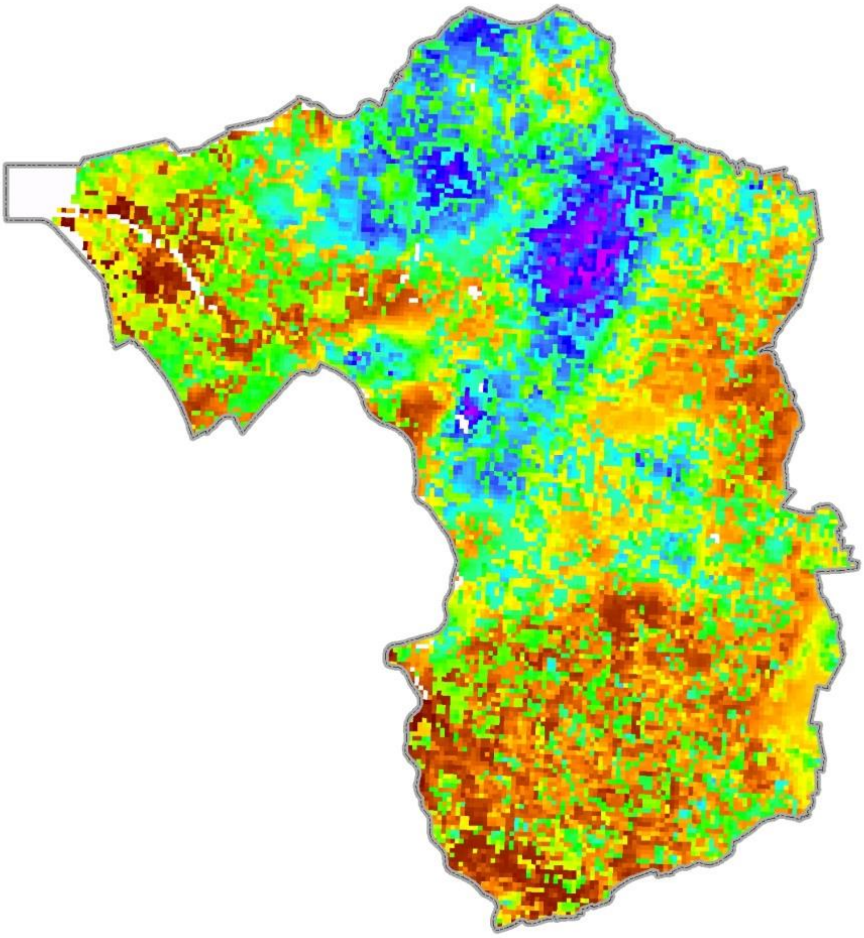
Groot Salland Waterschap
Veelzijdig met water

UNIVERSITY OF TWENTE.



[USING REMOTE SENSING DATA OF ACTUAL EVAPOTRANSPIRATION IN STRATEGIC AND OPERATIONAL WATER LEVEL MANAGEMENT]

Cover page image: ESI for 26-07-2013

Master's Thesis

Using remote sensing data of actual evapotranspiration in strategic and operational water level management

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ABSTRACT

The regional water authorities are responsible for good water quantity conditions in their region, they do so by management of the surface water levels. Using remote sensing data to identify drought conditions can improve water level management to create better conditions for crop growth. The actual evapotranspiration (ET_a) can be very different between areas, because it depends on the amount of water available in the soil. To make the best decisions in water level management it is important to know how ET_a is distributed over the area to know exactly how much water shortage there is in different areas and to find out how to optimize water allocation. In this research, remote sensing data of ET_a are used to assess the long-term drought conditions in the area of regional water authority Groot Salland and find out which areal characteristics have the most effect on drought. Also the short-term drought conditions were compared to the current water level management for several fixed drainage areas (FDAs) to find out if and how remote sensing data can be used to improve operational water level management. This research makes use of the Evaporative Stress Index (ESI), this index is a measure for the reduction in evapotranspiration from the potential evapotranspiration (ET_p). An ESI of 0.10 indicates that ET_a is 10 % less than ET_p.

The three year average ESI over the growing season of 2011, 2012 and 2013 was analyzed to find out which areal characteristics are explaining factors in the drought conditions seen. Four area characteristics were looked at. For altitude and freeboard (which is the difference between surface water level and ground surface level), the Pearson correlation was calculated and for land use and soil type the average ESI per category was calculated. The assessment shows that sandy soils suffer the most stress, followed by clay and peat. Forested areas suffer most stress, followed by urban/paved areas and grassland. Altitude and freeboard both show a weak positive correlation with ESI. This information has led to the creation of a drought vulnerability map, which can be used in determining strategic water level management. The drought vulnerability was determined using the findings of the statistical analysis. The drought vulnerability map can used in strategic water level management, to determine water level for new decrees or new target levels or to assess if water supply is going to the most vulnerable areas in times of need.

Assessment of the operational water level management in 2013 shows that RS data of ET_a can be useful for district managers and water level administrators and can help them to make better decisions in operational water level management. The information can also be used to inform farmers about drought conditions and help them to take decisions to irrigate. To compensate for the total evapotranspiration deficit by irrigation in 2013, the regional water authority would have had to supply almost double the amount of water than they did. To help district managers in their decision making the WGS drought monitor is introduced. The drought monitor shows, by using an easy to understand color coding system, how critical the drought condition in a certain area is. If published, the drought monitor could also be used by farmers to help them in deciding whether or not to irrigate their land.

This research has shown that RS data can be very useful in improving water level management, it can be used to determine long-term drought conditions and determine drought vulnerability according to certain area characteristics. This research gives an indication of expected long-term drought vulnerability, for better and more accurate results a longer data record should be used.

Operational water level management can be improved if ESI would be available on a day to day basis, the drought monitor that has been introduced is a first step in what could be the development of an operational drought monitoring tool for WGS and other water authorities.

This research suggests that water level management might not have as much effect on ESI as we would think, this indicates that ESI is very dependable on water input on land (i.e. precipitation or irrigation). To find out how much effect water level management has, further research is suggested in the form of a pilot area where one plot has a fixed water level throughout the growing season and one plot uses ESI as an input to adapt the water levels. This way the difference in average growing season ESI through adaptive water level management will be known. If the drought monitoring tool were to be used to give irrigation advice, further research should be done on the relationship between ESI and water input (through precipitation or irrigation).

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ASMR	Advanced Microwave Scanning Radiometer
ESI	Evaporative Stress Index
ET_a	Actual Evapotranspiration
ET_{def}	Evapotranspiration deficit
ET_p	Potential Evapotranspiration
ET_0	Reference Evapotranspiration
FDA	Fixed Drainage Area *Peilvak*
KNMI	Royal Netherlands Meteorological Institute *Koninklijk Nederlands Meteorologisch Instituut*
NDVI	Normalized Difference Vegetation Index
MODIS	Moderate Resolution Imaging Spectroradiometer
OWLM	Operational Water Level Management
P	Precipitation
PM	Penmann-Monteith
RS	Remote Sensing
SEBAL	Surface Energy Balance Algorithm for Land
SPI	Standardized Precipitation Index
SWL	Summer Water Level
SWLM	Strategic Water Level Management
TIR	Thermal Infrared
WGS	Regional Water Authority Groot Salland *Waterschap Groot Salland*
WWL	Winter Water Level

1 INTRODUCTION

Section 1.1 described the background and motivation for this research, section 1.2 described the state-of-the-art. In section 1.3 the goals and research questions can be found and section 1.4 provides a report outline.

1.1 BACKGROUND

Regional water authorities in the Netherlands are responsible for water level management, the arrangement of their water ways, flushing and dredging of city canals and wastewater treatment. All these efforts are made to assure safety against flooding and to warrant enough water of sufficient quality. Water level management is one of the main tasks and farmers are the most important actors. Good water level management assures good ground water conditions for agricultural land, which in turn makes sure that crop yield is at a maximum (Waterschappen, 2007). Mainly during the growing season, drought prevention is a very important part of water level management. Present day water level management at regional water authority 'Waterschap Groot Salland' is done in the traditional way, which mostly relies on experience, historic data, ground water levels, weather forecasts and the opinions of the water level administrators in the area. In this process, use is being made of reference or potential evapotranspiration measured at land based KNMI measuring stations.

KNMI produce the only publicly accessible drought metrics in the Netherlands, a continuous precipitation deficit graph and a continuous precipitation surplus map from the 1st of April until the 30th of September every year. The graph shows the national average cumulative difference between the precipitation (P) and reference evapotranspiration (ET_0) as a precipitation deficit, data is collected from 13 different weather stations. The map shows the geographical distribution of the cumulative difference between P and ET_0 as a precipitation surplus (inverse of precipitation deficit). Data is used from 139 measuring stations, ET data comes from less (how many is not disclosed) measuring stations because not all have the means to measure ET_0 (KNMI, 2014).

Where KNMI's drought index makes use of land based telemetry, many other drought indices used in other parts of the world make use of remotely sensed data due to the lack of in situ measuring stations (Anderson et al., 2013). The major distinction being the spatial distribution at which the data can be acquire. Besides that, there are many applications for RS-data (Allen et al., 2007). There are many different drought indices, much of them precipitation based and a few vegetation based. The main problem with the latter being that there is a significant delay in capturing drought, when vegetation shows drought effects it is usually too late to prevent damage. Using remotely sensed data of evapotranspiration to depict evaporative stress gives a much more accurate indication of 'real drought' (Anderson et al., 2011).

Drought is an extended period in which a region receives a deficiency in water supply. When looking at precipitation-based drought indices, the drought depicted is calculated without accounting for water supply besides precipitation, like irrigation or groundwater. When looking at evaporative stress, the direct effects of water shortage can be seen in the lowering of ET from its potential. When, for example, there hasn't been any precipitation for 10 days, but a farmer has irrigated his land, a precipitation based drought index could indicate drought when in fact this is not true. Because of the irrigation, there will not be evaporative stress and thus there is no 'real drought'.

Evapotranspiration is, with in the Netherlands around 550 – 620 mm per year (KNMI, 2015), the second largest (after precipitation, 725 – 975 mm per year in the Netherlands (KNMI, 2015)) and thus a major component of the land surface water cycle, and a very important factor in vegetation growth. With the foresight that the Netherlands will become more arid in the future and that droughts will become more probable with bigger spatial variations (Klein Tank et al., 2014), good water level management will become more and more important. Nowadays use can be made of remotely sensed data of ET and although many methods of estimating ET still make some use of in situ data (Tang et al., 2009), the spatial resolution can be much higher than in situ measurements. Besides that, with remote sensing (RS), actual evapotranspiration (ET_a) can be determined instead of potential evapotranspiration (ET_p) which is derived from in situ measurements. ET_a can be very useful to better identify and mitigate short- and long-term drought conditions in the Netherlands, because a reduced ET_a also means reduced crop growth (Doorenbos & Kassam, 1979).

Since 2011 WGS is in a partnership which by now consists of 13 regional water authorities in the Netherlands, called SAT-Water. This partnership collectively buys RS data and does research on this relatively new form of data collection and its usability (SAT-Water, 2014). WGS sees great potential in using RS data and wants to know if and how their water level management can benefit from the use of remote sensing data.

1.2 STATE-OF-THE-ART

Remote sensing has already been used in various studies to monitor drought. The ESI drought index, which is based on ET_a determined from thermal infrared (TIR) imaging and a surface energy balance model, is found to be equally good or superior to precipitation based drought indices. Especially moderate drought conditions are well captured by this index. Under severe and long-term drought conditions the index performs less (Choi et al., 2013), but in the Netherlands we do not have those kinds of drought problems yet. Anderson & Kustas [2008] used the evaporative stress index to map drought for different months in the USA. According to them, the ESI shows good correspondence with more commonly known drought metrics like the Standardized Precipitation Index (SPI), the Standardized Precipitation-Evapotranspiration Index (SPEI) and the Normalized Difference Vegetation Index (NDVI) and with patterns of antecedent precipitation but at significantly higher spatial resolution due to limited reliance on ground based observations.

This research focusses on the use of remotely sensed data of ET_a to identify long and short term drought conditions in the area of WGS and will answer questions relating to the usability and added value of remotely sensed data of ET_a in water level management.

1.3 RESEARCH GOAL & QUESTIONS

RESEARCH GOAL

The first goal of this research is to use remote sensing data to evaluate long-term drought conditions, the second goal is to explain which area characteristics are mostly affecting these drought conditions, the third goal is to combine these findings in a way that can be useful to strategic water level management (SWLM). The fourth and last goal is to find out how remote sensing data can be used to improve short-term drought mitigation through operational water level management (OWLM).

This study will be restricted to the area of regional water authority Groot Salland and will not go into detail on the quality of remote sensing data, the focus lies more on the usability of remote sensing data within the scope of this research.

RESEARCH QUESTIONS

1. How does current water level management look like and what role does evapotranspiration play in the decision making of the water level administrators?
2. How can remote sensing data of actual evapotranspiration be used to map and identify areas experiencing unusual water stress conditions, which major area characteristics are most affecting drought conditions and how can this information be used in strategic water level management?
3. How can remote sensing data of actual evapotranspiration be used to improve operational water level management to better mitigate drought conditions on a day to day basis?

1.4 REPORT OUTLINE

For this research, use will be made of remote sensing data bought by the SAT-water collaboration. For the years 2011, 2012 and 2013 a drought assessment will be made of the growing season, between the 1st of April and the 30th of September (183 days), within the area of WGS.

Chapter 2 gives a description of the study area and the available data, also a quality assessment of the remote sensing data can be found in this chapter. Chapter 3 describes the methods used to answer each of the research questions, per question a detailed description is given. Chapter 4 gives the results of the first research question, the current strategic and operational water level management of WGS is described here. In chapter 5 the long-term drought assessment can be found, this chapter gives the results of the statistical analysis of the 3 year average growing season ESI and describes the drought vulnerability map that has been created. The results of the short-term drought assessment can be found in chapter 6, here the operational water level management is compared to the ESI to find out if there are any possibilities of improvement. In the last section of this chapter the drought monitor is introduced. Chapter 7 is the last chapter, here the conclusions and recommendations of this research are given.

2 STUDY AREA & AVAILABLE DATA

In this chapter the study area and the available data will be described. In section 2.1 a general description of WGS will be given as well as several drought affecting characteristics of the area. The characteristics soil types, altitude, land cover and freeboard will be discussed. In section 2.2 the data that has been used for this research will be described. In section 2.3 the quality of the data will be discussed.

2.1 AREA DESCRIPTION

The regional water authority "Waterschap Groot Salland" is situated in the western part of the province of Overijssel and is one of the 24 regional water authorities in the Netherlands. The area of WGS is part of the Vecht/Zwarte Water catchment, which in turn is part of the Rhine catchment. The area is about 1,200 km^2 and houses some 360,000 people and many companies. Within the area, WGS is responsible for the management and maintenance of more than 4000 km of waterways, protection against floods, and guarantees the water quantity and quality in the area (WGS, 2015). Figure 2-1 shows where WGS (orange) is located in the Netherlands.

Figure 2-1 Regional water authorities of the Netherlands 2014 (Mijn Waterschap, 2015)

Most of the area, about 82 %, lies above mean sea level (NAP is used in the Netherlands), with the exception of the polders in the northwest. In the south east the “Sallandse heuvelrug” is a ridge of small hills with peaks of around 75 m + NAP. Figure 2-2 shows the altitude within the area of WGS. Most of the area is covered with a top layer of sand, the polder areas, which lie under mean sea level, are mostly peat and the areas along the river IJssel in the west and along the “Zwarte water/Zwarte meer” in the north are covered with clay, this is also shown in Figure 2-2.

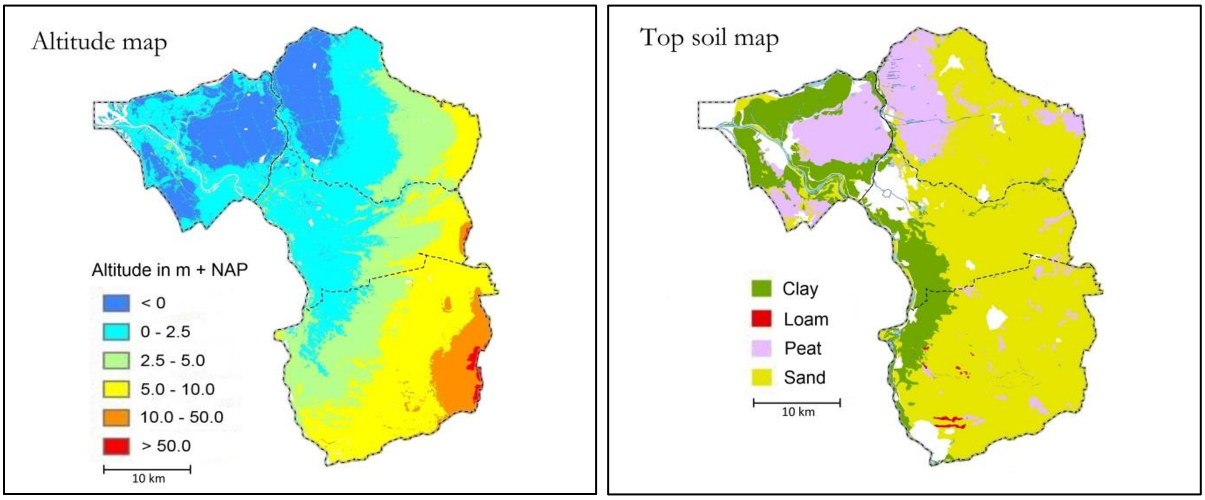

Figure 2-2 WGS altitude (left) and top soil layer (from WGS archives)

Figure 2-3 shows the main land use types in the area and the freeboard, which is the difference between ground surface level and the surface water level, for summer water level (SWL). About 70 % of the area consists of agricultural land, mostly grassland from cattle farmers. There are three cities (Zwolle, Kampen and Deventer) and several small villages. Most of the land in the southern part of WGS has a freeboard of over 100 cm, in the polder areas in the north the freeboard is lowest (mostly between 26 and 50 cm).

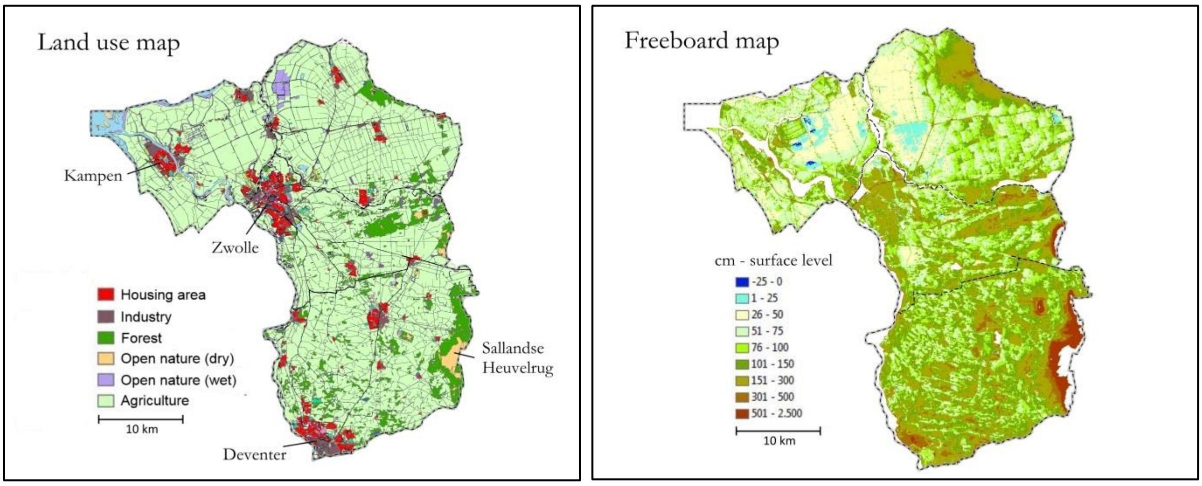

Figure 2-3 WGS main land use types (left) and freeboard (right)(from WGS archives)

2.2 AVAILABLE DATA

For this research, use was made of daily ET_a and ET_{def} (Evapotranspiration deficit; ET_p - ET_a) maps derived from remote sensing at a 250 m * 250 m resolution (i.e. 16 pixels per km^2). Data were available for the growing seasons (April 1st – September 30th) of 2011, 2012 and 2013. The area of WGS covers about 120,000 ha, so every map consists of roughly 19,000 pixels. Figure 2-4 gives an example of a daily ET_a and ET_{def} map.

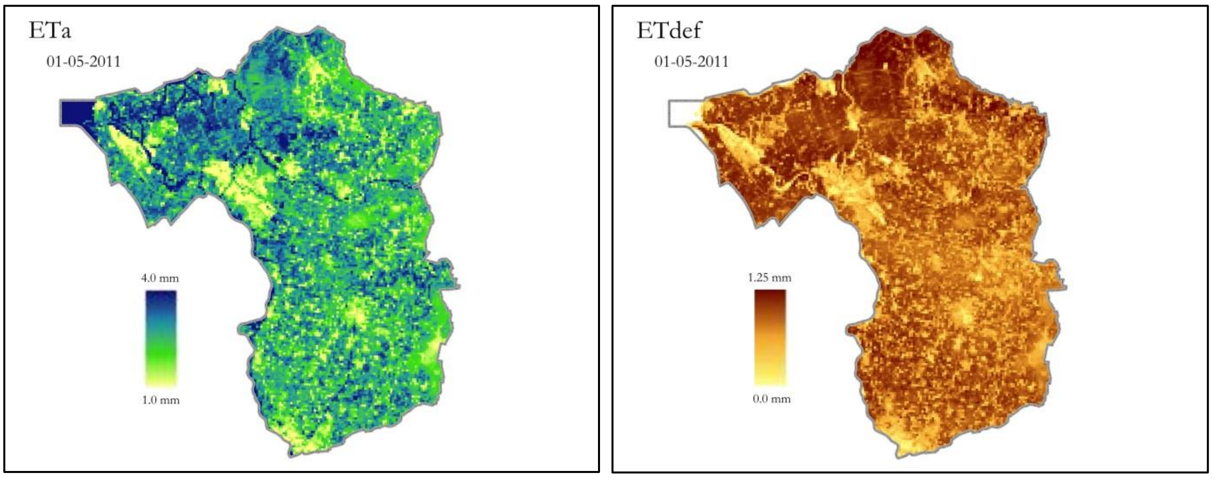

Figure 2-4 Available data: Daily ET_a (left) and daily ET_{def} (right) for the first of May 2011

The data were provided by the company eLEAF. The company makes use of their own self developed tool called ETLook, which uses an algorithm that has been evolved from the successful SEBAL model (eLeaf, 2014). ET Tool uses RS data from the MODIS sensors aboard NASA's Terra and Aqua satellites and from the AMSR sensor aboard NASA's Aqua satellite. SEBAL uses the energy balance to estimate certain aspects of the hydrological cycle, the energy balance can be quantified with RS data. From the raw RS data certain land surface characteristics can be determined, such as land surface temperature, albedo, leaf area index and a vegetation index. In addition to RS data, SEBAL makes use of some meteorological data such as wind speed, humidity, solar radiation and air temperature (eLeaf, 2014) to determine ET_a. ET_{def} is determined from the difference in ET_a and ET_p. ET_p is dependent on crop development and meteorological data, eLEAF derives crop development from RS data as opposed to KNMI who uses a theoretical approach to determine crop development. ET_p is the amount of evapotranspiration that can be reached if water isn't a limiting factor. ET_a is the actual amount reached due to the lack of availability of water. A detailed description of the SEBAL model and the working of remote sensing can be found in appendix A.

According to eLEAF, in the ET_{def} data to be used in ArcGIS, a non-deficit (ET_{def} = 0.0 mm) is given by an empty pixel (NoData). To calculate the composites, these pixels will have to be zero as ArcGIS cannot work with NoData pixels. To do this, the NoData pixels were reclassified using ArcGIS's spatial analyst tool. The area characteristics shown in section 2.1 are also data used for this research, but will not be further described here because the focus of this research is on remote sensing data of evapotranspiration.

2.3 DATA QUALITY

ET_p is dependent on crop development and meteorological data. According to Maurits Voogt, managing director of eLEAF, eLEAF extracts their crop development from RS data and KNMI uses a theoretical approach to determine crop development. To assess the quality of the RS data, the remotely sensed ET_p has been compared to ET_0 (reference crop evapotranspiration) from the KNMI measuring station located near Heino (red dot in Figure 2-5). KNMI calculates ET_0 using the Makkink method. To calculate ET_p for a certain crop, ET_0 has to be multiplied with a crop coefficient. The crop coefficient for grass is 1.0 (FAO, 2015).

Daily values of ET_0 are freely accessible and can be downloaded from KNMI's website. Daily values of ET_p were calculated using the remotely sensed ET_a and ET_{def}.

$$ET_p = ET_a + ET_{def} \qquad \text{(Eq. 1)}$$

For this comparison the average ET_p from fixed drainage area (FDA) 433 will be compared with ET_0. FDA 433 lies just west of the measuring station (Figure 2-5) and is used because it is the closest all grassland FDA to the measuring station, which suggest that the ET_p for this FDA should compare very well to ET_0. The daily values of ET_p and ET_0 were plotted against each other for each of the three years and the correlation as well as the difference in total growing season ET (ET_p divided by ET_0) was calculated. In Table 2-1 the values are given, ET_p in FDA 433 correlates very well to ET_0 and gives a good estimate of total growing season ET. The small difference between ET_p and ET_0 is most probably caused by the different methods of calculating ET and different assumptions used in these methods. According to eLEAF, there ET_p should be more accurate because they use remote sensing to derive crop development.

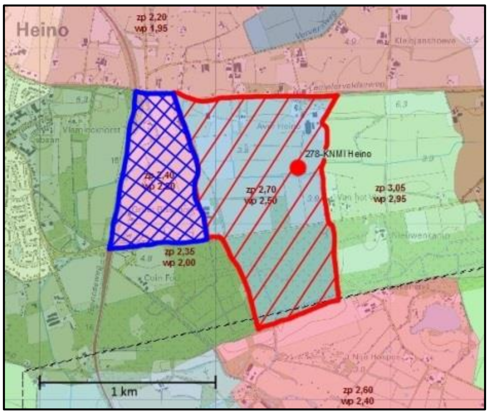

Figure 2-5 Location of FDA 433 (blue) and the KNMI measuring station (red dot)

Table 2-1 Data comparison ETp FDA 433 and ET0

Year	Correlation ET_0 and ET_p	ET_p/ET_0
2011	0.874	0.97
2012	0.916	0.97
2013	0.869	1.07

These numbers give good confidence in the quality of the RS data, it captures the trend of ET_p very well and total season ET_p estimates are within reasonable boundaries of ET_0 calculated at KNMI's measuring station near Heino (3% less for 2011 and 2012, 7% more for 2013). ET_p does sometimes show a different behavior than ET_0, which is probably caused by the different ways of determining crop development. In Figure 2-6 the data comparison for 2011 is shown, the comparisons for 2012 and 2013 can be found in appendix B.

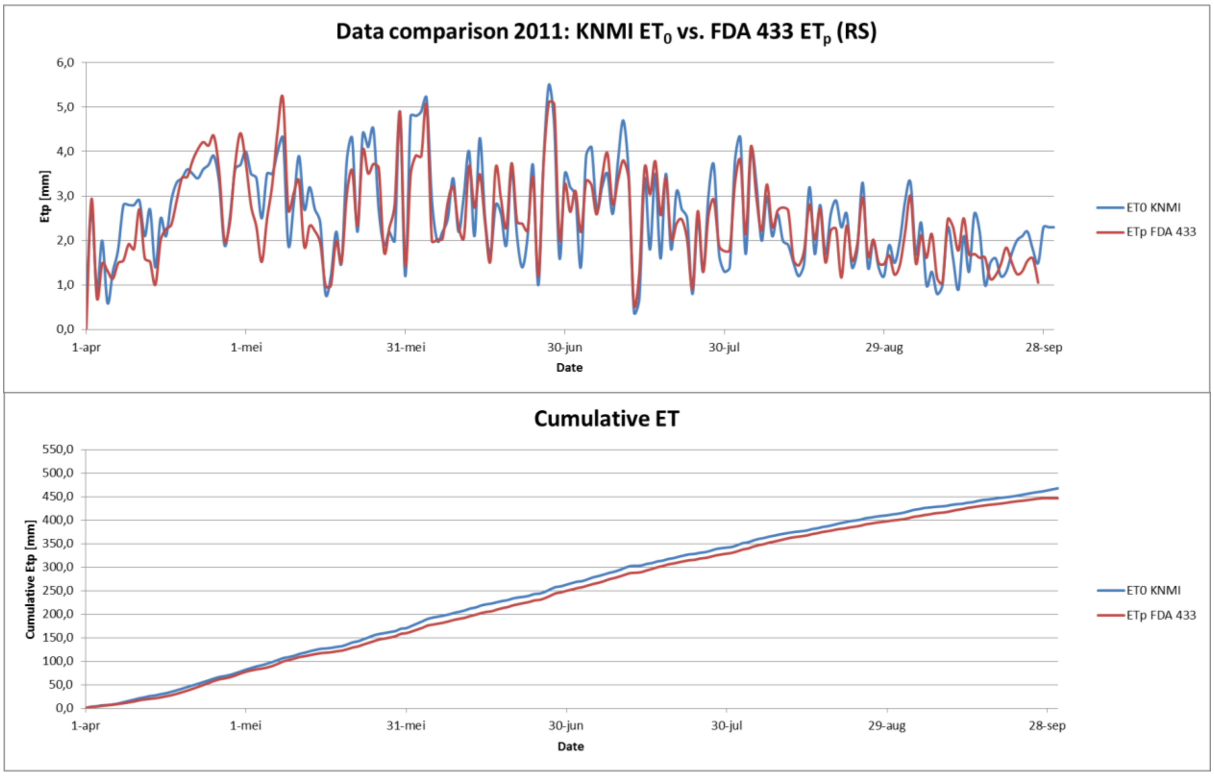

Figure 2-6 Data comparison 2011: KNMI ET_0 vs. FDA 433 ET_p (RS) (graph)

3 RESEARCH METHODS

In this chapter the different research methods used will be described. Section 3.1 describes the methods used to answer research question one, the methods used to answer research question twe can be found in section 3.2 and finally the methods used for research question three can be found in section 3.3

3.1 RESEARCH QUESTION ONE

To answer the first question and find out how current water level management looks like, several sources will be used. Main guidelines and policies can be found in documentation, but there might also be slight differences between different areas and maybe different district managers and water level administrators could have different opinions on how to operate the water levels. Therefore several district managers and hydrologists at WGS will be interviewed. Every other week the hydrologist have a meeting in which they discuss their activities, these meetings were also attended to get a better impression of how water level management works. These meetings were a great place to ask questions and to get feedback on the work already done. The workplace during this research was shared with three other people, among them one of the hydrologists (Francis de Graaf, one of here tasks is making water level decrees), she was a great source for this research question. Many days during lunch break we would take a walk with some colleagues, mostly with hydrologists, this was a great way to talk about and get feedback on this research. Also every other week, a meeting to discuss the progress of this research was planned. This meeting was also a good place to get information, besides that the daily supervisors (Marloes ter Haar for the first half of my research period, and Hedwig van Putten during the second half) were always available if there were any questions. In appendix C all important meetings and email contact that I had during my research can be found.

3.2 RESEARCH QUESTION TWO

To answer the second question, and assess the spatial variability of drought conditions the Evaporative Stress Index (ESI) will be used. This index uses both water supply (ET_a) and demand (ET_p) and determines a measure of drought by dividing them to see how much the ratio between supply and demand is. This makes ESI a very good index to assess real drought conditions, because by using ET_a and ET_p it automatically takes every source of water supply (i.e. Precipitation, groundwater and irrigation) into account. For this assessment the computer program ArcGIS will be used. ArcGIS is a geographical information system used for working with maps and geographical information, here the ESI can be visualized on the map of WGS. First daily maps will be made from the ET_a and ET_{def} data, equation 2 shows how daily ESI is calculated. From these daily maps, weekly, monthly and growing season composites can be made to show drought conditions at different time scales, equation 3 shows how a composite can be made from the daily ESI maps.

$$ESI\ of\ pixel\ (i,j)\ and\ day\ (t) = ESI_{i,j,t} = 1 - \frac{ET_{a;i,j,t}}{ET_{a;i,j,t} + ET_{def;i,j,t}} \quad \text{(Eq. 2)}$$

$$ESI_{i,j,composite} = \frac{1}{n}\sum_{t=1}^{n} ESI_{i,j,t} \quad \text{(Eq. 3)}$$

With n = number of days in the composite.

ESI always has a value between 0 and 1 (0 meaning no stress and 1 meaning maximum stress), an ESI of 0.20 essentially means that evapotranspiration is 20 % under its potential.

These composites can now be compared with certain area characteristics, of which four will be looked at: soil type, land use, altitude and freeboard at summer water level. The latter two are, just as ESI, continuous variables, so the Pearson correlation (r_{xy}) can be calculated to find out how strong these variables are related to one another, equation 4 shows how the Pearson correlation can be calculated. The Pearson correlation will be determined using the Band Collection Statistics tool in ArcGIS, which can calculate certain statistics between two valued map layers.

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} \quad \text{(Eq. 4)}$$

Where, n is the sample size, x_i and y_i are values of the two variables used in the calculation and $\bar{x}$ and $\bar{y}$ are the mean values of these variables. After the correlation is calculated it has to be tested for significance with the t-test for correlation (Davis, 2002). Equation 5 shows how to calculate the t value.

$$t = r\frac{\sqrt{n-2}}{\sqrt{1-r^2}} \quad \text{(Eq. 5)}$$

Where, n is the sample size and n – 2 equals the degrees of freedom (v). The value for t has to be higher than a predetermined critical value from the student's t distribution (table in appendix I). For this test a significance level of 1 % will be used and it is a two-tailed test, so 0.5 % on both sides of the distribution.

Because soil type and land use are categorical variables the Pearson correlation cannot be calculated, to find out how these variables relate to ESI the zonal statistics tool in ArcGIS will be used. This tool can calculate certain statistics (like mean, variance and standard deviation) between a categorical variable and ESI. So, for example it calculates the mean, variance and standard deviation for every ESI pixel within the land use polygons that are categorized as forest. To find out if the mean ESI for different categories are significantly different, here also a t-test will be done. To test for equality of two sample means the t-test has a different form, and the degrees of freedom (v) are now dependent on the sample size of both samples (Davis, 2002). Equation 6.1 shows the basic form of the t-test formula.

$$t = \frac{\bar{x} - \bar{y}}{s_e} \quad \text{(Eq. 6.1)}$$

With $\bar{x}$ and $\bar{y}$ being the two sample means, and s_e the standard error (or standard deviation). The standard error of the mean must be based on the characteristics of both samples, so s_e must be generalized as in equation 6.2.

$$s_e = s_p\sqrt{\frac{1}{n_x}+\frac{1}{n_y}} \qquad \text{(Eq. 6.2)}$$

Here, s_p is a pooled estimate of the standard deviation, found by combining the sample variances of the two data sets as shown in equation 6.3.

$$s_p^2 = \frac{(n_x-1)s_x^2+(n_y-1)s_y^2}{n_x+n_y-2} \qquad \text{(Eq. 6.3)}$$

The degrees of freedom (v) for this t-test is shown in equation 7

$$v = n_x + n_y - 2 \qquad \text{(Eq. 7)}$$

For this t-test also a significance level of 1 % will be used and the test is two-tailed.

These calculations will be done for the 3-year growing season composite of ESI to see how these characteristics relate to long-term ESI (since only three years of data have been used, long-term is relative here).

The findings of the statistical analysis will then be used to create a drought vulnerability map, which shows the relative vulnerability to drought within the area of WGS. This will be done as described below.

Using the statistics found each of the four maps will be given numerical values for every characteristic. Then these four maps will be combined, giving each of them a certain weight. This weight will also be determined according to the statistics found. At last the values in the combined map will be divided by the smallest value found creating a map which shows the relative drought vulnerability of a certain location (for example 1.25, or 25 % more vulnerable) within WGS to the location that is the least vulnerable (value 1).

3.3 RESEARCH QUESTION THREE

To assess short-term ESI and answer question three, HydroNET (an online software portal which enables water managers to make the best use of their resources (HydroNET, 2013)) will be used to make graphs of ESI for certain FDAs to be analyzed in depth. This will be done for the driest year, because the possibilities for improvement are probably the best here. For these areas the operational water level management in that year will be retrieved from ClearSCADA, which is a computer program used by WGS to monitor amongst others, surface water levels (Schneider electric, 2015). The ESI can then be compared to the water levels at that time, to find out if there is room for improvement. This will also be presented to the water level administrators to get their opinion on these findings and whether or not they think it could be of added value.

Per FDA assessed, the possible changes in water level management had ESI been known will be described. It will be difficult to quantify the amount of water needed to completely bring ESI to zero, for that a much more elaborate assessment would be necessary (including, for example, information on the relationship between soil moisture and ESI and the relation between soil moisture and precipitation input). A quantitative assessment can however be made of the amount of water it would take to compensate for the evapotranspiration deficit by for example irrigation, which requires added water supply. This will be compared to the amount of water already supplied in that year for water level management to see what the impact on OWLM would be.

At last a drought monitoring tool will be introduced. This tool will visualize ESI in an easy and understandable way using a color coded system which can easily be understood. This tool will be made using the knowledge gathered in this research and in collaboration with the district managers, it can be used by district managers and water level administrators to see drought conditions throughout their working area and use this information in their decision making. This tool can also be used as a communication tool towards farmers and for farmers themselves to get up to date information on drought conditions. Farmers can use this information to help them decide on whether or not to irrigate.

In Figure 3-1 the research methods are visualized in a box diagram per research question.

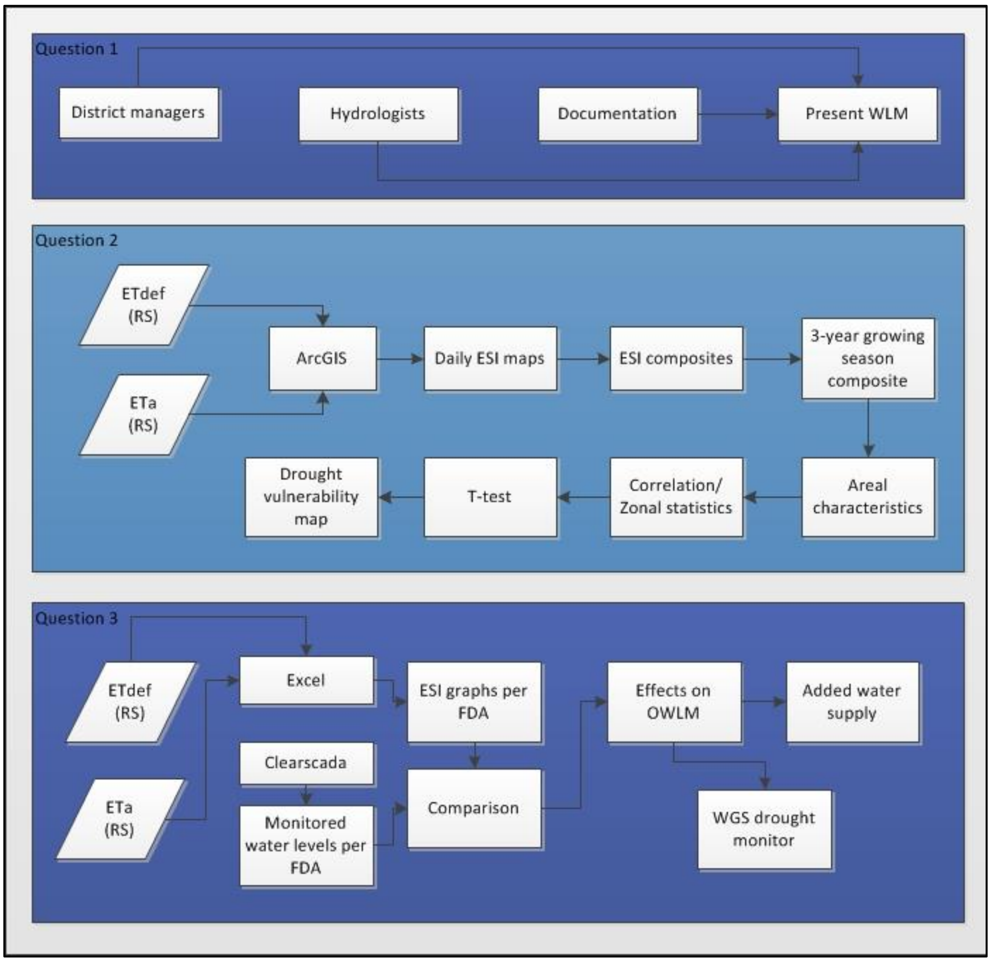

Figure 3-1 Research outline

4 WATER LEVEL MANAGEMENT

This chapter describes the water level management of WGS. In section 4.1 the general water level management is described. Section 4.2 describes the strategic water level management and shows how this is quite different for certain areas, how the operational water level management or day to day management of the water levels is done is described in section 4.3.

4.1 WATER LEVEL MANAGEMENT IN GENERAL

The regional water authority is responsible for water level management (WLM) of the surface water. Making sure that there is sufficient (but not too much) water is done with over a thousand waterworks like sluices, weirs and pumping stations. Sluices and weirs are used to block the water and retain it in the higher laying areas. Pumping stations are used to pump the water from the lower laying areas to higher areas to supply water where needed, in 2013 a total of 63 Mm^3 of water was supplied by the 10 biggest pumping stations in the area. Pumping stations are also used to pump water out of the polders to regulate the water levels there, this is because the polders lie beneath sea level and therefore receive a lot of water through seepage. In Figure 4-1 an example is given of a pumping station and a weir. The pumping station, Nieuw Lutterzijl, is used to pump water out of polder 'Mastenbroek' and the 'Koekoekspolder', which lie in the North-West of WGS.

Figure 4-1 Pumping station 'Nieuw Lutterzijl' (left) and an example of a weir (right)

WLM is predominantly directed at altering groundwater to the desired levels and to prevent water inconvenience. Depending on land use (e.g. grassland, agriculture, nature or urban area) the desired water levels will be determined (WGS, 2014). There is always a different winter and summer water level (WWL & SWL), WWL is lower because there is mostly water discharge due to high amounts of precipitation and limited amounts of ET and this assures enough carrying capacity for farmers to work their land. SWL is higher to retain more water and create good groundwater conditions for optimal crop growth. District managers are responsible for the operational water level management in their respective areas and they are the spokespersons from the regional water authority for their area. District managers work closely together with water level administrators who work in the field, it is their task to operate the manual waterworks and set the water levels as decided by their district manager.

4.2 STRATEGIC WATER LEVEL MANAGEMENT (LONG-TERM)

Water level management starts with determining the desired water levels to be kept, this is done so for every FDA. For areas vulnerable to land subsidence a water level decree (peilbesluit) is made to protect that area from further land subsidence, which means that the water levels in these areas are kept much closer to the surface (smaller freeboard). The water level decree is a legal document in which the water levels to be kept for a certain area (containing multiple FDA's) are registered for the long term (every 10 years), in Figure 4-2 the areas with a decree and the FDA's of WGS are shown. For the areas with a decree the water authority is legally bound to keep the levels within the determined limits. In all other areas, target levels are determined. Deviating from these target levels is allowed and these levels are not necessarily determined for a 10 year period. Target levels can be changed anytime, this is mostly done when certain interventions in an area significantly change the area and another water level is desired.

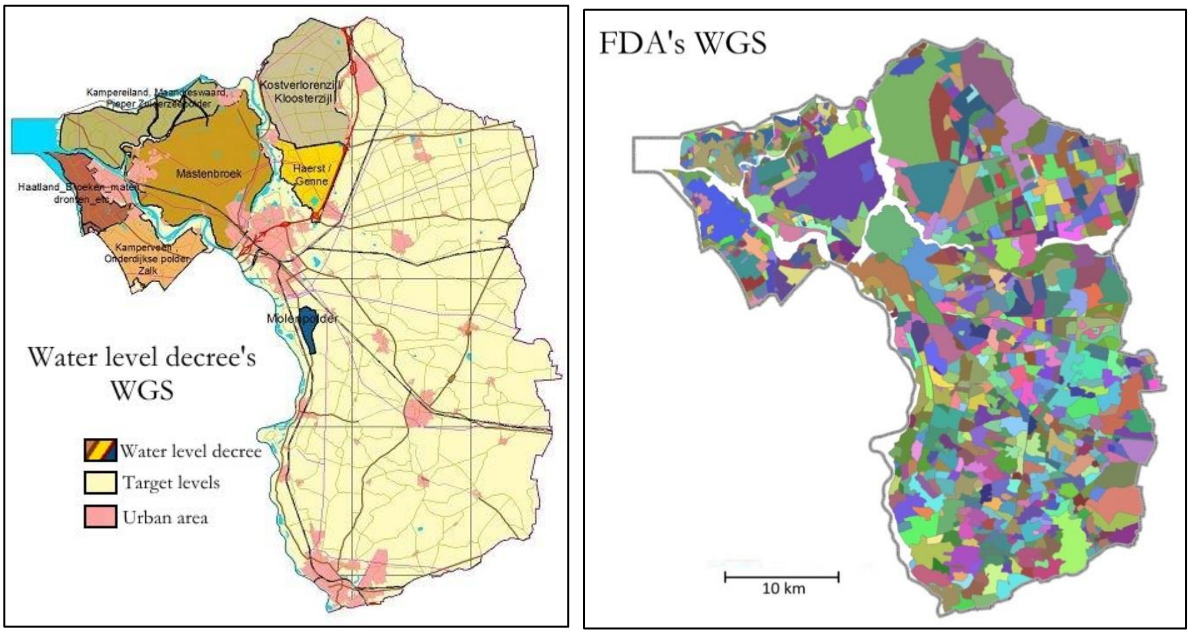

Figure 4-2 Areas WGS with a water level decree (left) and FDA's WGS (right)

A water level decree contains the following:

In the introduction the goal and used procedure of the decree are described. Relevant legislation and policy dictated by European, national and local governments and the regional water authority (being WGS) are described, following a site description and its history. Then a detailed area description is given, containing land use, altitude, land subsidence that occurred, geohydrology, soil composition, water management, former water level decree, waterworks, the used groundwater model and nature values/functions (for example, Natura 2000 areas). Then a conflict analysis is done, containing for example conflicts in water demands per function, groundwater levels and runoff. When all conflicts are known, new water levels are proposed and a description of per FDA is given. The expected effects of the new water levels on for example, land subsidence, seepage, agriculture, nature and surface water quality are described and finally the monitoring of these water levels is described. Most water level decrees nowadays are drafted in collaboration with stakeholders, their opinions are gathered through interviews (WGS, 2012).

In Table 4-1 an example is given of the summary for FDA 2 in the 2013 water level decree for area Haerst-Genne (Figure 4-2). The summary gives the soil type, results of the opinion poll with stakeholders, current average high and average low groundwater level, desired ground water level range (GT), water level in 1993, present water levels and new water levels (in this case no adaptation).

Table 4-1 Summary FDA 2 of water level decree Haerst-Genne 2013

Water levels decree summary FDA 2 Haerst-Genne 2013	
Soil type	Mostly peat; small part sand
Opinion poll results	person K (lower water level in fall/winter (peat))
Current groundwaterlevels	Map in water level decree
Desired GT	Mostly II; small part IV
Water levels 1993 (SWL/WWL)	-0.60 + NAP/-0.90 + NAP
Current water levels (decree 2003)(SWL/WWL)	-0.60 + NAP/-0.90 + NAP
Change water levels?	No
New water levels	-0.60 + NAP/-0.90 + NAP

4.3 OPERATIONAL WATER LEVEL MANAGEMENT (SHORT-TERM)

The area of WGS is divided into four districts, each with a district manager responsible for the operational water level management in that district. Besides that there is one manager responsible for the operational water level management in the urban areas. In Figure 4-3 the four districts and the urban areas of WGS are shown.

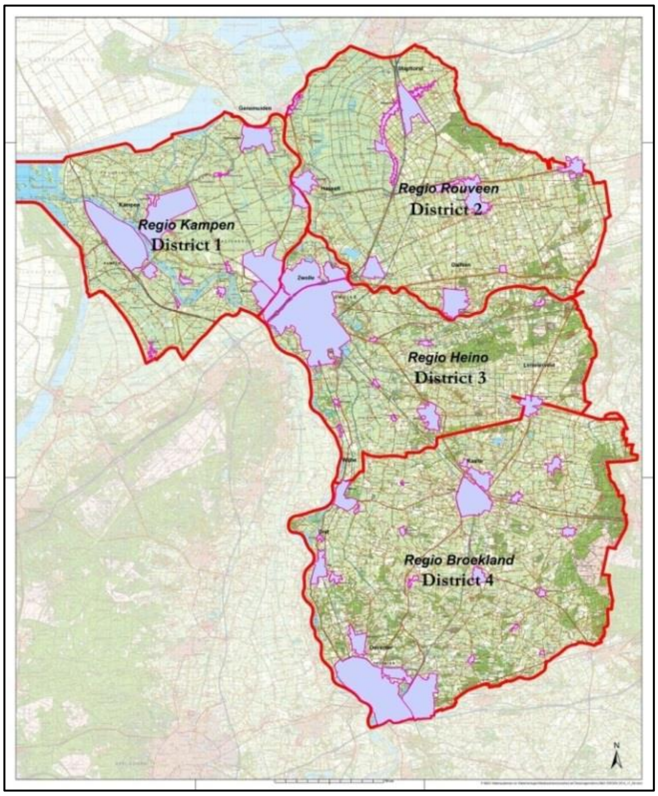

Figure 4-3 Districts WGS

The district managers work closely together with 2 or 3 water level administrators per district. The main task is to keep the water levels to their desired heights as described in the relevant decree or as described by the target levels. The pumping stations and some of the weirs operate automatically, the district manager can adjust the water level from behind his computer and the weirs and pumps in question will automatically keep these levels. The majority of weirs however are operated manually, this is the task of the water level administrators who work in the field. They check the water levels to be kept and adjust the weirs accordingly. In the winter, the waterways mostly have a draining function and the groundwater levels are above surface water level. In summer though, waterways are used to supply water and groundwater levels are usually gradually lowering. So the surface water level, which can be regulated, serves as a measure to slow down the lowering of the groundwater level to keep the ground from drying out due to evapotranspiration.

District managers and water level administrators do this for a great deal based on experience, they have a real feeling for the area they are working in. They know, based on experience and from the experience of the people living in the area, what to do to reach certain effects and they know how the area responds to certain inputs of water. Farmers in the area are very important actors and they are usually the ones that the district managers have the most interactions with. Most farmers have very strong opinions on how their land and the waters surrounding them should be managed. It can sometimes be very difficult to get farmers to agree with high water levels, because farmers are much more afraid of too wet conditions as they cannot work the land when the top soil is too wet and the carrying capacity of the soil is too low for their machines or their cattle. District managers have to communicate with the hydrologists when they are thinking of changing the water levels when it is for example exceptionally dry or wet, the hydrologist has more technical knowledge to assess if a change is acceptable. Weather predictions are of course also a great part of water level management, but under normal circumstances will not affect the water level management too much. However, when it is unusually dry or wet, sometimes the water levels will be set even higher or lower than the target levels to prevent too much or too little water coming into or getting out of the system due to precipitation and evapotranspiration. In water level decree areas, where the freeboard is much less than in target level areas, the water levels stay fixed, even in very dry situations. It seems that monitoring of daily hydrological fluxes is kept more on the background until extreme situations occur. ET data are currently not used in WLM, only indirectly through KNMI's cumulative precipitation deficit which they do use in operational water level management decisions.

An important factor in managing the water levels is maintenance of the water ways and the waterworks, to assure capacity of the system. This too is an important part of the job of a district manager and the water level administrators. They have to monitor the system and decide when maintenance has to occur. Maintenance consists of mowing the banks of waterways, dredging waterways and clearing obstructions, all to keep a consistent and reliable flow profile.

5 LONG-TERM DROUGHT CONDITIONS

In this chapter the long-term drought conditions will be assessed. Section 5.1 describes the quantitative assessment done for several areal characteristics affecting drought. In section 5.2 the drought vulnerability map is introduced, which has been created using the results from the quantitative assessment.

5.1 OVERALL GROWING SEASON ESI

In Figure 5-1 the three year average ESI of the growing season is shown. The ESI over the total record lies mostly between 0.06 and 0.10, the dark blue areas are open water and have a value lower than 0.06. On land the highest values lie just above 0.10. More ESI composites can be found in appendix D. Figure 5-2 shows the patterns of land use, forested areas have the highest ESI values. This is kind of counterintuitive because trees have a much deeper rooting zone, so water availability will be larger and evapotranspiration will reach its potential much easier (Zhang et al., 2001). Water levels in forested areas however are by far not as well managed as on agricultural land, which has a much denser network of waterways to feed the groundwater. Urban areas also show higher evaporative stress, which can be expected due to the large amounts of paved areas through which water cannot evaporate and the high amounts of surface runoff towards sewers drying out a city much faster. However, that is not very meaningful for this research as the focus lies on agricultural area. Patterns of altitude or soil type were expected, but do not appear in the ESI on first sight. Sand has a very high permeability and good hydraulic conductivity under highly saturated conditions, which makes it dry out faster than clay or peat soils. Higher laying areas might dry out faster due to higher amounts of seepage due to greater hydraulic head differences. A quantitative analysis of the results is described below.

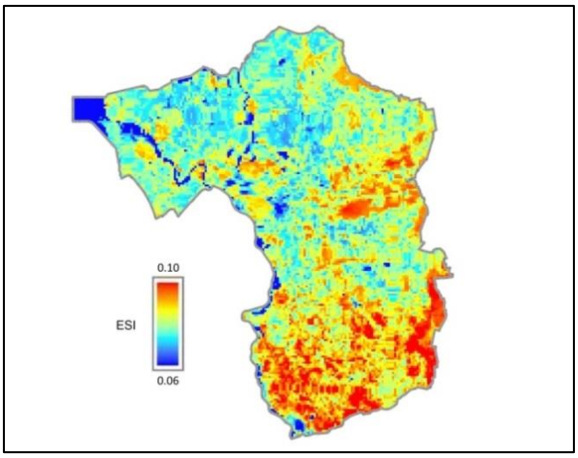

Figure 5-1 Three year average growing season ESI

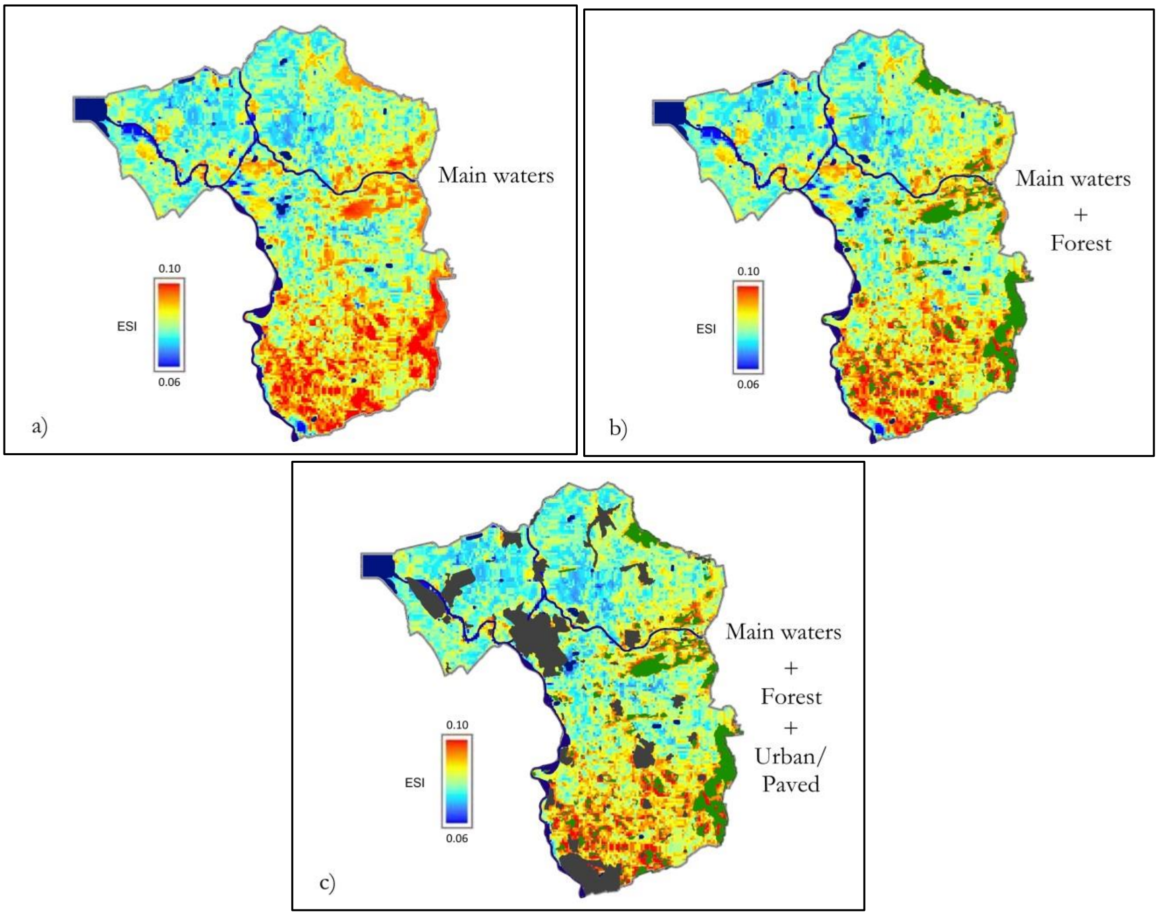

Figure 5-2 Different land use types overlaying long-term ESI (a) Shows the main waters (dark blue) (b) Forested areas are added (green) (c) Urban/paved areas are added (grey)

LAND USE

The following statistics were found for the three main land use types, being grassland, forest and urban/paved area. Forest shows the highest average ESI and grassland the lowest. Figure 5-3 shows a boxplot of the ESI statistics for land use. The box shows the mean, mean plus standard deviation, and mean minus standard deviation, the error bars show the minimum and maximum ESI.

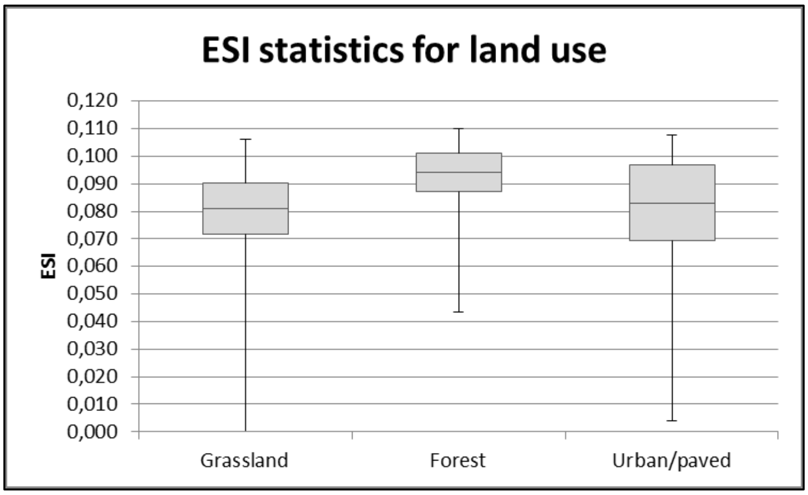

Figure 5-3 ESI statistics for land use

The degrees of freedom (equation 7) for every pair are very high ($n_g = 15814; n_f = 1567; n_u = 997$), so for the critical t-value in the Student's t distribution the last row (degrees of freedom = ∞) is used, for a two-tailed test the critical value for a significance level of 1 % (0.5 % on either side) equals 2.58 (Student's t distribution $n = \infty; 1 - \alpha = 0.995$; see appendix K). The t-values calculated according to equation 6 are 53.4, 26.7 and 6.3 for the respective pairs grassland-forest, forest-urban/paved and grassland-urban/paved. So the null-hypothesis of equal means can be rejected for every pair and thus the differences in ESI are significant and not caused by chance.

ALTITUDE

According to equation 4 there is a weak positive Pearson correlation (r) of 0.247 between altitude and ESI. To test for significance the same confidence interval of 1 % has been used. The degrees of freedom here is simply n-2, which is thus very high as the correlation is calculated using all pixels of ESI (around 19,000). The critical t-value is 2.58. The t-value calculated with equation 5 is 34.05, this is well over the critical value so the null hypothesis of no correlation can be rejected and the correlation is significant.

FREEBOARD

For the correlation between freeboard and ESI, the degrees of freedom and thus the critical t value are the same as for altitude. Equation 4 gives a weak positive Pearson correlation (r) of 0.173 between freeboard and ESI. The t-value according to equation 5 is 23.85, which is also well above the critical value which makes this correlation significant as well.

SOIL TYPE

For the three main soil types the following statistics were found. As seen in Figure 5-4, clay and peat are slightly different, with a higher ESI for clay. Sand clearly shows a higher average ESI, as was expected due to the permeability of sand being much higher than peat and clay.

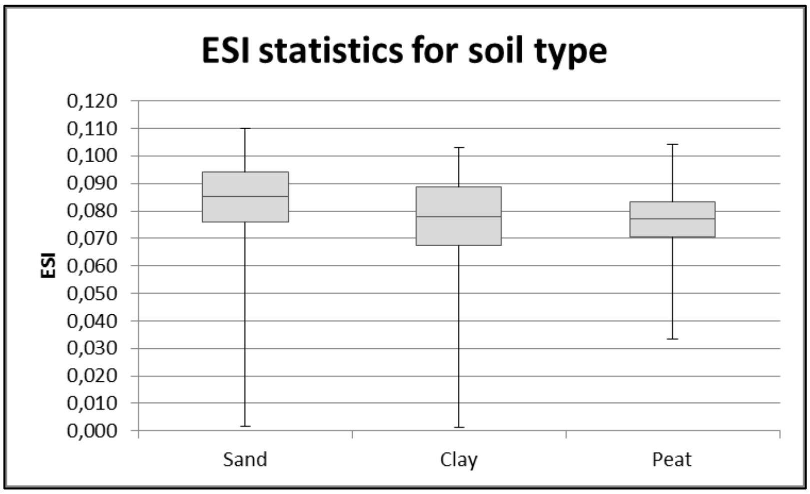

Figure 5-4 ESI statistics for soil type

Again the degrees of freedom (equation 7) for every pair are very high ($n_s = 11040; n_c = 2818; n_p = 3051$), so the critical t-value is the same as with land use, 2.58 for every pair (Student's t distribution $n = \infty; 1 - \alpha = 0.995$; see appendix K). The t-values calculated according to equation 6 are 35.8, 4.5 and 46.4 for the respective pairs sand-clay, clay-peat and sand-peat. This again means that the null-hypothesis of equal means can be rejected for every pair and thus the differences in ESI are significant and not caused by chance.

CROSSCORRELATIONS

There might also be some crosscorrelations between the areal characteristics, knowing them will prevent giving too much weight to certain characteristics causing drought when constructing the drought vulnerability map. Land use will not be assessed here, because the drougth vulnerability map will be constructed for grassland only. It is expected that especially freeboard and altitude will have a strong crosscorrelation due to the fact that within an FDA the water level is fixed at a certain level, so if the ground surface gets higher the freeboard automatically gets higher to. A quantitative assessment is given below, the same significance levels will be used and the degrees of freedom for all calculations are very high which gives the same critical t-value of 2.58.

Using equation 4, a moderate to strong Pearson correlation (r) of 0.538 between freeboard and altitude was found. The t-value according to equation 5 is well above the critical value. For the mean freeboard per soil type the following statistics were found. As shown in Figure 5-5, peat has the lowest average freeboard (58 cm), clay slightly higher (93 cm). Sand shows highest average freeboard (223 cm). This was also as would have been expected, because the peat soils are prone to land subsidence and freeboard is kept low to limit this.

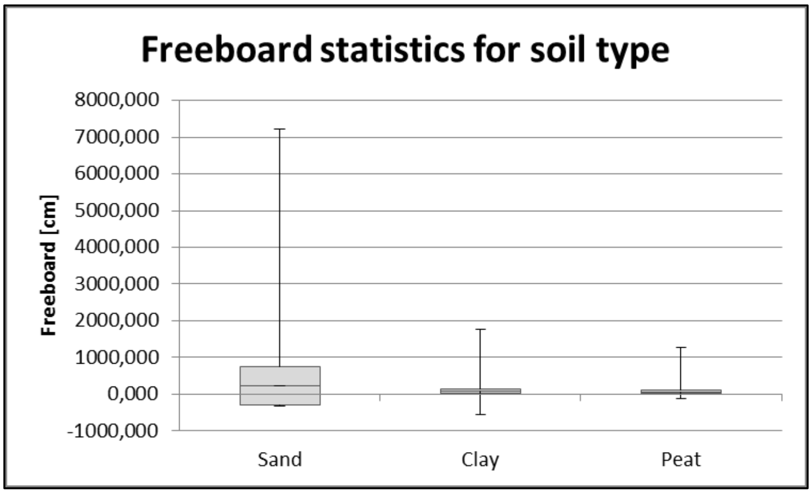

Figure 5-5 Freeboard statistics for soil type

For the AHN statistics per soil type the following were found. As shown in Figure 5-6, peat has the lowest average altitude (115 cm), clay slightly higher (125 cm). Sand shows highest average altitude (686 cm).

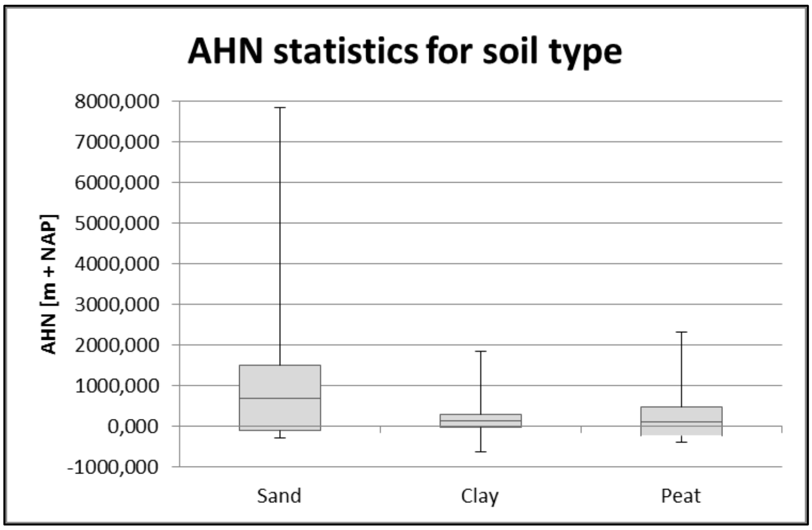

Figure 5-6 AHN statistics for soil type

5.2 WGS DROUGHT VULNERABILITY

Using the statistics found in the analysis of the growing season ESI, the drought vulnerability map can be made. In this map the expected long-term drought vulnerability in the area of WGS can be seen, this map can be used as an extra input variable in determining water levels for a water level decree or determining target levels. The drought vulnerability map can also be used to determine whether or not vulnerable areas can be easily supplied with water, if not this could be used as argumentation for new pumping capacity in a certain area. It can also be used to indicate areas that are very vulnerable and possibly give these areas priority over others in operational water level management during dry periods. The vulnerability to drought relates to the average ESI expected in a certain area over the whole growing season, the higher the vulnerability the higher the expected average growing season ESI and the higher the vulnerability the faster the ESI will rise when there is no precipitation. Drought vulnerability is shown as a relative value, so the area with the lowest vulnerability gets the value 1 and every other area a value greater than 1. A value of 1.2 then, indicates that an area is 20 % more vulnerable to drought than the least vulnerable area. A distinction can be made between natural and current drought vulnerability, the natural vulnerability is the vulnerability which can be explained with only the natural area characteristics (the characteristics land use, soil type and altitude, which we have limited to no influence on). Current drought vulnerability also takes the water level management into account by also including the effect of freeboard on ESI.

The values given to each map are the following:

- In the land use map, grassland has been given the value 1 and all other land uses NoData.
- In the soil type map, sand has been given the value 0.085, clay has been given the value 0.078, and peat has been given the value 0.077.
- In the altitude map, for an altitude above NAP the square root of the altitude in meters was taken and multiplied with 0.01. For an altitude below NAP the square root of the absolute value of the altitude in meters was taken and multiplied with -0.01.
- In the freeboard map for summer water level, the square root of the freeboard in centimeters was taken and multiplied with 0.01.

The values in the soil type map are the means found in the statistical analysis, these numbers form the basis of the vulnerability map. The altitude and freeboard are very gradual throughout the area, except for the 'sallandse heuvelrug' where altitude and freeboard are much higher. To not over exaggerate the impact of this area to vulnerability, the altitude and freeboard maps were given a square root function. Also, these maps were multiplied with 0.01 to create values in the same order of magnitude as the ESI values.

The natural drought vulnerability (NDV) map is then calculated as follows:

$$NDV = [x, y_{land\ use}] * [x, y_{soil\ type}] + 0.247 * [x, y_{altitude}]$$

The current drought vulnerability (CDV) map also takes the freeboard into account:

$$CDV = NDV + ((1 - 0.538) * 0.173 * [x, y_{freeboard}])$$

In the NDV and CDV equations, the values 0.247 and 0.173 are the correlation values between ESI and altitude, and ESI and freeboard respectively. The 1-0.538 part of the CDV equation reduces the weight of the freeboard because of the cross correlation between freeboard and altitude.

Calculation example (Grassland; Sand; 2.5 m + NAP; 50 cm freeboard):

$$NDV = [1] * [0.085] + 0.247 * \left[0.01 * \sqrt{2.5}\right] = [1] * [0.085] + 0.247 * [0.0158] = 0.0889$$

$$CDV = NDV + ((1 - 0.538) * 0.173 * \left[0.01 * \sqrt{50}\right) = 0.0889 + (0.462 * 0.173 * [0.0707] = 0.0945$$

At last the NDV and CDV were divided by their respective minimum values to find the relative NDV and CDV. Minimum NDV = 0.0722 and minimum CDV = 0.0722 (same minima due to rounding off).

$$NDV_r = \frac{0.0889}{0.0722} = 1.23 \qquad CDV_r = \frac{0.0945}{0.0722} = 1.31$$

So when looking at the natural characteristics only, the example area is 23 % more vulnerable than the least vulnerable area. However, due to current water level management this area is relatively more vulnerable. Figure 5-7 shows the current drought vulnerability for WGS, the natural vulnerability map can be found in appendix E.

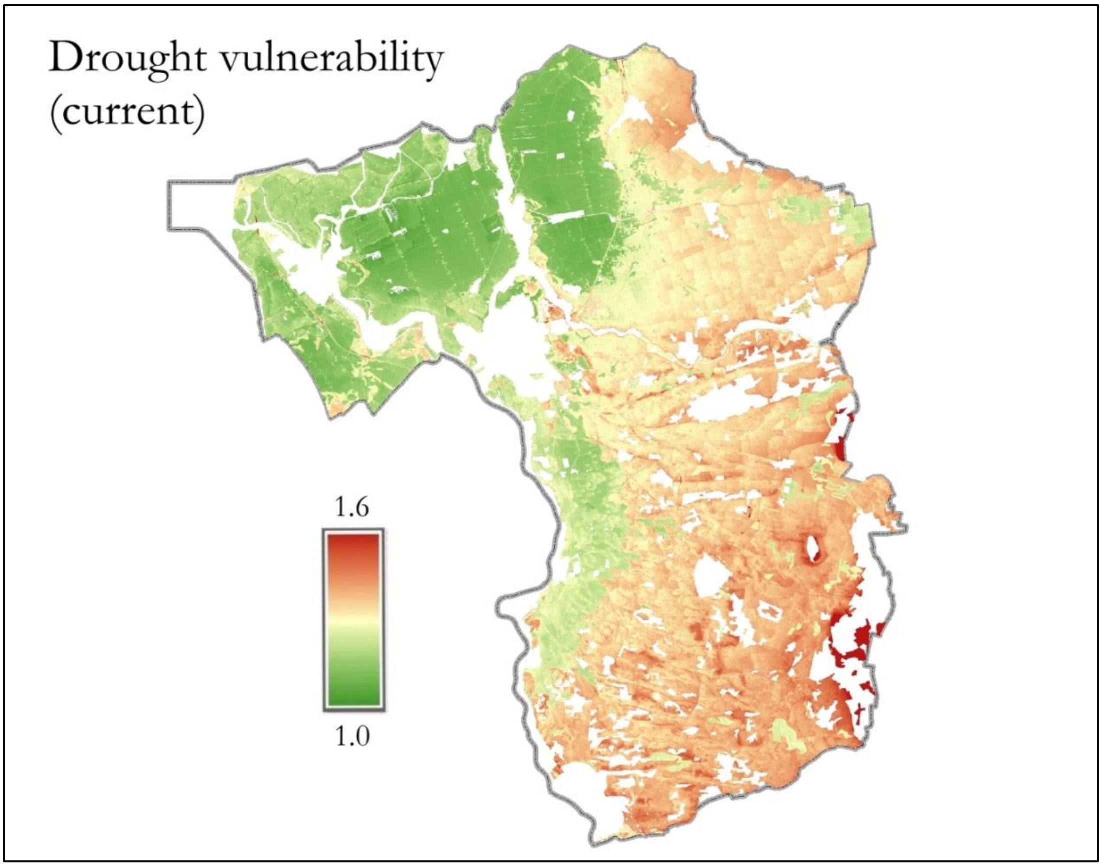

Figure 5-7 Current relative drought vulnerability for grassland

6 SHORT-TERM DROUGHT CONDITIONS

In this chapter, the possibilities of using ESI for short-term drought mitigation will be assessed. In section 6.1 the water levels of 2013 for several FDAs will be compared to the ESI to find out if and how much room there is for improving OWLM. Section 6.2 describes the possibilities for and the impacts on OWLM when using ESI for irrigation purposes to solve the evapotranspiration deficit. The last section describes a tool designed to visualize ESI in a comprehensible way to be used in either direct water level management or irrigational efforts.

6.1 ESI AND OPERATIONAL WATER LEVEL MANAGEMENT

Currently in water level management the district managers and water level administrators are not focusing on crop performance but rather on keeping the surface water at the desired levels. With the use of remote sensing data and in particular data of evapotranspiration, an insight in crop performance can be acquired. This information can give an extra dimension to water level management. When there is evaporative stress and thus crop growth is reduced and weather forecasts predict a longer period without precipitation, this information can help to make better decisions in water level management. This might look promising but, according to the district managers it is rarely possible to improve water level management.

Average growing season ESI in district 4 in 2013 is around 0.12, so ET_a is 12 % under its potential. For most crops, the yield reduction is somewhere between 0.70 and 0.90 of the reduction in ET_a which means that grass production was somewhere between 8.5 and 11 % under its potential for that year. Crop yield is directly proportional to ET_a and dependent on a crop coefficient (K_c) (Doorenbos, 1980). So there is definitely room for improvement. However, there were no restrictions in water supply and no irrigation prohibition in that year and according to district manager A. Koekkoek it simply is not possible to raise performance there. Throughout the growing season the groundwater level is lowering, water level management can slow this down but not prevent it (see Figure 6-1). In the two periods in 2013 where ESI is increasing to about 0.25 (June and July) the water levels are already set up high (even 5 – 10 cm beyond the target water levels), extra information on crop performance would not have changed that. During these more extreme cases of drought, the fact that the water levels are already set up so high in these areas makes clear that the only way to reduce ESI and improve crop performance is to apply it from above (i.e. irrigation). There might however be some room for improvement in times of less stress.

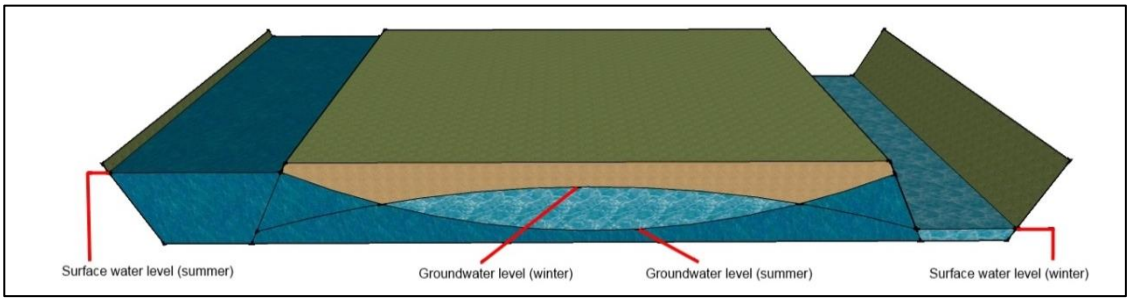

Figure 6-1 Difference between water levels for winter and summer

In the polders the water level is kept as close as possible to the land surface level to prevent land subsidence, up to a freeboard of just 10 cm in some small areas. Because of that one would expect that polder areas are much less vulnerable to drought. However, as can be seen in Figure 6-2, the ESI for polder Mastenbroek is not so different from that of district 4, where freeboard is much higher. This suggests that even in polder areas the groundwater is not able to supply enough water to the unsaturated zone to prevent ET_a from declining and that the saturation of the top 10 or 20 cm of the soil are very important for good evapotranspiration. This in turn raises a serious question about the efforts vs. the gains of operational water level management. If the unsaturated zone is drying out due to lack of precipitation and ET_a is dropping, how much effect does water level management really have? In 2013, as can be seen in Figure 6-2, it seems that there is sort of a plateau around an ESI of 0.25 for district 4 and 0.23 for polder Mastenbroek. This might be the point where groundwater supply to the unsaturated zone due to capillary rise and ET_a (demand) are in equilibrium, the peaty polder area has stronger capillary rise which could explain the 0.02 point lower plateau.

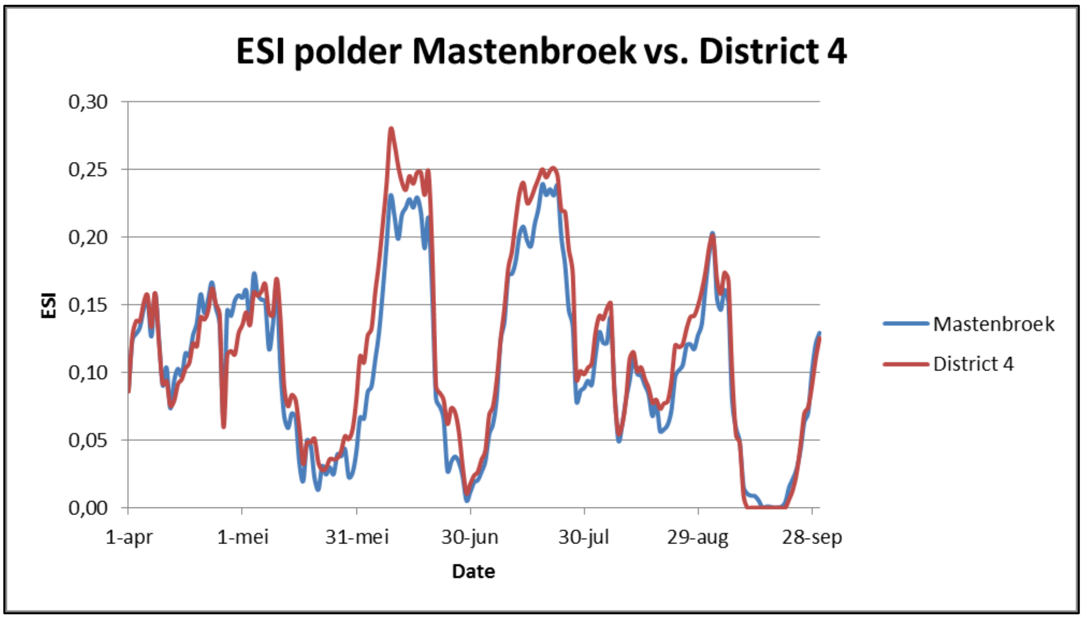

Figure 6-2 ESI for the year 2013 of polder Mastenbroek vs district 4

To get a better insight in the possibilities of improving the water level management, for four FDAs (one from each district) the ESI has been compared to the water levels kept during the growing season of 2013. These four areas are shown in Figure 6-3. FDA 41 is a polder area with a mixture of peat and sand soil, the water levels are kept at the defined level with a pumping station the three other FDAs are controlled with a weir. It is an all grassland FDA, as are FDA 308 and 392. FDA 659 has a mixture of grassland and forest, this FDA includes the Natura 2000 area 'Boetelerveld'. For the most part this FDA has a freeboard which lies between 101 cm and 300 cm, the other three FDAs have a freeboard mostly between 26 cm and 75 cm. The characteristics of these areas are given in Table 6-1, in this table the size of the FDA, the SWL, maximum P deficit, the end of season ET deficit and the average growing season ESI are also given. The analysis of FDA 308 and 392 are described below, the analysis of FDA 41 and 659 can be found in appendix F

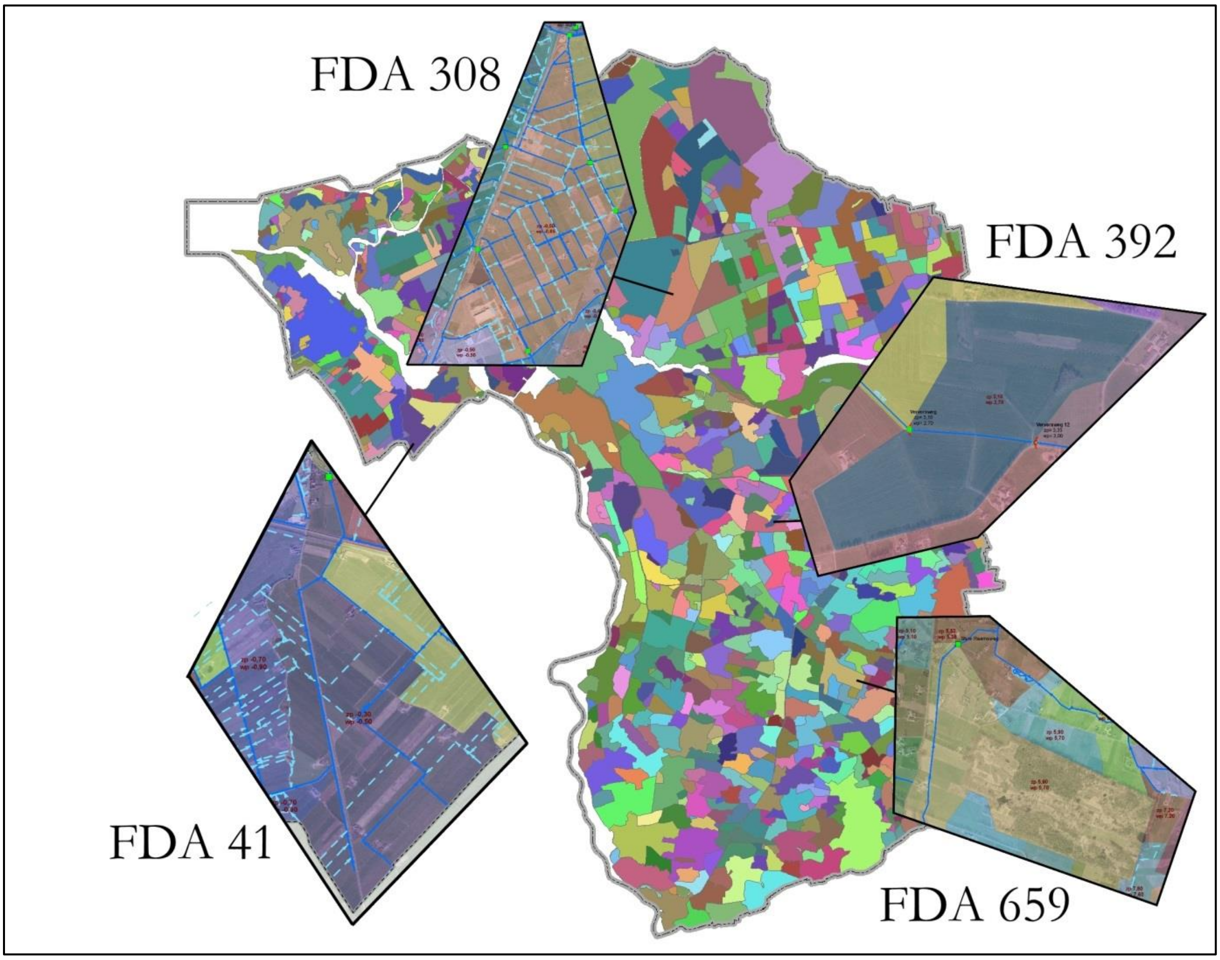

Figure 6-3 Four FDA's where ESI was compared to OWLM

Table 6-1 Characteristics of the assessed areas

District	1	2	3	4
Peilvak	41	308	392	659
Weir/pump	Adsum	Bouwman	Verversweg	Raamsweg
Area [ha]	350	595	31	243
Land use	Grassland	Grassland	Grassland	Grassland/Forest
Summer water level [m + NAP]	-0.30	-0.50	3.10	5.90
Freeboard range [cm]	26 - 75	26 - 75	26 - 75	101 - 300
Maximum P deficit [mm]	163.0	140.3	174.5	188.4
End of growing season ET deficit [mm]	56.6	52.6	52.8	67.1
Avg. ESI during growing season	0.107	0.103	0.097	0.125

FDA 308

As can be seen in Figure 6-4, in FDA 308 there is some fluctuation in the water levels during the growing season of 2013. This suggests a more reactive water level management. The drop in water level around the end of May, for example, is probably a reaction to the large amount of precipitation (19 mm) on May 29th. SWL (-0.50 m + NAP) is not reached until the 2nd week of May and stays at that level only shortly. According to district manager A. Soepenberg, this shouldn't have been this way and he says he never knew this. According to him, the water level administrators might have thought that SWL was -0.55 m + NAP. This indicates that miscommunication can also be a reason for differing water levels. However, Soepenberg acknowledges that knowing the ESI from day to day in 2013 might have resulted in some different actions. It might have provoked an earlier raise to SWL in the beginning of the season and it might have delayed the lowering of the water level half way June, when ESI was still very high. During the rest of the season and especially during the dry period in July the water levels could have been set up higher, which might have decreased the ESI for the rest of the growing season. Freeboard in this area is quite low, so the possibilities to raise the water levels even further than summer level are slim. Reducing ESI should not result in other negative effects, like a very low carrying capacity or water excess.

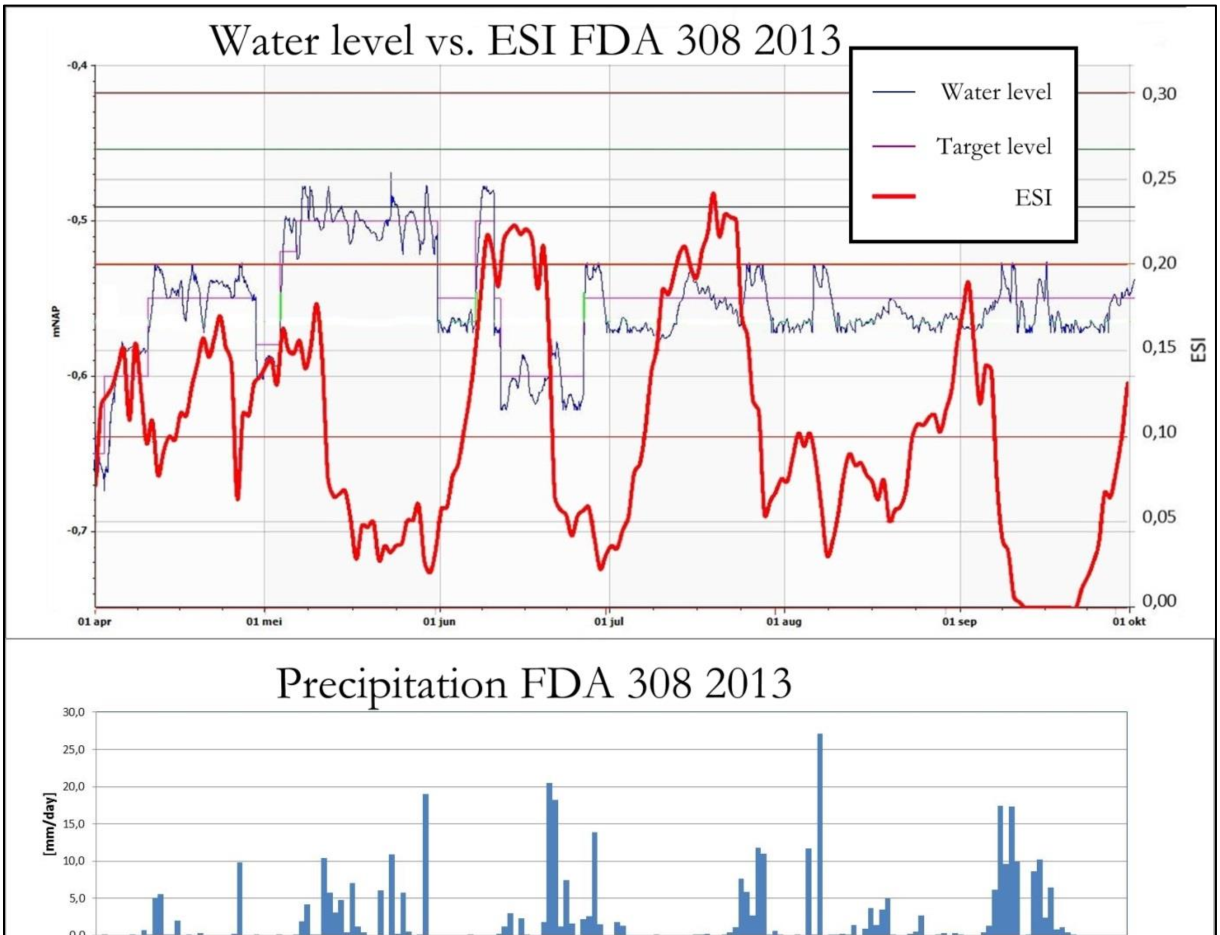

Figure 6-4 Water levels vs ESI and precipitation for FDA 308 in 2013

FDA 392

For FDA 392 the same applies as for FDA 308, knowing ESI could definitely provoke some changes in water level management here. In this area the fluctuations are much less, but summer water level is not reached until the end of July. The rest of the growing season the water level is kept 10 cm under summer level for unknown reasons. If ESI information would have been available, this could certainly be a reason to raise the water levels during the dry period of June and water levels would probably be raised earlier in July if weather predictions at that time also predicted a period without precipitation. Freeboard is again quite low for this area, so raising the water levels even further might not be possible.

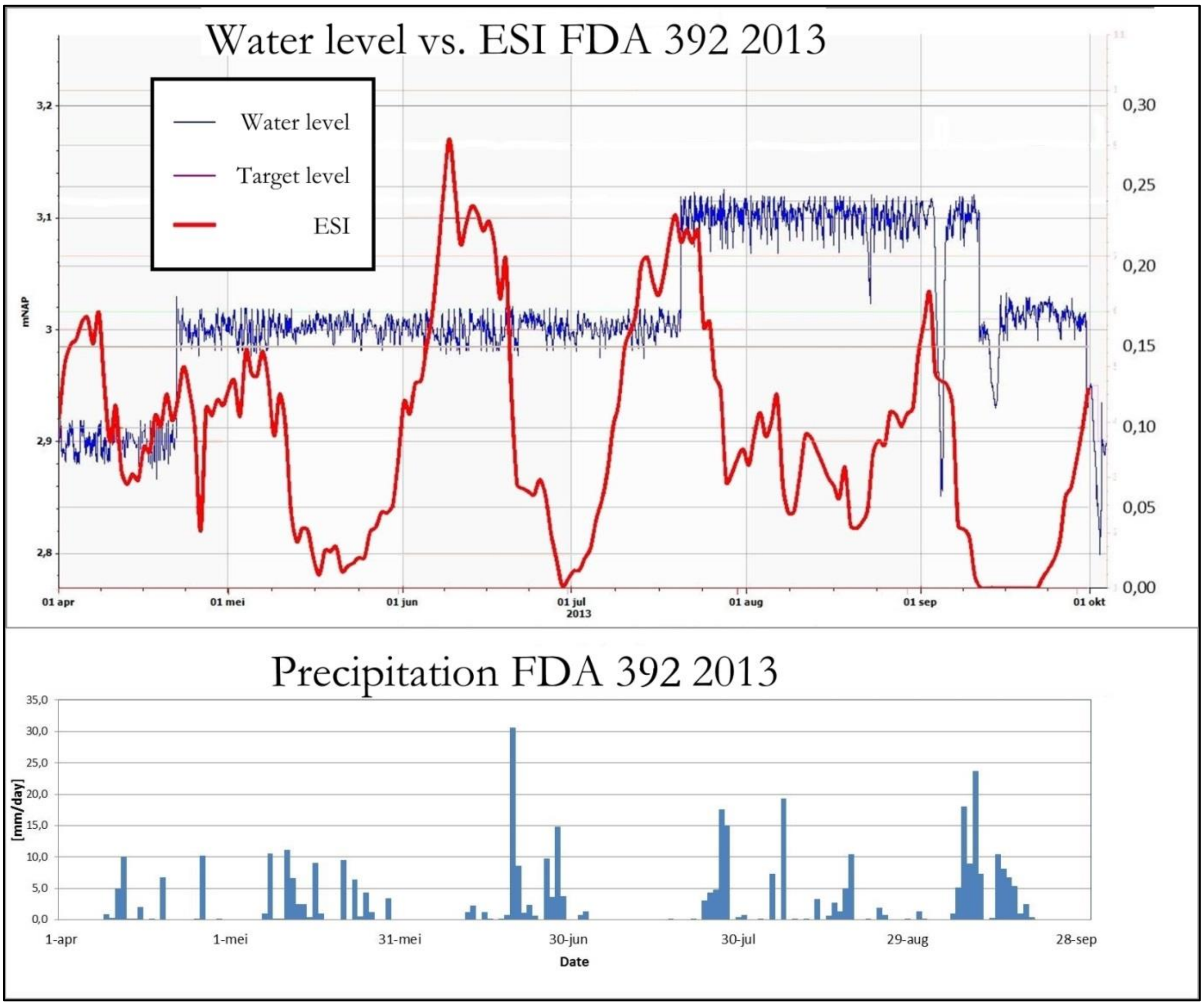

Figure 6-5 Water levels vs ESI and precipitation for FDA 392 in 2013

According to the analysis done for the four different FDAs it becomes clear that ESI does have added value and could provoke different actions in operational water level management. However, it still remains a question how much a higher water level would reduce ESI. Precipitation does affect ESI very well, as can be seen in the figures above. A drop in ESI is always around the same time of large amounts of precipitation. The data can definitely be used as a means of communication toward farmers. Farmers are the most important actors in water level management and when surface water levels are raised, farmers deliver the most resistance. Farmers are not always aware of the effects of drought on their crops, but they are rather worried for water excess. When the land is too wet and carrying capacity is too low, farmers might not be able to work their land or let cattle go outside. This all very directly affects the farmer because it limits the farmer in his daily work activities. That is probably the reason why they are much more concerned for water excess than stress conditions. Remote sensing can serve to substantiate the decisions of the water level administrators and district managers toward farmers making their job easier, and it might give farmers a better sense of the severity of drought in a particular period.

6.2 ESI AND IRRIGATION

Even though ESI can help improve water level management, the findings suggest that in periods of severe drought water has to be applied on land to keep enough moisture in the top soil so that evaporative stress can be released and crop performance can be improved. Irrigation is, according to the district managers seldom seen in the area of WGS. Many years ago farmers used to irrigate, but it became less and less because farmers find it too expensive and it is hard for them to see how much affect it really has because there are much more factors involved in creating a high yield. When, for example, a farmer does not irrigate his land one year and has a yield of 11.000 kg/ha and the next year he does irrigate and the yield is 11.500 kg/ha, he might come to the conclusion that it is not worth the effort. However, it could have just been that the potential yield in the second year was much lower due to lower ET_p. A farmer might not see that and come to the wrong conclusion about the efforts vs. the gains of irrigation. Lowering the ESI can however significantly increase yield. With average yields in the Netherlands around 10.000 – 12.000 kg/ha/year (Verantwoorde veehouderij, 2012) a yield loss of a 1.000 kg (which could be expected with an average ESI seen in 2013) due to lack of water would already mean a loss of € 250,-/ha/year, when only looking at the price of grass (Fauna Fonds, 2013). So if traditional water level management cannot be used to reduce drought in the more extreme situations, maybe the water authorities should focus more on awareness amongst farmers and give them more responsibilities towards preventing drought themselves. A way to do so would be to publish the ESI on WGS's website, maybe even with an irrigation advice. If farmers can see how much evapotranspiration is reducing and what this might mean in terms of yield losses, they might be willing to take on more responsibility themselves (in appendix G the effects and economic benefits of irrigation are further described). The water authorities would still have to supply the water to the areas to be irrigated, when this is done properly the focus of water management could shift from water level management to water quantity management.

Table 6-2 shows what that would look like for the four FDAs assessed earlier. The total evapotranspiration deficit over the growing season divided over the area gives the water need per hectare in a certain FDA to completely solve the evapotranspiration deficit. This is shown in l/min/ha to get a better understanding of the amount of water that has to be supplied on top of the water that was already supplied in current water level management. Total water supplied in 2013 through the big water inlets (the 10 biggest water supplying pumping stations supply water to regulate the water levels for over 80 % of WGS's area) equals just over 63 Mm^3, which is about 2.5 l/min/ha (see appendix H). So to solve the evapotranspiration deficit in 2013 through irrigation, water supply has to be almost doubled.

Table 6-2 Water supply needs for irrigation to completely solve the evapotranspiration deficit

District	1	2	3	4
FDA	41	308	392	659
Growing season ET def [m3]	198004	313219	16359	163140
Area [ha]	350	595	31	243
Supply needs [l/min/ha]	2.15	2.00	2.00	2.55

6.3 WGS DROUGHT MONITOR

To assist WGS and farmers in mitigating drought, the 'WGS drought monitor' is introduced. This tool displays drought in terms of ESI on a day to day basis. It uses a color coded system to show the severity of drought and the necessity for action. The average growing season ESI in 2013 lies around 0.10, this was chosen to be the critical ESI value for action and given the color red. When ESI is in the red, water levels should definitely be altered. When ESI lies in the orange range (0.05 – 0.10) a little more consideration should be taken into account when deciding whether or not to raise the water levels. Yellow areas are performing well and green areas are performing excellent. The drought monitor can be used by district managers and water level administrators to get a better insight in the drought conditions in their area and use this as an extra input in their decision making. It can also be used as a communication tool towards farmers to substantiate the decisions made by the water authority. It can be published on WGS's website to inform farmers about drought conditions and help them in their decision making to implement irrigation. In Figure 6-6 an example (more examples in appendix J) can be seen for the 1st of June 2013.

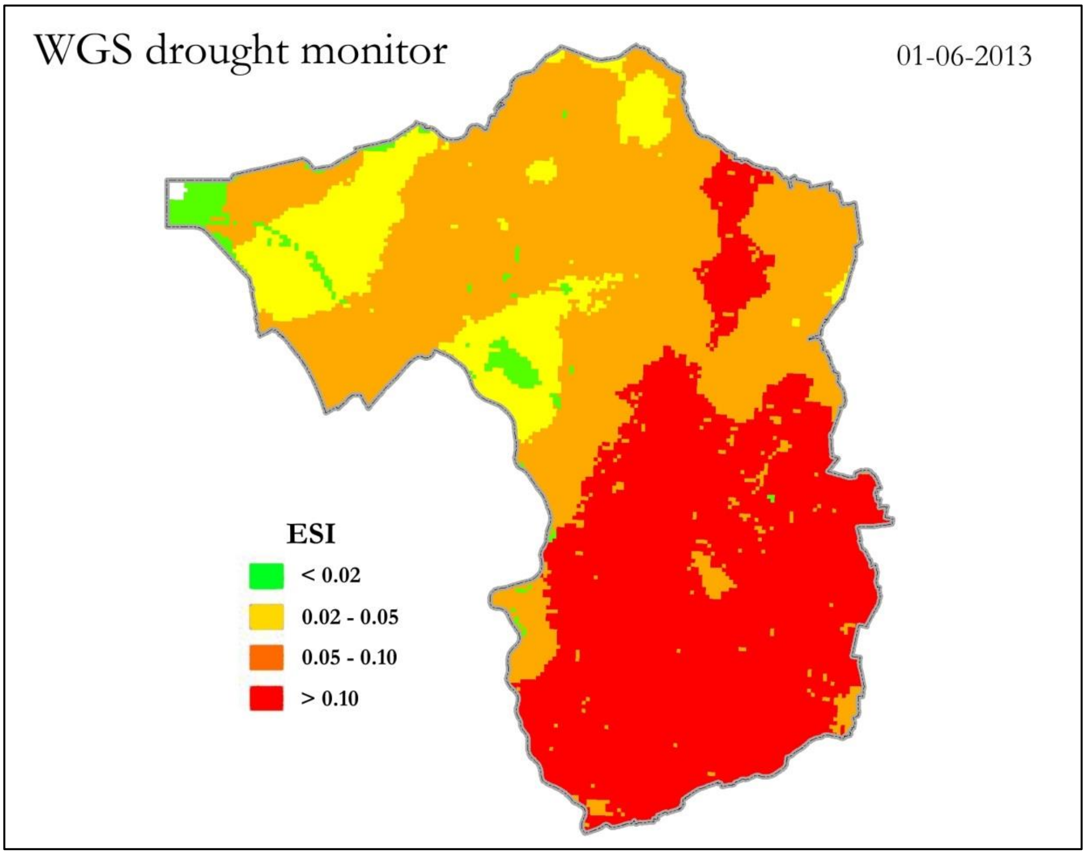

Figure 6-6 WGS drought monitor map for 03-07-2013

The drought monitor can be further developed to show drought per FDA, or if new RS data has a higher resolution per plot. Multiple color codes could be used to also show the trend in ESI. If this information would be made public by WGS, the possibilities are great. A mobile phone application could be developed for farmers, which locks on their GPS location and automatically reveals the ESI at that location. Whether or not daily updates can be made will still depend on the passing times of the Satellites used.

7 CONCLUSIONS & RECOMMENDATIONS

CONCLUSIONS

Eleaf's 'ET Tool' gives a good estimate of ET_p, the trend in ET_p from RS data compares very well to ET_0 from the KNMI measuring station at Heino and the total season ET_p estimate is within acceptable boundaries. Minor differences are most probably caused by the different methods of calculating ET, KNMI uses a theoretical approach to determine the crop development and eLEAF determines crop development from RS data.

The area of WGS is divided into four districts all with a district manager who is responsible for the OWLM of that district. Furthermore the area is divided into many FDAs, in which the water levels can be regulated independent of surrounding areas. Water levels for several areas vulnerable to land subsidence are registered in water level decrees, for other areas target levels are determined. The task of the district managers, who work together with water level administrators in the field, is to keep the water levels as determined in the water level decree or on target level. The district managers do this predominantly based on experience and in cooperation with the farmers, who are important actors in water level management. In more extreme cases of drought or water excess weather predictions start playing a role, ET plays a very minor role in WLM.

Assessment of the three year average growing season ESI composite shows that land use and soil type are the areal characteristics mostly affecting drought. Forested areas suffer most stress, followed by urban/paved area. Grassland suffers the least stress with an overall ESI of 0.081, indicating that over the three year record the average grassland ET_a in the area of WGS has been 8.1 % under its potential. Sand is the soil type most vulnerable to drought, which was also expected. Altitude and freeboard are moderately correlated to one another and share a weak positive correlation to long-term ESI. With these findings a drought vulnerability map was created, in which can be easily seen how vulnerable a certain area within WGS is to drought. This map should be used as an indication, the RS data is still very coarse and the data was only available for three years. To really say something about long-term ESI the data record should be at least ten to twenty years. The expectation is that the patterns seen could be quite the same, so sand soil will still have the highest ESI as will forested area. However, the severity of drought could be quite different.

Short-term ESI shows that evaporative stress is strongly related to lack of precipitation. Differences in short term ESI between areas are minor, even though one might expect that the polder areas, where groundwater tables are closer to the surface, would suffer less stress. This does raise a question about the effects of day to day operational water level management, and indicates that the best way to keep ET close to its potential is to supply water on land (through means of irrigation) which makes sure that the top layer (10 – 20 cm) is sufficiently saturated.

When comparing ESI to the water levels kept at several different FDAs it became clear that there is some room for improvement in OWLM. ESI indicates that water levels in most areas could have been raised to SWL much earlier and in some cases the decision to lower the water levels would probably not have been made if ESI would have been known. In the more severe cases of drought (high ESI in June and July) there is practically no room for improvement in OWLM, but much can be gained if this information is used for irrigational efforts. The introduced WGS drought monitor visualizes drought in a comprehensible way and it can give the district managers better information on real drought conditions to help make better decisions in OWLM, it can be used as a communication tool towards farmers to substantiate these decisions. If the WGS drought monitor would be published on WGS's website it can help farmers understand the severity of drought and the impacts on their crop development and make them decide to irrigate their land.

RECOMMENDATIONS

ASSESS DATA OF A VERY DRY YEAR

In this study there was only data available for the years 2011, 2012 and 2013. 2011 suffered a very dry spring, which was very noticeable in the ESI (ESI peaked at around 0.25). As were the two periods, in June and July, of stress in 2013. These three periods of stress were very noticeable in ESI, but overall these three years were not exceptionally dry. In 2013 the maximum cumulative precipitation deficit was around 200 mm, for 2011 is was around 160. The driest year in historical records is 1976 with a maximum cumulative precipitation deficit of around 340 mm. For that year there is most probably no RS data available, the driest year where raw RS data could be available is probably 2003 which had a maximum cumulative precipitation deficit of around 240 mm. To get a better insight in how ESI behaves, it would be very interesting to see how ESI behaved in that year. In 2013 the ESI peaked at around 0.25, will ESI reach even higher peaks in a year like 2003? Average ESI over 2013 was around 0.12, what would this be if the precipitation deficit reached 240 mm? Will average ESI increase linearly?

USE BETTER RESOLUTION AND A LONGER RECORD OF DATA

The RS data used still had quite a coarse resolution (250 m * 250 m), in the Netherlands the agricultural plots are usually smaller than that (for example 100 m * 200 m). With higher resolution RS data, the possibilities of use for water level management become much greater. There are for example pilots with water level regulated drainage, where agricultural plots are being fitted with drainage that lies under summer surface water level. So in summer the drainage pipes feed the ground with surface water, creating a very even groundwater level at the desired height. With higher resolution RS data, the differences between ESI for plots with and without water level regulated drainage can be compared. Also, three years of data is by far not enough to say something about real long term drought conditions. The patterns we see might be quite the same, but the severity is most probably very different. To get a real insight in long-term drought conditions at least a ten to twenty year record should be used, which might be possible because there's a good chance that the raw data is available. The spatial and temporal resolution of that data will most probably be lower than the RS data used in this research.

COMPARE ADAPTIVE OWLM TO FIXED OWLM

The ESI does not show very significant differences between areas, even though the water level management per area can differ quite a lot. Because ESI shows the direct effect of water shortage on evapotranspiration it would be very interesting to see what the actual benefits are of water level management in terms of ESI. This study suggests that this might not be as much as we think. A study examining the effects on ESI between an adaptive and a fixed OWLM should give some more conclusive answers. A pilot area could be assigned where one FDA will be managed actively using ESI as an input and one FDA will be managed using a fixed water level. The results can be used to assess the efforts of active OWLM

FURTHER DEVELOP THE DROUGHT MONITOR

The drought monitor that has been introduced is a first step towards the development of an operational drought monitoring tool for WGS and other water authorities. RS data cannot yet be delivered from day to day, because the passing times of the satellites used is less than once every day. ITC from University Twente (which could be the new supplier of RS data for SAT-Water) gets their data from the Sentinel-II mission that has a passing time of once every 6 days using two satellites, from the raw data 1 day estimates can be made. The end goal could be a drought monitoring application for mobile phone use, which can be used by district manager, water level administrators and farmers.

RELATIONSHIP ESI AND WATER INPUT

If the drought monitoring tool were to be used for irrigation advice, the relationship between ESI and the amount of water input through irrigation (or precipitation) has to be known. This way the amount of irrigation to lower ESI with a certain amount can be calculated. And, if precipitation is expected in say two days, the maximum ESI after those two days could be calculated as well as the lowering of ESI after precipitation to see if irrigation is still needed.

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APPENDICES

APPENDIX A: REMOTE SENSING & SEBAL

Remote sensing is a way of making earth observations by measuring radiation from remote locations (e.g. from a plane or satellite) and using these measurements to estimate state variables and fluxes, for example, altitude, temperature, concentrations, land-use, and many more (Schmugge et al., 2002). In this study we focus on hydrological state variables and fluxes, like precipitation, snow and ice cover, soil moisture, evapotranspiration, water storage, water level and water budget. There are two kinds of sensors: passive and active. Passive sensors detect natural radiation emitted or reflected by an object, active sensors emit radiation and measure the backscatter or reflection from an object. Besides electro-magnetic sensors, use is also being made of microgravity sensors to measure space-time variations in water storage (Tang et al., 2009).

In remote sensing the atmosphere plays an important role. It is essential to understand the effects of the atmosphere on the electromagnetic radiation travelling from earth to the sensor. The atmospheric constituents cause wavelength dependent absorption and scattering of radiation. These effects degrade the quality of images. Some of the effects can be corrected before the images are subjected to further analysis and interpretation (CRISP, 2001).

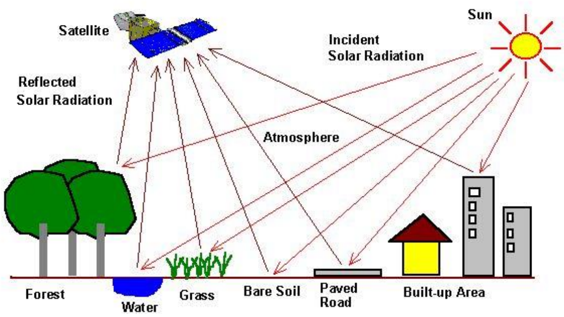

Figure 0-1: Schematization of passive sensing

In optical remote sensing, the backscattered or reflected solar radiation from the earth is sensed. The wavelength region usually extends from the visible and near infrared (commonly abbreviated as VNIR) to the short-wave infrared (SWIR). Different materials reflect visible and infrared light in different ways, they have different colors and brightness. The interpretation of these optical images requires knowledge of spectral reflectance signatures of various materials covering the surface of the earth. There are also sensors which measure thermal infrared radiation emitted from the earth, from this the earth's surface temperature can be derived. This kind of remote sensing is passive (CRISP, 2001).

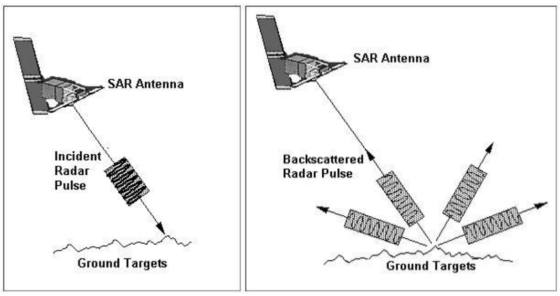

Figure 0-2: Schematization of active sensing

Active sensors emit pulses of (microwave) radiation to illuminate the areas to be imaged. Images are formed by measuring the radiation backscattered to the sensors. Advantages for active sensors include the ability to obtain measurements anytime, regardless of the time of day or season (NRCAN, 2014). Microwaves have an additional advantage as they can penetrate clouds. Disadvantage is the fact that active systems require the generation of a fairly large amount of energy to adequately illuminate targets (NRCAN, 2014). A microwave imaging system which can produce high resolution images of the Earth is the synthetic aperture radar (SAR). Since the physical mechanisms responsible for backscatter are different for microwaves, compared to visible/infrared radiation, the interpretation of SAR images requires knowledge of how microwaves interact with the targets (CRISP, 2001).

EVAPOTRANSPIRATION

Evapotranspiration is the process whereby water is transferred from the soil and/or the vegetation layer to the atmosphere, there are several physical processes required for this:

- A source of water
- A source of energy
- A sink for vapor

There are several approaches to estimate ET from remotely sensed estimates of surface energy fluxes, surface temperature, and vegetation properties (Tang et al., 2009). The use of remote sensing to estimate ET is presently being developed along two approaches: (a) land surface energy balance (EB) method that uses remotely sensed surface reflectance in the visible (VIS) and near-infrared (NIR) portions of the electro-magnetic spectrum and surface temperature (radiometric) from an infrared (IR) thermal band, and (b) Reflectance-based crop coefficient (generally denominated K_{cr}) and reference ET approach where the crop coefficient (K_c) is related to vegetation indices derived from canopy reflectance values (Gowda, et al., 2008).

GENERAL APPROACHES

The first approach is based on the rationale that ET is a change of the state of water using available energy in the environment for vaporization. Remote sensing based EB models convert satellite sensed radiances into land surface characteristics such as albedo, leaf area index, vegetation indices, surface emissivity and surface temperature to estimate ET as a "residual" of the land surface energy balance equation:

$$LE = R_n - G - H \quad (1)$$

Where, LE = latent heat flux, R_n = net radiant energy and G = soil heat flux and H = sensible heat flux, all expressed in W m^{-2}. LE can be converted into ET (mm h^{-1} or mm day^{-1}) using the latent heat of vaporization ($\lambda_v \sim 2.45\ MJ\ kg^{-1}$) and an appropriate time constant (Δt).

$$ET = \frac{LE}{\lambda_v} * \Delta t \quad (2)$$

R_n and G may be estimated locally using meteorological measurements and regionally by incorporating spatially distributed reflected and emitted radiation as:

$$R_n = (1 - \alpha)\, R_s + \varepsilon_a\, \sigma\, {T_a}^4 - \varepsilon_s\, \sigma\, {T_s}^4 \qquad (3)$$

Where, α is surface albedo, R_s is incoming short wave radiation (W m^{-2}), σ is the Stefan-Boltzmann constant (5.67 E-08 W m^{-2} K^{-4}), ε is emissivity and T temperature (K) with subscripts "a" and "s" for air and surface, respectively.

$$G = R_n(0.3324 - 0.024\, LAI)\big(0.8155 - 0.3032LN(LAI)\big) \qquad (4)$$

Where, LAI is the leaf area index. H is estimated using the aerodynamic surface-air temperature gradient (or combination of gradients) and aerodynamic resistance. A more detailed description of this approach can be found in Gowda et al. [2007].

In the second approach, red (R) and NIR reflectance measurements are used to compute a vegetation index such as the normalized difference vegetation index (NDVI) or the soil adjusted vegetation index, to determine the ET of a certain vegetation a reference ET is modified by vegetation specific coefficients reflecting the typical water use of specific crops or natural (unmanaged) vegetation (Anderson et al., 2012). The reference ET is computed using local meteorological measurements of incoming solar radiation, air temperature, relative humidity or dew point temperature, and wind speed (Gowda et al., 2008).

SEBAL MODEL

The supplier of the RS data to WGS, eLeaf, uses the ET Tool, which is evolved from the Surface Energy Balance Algorithm for Land (SEBAL) to determine actual and potential ET. SEBAL is an energy balance model that requires spatially distributed, visible, near-infrared and thermal infrared data which can be recovered from e.g. Landsat ETM, ASTER, NOAA or MODIS (eLeaf, 2014). In addition to satellite images, the SEBAL model also requires some meteorological data, such as wind speed, humidity, solar radiation and air temperature.

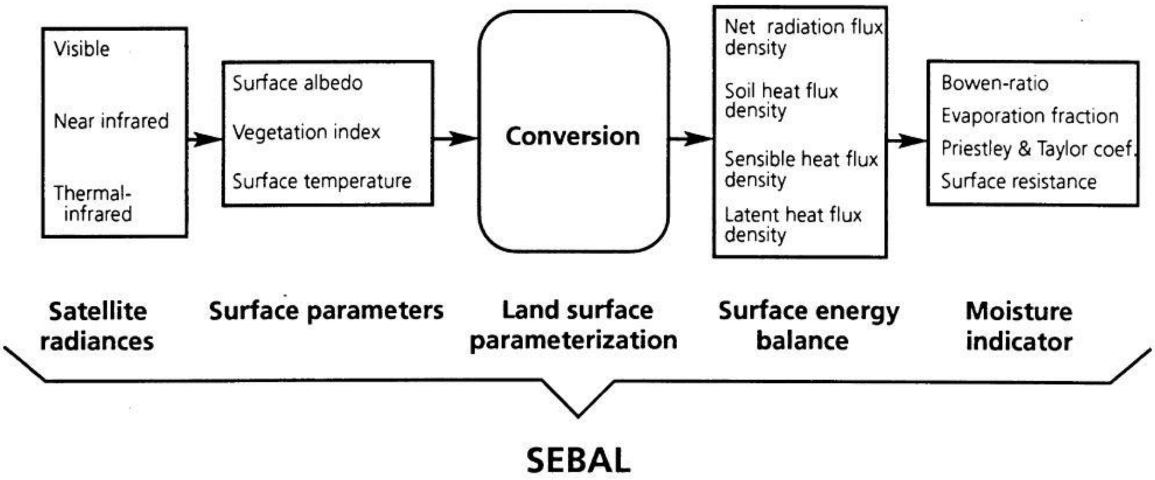

Figure 0-3: Principle components of the SEBAL model (Bastiaanssen, et al., 1998)

ET Tool produces the same outputs as SEBAL but for larger areas, whereas SEBAL is not particularly designed to model large areas. And in contrast to SEBAL, ET Tool is not affected by cloud cover in the satellite imagery. The daily temporal resolution of output from the ET Tool allows it to be used on an operation basis (eLeaf, 2014).

APPENDIX B: DATA COMPARISON

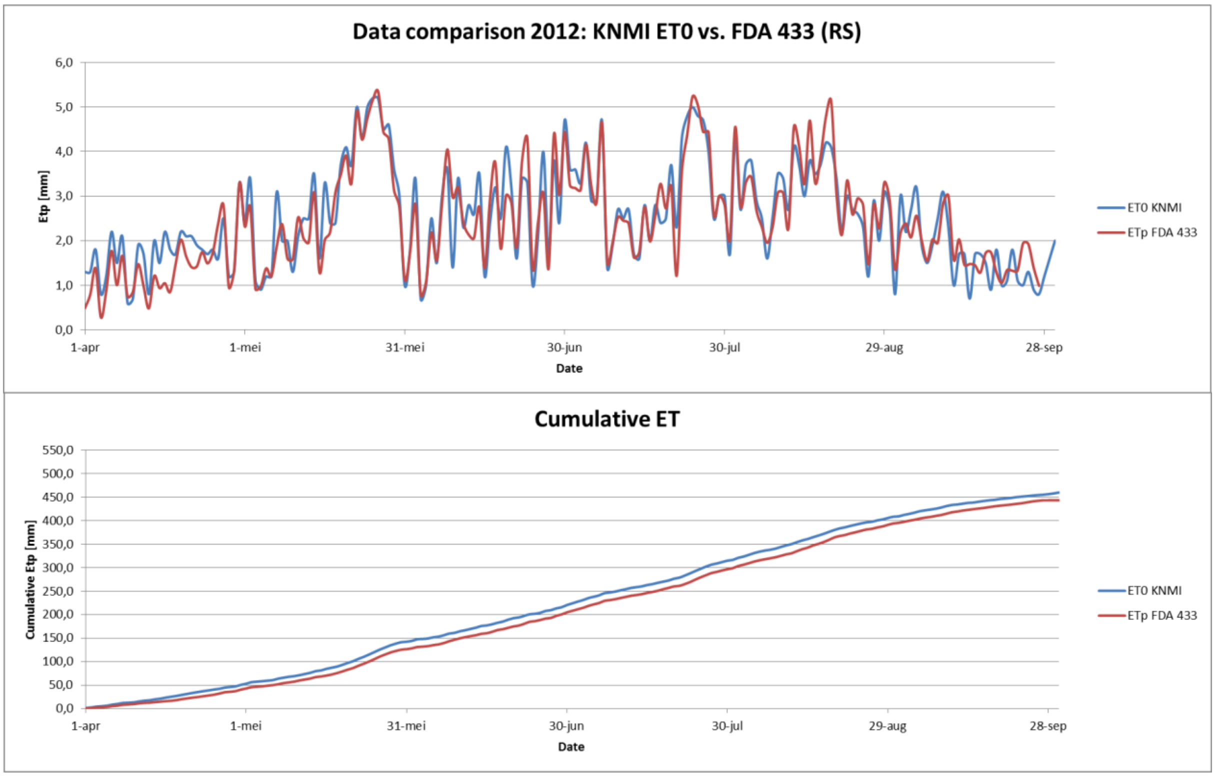

Figure 0-4 Data comparison 2012

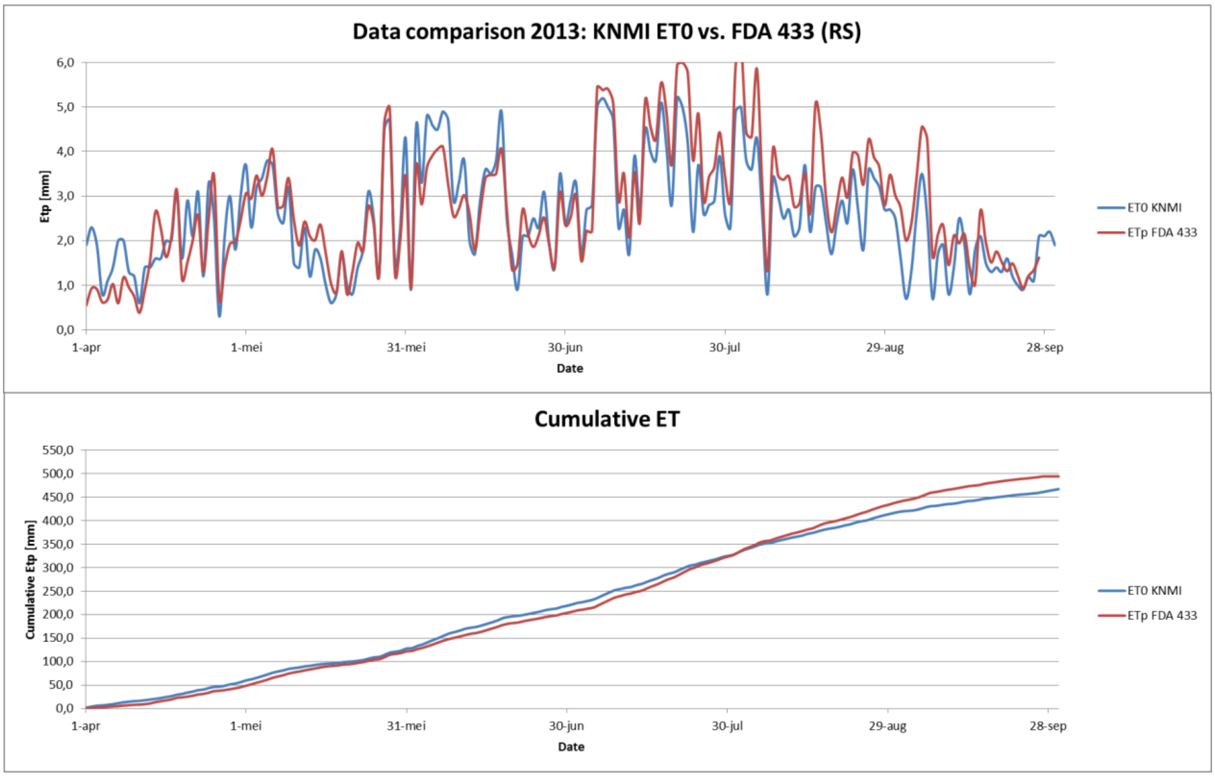

Figure 0-5 Data comparison 2013

APPENDIX C: MEETINGS AND EMAILS

Table 0-1 Important meetings and emails during this research

	Name	Function/Companie	Date	Regarding
Meeting	Andre Koekkoek	District manager, WGS	29-10-2014	Water level management
Email	Idse Hoving	Universitity Wageningen	10-11-2014	Yield reduction and evapotranspiration
Meeting	Bert van Olst	District manager, WGS	18-11-2014	Water level management
Email	Maurits Voogt	Managing Director, eLEAF	4-12-2014	Background RS data
Email	Maurits Voogt	Managing Director, eLEAF	10-12-2014	Background RS data
Meeting	Paul Jansen	District manager, WGS	2-2-2015	Water level management
Meeting	Paul Jansen	District manager, WGS	18-3-2015	Water level management
Meeting	Arjan Soepenberg	District manager, WGS	24-3-2015	Water level management
Email	Maurits Voogt	Managing Director, eLEAF	9-4-2015	Background RS data
Meeting		Hydrologists, WGS	Every other week	Research in general; Feedback; WLM
Meeting	Marloes ter Haar	Daily supervisor,	Every other week	Research in general; Feedback; WLM
Meeting	Hedwig van Putten	Hydrologists, WGS		
Lunchbreaks	Colleagues	WGS	3x per week	WLM; Research ideas

APPENDIX D: LONG TERM ESI MAPS

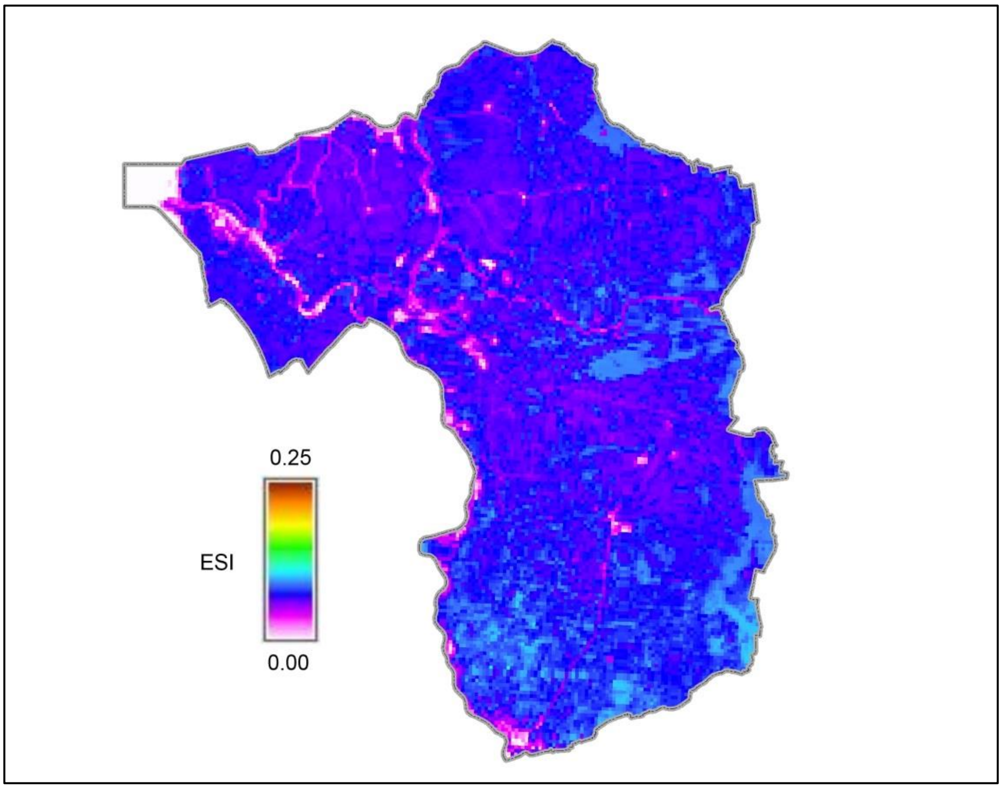

Figure 0-6 ESI 2011

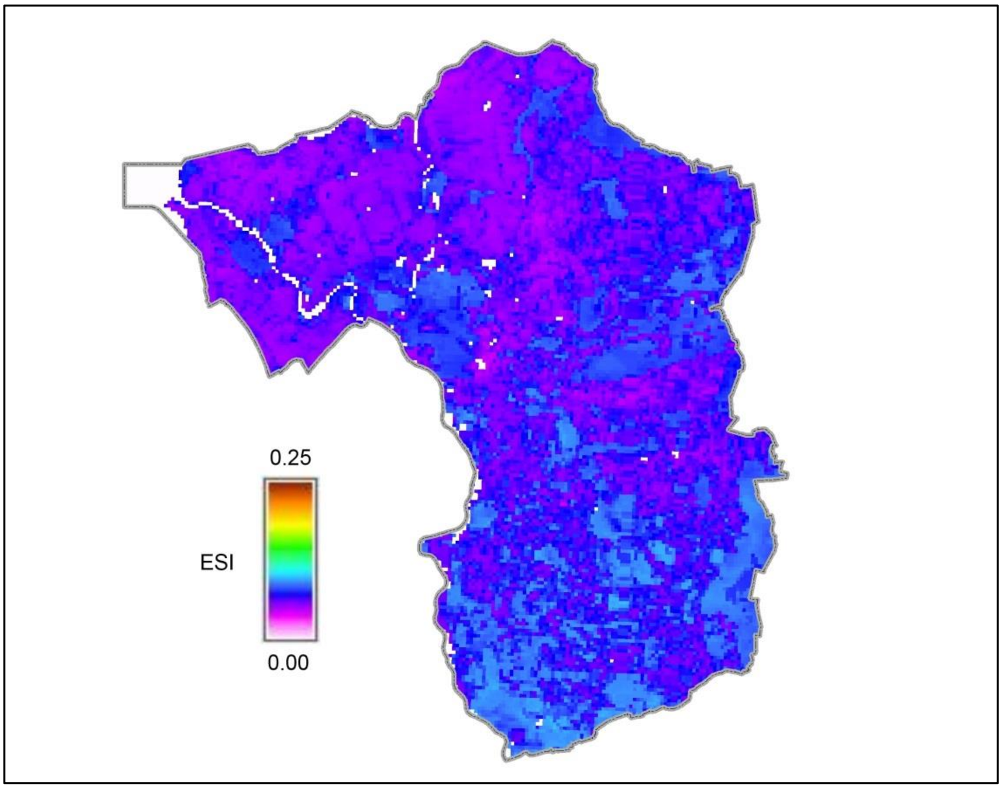

Figure 0-7 ESI 2012

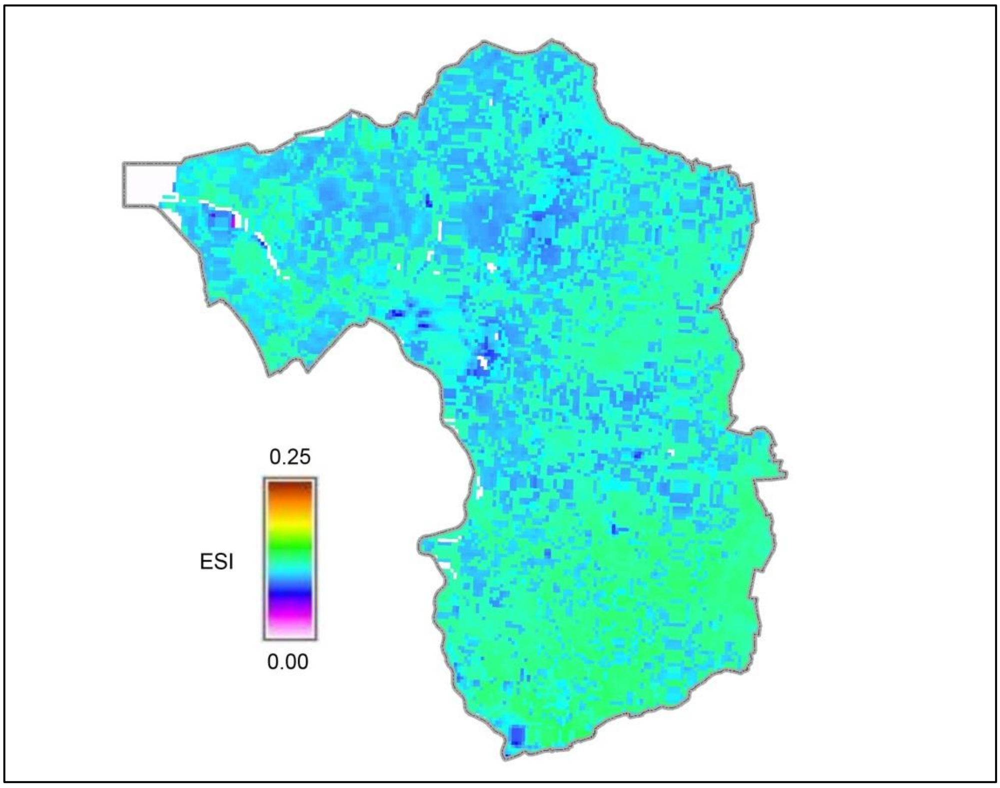

Figure 0-8 ESI 2013

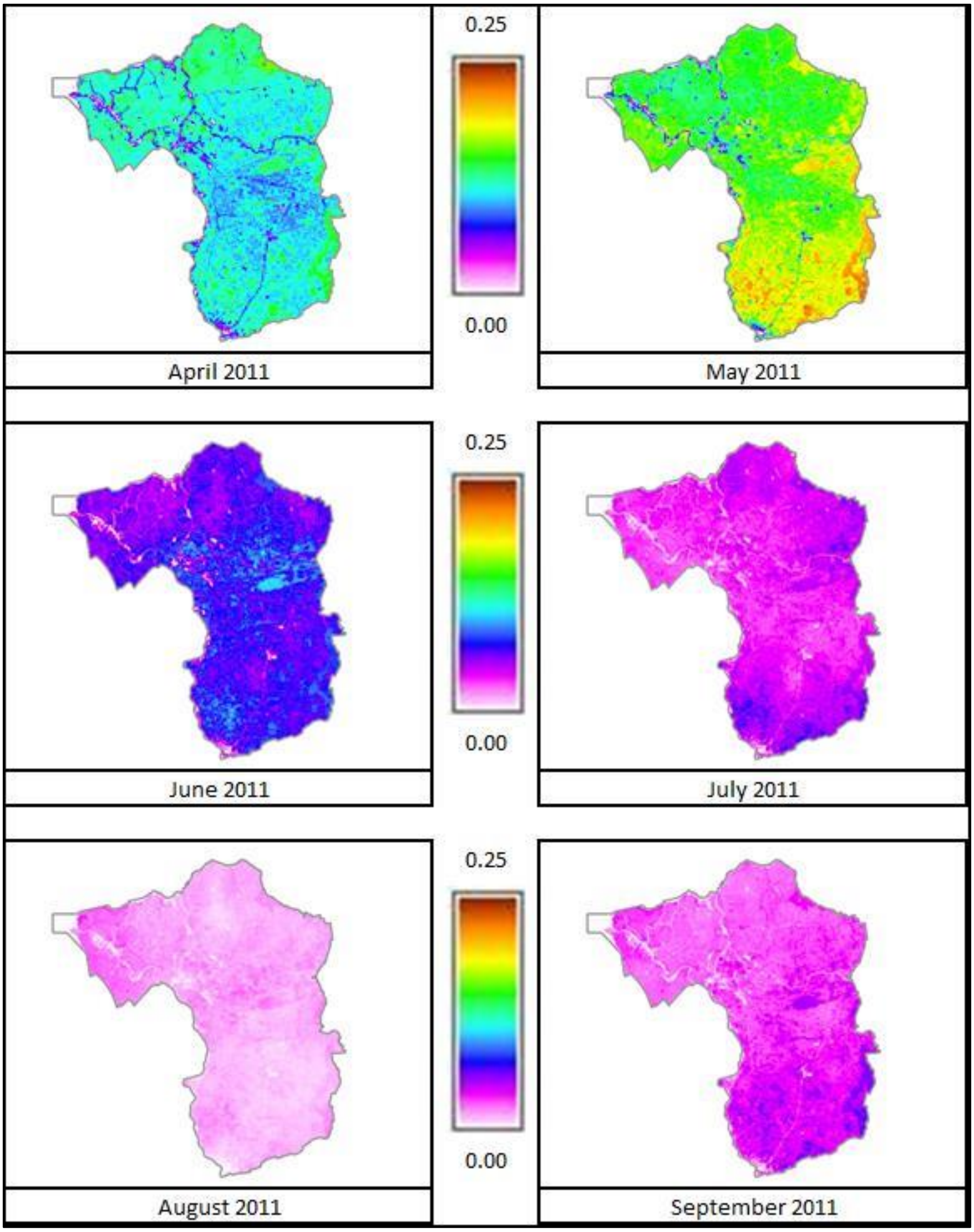

Figure 0-9 Monthly ESI 2011

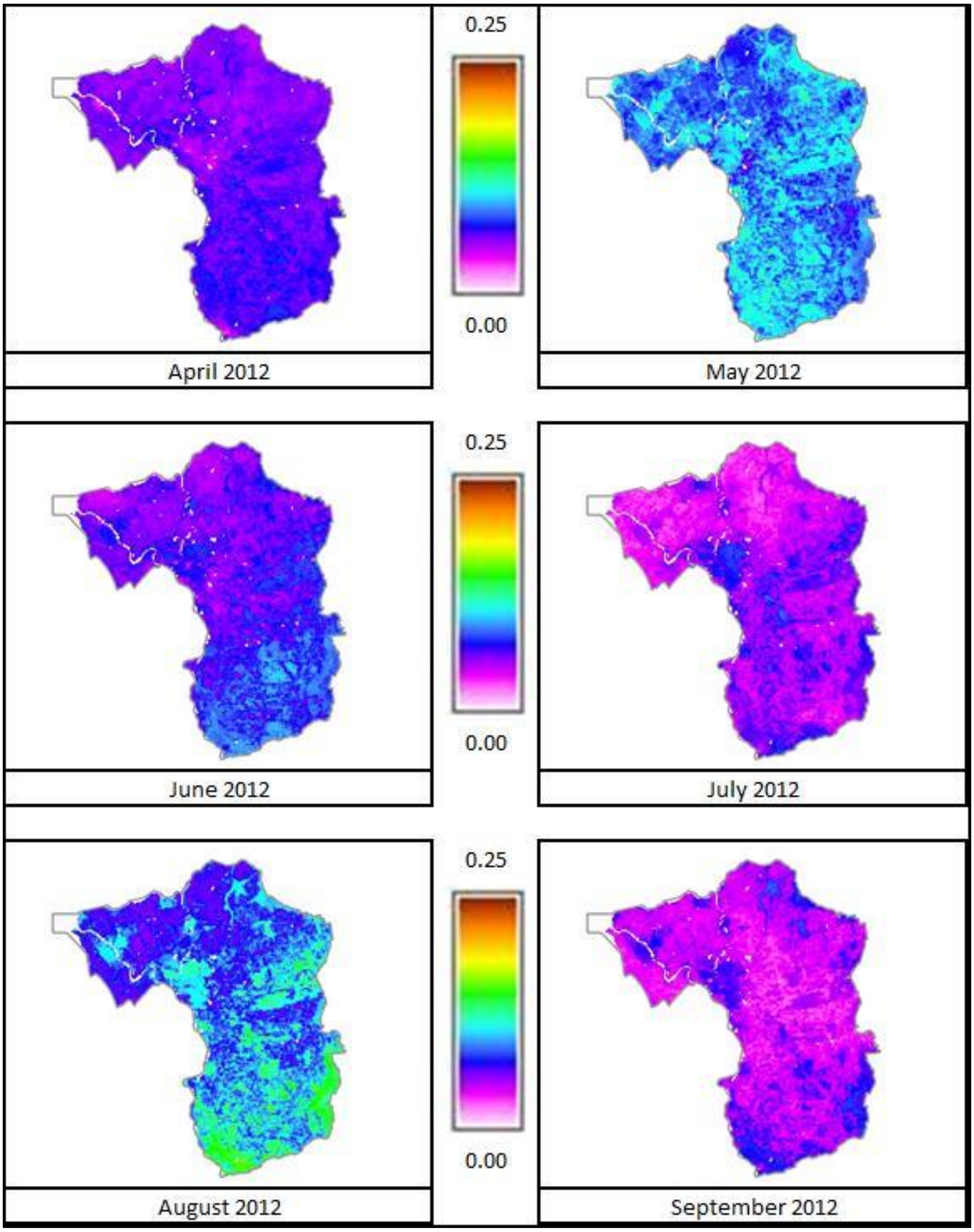

Figure 0-10 Monthly ESI 2012

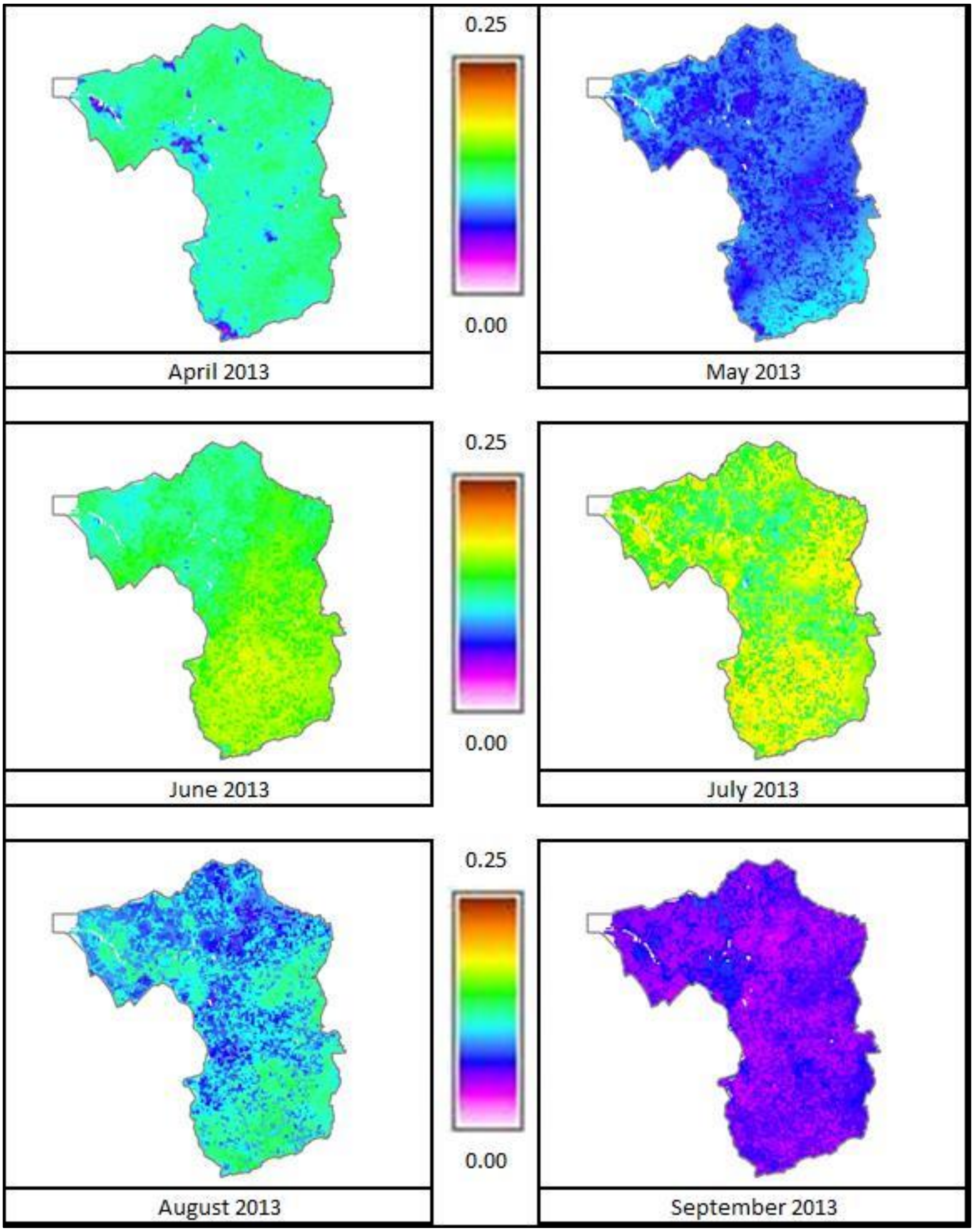

Figure 0-11 Monthly ESI 2013

APPENDIX E: NATURAL DROUGHT VULNERABILITY MAP

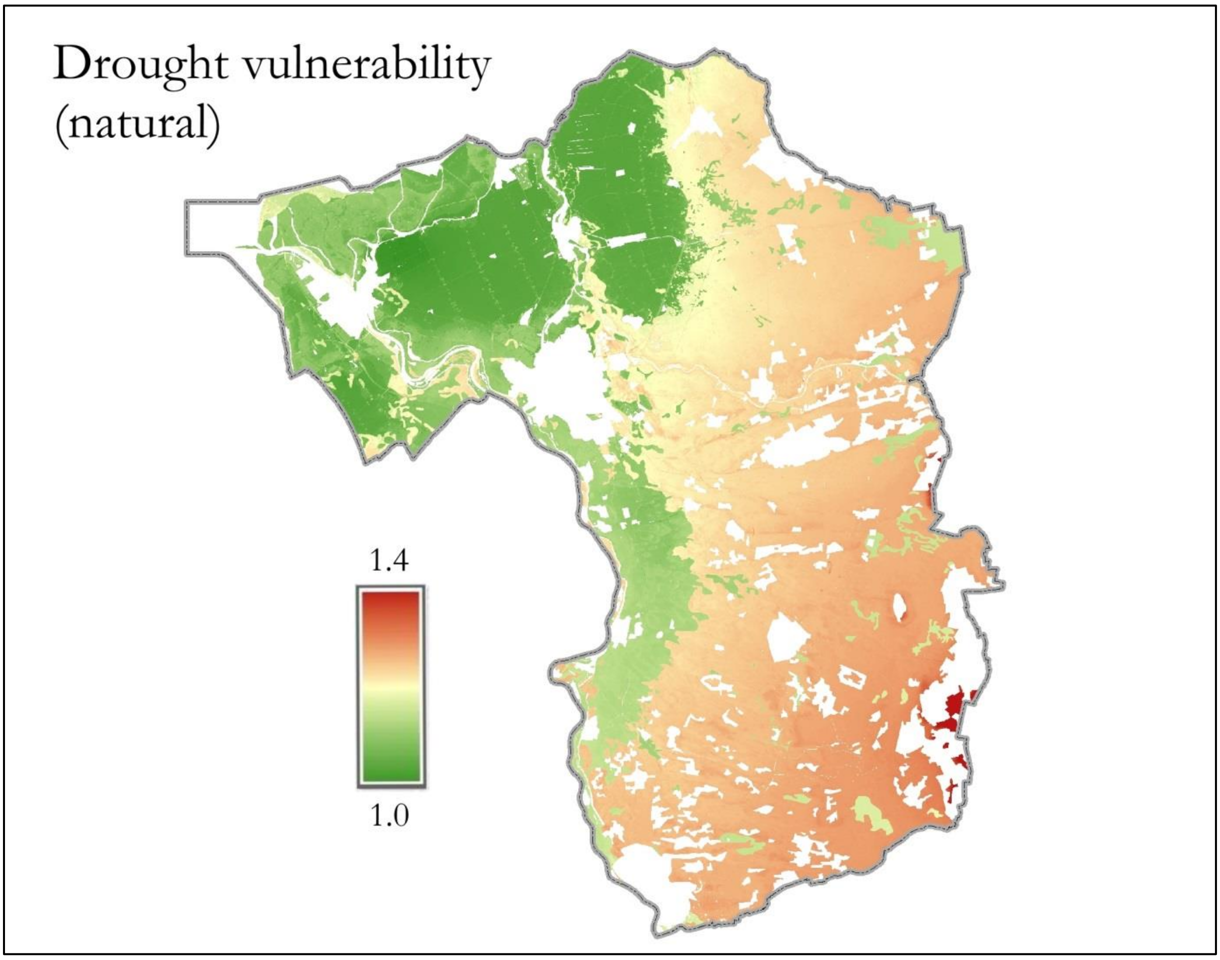

Figure 0-12 Natural drought vulnerability for WGS

APPENDIX F: COMPARING OWLM AND ESI

FDA 41

Figure 0-13 shows the water levels and the ESI in FDA 41 for the growing season of 2013. In FDA 41 the water level is kept at WWL (-0.50 + NAP) till the 1st of April, from then to the 1st of May the water level is gradually increased to SWL (-0.30 + NAP). During the rest of the growing season the water level is mostly kept on SWL, with an occasional fluctuation up or down. Why these fluctuations in the water level were made is sometimes hard to say because it is well over a year ago, but the drop in water level around the end of June was most probably because of the large amounts of precipitation around that time. In this area the water level management is done according to the water level decree. Freeboard in this area is quite low, so raising the water levels even more in the dry periods during June and July might not be possible. However, the ESI could prove to be a reason to raise the water levels from winter to summer level earlier as in the beginning of April the ESI is around 0.15.

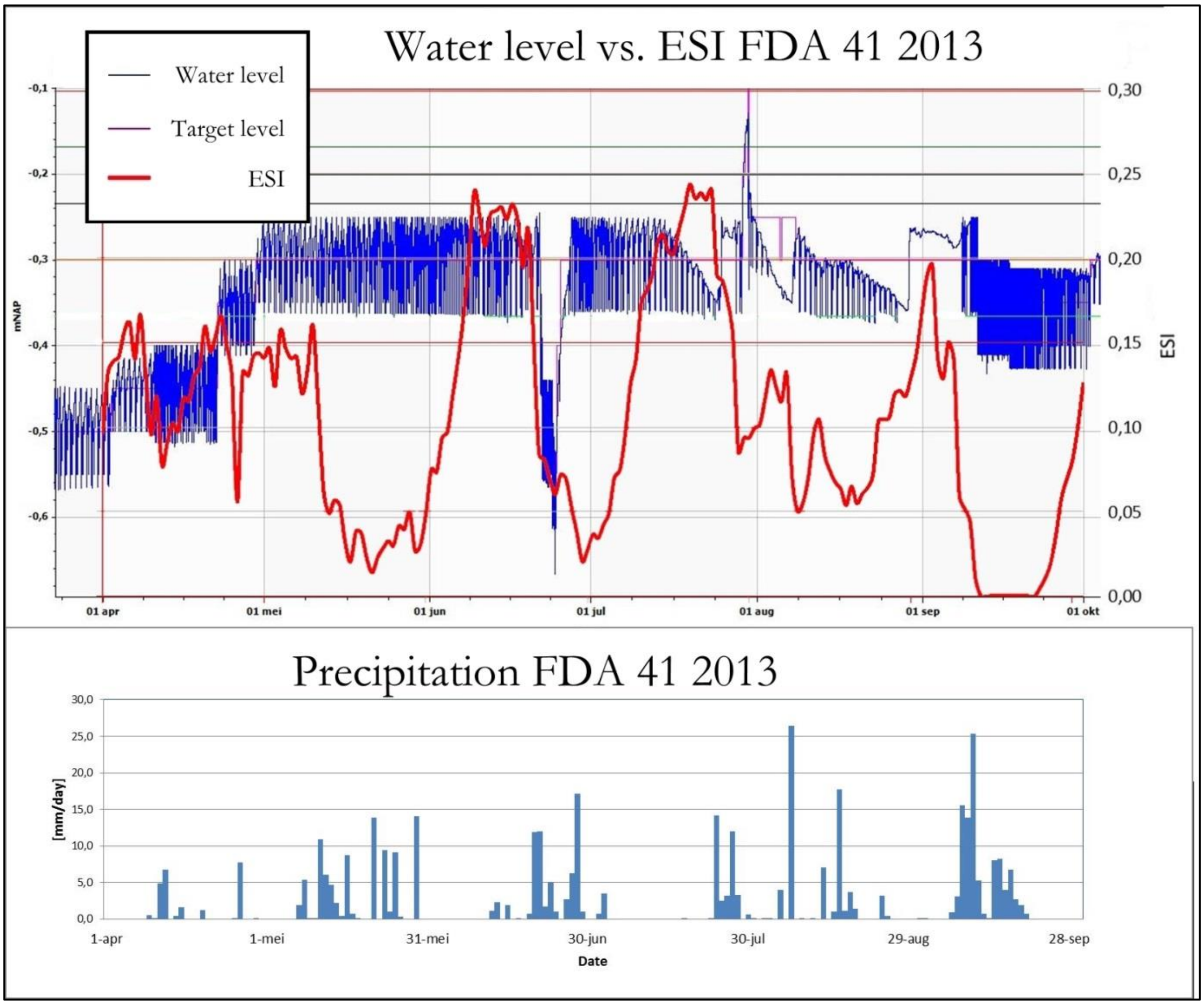

Figure 0-13 Water levels vs ESI and precipitation for FDA 41 in 2013

FDA 659

FDA 659 seems to be the only area amongst these four where the water level is set up higher than SWL (5.9 m + NAP) to actively try to counteract drought. The water level is set op to summer level some 10 days before the 1st of May and during the second week of May it is set up 5 cm above SWL. This is probably also what would have been done if ESI was known, the water level might even be raised earlier. The same goes for the dry period in June. In the beginning of June the water level is set up 5 cm above summer level and a few days later even to 10 cm above, this coincides nicely with the ESI peak of June. And the lowering of the water level back to SWL occurs at the same time as the ESI starts to drop due to precipitation. Would the ESI have been known, the water levels might have been set up even earlier and also the water levels during the ESI peak in July would have been raised. Figure 0-14 shows the comparison and the precipitation for FDA 659 in 2013.

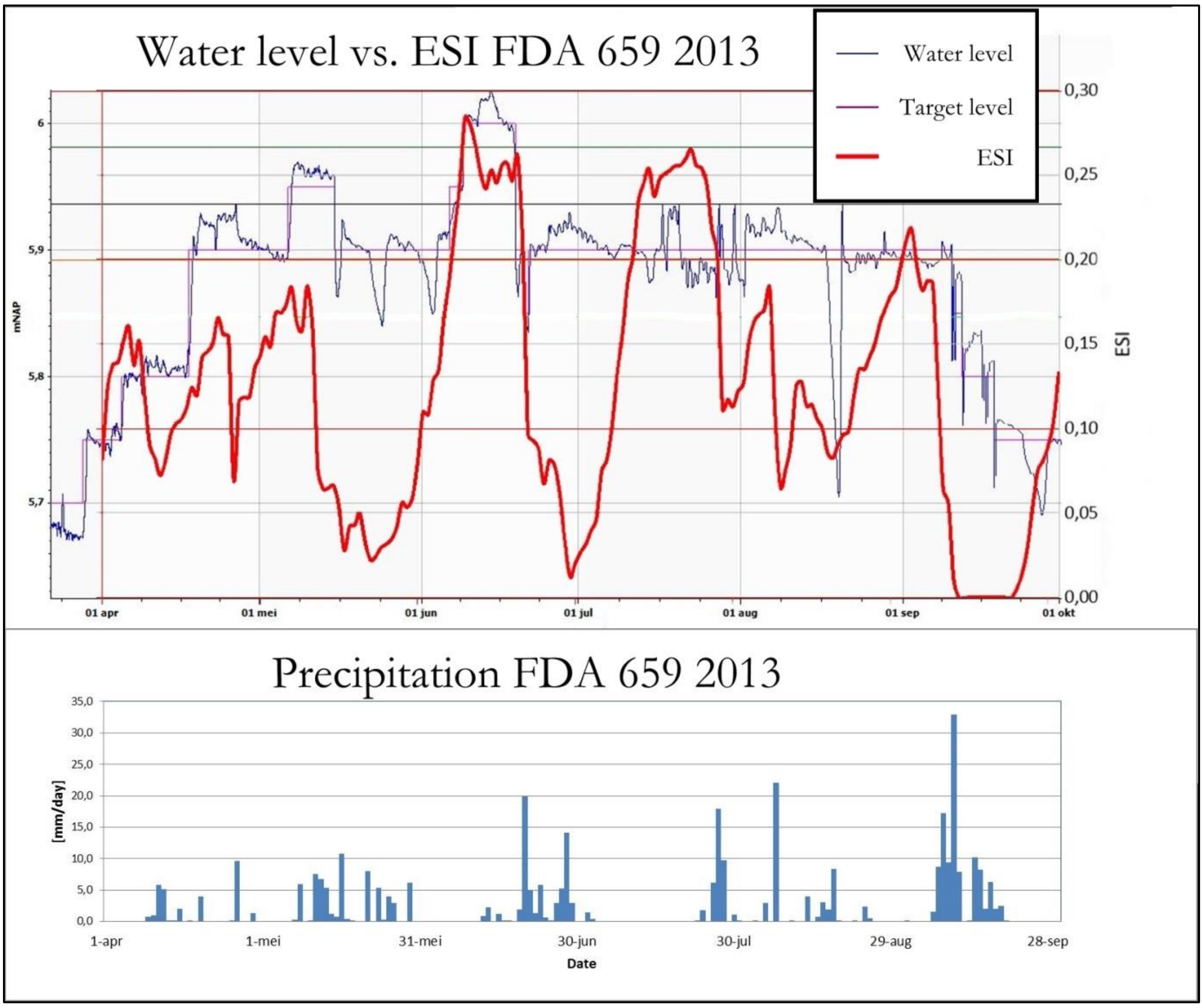

Figure 0-14 Water levels vs ESI and precipitation for FDA 659 in 2013

APPENDIX G: FINANCIAL BENEFITS IRRIGATION

Average dry matter yields for grassland lie between 10,000 - 12,000 kg/ha/year, the average for 'Koeien en Kansen Bedrijven' in 2011 was 11,300 kg/ha with a maximum of nearly 17,000 kg/ha (Verantwoorde veehouderij, 2012). Farmer Henry Steverink reached a dry matter yield of 15,000 kg/ha in 2010 by optimizing his grassland management with means like irrigation and fertilization (Veeteelt Magazine, 2010). Average prices for one kg dry matter of grass lie around € 0.25 (Fauna Fonds, 2013), so if we take a 10 % yield reduction due to evaporative stress we find a loss of € 250,-/ha if the potential yield is 10.000 kg/ha. This means that any amount lower than € 250/ha for irrigational purposes would create an economical advantage, and this is for the lowest potential yield and when looking at the market price for grass. Most farmers will be able to convert this grass to milk and then the economic advantage would be even higher. When looking at farmer Henry Steverink, who has a ration efficiency of 1.4 kg of milk per kg of grass, a 10 % yield reduction would mean a loss of little over € 800/ha if we take the average milk price of € 0.39 for 2014 (Boeren business, 2014). At a cost price for irrigation around € 5/mm/ha (WaterSense, 2012), Henry Steverink could have irrigated a total of 160 mm of water to reach a breakeven point. However, ration efficiency is also quite variable and lies between 0.75 and 1.75 (Duurzaam boer blijven, 2009). Figure 0-15 gives the margins of loss for a 10 % reduction in evapotranspiration for different potential yields.

Potential yield [kg/ha (dry matter)]	Grass (€ 0.25/kg)	Ration efficiency	Milk (€ 0.39/kg)
10.000	€ 250,00	0,75	€ 292,50
		1,25	€ 487,50
		1,75	€ 682,50
12.500	€ 312,50	0,75	€ 365,63
		1,25	€ 609,38
		1,75	€ 853,13
15.000	€ 375,00	0,75	€ 438,75
		1,25	€ 731,25
		1,75	€ 1.023,75

Figure 0-15 financial losses for a 10% yield reduction for different potential yields

Pumping station	1000 m3/year
Ankersmit	29685
Marswetering	1518
Eemsland 1 & 2	10918
Langewijk	16421
Vechterweerd	195
Zalk	1141
t Katje	151
t Zwaantje	1653
Rietberg	1580
Totaal	63262
80 % area WGS [ha]	96000
Water supply [l/min/ha]	2,50

Figure 0-16 Water supply from the biggest pumping stations in the area of WGS 2013

APPENDIX I: STUDENT'S T DISTRIBUTION

De Student (of t-verdeling)

In de tabel staat bij bepaalde n en $(1-\alpha)$ de waarde van t waarvoor geldt: $P(T_n \leq t) = 1 - \alpha$ als T_n een Student-verdeling met n vrijheidsgraden heeft.

Voorbeeld

$P(-2.02 < T_5 < +2.02) = P(T_5 < 2.02) - P(T_5 < -2.02) =$
$0.95 - P(T_5 > 2.02) = 0.95 - 1 + P(T_5 \leq 2.02) =$
$0.95 - 1 + 0.95 = 0.90.$

$1-\alpha$	0.90	0.95	0.975	0.99	0.995	0.9975	0.999	0.9995
n=1	3.08	6.31	12.71	31.82	63.66	127.32	318.33	636.67
n=2	1.89	2.92	4.30	6.96	9.92	14.09	22.33	31.60
n=3	1.64	2.35	3.18	4.54	5.84	7.45	10.21	12.92
n=4	1.53	2.13	2.78	3.75	4.60	5.60	7.17	8.61
n=5	1.48	2.02	2.57	3.37	4.03	4.77	5.89	6.87
n=6	1.44	1.94	2.45	3.14	3.71	4.32	5.21	5.96
n=7	1.41	1.89	2.36	3.00	3.50	4.03	4.79	5.41
n=8	1.40	1.86	2.31	2.90	3.36	3.83	4.50	5.04
n=9	1.38	1.83	2.26	2.82	3.25	3.69	4.30	4.78
n=10	1.37	1.81	2.23	2.76	3.17	3.58	4.14	4.59
n=11	1.36	1.80	2.20	2.72	3.11	3.50	4.02	4.44
n=12	1.36	1.78	2.18	2.68	3.05	3.43	3.93	4.32
n=13	1.35	1.77	2.16	2.65	3.01	3.37	3.85	4.22
n=14	1.35	1.76	2.14	2.62	2.98	3.33	3.79	4.14
n=15	1.34	1.75	2.13	2.60	2.95	3.29	3.73	4.07
n=16	1.34	1.75	2.12	2.58	2.92	3.25	3.69	4.02
n=17	1.33	1.74	2.11	2.57	2.90	3.22	3.65	3.97
n=18	1.33	1.73	2.10	2.55	2.88	3.20	3.61	3.92
n=19	1.33	1.73	2.09	2.54	2.86	3.17	3.58	3.88
n=20	1.33	1.72	2.09	2.53	2.85	3.15	3.55	3.85
n=21	1.32	1.72	2.08	2.52	2.83	3.14	3.53	3.82
n=22	1.32	1.72	2.07	2.51	2.82	3.12	3.51	3.79
n=23	1.32	1.71	2.07	2.50	2.81	3.10	3.48	3.77
n=24	1.32	1.71	2.06	2.49	2.80	3.09	3.47	3.75
n=25	1.32	1.71	2.06	2.49	2.79	3.08	3.45	3.73
n=26	1.31	1.71	2.06	2.48	2.78	3.07	3.44	3.71
n=27	1.31	1.70	2.05	2.47	2.77	3.06	3.42	3.69
n=28	1.31	1.70	2.05	2.47	2.76	3.05	3.41	3.67
n=29	1.31	1.70	2.05	2.46	2.76	3.04	3.40	3.66
n=30	1.31	1.70	2.04	2.46	2.75	3.03	3.39	3.65
n=40	1.30	1.68	2.02	2.42	2.70	2.97	3.31	3.55
n=50	1.30	1.68	2.01	2.40	2.68	2.94	3.26	3.50
n=100	1.29	1.66	1.98	2.36	2.63	2.87	3.17	3.39
n=200	1.29	1.65	1.97	2.35	2.60	2.84	3.13	3.34
$n=\infty$	1.28	1.64	1.96	2.33	2.58	2.81	3.09	3.29

Figure 0-17 Student's t distribution (Meijer, 2015)

APPENDIX J: WGS DROUGHT MONITOR MAPS

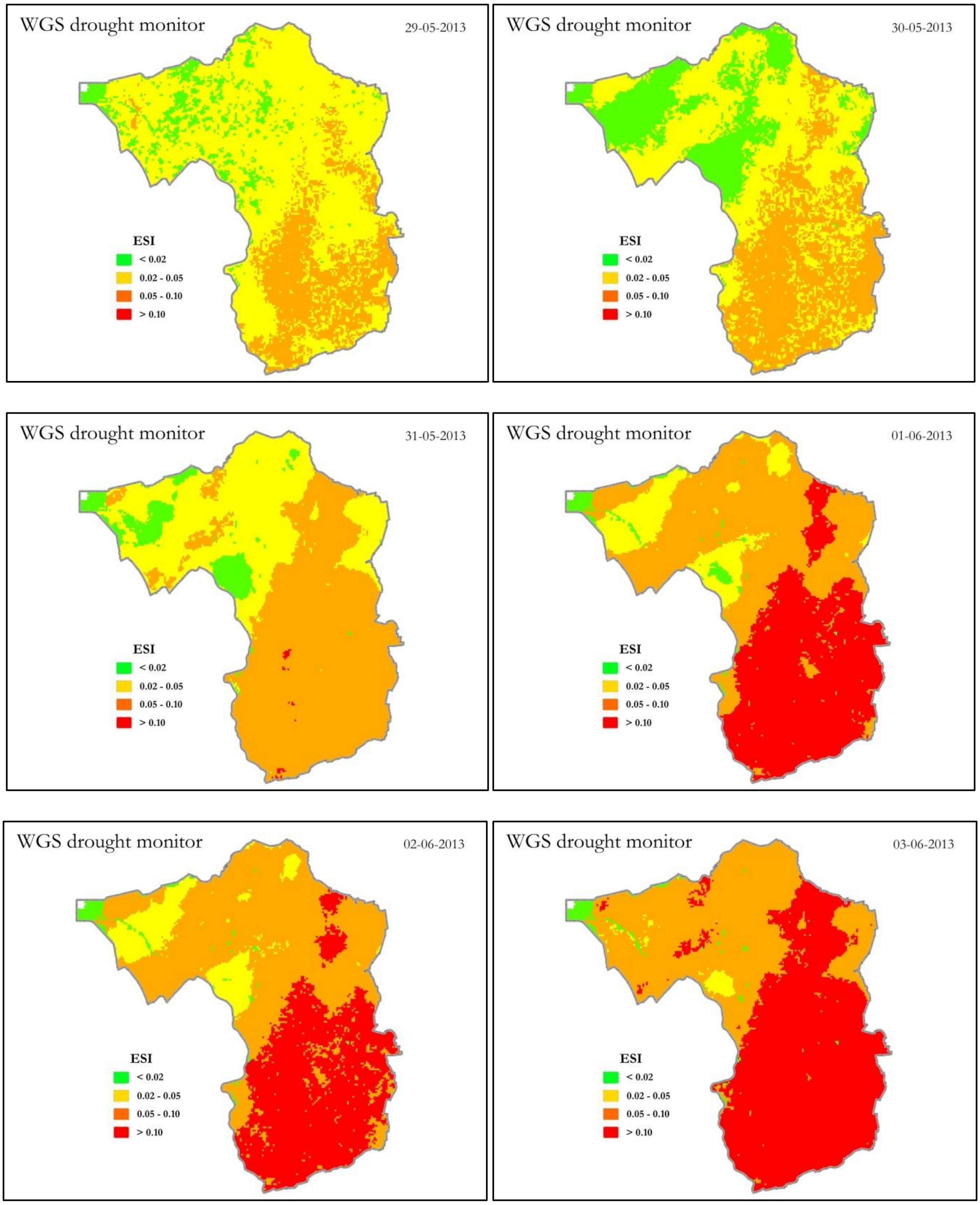

Figure 0-18 WGS drought monitor 29-05-2013 till 03-06-2013