THE BALANCE BETWEEN THE GREEN- AND BLUE WATER FOOTPRINT OF CROPS IN GRONINGEN FROM 1990 TO 2050

Bachelor's thesis

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Abstract

The research looks at the balance between the green water footprint and the blue water footprint for the crops winter wheat, sugar beet and potato in the province of Groningen for the period 1990-2050. It also aims to find out which climatic variables contribute most to the respective water footprints. It will do so according to the following research question:

"What is the effect of climate change on the balance between the green water footprint and the blue water footprint over the period 1990-2050 for the most predominantly grown crops in the province of Groningen?"

A data set of the KNMI is used to analyse past climatic data and the HadGEM2-ES model is used for future climatic data predictions with pathway RCP4.5 of the IPCC. To determine the yearly crop water requirements of all crops the CROPWAT model of the FAO is used.
The results show an increase in crop water requirements for all crops. The green water foot print decreases whereas the blue water footprint increases. The balance shifts from a predominantly green water footprint to a more balanced mixture of green water footprint and blue water footprint.
The results from the regression analysis show that the variables that contribute most to the green water footprint and the blue water footprint are average temperature and the number of sun hours. The regression coefficient is negative for the green water footprint and positive for the blue water footprint, meaning that an increase in the mentioned variables causes a decrease in the green water footprint and an increase in the blue water footprint. These findings show that the need for irrigation water will rise in the future. This increased need calls for increased water shortage preparedness of the waterboards Noorderzijlvest and Hunze en Aa's.

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1. Introduction

1.1 Background

Due to a changing climate we will see increasingly wet winters and dry summers (Schmidli et al., 2007). This puts an immense strain on the rain (green) water availability in the summer, when most agricultural practice takes place. In the past little to no irrigation (blue) water has been used for agriculture, but due to an increasing demand for water that has changed over the years. The increase in blue water use has put a huge strain on the groundwater level and in the summers of 2018 and 2019 it became prohibited to use surface water for irrigation in some regions in The Netherlands (Boerderij.nl, 2018).

A lot of research into the water footprint has been done since the concept was first introduced in 2002 (Hoekstra and Hung, 2002) but since the concept is so new there are some gaps in the research. There has been research into the green water footprint and the blue water footprint separately, but as far as I am aware no research has been done in the balance between the two. Moreover, most of the research that has been done on water footprints took place on the global scale (Chapagain et al., 2005; Chapagain and Hoekstra, 2011; Liu et al., 2013). Results on the global scale could differ drastically from the local results. By doing research on the local scale better strategies can be adopted to combat possible problems.

With the use of existing climate models it is possible to calculate future crop water requirements of crops and future effective precipitation, average temperature, sun hours and wind speed. Through combining the findings from these calculations it is also possible to calculate future total-, green- and blue water footprint and thus predict the balance of the green and blue water footprint for the next decades. This is very interesting to do because it can give insight in whether the crops grown in the province of Groningen are sustainable or not. This can help farmers to adapt their farming strategies to better suit the future climate conditions. Furthermore it can also give insight in possible measures that have to be taken by the waterboard Noorderzijlvest and Hunze en Aa's to prevent water shortages. As of now most projects of these waterboards focus on what to do with a surplus of water and how to prevent floods (Waterschap Noorderzijlvest, 2020; Waterschap Hunze en Aa's, 2020). In the future, however, that strategy might have to change to one where the focus shifts slightly more to the containment of water and how to combat water shortages in the summer.

1.2 Research Problem

The aim of this research is to examine how the balance of the green and blue water footprint in the province of Groningen has changed over the past years and how it will change in the future, this will be done through the research question:

"What is the effect of climate change on the balance between the green water footprint and the blue water footprint over the period 1990-2050 for the most predominantly grown crops in the province of Groningen?"

Some questions that arise from this research question are: "How has the balance between the green water footprint and blue water footprint changed over the period 1990-2019?"; "What are the predictions for the future change of the green and blue water footprint?"; "Is there a significant change in the total water footprint, the green water footprint and the blue water footprint before 2020 and after 2020?"; and "What are the past and future crop water requirements for the most predominantly grown crops in the province of Groningen?”. Furthermore this research aims to find out which climatic components attribute most to the total-, green-, and blue water footprint.

1.3 Structure

In the first part of this thesis existing literature on water footprints in relation to agriculture and in relation to climate change is reviewed. Based on this literature a conceptual model with all the different concepts and variables is made. The conceptual model shows how all these variables influence each other. The three hypotheses from this theses consequently follow for the theoretical framework and the conceptual model. After this the methodology is explained, which shows how the data is collected and analysed. This section also provides a critical reflection on the reliability and validity of the data.

After explaining the methodology the results are shown. The chapter contains graphs showing the trajectories of the crop water requirements and the different water footprints of all crops. Additionally shows the statistical analyses that are conducted. In the discussion the results are analysed in greater depth and linked to theory.

The last section of this thesis shows the conclusion. In the conclusion the results are related to the different research questions that are mentioned in the problem statement. The conclusion also discusses the limitations of this research. Additionally it provides policy recommendations and suggestions for future research.

2. Theoretical Framework

2.1 Theory

The water footprint of a product is defined as the total volume of freshwater that is needed to produce the product, or, as I define it in this research, the total volume of freshwater that is needed to grow a certain crop (Chapagain et al., 2005). The water footprint can be split up into three categories: the green water footprint, the blue water footprint and the grey water footprint (Makate et al., 2017; Muratoglu, 2020). The green water footprint regards all infiltrated rainwater that is taken up by plants; blue water regards all infiltrated irrigation water that is taken up by plants and grey water is the amount of water that is needed to assimilate the pollution (chemicals) in the water (Chapagain and Hoekstra, 2011). Grey water will not be used for this research because it is beyond the scope of this thesis.

The study area of this thesis is the province of Groningen, which is located in the north of the Netherlands (map 1).

Map 1 *Groningen (Highlighted) (Wikimedia, 2011)*

Groningen is chosen as the study area because around 80% of the surface is arable land (Provincie Groningen, 2020), which is higher than the Dutch average of 65% (Atlas Natuurlijk Kapitaal, 2017). The predominant soil type in Groningen is clay from tidal and mudflat deposits in the north, and peat in the southeast (Meijles, 2015). The crops that are used in this research are winter wheat, sugar beet and potato. These crops are chosen because together they take up almost 77% of the arable land (CBS, 2020). Groningen has a Cfb climate on the Köppen climate scale, which is defined as a temperate climate with precipitation all year around (Peel et al., 2007).

Important concepts that are used in this thesis are evapotranspiration, effective precipitation and crop water requirements. Evapotranspiration is the sum of evaporation and transpiration through vegetation and is expressed in mm per unit time (Allen et al., 1998). Evapotranspiration (ET_0) is used to calculate the water footprint and can also be split up into green water evapotranspiration (ET_g) and blue water evapotranspiration (ET_b).

Effective precipitation is used to calculate the green water evapotranspiration and is defined as precipitation that is actually stored in the soil (Allen et al., 1998). This differs from total precipitation because not all water is taken up by the soil, as some of the precipitation evaporates before it can be taken up and some of the water goes to deep into the soil, which is called deep percolation (Allen et al., 1998).
Another variable that is used to calculate evapotranspiration is crop water requirement which is the amount of water that is needed to grow a certain crop (Huang et al., 2018). The crop water requirement can be calculated through the CROPWAT model of the Food and Agriculture Organisation (FAO) of the United Nations (2020a). The model makes use of the Penman-Monteith equation of moisture balance to calculate the ET_0.
The last factor that goes into calculating the water footprints is the crop yield of the respective crops (Huang et al., 2018).

Research by Ercin and Hoekstra (2014) predicts that the total water footprint of agricultural production will show an increase over the period 2000 to 2050 in all scenarios that are presented, both the market oriented scenarios and the sustainability oriented scenarios. Furthermore the research shows that the share of the green water footprint will decrease slightly and the share of the blue water footprint will increase in the two sustainability oriented scenarios. This study, however, focusses mostly on changes in consumption and not on changes in climate. When taking climate change into account the shift from green water to blue water becomes more apparent. It is expected that on the global level the use of irrigation water for agricultural purposes will rise by 5 to 27 percent (Liu et al., 2013). Additionally the study of Liu et al. shows that water shortage will become a much more pressing problem over the next decades because of climate change. This are the expected changes on the global scale. Looking more at the regional scale Huang et al. (2018) found similar results for the Hebei province in China. In their study they looked at how the green- and blue water footprint will change for specific crops.

The effect of climate change on the different water footprints has been proven to exist (Liu et al., 2013). However, in none of the studies that mentioned the effects of climate change it is explicitly stated what factors of climate change actually contribute to changing the water footprints. It has been claimed that the change in the distribution of precipitation over the year has an impact on the water footprints (Schmidli et al. 2007; Liu et al., 2013; Kovats et al., 2014; Ding et al., 2018). The other results of climate change, most prominently a rise in temperature, have only been linked to the water footprint and crop water requirements by Huang et al., (2018). In their research they claim that the dominant factors impacting the blue water footprint are effective precipitation, temperature and wind speed.
The current climate change predictions that are relevant for this research area are that the temperature will rise, and that there will be more precipitation during the winter and less precipitation during the summer (Kovats et al., 2014; Schmidli et al., 2007).

This research combines existing knowledge on water footprints, climate change, and crops and aims to apply that on the case of Groningen. The focus of this research is on the local scale level and concerns three crops. This ties into the criticism that water related issues should be addressed on the regional or local level and not on the global level (Gawel and Bernsen, 2011; Wichelns, 2011; Perry, 2014).

2.2 Conceptual model

For the conceptual model there are five key variables to take into account. The most important variables are the green water footprint and the blue water footprint. Those two variables are both dependent variables; the green water footprint is dependent on effective green evapotranspiration and crop yield, and the blue water footprint is dependent on blue evapotranspiration and crop yield. The green evapotranspiration in turn is determined by the crop water requirement and effective precipitation. Blue evapotranspiration is determined by crop water requirement minus green evapotranspiration. The crop water requirement is determined by the crop data of the different crops (crop coefficient, rooting depth and growth period), and the reference evapotranspiration. The factors that influence the reference evapotranspiration are temperature, sun hours, wind speed and humidity.

The independent variables in this research are crop yield, effective precipitation, temperature, sun hours, wind speed and humidity. All the other variables are dependent variables. The green water footprint and the blue water footprint are used as the key dependent variables.

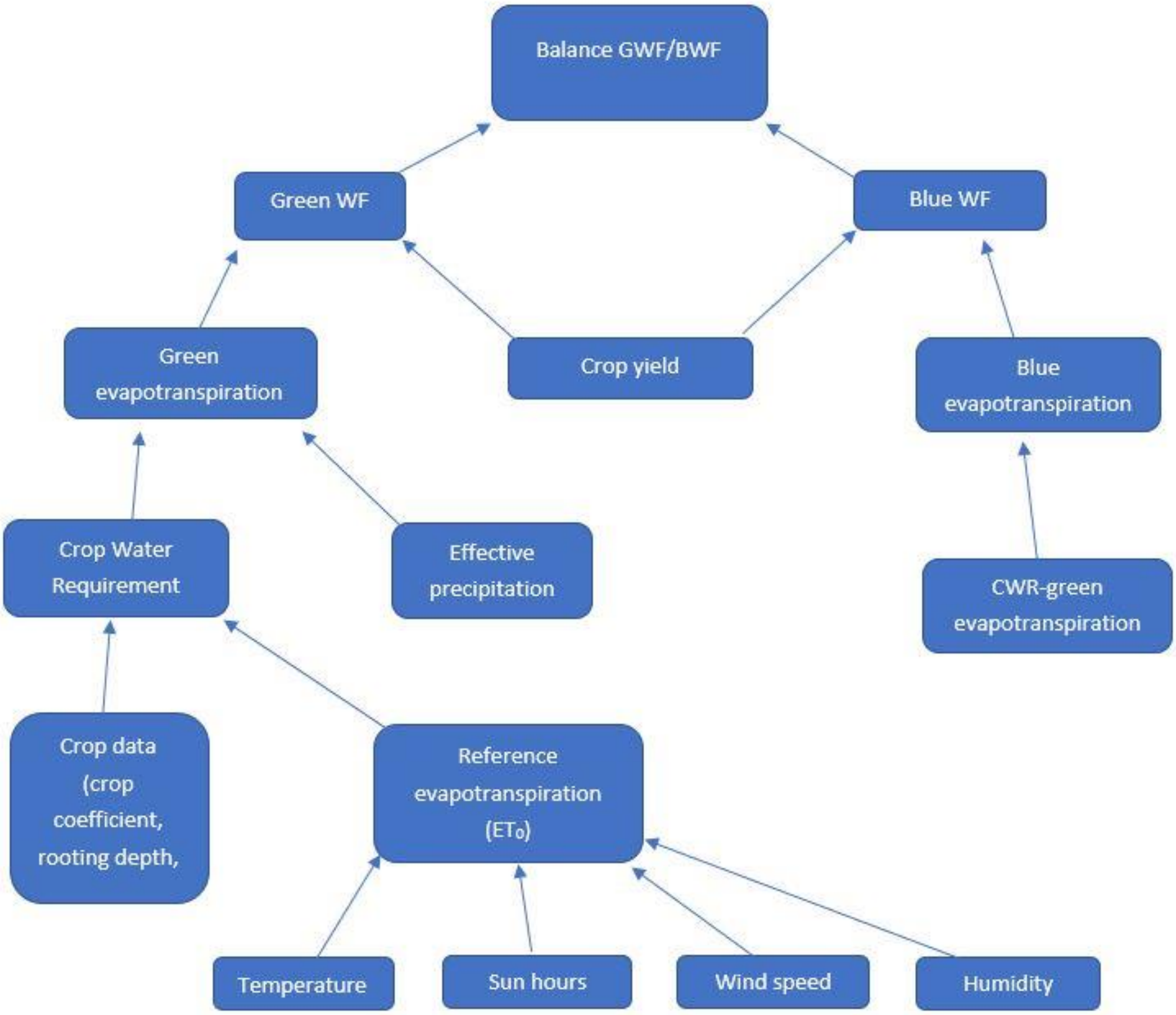

Figure 1 Conceptual model

2.3 Hypotheses

It is expected that there is an effect of climate change on the balance between the green and the blue water footprint. It is difficult to say what the expected effect is because climate change is not the only variable that influences the water footprint. The future crop water requirements of the crops studied in this research also need to be taken into account to make estimations about the effect of climate change on the balance in of both water footprints. Nevertheless it is to be expected that there will be a shift in the balance between the green and blue water footprint that is caused by climate change. The current climate change predictions that are mentioned in the theoretical framework will have an influence on the effective precipitation for the growth period of winter wheat, sugar beet and potato. The effective precipitation in turn heavily influences the green water footprint as can be seen in the conceptual model. These changes in the climate will most likely have the effect that there is less effective precipitation during the summer, when sugar beet and potato are grown. As a result of this it is expected that the green water footprint will decrease, and that the blue water footprint will increase.

I expect to find that effective precipitation, temperature and wind speed will contribute most to the change in the water footprints. Those are the factors that have been linked to impact the blue water footprint (Huang et al., 2018). Moreover, those variables are at the base of the conceptual model, so they influence almost every other variable.

H1: There is an effect of climate change on the balance between the green water footprint and the blue water footprint.

The null hypothesis is: there is an effect of climate change on the balance between the green water footprint and the blue water footprint.

The alternative hypothesis to the null hypothesis is that there is no effect of climate change on the balance between the green water footprint and the blue water footprint.

H2: After 2020 the green water footprint will be lower than before and the blue water footprint will be higher than before.

The null hypotheses of this expectation are: there is no difference in the means of the green water footprint before 2020 and after 2020; and: there is no difference in the means of the blue water footprint before 2020 and after 2020. The alternative hypotheses are: there is difference in the means of the green- and blue water footprints, respectively, before 2020 and after 2020.

H3: The factors that influence the water footprints most are effective precipitation, temperature and wind speed.

The null hypothesis for this expectation is: there is no relationship between effective precipitation, temperature and wind speed and the respective water footprints. The alternative hypothesis that follows from the null hypothesis is: there is a relationship between effective precipitation, temperature, wind speed and the respective water footprints.

3. Methodology and data

3.1 Methods

To calculate the green and blue water footprint of the crops, the following equations are used:

$$WF_{green} = 10 \times \frac{ETgreen}{Y} \quad (1)$$

$$WF_{blue} = 10 \times \frac{ETblue}{Y} \quad (2)$$

In these equations WF_{green} is the green water footprint of a crop measured in m^3/kg, WF_{blue} is a crop's blue water footprint (m^3/kg). ET_{green} and ET_{blue} (mm/month) are the green and blue water evapotranspiration respectively. 10 is used as a constant to convert water depth (mm) into water volume (m^3/ha), and Y is the crop yield (m^3/ha) (Huang et al., 2018).
To calculate the ET_{green} and the ET_{blue} two other equations are needed:

$$ET_{green}[c,q,m] = \min(CWR[c,q,m], P_{eff}[q,m]) \quad (3)$$

$$ET_{blue}[c,q,m] = \max(0, CWR[c,q,m] - ET_{green}[c,q,m]) \quad (4)$$

$ET_{green}[c,q,m]$ is the green water evapotranspiration for a certain crop, c, in a certain area, q, for a certain month, m. This is calculated as the minimum value between the crop water requirement, CWR, and effective rainfall, P_{eff}. The blue evapotranspiration, $ET_{blue}[c,q,m]$, equals the difference between the crop water requirement and the green evapotranspiration. To determine the effective precipitation the USDA method is used. The method converts actual precipitation into effective precipitation based on 50 years of field observations (Allen et al., 1998) The accuracy of this method is classified as medium, but the method is easy and quick to use. Moreover this method is the preferred method in areas with a low intensity of rain fall and a high soil infiltration rate (Allen et al., 1998). Western Europe is classified as such (Schmidli et al., 2007), thus this is the method that will be used.
The crop water requirement is calculated by multiplying the reference evapotranspiration, ET_0 (mm/month) by the crop coefficient, K_c, over the period of growth (Novo et al., 2009). ET_0 will be calculated through the Penman-Monteith equation, as is recommended by the FAO.

3.2 Data collection

The data that is needed for these equations can be retrieved from the Royal Netherlands Meteorological Institute (KNMI), the Climate Data Store of Copernicus (Copernicus, 2020) and the FAO (2020b). The monthly precipitation values will be retrieved form the KNMI weather station Groningen/Eelde because that station is closest to the study area (KNMI, 2020). The growth period of the most predominant crops in Groningen – wheat, sugar beets and potatoes (CAB, 2011) – will be retrieved from the FAO (1998), as will the growth time of the crops and the crop coefficients. The crop yield of the selected crops will be obtained from the Dutch Central Bureau of Statistics (CBS) for the years 1990-2019. To predict future crop yield the average values of the crop yield from 2009-2019 will be taken. This is because the crop yield for all crops has not changed much over the last 10 years. For this research the assumption is made that the crop coefficient, critical depletion, yield response and other crop data will stay the same.

In order to make predictions about future precipitation rates, temperature, sun hours and wind speed the HadGEM2-ES model was used with input data from the KNMI-RACMO22E model. There was no data available on future humidity, so humidity will not be included in the analysis. The output data of the projection is in a NetCDF4 format. This is a three dimensional format which shows longitude, latitude and time. The data was analysed using the Panoply program of NASA (NASA GISS, 2020).

The Representative Concentration Pathway 4.5 (RCP4.5) of the IPPC was chosen as the input scenario to the model. This is one of the intermediate scenarios in which it is assumed that at the end of the 21st century the radiative forcing stabilises after reaching 4,5W/m^2 (IPCC, 2020). This RCP is chosen because it is an intermediate scenario and it is likely to happen if some mitigation against climate change takes place in the 21st century (IPCC, 2020).

3.3 Data analysis

A paired samples t-test was carried out to test the difference in crop water requirement, total water footprint, green water footprint and blue water footprint for the period 1990-2019 and the period 2020-2049. The probability value was set at p=>0.05 which is the standard margin when testing for significance (Burt et al. 2009).

Additionally a multiple linear regression analysis was conducted to find out which variables contribute the most to the total water footprint, green water footprint, and blue water footprint. The forward method was used to add variables to the regression model. This was done to find out which variables contribute most to the adjusted R^2 – the explained variance – of the model. Another benefit of the forward method is that the non-significant values are not included in the model. This ensures a better inside in what factors actually contribute to the different water footprints and how much each variable adds to the explained variance (Burt et al., 2009).

3.4 Reliability and validity

The datasets of the KNMI and the CBS that are used for this research are both reliable and valid. The data from both datasets are recorded numbers from the past in absolute numbers. As a result of this there has been no research method bias in selecting the data, which means that if another researcher would carry out the exact same research they would get the same results as presented in this thesis (Noble & Smith, 2015).

The data from the HadGEM2-ES model on the other hand is a lot less reliable and accurate. It is impossible to make exact statements about future weather conditions. The output of the model shows merely an estimation. Moreover, it projects the data on a different scale level than used in this research. This has a negative impact on the accuracy of the data. The chosen IPCC scenario is an intermediate scenario between two outliers and is likely to occur if some measures against climate change are taken on the global level. It is not certain yet what measures are going to be taken against climate change in the future. This means that another scenario than the one used in this research might actually happen. It is however the most likely scenario of the three presented scenarios (IPCC, 2020).

4 Results and discussion

4.1 Results

Over the period 1990-2050 (the shaded areas in all figures indicates projected data) the crop water requirements for the crops winter wheat, potato and sugar beet have all risen slightly (figure 2). It is also illustrated in the figure that there is no clear upward trend, with the exception of winter wheat, due to the huge variety in crop water requirements between the different years. The results from the paired samples t-test however show that there is a difference between the crop water requirements before 2020 and after 2020, the values after 2020 being higher than the values before 2020 (table 1 to 3). The difference is the biggest for winter wheat and smaller for sugar beet and potato. The rise was to be expected as the average number of daily sun hours, average minimum temperature, and average maximum temperature have also increased. Those variables are used to calculate the CWR so an increase in the variables causes an increase in the crop water requirement.

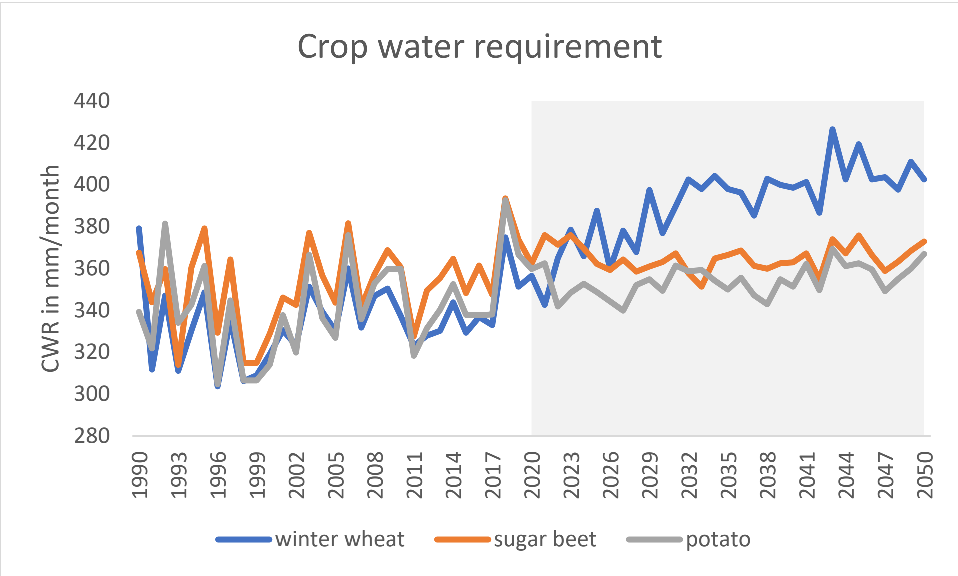

Figure 2 The crop water requirements of winter wheat, sugar beet and potato

The total water footprint of sugar beet and potato shows a decrease up until 2018, after which the decrease comes to a stop and evens out (figure 3). For the green water footprint on the other hand the decrease continues well into the future (figure 4). The total- and green water footprints show similar trajectories for sugar beet and potato after 2020. This is due to the fact that a fixed number has been taken as the future crop yield.

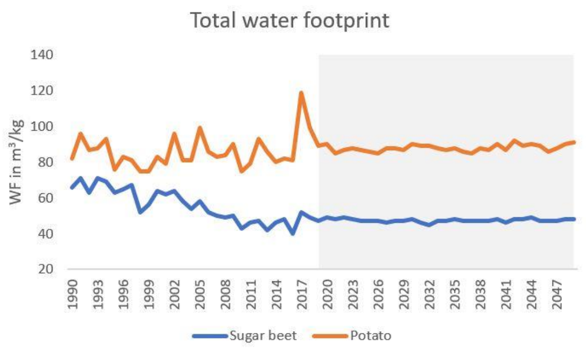

Figure 3 The total water footprint of Sugar beet and potato

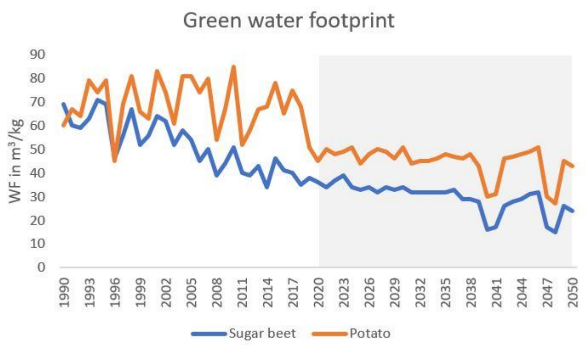

Figure 4 The green water footprint of sugar beet and potato

The green water footprint and total water footprint of winter wheat can be seen in figure 5. Similarly to sugar beet and potato, both water footprints decrease until 2020. In contrast to the other crops however, both water footprints start to rise again after 2020. In the years after 2030 those paths start to diverge more and more.

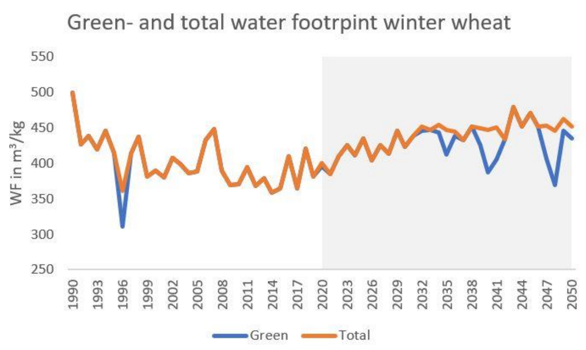

Figure 5 The green water footprint and total water footprint of winter wheat

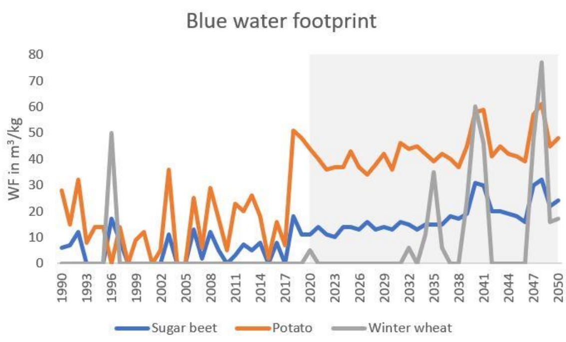

Figure 6 The blue water footprint of sugar beet, potato and winter wheat

When looking at the blue water footprints of all crops (figure 6), there is a clear difference in the blue water footprint before 2019 and after 2019 for all crops. The blue water footprint after 2019 is considerably higher than before. This can also be seen in the results from the paired samples t-test (table 1 to 3). This increase can be explained by the unchanging total water footprint and the decrease in the green water footprint. The exception to this trend is the crop winter wheat. Winter wheat has a very low need for blue water with a few outliers.

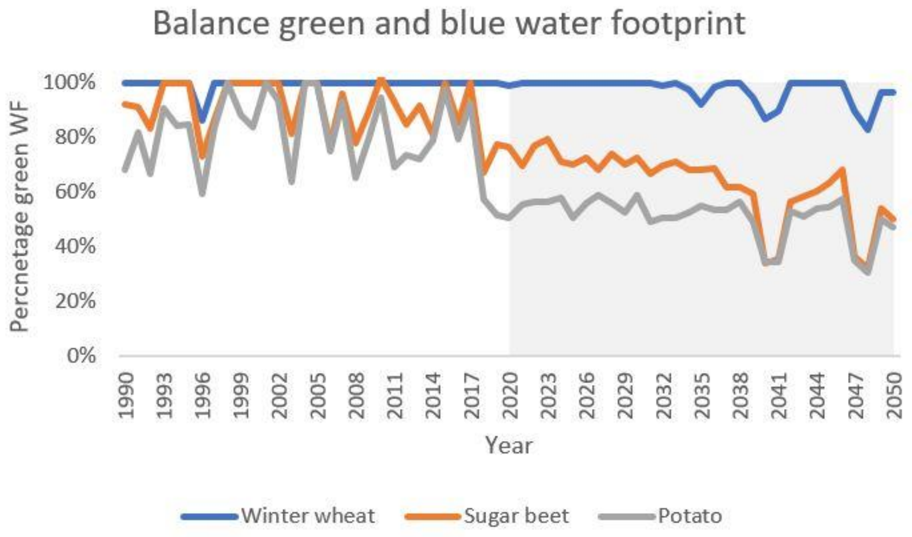

Figure 7 The balance between the green water footprint and blue water footprint for winter wheat, sugar beet and potato

Figure 7 shows the balance between the green water footprint and the blue water footprint. The Y-axis shows the green water footprint as a percentage of the total water footprint. What can be observed is that up to 2018 the share of the green water footprint always exceeds 60%. After 2018 it starts to dip below that line. What can also be seen is that the balance changes the most for potato, followed closely by sugar beet. Winter wheat has an almost entirely green water footprint. There are only a few years in which the share of the green water footprint is not 100% and even then it does not come below 80%.

A factor that has caused the overall water footprint to decrease over time is the crop yield. Even though the CWR has stayed the same or even increased slightly, an increase in crop yield for mostly sugar beet and potato has caused the total water footprint to decrease. This decrease in the total water footprint influences the balance between the green water footprint and the blue water footprint. It causes the blue water footprint to increase less than it would have if the total water footprint stayed the same. Even though the green water footprint decreases due to a decrease in effective precipitation and a more or less stable crop water requirement, the blue water footprint does not increase as much as expected because of a decrease in the total water footprint.

A paired samples t-test was run to test whether or not there was a difference in the water footprints and crop water requirements from 1990 to 2019 and 2020 to 2049 (labelled pre 2020 and post 2020 respectively). In the model the values after 2020 are subtracted from the values before 2020. This means that a negative difference in the mean indicates an increase and a positive difference indicates a decrease. The test was run for all three crops. For the paired samples t-test the null hypothesis was: 'there is no difference in the means from the values from 1990 to 2019 and the values from 2020 to 2049'. What can be seen in tables 1 to 3 is that in almost all cases a difference between the two periods is proven to exist. There has been an increase in the crop water requirements for all crops and an increase in the blue water footprint for all crops. Additionally the green water footprints of sugar beet and potato show a decrease.

Table 1 (Winter wheat)

Paired Samples Test

		Paired Differences							
					95% Confidence Interval of the Difference				
		Mean	Std. Deviation	Std. Error Mean	Lower	Upper	t	df	Sig. (2-tailed)
Pair 1	CWR pre 2020ww - CWR post 2020ww	-54,9867	23,7867	4,3428	-63,8688	-46,1046	-12,661	29	,000
Pair 2	Wftotal pre 2020ww - Wftotal post 2020ww	-36,633	48,503	8,855	-54,745	-18,522	-4,137	29	,000
Pair 3	Wfgreen pre 2020ww - Wfgreen post 2020ww	-12,0867	59,9383	10,9432	-34,4680	10,2947	-1,104	29	,278
Pair 4	Wfblue pre 2020ww - Wfblue post 2020ww	-9,400	23,497	4,290	-18,174	-,626	-2,191	29	,037

Table 2 (Sugar beet)

Paired Samples Test

		Paired Differences							
					95% Confidence Interval of the Difference				
		Mean	Std. Deviation	Std. Error Mean	Lower	Upper	t	df	Sig. (2-tailed)
Pair 1	CWR pre 2020sb - CWR post 2020sb	-12,2700	21,4156	3,9099	-20,2667	-4,2733	-3,138	29	,004
Pair 2	Wftotal pre 2020sb - Wftotal post 2020sb	9,067	9,762	1,782	5,421	12,712	5,087	29	,000
Pair 3	Wfgreen pre 2020sb - Wfgreen post 2020sb	21,600	8,704	1,589	18,350	24,850	13,592	29	,000
Pair 4	Wfblue pre 2020sb - Wfblue post 2020sb	-12,3200	7,9401	1,4496	-15,2849	-9,3551	-8,499	29	,000

Table 3 (Potato)

Paired Samples Test

		Paired Differences							
					95% Confidence Interval of the Difference				
		Mean	Std. Deviation	Std. Error Mean	Lower	Upper	t	df	Sig. (2-tailed)
Pair 1	CWR pre 2020p - CWR post 2020p	-12,4767	23,6535	4,3185	-21,3090	-3,6443	-2,889	29	,007
Pair 2	Wftotal pre 2020p - Wftotal post 2020p	-1,933	9,329	1,703	-5,417	1,550	-1,135	29	,266
Pair 3	Wfgreen pre 2020p - Wfgreen post 2020p	24,067	12,600	2,300	19,362	28,771	10,462	29	,000
Pair 4	Wfblue pre 2020ww - Wfblue post 2020p	-27,067	13,704	2,502	-32,184	-21,950	-10,818	29	,000

For winter wheat the differences in crop water requirement, WFblue and total WF were significant which means that there is a difference in those variables between pre 2020 and post 2020. The means of the significant variables is higher post 2020 than pre 2020.
For sugar beet the differences between all four variables were significant. There is a decrease in total water footprint and in the green water footprint, and an increase in crop water requirement and blue water footprint.
For the crop potato the differences in crop water requirement, green water footprint and blue water footprint were significant. The differences in total water footprint were not. The crop water requirement and blue water footprint increased whereas the green water footprint went down.

To determine which variables contribute to the respective water footprints a multiple linear regression was run. The null hypotheses for all tests was 'there is no linear relationship between the water footprint and the independent variables'. The results from the multiple linear regression can be seen in table 4. The results show that the average temperature and the number of sun hours have the biggest impact on the on all water footprints, as they occur the most and contribute most to the adjusted R Square. The adjusted R Square differs greatly between each model; the biggest being 0,684 for the green water footprint of sugar beet, and the smallest being 0,159 for both the blue water footprint of winter wheat.

Table 4 Results from the regression analysis

	Entered variable	Regression Coefficient	Adjusted R Square	Significance
WFtotal winter wheat	Average temperature	,630	,353	,000
	Wind speed	,236	,399	,022
WFgreen winter wheat	Average temperature	,641	,196	,000
	Sun hours	-,322	,255	,021
WFblue winter wheat	Sun hours	,460	,075	,018
	Wind speed	,348	,159	,011
WFtotal sugar beet	Sun hours	-,108	,272	,000
	Wind speed	,326	,347	,007
	Average temperature	-,424	,458	,001
WFgreen sugar beet	Average temperature	-,528	,529	,000
	Sun hours	-,320	,655	,000
	Wind speed	,206	,684	,016
WFblue sugar beet	Average temperature	,579	,466	,000
	Sun hours	,309	,569	,000
	Effective precipitation	-,204	,595	,034
WFtotal potato	Sun hours	,511	,249	,000
WFgreen potato	Average temperature	-,466	,392	,000
	Sun hours	-,297	,443	,014
WFblue potato	Average temperature	,481	,527	,000
	Sun hours	,442	,656	,000

What can also be seen in table 4 is that for the total water footprint the regression coefficients are positive with the exception of the water footprint of sugar beet. The positive regression coefficients mean that the water footprint will increase as the variables average temperature, sun hours and wind speed increase (Burt et al., 2009). The positive regression coefficient is plausible because a rise in the independent variables causes an increase in the crop water requirement, which heavily influences the water footprint.
When looking at the blue water footprint the regression coefficients are all positive, except for effective precipitation. This means that an increase in the variables average temperature, sun hours and wind speed cause an increase in the blue water footprint. The negative regression coefficient for precipitation means that a decrease in precipitation causes an increase in the blue water footprint.

4.2 Discussion

The total water footprint of the crops winter wheat and sugar beet has decreased over the last 30 years but this decrease will come to a stop (figure 2). The decrease is mainly due to the increase in crop yield per hectare for those crops. The crop yield of especially sugar beet has increased a lot. This can be explained by the advancements and genetic modifications which increase the crop yield (Hoffmann & Kenter, 2018). The reason the decrease has come to a stop is that the future crop yield is calculated as an average of the last ten years in this research. In reality the crop yield per hectare might continue to increase, but calculating that has not been a focus of this research.

The similar trajectories of the green water footprints of sugar beet and potato are also a result of the set future crop yield. The slight variance of the lines can be explained by the precipitation in the months of growth for both crops. Those differ slightly as sugar beet has a longer growth period and therefore the effective precipitation in the growth period differs slightly.

As shown in figure 1 the crop water requirements for winter wheat show a sharper increase than for the other crops. This in combination with an unchanged crop yield explains the rise in total water footprint after 2020. It can also be noticed that the green water footprint mostly overlaps with the total water footprint. In the years both water footprints overlap there is enough effective precipitation to meet the crop water requirements of winter wheat, so no blue (irrigation) water is needed to grow winter wheat.

The almost non-existent blue water footprint of winter wheat can be attributed to the fact that winter wheat has a low crop coefficient, which means the crop water requirements are low. Winter wheat grows during the winter in low temperatures which drastically lower the ET_0 of the crop, which also causes the crop water requirements to be low. Moreover winter wheat takes the longest to grow so it gets the most precipitation (Schmidli et al., (2007). In the future this might change however as can be seen in figures 1, 4 and 5. The crop water requirement and total water footprint will increase the coming decades, as will the blue water footprint.

These results are in line with the findings of Liu et al. (2013) whose research showed similar results on the global scale; and Huang et al. (2018) who found similar results for the Hebei province in China. There is a slight contrast with the findings of Ercin & Hoekstra (2013) who predict the decrease in the green water footprint to be much smaller than the results of this research show. Additionally their research also shows a much smaller increase of the blue water footprint. This can be explained by the fact that they do not include climate change in their models, as they choose to focus on the consumption demand.

The fact that the average temperature, the number of sun hours and wind speed have the biggest impact on the respective water footprints is not in line with the expectations. It was expected that the effective precipitation would play a much larger role (footprints (Schmidli et al. 2007; Liu et al., 2013; Kovats et al., 2014; Ding et al., 2018). Furthermore, the number of sun hours was not mentioned in any of the papers to have an impact on the water footprints. In calculating the ET_0 however the number of sun hours is an important component of the equation, this explains its importance in the regression model and its presence in the conceptual model.

The variable effective precipitation was only significant in one model, WFblue for sugar beet. This is different from what was expected. It was expected that effective precipitation would have a big impact on all water footprints. This result is also not in line with the results presented by Huang et al. (2018) in whose research effective precipitation played a big role in the composition of the water footprints.

The change in the balance between the green water footprint and the blue water footprint is attributed to a decrease in green water footprint and an increase in blue water footprint. The green water footprint shows a decrease because of a decrease in precipitation during the summer months. The blue water footprint shows an increase because of a decreasing green water footprint and an increased crop water requirement. This results in a shift in the balance from predominantly green water footprint to a mix of green and blue water footprint. The green water footprint is still bigger than the blue water footprint, but that may change in the even further future.

5. Conclusion

In this research I looked at how the balance between the green- and blue water footprint changed over the period 1990-2050 for the crops winter wheat, sugar beet and potato in the province of Groningen. This was done by analysing climatic data from the KNMI, future climate projections from the Copernicus Institute, crop yield data from the CBS and crop data from the FAO. The hypotheses were that the balance would shift from a predominantly green water footprint to a mixture of green- and blue water footprints for all crops; that climate change would influence the water footprints; and that precipitation, temperature and sun hours would have the biggest impact on the water footprints.

The results show that the balance of the green- and blue water footprint does indeed shift from being predominantly green to a mixture of both green and blue.

The second hypothesis is accepted. The means of the blue water footprints of all crops are significantly higher after 2020 than before 2020 and the means of the green water footprints of sugar beet and potato are significantly lower after 2020 than before 2020.

The last hypothesis is rejected. Temperature and wind speed have a big impact on all water footprints. They are significant in most models and they contribute most to the explained variance. Precipitation on the other hand was only proven to be significant in one model and contributed little to the explained variance. The number of sun hours was a significant variable in some models which was unexpected because it was not mentioned in any of the literature.

There have been a number of limiting factors in this research. First and foremost the reliability of the future climatic data. Even though an intermediate scenario, RCP 4.5, of the IPCC was used it is still very likely that the actual future data will differ from the data used in this research. Furthermore, the data projection that was used is a continental projection for the entirety of Europe. The data used for this research is very local, so it most likely is not very precise.

Another limitation is the crop data and crop yield data. In this research the assumption has been made that crop data and crop yield data will stay the same in the next thirty years. This will, very likely, not be the case at all. Crops will probably become more efficient and the crop yield per hectare will probably see a further increase. My knowledge on both those variables is not sufficient to incorporate those changes correctly in this research. Furthermore, no distinctions have been made in the spatial distribution of both crops and weather variations as that has been beyond the scope of this thesis.

Further research into this topic could include the second shortcoming of this research and include a calculation on future crop yields. Additionally future research could include soil analysis. By studying the soil properties a more precise estimation of the effective precipitation can be made.

It would also be interesting to conduct research in different areas in the Netherlands that are subjected to water shortages more than Groningen – for example the south and east of the Netherlands – or on a different scale level.

Following this research there are some policy recommendations that can be made. As the results show, the blue water footprint is increasing. Therefore it is commendable that the waterboards Noorderzijlvest and Hunze en Aa's start preparing for an even bigger pressure on irrigation water in the summer months. Moreover further research into alternative irrigation methods and schedules is desirable to prevent the pressure on the ground water from becoming too burdensome.

References

Allen, R. G., Pereira, L. S., Raes, D. and Smith, M. (1998). Crop evapotranspiration - Guidelines for computing crop water requirements. *FAO Irrigation and Drainage,* 56, chapter 1

Boerderij.nl (2018). "Droogte zeker tot diep in volgende week". Retrieved from: https://www.boerderij.nl/Home/Nieuws/2018/7/Nu-ook-beregeningsverbod-Veluwe-304311E/ accessed on 28-02-2020

Burt, J. E., Barber, G. M. and Rigby, D. L. (2009). *Elementary statistics for geographers*. 3rd edn. New York: Guilford Press.

CAB (2011). Landbouw in Noord-Groningen. Retrieved from https://kennisplatformbewoners.nl/fileskpb/Landbouw_Noord-Groningen_-_Project_Bedreigd_Bestaan_0.pdf accessed on 28-02-2020

CBS (2020). Akkerbouwgewassen; productie naar regio. *CBS Statline.* Retrieved from https://opendata.cbs.nl/statline/#/CBS/nl/dataset/7100oogs/table?ts=1593863323549 last updated on 03-07-2020

Chapagain, A. K., Hoekstra, A. Y., Savenije, H. H. G. and Gautam, R. (2005). The water footprint of cotton consumption: An assessment of the impact of worldwide consumption of cotton products on the water resources in the cotton producing countries. *Ecological Economics,* 60 pp 186-203

Chapagain, A.K. and Hoekstra, A. Y. (2011). The blue, green and grey water footprint of rice from production and consumption perspective. *Ecological Economies,* 70(4), pp. 749-758

Copernicus (2020). *Climate data store.* Retrieved from https://cds.climate.copernicus.eu/cdsapp#!/dataset/projections-cordex-single-levels?tab=form accessed on 28-04-2020

Ding, D., Zhao, Y., Guo, H., Li, X., Schoenau, J. & Si, B. (2018). Water footprint for pulse, cereal, and oilseed crops in Saskatchewan, Canada. *Water,* 10(11)

Ercin, A. E. & Hoekstra, A. Y. (2014). Water footprint scenario's for 2050: a global analysis, *Environment International,* 64, pp. 71-82

Hoffmann, C. M. and Kenter, C. (2018). Yield potential of sugar beet – have we hit the ceiling?. *Frontiers in plant science,* 9

FAO (2020a). *CROPWAT*. Version 8.0 Rome, Italy: Food and Agriculture Organisation of the United Nations

FAO (2020b). *Crop Water Information.* Retrieved from http://www.fao.org/land-water/databases-and-software/crop-information/en/ accessed on 13-05-2020

Gawel, E. and Bernsen, K. (2011). Do we really need a water footprint? Global trade, water scarcity and the limited role of virtual water. *Gaia-Ecological Perspectives for Science and Society,* 20(3), pp. 162-167.

Hoekstra, A.Y., Hung, P.Q. (2002). Virtual water trade: A quantification of virtual water flows between nations in relation to international crop trade. *Value of water.* Research report series No. 11, UNESCO-IHE

Huang, H., Han, Y. and Jia, D. (2018). Impact of climate change on the blue water footprint of agriculture on a regional scale. *Water science and technology: Water supply,* 19(1), pp. 52-59

IBM Corp. (2019). *IBM SPSS Statistics for Windows*. Version 26.0. Armonk, NY: IBM Corp.

IPCC (2020). Climate Change 2014 Synthesis Report Fifth Assessment Report. Retrieved from: https://ar5-syr.ipcc.ch/index.php accessed on 28-02-2020

KNMI (2020) *Maand- en jaarwaarden*. Retrieved from https://www.knmi.nl/nederland-nu/klimatologie/maandgegevens accessed on 28-02-2020

Kovats, R.S., Valentini R., Bouwer L. M., Georgopoulou E., Jacob D., Martin E., Rounsevell M., &

Soussana, J. F. (2014) Europe. *In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1267-1326.

Liu, J., Folberth, C., Yang, H., Röchkström, J., Abbaspour, K., Zehnder, A. J. B. (2013). A Global and Spatially Explicit Assessment of Climate Change Impacts on Crop Production and Consumptive Water Use. *PLOS ONE,* 8(2): e57750. https://doi.org/10.1371/journal.pone.0057750

Makate, C., Wang, R. & Tatsvarei, S. (2018) Water footprint concept and methodology for warranting sustainability in human-induced water use and governance, *Sustainable Water Resources Management,* 4(1), pp. 91-103.

Meijles, E. (2015). A geological history of Groningen's subsurface. *Department of Physical Geography of the University of Groningen*

Muratoglu, A. (2020). Assessment of wheat's water footprint and virtual water trade: a case study for Turkey. *Ecological Processes,* 9(1)

NASA GISS (2020). *Panoply netCDF, HDF and GRIB Data Viewer.* Version 4.11.3. NY: NASA GISS

Noble, H. & Smith, J. (2015). Issues of validity and reliability in qualitative research. *Evidence based nursing,* 18(2), pp. 34-35

Novo, P., Garrido, A., Varela-Ortega, C. (2009). Are virtual water "flows" in Spanish grain trade consistent with relative water scarcity? *Ecological Economies,* 68(5) pp1454-1464

Peel, M. C., Finlayson, B. L., and McMahon, T. A. (2007). Updated world map of the Köppen-Geiger climate classification, *Hydrological Earth System Science*, 11, pp. 1633–1644, https://doi.org/10.5194/hess-11-1633-2007

Perry, C. 2014. Water footprints: Path to enlightenment, or false trail? *Agricultural Water Management,* 134, pp. 119-125

Provincie Groiningen (2020). Landbouw *De staat van Groiningen* Retrieved from https://destaatvangroningen.nl/ob18-landbouw.html accessed on 04-07-020

Schmidli, J., Goodess, C.M., Frei C., Haylock M. R., Hundecha Y., Ribalaygua J., & Schmith, T. (2007). Statistical and dynamical downscaling of precipitation: an evaluation and comparison of scenarios for the European Alps. *Journal of Geophysical Research*, 112(D4)

Waterschap Hunze en Aa's (2020). *Projecten.* Retrieved from https://www.hunzeenaas.nl/projecten/ accessed on 20-06-2020

Waterschap Noorderzijlvest (2020). *Projecten.* Retrieved from https://www.noorderzijlvest.nl/ons-werk/projecten/ accessed on 20-06-2020

Wichelns, D. (2011). Do the virtual water and water footprint perspectives enhance policy discussions? *International Journal of Water Resources Development* 27(4), pp. 633-645.

Wikemedia (2011). Groningen in the Netherlands. *Wikimedia Commons* Retrieved from https://nl.wikipedia.org/wiki/Bestand:Groningen_in_the_Netherlands.svg accessed on 07-07-2020