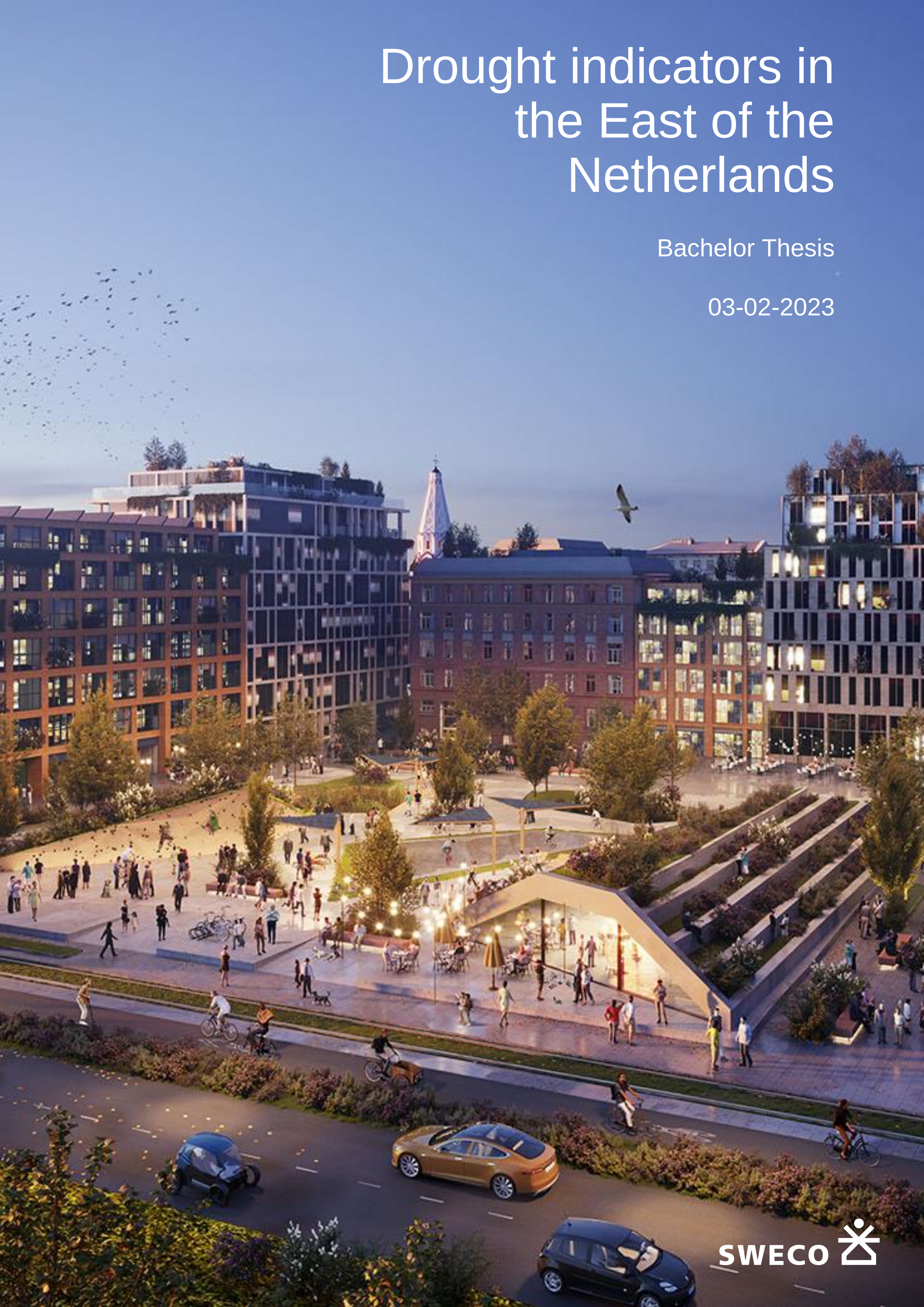
Drought indicators in the East of the Netherlands

Bachelor Thesis

03-02-2023



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1. Introduction

The development of the Netherlands has been conditioned by the implementation of different water management strategies, which has allowed part of the country to be under sea level. These systems are mainly composed of fresh water supply and flood protection policies. The Netherlands relies on freshwater from the Rhine and the Meuse and groundwater storage. However, such storage is filled through water infiltration into the soil during precipitation. An alteration to the infiltration rates has been one of the side effects of climate change. Such alteration results from increased temperatures, which has led to an evaporation increase. Since the amount of evaporation has also increased, less water has been able to store. As a result of less fresh water being stored, groundwater availability is decreasing through the dry months, resulting in drought (Siepman, 2022).

In the process of drought prediction, the Netherlands uses different drought indicators. The calculation of these indicators is based on the data recollected by the different waterboards across the Netherlands. Some data required for calculating these indicators can be precipitation, groundwater levels, or reference evapotranspiration data. The results recorded are usually correlated to the temperature and the season undergoing at the specific moment. Nevertheless, in recent years, the data has been recording negative shifts due to climate change.

Due to such shifts, implementing new drought indicators has been one of the measures implemented by Dutch authorities to improve the prevention and mitigation of droughts. Therefore, further analysis and comparisons have been developed to understand the reliability of these indicators and their importance. The results provided by these analyses have allowed us to determine the indicators' reliability and understand the importance of using multiple indicators.

2. Context

Throughout the years, the Netherlands has been exposed to meteorological consequences derived from Climate Change. These consequences have manifested in the past years as more extended droughts and shorter but more intense rain periods (*Droogte,* 2019). It is recognized that heavy precipitation is associated with a more intense hydrological cycle, which is known to be one of the many consequences of climate change. It is estimated that due to the new meteorological conditions, the maximum hourly precipitation will increase from 7% to 25% around 2050, and the number of wet days will decrease by 6% to 10% (*Droogte,* 2019).To track such events, the Netherlands utilizes different indicators. These indicators allow for forecasting droughts, water demand, water shortages, and the possibility of water supply. Until 2021, the Netherlands only used the Precipitation Deficit as their only drought indicator (*Nieuw Groeiseizoen met Uitbreiding Droogtemonitor* 2021); after 2021, the Netherlands started to use the SPEI (Standardized Precipitation Evapotranspiration Index) , the SPI (Standard Precipitation Index), and the SGI (Standardized Groundwater Indicator) drought indicators.

2.1 Drought Indicators

Drought indicators are variables or parameters used to describe drought conditions (Group, 2016). Each country selects different indicators, based on different factors such as: the input data that each country is able to gather or the type of drought that they are trying to predict (for more information see Appendix A). Once this criteria is clarified, each country will individually select their national indicators. These indicators, can or cannot be globally used indicators (for more information refer to Appendix A).

The Netherlands, started to record precipitation data in its first meteorological station in 1906 in De Bilt. In 1957, this station started to record the first reference evapotranspiration data of the Netherlands. Currently, the Netherlands has 27 (*Droogteportaal,* 2022) stations, that record precipitation and reference evapotranspiration data. With the above mentioned data availability, the Netherlands has been able to use indicators to forecast meteorological, agricultural or hydrological droughts. The Netherlands uses drought indicators of four out of the five drought indicators categories (refer to Appendix A).

In the past years, the KNMI (Koninklijk Nederlands Meteorologisch Instituut), started to implement the use of different drought indicators. Until 2021, the Netherlands, only used one Meteorology Indicator, as a method to predict drought. Due to the changing weather events, the KNMI, started to notice the limitations of the Precipitation Deficit, which made them decide on including new indicators.

For a better understanding of the current indicators that are used or will be used in the Netherlands (some indicators, will be used in the future, since at the moment, KNMI does not have enough data to model these indicators, and is currently working on data recollection, to guarantee accurate results). Table 1, provides a list with all the indicators that are or will be used in the Netherlands. This list, contains a description, the benefits and the different calculation methods, required for each indicators.

Table 1: Indicators that are used in the Netherlands

Indicator	Description	Benefits	Calculation Method
Meteorology Indicator			
SPI (Standard Precipitation Index)	SPI is an indicator developed in 1992. In 2009 the WMO, recommended this indicator as the main meteorological index that countries should use to monitor and follow drought conditions. SPI, has an intensity scale. If the SPI continuous to reach a value of -1, then a drought event is considered. If it reaches a value of 0, the drought event has ended (Group, 2016).	SPI can be calculated with data missing. If the amount of recorded data is not enough, a “Null” value will be recorded. Once the amount of data increases, then the SPI calculation will be resumed. SPI has a wide application , can be applied on events that affect agriculture, water resources or other sectors (Group, 2016).	The actual amount of rain is measured. Then is compared with distribution that was determined from the historical time series, after it has been transformed into a normal distribution. The results are then translated to wet or dry classification (*Climate Data Guide,* 2023).

SPEI (Standardized Precipitation Evapotranspiration Index)	SPEI uses monthly precipitation and temperature data as input requirements SPEI can be used to monitor conditions associated with drought impacts. Monthly updates allow it to be operationally. The longer the amount of data is, the more robust the results are (Group, 2016).	The calculation of this index, only requires climatological information. For modelling this indicator, no assumptions are needed, since the input parameters need to be measured by a metrological station. SPEI has low data requirements, and the input data required, are the two main elements that determine drought severity (Deser et al., 2022).	The difference between the amount of precipitation and reference evapotranspiration needs to be known. Then the current quantity is compared with the normal distribution determine from the historical time series. The results, are translated into wet or dry classification (Vicente-Serrano et al., 2010)
Precipitation Deficit	Is the cumulative difference between precipitation and reference evapotranspiration (*Select a time series,* 2023).	Takes into consideration precipitation data. It allows to see a visual representation on how the weather in the Netherlands has progressed over the specific period of time. The precipitation deficit can be calculated on a daily basis (*Select a time series,* 2023).	Is the cumulative difference between reference evapotranspiration and precipitation. Starting on April 1st and ending on September 30th. Once the cumulative difference is negative, it is set to 0 (*Select a time series,* 2023).
Soil Moisture Indicators			

Soil Moisture Index (SMI)	Provides information on the severity of agricultural drought. This index is classified from no drought to extreme drought (Hogg et al., 2013).	It is based on continuous soil moisture measurement for over 8 years. The soil texture information is available which allows to quantify available soil water. It can be combined with hydrological models for other regions or time periods (Hogg et al., 2013).	One-layer "bucket" water balance model, that uses daily maximum temperature, dew point temperature, minimum temperature, the site altitude, monthly mean value of minimum temperature (Hogg et al., 2013).
Hydrological Indicators			
Standardized Groundwater level Index (SGI)	The SGI is build on the SPI, it accounts for the differences in the form and characteristics of groundwater levels and precipitation time series (Bloomfield & Marchant, 2013).	Can be calculated over different time series. Good correlation between SPI and SGI, which translates into a robust index of groundwater (Bloomfield & Marchant, 2013).	Is estimated by using a non-parametric normal scores to transform of groundwater levels for each calendar month. These results are then merged, to form a continuous index (Bloomfield & Marchant, 2013).
Remote Sensing Indicators			
Normalized Difference Vegetation Index (NDVI)	NDVI, measures the greenness and the density of the vegetation of an area, through satellite images (*NDVI mapping in agriculture, index formula, and uses* 2022).	A correct interpretation of the NDVI results, help to raise healthier yields and take better care of the environment (*Remote Sensing waterkwantiteits- en waterkwaliteitsbeheer* 2022).	Healthy vegetation has a specific reflecting curve, that allows to calculate the difference of two values. Visible red and near infrared. Such difference is then expressed as a value between -1 and 1 (GISGeography, 2022).

Drought indicators provide clarity regarding how severe a drought is, or how a drought is affecting different parts of the Netherlands. Figure 1 provides a visual representation of the registered Precipitation Deficit of the Netherlands in 2022 and 2019. With the information provided by Figure 1, it can be concluded that the registered deficit in 2022, was higher than the registered deficit in 2019.

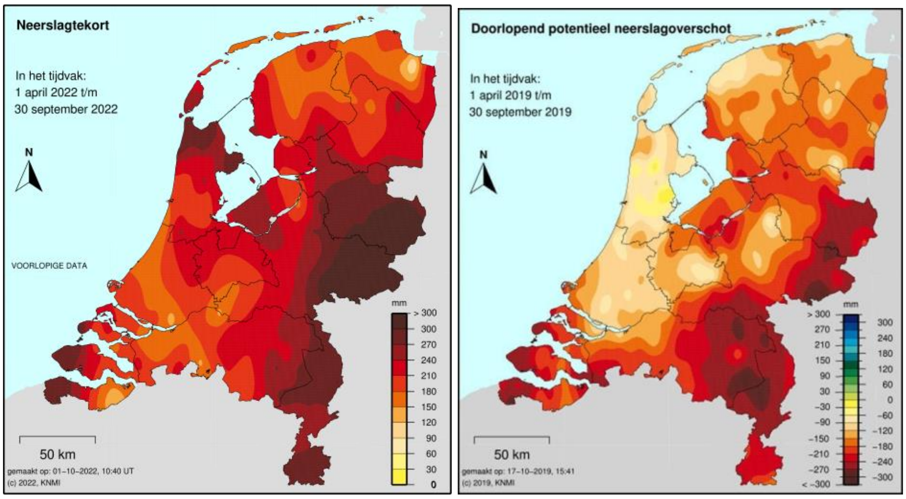

Figure 1: Precipitation deficit of 2022 (Neerslagtekort / Droogte, 2022) (left) and 2019 (Gastblog, 2021) (right)

As observed in Figure 1, the Eastern part of the Netherlands was exposed to a more considerable precipitation deficit. The increasing droughts in the East of the Netherlands (provinces of Overijssel and Gelderland) are due to rising temperatures (higher evapotranspiration) and changing rainfall. Research has shown that the drought registered in 2018 was directly linked to the consequences of global warming. Because of this observation, the research developed through this bachelor thesis focused on the East of the Netherlands. Nevertheless, due to its considerable extension, the performance of this bachelor thesis has been determined by the data recollected by the Vechtstromen waterboard.

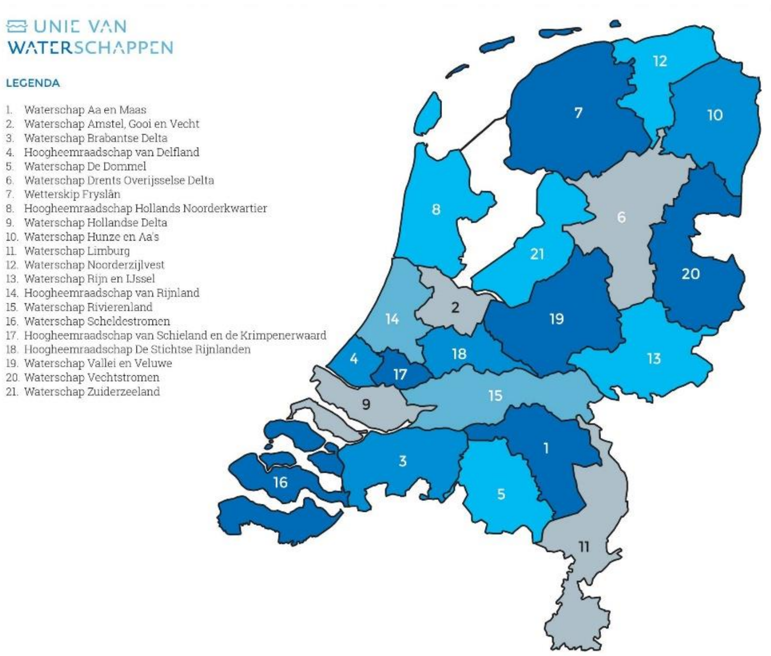

Figure 2: Waterboards in the Netherlands (Waterschap 2021)

Figure 2, shows a map of the Netherlands. This map is divided into different sections, each representing a different waterboard. The waterboards division in the Netherlands is not equitable to the division of provinces. As mentioned above, this assignment has been conducted with data gathered from the Vechtstromen waterboard, number 20, in Figure 2.

The development of this bachelor thesis, has been done with the data recollected by Vechtstromen waterboard. The Netherlands has multiple meteorological stations that record, precipitation, reference evapotranspiration, temperature or groundwater levels data. Figure 3 shows a close up of the area where this assessment has been performed. The small triangles that can be seen in Figure 3, are the different stations that recollect SPEI and SPI data.

Figure 3: Eastern region (Twente) where the project will be developed (Droogteportaal 2022)

3. Research Questions

In 20121, the Netherlands started implementing new drought indicators due to the environment to which the precipitation deficit was applied had changed. As mentioned, the precipitation deficit is calculated from April 1st until September 30th (the growing season). However, since spring has become drier, using new indicators is required to analyze the new undergoing climate scenarios. For this reason, this Bachelor's Thesis aims to understand the reliability of the different drought indicators and analyze their performance when applied to the east of the Netherlands. To address this goal, the following research questions will be answered through the development of this bachelor thesis.

1. What is the effect of utilizing different indicators (e.g., SPEI, SPI, SGI, and Precipitation Deficit) on portraying up-to-date water shortages, specifically in the Eastern part of the Netherlands?
2. To what extent is it possible to improve the current calculation methods to guarantee that an indicator (or a combination of indicators) can provide up-to day representation of water scarcity?
    a. To what extent does the off-bound data impact the data recollected between April 1st and September 30th, applied for drought prediction?
3. How do the drought indicators provide additional information concerning drought management?

3.1 Research model

For the competition of this bachelor thesis, a research model detailing the corresponding steps required for answering the above-mentioned research questions has been elaborated. Figure 4 shows the different steps that have been taken to guarantee the completion of the thesis.

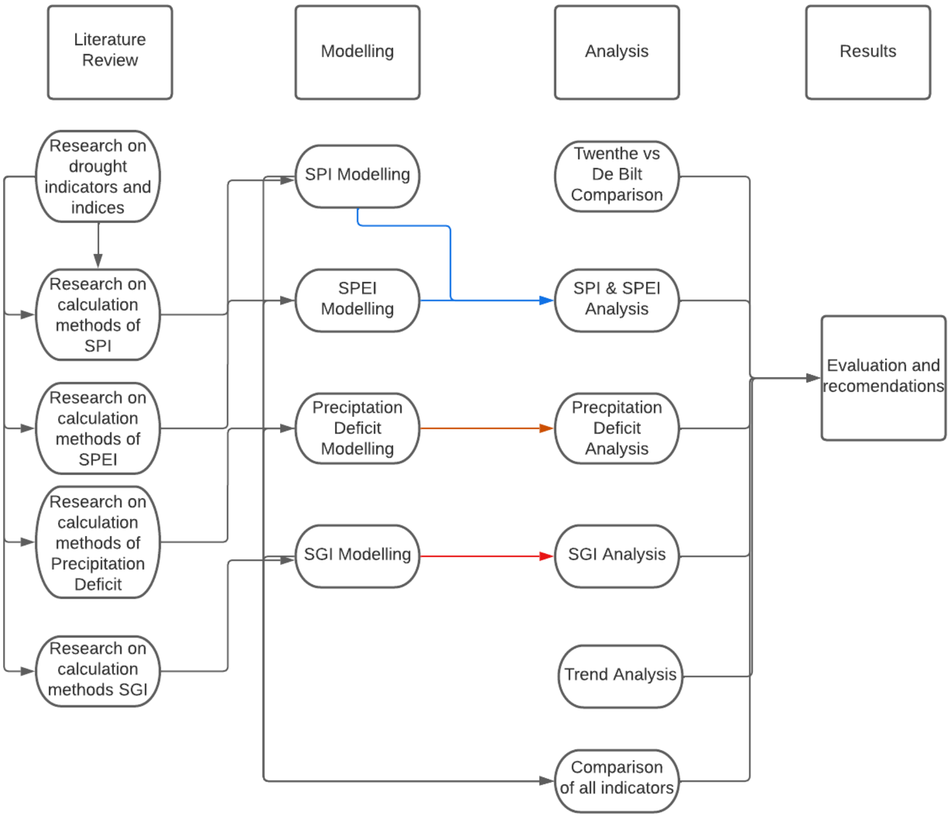

Figure 4: Research Model

4. Methodology

Once it has been known the indicators that the Netherlands uses to predict and track its droughts, further analysis and evaluation of their performances have been developed. For the development of this analysis, different python models have been developed. First, individual models for each indicator have been built. Then, once it has been possible to guarantee the reliability of each model, their corresponding analysis has been performed.

4.1 Calculation methods

The Python models developed for calculating these indicators are composed of three input parameters: precipitation, reference evapotranspiration and groundwater levels.

The data availability differs depending on the meteorological station used to develop the analysis. For the development of this assignment, two meteorological stations have been used. The first meteorological station is De Bilt, and the second is Twenthe.

Large amounts of data availability are necessary to implement these drought indicators successfully. The Netherlands started to record precipitation data in De Bilt in 1906, allowing it to have over 100 years of data. The station in Twente started to record precipitation data in 1974, allowing it to have over 40 years of data. Due to the large data availability in both stations, it is now possible to calculate, calibrate or validate different drought-predicting models.

The Meteorological stations also gather reference evapotranspiration data. Reference evapotranspiration in the Netherlands is calculated through the Makkink Method. The Makkink method requires mean air temperature and incoming shortwave radiation (Habimana, 2020) observed in the required location, as shown in Eq. (1)

$$ET_o = 0.65 \left(\frac{\Delta}{(\Delta + \gamma)L_v}\right) R_s \tag{1}$$

where, $ET_{o,i}$ stands for reference evapotranspiration, Δ stands for slope vapour pressure curve, γ stands for psychrometric constant, L_v stands for latent heat of vaporisation and R_s is the daily incoming solar radiation.

Groundwater levels are recorded in various locations in the Netherlands. Such information is recorded through manual and automatic measurements. For example, the Netherlands recorded groundwater levels in Enschede in 1987 and automatic measurements in 2005. The current calculations are based on combining both sets of data.

This information developed the first four python models that calculated the Precipitation Deficit, the SPI, the SPEI, and the SGI. The following section explains the different calculation methods used for each indicator.

4.1.1 Precipitation Deficit

The precipitation deficit, is established as the cumulative reference evapotranspiration minus the precipitation (Zamani et al., 2015). As seen in Eq. (2)

$$PD = ET_o - P \tag{2}$$

Where P stands for precipitation of one specific day, and ET_o stands for reference evapotranspiration of that specific day.

This calculation is done with data between April 1st and September 30th and set to 0 every time the cumulative precipitation deficit is lower than 0 (*Select a time series,* 2023).

Figure 5 shows the different precipitation deficits calculated with data from Twenthe Meteorological Station, from 1987 (the first year they recorded reference evapotranspiration data), until 2022. The information provided on the Y – axis indicates the cumulative precipitation deficit, and the information provided on the X – axis shows the years to which these results belong. Such a graph allows us to see that in the most recent years, Twenthe has had a significant precipitation deficit.

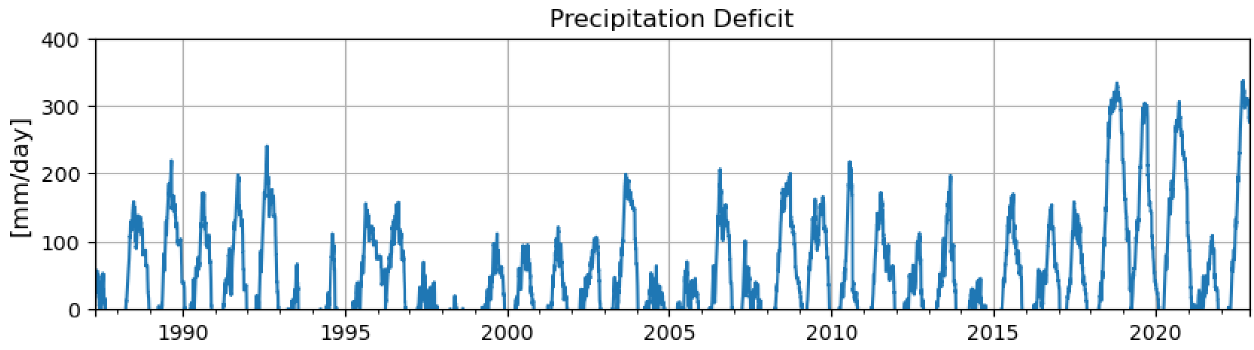

Figure 5: Precipitation Deficit Twente 1987 to 2022

Figure 6 shows the cumulative precipitation deficit in Twenthe from the 1st of April (red vertical line) until the 30th of September (green vertical line) during 2018, 2019, 2020, and 2022. The information on the X – axis represents the month of the year, and the information on the Y – axis, represents the deficit each has had.

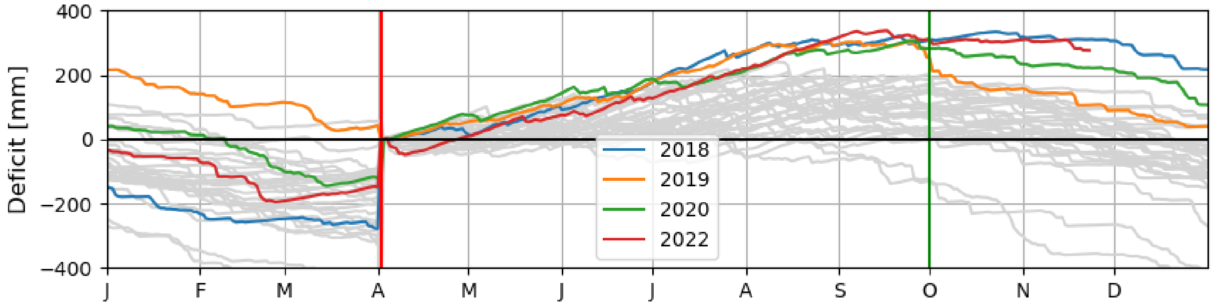

Figure 6: Precipitation Deficit of 2018, 2019, 2020 and 2022 of station Twenthe

4.1.2 SPI (Standard Precipitation Index)

The SPI (Standard Precipitation Index) is a drought indicator based on the accumulated precipitation of a specific period. Such accumulation is then compared with the long-term average precipitation of that period. To standardize these results, they are then divided by the standard deviation of the precipitation for that period (Climate Data Guide 2022). As seen in Eq. (3).

$$SPI = \frac{P - P^*}{\sigma_P} \tag{3}$$

where P stands for precipitation, P^* is the mean precipitation, and σ_P is the standard deviation of the precipitation.

As mentioned above, theoretical reports indicate that applying the normal distribution formula is necessary for calculating SPI. However, since precipitation values cannot be negative, it has been determined that the data will not fit a normal distribution. For this reason, it was decided that it would be necessary first to look at which distribution the data would fit and then determine the best calculation method for SPI.

Figure 7 is a fitted histogram and distribution of the precipitation data. As can be observed, Figure 7 is right skewed, indicating that the precipitation data does not fit a normal distribution, but instead, it fits a gamma distribution.

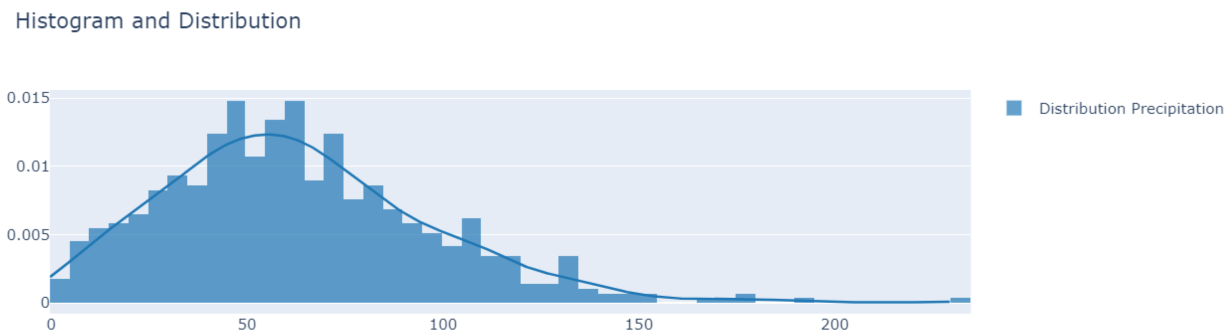

Figure 7: Precipitation data distribution

For this reason, the SPI was first calculated through the cumulative gamma distribution formula (*Gamma Distribution* 2022). Seen in Eq. (4) and Eq. (5).

$$F(x) = \frac{\Gamma_x(\gamma)}{\Gamma(\gamma)}$$

(4)

Where,

$$x \geq 0;\ \gamma > 0\ ()$$

(5)

where, γ is the shape parameter, β is the scale and Γ is calculated through Eq. (6).

$$\Gamma(a) = \int_0^\infty t^{a-1} e^{(-t)} dt\ ()$$

(6)

Once the cumulative gamma distribution was calculated, it was necessary to normalize the result by applying an inverse cumulative distribution function (*Gamma Distribution* 2022). Seen in Eq. (7).

$$x = G(\alpha) = G(F(x))$$

(7)

Where, $G(\alpha)$ is the normal percent point function, that is replaced by the percent point function of the gamma distribution.

Figure 8 shows the SPI results from Twenthe between 1974 and 2022. An upbeat (blue section of the graph) SPI indicates that a specific period has been wet, and a negative value (red section of the graph) indicates that the overall period has been drier than usual (Daniels, 2021).

Three different types of SPI were calculated. SPI – 3, SPI – 6, and SPI – 12. Each “SPI-” represents a different time scale. To represent such values, an overall time scale is used. For example, this time scale can be defined as “SPI-12”. This indicates that the provided data, or graph, represents the SPI results from the last 12 months (Daniels, 2021). The division of these results can help to determine if there is a meteorological drought, a hydrological drought, or a multi-year drought. Meteorological drought is defined when the SPI results are negative for less than six months. Hydrological drought is determined when the abovementioned indicators are negative for 12 months. Moreover, a multi-year deficit is caused when the needles are negative for more than 12 months (Daniels, 2021).

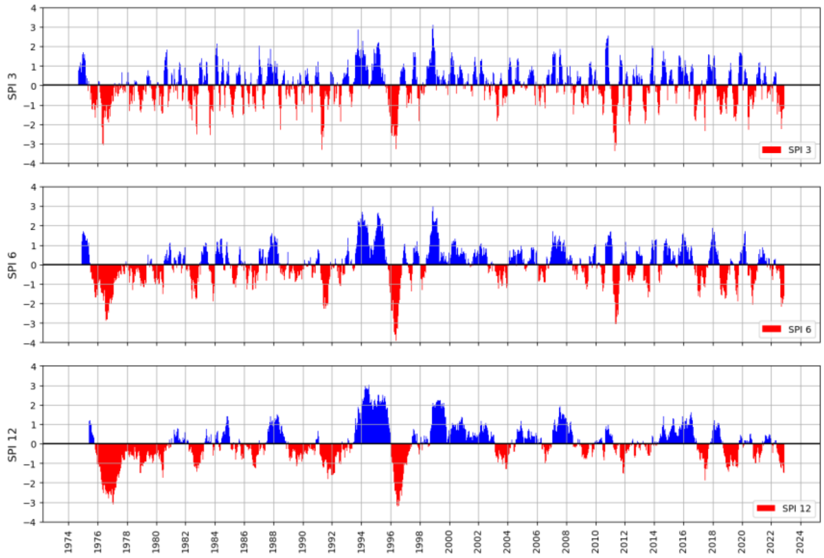

Figure 8: SPI results of region of Twente between 1974 and 2022 using a window of 3, 6 and 12 months

4.1.3 SPEI (Standardized Precipitation and Evapotranspiration Index)

The SPEI (Standardized Precipitation and Evapotranspiration Index) is an indicator that bases its calculation on precipitation and references evapotranspiration data. The first step towards calculating this indicator is determining the climatic water valance (D_i). The climatic water balance is the difference between precipitation and reference evapotranspiration (Vicente-Serrano et al., 2010). See Eq. (8).

$$D_i = P_i - ET_{o,i} \tag{8}$$

where P_i is the precipitation of the month "i", $ET_{o,i}$ is the reference evapotranspiration of the month "i". As mentioned above, the reference evapotranspiration has been calculated using the Makkink Method.

For calculating the SPEI, the climatic water balance has been fitted into a distribution. Figure 9 shows the fitted histogram and its corresponding distribution. This distribution fits a log-logic distribution (Vicente-Serrano et al., 2010).

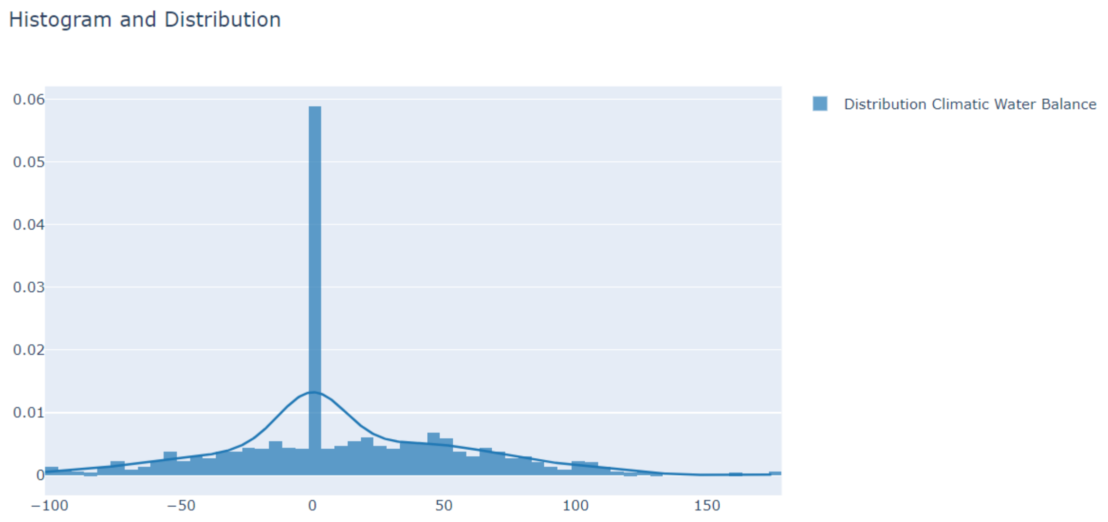

Figure 9: Climatic water balance Histogram

For this reason, the SPEI, was first calculated by using the probability density function of D according to the Log-logistic distribution (Vicente-Serrano et al., 2010). Seen Eq. (9).

$$F(x) = \left[1 + \left(\frac{\alpha}{x - \gamma}\right)^{\beta}\right]^{-1} \qquad (9)$$

where, α stands for scale, β stands for the shape, γ stands for the shape of the function and x stands for the origin parameters.

Once these values where obtained, they required to be standardized, so the SPEI could be obtained (Vicente-Serrano et al., 2010). The standardization process was done through Eq. (10) and Eq. (11).

$$SPEI = W - \frac{C_0 + C_1 W + C_2 W^2}{1 + d_1 W + d_2 W^2 + d_3 W^3} \qquad (10)$$

where

$$W = -2\ln(P)\, for\ P \leq 0.5 \qquad (11)$$

and P is the probability of exceeding a determined D value, P= 1- F(x). If P>0.5, then P is replaced by 1-P, and resultant sign of SPEI is reversed. The constants are $C_0 = 2.515517$, $C_1 = 0.802853$, $C_2 = 0.010328$, $d_1 = 1.432788$, $d_2 = 0.189269$, $d_3 = 0.001308$.

After trying to gather the SPEI results with the Log-logistic distribution, did not provide accurate results. For this reason, it was required to modify the code in python, and change the Log-logistic distribution into a gamma distribution.

Three different types of SPEI were calculated. SPEI – 3, SPEI – 6, and SPEI – 12. Each "SPEI-" represents a different time scale. To represent such values, an overall time scale is used. For example, this time scale can be defined as

"SPEI-12". This indicates that the provided data, or graph, represents the SPEI results from the last 12 months (Daniels, 2021).

Figure 10 shows the SPEI results from the Twente region between 1987 and 2022. A positive (blue section of the graph) SPEI indicates that a specific period has been wetter than expected, and a negative value (red section of the graph) indicates that the overall period has been drier than usual (Daniels, 2021). The SPEI has also been calculated for the three months, six-month, and twelve-month time scales.

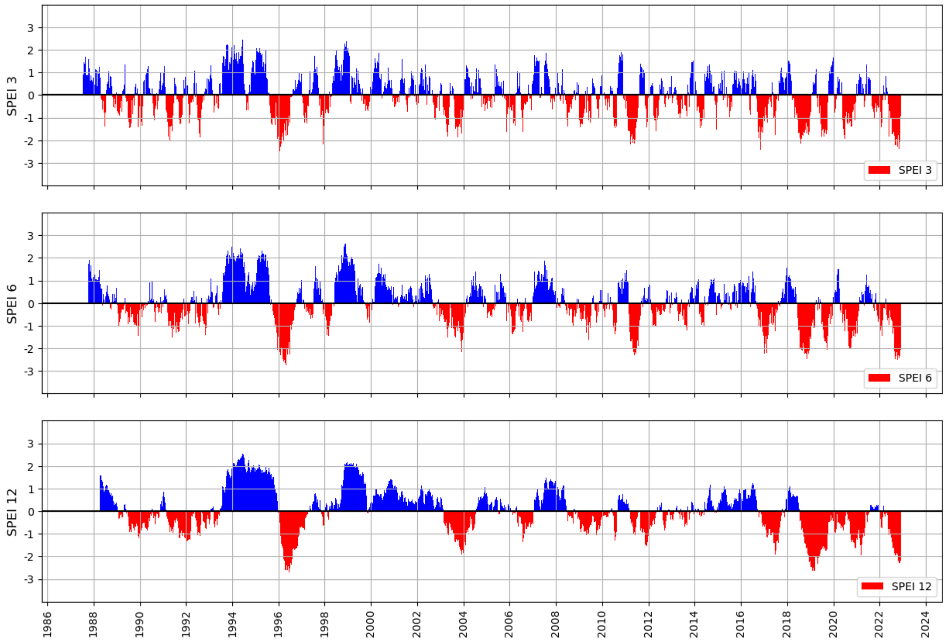

Figure 10: SPEI results of Twente between 1974 and 2022 using a window of 3, 6 and 12 months

4.1.4 SGI (Standard Groundwater Index)

The SGI (Standard Groundwater Index) is a drought indicator that utilizes groundwater levels and analyses the fluctuation of these levels to determine if a critical area is undergoing a drought. The SGI is equivalent to SPI used to evaluate precipitation shortages (Kubicz, 2019).

The recorded groundwater levels are later compared with the long–term average groundwater levels of that specific period. These results need to be standardized. To achieve this goal, the gathered results are then divided by the standard deviation of the groundwater level for that specific period (Kubicz, 2019). As seen in Eq. (12).

$$SGI = \frac{G - G^*}{\sigma_G} \tag{12}$$

where G stands for groundwater levels, G^* is the mean groundwater levels, and σ_G is the standard deviation of the groundwater levels.

To ensure that the recorded data, fit a normal distribution, the recorded groundwater levels have been fitted into a histogram. Figure 11 shows the results of the fitted histogram. As can be observed in the Figure 11, the gathered data does not fit a normal distribution.

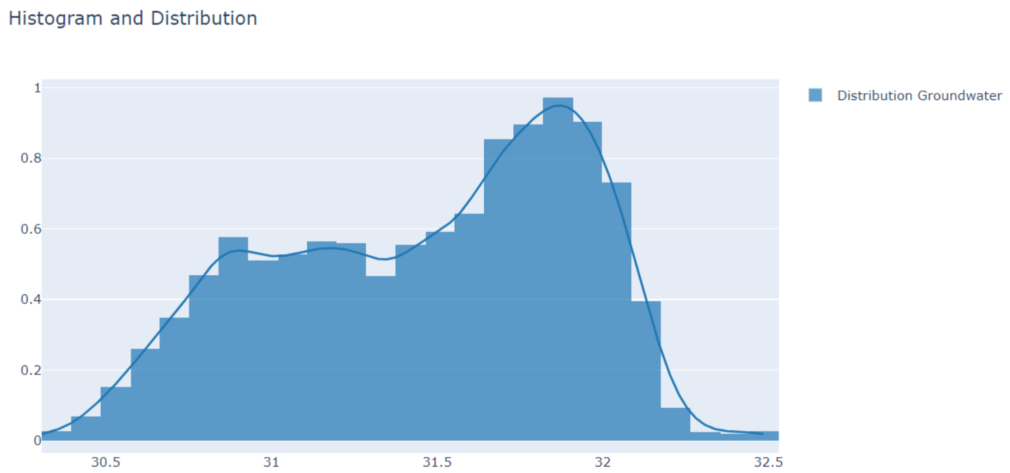

Figure 11: Groundwater levels histogram

The calculation of the SGI, is based on using nonparametric transformation, instead of using distribution fitting (Babre et al., 2022). In order to march normally distribution data strings, a parameter logarithmic function was used (Kubicz, 2019). As seen in Eq. (13) (Learncuriously, 2018).

$$f(X) = \log(X_i) \tag{13}$$

where X_i stands for the groundwater levels, and $f(X)$ is the standardized groundwater level. Once this formula was applied, it was possible to apply the previous formula of the SGI, that stands as the following Eq. (14) (Kubicz, 2019).

$$SGI = \frac{f(X) - f(X)^*}{\sigma_{f(X)}} \tag{14}$$

where, $f(X)$ is the standardized groundwater level, $f(X)^*$ average value of the standardized groundwater level and $\sigma_{f(X)}$ is the standard deviation of the standardized groundwater levels.

Through the application of these equations, the SGI results shown in Figure 12, have been gathered. Figure 12 shows the SGI results from the Twente region from 1987 – 2022. A positive (blue section of the graph) SGI indicates that a specific period has been wet, and a negative value (red section of the graph) indicates that the overall period has been drier than usual.

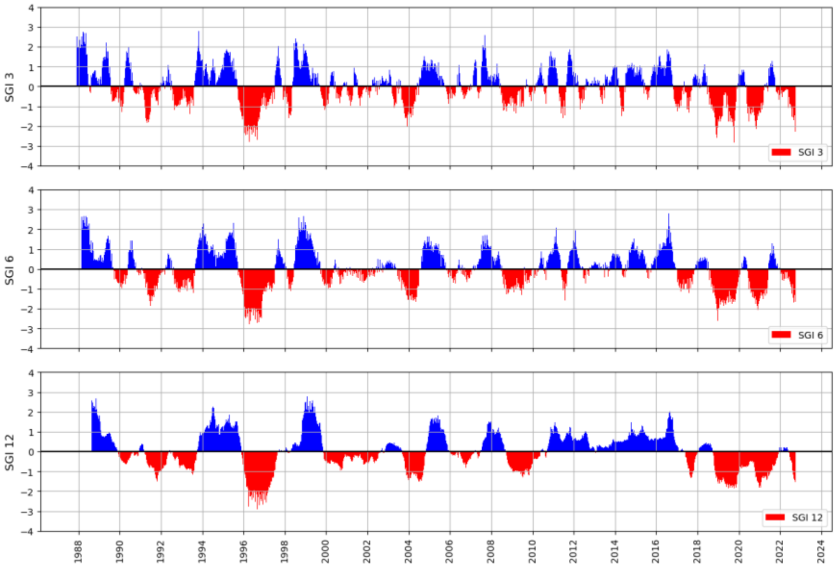

Figure 12: SGI results of Enschede 1987 – 2022 using a window of 3, 6 and 12 months

5. Analysis

5.1 Twente and De Bilt Comparison

Due to climate change, over the last decade, the Netherlands has experience extreme weather events such as, extreme droughts and heave precipitation (van Tilburg & Hudson, 2022). Due to the elevation change, freshwater availability in the Netherlands depends on its location. Figure 13 is an elevation map of the Netherlands.

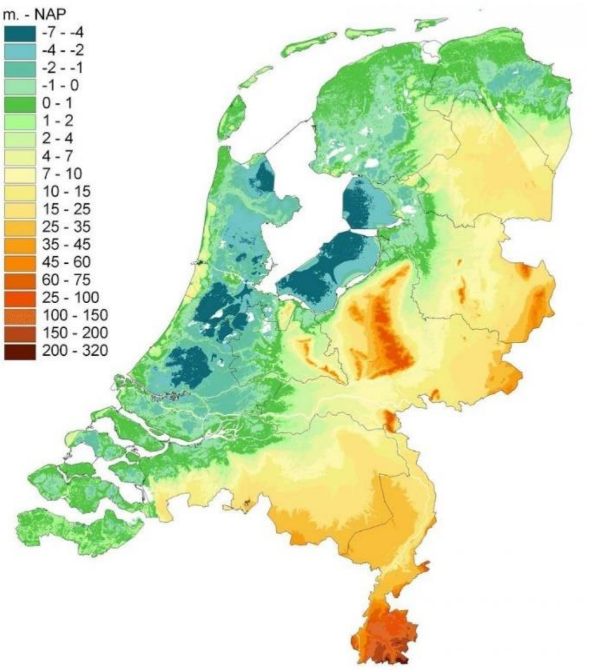

Figure 13: Elevation map of the Netherlands (Blom-Zandstra et al., 2009)

As observed, the eastern part of the Netherlands is higher than other parts. Research has shown that the parts of the Netherlands with a higher elevation have a higher struggle battling droughts (Wanders, 2020). To better understand the droughts in the Netherlands, the precipitation deficit of two meteorological stations has been compared. The first meteorological station is De Bilt, and the second is Twenthe.

Figure 14 shows the precipitation deficit of Twenthe and de Bilt, calculated from April 1st until September 30th. It can be observed that the precipitation deficit registered by De Bilt some years, was higher than the precipitation deficit registered by Twenthe. Nevertheless, the precipitation deficit registered by

Twenthe in 2018, 2019, 2020, and 2022 is higher than the one registered in De Bilt.

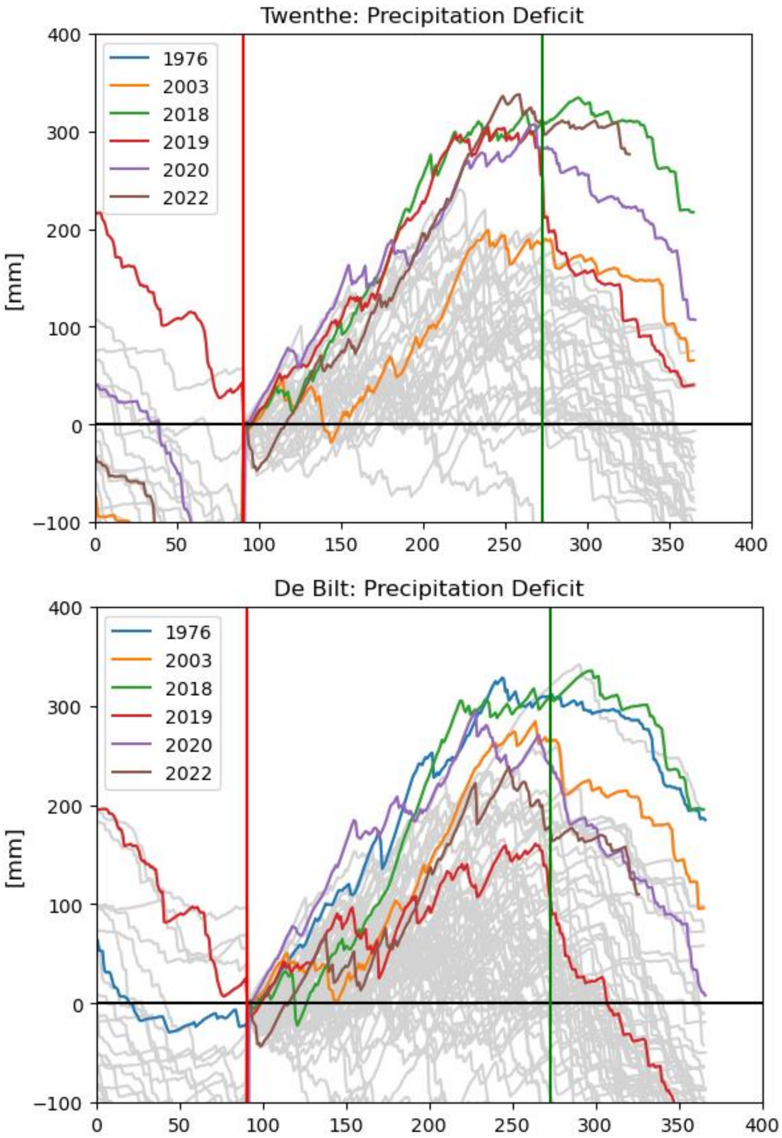

Figure 14: Precipitation deficit in Twente (Top) and precipitation deficit of De Bilt (bottom)

Due to the significant change in results, precipitation, reference evapotranspiration, and temperature comparison between the two stations have been developed. The overall purpose of analyzing this comparison is to understand the differences in the results.

For the development of this analysis, the data has been represented through a boxplot graph. A boxplot graph visually shows the distribution of numerical data and the skewness by displaying the data quartiles and averages. Figure 15 shows the different sections of the boxplot.

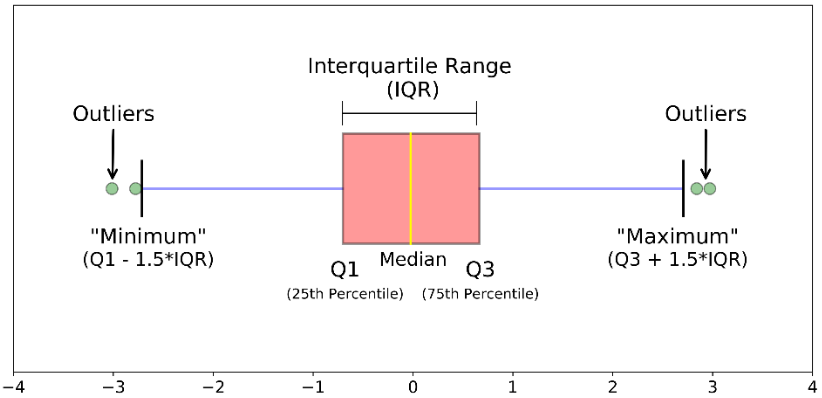

Figure 15: Boxplot representation (Agarwal, 2019)

- Minimum: lower score
- Q1 (lower quartile): 25% of the data falls below the lower quartile.
- Median: the median marks the data's midpoint.
- Q3 (upper quartile): 75% of the scores fall below the upper quartile value.
- Maximum: highest score.
- IQR (interquartile range): is the middle, showing 50% of the boxplots (Mcleod, 2019).

Figure 16 compares the monthly temperatures registered in De Bilt and the monthly temperature registered in Twenthe. The information provided in the X – axis represents the month of the year, and the information provided in the Y – axis, represents temperature values that range from -5 up to 20.

The temperatures registered during the first months of the year (January – March) indicate that the temperatures registered in Twenthe are lower than the minimum temperature registered in De Bilt. At the same time, the median of these three months registered in Twenthe is also lower than the median registered in De Bilt. The temperatures registered in the following three months (April – June) indicate that during these three months, the data recorded in Twenthe, the range of maximum and minimum temperatures, is broader compared to the data recorded in De Bilt. Nonetheless, the temperatures registered in the six following months (July – December) show similar maximum, minimum, and median values. For this reason, it can be determined that the recorded temperature data is similar in both stations.

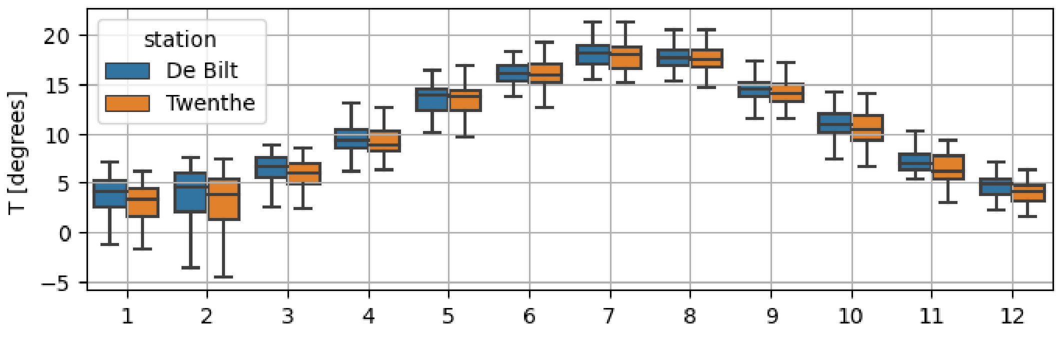

Figure 16: Monthly temperature from Twenthe and De Bilt

Figure 17 compares the monthly reference evapotranspiration registered in the station in De Bilt and Twenthe. The information displayed in the X–axis represents each month of the year, and the information displayed on the Y – axis, is a range of reference evapotranspiration values that go from 0 mm/month up to 125 mm/month.

The reference evapotranspiration registered during the first two months indicates that the data in both stations are similar. Nevertheless, the reference evapotranspiration registered in March in the station of De Bilt has a higher maximum value and a lower minimum value compared to the data recorded by the Twenthe station. Nonetheless, the data gathered from the following months (April – December) indicate that the data gathered by the Twenthe station had higher maximums and lower minimums compared with the data gathered by the station De Bilt. Notwithstanding, the median value of both stations was similar. With this information, it can be presumed that the Twente is subjected to higher reference evapotranspiration.

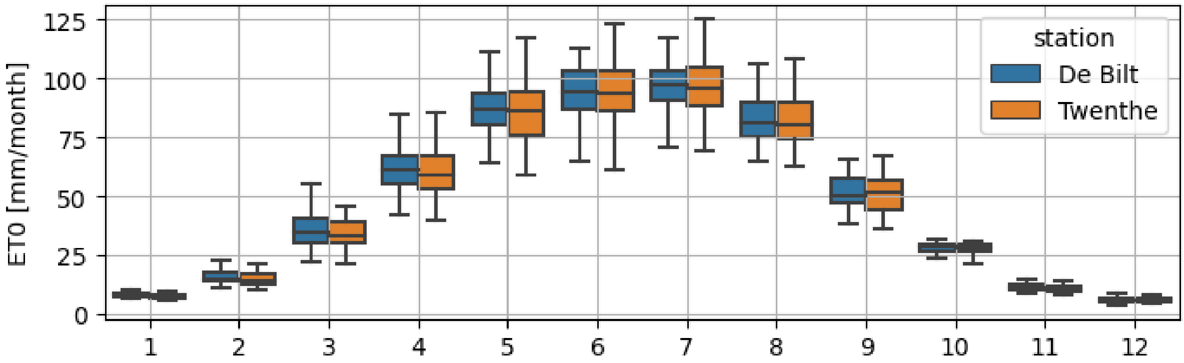

Figure 17: Monthly reference evapotranspiration of Twenthe and De Bilt

Figure 18 compares the monthly precipitation registered in station de Bilt and Twenthe. The information displayed in the X–axis represents each month of the year. The information displayed in the Y – axis is a range of precipitation values from 0 mm/month to higher than 150 mm/month. The precipitation recollected from the two stations displays that De Bilt registered higher precipitation maximums compared to the data registered in Twente.

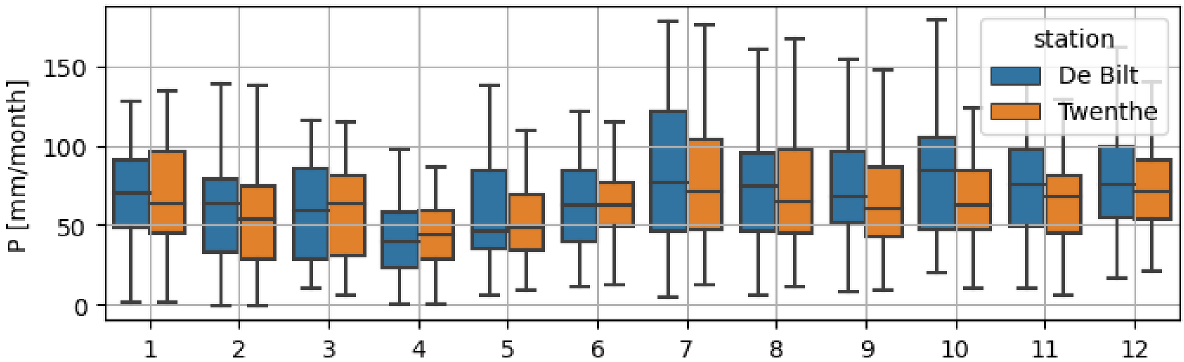

Figure 18: Monthly precipitation of De Bilt and Twenthe

5.2 SPI & SPEI Analysis

As of 2021, the Netherlands has been using the SPEI and SPI indicators drought indicators. However, the results of these indicators vary depending on the location from which the data is recollected. In the Netherlands, different stations record SPEI and SPI information.

Due to the location change, the results gathered by each station might differ. Therefore, to better understand how the drought varies, the SPEI and SPI results of the meteorological station in the Twente region and the results of the meteorological station in De Bilt have been compared.

De Bilt station started recording precipitation data in 1906 and reference evapotranspiration data in 1957. The fact that data started to be recorded early on has led to a large amount of data availability, allowing the use of new drought indicators, such as SPI and SPEI, since they require at least 30 years' worth of data to provide reliable results. Twente's meteorological station started recording precipitation data in 1974 and reference evapotranspiration data in 1987. They provide input information for calculating the SPEI and SPI in the Twente region.

The results provided by SPI and SPEI can vary. Table 2 shows the meaning of different SPI and SPEI results.

Table 2: SPI and SPEI results table (Long et al., 2018)

SPEI and SPI	Meaning
≤ -2.0	Extreme drought
-1.50 to -1.99	Severe drought
-1.0 to -1.49	Moderate drought
-0.5 to -0.99	Mild drought
-0.49 to 0.49	Normal
0.5 to 0.99	Mild wet
1.0 to 1.49	Moderate wet
1.50 to 1.99	Severe wet
≥ 2.0	Extreme wet

As stated in before, the SPI has been calculated by normalizing a gamma distribution. To compare the results provided by the stations, the SPI has been calculated for the 1974 – 2022 period.

Figure 19 shows the calculated SPI for De Bilt. Three different types of SPI were calculated. SPI-3, SPI-6 and SPI-12.

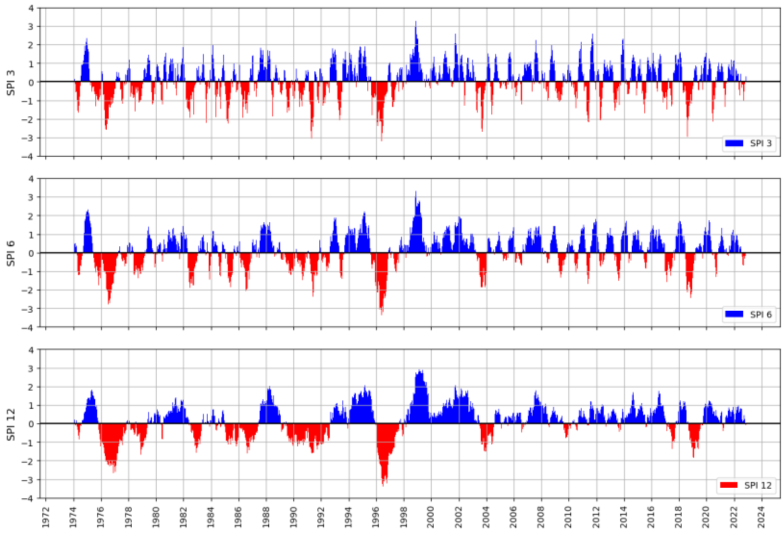

Figure 19: SPI De Bilt

Figure 20 shows the calculated SPEI for De Bilt. Three different types of SPEI were calculated. SPEI-3, SPEI-6 and SPEI-12.

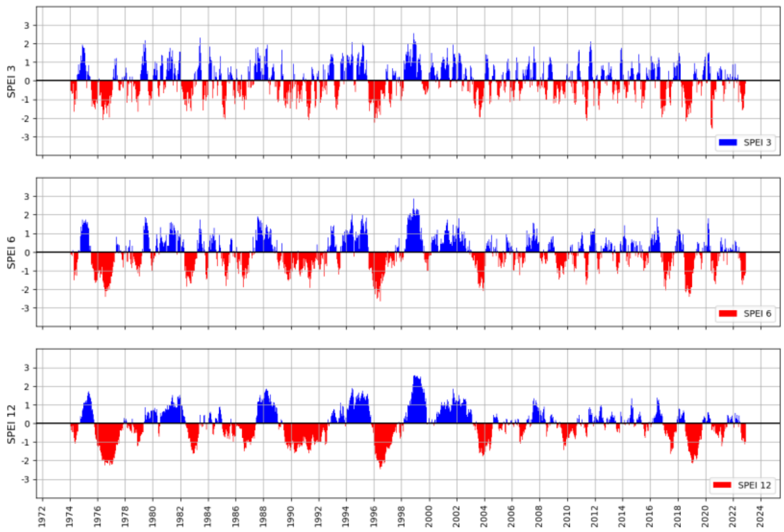

Figure 20: SPEI De Bilt

From Figure 19 and Figure 20, it can be seen that De Bilt suffered of three extreme droughts.

- The first extreme drought was registered in 1976. These droughts were followed by a short amount of precipitation, conditioning the area's recovery. For this reason, the drought was prolonged until 1978.
- The second extreme drought originated in 1996. This drought registered an SPEI - 12 value of ≤ -2.0 and an SPI – 12 value of ≤ -2.00. The drought of 1996 was later followed by large amounts of precipitation, allowing the area to recover.
- The third extreme drought originated in 2018, reaching SPEI – 12 and SPI – 12 values of ≤ -2.0. The aftermath of this drought was carried out until the end of 2019, when the area recovered due to precipitation.

However, the area has been experiencing severe/moderate droughts regardless of the precipitation.

Figure 21 is the graphical representation of the SPI of the Twenthe meteorological station. Three different “SPI-” where calculated. SPI – 3, SPI – 6 and SPI – 12.

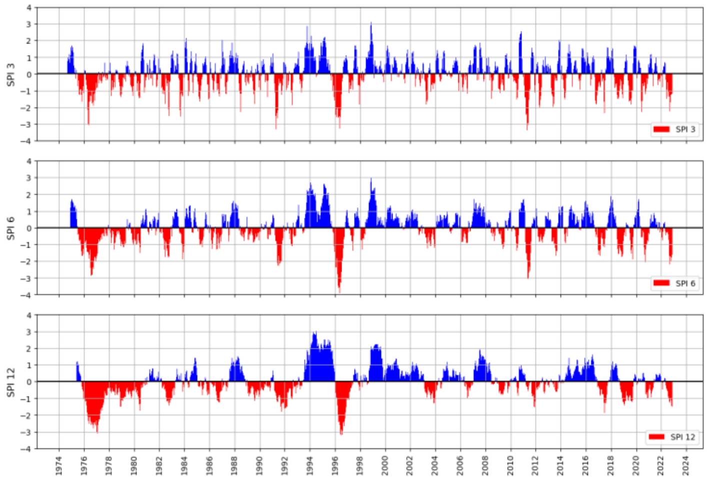

Figure 21: SPI Twenthe

Figure 22 is the graphical representation of the SPEI of the Twenthe meteorological station. Three different “SPEI-” where calculated. SPEI – 3, SPEI – 6 and SPEI – 12.

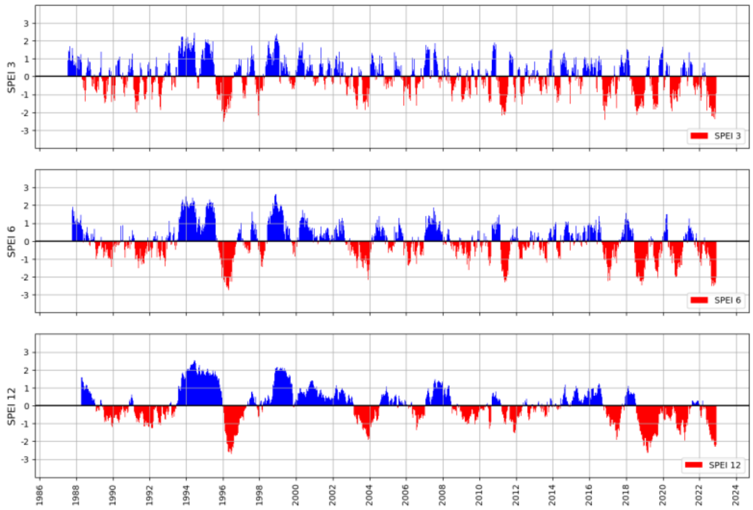

Figure 22: SPEI Twenthe

From Figure 22 and Figure 21, it can be observed that Twente had multiple extreme drought events.

- The first extreme drought was registered in 1976. This drought was later followed by very short amounts of precipitation, which prolonged the drought up to 1981. This drought had a maximum SPI – 12 of -3.0.
- The second extreme drought registered was in 1996. This drought reached a maximum SPI – 12 of -3.0 and SPEI – 12 of -2.5. This event was later followed by a large amount of precipitation, allowing them to

recover. Until 2003, this area had an SPI – 12 and SPEI – 12 over 0, indicating regular or wet episodes.

- The third extreme drought was registered between 2003 and 2004. This drought event reached an SPEI – 12 of -2.0. This event was later followed by abundant precipitation allowing the area to recover until 2008 when the area experienced moderate droughts over five years.
- The fourth extreme drought was registered from 2018 until 2020. This drought reached SPEI – 12 values of -2.5 and SPI – 12 values of -1.80. This event was later followed by precipitation in 2021.
- The fifth extreme drought was registered in 2022. This drought reached an SPEI – 12 of ≤ -2.00 and an SPI – 12 of -1.5. The Twente region is still in ongoing drought since the registered amount of precipitation is still low. Figure 23 shows the amount of precipitation registered in the Netherlands from the 1st to the 20th December. The region of Twente (inside the red circle) has registered low precipitation data.

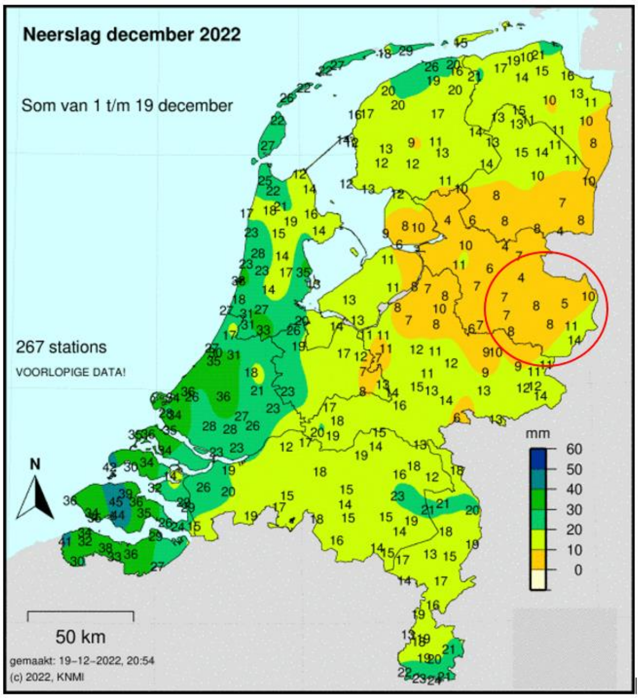

Figure 23: Precipitation data registered in the Netherlands (Droogtemonitor 2022)

By comparing the SPI results provided by Figure 19 and Figure 21, it has been observed that the drought in 1976 in Twenthe was more extreme and had a longer duration than the drought registered in De Bilt. On the other, the SPI results show that the drought in 2003 in De Bilt lasted longer than in Twente. Therefore, without taking into consideration the 2003 results, over the last past decade, Twenthe has registered more severe droughts than De Bilt. The SPI bases its calculation on precipitation data, and it can be assumed that the amount of precipitation registered in De Bilt is higher than that in Twenthe.

On the other hand, by comparing the SPEI results shown in Figure 20 and Figure 22, it can be concluded that the gathered results diverge from each other. As mentioned before, the input data required for calculating the SPEI are precipitation and reference evapotranspiration data. The Twenthe station started to record reference evapotranspiration data in 1987, which allowed the analysis to start in 1987.

Since the Netherlands experienced extreme drought in 1976, it has been considered that it would be interesting to see how drought indicators other than the precipitation deficit predicted the severity of this drought. For this reason, the SPEI of De Bilt has been calculated from 1974 until 2022.However, there has been a comparison of the information provided by the stations at De Bilt and Twenthe from 1987 to 2022. As shown in Figure 20 and Figure 22, the SPEI results calculated with data from Twenthe correlate with more extreme and prolonged droughts compared to the SPEI of De Bilt. During the 2018 – 2022 period, it can be observed that the SPEI – 12 results of Twenthe indicate that this area was experiencing a drought over a prolonged period. Such drought stopped in 2021 but reappeared in 2022. On the other hand, the SPEI – 12 results from De Bilt over the 2018 – 2022 period show an intermittent combination of dry and wet years.

The fluctuations in precipitation in each station record cause the disparity in these graphs. Although, as seen above, the temperature and reference evapotranspiration data do not diverge from De Bilt and Twenthe, the recorded precipitation data is significantly different.

5.3 SGI Analysis

The SGI (Standard Groundwater Index) uses the registered groundwater level to determine if a specific area could or is undergoing a wet or dry period. Therefore, the results gathered by this indicator can deviate depending on the area where the data is recollected. To understand the deviation from the results, the SGI of the groundwater levels registered in Enschede and Tubbergen has been compared. The distance between these two locations is 27.8 Km, both located in the province of Overijssel.

The SGI results can be classified into different dry or wet period categories. Table 3 shows the possible results and their corresponding explanation.

Table 3: SGI result table (Bloomfield & Marchant, 2013)

SGI	Meaning
≤ -2.0	Extreme drought
-1.50 to -1.99	Severe drought
-1.0 to -1.49	Moderate drought
-0.5 to -0.99	Mild drought
-0.49 to 0.49	Normal
0.5 to 0.99	Mild wet
1.0 to 1.49	Moderate wet
1.50 to 1.99	Severe wet
≥ 2.0	Extreme wet

Figure 24, shows the SGI results gathered from groundwater level data recollected in Enschede. These SGI results, from the recollected data in Enschede showed that Enschede experienced different severe droughts through the years. The three severest droughts registered that happened between 1988 – 2022, have been explained.

- The first severe drought registered occurred between 1996 – 1997, with an SGI result lower than – 2.0. This results was later followed by extreme wet periods that started in 1998 – 2000 that reached a > 2.0 SGI result.
- The second severe drought registered occurred between 2018 – 2020, with an SGI results that fluctuated between -0.5 and -2.0. This extended drought was later followed by a normal period of groundwater levels.
- The third severe drought was registered during 2020, the SGI result registered was of -1.5.

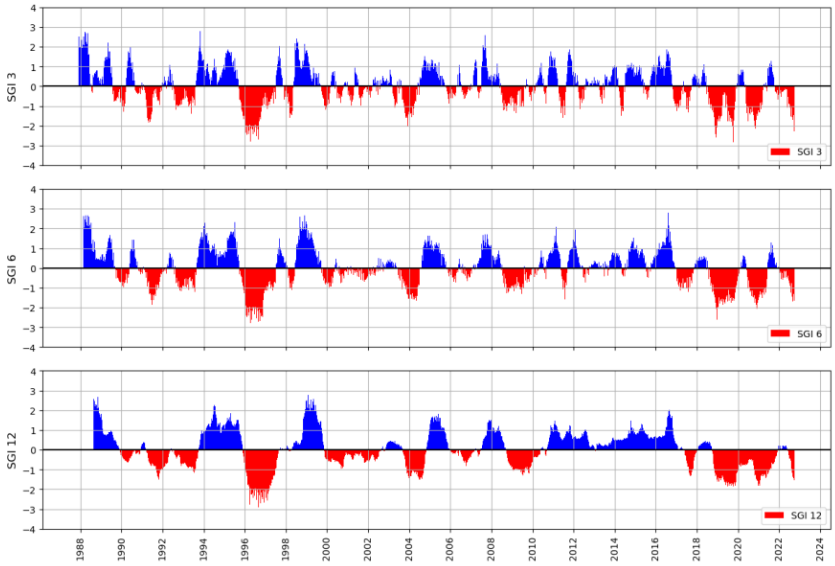

Figure 24: SGI results from groundwater levels in Enschede

Figure 25, shows the SGI results from the groundwater levels in Tubbergen. These SGI results, from the recollected data in Tubbergen showed that Tubbergen experienced different severe droughts through the years. The three severest droughts registered that happened between 1988 – 2022, have been explained.

- The first severe drought registered was between 1990 – 1993. The SGI registered during this period of time fluctuated between -0.5 and -2.5. After 1993, wet periods where registered.
- The second severe drought was registered between 1996 – 1998. The SGI registered during this period fluctuated between -2.0 and -1.0. After this prolonged drought, Tubbergen experienced a wet period but was shortly followed by a moderate drought.
- The third severe drought was registered between 2019 - 2021. The SGI results registered during this time fluctuated between -1.0 and -2.5. This prolonged drought was later followed by a short wet period, that was followed by another severed drought in 2022, with an SGI of -2.5.

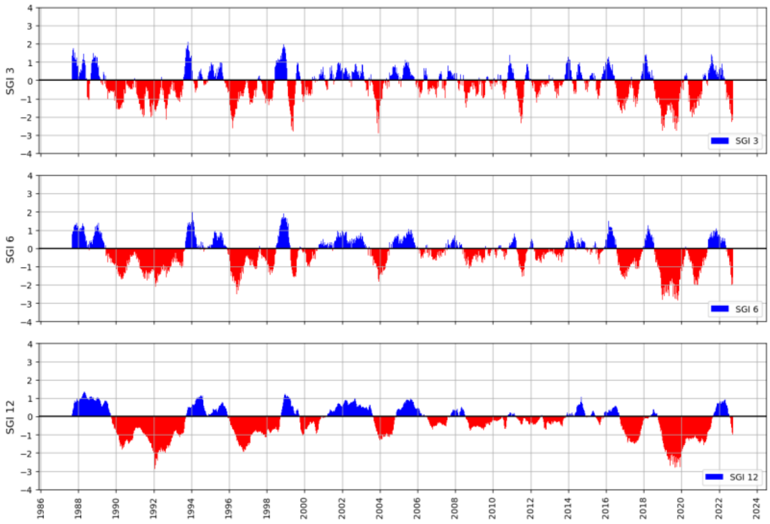

Figure 25: SGI results from groundwater levels in Tubbergen

By comparing the results from Figure 25 and Figure 24, it has been possible to see the difference between the SGI results from Enschede and from Tubbergen. As it can be observed, the SGI results registered in Tubbergen show more severe and more frequent droughts, indicating that the area of Tubbergen is dryer than the area of Enschede. Since both locations belong to the Twente area, it can be concluded that the droughts affecting the east of the Netherlands can be more extreme in some areas, regarding of the proximity of different cities.

5.4 Precipitation Deficit Analysis

As mentioned before, the Netherlands uses the precipitation deficit as one of its drought indicators. The input data for calculating this indicator is the daily precipitation recorded from April 1st until September 30th. The reasoning behind only using this period of time was that during October – March, the Netherlands would register a large amount of precipitation, and a short amount of reference evapotranspiration, due to the low temperatures and the reduced hours of sunlight.

Figure 26 shows the precipitation deficit calculated for the years 2003, 2018, 2019, 2020, and 2022, with data gathered from April 1st until September 30th. The precipitation deficit in the Netherlands is calculated as the cumulative difference between the reference evapotranspiration and the precipitation. The cumulative difference is set to 0 when it becomes negative. The red line in the graph represents April 1st, and the green line represents September 30th.

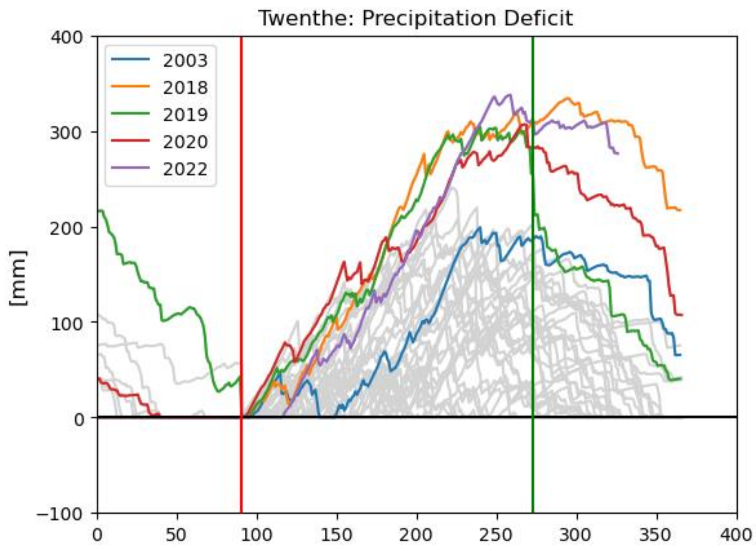

Figure 26: Precipitation Deficit from April 1st until September 30th

To see if the increase in temperature and evapotranspiration is leading to droughts developing earlier, the precipitation deficit from March 1st up to September 30th was calculated. These results are shown in Figure 27.

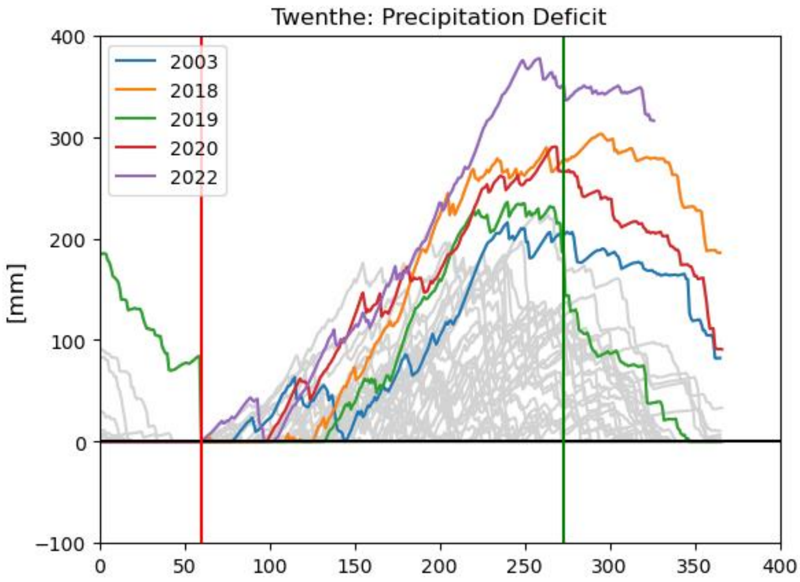

Figure 27: Precipitation Deficit from March 1st until September 30th

By comparing Figure 27 and Figure 26, it can be seen that the precipitation deficit changes. The precipitation deficit in 2022, 2018, and 2020 increases, the precipitation deficit in 2019 decreases, and the precipitation deficit in 2003 stays quite similar.

Such a change in the results is due to the data recorded during March. In Figure 27, it can be seen that 2022, 2018, and 2020 started to have a precipitation deficit before April, indicating that March was very dry, conditioning the results. Nevertheless, it can also be observed that 2003 and 2019 do not have a deficit at the beginning of March; instead, they show the first signs of a precipitation deficit after April 1st. Indicating that both years had very wet March, conditioning the calculation of the precipitation deficit.

5.5 Trend Analysis

As observed prior, the region of Twente has been exposed to multiple droughts. Therefore, a trend analysis has been developed to assess if the experienced droughts have been the aftermath of a trend in the precipitation and the reference evapotranspiration data.

The development of this analysis has been composed of determining the registered annual precipitation, reference evapotranspiration and temperature data of the meteorological station of Twenthe. Based on this information, it has then been possible to see if the data was undergoing a specific trend and determine the type of trend that has happened over the years. Finally, a linear regression line is plotted to determine the trend the data might have been experiencing.

Figure 28 shows the annual precipitation recorded each year. The plotted graph of the precipitation data allows us to observe the changes experienced over the amount of precipitation registered in Twenthe during the past years. It can be observed that during 1993 – 1994, the annual registered precipitation was over 1000 mm/year. Nevertheless, in 1995, due to a drought, the registered amount of precipitation decreased to 650 mm/year.

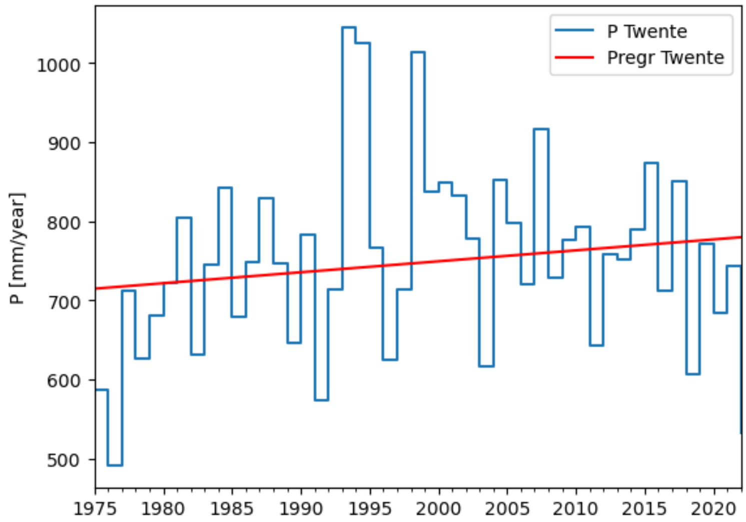

Figure 28: Trend precipitation data

Figure 29, shows the trend analysis developed for the reference evapotranspiration data gathered by the Twenthe meteorological station. This trend shows the registered annual reference evapotranspiration. As can be observed, a regression line has also been plotted. The slope of this regression line can be used to predict the future growth that the reference evapotranspiration can experience. As can be observed, the slope of the plotted regression is 3.4390. Therefore, in 10 years, the registered annual reference evapotranspiration will increase by 34.39 mm/year. This expected growth is 2.48 more than the registered growth expected for the precipitation data. Such a situation can lead to conclude, that due to such growth, during a more extended period, the registered reference evapotranspiration will be higher than the registered precipitation data, which can conclude in more extended and more severe droughts.

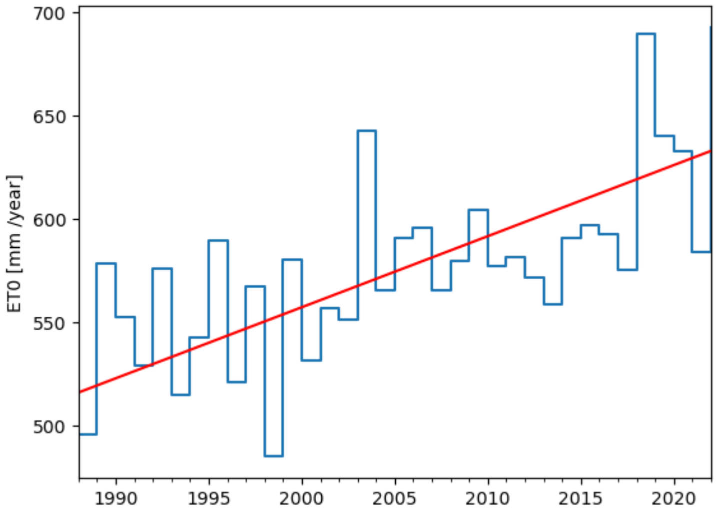

Figure 29: Trend reference evapotranspiration data

Figure 30, shows the trend and regression line developed with the mean annual temperature registered by the Twenthe meteorological station. The regression line, provides information on how the annual average temperature might increase through the years. The regression line has a slope of 0.0282. Due to such trend, it can be assumed that in 10 years, the average annual temperature will increase by 0.282 °C. On the other hand, it can also be observed that the registered annual mean temperature has started to increase through the years. In 1956, it registered a value of 7.8 degrees, and in 2022 it registered a value of 12.07 degrees, which is a 4.27 degrees difference in 66 years.

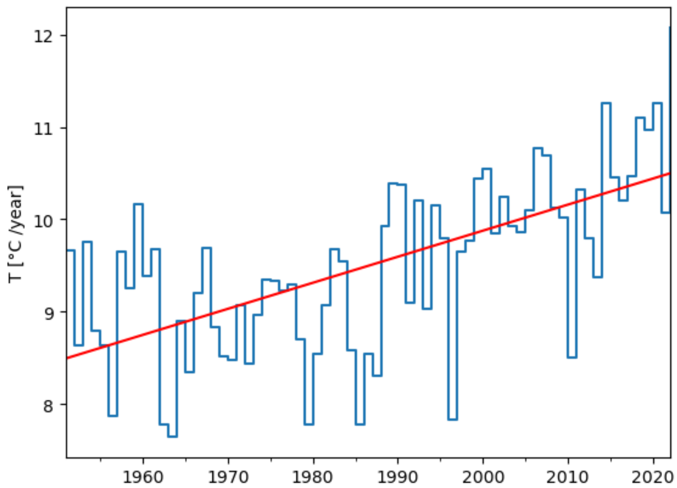

Figure 30: Trend of temperature data

The results from this analysis show that the east of the Netherlands will undergo warmer periods in the future. On the other hand, if the temperatures keep rising, the reference evapotranspiration will follow, compromising the amount of precipitation that will infiltrate to the ground. This situation can result in prolonged and more severe droughts.

6. Discussion

Due to the different results gathered during the analysis process, two main focus points have been further discussed. The first point has been the importance of using different drought indicators and the correlation that they present. The second point has been to analyze and determine if the precipitation deficit would require updating its calculation system.

6.1 Comparison of drought indicators

The use of different drought indicators requires the use of different input data. Each indicator's information portrays how dry and wet events affect freshwater resources. A comparison between the four indicators has been made.

For developing this comparison, the years 2003, 2018, 2019, 2020, and 2022 have been modeled. The information provided on the X – axis is the month of the year for which these results were recorded, and the information on the Y – axis can be the SGI, SPEI, SPI results or the calculated precipitation deficit.

During the precious analysis, the precipitation deficit of January – March was also available. Nevertheless, the calculations were restarted on April 1st. The SGI, SPI, and SPEI have been calculated for six months. By having a period of 6 months, the SPEI – 6, SGI – 6, and SPI – 6 during September indicates how dry or wet the period of April – September was (Klimaatdashboard nu ook voor Neerslag en droogte 2021).

Figure 31 shows a comparison between SPEI – 6, SPI – 6, SGI – 6, and the precipitation deficit registered by Twenthe. As can be observed, the types of droughts registered by each indicator can fluctuate. The drought registered by the SGI – 6 in 2018 reached extreme drought levels between November – December. Nevertheless, the SPEI – 6 started to register the initiation of a dry period during June that lasted until December, and the SPI – 6, started to register the beginning of a dry period in July. This dry period later evolves towards an extreme drought in November and carries until December. On the other hand, the precipitation deficit starts at the beginning of April, and lasts until September, registering its highest deficit at 300 mm.

Due to the different results provided by this comparison, it is observed that different indicators are necessary to determine the type of drought affecting different freshwater resources. By knowing the specific type of drought each indicator is undergoing, it is then possible to implement specific measures to reduce or prevent the negative impact of the drought.

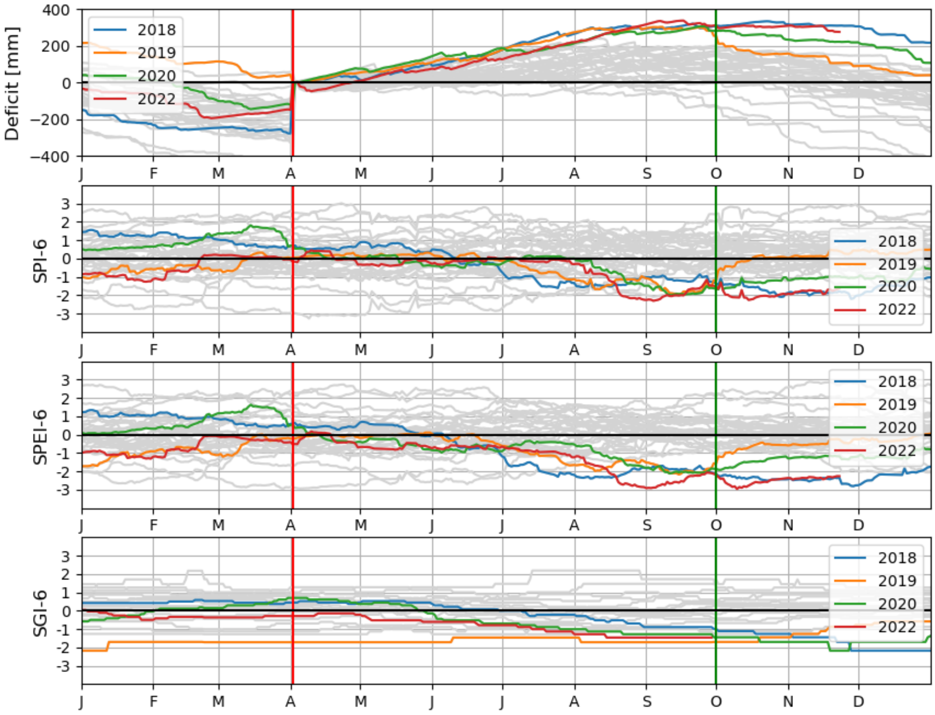

Figure 31: Comparison between SIG - 6, SPI - 6, SPEI - 6 and Precipitation Deficit of 2018

6.2 Analysis on the calculation system of the precipitation deficit

During the analysis, the precipitation deficit was calculated in two different scenarios. The first scenario was to start the calculation from April 1st until September 30th, and the second calculation was to start from March 1st until September 30th. Due to the difference in results, the precipitation deficit has also been calculated with the following starting dates, January 1st, February 1st, March 1st, and April 1st. By doing these calculations, it has been possible to compare the different results.

Figure 32 shows the comparison between the four mentioned scenarios. As can be observed, the different scenarios differ from the provided results. The modeled years are 2003, 2018, 2019, 2020, and 2022. A short explanation of each year has been provided to understand better how the different scenarios behaved on the change of calculation.

- January 1st: the results from initiating the calculation of the precipitation deficit on January 1st showed that the calculated precipitation deficit did not reach the record compared to the results gathered from when the calculation started on April 1st. When the calculation started on January 1st, the precipitation deficit began in mid-June, reaching a maximum deficit of 200 mm in 2022. This is due to including wet months during the calculation, which could be January, February, and March.
- February 1st: the results from initiating the calculation of the precipitation deficit on February 1st have shown that in 2003, the precipitation deficit started to appear during March, indicating that the drought suffered in 2003 started prior to April 1st. On the other hand,

the years started to show a deficit between May and June; the calculated deficit reached a maximum of 300 mm. Compared to the results provided by the calculation of the precipitation deficit on April 1st, a difference in the initiation of the deficits can be observed. For this reason, it can be assumed that February is a wet month.

- March 1st: The results from initiating the calculation of the precipitation deficit on March 1st have shown that in 2003 and 2022, the precipitation deficit started during March. This information showed that the drought experienced in these two years began earlier than April 1st. On the other hand, it can also be observed that the deficit registered in 2019 started to appear in mid-May and not at the beginning of April, referencing that March 2019 was a wet month. On the other hand, the highest precipitation deficit registered during the calculation of March 1st and September 30th was 400 mm.
- April 1st: the results provided by initiating the calculation of the precipitation deficit on April 1st have shown that the 2022 deficit only appeared at the end of April. On the other hand, the other deficits in 2003, 2018, 2019, and 2020 started to appear during the first days of April. These results indicated that the registered deficit during April 2003, 2018, 2019, and 2020 was more significant than the deficit in 2022. On the other hand, the maximum registered deficit was of 300 mm.

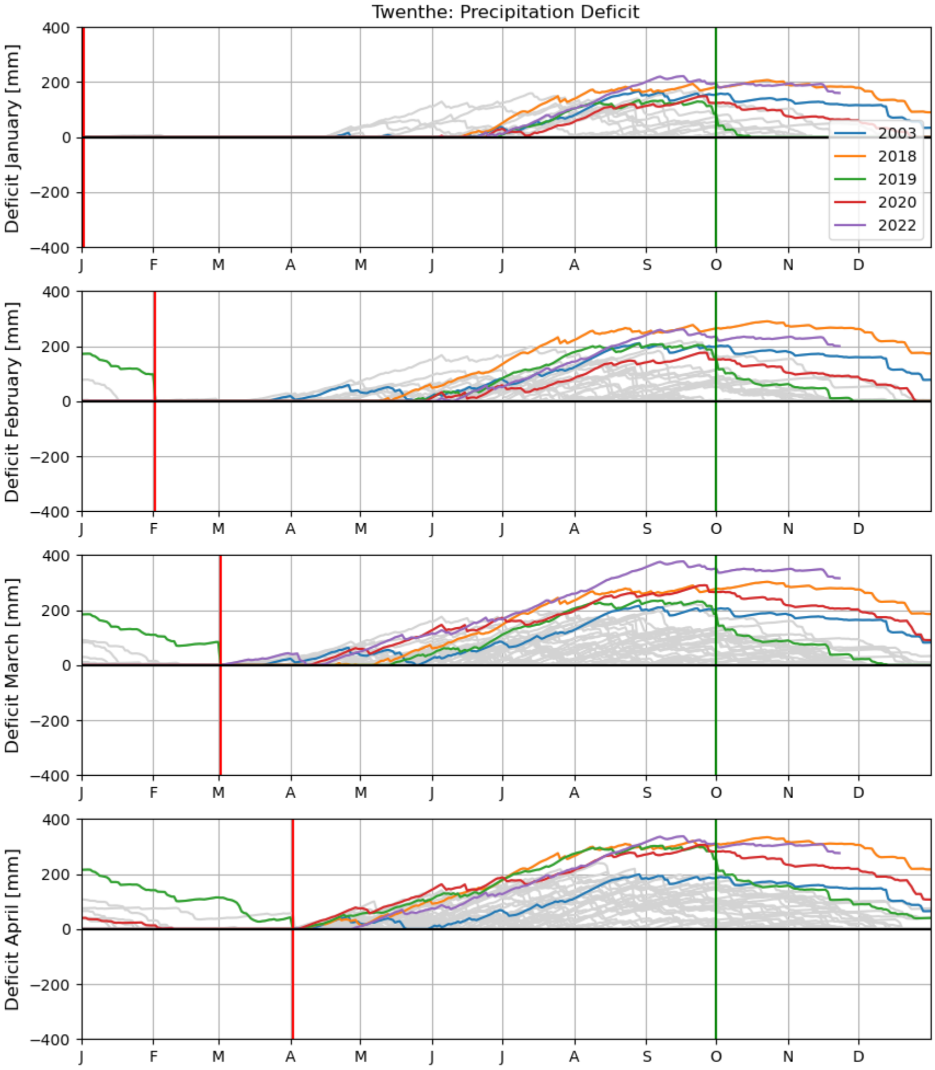

Figure 32: Precipitation Deficit Comparison

From the descriptions mentioned above, the period used for calculating the precipitation deficit influences the perception of the severity of the drought and the maximum deficit that is registered. When this calculation method was implemented, the defined period was correlated to the dry periods that the Netherlands would go through. For example, October – March was wet, and April – September was dry. Nevertheless, due to the consequences of climate change, the dry periods have started to initiate earlier and become more extreme. For example, between 2003 and 2022, the experienced droughts began at the beginning of March. Therefore, by calculating the precipitation deficit on March 1st, it was possible to see more clearly the magnitude and severity of the drought. On the other hand, for the years that the drought did not start during March, the gathered precipitation deficit did not experience a significant impact on the gathered results compared to the results provided from the deficit calculated from April 1st. For this reason, it would be recommended to extend the period for calculating the precipitation deficit from April 1st – September 30th to March 1st – September 30th.

7. Conclusion

This bachelor thesis has aimed to understand the reliability of the different droughts indicators and analyze their performance when applied to the east of the Netherlands. Through further analysis, it has been possible to derive different conclusions that have provided answers to mentioned research questions. Due to the extension and analysis performed through this bachelor thesis, the different conclusions have been separated into different sections.

For research question 1: What is the effect of utilizing different indicators (e.g., SPEI, SPI, SGI, and Precipitation Deficit) on portraying up-to-date water shortages, specifically in the Eastern part of the Netherlands?

- The effect of using different drought indicators provides a broader knowledge of the severity of the drought and the effect of the drought on different sources of fresh – water. It provides detailed information that can be used to develop drought prevention plans. Due to the different input data that indicators require, the use of different drought indicators provides detailed information on droughts' impact on them. It indicates when droughts start, how severe they are, how long they last and when the situation starts to improve.

For research question 2: To what extent is it possible to improve the current calculation methods to guarantee that an indicator (or a combination of indicators) can provide up-to day representation of water scarcity?

    a. To what extent does the off-bound data impact the data recollected between April 1st and September 30th, applied for drought prediction?

- The current drought indicators provide information on the different calculation methods they are subjected to. Prior, a comparison between four different time series was used to calculate the precipitation deficit. Such comparison has provided evidence that the calculation of the precipitation deficit should change its calculation period from April 1st – September 30th to March 1st – September 30th. The results provided earlier show that the dry periods in Twenthe are starting earlier. For this reason, it is necessary to include the effects of this adjacent period so that the deficit calculation can be more precise.

For research question 3: How do the drought indicators provide additional information concerning drought management?

- The use of drought indicators helps to understand how drought affects a specific area. If it is possible to understand what sources of fresh water this drought is threatening, tailored measures can be applied. For example, drought caused by a diminishing amount of precipitation. However, it has not harmed the groundwater levels. Specific measures to reduce the impact of the drought on the groundwater levels could be taken into place.

8. References

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Appendix A

Abrupt or prolonged weather changes can negatively affect a specific area. For example, suppose the amount of precipitation undergoing over a specific area is more extensive and prolonged than the amount for which it was initially designed. In that case, that area can be exposed to flooding. On the other hand, the opposite scenario can also occur. If an area is exposed to little amounts of precipitation and more significant amounts of evaporation over a prolonged period, that area can be exposed to drought.

As a result of climate change, such abrupt weather events have become more frequent, challenging the water management systems and strategies that different countries have had in place. As a result, water management organizations are now invested in predicting extreme weather events so that appropriate measures can be implemented and minimize risks and negative impacts. One of the current measures is drought indicators. Drought indicators predict if a specific area will be experiencing below-average precipitation that affects the soil's moisture and the amount of water in streams, rivers, lakes, and groundwater levels (Drought, 2022).

Over the last decades, different drought indicators have been developed due to their versatility; some indicators can be used more than others. The ability of the different indicators to predict the type of drought an area is undergoing depends on their required input data. For englobing and explaining the most used indicators, the World Meteorological Organization developed a handbook called "Handbook of Drought Indicators and Indices ." In the handbook, the indices are classified into five groups. Such classification is based on the input data that the indicators require or the type of drought they predict. The different groups are:

- **Meteorology:** Indicators found in the meteorology group help to predict meteorological drought. A shortage of precipitation causes meteorological drought over a specific period. Dry weather patterns that dominate an area, are the leading cause for creating a climatological drought (Nag, 2018).

- **Soil Moisture:** indicators found in the soil moisture classification help to predict soil/agricultural drought. Soil Moisture drought connects meteorological droughts to agricultural impacts. For example, a change in precipitation levels over a sustained period, or a change in soil or erosion, might lead to a soil moisture drought. The input data considered for the prediction of this drought are: potential and actual evaporation, transpiration, and soil moisture decrease (Nag, 2018).

- **Hydrology:** indicators found in the hydrology classification are those indicators that help to predict or determine hydrological droughts. Hydrological droughts occur when the water supply becomes scarce due to low water levels in water bodies such as lakes, rivers, or reservoirs. This type of drought is created through the worsening of a meteorological drought (Nag, 2018).

- **Remote sensing:** indicators found in the remote sensing classification help to recollect information from landscapes or areas with vegetation through drones or satellite data. Light is reflected on these areas, and the change to one color indicates how dry or wet that area is. Such information provides knowledge about plant growth and health, helping on categorizing these areas into different land classifications such as water, forest, pasture, etc. (Brecht, 2018).

- **Composite or modelled:** indicators found in the composite or modeled classification aggregate multi-dimensional processes into simplified concepts. These indicators help to provide detailed information to policymakers or strategists regarding a specific area undergoing a particular situation (*Composite indicators* 2022).

Regarding the classification mentioned above, some indicators are used more frequently than others. This can be a consequence of how easy or hard they can be to calculate or if the indicator has been designed for calculating the drought of a specific country or climate.

Nevertheless, research has shown that when experts need to select a drought indicator, there make such a decision based on specific criteria. Between 2014 and 2015, a survey was conducted that asked DEWS (Drought Early Warning System) experts to insinuate the different criteria that they used when it came down to deciding what drought indicator they would choose. Figure 33 shows the different criteria that the experts consider relevant when an indicator needs to be chosen. The relevance of this specific criteria is set on the X- axis. It goes from Unimportant to Very Important. On the Y – axis, the different criteria are listed. On the right side of the Y – axis, the number of experts that responded to these specific questions is given. As can be observed, Data availability and Timeliness of data are two criteria that are considered crucial when it comes down to deciding which indicator to use.

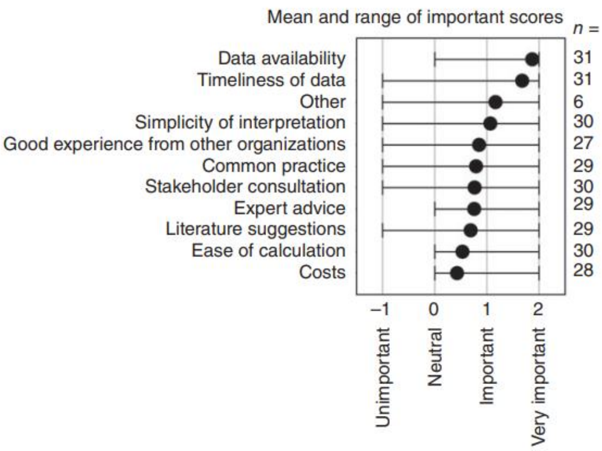

Figure 33: Indicator Criteria (Bachmair et al., 2016)

As stated before, the WMO developed a list of the most used indicators. Nevertheless, from this list, some indicators are used on a larger global scale due to their versatility, calculation, or computation method, such list, can be found in Table A1.

Table A1 provides a list of the indicators used on a global scale. This list also provides a description and benefits that each indicator has.

Table A1: Globally used drought indicators

Indicator	Description	Benefits
Meteorology Indicator		
SPI (Standard Precipitation Index)	SPI uses historical precipitation records, that can be computed at any number of time scales. It can be calculated on minimum 20 years' worth of data. But ideally would be 30 years' worth of data. It can be calculated for short or long-term periods. SPI can be calculated on different time scales. Depending on the type of drought, one time scale or another is recommended (Group, 2016).	The actual amount of rain is measured. Then is compared with a distribution that was determined from the historical time series, after it has been transformed into a normal distribution The results is then translated to wet or dry classification (Group, 2016)
SPEI (Standardized Precipitation Evapotranspiration Index)	SPEI uses the SPI components, but it also includes temperature components. SPEI uses a simple water balance calculations SPEI has the ability to identify very dry or very wet events. (Group, 2016)	Since temperatures are included, for calculating SPEI, it is possible to know the impact of the temperatures on a drought situation. This method is applicable to all types of climates. Due to its standardization, all the results are comparable (Group, 2016).
PDSI (Palmer Drought Severity Index)	It measures the availability of moisture in the region, monitored using a water balance equations. PDSI, incorporates temperature, precipitation, soil moisture and the previous PDSI value (Group, 2016).	The Index has been tested under different scenarios and illustrated the benefits of using precipitation, temperature, and soil characteristics in characterizing droughts (Group, 2016).
CMI (Crop Moisture Index)	CMI is designed as a drought index, that is suited for predicting drought impacts on agriculture (Group, 2016). It responds rapidly, to changing conditions during growing season.	It has a weighted output, which allows for comparing different climate regimes. It responds quickly to rapid changing conditions (Group, 2016).
Sc-PDSIV (Self-Calibrated Palmer Drought Severity Index)	Is based on the original PDSI, and replaces the original constants, with calibrated values. These values are calibrated depending on the	Since this index, adapts to different locations, the index, is able to reflect in a more specific manner, what is happening in a determined location.

	characteristics of each station location. The self-calibrated nature, changes for each station, based on the climate of each location. This index, is able to portray the results for wet or dry scenarios (Group, 2016).	Having more specified information, allows for a more accurate comparison between different regions. Different time steps, can be calculated (Group, 2016).
Deciles	Deciles look at different timescales and time steps. They can be used meteorological, agricultural and hydrological drought situations (Group, 2016).	Only one variable is required, which makes the methodology simple and flexible. Current data can be put in historical context, which makes it possible to recognize drought. It can be used on wet or dry conditions (Group, 2016).
SWSI (Surface Water Supply Index)	SWSI, takes into account the work done with PDSI, but includes additional information such as water supply data. It can identify the rate of different types of drought. Calculations and results cannot be compared, since they are each unique to their study (Group, 2016).	For calculating SWSI, all the different water resources of a basing are taken into consideration. Which foreshadows the hydrological health of a specific region or area (Group, 2016).
	Soil Moisture Indicators	
Soil Moisture Anomaly (SMA)	Can use monthly or weekly precipitation and potential evapotranspiration data. A water balance equation can be used. This indicator allows to see the degree of dryness or saturation of the soil, compared to normal conditions. It shows the soil moisture stress, that affects crop production (Group, 2016).	It considers temperature and precipitation data, PDSI aspects that allow to change constants are included. It is able to determine moisture at different soil layers. Is adaptable to different locations (Group, 2016).
	Hydrology Indicator	
Palmer Hydrological Drought Severity Index (PHDI)	This indicator is based on the original PDSI. It takes into consideration long-term dryness that affects water storage, streamflow and groundwater. PHDI, has the ability to calculate when a drought will end, based on using a precipitation ratio of moisture received to moisture required to end a drought (Group, 2016).	For the application of this indicator, the total water system is considered due to its water balance approach (Group, 2016).

Standardized Streamflow Index (SSFI)	SSFI has been developed by using monthly streamflow and the normalization methods implemented for the calculation of SPI. Can calculate for observed and forecasted data, which provides a perspective on high and low flow periods that can be associated with droughts and floods (Group, 2016).	Can be calculated through the SPI calculation program. Streamflow data is the only input parameter, it allows for missing data, making it easier to use (Group, 2016).
Surface Water Supply Index (SWSI)	SWSI is a hydrology-based indicator. It uses groundwater well levels data to assess the impact of drought on groundwater recharge (Group, 2016).	Assessing groundwater drought is crucial for agricultural and municipal water strategies (Group, 2016).
Remote Sensing Indicator		
Normalized Difference Vegetation Index (NDVI)	NDVI, uses the global vegetation index data, which is produced by daily radiance. It is measured in visible and in near-infrared channels. The greenness is measured over a seven-day period, to reduce cloud contamination (Group, 2016).	Innovative system that uses satellite data to monitor the health of vegetation through drought episodes. It has a high resolution and a good spatial coverage (Group, 2016).
Vegetation Condition Index (VCI)	VCI is used to identify droughts at the beginning of these episodes, especially in areas, where drought episodes are not defined. It focus on the impact of the drought on the vegetation, and is able to provide information on the start, duration and severity of the drought (Group, 2016).	It has, a high resolution and a good spatial coverage (Group, 2016).
Composite or modelled indicator		
Combined Drought Indicator (CDI)	It is composed by three warning levels (watch, warning and alert). It integrates three drought indicators, SPI, Soil Moisture and Remotely sensed vegetation data (Group, 2016).	It has a good and high resolution spatial coverage. It uses a combination between remotely senses and surface data (Group, 2016).

Multivariate Standardized Drought Index (MSDI)	Uses precipitation and soil moisture data. Based on this data, it investigates their corresponding deficits (Group, 2016).	Gridded and global data also represents areas. Since it has a wet and dry scale, it can monitor more than just droughts. It is good to use it in areas where its lacking good surface observations (Group, 2016).

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