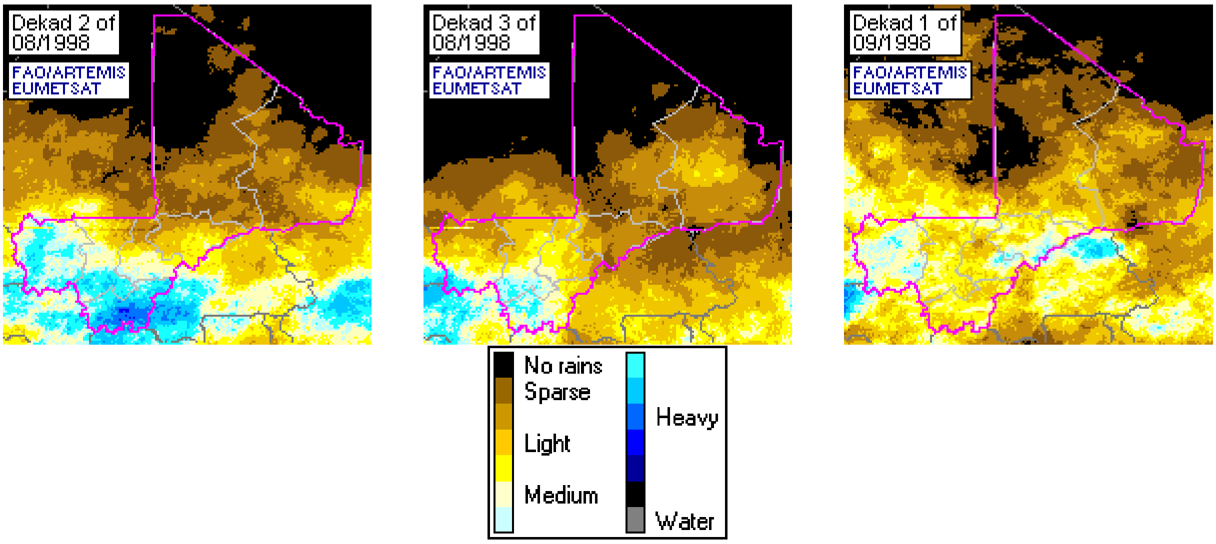


Figure 6-2 ARTEMIS CCD images of Mali in 1998

The CCD data used in the ARTEMIS system (figure 6.2) do not indicate any of these areas during the considered period. A few remarks can be made on this. First of all these CCD values do not take into account anything beside the considered decade. SWI on the other hand is the result of a model that is run over a longer period of time. Successive small shortages that can become important on a long term, are discarded completely by ARTEMIS data. Furthermore, the interpretation of ARTEMIS data, i.e. CCD or NDVI values, and the derived drought information is not as unambigious as the SWI values. SWI values indicate very clearly where problem areas can be expected, while CCD images of several decades have to be analyzed to come to the same level of information, if possible at all.

6.4 General conclusion from the qualitative analysis

A last remark on differences between the physical relations of the indices is that CCD derived indices indicate rain quantities in an area. However rain may run-off or infiltrate and be either available to agriculture locally or 'downstream'. Ms and SWI seem to measure more or less the net water remaining in the area.

SWI is in this respect more related to effective rainfall than to total rainfall. Effective rainfall is defined as the water available for crop growth (total rainfall minus evaporation, run-on run-off and other losses.

The conclusion that the indices have a strong complementarity leads to a second conclusion. The scatterometer derived indices really have an additional value and a physical relationship with what happens with crops in the region under study. In other studies it is a being researched whether this relationship can be quantified to the extent that crop conditions can be monitored and yields can be forecasted. At this stage of development of the SCAT-indices it is too early to make an absolute statement on this application. However the statement that there is complementarity with CCD-values and NDVI-values together with the relatively good calibration of the instruments from which the SCAT-indices are derived, through a convergence of evidence, suggest that further research to improve the SCAT-indices has the potential of leading to better crop monitoring and yield forecasting than what is currently possible.

7 Benefits and costs of the use of scatterometer derived indices in ARTEMIS

7.1 General benefits of the scatterometer derived indices

The complementarity of the indices has been described in Section 6.2. It is clear that there is additional value to be obtained from the use of the two scatterometer derived indices taken into consideration in this study, the Ms and the SWI. It is also obvious that the two indices do not replace the classic ARTEMIS-indices such as the CCD and NDVI.

The detailed analysis of the introduction of scatterometer derived indices in systems that are developed by customers of ARTEMIS products has not been executed in detail, since these systems with FAO are rather informal. GIEWS uses the ARTEMIS data products as one input next to many other signals concerning food security, such as market prices, national estimates, etc. From this it can be concluded that if a GIEWS-specialist uses three or four remote sensing indices in stead of two, the workload increases somewhat but not significantly in relation to the evaluation of all sources of data.

More research on this aspect is required and possibilities therefore are outlined in following sections.

7.2 How to evaluate benefits for ARTEMIS

Operational information services on environmental conditions in Africa and the Near East are since 1988 routinely provided by the ARTEMIS system to the FAO Global Information and Early Warning System (GIEWS) on Food and Agriculture, the Desert Locust Plague Prevention Programme and regional and national food security early warning systems in Eastern, Western and Southern Africa (IGAD, SADC).

In other words ARTEMIS system is the data provider for services and programmes elsewhere within FAO. From this it follows that these and other end users give reason of being to ARTEMIS. From the conclusions drawn earlier it is clear that there is significant added value for these users in the SCAT-derived indices. However in this study no uniform and clear answer has been obtained from this broad, diverse and geographically distributed group of users.

On the other hand, if the SCAT-indices are to be made available through ARTEMIS, the costs of this activity has also to be brought up by the users of the data. Therefore it is of interest to consider these costs in some detail.

7.3 Costs of implementation of SCAT-indices

If the costs and benefits of implementation and use of the scatterometer data into the ARTEMIS system are evaluated one must make a differentiation between three different cost components. For the sake of reasoning we take an area as Africa as the basic accounting unit for these calculations. The calculations have been split in calculation of three aspects:

- the cost of system development to provide the indices on a routine basis;
- the costs of the basic data sets;
- the costs of the periodical (weekly or per decade) production of indices.

Operationalisation / software development:
This implies the costs to implement the scatterometer into the daily processing and distribution practice of the ARTEMIS system by developing a technical environment which

enables the automated download, quality check, processing and distribution of this data source. The first parts of the data processing chain may be done by a service provider outside from FAO. Costs for the operationalisation of activities as downloading, quality check and processing in a commercial environment are based on the quantity of software that needs to be written. For the processing of the scatterometer most of the basic software is available. However at this stage of research this software can best be characterized as experimental scientific software not suitable for use in an operational environment. Therefor it needs to be adapted and export functionality needs to be added. Special attention in this framework needs to be paid to the internal FAO formats that are used in the ARTEMIS system. This IDA format is well documented and it is possible to include this in the processing software. Example code for the creation of the IDA format is already transferred from the FAO to NEO. The final distribution of the data by the FAO is the last part of the chain to provide customers with the data. For the operationalisation of this part of the chain the structure in which the data has to be provided needs to be designed analogue to that of data sources as NDVI and Meteosat. This focuses on the assessment of the processing capacity and naming conventions for the data streams.

As a gross estimation, the man time needed for the development and adjustment of the pre-processing software is in the order of three months. This would cover the costs of porting the written code and develop a user friendly flexible scatterometer data processing facility. Design of the system for the operational distribution of scatterometer data into the FAO ARTEMIS system will take about two months. An estimated total of 60,000 Euro would permit the development of this system.

Data costs
The data costs for the ERS-scatterometer are low. A year of scatterometer data in global coverage are, for commercial purposes, to be purchased from a commercial distributing entity, operating on behalf of ESA and will not cost more than 10,000 Euro. If the African part is taken from this, one could roughly say that 5,000 EURO would suffice for this area. For this sum all data recorded can be obtained. This implies that with SCAT-observations can potentially be made available for Africa on a two, three or four day revisit time for most of the area. However data provision by ERS depends on the operation of the satellite. The scatterometer is turned off when the SAR is operating or other maintenance work on the satellite is being performed. Also for other reasons historic data series show gaps. Data provision from the scatterometer on board of ERS-2 cannot be commercially guaranteed yet, which is illustrated with the loss of ERS-1.

In the future (from 2004 onwards) the ERS-scatterometers will be replaced by ASCAT on board of METOP. The METOP-series of satellites will make data available on an operational basis like meteorological satellites, and will be operated by EUMETSAT. It is supposed that data from these satellites for Africa on a daily basis would be in the order of 20,000 to 40,000 Euro per year.

Periodic (weekly or per decade) soil moisture data provision costs:
The costs for the operational provision include the equipment needed for the processing and the man time needed to download, perform a quality check, process and distribute the data at the external data products provider and at FAO.
As for the equipment at FAO one can say that it is sufficient to use an up to date PC with operating system and processing software. This PC needs a large hard disk storage capacity and a large processing capacity. Procurement costs for this equipment are in the order of 8,000 EURO.

For the distribution activity towards ARTEMIS at the external service provider it is foreseen that extra capacity is added to the already operational internet distribution facility.
Concerning the personnel costs in the processing and distribution of scatterometer data it is foreseen that after the set up of the system the time spend to operate the system will be limited to one and a half day per week. (This includes the collection of data from the FTP server, perform a quality check, calculation of soil moisture parameters and the distribution of the data to an FTP site at the FAO). In total the time needed to process the data will amount to 4 man months per year, leading to a total necessary budget of 44,000 EURO per annum.

The validation and distribution activity within FAO is estimated at a few hours per week in addition to the already ongoing activities in this field.

7.4 Cost comparison with other ARTEMIS activities

How do the costs mentioned above relate to the actual costs of operating the ARTEMIS system? In the current situation the data costs for ARTEMIS are provided from external sources and are free for FAO. Either the data distributors supply the funds for this or external funds are sought as in the case of the newly acquired SPOT VEGETATION data. When these costs are compared to the scatterometer data (price for the African data is 5,000 EURO per year) one can say that the already used data are more economic, but of course this is an artificial comparison.
However if the real costs for the scatterometer data are compared to the real cost of the other data the scatterometer data are very economic. Possibly these data costs can also be taken on by data distributors.

Concerning the cost of personnel and materials used in ARTEMIS at FAO, it can be stated that over the past years on average 3 persons are working fulltime on the design, extension and maintenance of ARTEMIS. Especially the inclusion of new data sources in the system takes time in the preparation of the on-line provision of data, design of the data structures and implementation.

The extra costs in validation and running of the extra data products are relatively small.

All in all, the total costs for the running of an operational service providing SWI- and Ms-values would cost something in the order of 55,000 Euro per annum, exclusive of the investment cost in system development.

8 Evaluation and exploitation of the scatterometer derived indices

8.1 General

In the same timeframe as the FAOSCAT project , two other projects have been executed focussing on the evaluation of the practical use of the ERS-scatterometer based methods in drought and yield monitoring. These projects are the SCATMALI and SCATYIELD projects which have been executed under the ESA Data User Programme. In this Section a summary will be given of the achievements of these projects including an evaluation of the practical use of the method. Also an evaluation is presented on how the results of all three projects have lead to the definition of operational products and which research and development activities have to be undertaken to widen the scope and quality of these products as well as the organisation of NEO and partners to exploit the benefits of the method.

8.2 The SCATMALI and SCATYIELD projects

The SCATYIELD project is a follow-up for the SCATMALI project, executed in 1998 under the ESA Data User Programme. Under this project, topsoil humidity and soil profile water indices were derived from ERS-scatterometer signals for Mali in West Africa. From these data local and regional dry spells and their impact on crop development were identified and validated in the field during the growing season of 1998. Also the estimates for regional planting dates derived from scatterometer measurements matched the observations in the field. In conclusion, as the first demonstration of an innovative method of backscatter signal processing, promising results were obtained. In this project important feed-back was provided by Malinese counterparts and Malinese governmental organisations, who much appreciated the results, though they were in fact experimental and for one year only.

In the SCATYIELD project the developed methods were to be tested over a larger area in Africa and a second area in Russia. Secondly, the developed methods to detect crop stress during specific moments of the growing season were to be integrated into new methods for end-of season yield estimations. These methods were to be operationalised into service demonstrators. The results obtained were presented to potential customers and a business plan for the exploitation of results was to be prepared.

The projects have been executed by a project team with the following responsibilities:

- Technical University of Vienna, Institute of Photogrammetry and Remote Sensing in Austria responsible for retrieval of soil moisture information from scatterometer data;
- Catholic University of Leuven, Institute for Land and Water Management in Belgium responsible for the development of indicators for cropping conditions in Africa;
- ALTERRA, (formerly know the Staring Centre DLO) in Wageningen, responsible for the integration of the scatterometer data into the CGMS plant grow model and improvement of the applied methods in Russia;
- DSI, Dokuchaev Soil Institute in Moscow was responsible for the collection of verification data for the Russian area. Soil data, meteorological data and crop yield data were collected in this framework;
- The Institute for Rural Economy, Laboratory for Soil Water and Plants with the Regional Agronomic Centre in Bamako, Mali responsible for field data collection and validation of preliminary results;

- NEO, Netherlands Geomatics & Earth Observation B.V., from Lelystad, The Netherlands, responsible for overall project management, business plan development and the integration of the soil moisture information, the indicators for cropping conditions, soils and climate data.

The larger African area of interest for the SCATYIELD project is situated between longitudes of 9 and 17 degrees North and the latitudes 18 degrees West and 5 degrees East covering an area with the dimensions of 6.8 Mkm^2. It includes the countries of Senegal, Gambia, Mali, Burkina Faso, Guinee Bissau and parts of the adjoining countries.

The second study area is situated in Russia and Ukraine. Longitude is between 30 and 42 degrees East; the latitude is between 44 and 56 degrees North. The land area is approximately 1.1 Mkm^2.

In general for both study areas a set of methods is employed, incorporating the following elements:

- Soil moisture information is retrieved from the scatterometer using directional aspects of the measured backscatter on the three antennae of the ERS-scatterometer. The method is described in Section 3 of this report;
- Data are collected on weather, soils, crops, land use and agricultural statistics for the project areas;
- Methods are developed to integrate scatterometer derived information with the auxiliary information through simulation models for water balances and crop growth. These methods have led to the development of different indices for drought, crop performance, planting dates, etc.;
- Validation activities has been carried out for the respective indices for historic years and in near real time for growing seasons in 1998 and 1999.

The analysis starts with assimilating of the existing data series of scatterometer (1992-1998) observations and the auxiliary information. These are integrated. The result of this analysis is a calibration of the integrated methods to field observations. Usually in this analysis the results of models are compared with and without scatterometer input, since reliable field data are scarce for both study areas;

In West Africa specifically developed plant growth models have been the basis for further work. These models are an in-house development assimilating soil profile water as derived from the scatterometer and an infiltration model. The model calculates plant production and water use requirements at each growth stage, based on Doorenbos and Kassam (1979). In Russia use has been made of the so-called CGMS, a system for Crop Growth Monitoring based on WOFOST crop modelling software. The CGMS and the developed databases for this system are used in the Agricultural Information System operated since 1994 by the Joint Research centre of the European Commission in Ispra, Italy. It is a European system that is developed to assimilate more and more data. The CGMS has been developed by the predecessor of ALTERRA, the Winand Staring Centre in Wageningen, The Netherlands.

Also other information is derived from scatterometer data. This information relates to the transition between freezing and thawing as well as to planting dates. Freezing and thawing is important regarding the estimation of the start of the growing season in Russia. In Africa planting dates have been estimated from initial changes in scatterometer derived top soil moisture at the start of the growing season. Another test has been executed using the scatterometer data for the area of the Ukrain adjacent to the study area, comparing the behaviour of the SWI over the season relative to gravimetrically determined soil moisture data.

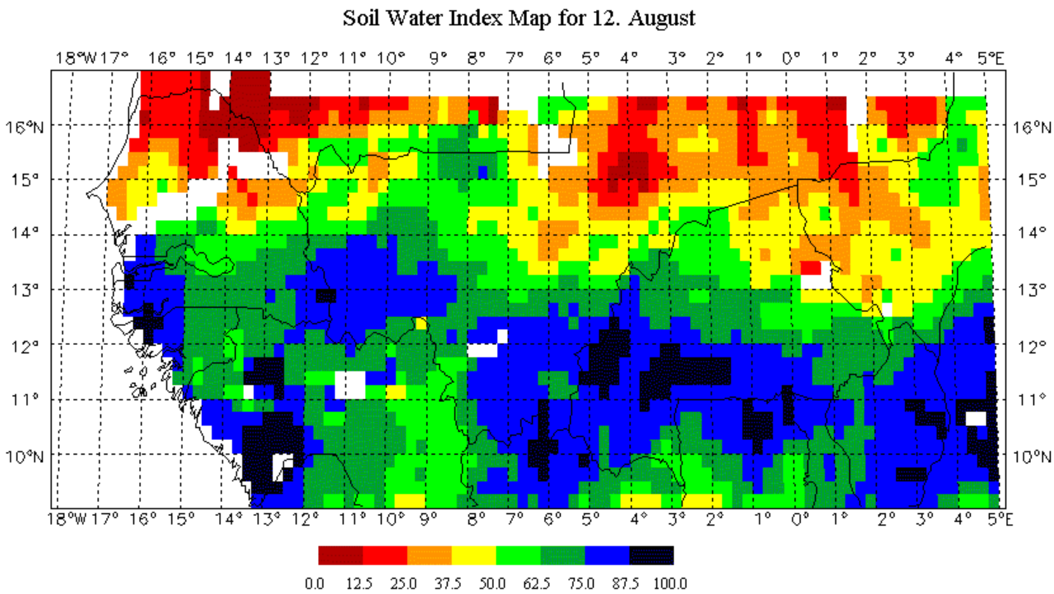


Figure 8-1 Soil Water Index for African Study Area, August 12 1999

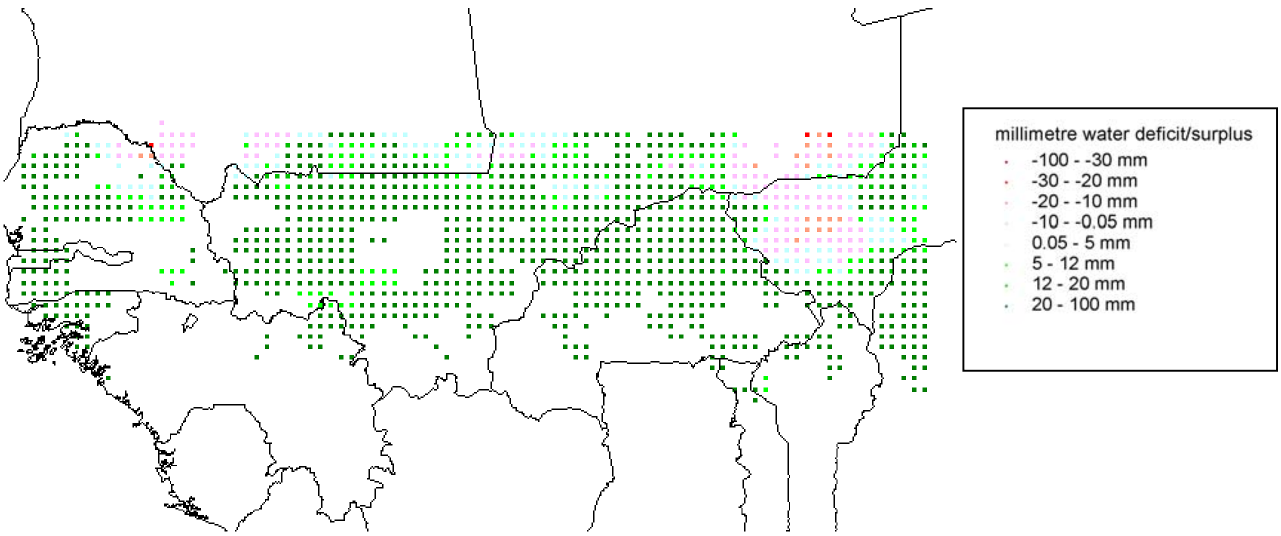


Figure 8- 2: Crop Perfance Index values for week 36 of 1999

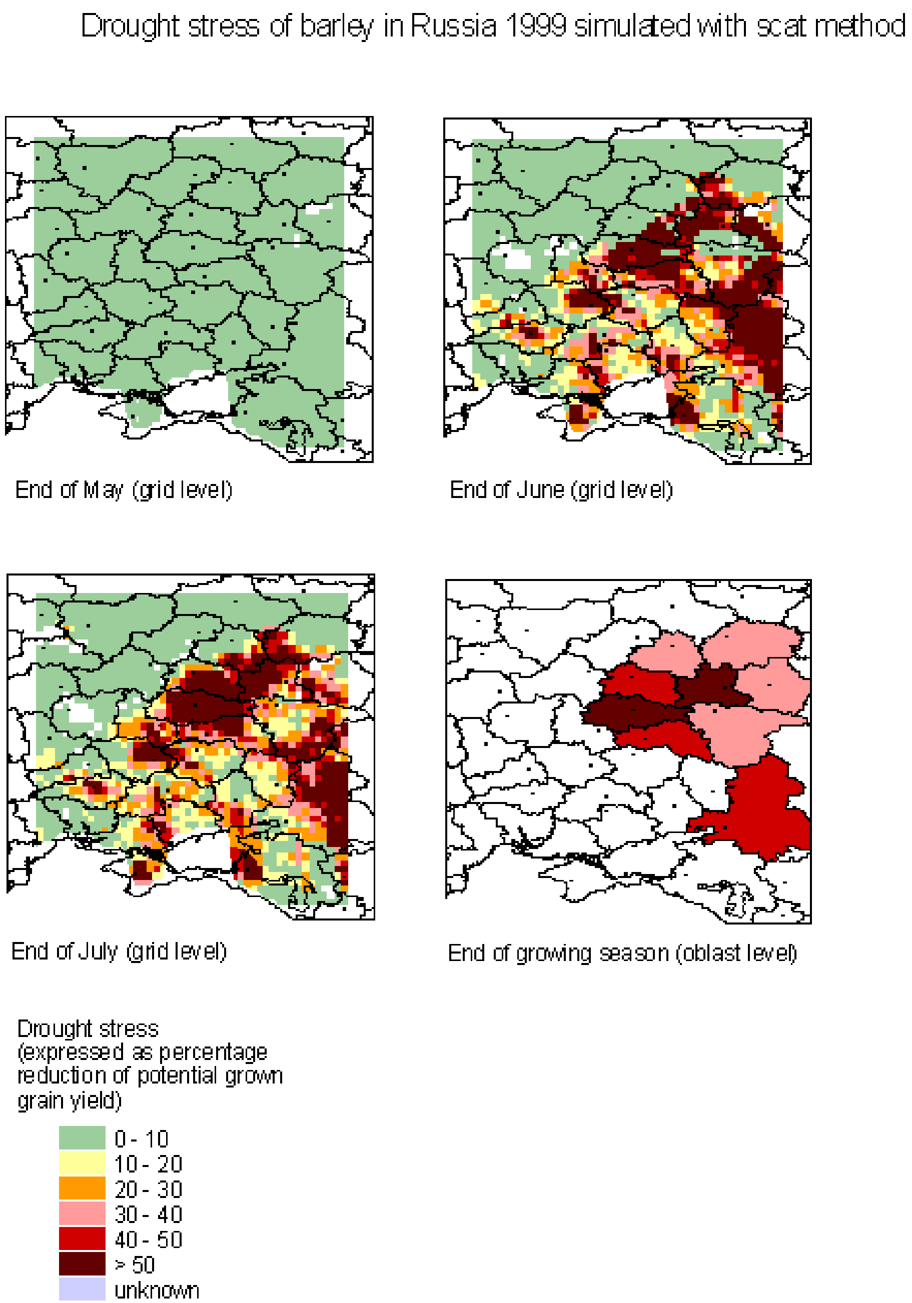


Figure 8-3 Drought stress of barley in Russia calculated with the scatterometer method

8.3 Evaluation of results

The use of the FAO soil database enables the global application of the scatterometer models, where no appropriate, more detailed soil maps and soil data bases are available. This database is a valuable source for the application of a scatterometer based global drought early warning system.

The infiltration model in the Soil Water Index still has a systematic bias, but the reasons for this indicate that repairs are most feasible. In the beginning of the growing season soil moisture may be underestimated, whilst at the end of the growing season it may be overestimated. Improvements of the SWI may require a more in-depth analysis of soil physics per soil type and/or compensation mechanisms must be introduced regarding seasonal aspects. This latter aspect may be based on the increase in evaporation from the soil during a growing season, due to its rise in temperature. In this respect the current SWI is not yet suitable to quantify yield reductions due to drought, whilst it is still most useful to infer drought and crop stress. However it most certainly is a major improvement in obtaining a quick and detailed overview of soil moisture conditions when compared to rainfall data, both in availability, speed and costs. Integration of SWI-processing with thermal remote sensing data is an attractive solution to improve the SWI.
Both the yield model for Mali and Russia have yielded significant results over respective study areas when scatterometer data have been used as input. A general observation, based on convergence of evidence during two projects, is that the models perform better with scatterometer derived input than with input from other sources. The yield models used vary significantly with respect to demand for auxiliary information. CGMS in particular is sensitive to lacking crop and meteorological information. Alternatively CGMS seems, also for use in Africa, in the long run a better option, since the internal qualities of the WOFOST-model take into account the physical reality of the plant much better and has a clear potential for improvement with respect to yield forecasts under drought stress. In the model used in Africa many factors may be important but cannot be incorporated. It is useful to consider if additional remote sensing data sources can help to improve the CGMS-performance thus decreasing the need for non-remotely sensed data.

Further improvements of the modelling aspects are related to:

- Knowledge on crop varieties has to be included for every case study;
- Landscape and land use variations within pixels are not taken into account. However drought may be important to area on the top of the landscape whilst crops growing in valleys do not experience any drought stress. It depends on the use of respective landscape elements whether an observed drought leads to yield reductions;
- The estimates for initial soil moisture at sowing in areas with frost and snow are unreliable in all methods. It is supposed that other remote sensing data may provide relevant information to solve this problem, e.g. the thermal sensor on ATSR of the ERS-satellites;
- The response to drought stress in CGMS, which is equal in both methods, has shortcomings. The drop of soil moisture below the critical soil moisture lead to a sudden decline in growth. In reality damage from drought builds up more gradually: better water consumption strategy or by getting water from the subsoil below the main rooted zone. The description of death of leaves due to drought stress could be improved as well. In CGMS it is assumed that here is accelerated decay leading to immediate death of the eldest leaf age classes, but it does not affect the ageing of younger leaves. Finally, the effect of drought stress on yield depends on crop stage. Many crops are more sensitive to stress during a critical period such as flowering. This is not included in CGMS so far.

For the extended study area in Africa there is no need to change parameter settings in relation to those determined for the Mali. This brings us to the conclusion that it is likely that for hot tropical semi-arid climates, the currently available expertise on scatterometer data can readily be applied in other areas with similar climatic conditions.
The distinction between frost and thaw, cannot be consistently made over the Russian study area, without auxiliary information. An attractive alternative for additional information

is to derive this from other remote sensors, in particular from the ATSR, since it provides information in thermal wavelengths and is operated from the same platform.

8.4 Exploitation of results in DRYMON

Both SCATMALi and SCATYIELD projects have led to innovative products. These products may provide a basis for future business development. This future business is referred to as DRYMON, an acronym for Drought and Yield Monitoring.A number of potential customers have been identified for DRYMON products, such as:

- FAO ARTEMIS (remote sensing information provider with FAO in Rome);
- FAO GIEWS (global crop information analysts for food security with FAO;
- AGRYHYMET (agro-meteorological information provider of the UN);
- Joint Research Centre of the European Commission;
- WORLDBANK;
- International and National Development Co-operation Agencies;
- National and international Early Warning systems;
- Nature protection agencies;
- Climate researchers;
- National Crop Information Systems;
- Commercial agricultural commodity brokers;
- Water management agencies.

These potential customers can be classified in scientific developers and end users. A second distinction can be made in customers for yield information and customers for drought information.

Scientific developers are interested in new remote sensing methods. They require DRYMON products with a non-operational status and by and large at non-commercial delivery conditions. These user requirements can be met with currently operational products. The scientific customers are of particular interest to DRYMON, since they offer a possibility for wider testing and validation.

End users have more operational requirements. They employ existing methods to monitor yield and drought conditions and often have developed expertise in using these methods. In this case DRYMON products require a certain credibility, quality and operationality. In 2000 a commercial delivery and price setting of DRYMON products is not feasible. However joined product development and testing is interesting to many end users.

For all customers the current spatial resolution of DRYMON-products of 50 * 50 km is not very appealing. The characterisation of individual pixels with respect to run-off, run-on, land use and landscape may be an essential step to get a sub pixel accuracies.

Drought information has a wider customer base than yield information and refers to water management on a catchment scale, fire protection, (risk of flooding, etc). In this case the customer is interested in the severity of a developing drought. Also this product requires the use of the full set of SCATYIELD methods. Products shall be supplied at a temporal resolution of decade or week.

DRYMON may ultimately be able to produce timely and reliable information with the required degree of spatialisation and the specific needs of diverse customers. There is a significant market for this information. Given the high degree of automation that can be reached and the supposedly relatively low cost of data from ERS and METOP, there is all reason to assume that products can be manufactured at prices that will not be prohibitive to end users.

In ranking from low to high complexity and integration with other data, DRYMON products are presented in Table 8-1. Not all these products can be supplied for the year 2000. For most products during an initial year calibration and parameterisation are required, but in principle they can be manufactured.
Concerning the DRYMON-products that cannot be manufactured today objectives for research and development issues for the period 2001-2003 have been formulated. These objectives are illustrated in Figure 8-4. The second aspect that is at least as important to make DRYMON products accepted in the market is validation of the products for every new area, soil, climate, crop, etc. This activity can be seen as a joined research and development activity with a customer that may take more than one growing season.

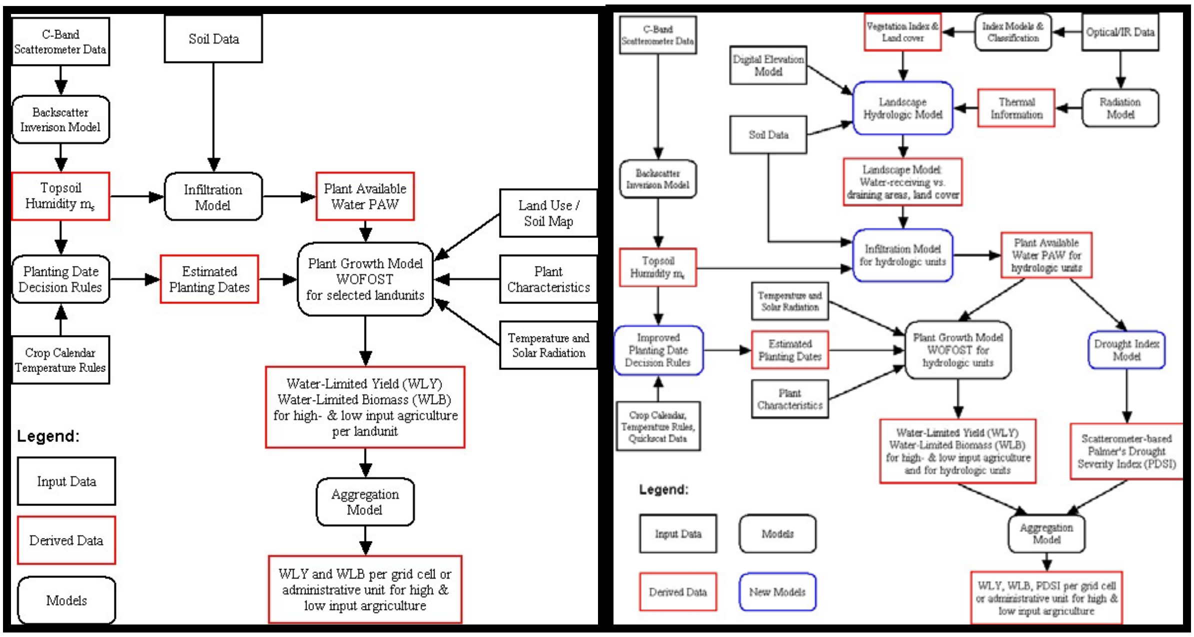


Figure 8-4 Current and future operational methods for DRYMON The new developments to be carried out within this project are indicated by the blue rounded rectangles

In order to increase efficiency and reduce costs for operational services in information provision the DRYMON production chain will be centred on one location. Under future commercial exploitation, NEO will be able to manufacture the full line of DRYMON products. This can be achieved if respective roles of partners within the consortium are identified and mechanisms for compensation of costs have been agreed. Respectively, the roles of developer, supplier and consultant can be distinguished within the consortium. The revenue basis for the developers are royalties on software to be used under an 'exclusive' license by NEO. The suppliers' revenue basis is the sale of information products and applications. The consultant's revenue basis is the man hour spent on the provision of services within the DRYMON framework. The most likely form for the partnership to operate is the European Economic Interest Group.

The market strategy for the period 2000-2003 will be based on the acquisition of assignments and subsidies that will permit DRYMON to achieve acceptation in the market and product maturity. Part of these assignments and subsidies can be acquired under national and international research & development programmes. Secondly market development and demonstration projects can be acquired. DRYMON service provision to scientific customers may be a third source of funding. Operational assignments in developing countries are a fourth option if funding from the international donor community can be acquired. DRYMON products will also be marketed through EURIMAGE if their tender for ERS ENVISAT data distribution is successful.

Table 8-1 Actual and Potential DRYMON Products

DRYMON Product name	Characteristics	Delivery time	Coverage
Top Soil Humidity Index (%)	Surface humidity expressed as percentage between dry and wet top soil	1-5 days from satellite data acquisition	all main cultivable parts of the earth, excluding dense forest zones
Soil Water Index (no dimension)	Index for plant available water in the first meter of the soil profile for a standard soil, expressed as a dimensionless parameter	1-5 days from s.d.a.	all main cultivable parts of the earth, excluding dense forest zones
Plant Available Water index (mm/m)	Index for plant available water in the first meter of the soil profile for a standard soil, expressed as a dimensionless parameter	1-5 days from s.d.a.	all main cultivable parts of the earth, excluding dense forest zones
Soil specific PAW (mm/m)	Index for plant available water in first meter of the soil profile for a specific soil	1-5 days from s.d.a	all main cultivable parts of the earth, excluding dense forest zones
Differential PAW or SPAW (relative to similar period in average year) (%)	Ratio between actual and average year for indices mentioned above	3-5 days from s.d.a	all main cultivable parts of the earth, excluding dense forest zones
Crop Performance Indicator for specific crop (PAW or SPAW based) (%)	Provides information on actual yield reduction in crop production due to drought during a certain period	3-5 days from s.d.a	all main cultivable parts of the earth, excluding dense forest zones
End-Of-Season Yield Indicators for specific crop (kg/ha)	Forecasts during the growing season based on yield reductions due to drought relative to the average yield	5-10 days from s.d.a	all main cultivable parts of the earth, excluding dense forest zones
Planting Date / Vegetation Emergence Indicators (calendar date)	Crop specific starting dates of the growing season in a specific pixel (start of the growing season for the yield simulation)	10 days from s.d.a from the beginning of the event	all main cultivable parts of the earth, excluding dense forest zones
Drought Early Warning Indicator (scale from 1-5)	Indicating during a growing season the development of a drought	10 days from from s.d.a the beginning of the event	all main cultivable parts of the earth, excluding dense forest zones
Drought Severity Index (scale from 1-5)	Indicating the intensity of a drought, through its cumulative impact on vegeation and/or crop development	10 days from the beginning of the event	all main cultivable parts of the earth, excluding dense forest zones
Soil Humidity Climate Balance (climate studies)	Indicating cumulative soil humidity as an expression of dry and wet years per decade for climate studies	end-of-year	all main cultivable parts of the earth, excluding dense forest zones
Landscape differentiated PAW, SPAW, CPI, EOSY, PDE, DEW, DSI and SHB	For all previous indices taking landscape specific run-off, and run-on into account	from 2002 onwards	all main cultivable parts of the earth, excluding dense forest zones

The products mentioned above will have a pixel size of 50 * 50 km, but can also be provided at marginal extra costs for regions or nations. Where relevant the products will be produced on a weekly or decade basis, the delivery time applies to these products. Quality and reliability of actual data will be specified in the contract between customer and NEO. The costs will be specified on data provision for a growing season per year for an area of 1,500,000 km^2. Delivery time of products sometimes depends on retrocalculations. E.g. a drought can only be indicated if it has been dry for a significant time. Products to be produced over an area, crop or land use system, new to NEO require a calibration effort and a field data collection activity, during and prior to the first year of service provision. This effort leads to additional cost as a function of complexity of the required product and the situation in the area to be monitored. NEO is not liable for direct or indirect damages occurring for a customer related to the fact that satellite observations are not acquired with a satisfactory frequency.

One important element in the marketing strategy will be to avoid the traditional error of 'overselling'. From the point of view of continuity for NEO, this is of vital commercial importance.
No competitors offer DRYMON products. However many competitors offer ‘traditional’ remote sensing based services and products in drought and yield monitoring. The merit of DRYMON methods may not be obvious to customers. This can only be achieved by publicity on the product and a long period of time for validation in the market place. Publications may lead to the spread of knowledge beyond the influence of consortium partners. However it is more important to the consortium to advance the technology in as wide a circle as possible than to restrict access to results obtained so far.

NEO is committed to the development of DRYMON for two reasons. The first reason is that the scatterometer information enable water balance and crop growth models to perform significantly better once measured soil moisture data are provided as input. A second reason is that for NEO know-how in handling complex data and producing information is core business. For our staff a variety of professional challenges exist. Nevertheless, DRYMON is intellectually by far the most demanding and challenging. The opportunity to work on this is a reason to join or stay with NEO.

NEO recognizes two major risks in the near future for DRYMON. These risks are:

- the period between the end of the lifetime of the scatterometer on board of ERS-2 or other vital systems on this satellite, and data provision by ASCAT on the METOP series of satellites may be too long. Also no guarantees can be given for continued data provision by ERS-2 to interested customers for the growing seasons of 2000-2003, which makes it unlikely that a customer will or may rely on this data source;
- the data stream from METOP will be managed through EUMETSAT and the national meteorological agencies. NEO nor any commercial service provider can have any influence whatsoever on the data products and services that may come out of this chain of data acquisition and value-adding into basic or advanced products. History has proven that meteorological agencies are capable of destroying business opportunities of companies, e.g. by not providing the required data products as well as by providing the final information products for free. NEO tries to exert an influence on EUMETSAT, through the national meteorological agency KNMI, but it is clear that company interests do not really play any role in decision making processes within EUMETSAT.

The business development for DRYMON for the period to 2004 requires a backbone in validation and methodological research as well as activities in market development. The necessary volume of activities that permit successful development is in the order of 2 M Euro till 2004.

The costs of DRYMON products that can be delivered now, all operational and methodological limitations included, can be described as a function of three options. It is assumed that the scatterometer continues to acquire data with a satisfactory frequency of observation. Of course, if the data cannot be delivered we cannot ask a customer to pay. For the areas in Russia and the Sahel, where SCATYIELD was executed, the consortium can provide the information on a routine basis without further calibration (Option 1). For all areas without previous work, we have to acquire, process and analyse historic images (Option 2) E.g for other areas in the Sahelian belt (Niger, Tchad, Sudan, etc.) in Africa, we may consider this option. For all other 'new' areas data collection and analysis on weather, soils and crops is necessary during the first year of data provision (Option 3). Option 3 also applies if new crops are to be taken into account or new soils are to be included in Russia, since these as well involve calibration, etc.

A project would consist of the provision of Soil Water Indices (SWI and DSWI's) per decade as well as e.g. Drought Related Yield Reductions for a cereal per decade (such as barley, wheat, millet and sorghum, sown and harvested in 2000. These products would be licensed and provided on a pixel basis of 50 * 50 km, delivered over the Internet as pictures, with a legend per area of e.g. 1.500.000 km2, within 7 working days. The costs for the delivery of these products during one growing season are presented in Table 8-2.

Table 8-2 Estimated cost break-down for operational products on a project basis

Cost element	**Option**	**Cost in Euro**
Costs of data	1	2.000
Costs of royalties to developer partners	1	5.000
Personnel and facilities for periodic data production and dissemination		8.000
Costs of scatterometer imagery calibration	2	6.500
Costs of field data collection and analysis, subcontracting, etc.	3	6.000-26.000
Cost of external data procurement	3	5.000
Management costs (sales, liaison with ESA and customer, etc.)	All	1.000-5.000

ANNEX 1 An alternative method of analysis

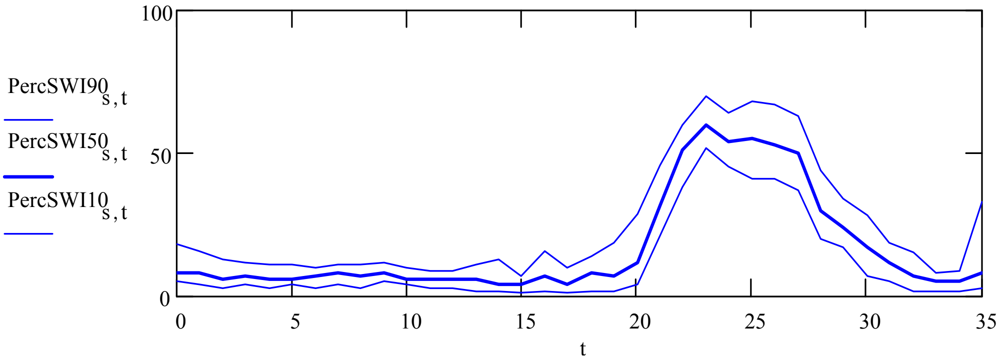
An alternative, although rather extensive, method of analysis of the relationship between NDVI and SWI is trying to state explicit a functional relationship. This will consist for each cluster/segment of a prediction of NDVI in the next decade, based upon the values of NDVI and SWI in the current decade. Stated otherwise: evaluate the model of a cluster/segment with as parameters SWI(t), NDVI(t) and NDVI(t+1).
In order to be able to fit such a model, extreme values must be avoided. The use of a percentile-estimator or robust rank order may be feasible. Plots of 10%-, 50%- and 90%-percentile-curves for 1995 are given in Figure 0-1.

It may be observed in the plots that the variance in the data is considerable. Besides the 10%-percentile can reach zero in SWI and not zero in NDVI and vise versa and the 90% percentile has clearly more variance than the 50% percentile. Hence the 50%-percentile is used as the data to be processed. However also in these curves outliers, i.e. local minima, can be pointed out. These local minima are removed using a treshold-value: where a dip in the curve deviates from the local mean more than the treshold, the local mean is used as datapoint.

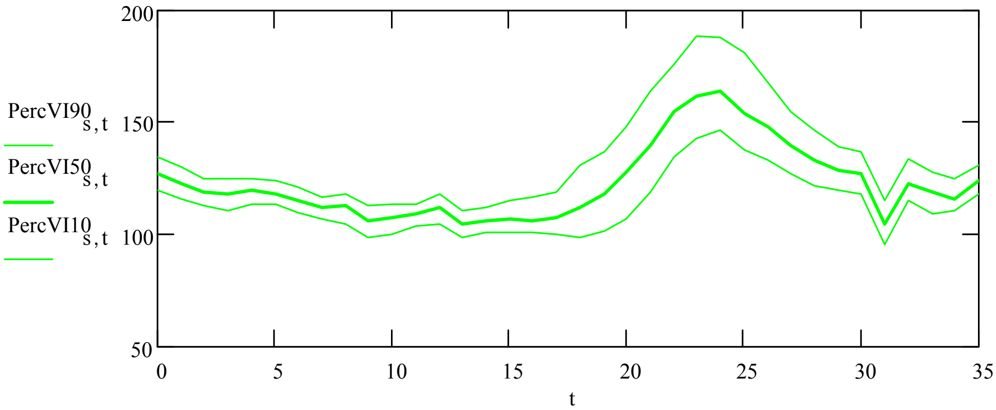
From this point NDVI(t), SWI(t) and NDVI(t+1) are plotted and a model that is fits through this curve is to be described (Figure 0-2).

Although a fitting of a model is not carried out in this project, it shows some promises. Although within the context of this project it must be concluded that the use of the convergence between NDVI and SWI is not feasable on a practical basis, SWI can possibly be used as an improvement of a prediction of NDVI for the next decade. The analysis and construction of such a model should be the basis of an other (new) project.

s := 3



Percentiles of swi as function of decade index t



Percentiles of ndvi as function of decade index t

f(x) := if(x=s, 1, 255)   map1 := funmap(Cross95clusters, f)   s = 3

Black is area selected by cluster index s

F

Figure 0-1 Example of percitile-curves for a cluster/segment of SWI

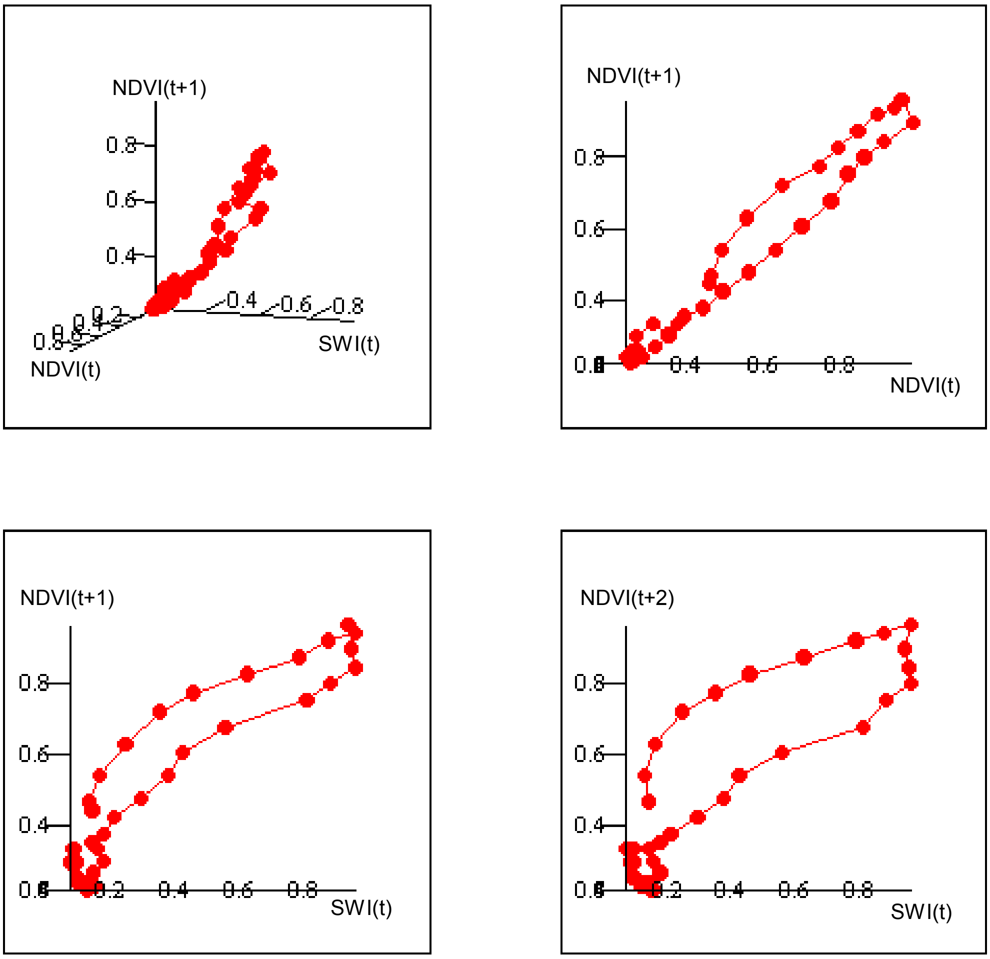


Figure 0-2 Example of a scatterplot of the data for a cluster

ANNEX 2 References of literature

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